CHAPTER - 4

PETROGRAPHY

"Experimental geology has this in common with all other branches of our science, petrology and palaeontology included, that in the long run it withers indoors"
Phillip H. Kuenen

4.1 Introduction

Petrography is the most effective primary tool and direct method to characterize the nature of magma's final product, which is reflected in a specific mineral assemblage of igneous rocks as a result of crystallization. Textural features differentiate the major rock-types into igneous, metamorphic and sedimentary ones but play a crucial role while determining the geochemical behaviour and physico-chemical environments of rocks. Photomicrograph and reaction texture play a crucial role in metamorphic petrology. Pressure and temperature conditions affect the pre-existing mineral assemblages, and accordingly, it is known as prograde and retrograde metamorphic conditions. Protolith represents the parent rock, which existed before metamorphism. Metamorphic rocks preserve the original texture in low-grade facies and determine potential protoliths. As the metamorphic grade increases, the original texture is replaced with the metamorphic textures. Igneous rocks are formed by the differentiation processes (crystallization, fractionation, mixing, and assimilation) during a liquid or magma cooling. Petrography includes megascopic and microscopic observations which can reveal the involved magmatic processes and nature of melt composition based on the mineral assemblages, mineral size, shape and their cumulus and intercumulus proportions etc. A crystal or mineral developed through the first nucleation at liquidus, followed by diffusion of elements and growth rates that depend upon compositions, prevailing physical conditions of magma such as fugacity, pressure, temperature, nature of emplacement (intrusive or extrusive) and type of protolith for generating these melts.

The petrographic observations of high-grade gneisses, granulites and related rocks of Daltonganj region of Chhotanagpur Granite Gneiss Complex (CGGC) have been documented in order to establish *P-T* conditions and metamorphic evolutionary history. Further electron probe microanalyses (EPMA) of silicate minerals constituting these granulites and high-grade gneisses have been carried out from the representative samples of studied lithotypes, which usually help deciphering mineral-chemical evolution, classification, elemental substitution relationships, *P-T* estimation for exchange reaction on equilibrium condition, multistage of metamorphism condition recognized by zoning minerals, and oxygen fugacity determined by the ilmenite-magnetite association.

4.2 Petrography

The detailed petrographic characters of different rock types are described, emphasizing their mineral associations' textural characteristics and reaction relationship from the study area. The textural characteristics have been made to decipher the time relationships between crystallization and the different deformation phases. Various structural phenomena are considered to be progressive events against the metamorphism, which has been dated are;

i. The first stage of deformation (D_1) and folding (F_1) are developed on bedding plane (S_1) with the formation of axial plane foliation (S_2),
ii. The second stage of deformation (D_2), related with (F_2) fold is formed with the axial plane foliation (S_3).

The geochronological investigation of mineral crystallization, growth and deformational history relies on porphyroblasts between the rock fabrics (S_e) and internal trails (S_i) [277, 278]. Most deformed metamorphic rocks are characterized by preferred orientation. The relationship between S_i and S_e is not well documented in granulite facies of rocks due to crystallization during post kinematics phase after deformation compared to those from the lower grade greenschist and amphibolite facies. However, the study area's granulites have undergone multiple deformation and poly-metamorphism. The rocks of the studied areas exhibit tremendous metamorphic reaction textures that participate in the formation of various mineral assemblages and are documented by various reaction corona and symplectites intergrowth. Here, it is defined that high-grade granulites hold strong refractory mineral phases such as garnet, orthopyroxene, clinopyroxene, amphibole, plagioclase, sillimanite, and cordierite. That is competent to retain evolutionary history signatures through "arrested" and "frozen-in" textures. It is strongly felt that disequilibrium textures in rocks are more promising contestants for detailed petrological examinations. The metamorphic textures retained in high-grade rocks exert fine control in deducing orogenic *P-T* path. Therefore, critical investigation of such textural features preserving *P-T* path segments' signatures can be highly advantageous.

4.3 Preparation of thin polished section

4.3.1 Introduction

Besides a good microscope and its standard set of accessories, the first and foremost requisite for successful mineralogical investigation is a well prepared and highly polished rock sample. This is a challenging and specialized job, particularly for such minerals like garnet, biotite, cordierite, plagioclase, clinopyroxene, orthopyroxene, K-feldspar, quartz etc. A thin section of rock chips is prepared for petrographic investigation with a microscope; a standard thickness of the slide is approximate 0.035

mm. For thin section preparation, thin rock chips are pasted with a glass slide and grinding with the carborundum powder until a thin layer of rock.

4.3.2 Method

Firstly, colour, grain size and texture are seen in natural light for rock samples. After that, rectangular chips are prepared for each sample (dimension: L*B*T; 2 inches * 1 inch * 0.25 inch) for preparing slides using a diamond saw blade. The practical experience of the present author and the literature dealing with the preparation of polished rock samples show that the attitude of individual minerals and their associates in the course of polishing is not uniform. For different minerals and their associates, different techniques are taken into consideration. The classical polishing on a billiard table cloth may be superior for specimens containing minerals with many cracks, but they should be near the same hardness. The final polishing is done manually on a grinder pitch; it gives excellent results but is time-consuming.

In recent years, the quality of polished sections has improved since the material used for impregnation has been replaced more and more by plastics. One of the most efficient methods to have an excellent finish in the last stage of polishing rock samples, particularly for such opaques having more hardness are to use diamond power plates of different grain sizes. Synthetic diamond is made of fine round octahedral crystal of the same size, different from the powdered natural material. Likewise, synthetic alumina was also found useful for obtaining better results.

After cutting the appropriate pieces of rock samples, now these rock chips are grinded on a rotating lap (850 rpm) using silicon carbide (SiC) powder of 120 mesh size for 20 minutes with the addition of few droplets of water. The above step is repeated with 220 mesh size powders, and then good quality of mineral grain boundary is observed. Afterwards, 600 and 800 mesh size powders are used to polish on glass plate. The sample is then mounted on glass slide with the help of Araldite (resin & hardener); oblique angle pressure is applied to the chips against glass slide to eliminate air bubbles. A petro-thin machine is further used to minimize the chips' thickness and reduce the grinding time, and the rock slide is again grinded on a glass plate using silicon carbide powder (600, 800 & 1000 mesh sizes) until the thickness is attained to 0.035 mm.

The samples are then prepared for polishing by alumina gel or synthetic diamond on the cloth. Two precautions are taken into consideration at the time of polishing. Firstly while changing the section form one plate to the other, the thin section is thoroughly washed to avoid contaminations and secondary the sample is put on the lap and rotated in a circular mode opposite to the rotation of the lap and uniform light pressure is applied while doing the final diamond polishing. The time for the individual polishing section varies from 10 to 30 minutes, depending upon the hardness of minerals.

4.4 Petrography of the thin section

The petrographic study has done by the microscope (LEICA DM 2500 P). It is a combination of incident light and transmitted light; the segments can be controlled individually or jointly. Three magnification lenses (2.5X, 5X and 20X) have used to petrographic studies.

These are some rocks find out under field investigation. Now, the megascopic and microscopic characteristics of the collected rock samples are described under the following heading:-

1. High-grade gneiss

2. Pelitic granulite
3. Mafic granulite
4. Migmatite granite gneiss
5. Sillimanite-biotite-graphite schist
6. Amphibolite

4.4.1 High-grade gneiss

4.4.1.a Megascopic characters

The high-grade gneisses are mainly composed of garnet, orthopyroxene, gedrite, cordierite, biotite and quartz along with accessory minerals such as Fe-Ti oxide and monazite. Two distinct metamorphic assemblages: garnet- orthopyroxene- gedrite gneisses and garnet-cordierite-gedrite gneisses have been observed. The mineral abbreviations are taken from [279]. The leucocratic layers are composed of garnet, orthopyroxene, and quartz generated by partial melting or metasomatism during the prograde metamorphism. The leucosomes exist as discreet in the gneissic rocks (Fig.4.1a). The high-grade gneisses show greasy and resinous appearance. The melanocratic layers include restitic mineralogy in the form of gedrite and biotite. Garnet is present in abundant amounts in these rocks, and it is displaying a red to pinkish tinge on the rock, and grain size varies from medium to coarse grain. Gedrite shows grey to black colour with coarse-grained, and it can be easily distinguished in the field locality (Fig.4.1b), whereas biotite present in the form of coarse flakes.

4.4.1.b Microscopic characters

Fabric- The fabric is typically gneissose, and the foliation is characterized by parallel orientation of gedrite and biotite. The rocks are distinctly banded in some samples, with alternating dark and light colour bands. The former consists of predominantly garnet-biotite- gedrite with minor magnetite, while in later coarse quartz and cordierites are dominant.

