CHAPTER - 3

PETROGRAPHY : MINERAL PARAGENESES, TEXTURAL FEATURES AND METAMORPHIC REACTIONS

This Chapter describes the results of petrographic examination of 300 thin sections and megascopic examination of over 400 samples in the field and laboratory.

In addition to petrographic characterization of different rock types in terms of mineral paragenesis and texture, significant petrographic features and relevant mineral reactions as reflected from critical textures of the rocks from each group have been mentioned. It is pertinent to mention that solid solution composition of different phases as described in this chapter are taken from mineral chemistry data (Chapter 4 ). The mineral paragenesis with respect to different rock types and their modal compositions are shown in Table 4.1 (Chapter 4 ). Description of different rock types are given in the following pages.

3.1 METABASIC ROCKS

In the amphibolite zone the commonly observed mineral parageneses in metabasic rocks are designated under the common term 'amphibolite', while those in the granulite zone and which are characterized by coexistence of orthopyroxene and clinopyroxene are termed as basic granulites.
3.1.1 Amphoibolites

The term 'amphibolite' is designated here to a group of hornblende and plagioclase-bearing fine- to medium- grained, greenish black rocks with a crudely developed foliation. The foliation in the rocks is defined by commonly developed parallelism of coarse prismatic grains of hornblende (pargasite) and oriented long axis of plagioclase (An$_{30}$ - An$_{33}$) grains with xenoblastic grains of colourless clinopyroxene (salite); the gneissic foliation is occasionally seen to be overprinted by a moderate to well developed inequigranular granoblastic texture. The polygonal mosaic in the rocks is formed by sub-idioblastic grains of hornblende, plagioclase; xenoblastic grains of clinopyroxene, opaque phases (ilmenite, magnetite, pyrite) and minor quartz which share stable contact with each other. The other minor phases in the rocks include rounded zircon, sphene and apatite. In clinopyroxene-bearing variety texturally clinopyroxenes are of two types: clinopyroxene occurring as xenoblastic grains at the contact with hornblende and plagioclase and as an aggregate of minute vermicular grains showing dactylitic intergrowth: with plagioclase and opaque phases (plate 3.1). In both types of amphibolite, hornblende is commonly green brown in colour and usually crowded with concentration of exsolution granules of ilmenite along its border or within fracture or cleavages (plate 3.2).

Retrogradation of clinopyroxene- bearing amphibolite is prominent. The common alteration products of the matrix minerals are garnet, deep brown biotite, bluish green hornblende along with an aggregate of secondary quartz. Growth of tiny rims of colourless garnet along the border of clinopyroxene and hornblende (Plate.3.1),
mantling of fibrous bluish green hornblende on the clinopyroxene grains, dactylitic intergrowth of bluish green hornblende and quartz grains as well as pseudomorphous replacement of brown hornblende by biotite clearly indicate that all these minerals are secondary after matrix minerals.

Summarising all these petrographic informations, it is clear that amphibolite in the area attained an upper amphibolite facies during peak of metamorphism and then followed by a period of annealing recrystallization.

### 3.1.2 Basic granulites

The term 'basic granulite' is referred to orthopyroxene, clinopyroxene, plagioclase, hornblende bearing rocks with granoblastic polygonal texture. Basic granulites are represented by hornblende pyroxene granulites and hornblende poor pyroxene granulites. Virtually in every case the latter variety contains upto 2% hornblende, it is designated here as 'pyroxene granulite' in an extended sense of the term.

Basic granulites are dark coloured, medium- to coarse- grained rocks with the average grain size between 1.0 mm to 2.5 mm. Texturally, the rocks are polygonal to interlobate; the granoblastic texture is defined by xenoblastic grains of orthopyroxene (hypersthene to ferrohypersthene), clinopyroxene (salite) and plagioclase (An$_{48}$ - An$_{78}$). A crude gneissosity is, however observed in hornblende rich variety.

Green brown hornblende is ubiquitous in these basic granulites and usually crowded with tiny exsolution
granules of ilmenite. Textural relations, such as complex symplectites of pyroxene, plagioclase and ilmenite at the contact with green brown hornblende (Plate 3.3) and abundant pseudomorphed crystals of pyroxene replacing green brown hornblende containing inclusion of optically continuous grains of hornblende (Plate 3.4) indicate prograde break down of hornblende. The relevant reaction is,

\[
\text{hornblende} + \text{quartz} \rightarrow \text{orthopyroxene} + \text{clinopyroxene} + \text{ilmenite} + \text{plagioclase} + \text{H}_2\text{O}
\]

As a consequence of this reaction, the mineral parageneses, observed in the area are hornblende-orthopyroxene - clinopyroxene - plagioclase - ilmenite (hornblende pyroxene granulites) and orthopyroxene - clinopyroxene - plagioclase - ilmenite - quartz (pyroxene granulites). It is worth mentioning that universal presence of quartz (upto 4% modally) and antiperthitic plagioclase is a characteristic feature in many pyroxene granulites.

