CHAPTER III

PETROGRAPHY

The area comprises metabasics, metapsammites, metapelites and metasemipelites broadly grouped into the two formations which consist of different mappable members discussed in the previous chapter. A perusal of literature on the study area clearly brings out the paucity of petrographic data on these rocks. An attempt has been made in this chapter to present the salient petrographic characters of these rocks which help in deciphering their nature of metamorphism and petrogenesis discussed in chapter VI. Majority of these rocks bear textural and mineralogical evidences favouring polyphased metamorphism and deformation.

The lithologic units of the Jakhri and Rampur formations have been regrouped into different petrographic units (Table 3.1) for description and convenience because most of the rocks exhibit similar mineral assemblage and texture. Even such petrographic units have been considered for the description which are not mappable on the scale used in the present investigation since thin bands of these units may have some petrogenic significance. The different petrographic units are described in sequel.
Table 3.1
Petrographic units of Rampur area.

Metabasics:

a) Greenschists:
   i) Talc-tremolite schist
   ii) Tremolite-actinolite schist
   iii) Actinolite-tremolite-biotite schist
   iv) Chlorite-actinolite-biotite schist
   v) Biotite-hornblende schist
   vi) Hornblende-biotite-actinolite schist
   vii) Hornblende-actinolite-tremolite schist

b) Amphibolites:
   i) Schistose amphibolite
   ii) Massive amphibolite

Metapsammites:

a) Flaggy quartzite
b) Quartzite
c) Micaceous quartzite

Metapelites:

a) Mica schist
b) Felspathic mica schist

Metasemipelites:

Quartz-mica schist
Metasemipelite is represented in the area by quartz-mica schists (Chiksa Member) of the Jakhri Formation. The percentage of quartz exceeds that of combined total percentage of mica and felspar minerals. The modal percentages of these minerals have been presented in table 3.2.

**Quartz-mica Schist:**

Medium to fine grained quartz-mica schist is brownish white, greyish green to silvery grey in colour and is characterized by prominent foliation ($S_1 = S_2$) resulting from alternate metapelitic and metapsammitic bands together with preferred arrangement of the constituents of micaceous minerals. Small pockers and crinkles are commonly observed on the schistosity plane. Occasionally a mineral lineation parallel to the axis of crinkles is also observed.

Under the microscope, the schist exhibits a granoblastic texture and marked schistosity which is due to the preferred alignment of micaceous minerals and elongate quartz grains. Alternate quartz-rich and mica-rich bands are running parallel to the schistosity (Plate 9.a) which, at times, is crinkled and warped (Plate 9.a, b).
Table: 3.2 Average modal composition of metapelites, metasemipelite, and metapsammites (Volume percent data).

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Metapelites</th>
<th>Metasemipelite</th>
<th>Metapsammites</th>
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<tr>
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<tr>
<td>Muscovite</td>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td>1.50</td>
<td>1.15</td>
<td>1.55</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>Garnet</td>
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</tr>
<tr>
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<td>7.25</td>
</tr>
<tr>
<td>Plagioclase (av. of 3 samples)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Potash plagioclase</td>
<td>-</td>
<td>4.83</td>
<td>-</td>
</tr>
<tr>
<td>Potash Felspar</td>
<td>-</td>
<td>4.83</td>
<td>-</td>
</tr>
<tr>
<td>Epidote</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tourmaline</td>
<td>3.15</td>
<td>3.10</td>
<td>2.80</td>
</tr>
<tr>
<td>and other accessories</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 = Mica schist (av. of 5 samples). 2 = Felspathic mica schist (av. of 3 samples).
3 = Quartz mica schist (av. of 3 samples). 4 = Flaggy quartzite (av. of 2 samples).
5 = Massive quartzite (av. of 4 samples). 6 = Micaceous quartzite (av. of 2 samples).
The rock is composed mainly of quartz, muscovite and biotite with chlorite, garnet and felspar in subordinate amounts. Tourmaline, sphene, apatite, opaques and sometimes zircon form the minor constituents. The relative amount of muscovite and biotite varies in different thin sections though both of them are usually present.

Quartz forms the dominant mineral constituent and occurs as xenoblastic grains. It has recrystallized to form big porphyroblasts showing strain effect. It occurs in two forms, i.e., small lenticles (quartz-I) forming small rounded or elongated grains and as recrystallized porphyroblastic type (quartz-II) which forms elongate lensoid crystals aligned parallel to the plane of schistosity. Sutured outlines, interlocking behaviour and composite nature are characteristic. Outlines of original grains in recrystallized porphyroblasts can still be clearly made out under the crossed nicols and are marked by minute and dusty inclusions around the individual grains. The mineral shows an undulatry extinction and first order interference colours. Development of deformation lamellae is observed in some grains. Inclusions of muscovite and opaques are quite common.