Microscopic investigations of the high-grade gneisses show the three distinct types of mineral assemblages in which either orthopyroxene is present or absent in the following paragenesis:

(i) Garnet-orthopyroxene-cordierite-gedrite-biotite-quartz,
(ii) Garnet-gedrite-cordierite-biotite-quartz,
(iii) Garnet-gedrite-cordierite-biotite-chlorite-quartz,
The assemblages may also include minor amounts of ilmenite, magnetite, apatite etc.

Chlorite

Chlorite occurs in the form of medium to coarse flakes and associated with biotite or individual laths. It occurred as inclusion within gedrite and consumed to form $garnet_1$ and $gedrite_1$ due to the reaction (Fig.4.1c).

Chlorite + quartz → $garnet_1$ + $gedrite_1$ + H_2O. (1)

Biotite

Biotite shows the characteristic pleochroism, X = straw yellow, Y = Z = dark brown, where X < Y = Z (Fig.4.1d). It occurs in elongated linear flakes and laths wrapped around the garnet, cordierite, and gedrite. Late retrograde biotite occurs as coarse flakes or symplectite of quartz + biotite rimming xenoblastic of garnet. It also occurs as inclusions in garnet, cordierite, gedrite etc. the textural relation evident by synkinematic crystallization of biotite during D_1 deformation. Majority of the biotite grains are associated with chlorite. The inclusion of Al-rich biotite trail in gedrite grain (Fig.4.1d), which is in contact with cordierite, suggests the reaction.

Al-rich biotite + quartz → $gedrite_1$ + cordierite + K-feldspar + H_2O (2)

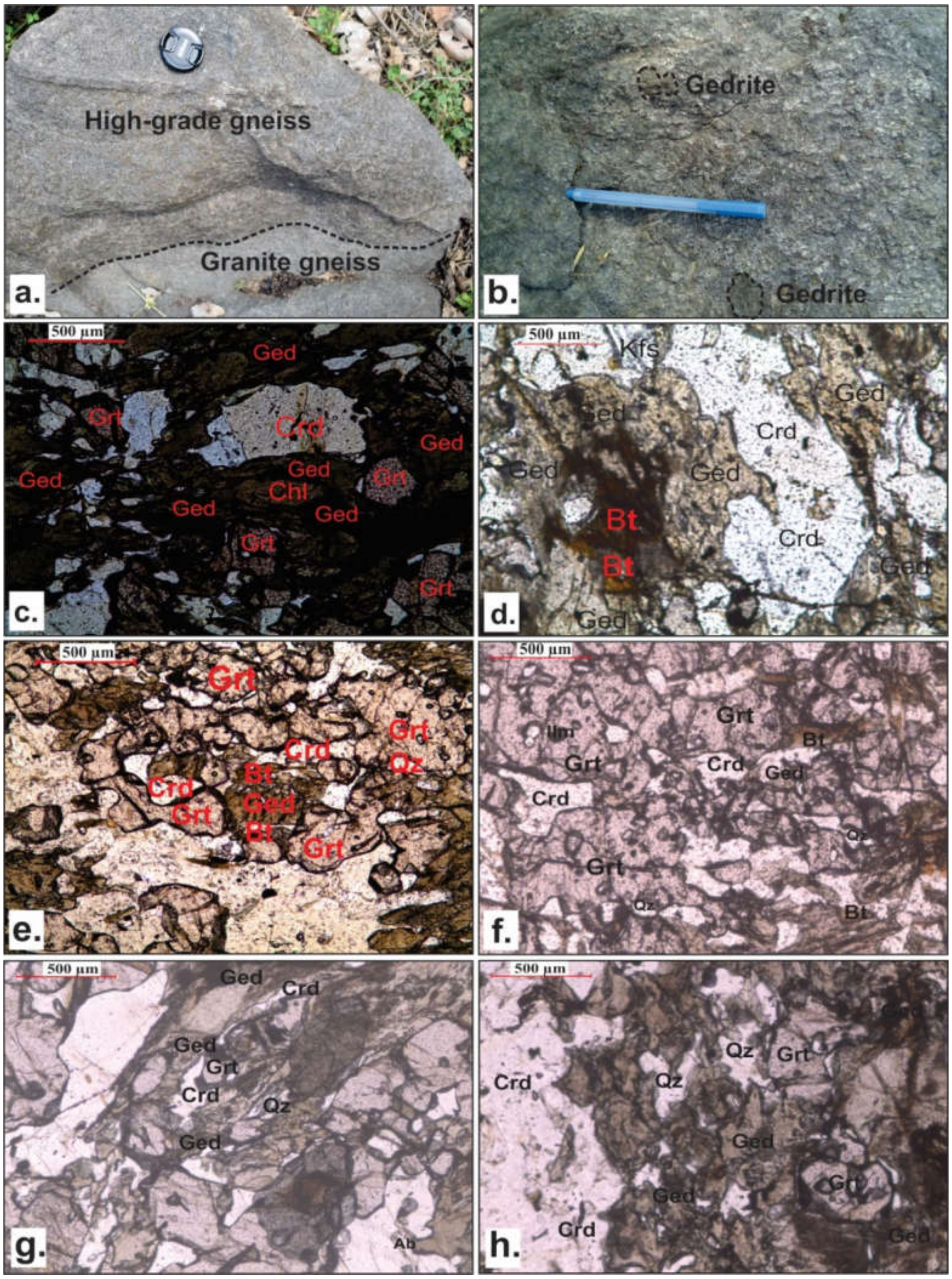


Figure 4.1. Field photograph of the High-grade gneiss (HGG); (a) HGG associated with granite gneiss, (b) gedrite appeared as dark grey colour in HGG. Photomicrographs illustrating the textural relations in HGG: (c) Chlorite completely rimmed by gedrite, (d) A small grain of brown Al-rich biotite present as inclusion in gedrite and gedrites are surrounded by a huge mass of garnet and cordierite, (e) garnet contains the inclusion of amphibole, cordierite, biotite, (f) Inclusion of cordierite, gedrite, biotite, quartz and ilmenite in garnet, (g) Corona texture in which garnet is rimmed by cordierite followed by gedrite, (h) Garnet rimmed by gedrite.