Garnet, biotite and bluish green hornblende are texturally secondary phases. Garnet (almandine with low pyrope content) chiefly occurs as corona at the contact between orthopyroxene and plagioclase. Bimodel rims of garnet (1 quartz) (Plate 3.5) or garnet-quartz symplectites at the contact between orthopyroxene and plagioclase indicate a reaction of the type,

\[
\text{orthopyroxene} + \text{anorthite} \rightarrow \text{garnet solid solution} + \text{quartz}
\]

This reaction tends to move the composition of plagioclase towards andesine; also decrease of \( \text{Al}_2\text{O}_3 \) contents in pyroxene grains at the contact with coronitic
garnet (Mineral chemistry, Chapter 4). This feature is also evident from other granulite terrains (Harley, 1983, 1985a; Ellis and Green, 1985) and is considered as textural inference for IBC - path.

One of the frequently observed textural features in the basic granulites is pseudomorphed grains of deep brown biotite replacing orthopyroxene and K-feldspars (plate 3.6) and intimate intergrowth of biotite and quartz. This feature indicates the stabilization of hydrous phase, biotite at the expense of orthopyroxene and K-feldspar which can be written as:

\[
\text{orthopyroxene} + \text{sanidine} + H_2O \rightarrow \text{biotite} + \text{quartz}
\]

Textural features in the rocks also show that such fluid induced retrograde reactions are further responsible for the stabilization of bluish green secondary hornblende at the expense of pyroxene (Plate 3.7) and garnet.

3.1.3 Retrograded basic granulites

This group of rocks is represented as crudely foliated biotite-hornblende gneisses in which the granulite facies parentage of the rocks is indicated occasionally by textural features like clinopyroxene relics in hornblende-quartz aggregate as well as post kinematic growth of garnet corona around relict grains of orthopyroxene. The commonly developed mineral parageneses in retrograded granulites are as follows:

(1) plagioclase - quartz - biotite - grossular rich garnet - k-feldspar - (relict orthopyroxene)
(2) hornblende - plagioclase - biotite - sphene - (relict clinopyroxene)

Several significant textural features which relate the transformation to this group are observed. Development of radiating aggregate consisting of fine grained brownish biotite rods symplectitically intergrown with quartz indicates initial stage of alteration of orthopyroxene.

In most thin sections bluish green hornblende partially develops replacing deep brown biotite and in extreme cases biotite is seen to be completely replaced by bluish green hornblende.

The alteration of clinopyroxene is indicated with the development of symplectitic aggregate of bluish green hornblende and quartz along the border within cleavage traces of clinopyroxene grains. In some cases clinopyroxene are completely replaced by pseudomorph of hornblende porpryroblast; discrete grains of optically continuous clinopyroxene occurs as relict within the hornblende. In garnetiferous variety of retrograded basic granulites, garnet always occur as tiny rims after intergrown with quartz, around orthopyroxene as well as hornblende. The retrogradation is also reflected from the development of thin rims of opaque oxides around sphene (plate.3.8). The primary metamorphic hornblende show a change in colour from green-brown to bluish green at the outer rims. Recrystallisation of biotite is frequently observed at the rims of large flakes of hornblende.
In summary, the overall textural relation in this group of rocks indicates retrograde reactions of granulite facies assemblages during fluid enhanced condition stabilising more hydrous assemblages characterizing an amphibolite facies paragenesis.

3.2 QUARTZOFELDSPATHIC GNEISSES:

The quartzofeldspathic gneisses are characterized by the following general mineral assemblage:

K-feldspar - plagioclase - quartz - biotite ± hornblende ± ilmenite ± magnetite ± garnet ± zircon ± apatite.

The quartzofeldspathic gneisses in the amphibolite zone are partly finely banded, partly coarse-grained rocks with schliren texture made up of plagioclase-quartz as well as microcline and biotite in varying proportions. Towards the southern part in the granulite zone, the quartzofeldspathic gneiss with a platy quartz texture is predominant. These rocks might be considered as the most typical granulite grade rocks in the area. They contain schlieren, streaks and bands of coarse-grained garnet-biotite gneisses with mostly flaser texture. In the south-western part of the granulite zone the rocks are characterized by a migmatitic banding in centimeter scale with biotite-rich melanosome and granitic leucosome with rare occurrence of idioblastic garnets.