Muscovite constitutes the dominant mica in some thin sections whereas in others it forms a minor constituent.
It occurs in two forms, i.e., elongated and twisted laths (muscovite-I) and big porphyroblasts (muscovite-II). Muscovite-I defines the main foliation ($S_2$) in the rock and contains the inclusions of opaques mostly concentrated along the cleavage planes. Sometimes, muscovite-I itself occurs as inclusion in other minerals. The porphyroblasts of muscovite-II, lying oblique to $S_2$-surfaces (Plate 9.c), are of post tectonic origin and exhibit a faint pleochroism from light yellow to colourless pointing to its being ferrimuscovite. One set of prominent cleavage marked by opaque dusty inclusions is characteristic of this mineral.

Biotite is often subordinate in amount to muscovite except in a few thin sections in which its percentage exceeds that of muscovite. Two types of biotite are encountered. It occurs as small, elongated, bent and contorted flakes or shreds (Biotite-I). Biotite-I along with muscovite-I defines the foliation in the rock (Plate 9.a). It shows a marked pleochroism with $X =$ pale brown, $Y = Z =$ greenish brown and parallel extinction when unstrained. Biotite alters to chlorite-I and muscovite-I along with the release of oxides of iron.

The second type (biotite-II) is lepidoblastic in habit and occurs as sieved porphyroblasts containing inclusions of quartz and opaques. It is superimposed over
the main foliation \((S_2)\). Pleochroism is well marked with \(X = \text{light yellow}, Y = \text{brown}\) and \(Z = \text{deep reddish brown}\). It is characterised by the \(2V(-) = 22^\circ\) and refractive index \(Y = 1.642\). It often alters to chlorite-II and muscovite-II with which it is often interleaved.

**Chlorite**, forming a minor constituent of the schist, occurs in two varieties and is generally the alteration product of biotite-I and biotite-II. Chlorite-I is flaky and the flakes are aligned along the schistosity which is superimposed by the porphyroblasts of chlorite-II. The mineral is light green to green in colour and is pleochroic. It is distinguished by its porphyroblastic habit, oblique extinction of about \(2^\circ-3^\circ\) and its biaxial character. A few grains of penninite are also observed and are characterized by parallel extinction and typical anomalous Berlin blue interference colour.

**Garnet** is sporadically present in some thin sections. It is usually colourless to light pink in colour. The mineral occurs as xenoblastic rounded crystals (garnet-I) and occasionally as six-sided porphyroblasts (garnet-II). (Plate 11.d). Inclusions of quartz and oxides of iron are abundant in the former and are arranged in S-shaped trails whereas the latter has a sieved core with relatively compact
peripheral zones. Porphyroblasts of both the types are fractured and alter along the cracks to chlorite.

**Felspars** occur in minor amount as small anhedral or irregular interstitial grains and sometimes as porphyroblasts superimposed on the schistosity. It is mostly twinned on albite-law but a few untwinned grains have also been recognized. The extinction angle varies from 12°-15°. It is albite (An≤10) in composition (Michel-Levy method) with 2V (+) = 79°-81° and refractive indices ω = 1.534, γ = 1.541. The cleavage traces are mostly aligned across the S2-surfaces. The occurrence of microcline is less common. It is untwinned and difficult to distinguish from quartz.

The opaques occur in patches and segregation along the foliation. **Apatite** forms minute prisms scattered throughout the thin section. **Sphene** occurs as lozenge shaped or irregular grains characterized by slight pleochroism and high polarisation colours. Along the margins, it alters to leucoxene. A few grains of epidote, tourmaline and zircon are also observed.

**METAPELITES**

This group of rocks occurring in the study area is represented by mica schist (Dhar Ivlember) and felspathic
mica schist (Shah Member) of the Jakhri Formation. These are medium to coarse grained, well foliated with prominent schistosity ($S_2$) along which they split into sheets or slabs. These can be readily distinguished both megascopically and microscopically by the variation in their colour, grain size and mineral composition.

The division of these metapelites is mainly based on the relative abundance of some diagnostic minerals. Table 3.2 gives the modal percentage of the representatives of these rocks. These schists are the most interesting and significant group of rocks as they show not only the variation in mineralogy and common megascopic and microscopic characters but also they have preserved earlier textures and structures even after their polyphased metamorphism and deformation. The relict textures of metapelites as well as those shown by the green schists of Rampur Formation are of great significance in tracing out the metamorphic history of Rampur area (Chapter VI). It is with this view that they have been studied in detail.

The schists show at least three $S$-surfaces (Chapter IV). The earlier $S_1$-surfaces (bedding schistosity) are defined by fine grained micaceous minerals and by the boundary surfaces of quartz-rich and quartz-poor bands. The
bedding schistosity, in most of the cases, occurs as relict structure superimposed by prominent axial plane schistosity ($S_2$-surfaces, $S_1 = S_2$). The schistosity ($S_2$) is defined by the flaky minerals and quartz lenticles. The $S_2$-surfaces, referred to as crenulation cleavage, are defined primarily by bending of mica flakes and slip of microlaths along a new plane and to less extent by the reorientation and parallelism of flaky minerals.