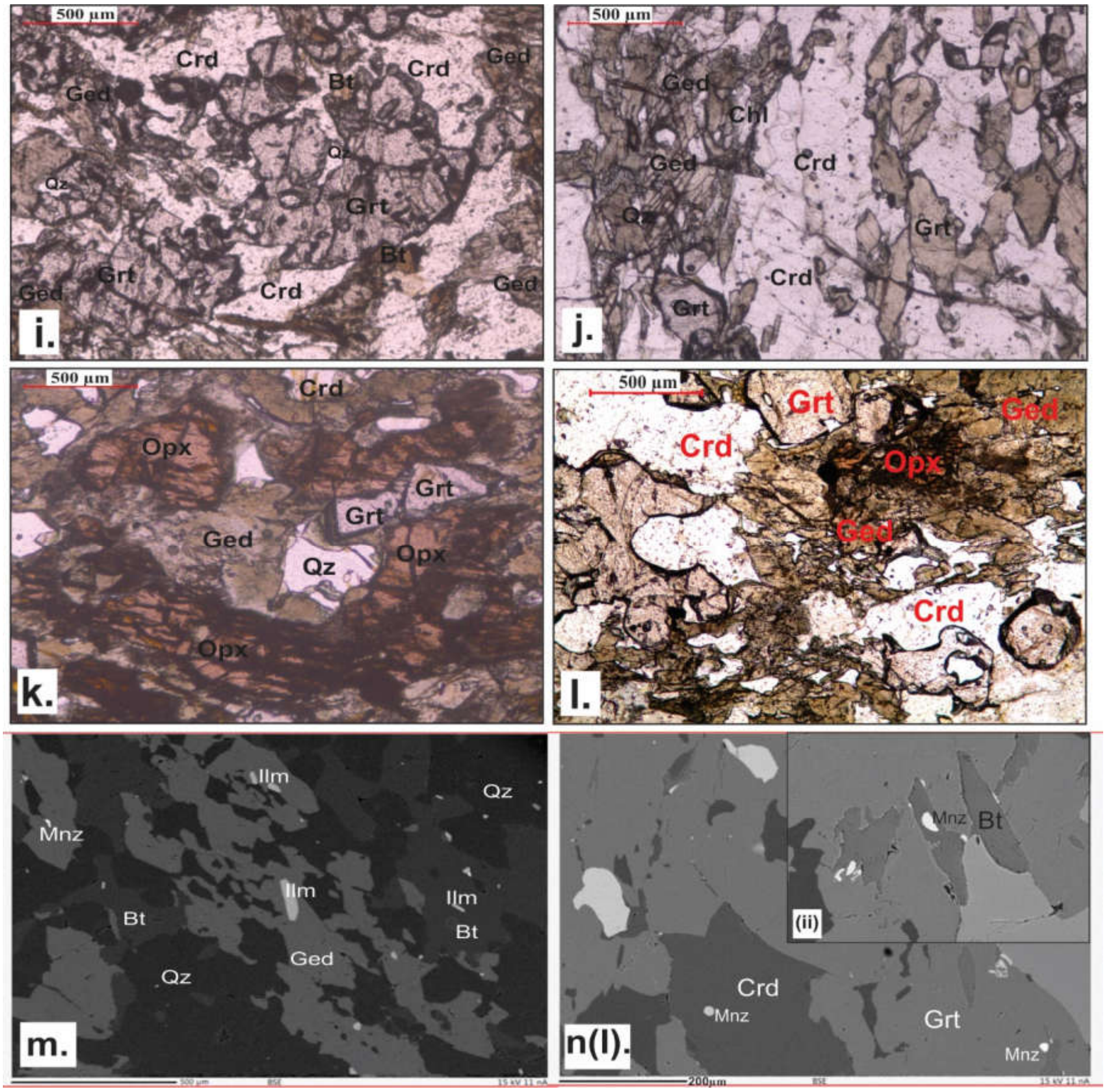


Figure 4.1 (Continue….). (i) Garnet and biotite surrounded by cordierite and gedrite, (j) Gedrite laths are defines a foliation within the rock, Chlorite completely rimmed by gedrite, (k) Gedrite rimmed by orthopyroxene and garnet occurs as inclusion within orthopyroxene, (l) Opx rimmed by garnet and gedrites, (m) BSE image shows some accessory minerals, i.e., monazite and ilmenite with other minerals like gedrite, biotite and quartz, (n) Inclusions of monazite in different mineral phases.

Garnet

Garnet occurs as coarse xenoblast and poikiloblast and containing linear trails of biotite with S_i parallel to S_e, suggesting post-kinematic crystallization concerning the first phase of deformation (D_i). Gedrite and biotite surrounded by various crystals of garnet (Fig.4.1e). Garnet shows poikiloblast texture and contains gedrite, cordierite, biotite, and quartz as inclusions (Fig.4.1f), as a prograde condition. However, garnet also contains some heavy minerals like; ilmenite, magnetite, monazite, etc. In some places, garnets are surrounded by cordierite grains and further rimmed by gedrite (Fig.4.1g). This corona texture leads to the reaction

$$\text{Garnet}_1 + \text{quartz} + H_2O \rightarrow \text{cordierite} + \text{gedrite}_2 \quad (3)$$

At places cordierite includes gedrite and is rimmed by garnet-quartz symplectite, suggesting a reversal of the reaction (3).

Garnet and quartz at places were completely wrapped by gedrite coexisting with cordierite (Fig.4.1h). This textural relation suggests the reaction

$$\text{Garnet}_1 + \text{quartz} \rightarrow \text{gedrite}_2 + \text{cordierite} + H_2O \quad (4)$$

A corona texture is observed in which corroded garnet and biotite are partially wrapped by cordierite and gedrite (Fig.4.1i) provides the evidence of reaction.

$$\text{Garnet}_1 + \text{biotite} + \text{quartz} \rightarrow \text{gedrite}_2 + \text{cordierite} + \text{K-feldspar} + H_2O \quad (5)$$

Garnet shows the two distinct stages as garnet_1, the dominant garnet in the rocks coexisting with gedrite, cordierite and biotite.

Cordierite

Xenoblast and coarse aggregates of cordierite wrap the porphyroblast of garnet and gedrite (Fig.4.1c-i). Cordierites have a significant yellowish pleochroic halos feature due to zircon inclusion and sector twinning. Corroded cordierite is thoroughly rimmed by garnet which provides evidence of the prograde metamorphic condition. Another retrograde metamorphic feature has been distinguished by the cordierite rims around garnet (Fig.4.1i) and biotite flakes, where cordierites are developed by the breakdown of garnet in the availability of biotite and quartz by reaction (5). Cordierite shows some alteration along the grain boundaries and the fractured zone. Cordierite includes magnetite, quartz, monazite, etc. as inclusions.

Gedrite

Gedrite is coarse-grained and has idioblastic prisms in thin sections. It is commonly associated with quartz and cordierite biotite to define foliation S_2 and S_3 (Fig.4.1j). It shows parallel extinction and pleochroism in which the colour varies from yellowish-green to greenish-brown, X=pale yellowish-green, Y=pale greenish-brown, Z=dark greenish-brown, $X<Y<Z$. It contains inclusions of cordierite, biotite, quartz, etc. Three distinguish morphology of gedrite crystals have been observed. The first gedrite has elongated nature with the fibrous grain (2–3 mm), and thickness is 0.15–0.20 mm, and it defines the foliation in the rocks (Fig.4.1c). The second gedrite occurs as idioblastic, and present a tremendous amount within this rock (Fig.4.1f,g&j), whereas the third type of gedrite has prismatic nature (Fig.4.1k). Therefore, three types of gedrite1, gedrite2 and gedrite3 formed during different evolutionary processes. Gedrite1 contains the trail of biotite and chlorite as inclusion which suggests the appearance of gedrite1 in the rock due to the breakdown of chlorite + quartz and biotite + quartz, from reactions (1 and 2) (Fig.4.2c&d). Gedrite2 includes garnet1 and cordierite and forms due to reaction (3–5). The orthopyroxene surrounds Gedrite3.

Orthopyroxene

Orthopyroxene is small to medium-grained (1–2 mm) and idioblast to xenoblasts in the high-grade gneiss. Photomicrographs show pinkish colour due to iron enrichment with strong pleochroism X= yellow, Y=pink, Z=green; $X<Y<Z$. At places, gedrite + quartz are completely rimmed by orthopyroxene, garnet and cordierite (Fig.4.1k). This textural relation provides the evidence through which orthopyroxene and garnet$_2$ appear in the rocks due to the reaction;

Gedrite$_3$ + quartz → orthopyroxene + garnet$_2$ +cordierite + H_2O (6)

The second state of the garnet named as garnet$_2$ coexisted with orthopyroxene and formed due to breakdown of gedrite. The peak-metamorphic minerals have preserved inclusions that are consumed during progressive metamorphism. Orthopyroxene forming reaction suggests the peak metamorphic condition as the formation of garnet-orthopyroxene-amphibole assemblage, with the reaction;

Gedrite + quartz → orthopyroxene + garnet + melt (7)

Orthopyroxene is rimmed by retrograde biotite, and at some places, orthopyroxene is partially rimmed by garnet, cordierite and gedrite (Fig.4.1L). It suggests a retrograde metamorphic condition, where orthopyroxene consumes to form garnet-cordierite-gedrite as a new assemblage, with the reaction;

Orthopyroxene + melt → garnet + cordierite + gedrite (8)

Ilmenite

Ilmenite occurs as elongated and prismatic grains, which are very fine-grained and present as inclusion in gedrite, biotite, garnet and other mineral grains (Fig.4.1m).

Minor constituents

These include monazite, magnetite, apatite etc. Magnetite occurs as irregular grain and as dust. Monazites occur as irregular inclusion grain within garnet, quartz and cordierite (Fig.4.1n).

4.4.2 Pelitic granulite

4.4.2.a Megascopic character

Pelitic granulites are massive and medium to coarse grained with grey to pinkish colour due to the abundance of garnet (Fig.4.2a) and a greasy appearance and a granulitic texture. Large size of garnet grains are appeared on the rock surface (Fig.4.2b). The pelitic rock consists mainly of garnet, cordierite, sillimanite, biotite, plagioclase, K-feldspar, quartz, and opaque minerals (ilmenite and magnetite).

4.4.2.b Microscopic character

Fabric- the fabric is typically containing gneissose texture with a well-defined foliation due to parallel orientation of biotite and sillimanite flakes alternating with a fine mosaic of garnet, quartz and cordierite. Pelitic granulites contain medium to large garnet with rounded to subhedral grains. Medium-sized biotite grains wrapped around the garnet and adequate biotite, sillimanite, cordierite, and plagioclase occur as inclusion in garnet. Cordierite (35%) is present as a dominant mineral with garnet (25%), biotite (15%), quartz (10%), plagioclase (7%), and sillimanite (5%).

Mineral assemblages

I. Garnet-cordierite-sillimanite-K-feldspar-plagioclase(An_{25-30})-quartz

II. Garnet-cordierite-sillimanite-biotite-quartz

III. Garnet-cordierite-biotite-sillimanite-plagioclase(An_{30-35})-quartz

Besides these, the assemblages may also include minor amounts of magnetite, apatite ilmenite etc.