The quartzofeldspathic gneisses are mostly granodioritic in composition although a variation from granitic to tonalitic composition is also evident.
3.3 METAPELITES:

The general assemblage of the metapelite in the area is,

sillimanite - garnet - k-feldspar - biotite - plagioclase - quartz - ilmenite (± staurolite ± rutile ± spinel ± zircon ± apatite + sec.biotite + sec.garnet)

The metapelites are characteristically coarse-grained and well banded rocks with alternating sillimanite / biotite-rich layers and coarse-grained quartofeldspathic layers in which xenoblastic grains of k-feldspar, quartz and plagioclase (An$_{21}$-An$_{27}$) define a granoblastic polygonal fabric. Texturally, two kinds of garnet are recognized. The matrix garnet frequently occurs as porphyroblast containing inclusions of sillimanite and biotite; the inclusions within garnet are swinging parallel to the external schistosity (Se) defined by biotite and sillimanite that warp the garnet (Plate.3.9). Moreover, in few samples of metapelites, the elongated grains of garnet interlaminated with sillimanite and biotite (very rarely spinel) define a strong preferred orientation of the rocks parallel to $S_1$ - schistosity (Plate3.10). These two features indicate a syntectonic origin of the garnet. On the other hand, garnets belonging to second generation form idioblastic grains, totally free from inclusions and locate in the leucocratic portion of the rocks. Fine scale veins of quartofeldspathic compositon and occurrence of secondary biotite along the border of the garnet idioblasts and symplectitic intergrowth of biotite and quartz are conspicuous around idioblastic garnet.
The significant textural features preserved within metapelites indicate abundant evidences of reaction. As for example, rarely preserved inclusion of staurolite within syntectonic garnet porphyroblast in close association with garnet, biotite, sillimanite, spinel indicates staurolite consuming reaction,

\[ \text{staurolite} \rightarrow \text{biotite} + \text{sillimanite} + \text{garnet} + \text{spinel} + H_2O \]

This metamorphic reaction as indicated from the textural feature of metapelites inferred a prograde PT-path traversed by the rocks during metamorphism. The post peak retrograde reactions are indicated from symplectic intergrowths of biotite+quartz or biotite+quartz+plagioclase. The growth of inclusion free idioblastic garnet are texturally considered as a consequence of post kinematic retrograde melting. The relevant reaction is,

\[ \text{biotite} + \text{sillimanite} + \text{quartz} \rightarrow \text{garnet} + \text{k-feldspar} + \text{melt} \]

It is worth mentioning that post kinematic porphyroblast of k-feldspar accompanying garnet contains inclusions of sillimanite and biotite.

In summary, the overall petrographical study of metapelites indicates that recrystallisation of sillimanite, biotite, garnet probably took place during peak metamorphic condition which was followed by post peak melting resulting in the growth of garnet and k-feldspar of second generation and finally underwent subsequent retrogression and stabilization of hydrous phases.
3.4 CALC-SILICATE GNEISSES

The calc-silicate gneisses are dark coloured, medium- to coarse-grained well banded rocks characterized by overall granoblastic texture. The mineral present in calc-silicate gneisses in variable proportions are plagioclase (An$_{88}$-An$_{93}$) - clinopyroxene (salite) - hornlende - quartz - calcite with accessory amounts of sphene, grossular rich garnet and opaque oxides. In the granulite zone the calc-silicate gneisses are characterized by universal presence of scapolite.

Texturally, the rocks commonly exhibit a granoblastic texture. The polygonal mosaic is defined by xenoblastic grains of clinopyroxene, plagioclase, rarely hornblende and calcite. In hornblende-rich variety prismatic hornblende and elongated grains of plagioclase define a crude foliation overprinting the granoblastic fabric. In granulite zone specially scapolite-bearing calc-silicate gneisses exhibit a foliation defined by xenoblastic aggregate of scapolite. Garnet in the scapolite-bearing calc-silicate variety are of two types: subidioblastic grains of garnet of almandine-grossular composition (Mineral Chemistry, chapter 4) shares smooth contact with clinopyroxene, plagioclase and scapolite while garnet, virtually grossular in composition, occurs strictly as coronitic rims around clinopyroxene grains at the contact with plagioclase. One of the common features of the calc-silicate gneiss in the granulite zone is a frequent development of almandine-grossular rich garnet at the contact between clinopyroxene, calcite and scapolite (Plate.3.11). This critical but very common textural
feature indicates an important reaction which can be modelled as,

$$5\text{grossular} + \text{almandine} + 6\text{CO}_2 \rightarrow 2\text{scapolite} + 3\text{hedenbergite} + 4\text{calcite}. $$

From this textural relationship the decarbonisation reaction seemed to have taken place during the peak metamorphic temperature. On the other hand metamorphic reaction characterizing post peak temperature is also known from notable textural feature such as symplectitic intergrowth of plagioclase and calcite along the border of scapolite (Photo 3.12) indicating a reaction,

$$\text{CaAl}_2\text{Si}_2\text{O}_8, \text{CaCO}_3 \rightarrow \text{CaAl}_2\text{Si}_2\text{O}_8 + \text{CaCO}_3$$

which had taken place in response to the cooling of the rock.