Megascopically, the mica schist is a medium grained rock showing greenish grey or brown colour and is at times slightly more greenish in colour due to high percentage of chlorite. The rock is characterised by well developed schistosity ($S_2$). Quartz, biotite, muscovite, chlorite and sometimes garnet are recognisable. Some bands in the rock, depending upon their composition, show a very prolific growth of garnet while others have a few crystals or none at all.

The mesocratic, greyish brown, felspathic mica schist is a medium grained and well-foliated rock. It is characterized by fine greyish streaks of quartzofelspathic material which alternates with the bands of mica minerals. Sporadic studs or thin lenticles of felspar and quartz appear in the rock along the schistosity. Micaceous minerals

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wrap around felspar and quartz lenticles thereby apparently showing bending of the schistosity (S₂).

Under the microscope, these schists are medium to coarse grained and crystalloblastic. The parallel to subparallel alignment of flaky minerals and elongate quartz grains mark the plane of schistosity (S₂) (Plate 9.e, f). In most of the cases, the bedding schistosity (S₁) has been partially or completely obliterated by the schistosity (S₂). At times, S₁ and S₂ run parallel to each other. Thin composite lenticles of quartz-rich bands define the relict bedding (S₁) which is parallel to the schistosity (S₂) and can be easily recognised in these schists. The main schistosity (S₂) is, at times, folded into microfolds (Plate 9.d) with the development of crenulation cleavage (S₃) which is well developed in the felspathic mica schists (Plates 9.e, 11.c). Small quartz grains are often segregated in the hinges of microfolds.

These schists show variations in texture and physical characters. Though the mineralogical composition is nearly similar yet there is a marked difference in the proportions of the mineral constituents (Table 3.2). In order to avoid repetition, their optical characters have been described together.
The mica schist is composed essentially of quartz, mica, garnet, chlorite and some felspars whereas in felspathic mica schist quartz, micas and felspars form the dominant minerals. Some thin sections contain good amount of tourmaline. Epidote, sphene,apatite, opaques and rarely zircon form the minor constituents of these schists. The relative proportions of these constituents, however, vary from place to place. The occurrence of some of these minerals is restricted to a particular schist and is absent from the other.

Quartz, forming an important constituent in most of the thin sections, occurs as recrystallised xenoblastic grains of varying size and shape and is of two generations. Quartz-I occurs as small anhedral or rounded to subrounded grains which are water-clear and devoid of any inclusions. It is confined to the groundmass and occurs as inclusions in porphyroblasts of other minerals such as garnets, micas, felspars and also in quartz-II (Plate 10.a). Quartz-II forms medium to coarse grained, lensoid elongate masses which are aligned with their longer axis parallel to the schistosity ($S_2$). The grains have sutured outlines, form interlocking aggregates and often contain inclusions of sericite, quartz-I and at times dusty opaques. Wavy extinction and the first order interference colours are
characteristic. Big composite augen-shaped porphyroblasts of quartz are composed of two or three grains and their outlines can still be deciphered. Quartz grains are fractured and have been filled by wisps of mica and opaque minerals. Deformation lamellae are also observed in some grains.

Micas constitute the next dominant minerals and are represented mainly by biotite and muscovite. In some thin sections, chlorite is quite abundant. They together often dominate over quartz in modal percentage.

Biotite is one of the dominant minerals of mica schist whose percentage is less in felspathic mica schist as compared to the mica schist. Two generations of biotite have been recognised. Biotite-I occurs as flakes and elongate lath and shreds which define the schistosity ($S_2$) in these rocks together with muscovite-I. It varies in colour from greenish brown to brown showing distinct pleochroism ($X = \text{pale yellow}, Y = \text{brown and } Z = \text{greenish brown}$) and the refractive index $\beta = 1.644$. The body colour of the mineral often masks the pleochroism. Biotite-I exhibits a nearly straight extinction but when strained or present in the hinge region of microfolds, a wavy or undulose extinction is characteristic. Biotite-II occurs as reddish brown porphyroblasts which are superimposed over
the main schistosity \( (S_2) \) and are well developed in both mica schist and felspathic mica schist. Biotite-II is intimately associated with muscovite-II and the two are often interleaved. It is pleochroic from \( X = \) pale yellow, \( Y = \) brown to \( Z = \) deep reddish brown showing \( 2V \) (\(<\text{ve}\)) = 22° and strong birefringence = 0.043. Cleavage is well manifest in all the grains except the basal sections. The basal sections and the cleavage planes are marked by deep brown or black opaque minerals. Sometimes biotite-I alters to chlorite, muscovite and oxides of iron along the cleavage planes.