Garnet

Garnet grains are characterized by their unique isotropic optical property in polarized light and range in size from 0.1 to 0.6 mm in diameter. They are always present in sporadic amount and occur characteristically as small to medium xenoblasts with a

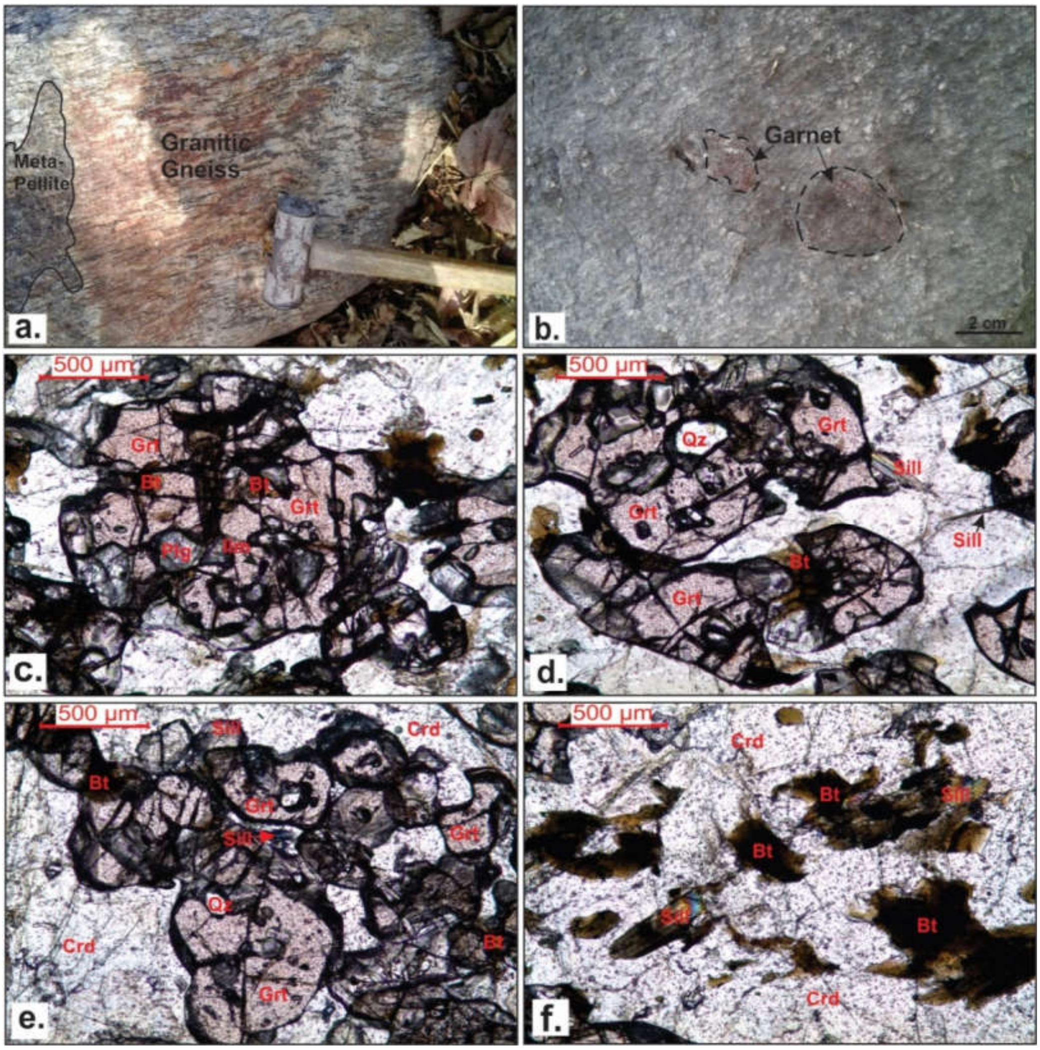


Figure 4.2. Outcrop photographs showing field features of the studied rock types (a & b). (a) Melanocratic Pelitic granulites present as enclaves form within the Granitic gneisses groundmass. (b) Porphyroblastic garnet (size; 2-3 cm) present within the Pelitic granulites. (c) Photomicrograph of Pelitic granulites showing biotite and plagioclase present as inclusion within porphryblastic garnet. (In plane-polarized light). (d) Flakes of sillimanites are associated with the garnet whereas biotite and quartz present as inclusion in garnet. (ppl) (e) Sillimanite needle, biotite and quartz present within the garnet whereas cordierite present as groundmass. (ppl). (f) Biotite flakes are wrapped around sillimanite needle within the groundmass of cordierite. (ppl).

dodecahedral outline. Fine-grained sizes of quartz, plagioclase, biotite and ilmenite minerals are present as inclusion in porphyroblastic garnet and boundary of garnet grains are corroded (Fig.4.2c).

Quartz + plagioclase + biotite → garnet + H_2O (1)

At some place garnet contains an inclusion of biotite, this textural relation provides the evidence of prograde garnet formation due to following metamorphic reaction:

Biotite + quartz → garnet + K-feldspar + melt (2)

Biotite and quartz occur as inclusion within garnet grains where sillimanite flakes are adjacent to the garnet porphyroblast (Fig.4.2d).

Biotite + quartz → garnet + sillimanite + plagioclase + H_2O (3)

Garnet is associated with the needles of sillimanite. At places, the corroded boundary of garnet is rimmed by cordierite and cordierite-quartz symplectite intergrowth (Fig.4.2e), suggesting that cordierite is formed from the following reaction:

Garnet + sillimanite + quartz + H_2O → cordierite (4)

At one place garnet, cordierite and K-feldspar overprinting the foliated fabric of the matrix defined by trails of biotite and sillimanite (Fig.4.2e) give evidence of the following reaction:

Biotite + sillimanite + quartz → cordierite + garnet + K-feldspar + H_2O (5)

Cordierite

Cordierite occurs as granular aggregate rimming xenoblasts of garnet and needles of sillimanite with overprinting the matrix's fabric. The textural relation suggests that the cordierite is formed by the breakdown of garnet in the presence of sillimanite and quartz, reaction (4). At some places, cordierite is formed by the ingesting of needles of sillimanite and biotite flakes (Fig.4.2f). Biotite occurs along the cracks of cordierite.

Biotite + sillimanite + quartz → cordierite + melt (6)

Biotite + sillimanite + quartz → cordierite + K-feldspar + melt (7)

Biotite

It shows pleochroism, varying from yellowish-brown to dark brown, most biotite flakes oriented parallel to S_2 foliation, whereas few flakes show S_3 foliation (Fig.4.2f). Biotite also occurs between the contacts of K-feldspar and cordierite. The lattice gives biotite the preferred alignment of the dominant S_2 fabric and is sometimes weakly wrapped around cordierite grains.

Sillimanite

It occurs in fine needles intergrown with biotite and garnet (Fig.4.2d). Most of the sillimanite needles occur as inclusion within the porphyroblasts of garnet, cordierite and k-feldspar or trails within the matrix (Fig.4.2e). The textural relation suggests its crystallization as broadly coeval with biotite.

Plagioclase

This is characteristic of their distinctive lamellar polysynthetic twinning; they consist of sillimanite trails as inclusions. Their contact with biotite grains is often ragged. K-feldspar is mostly mesoperthitic with lamellar intergrowth of plagioclase in the main mass of K-feldspar characterized by showing quadrille structure.

4.4.3 Mafic granulite

The term mafic granulite has been used only for the granulite of hypersthene-diopside- plagioclase composition. The perthite may or may not be present. The mafic granulite corresponds to mafic charnockite of [114].