In summary, mineralogical and textural relations in calc-silicate gneisses lead to the following inferences:

(i) the rocks underwent intense deformation during granulite facies metamorphism;
(ii) this was followed by thorough annealing recrystallisation of the rocks manifested in the development of granoblastic mosaic;
(iii) decomposition of scapolite into plagioclase + calcite near peak temperature, and
(iv) development of coronitic garnet presumably during cooling.
3.5 QUARTZ DIORITES

This group comprises a series of rocks of variable compositions, ranging from diorite through tonalite to granodiorite. The common minerals in order of abundance in the rocks are plagioclase, hornblende, biotite, quartz, K-feldspar, orthopyroxene, opaque oxides and garnet.

The rocks are characteristically coarse-grained and preserved late metamorphic imprints. Texturally, two varieties of plagioclase are distinguished: recrystallised fine-grained untwined plagioclase and plagioclase megacryst which is characterized by complex igneous twinning and distinct zoning. Quartz is an essential mineral but in minor amounts. Matrix hornblende, biotite and rarely orthopyroxene are common mafic minerals in the rocks. Bluish green hornblende + quartz symplectites, pseudomorphed crystals of hornblende replacing pyroxene, and garnet overgrowth on biotite are the common features of these rocks. In the zone of intense deformation, the rock shows a reduction of grain size and development of mortar texture.

In summary, quartz diorites preserve well defined igneous signatures such as zoning in plagioclase, exsolution in pyroxene which were overprinted by late recrystallisation leading to the development of amphibolite facies assemblage.

3.6 DOLERITE DYKE

Dolerites are dark greenish to dark grayish, coarse-grained rocks containing plagioclase, pyroxene and opaque phases. In thin section, subhedral grains of
plagioclase are seen to occur within phenocrysts of pyroxene (ophitic or subophitic texture). Development of secondary hornblende (uralite) around pyroxenes have been observed. The general texture is porphyritic. Subophitic texture is also common.

The overall petrographical and mineral reaction studies of the different litho-units of the area lead to the following inferences for the rocks of the area.

1. A gradual change of the mineral assemblage from north to south over a lateral distance of few Km within the individual rock types.

This is clearly reflected from the transformation of hornblende + plagioclase bearing metabasic rocks into two pyroxene granulites, and stabilization of scapolite in calc-silicate gneisses in southern part.

2. A change in mineral assemblage, with time, in relation to deformational episodes.

This is evident from the development of second generation of minerals at the expense of peak-metamorphic ones during late metamorphic history. The well illustrated examples are the growth of coronitic garnet at the expense of orthopyroxene and plagioclase in basic granulites, grossular rich garnet at the expense of clinopyroxene and plagioclase in calc-silicate gneisses and decompositon of garnet in metapelite leading to the development of second generation of biotite.
Plate 3.1. Dactylitic intergrowth of minute clinopyroxene, opaque phases and plagioclase. Note the development of tiny rims of coronitic garnet along the borders of clinopyroxene and hornblende; plane polarized light; 100x.

Plate 3.2. Elimination of opaque granules along the borders of green brown hornblende in amphibolite; plane polarized light; 100x.
Plate 3.3. Symplectitic intergrowth of orthopyroxene, plagioclase and ilmenite along the corroded border of green brown hornblende in basic granulite; plane polarized light; 100x.

Plate 3.4. Pseudomorphed crystal of orthopyroxene poikiolitically contains optically continuous grains of green brown hornblende as inclusions; plane polarized light; 100x.
Plate 3.5. Bimodel rims of garnet and quartz at the contact between orthopyroxene and plagioclase in basic granulite; plane polarized light; 250x.

Plate 3.6. Replacement of orthopyroxene and K-feldspar by deep brown biotite in basic granulite; plane polarized light; 250X.
Plate 3.7. Development of secondary bluish green hornblende at the borders and within fractures of orthopyroxene in basic granulite; plane polarized light; 100X.

Plate 3.8. Tiny rim of sphene around opaque oxide in retrograded basic granulite; plane polarized light; 250X.
Plate 3.9. Warping of porphyroblastic garnet by biotite-sillimanite aggregate which define the schistosity of the rock. Note the inclusions within garnet tend to swing parallel to the external schistosity; crossed polarized light; 100X.

Plate 3.10. Elongated garnet along with prismatic biotite shows strong preferred orientation in metapelitic plane polarized light; 100X.
Plate 3.9

Plate 3.10
Plate 3.11. Development of almandine - grossular garnet at the contact between clinopyroxene and calcite-scapolite grains; Cross Nicols; 100X.

Plate 3.12. Symplectitic intergrowth of plagioclase and calcite at the contact of scapolite; Cross Nicols; 250X.