Inclusions of quartz, sericite, opaque minerals and zircon are commonly observed in the biotite. Pleochroic halos are common around zircon inclusions. Often porphyroblasts of biotite-II contain inclusions of magnetite or hematite and rarely of biotite-I as well as chlorite-I.

Muscovite occurs as colourless to pale shreds and flakes. It is of two generations. Muscovite-I forms minute flakes and shreds which are aligned along the schistosity \( (S_2) \). Though muscovite-I has been formed primarily from the recrystallization of sericite as a result of increasing grade of metamorphism yet some of it appears to be an alteration product of biotite-I since it contains a relict
core of the latter. The cleavage planes of such muscovite are filled by specks of iron ore. Muscovite-II (ferri-muscovite) occurs as porphyroblasts which are closely associated and often interleaved with biotite-II as well as with individual grains superimposed over the schistosity. It exhibits a very faint pleochroism from light yellow to colourless and has the indices of refraction $\alpha = 1.555$, $\beta = 1.586$ with $2V (-) = 41^\circ$. High polarisation colours and straight extinction are characteristic. However, when the grains are strained or deformed, they show wavy extinction. Cleavage is well developed and marked by dusty inclusions of iron oxides or thin shreds of biotite indicating it to be an altered product of biotite-II. At times, muscovite contains inclusions of quartz, iron ore, felspar and less commonly tourmaline.

Chlorite though does not form a major constituent of the schist yet some amount of it is always encountered in thin sections. Chlorite occurs in three varieties. Chlorite-I occurring as minute flakes and shreds, aligned parallel to schistosity, is pleochroic from pale green to light bluish green. It is associated with biotite-I. Chlorite-II forming porphyroblasts is an alteration product of biotite-II. It is greenish in colour showing pleochroism from colourless to green. The porphyroblasts show cleavage
and are superimposed on the schistosity. The flakes or porphyroblasts of chlorite-III occur in patches surrounding the garnet-II porphyroblasts or fill the cracks in them. A well marked pleochroism from pale to pistachio green is characteristic of this mineral.

Garnet sporadically occurs in the metapelites. It shows a wide range of variation in size, frequency, amount, pattern of inclusions, fracturing and alteration. The garnet is mainly restricted to mica schist and is rare or absent in felspathic mica schist. Garnet occurs in the form of crystals which vary in size from tiny specks or skeletal irregular grains to big idioblastic porphyroblasts. It varies in colour from pale pinkish to pinkish and is characterised by high relief due to which it stands out boldly against the groundmass. The mineral is isotropic in nature but when highly strained it shows a slight anisotropism.

Garnet porphyroblasts sometimes grow without disturbing the schistosity. At times, the schistosity is apparently displaced with the development of augen-shaped garnet in the centre and quartz-mica aggregates in the pressure shadow region (Plate 10.b).
Based on variations in the form and pattern of inclusions, the following types of garnet have been distinguished. Garnet-I occurs as irregular/skeletal xenoblastic crystals. The grains are full of helicitic inclusions of quartz, sericite and oxides of iron (Plate 10.c). The inclusions in the central portion are fine grained and exhibit a coarsening in grain size towards the peripheral zone. Garnet-I represents the rolled or rotated variety of garnets (Plate 10.f). The inclusions in the garnet-I are arranged in spiral form and simulate S- or Z-shaped pattern (Plate 10.c, d). Another characteristic feature shown by garnet-I is the continuity of Si and Se. These patterns of inclusions have been regarded as evidences of synkinematic growth (Spry, 1969) or para-crystalline growth (Read, 1948). This indicates that the garnet underwent rotation during its growth.

Garnet-I, at places, is highly fractured (Plate 11.b). The fractures run for the whole length of the crystal (Plate 10.f) and extend beyond into the groundmass but they are generally confined within the porphyroblast. The fractures are occasionally filled with quartz, chlorite and iron ore leaving islands of fresh unaltered garnets surrounded by the alteration product. Sometimes, the garnet porphyroblasts have been broken and crushed into a
number of small individuals (Plate 10.e) which form dumb-bell shaped aggregate - the voids being filled by recrystallized quartz. Garnet-II forms rounded to subrounded and rarely tabular or idioblastic porphyroblasts superimposed over schistosity.

Felspar varies in composition, amount and grain size in both types of schists. It is represented by orthoclase, microcline and plagioclase. Both the twinned and untwinned varieties of plagioclase have been recognized. Albite and oligoclase represent the plagioclase. The albite (An_{5-10}), as determined by Michel-Levy method, shows 2V(+v) = 79°-81° with an extinction angle of 12°-15° whereas the oligoclase (An_{18-20}), as determined by Michel-Levy method, shows 2V (+ve) = 85° and extinction angle of 2°-4°. These felspars are characterized by polysynthetic twinning on albite law but clouded untwinned grains are also not uncommon.