4.4.3.a Megascopic character

Mafic granulites are dark grey to black colour show granoblastic texture, and it generally occur as in boulder shape (Fig.4.3a&b), whereas sometimes present as

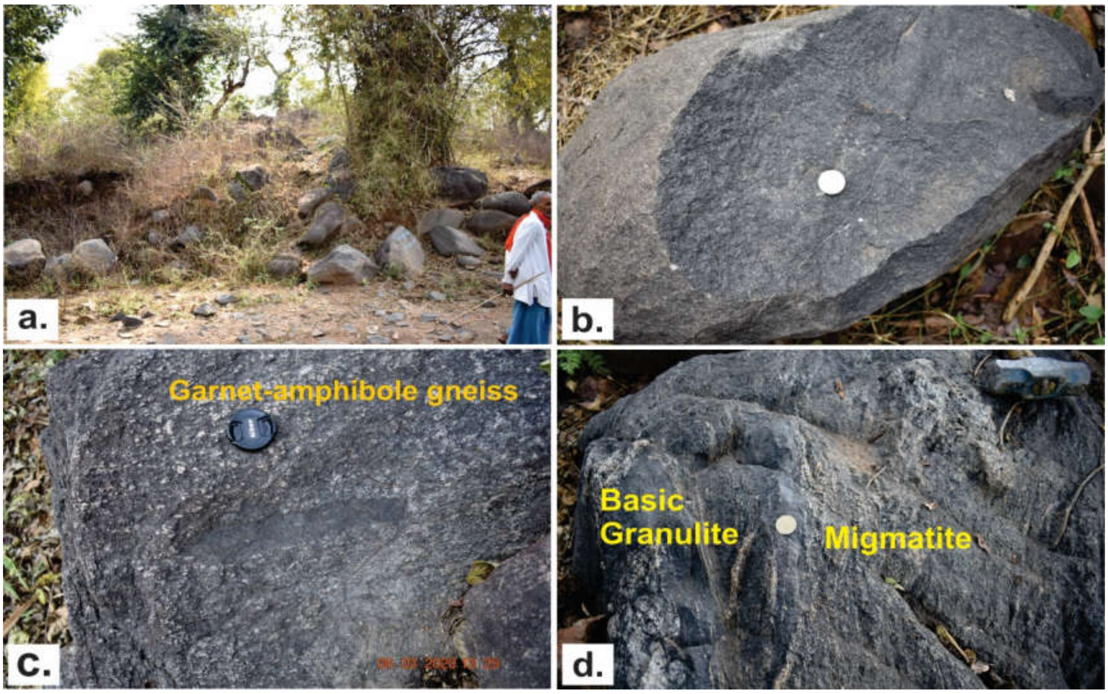


Figure 4.3. Field photographs of mafic granulites form the southern margin of the Daltonganj: (a) various boulders of mafic granulites distributed in the area, a villager stand as scale, (b) It represents a close view of mafic granulite boulder, (c) mafic granulite present as enclaves within garnet-amphibolite gneiss, and (d) mafic granulite associated with migmatites.

enclaves within-country rocks (Fig.4.3c&d). The mafic granulites are characterized by medium to coarse-grained with granulitic texture. Mafic granulite varies from equigranular granoblastic to nematoblastic or gneissose fabric in which prism of pyroxene, amphibole and biotite have preferred orientation in the direction of the plane of foliation. Often elongated magnetite and ilmenite grains also define foliation in the rocks. The pyroxene and plagioclase are visible in hand specimen. The pyroxene shows metallic lustre (Fig.4.3b).

4.4.3.b Microscopic character

Fabric- The mafic granulites are lacking hydrous phases are typically massive. Granulites dominated by hornblende and biotite also show triple junctions at grain contacts, which indicate through recrystallization, although the degree of annealing varies from sample to sample. Mafic granulites consist of two types of assemblages, i.e., garnet-bearing and garnet absent mafic granulite.

(i) Garnet bearing mafic granulites

The garnet-bearing mafic granulite reveals that it contains mafic minerals; garnet, clinopyroxene, amphibole, plagioclase, ilmenite, and quartz. The amphibole is present in huge amounts and appears prismatic to anhedral shape (Fig.4.4a). The garnets are ubiquitously rimmed by a thick corona of symplectic plagioclase + clinopyroxene ± amphibole (Fig.4.4b). The garnet porphyroblast shows corroded boundary with the granoblastic mosaic appearance and contains amphibole, plagioclase, and ilmenite as inclusion (Fig.4.4c), whereas at some places patchy amphibole replaces garnet and clinopyroxene.

(ii) Garnet absent mafic granulites

Petrography reveals that this study area's mafic granulites are dominated by orthopyroxene, clinopyroxene, plagioclase, amphibole, quartz, and biotite, whereas iron oxides (ilmenite and magnetite) constituting the rest of the phases. Opx-Cpx exsolution texture is shown in mafic granulites, in which lamellae of opx present in cpx mass (Fig.4.4d) Two generations of amphibole are present, in which amphibole and quartz occur as inclusion within orthopyroxene (Fig.4.4e), and orthopyroxene is rimmed by amphibole (Fig.4.4f). Orthopyroxene and clinopyroxene are completely rimmed by amphibole, suggesting retrograde metamorphism (Fig.4.4f). A symplectitic texture was observed, in which micro-grains of orthopyroxene and clinopyroxene were distributed within plagioclase (Fig.4.4g). Ilmenite & magnetite occur as accessory phases (Fig.4.4h).

Mineral assemblage

I. Garnet-clinopyroxene-amphibole-plagioclase-quartz

II. Orthopyroxene-clinopyroxene-amphibole-plagioclase-quartz

III. Orthopyroxene-clinopyroxene-amphibole-biotite-plagioclase-quartz

IV. Orthopyroxene-amphibole-biotite-plagioclase-quartz

Besides the minerals mentioned above, it also includes magnetite, ilmenite apatite, zircon etc.

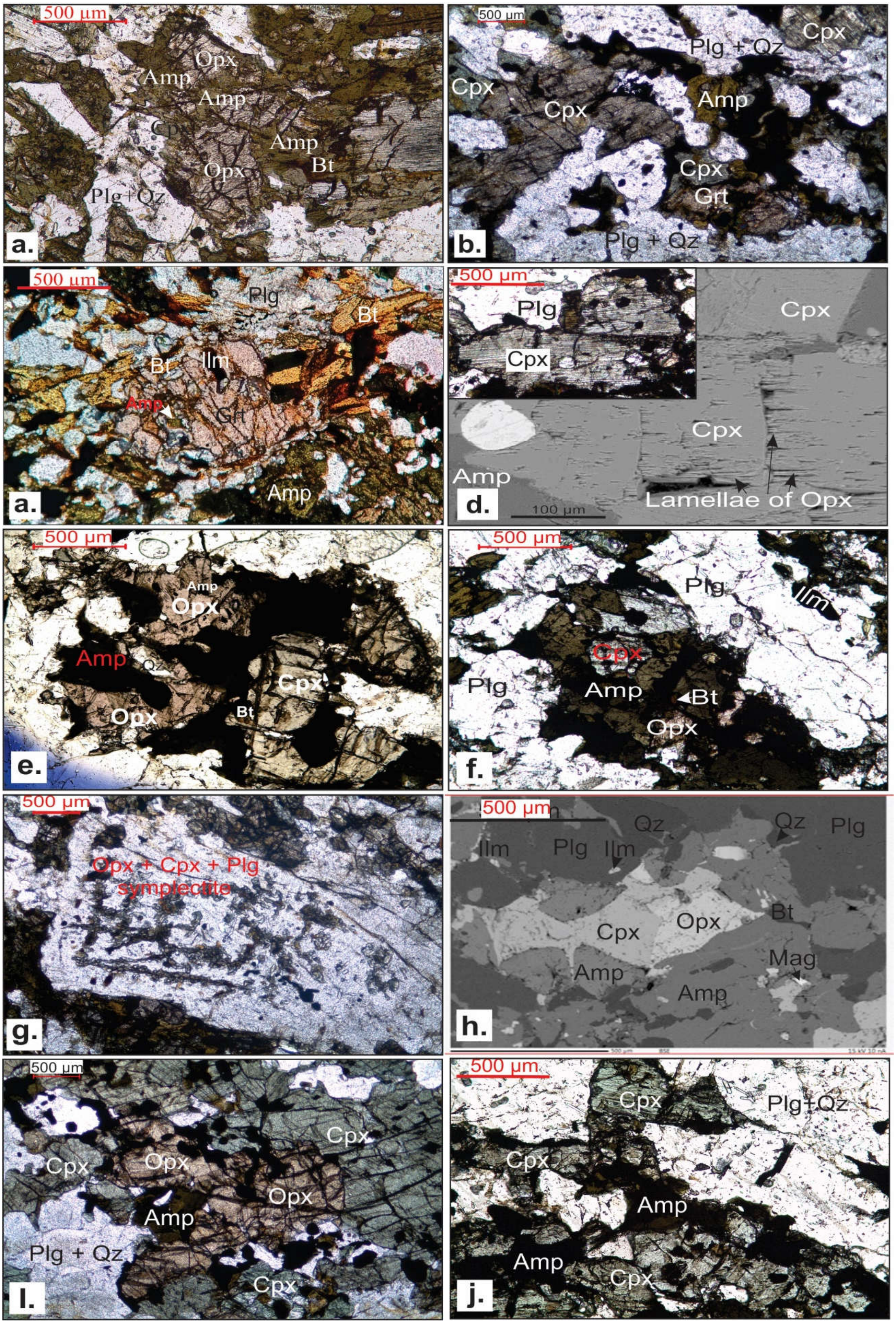
Garnet

It occurs as coarse to fine-grained xenoblastic crystals. Inclusion of quartz, magnetite, hornblende, clinopyroxene, and plagioclase are present in garnet. It rarely occurs in mafic granulite in the assemblage garnet-clinopyroxene-amphibole-plagioclase-quartz. Garnet is partially and completely rimmed by hornblende and clinopyroxene (Fig.4.4c). At some places it contains hornblende and plagioclase as inclusions, which give evidence of the reaction as fallow:

Amphibole + plagioclase → clinopyroxene + garnet + H_2O (1)

Orthopyroxene

It is pleochroic; X = yellow, Y = pink, Z = green, X<Y<Z. It occurs as sub-idioblastic to xenoblastic grains and in few specimens as idioblastic crystals (Fig.4.4i). Orthopyroxene porphyroblast is poikiloblastic with inclusions of amphibole, biotite, quartz, and ilmenite (Fig.4.4i). At some places, granular aggregates of orthopyroxene rimming coarse orthopyroxene prism and provides evidence of post-crystalline deformation. Orthopyroxene is commonly rimmed by hornblende, biotite, and clinopyroxene, and also contains corroded hornblende, biotite, and quartz within them (Fig.4.4e). The textural relations described above provide the evidence of the following



500 µm
Opx
Amp
Amp
Amp
Bt
Opx
Plg+Qz
a.
500 µm
Cpx
Plg + Qz
Cpx
Cpx
Amp
Cpx
Grt
Plg + Qz
b.
500 µm
Plg
Bt
Bt
Ilm
Amp
Grt
Amp
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500 µm
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Lamellae of Opx
100 µm
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Amp
Qz
Cpx
Bt
Opx
e.
500 µm
Plg
Ilm
Cpx
Plg
Amp
Bt
Opx
f.
500 µm
Opx + Cpx + Plg
symplectite
g.
500 µm
Qz
Qz
Plg
Ilm
Plg
Ilm
Cpx
Opx
Bt
Mag
Amp
Amp
h.
500 µm
Cpx
Opx
Cpx
Opx
Amp
Plg + Qz
Cpx
I.
500 µm
Cpx
Plg+Qz
Cpx
Amp
Amp
Cpx
j.

Figure 4.4. Photomicrographs of various mineral association of mafic granulites are showing (a) Amphibole occur as prismatic and anhedral shape, (b) Garnet rimmed by cpx, amp and plg, (c) Garnet consists of amphibole, biotite, plagioclase and ilmenite as inclusion, (d) Back Scattered Electron (BSE) image shows thin lamellae Opx occur in Cpx, (Inset image represents Photomicrograph shows an exsolution texture within Opx and Cpx), (e) Amphibole represents two modes of generations, (f) Opx, Cpx, and Bt occur as inclusion in Amp porphyroblast, (g) Symplectitic texture, in which micro-grains of orthopyroxene and clinopyroxene were distributed within plagioclase, (h) BSE image shows the textural association of different minerals opx, cpx, amp, bt, plg, qt and ilm, (i) Idioblastic to sub-idioblastic grains of opx and cpx with inclusion of amp, (j) Clinopyroxene present as prismatic and idioblastic texture.

prograde and retrograde reaction:- Prograde:

Amphibole + quartz → orthopyroxene+ clinopyroxene+ plagioclase + H_2O (2)

Amphibole + biotite + quartz → orthopyroxene + plagioclase + K-feldspar + H_2O (3)

Retrograde:

Orthopyroxene + clinopyroxene + plagioclase + H_2O → amphibole + quartz (4)

Clinopyroxene

It is colourless to light green, medium-grained prismatic crystals, sub-idioblastic to idioblastic (Fig.4.4i). Coarse clinopyroxene is poikiloblastic containing inclusions of amphibole, biotite, quartz and ilmenite (Fig.4.4j). Clinopyroxene is rimmed entirely or partially by biotite and hornblende. Often the magnetite rimmed the clinopyroxene grains completely, evidence of post-crystalline deformation is revealed by wavy extinction. Corroded clinopyroxene occurs within hornblende, which suggests retrograde reaction.

Amphibole

It shows characteristics pleochroism; X= yellowish-green, Y= green, Z= greenish-brown, $X<Y<Z$, and is typically yellowish-green in colour. It occurs in variable amounts. It defines the prominent foliation (S_2) and biotite, diopside and hypersthene.

It shows two distinct generations of crystallization. The pyroxenes rim commonly fine-grained aggregates of amphibole with occasional quartz development (Fig.4.4g). This textural feature suggests the reaction; (1) this may represent amphibole of an earlier generation which has reacted to form pyroxene through the reaction. (2) It also includes magnetite, ilmenite, biotite, clinopyroxene, orthopyroxene, and plagioclase.

Biotite

It occurs as coarse flakes and shows pleochroism: X= pale greenish-yellow, Y=Z= dark brownish-green, X<Y=Z. It defines the foliation S_2. It occurs as idioblastic to sub-idioblastic aggregates. It occurs as inclusions within orthopyroxene, clinopyroxene and hornblende. The xenoblasts of an earlier generation occur within opx and cpx. Biotite of the first generation is dark brown coloured, while the second generation's biotites are lighter in colour. Biotite flakes with hornblende within orthopyroxene suggest the reaction (2). Biotite-quartz symplectite is also seen in some of the thin sections. Biotite contains inclusions of magnetite hornblende and quartz.

Plagioclase

It occurs as a medium to coarse-grained, idioblastic to sub-idioblastic aggregate. The myrmekitic and symplectitic intergrowth are common. The plagioclase shows undulose extinction and deformed twinned lamellae, which provide the signature of post-crystalline deformation. Plagioclase contains inclusions of orthopyroxene and clinopyroxene. Some porphyroblast of plagioclase contains hornblende, pyroxene, quartz, and ilmenite inclusions in a single grain, thus showing the poikiloblastic texture (Fig.4.4h).

Quartz

It commonly occurs as equant xenoblasts showing wavy extinctions, indicating post-crystalline deformation. Coarse-grained quartz which does not show wavy extinction indicates its crystallization when all the deformation ceased. It occurs in lesser amounts. The fine-grained granular aggregate of quartz occurs along grain border.

Minor Constituents

These include quartz, K-feldspar, magnetite, ilmenite, apatite, zircon, etc. Magnetite sometimes occurs as coarse-grained crystals of irregular shape along the interstices of quartz-plagioclase mosaic. Inclusions of quartz, plagioclase, diopside, biotite, hypersthene etc. have been identified within coarse magnetite. Some of them coarse magnetite grain overprint the matrix's foliated fabric and contain linear trails of biotite (S_1) merging with the matrix's foliation (S_e).

4.4.4 Migmatitic granite gneiss

4.4.4.a Megascopic character

Different varieties of migmatitic gneisses occupy the area's significant part as the dominant rock type. It is medium to coarse-grained mesocratic rocks with a well-developed gneissose structure and deformation (D_1 and D_2) (Fig.4.5a&b). These gneisses show augen structure. The migmatitic gneisses include the varieties: biotite-granite gneiss and hornblende-biotite-granite gneiss.

4.4.4.b Microscopic character

Fabric- The fabric is typically gneissose with a well-defined foliation due to parallel orientation of biotite flakes and hornblende alternating with a granular mosaic of K-feldspar and plagioclase. In hornblende-biotite-granite gneiss the foliation is defined by prismatic hornblende aligned parallel to the foliation. These gneisses consist of