Alkali felspar is more or less restricted to felspathic mica schist. However, it is not uncommon in the other variety. Potash felspar is mostly orthoclase and sometimes microcline. Orthoclase is mostly associated with plagioclase. The mineral is clouded and both the twinned (Carlsbad twinning) and untwinned grains have been observed with low angle extinction (27°). Microcline
occurs in patches inbetween the quartz grains. It shows feebly developed cross-hatched twinning and contains inclusions of sericite, showing criss-cross pattern.

Epidote is pale green to yellowish in colour and shows feeble pleochroism from pale yellow to light golden yellow. It occurs generally as small anhedral grains and rarely as porphyroblasts showing two sets of cleavage as also first or second order interference colours. Yellowish brown to bluish tourmaline generally occurs as prismatic crystals or small laths. The mineral is usually disseminated throughout the thin sections. At times, it forms large porphyroblasts which are characterised by inclusions of quartz. It shows high relief, strong pleochroism and blue-green interference colours.

Sphene occurs as light brown to colourless and xenomorphic or lozenge-shaped grains which are characterised by high relief, feeble pleochroism and high order interference colours. It has altered to leucoxene along its borders. Colourless tabular laths of apatite showing pitted surface under ordinary light are characterised by high relief and first order polarisation colours. Black, reddish brown or brownish black opaque minerals occur as fine dust and minute irregular grains disseminated throughout the thin sections or as thin rims around garnet as well as
along the cleavage planes of biotite and muscovite.

**Metapsammites**

Metapsammites form the second dominant group of rocks after metabasics in the Rampur Formation. This group is characterized by an increase in the psammitic constituents as compared to the pelites and is represented by different types of quartzite (Table 3.1). The modal composition of this rock has been presented in table 3.2. Three S-surfaces are discernible in these rocks. The earliest S$_1$ surface is defined by flakes of sericite and boundary surfaces of quartz-rich and quartz-poor bands. In many cases, S$_1$-surfaces are superimposed by the dominant S$_2$-surfaces but, at times, S$_1$- and S$_2$-surfaces intersect at an angle near the fold apices. The S$_3$-surfaces are feebly developed.

Megascopically, medium to fine grained flaggy quartzite is characterized by well defined slaty cleavage (S$_2$) and its flaggy nature. The quartzite of the Zaghat-Khana Member is massive to sub-schistose, compact and medium grained in nature. Micaceous quartzite of Darshai Member is compact and medium to fine grained. It is often stained red due to leaching of iron. Mica-rich layers impart schistose structure to it. It is friable and characterized by well developed schistosity (S$_2$).
Under the microscope, the flaggy quartzite and quartzite exhibit fine to medium grained granoblastic texture. The fine shreds of flaky minerals and elongate quartz grains mark the slaty cleavage ($S_2$). Tiny specks of sericite denoting the bedding cleavage ($S_1$) and lying, at times, oblique to the $S_2$-surfaces, are also observed. In most of the cases, the $S_1$-surfaces run parallel to $S_2$-surfaces ($S_1 = S_2$). The crenulation of cleavage ($S_2$) is not well marked. The rocks from the vicinity of the thrust show granulation and crushing of quartz grains.

The fine to medium grained micaceous quartzite exhibits crystallloblastic to granoblastic texture. It shows a crude schistosity ($S_2$) (Plate 11.a) which becomes more prominent with increase in mica content. The quartz-rich and mica-rich layers define the relict bedding schistosity ($S_1$). This is superimposed by the main schistosity ($S_2$). Mortar texture is very well observed in all varieties of quartzites. It is exhibited by the big porphyroblasts of the quartz surrounded by smaller ones (Plate 11.a).

Though the various types of metapsammites (Table 3.1) show nearly the same mineralogical composition yet there is a marked difference in the proportion of different mineral constituents (Table 3.2).
The rocks mainly comprise quartz, micaceous minerals (muscovite and biotite) with chlorite, felspar, epidote, sphene and opaques. These minerals show almost similar optical properties as discussed in quartz-mica schist. To avoid repetition, only the important and characteristic optical properties of these minerals are given below.

Quartz forming the dominant mineral constituent is of two generations (quartz-I and quartz-II). These are of two distinct grain sizes, i.e., small lenticles (quartz-I) and recrystallized porphyroblasts (quartz-II). These porphyroblastic elongate grains often show wavy extinction and sutured outlines with the surrounding smaller grains of quartz in some of the coarser types.

Muscovite constitutes the dominant mica in some of the thin sections while in others it forms only a minor constituent. In flaggy and micaceous quartzites, it occurs as elongated and twisted laths as well as big porphyroblasts but in the case of quartzites, it occurs as small specks. Biotite occurs as streaks showing alteration to chlorite. In association with muscovite, it imparts a distinct foliation to the rock. At times, it is bent around the bigger grains of quartz.