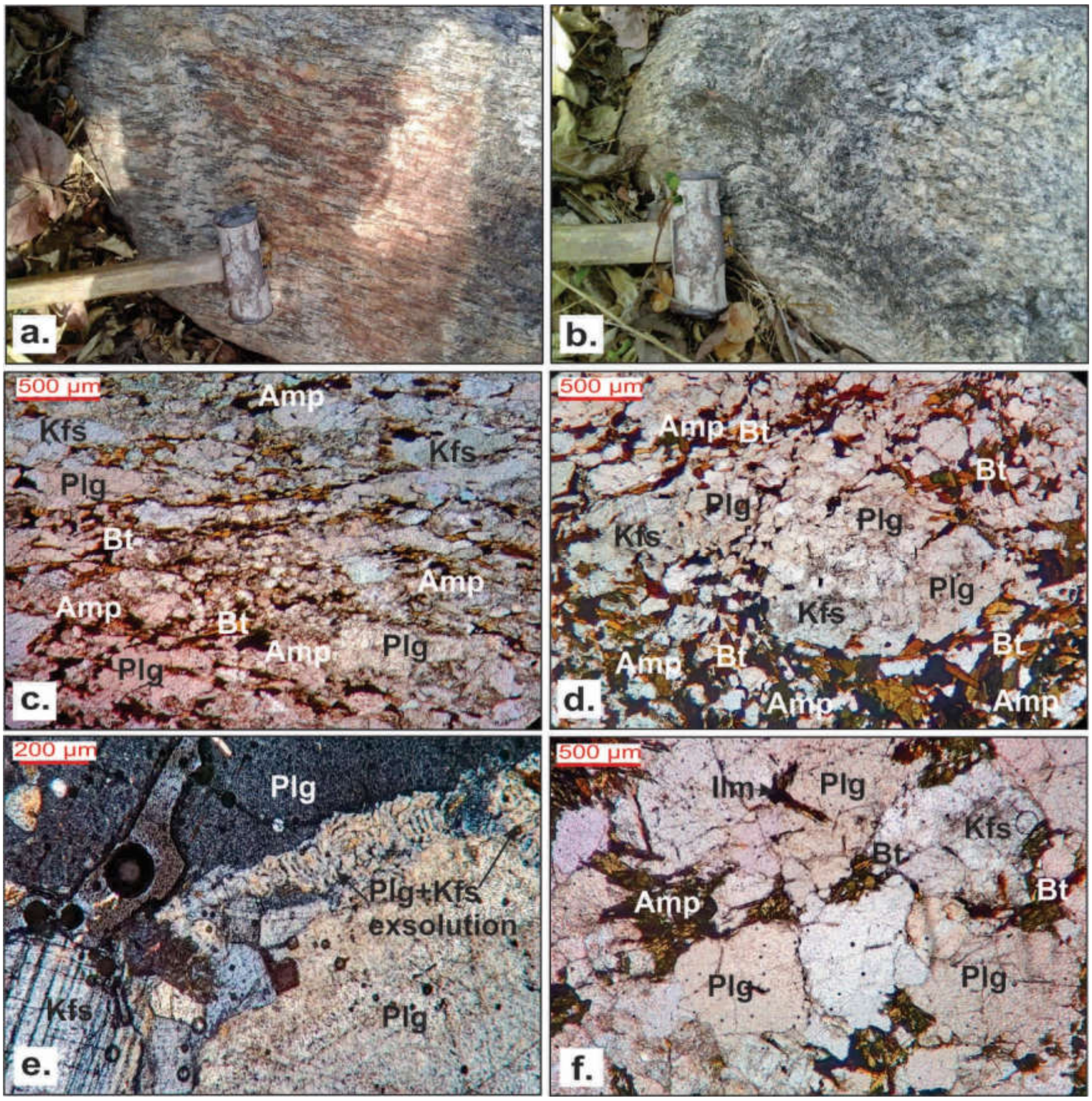

Figure 4.5. Field photographs of migmatitic granite gneiss (a) Gneissose structure and (b) Deformation structure; Photomicrographs of various mineral association are showing (c) Amphibole with biotite define the schistosity S_2, (d) Biotite and amphibole arrange as foliation with K-feldspar and plagioclase mosaic layer, (e) Exsolution texture of plagioclase and K-feldspar, (f) Inclusion of amphibole, biotite, quartz, ilmenite within the plagioclase.

hornblende, biotite, K-feldspar, plagioclase, quartz, perthite, as major constituents and garnet, epidote, magnetite, zircon, apatite as minor constituents. Compositions contrast in these gneisses is defined by the alteration of leuco and mafic-rich layers with prominent dark and light bands, viz., melanosome and leucosome.

Mineral assemblages

I. Hornblende-biotite-K-feldspar(microcline)-plagioclase-quartz.

II. Biotite-plagioclase-K-feldspar-quartz

Besides the mineral mentioned above, the assemblages may also include minor amounts of garnet, magnetite, epidote, apatite, zircon etc.

Hornblende

It occurs as coarse idioblastic to subidioblastic grains more pleochroic from yellowish green to greenish-brown. Hornblende idioblasts with biotite define the schistosity S_2 (Fig.4.5c). These textural relations suggest syntectonic crystallization of hornblende concerning the D_1 deformation. At some places, small sub-idioblasts of hornblende are randomly oriented. Hornblende is sometimes thoroughly rimmed by biotite and plagioclase.

Biotite

It occurs as coarse flakes both in hornblende-biotite granite gneiss and biotite-granite gneiss. It is the most dominant mineral in the biotite-granite gneiss. Biotite flakes are oriented parallel to the foliation along with hornblende and inequant quartz grain (Fig.4.5d) alternating by a granoblastic mosaic of K-feldspar and plagioclase. At some places, biotite flakes define the S_2 foliation are microfolded during the D_2 phase of deformation. Biotite flakes warp around quartz, plagioclase, hornblende, K-feldspar to formed "Augen" structure.

Plagioclase

Plagioclase crystals vary in grain size greatly. They are coarse-grained, subidioblastic to idioblastic. The anorthite content varies from some of the plagioclase grains show albitic rim and contact with microcline. This may be due to the migration of sodium during exsolution of microcline (Fig.4.5e). Inclusions of amphibole, ilmenite, quartz, biotite, and apatite are present. Plagioclase also shows antiperhitic intergrowth (Fig.4.5f). Plagioclase show deformed liner lamellae and wavy extinction indicating post-crystalline deformation. Most of the crystal shows albite twinning. Myrmekitic intergrowth of quartz and plagioclase occurs contact of K-feldspar.

Quartz

Quartz commonly occurs as inequant and equant shape with parallel foliation S_2 characterized by biotite and hornblende. Lenticular aggregates of quartz are wrapped by biotite and hornblende. Sometimes the biotite-granite gneiss gives evidence of mylonization where coarse undeformed quartz occurs within the fine-grained aggregates of quartz.

Minor constituents

These include garnet, ilmenite, magnetite, apatite, zircon, epidote, etc. Magnetite and ilmenite occur in the matrix and also as inclusions. Epidote is rimmed by hornblende. Garnet is also rimmed by hornblende and occurs as inclusion within hornblende. Ilmenite mostly occurs as elongated grains, and epidote occurs in hornblende-biotite-garnet gneiss. Garnet occurs as corroded relict and as xenoblasts containing hornblende quartz.

4.4.5 Sillimanite-biotite-graphite schist

4.4.5.a Megascopic character

These are fine to medium-grained black colour rock. These rocks have soppy feel due to the presence of abundant graphite. The foliation is characterized by linear arrangement of graphite and biotite flakes with quartz. The most dominant minerals are biotite, sillimanite and graphite. The quartz bands in schists are commonly discontinuous and parallel to S_2 – surface defined by graphite, biotite, and sillimanite orientation.

4.4.5.b Microscopic character

Fabric - These rocks show schistose structure with well-developed schistosity (S_2) defined by linear arrangement of flaky graphite, biotite, and sillimanite (Fig.4.6a). In some thin section, S_2 schistosity is microfolded. This textural evidence suggests two-phase of deformation D_1 and D_2. During D_1 deformation S_2 schistosity was formed while D_2 deformation resulted in micro folding of S_2.

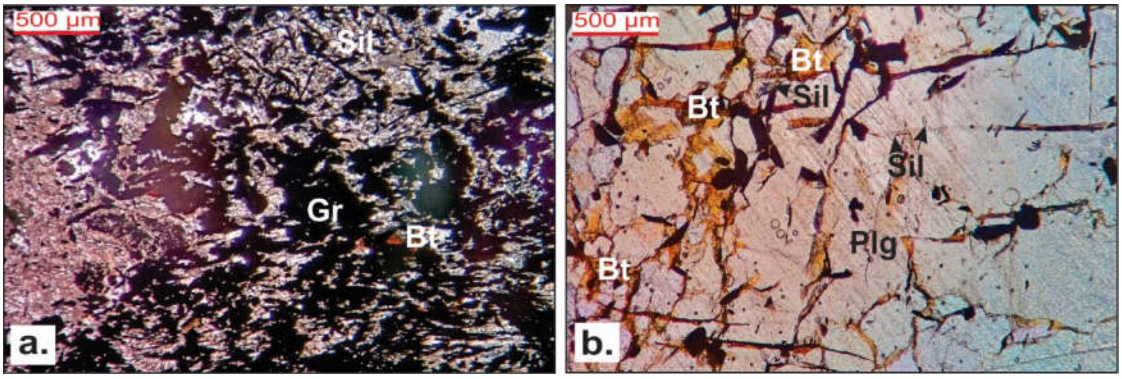

Figure 4.6. Photomicrographs represent (a) Linear arrangement of graphite, biotite and sillimanite, (b) Sillimanite interlayer with biotite.

Mineral assemblages

I. Sillimanite-biotite-graphite-quartz

II. Graphite-sillimanite-quartz

III. Graphite-biotite-quartz

Besides these other minor minerals are present magnetite and ilmenite.

Sillimanite

It occurs both as fine needle and prismatic crystals. The sillimanite needle is associated with graphite flakes and defined the S_2 schistosity. Sillimanite is interlayered with biotite (Fig.4.6b). It is also associated with inequant quartz grains graphite flakes are either aligned parallel to the orientation of sillimanite or cut-across the needle of sillimanite. The textural relation suggests the chronology of crystallization concerning D_1 and D_2 deformation.

Biotite

Biotite is the dominant mineral in the schist. Biotite flakes are weakly deformed. Biotite flakes, graphite and sillimanite, are arranged linearly, which defined the schistosity (S_2) in the rock. At some places, the flakes of biotite defining S_2 are microfolded during the D_2 deformation. Biotite feebly deformed. Biotite is most commonly associated with a flattened grain of quartz. Inclusion of quartz and graphite are present in biotite.

Graphite

It is the most dominant constituents in the schists. It occurs as coarse flakes oriented parallel to the schistosity S_2. The flakes of graphite are microfolded and defined S_3 crenulation cleavage schistosity related to D_2 deformation. It contains the inclusion of biotite, quartz, sillimanite.

Quartz

Quartz occurs as xenoblasts and also as elongated grains. Sometimes inequant quartz defines S_2 associated with biotite, sillimanite and graphite. Quartz shows the effect of intense post-crystalline deformation. Few coarse and undeformed quartz grains are also present. The texture relations suggest syntectonic crystallization of quartz concerning D_1 deformation followed by its recrystallization during static phase after the deformation.

4.4.6. Amphibolite

The term amphibolite has been applied for amphibole rich rocks, which retain their original texture, in which the pyroxene have been uralitized so that the mineralogical composition approaches that of medium-grade metamorphic rocks.

4.4.6.a Megascopic character

These are small to medium grained dark grey colour rocks. They are massive but some sample in hand specimen show alignment of hornblende, biotite and clinopyroxene parallel to S_2 foliation. Amphibolite varies from equigranular granoblastic to nematoblastic or gneissose fabric. Prism of amphibole, clinopyroxene and biotite have preferred orientation in the foliation plane (1) the amphibolite shows dark greenish-black colour in which hornblende and, plagioclase is visible in hand specimen. These rocks are tough and compact.

4.4.6.b Microscopic character

Fabric- These rocks are characterized by relict of ophitic texture in which laths of plagioclase are partially or entirely embedded in clinopyroxene. The amphibolite shows foliation due to parallel orientation of hornblende, biotite and plagioclase crystals. The amphibolite shows characteristic nematoblastic fabric in which prismatic crystal of hornblende is oriented parallel to schistosity S_2. It also shows granular, granoblastic or gneissose fabric. In some sample biotites flakes along with hornblende define the foliation. These are well-foliated medium to a coarse-grained rock consisting (with or without relict clinopyroxene), plagioclase and minor amounts of ilmenite, magnetite, zircon, and apatite.

Mineral assemblage

I. Clinopyroxene-hornblende-plagioclase-biotite-K-feldspar-quartz

II. Clinopyroxene-hornblende-plagioclase-quartz

Besides mineral mentioned above, it also includes magnetite, ilmenite, zircon etc.

Clinopyroxene

It occurs as small xenoblasts and shows ophitic texture in which plagioclase laths

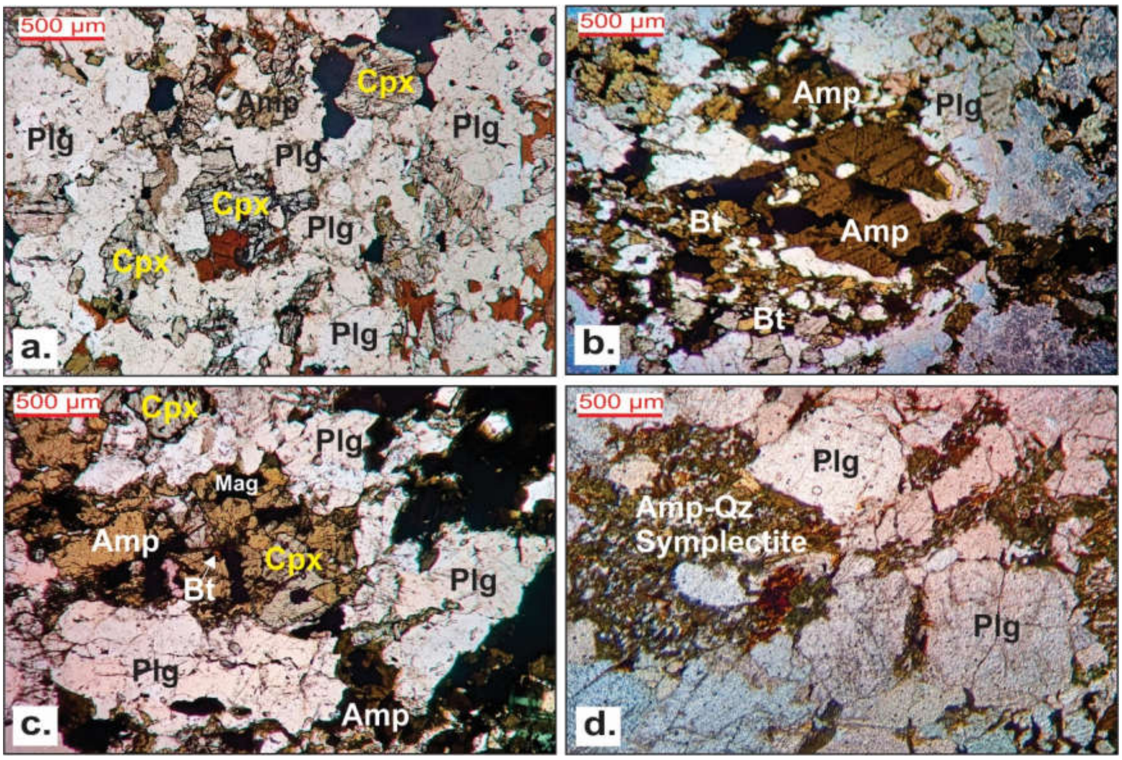

Figure 4.7. Photomicrographs represent (a) Ophitic texture between clinopyroxene and plagioclase, (b) Orientation of amphibole, (c) Amphibole included the clinopyroxene, biotite, plagioclase and magnetite, (d) Amphibole and quartz symplectite.

are embedded within clinopyroxene crystals (Fig.4.7a). In amphibolite, clinopyroxene is rimmed by amphibole, and textural relation suggests that clinopyroxene is replaced by hornblende. It also contains inclusions of magnetite, hornblende, biotite etc.

Amphibole

It occurs as coarse xenoblastic to prismatic crystal. It is highly pleochroic with; X = pale green, Y = green, Z = deep green, $X<Y<Z$. It shows granoblastic texture due to fine mosaic of xenoblasts and few of the rocks, amphibole xenoblasts are parallel arrangement to the foliation (S_2) (Fig.4.7b). In some samples, it occurs as coarse prismatic crystal which contains inclusions of clinopyroxene, biotite, magnetite and plagioclase (Fig.4.7c). It also gives evidence of ophitic texture. It is rimmed by plagioclase and biotite. Hornblende replaces plagioclase, and at places, the former makes a reaction rim around it. Hornblende is of two generations; earlier generations' hornblende is dark green to light green, and oriented parallel to foliation whereas hornblende of later generations are greenish-brown in colour and forms granoblastic texture and sometimes hornblende-quartz symplectite also (Fig.4.7d).

Biotite

It occurs as coarse flakes and prismatic crystal. It defined nematoblastic texture associated with hornblende. Biotite occurs as inclusion within clinopyroxene, hornblende and plagioclase. At places, biotite is rimmed by magnetite, hornblende, clinopyroxene etc.

Feldspar

It includes both plagioclase and orthoclase, whereas plagioclase occurs as coarse xenoblasts and lath shaped crystals. The laths of plagioclase are partially embedded in clinopyroxene. In most samples, plagioclase shows an antiperthitic texture and reflects deformed twin lamellae that provide post-crystalline deformation evidence. Hornblende is replaced by plagioclase.

Quartz

It occurs as both equant and inequant shape. It forms symplectite with hornblende, biotite etc. It shows wavy extinction suggesting post-kinematic crystallization after D_2 deformation. Coarse-grained quartz which does not show wavy extinction indicates crystallization when all the deformation ceases.

Minor Constituents

These include magnetite, ilmenite, apatite, zircon, epidote etc. Magnetite may occur as coarse-grained of irregular shape along quartz and plagioclase mosaic interstices.