Chlorite is mainly associated with streaky biotite
and is the alteration product of the latter. Felspar is mostly plagioclase which shows twinning on the albite law. Epidote, observed in all varieties of quartzite, is of pistacite type. Sphene is mostly associated with magnetite. It alters to leucoxene along its margin. It is a common accessory mineral in flaggy quartzite. Oxides of iron occur in patches and segregations along the foliation. They are often formed due to alterations. A few grains of tourmaline and zircon are also observed.

METABASICS

A major part of the Rampur Formation is comprised of metabasic rocks which have been classified by the author as: (i) greenschists and (ii) amphibolites based on their field characteristics and petrographic criteria.

The author, while classifying these rocks, has considered that though the terms 'greenschist' and 'amphibolite' facies are rather well defined (Turner and Verhoogen, 1960; Turner, 1963; Francis, 1956) yet there is no sharp distinction between the rock terms 'greenschist' and 'amphibolite'. The connotations are vague and the striking difference appears to be mainly on the basis of texture and the grain-size boundary seems to be placed at about 1-2 mm for amphiboles but the distinction is somewhat
arbitrary (Spry, 1969) and that greenschists are more foliated and amphibolites are more granular. The term 'greenschist' is used to denote a fine grained, foliated, green coloured schist with an approximately basic igneous chemical composition and containing abundant amphibole and/or chlorite (Spry, 1969). Transitional rocks have been called hornblende schist and this term has also been used synonymously with schistose amphibolite.

Greenschists:

The green or dark green schistose rocks whose colour is due to the abundance of one or more green minerals and which comprise the Dansa Member of the Rampur Formation have been classified into various petrographic units (Table 3.1).

The division of greenschist is mainly based on the relative abundance of diagnostic minerals. Table 3.3 gives the average modal composition of these rocks.

These schists comprise the most significant group of rocks in the area. They have preserved the earlier textures and structures even after their polyphase metamorphism and deformation. Though they show variation in mineralogy yet similar megascopic and microscopic characters are observed in them.
Table 3.3 Average modal composition of the metabasics of the area (Volume percent data).

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<td>8.20</td>
<td>7.70</td>
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<tr>
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M = Number of samples.
The schists show at least three $S$-surfaces (Chapter IV). The earlier $S_1$-surface (bedding cleavage) is defined by the orientation and crystallization of chlorite and sericite. The slaty cleavage ($S_2$) is defined by parallel and subparallel alignment of chlorite and of the longer axis of quartz grains. The crenulation cleavage ($S_3$) is characterized by bending and alignment of mica minerals mainly by rotation.

Macroscopically, greenschists are fine grained and green or dark green in colour. The rocks are characterized by well defined slaty cleavage ($S_2$).

Under the microscope, these schists are fine grained. They show different types of textures, e.g., tremolite-actinolite schist and actinolite-tremolite-biotite schist show poikiloblastic texture (Plate 12.a, b); talc-tremolite schist shows relic pilotaxitic texture (Plate 12.c); chlorite-actinolite-biotite schist is glomeroporphyritic (Plate 12.d, e) while biotite-hornblende schist and hornblende-biotite-actinolite schist exhibit porphyroblastic textures (Plate 12.f). The parallel to subparallel alignment of micaeous minerals and elongate quartz lenticles mark the slaty cleavage ($S_2$). The cleavage, at times, is folded into microfolds (Plate 13.a) resulting in the development of crenulation cleavage (Plate 13.b, c) particularly exhibited by the chlorite-actinolite-biotite schist.
These schists show variations in their textural and physical characters. However, no appreciable variation is observed in their mineralogy. In order to avoid repetition, their optical characters have been described together.

The greenschists are composed essentially of actinolite, tremolite, chlorite, epidote, felspars and diopside. Some sections contain calcite. In hornblende-actinolite-tremolite schist and hornblende-biotite-actinolite schist, hornblende forms an important constituent (Table 3.3) whereas talc forms an important constituent of talc-tremolite schist. Quartz, ilmenite, sphene, zircon and iron oxides constitute the accessory minerals. In some of the varieties, antigorite is present in minor amount. The relative proportions of these constituents, however, vary from place to place.

**Actinolite** is an important constituent of the greenschists. The mineral is fine-to medium-grained, xenoblastic to lath-shaped in character often becoming granular (Plate 13.d, e). It is colourless to pale green and shows slight pleochroism as also oblique extinction (CA 12°-15°). Diamond-shaped cross sections of the mineral show two sets of amphibole cleavage with symmetrical extinction. Optically, the minerals is biaxial.
(-ve) with length slow characters and larger 2V (= 79°-80°). It is distinguished from hornblende by its weak pleochroism.

Tremolite occurring as prismatic grains or in fibrous colourless laths is usually aligned as small porphyroblasts in the plane of the schistosity (Plates 12.a; 13, f; 14.a, b). The mineral is identified by fairly high relief, one set of perfect cleavage, irregular cross fractures, extinction angle (ZAC) 15°-18°, second order interference colour and its length slow character.

Green coloured chlorite, exhibiting scaly to subtabular or fibrous habit (Plates 12.e; 14.c, d, e, f), forms an important constituent of chlorite-actinolite-biotite schist whereas in other types it occurs in small quantities. It shows weak pleochroism in different shades of green or anomalous brownish or bluish colour. It is also found as the alteration product of actinolite in chlorite-actinolite-biotite schist.

Epidote is quite common in these rocks and its amount is variable. It varies in size from tiny granules to large porphyroblasts with well developed cleavage (Plate 15.a). It also tends to occur as idioblastic prisms elongated parallel to the plane of schistosity. Small anhedral grains of epidote showing pistachio green colour and characteristic
pleochroism from yellow to olive green are identified by their high relief, strong birefringence and mottled appearance under the crossed nicols. The mineral exhibits one set of perfect cleavage and almost parallel extinction. Clinocloisite occurring, more or less, as elongated crystals are faintly pleochroic from grey to light yellow. Extinction varies from 0°-3°. The mineral is optically +ve with 2V varying from 65°-90° and shows weak birefringence (0.009 to 0.011).

In some of the thin sections, epidote and related minerals appear to have formed due to the saussuritization of plagioclase (Plates 13.e; 15.b, c, d) and by the breakdown of other ferromagnesian minerals (Plates 15.e, f; 16.a, b).

Felspars are represented both by plagioclase and potash felspars. Plagioclase is dominant in tremolite-actinolite schist, actinolite-tremolite-biotite schist and talc-tremolite schist whereas potash felspars are mainly restricted to hornblende-actinolite-tremolite schist, hornblende-biotite-actinolite schist and biotite-hornblende schist.

The dominant plagioclase in talc-tremolite schist, chlorite-actinolite-biotite schist and tremolite-actinolite
schist is albite (An\(_{0-7}\)). It occurs as idioblastic porphyroblasts enclosing strings of epidote or actinolite needles. The porphyroblasts are sometimes sieved and riddled with inclusions (Plate 16.c). Both untwinned and twinned grains are observed. Twinning is on the albite law. In actinolite-tremolite-biotite schist, oligoclase (An\(_{20-25}\)) occurs as small grains or elongated porphyroblasts arranged parallel or subparallel to the foliation. Twinning, when present, is according to albite or pericline law. The porphyroblasts are sieved and riddled with inclusions of quartz. The plagioclase felspars are saussuritised (Plates 13.e; 15.b, c, d; 16.d).

Amongst the potash felspars, orthoclase is usually observed which occurs as subhedral porphyroblast having 6°-8° extinction angle. Both twinned and untwinned grains are observed and where twinning is present, it is on the Carlsbad law.

A few small granular grains of yellowish diopside showing very weak pleochroism but having slightly higher relief than the neighbouring amphiboles are characterized by two sets of pyroxene cleavage as well as one set of well developed parting, oblique extinction (Z\(\angle C = 38°-40°\)) and second order blue interference colours. The mineral is biaxial, optically +ve with 2V = 54°-56°.
Bluish green hornblende occurs as lath-like prismatic plates which are aligned parallel to each other and define the schistosity (Plate 16.e). Hornblende shows sutured boundaries. It is distinguished by its pleochroism $X = $ pale green, $Y = $ green and $Z = $ bluish green, birefringence $= 0.018$, amphibole cleavage (Plate 16.f), extinction angle ($ZAC$) of $7^\circ-12^\circ$ and $2V(\gamma) = 71^\circ$.

Talc along with acicular needles of tremolite shows preferred orientation (Plate 12.c) and is restricted to talc-tremolite schist. It exhibits flaky habit and is often bent. It is identified by a low first order grey interference colour.

Biotite is pale pinkish brown to deep brown in colour and occurs as elongated tiny flakes or laths trending parallel to the foliation of the rock. It is pleochroic from $X = $ light yellow, $Y = $ brown to $Z = $ deep reddish brown. Sometimes, the flakes are bent and deformed.

Calcite, forming large crystals, occurs as vesicular fillings in the green schists. It shows a perfect rhombic cleavage (Plate 17.a) with symmetrical extinction. High birefringence and high order polarisation colours are characteristics of this mineral. Polysynthetic twinning is common.
Quartz occurs in small subhedral to anhedral grains. At times, it is rather difficult to distinguish it from small untwinned felspar grains but when occurring as recrystallized larger grains, it is easily distinguishable. It occurs mostly as inclusions. Undulatory extinction and sutured outlines are usually observed.

Antigorite occurs as fibrolamellar aggregates and is distinguished by its parallel extinction and first order grey to yellow polarization colours as well as its length slow character and weak birefringence.

Other minor constituents like ilmenite, sphene, zircon and opaques are scattered throughout the thin sections in the form of small irregular grains, streaks or aggregates.

Amphibolites:

The dark green or dark greenish black, medium grained, rocks which are composed mainly of hornblende and plagioclase have been classified into: (a) massive amphibolites and (b) schistose amphibolites. This division, mainly descriptive, is based on their physical and textural characteristics. The main difference between the two is that the massive amphibolite is very hard and compact whereas the schistose type is characterised by well developed foliation.
Under the microscope, amphibolites are fine-to medium-grained showing symplectic (Plate 17.b) or blasto- ophitic (Plate 17.c) textures. In some of the thin sections, relict igneous textures (i.e., ophitic, intersertal, porphyritic, etc.) have been identified (Plate 17.d, e, f). The schistosity is defined by the preferred alignment of hornblende prisms (Plate 17.f; 18.a, b) though a few crystals of the mineral show oblique relationship with the foliation (Plate 18.c). Some thin sections, however, show nematiclastic texture (Plate 18.d).

The rocks are composed of hornblende, plagioclase (An$_{20-30}$), epidote, quartz, biotite, sphene, ilmenite and rutile. The mineral constituents vary in proportion in different thin sections (Table 3.3). However, no appreciable variation in the optical characters of the minerals are observed and hence they have been described together.

**Hornblende** forms the chief mineral constituent. It occurs as pale green elongated grains and laths, sometimes, aligned parallel to the foliation (Plate 18.b, e) and shows a wide range of dimensions varying from 0.25 mm to 2 mm in length and 0.1 mm to 0.5 mm in breadth. Some hornblende laths show decussate texture and are poikiloblastic in habit (Plates 17.e; 18.f; 19.a). It is often
intergrown with plagioclase thus simulating relict ophitic texture. The length slow prismatic crystals of the mineral show extinction ($Z\perp AC$) varying from $15^\circ$–$20^\circ$. Fasal sections show two sets of amphibole cleavage at $56^\circ$ and symmetrical extinction. Birefringence varies from 0.020 to 0.023 and $2V (-)$ from $66^\circ$–$72^\circ$. The common types of pleochroism exhibited by this mineral are $X =$ greenish yellow, $Y =$ pale green and $Z =$ olive green to green.

Simple and repeated twinning is sometimes observed (Plate 19.b). Some crystals of hornblende show schiller structure (Plate 19.c) in their core and sometimes relics of pyroxene are also observed (Plates 17.e, f; 19.d). Sometimes, the porphyroblasts of hornblende are sieved (Plate 19.b) and are riddled with inclusions of quartz, felspar and epidote. Alteration to chlorite and epidote (Plate 19.e) is common and the cleavage planes are often marked by reddish brown tinge.

Plagioclase ($An_{20-30}$) is quite common. It occurs as small laths and also as big porphyroblasts arranged along the schistosity. Generally, the mineral is untwinned but relict twinning on albite law is faintly visible in most of the crystals (Plate 19.b). Plagioclase shows extensive alteration to epidote thereby suggesting that it must have been more calcic before its alteration.
The plagioclase shows saussuritization and the relict twinning in such felspar crystals is well-preserved (Plate 19.f).

Epidote is a very common mineral in amphibolites. It occurs as small idioblastic crystals ranging from 0.1 to 0.35 mm in length and 0.04 to 0.23 mm in breadth. The length ; breadth ratio varies from 2 to 3.5. It is characterized by a perfect cleavage (001), extinction angle (XAC) varying from 2° to 4°, high birefringence = 0.017-0.025 and 2V (-) = 80°-87°. It is pleochroic with X = light yellow, Y = pale greenish yellow and Z = light lemon yellow. Some crystals show zoning. Clinozoisite occurs as slightly more elongated crystals which are faintly pleochroic from colourless to light yellow. Extinction (XAC) varies from 0°-3°. Birefringence from 0.010 to 0.018 with 2V (+) varying from 85°-87°.

Epidote and clinozoisite are the alteration products of hornblende and plagioclase (Plate 19.e). These are associated with hornblende, biotite and sphene. Large epidote grains have inherited some of the characters of hornblende (i.e., cleavage) and some larger grains of clinozoisite contain inclusions of relict plagioclase. In such a case, the grains of epidote align themselves parallel to the hornblende crystals thereby
rendering their identification rather difficult. However, the anomalous blue interference colour and rather parallel extinction shown by the epidotes help to distinguish them from the hornblende. Epidote minerals are often concentrated in the vicinity of the plagioclase (Plate 19.e).

Quartz occurs mostly as interstitial xenoblastic grains and also as inclusions in the sieved hornblende (Plate 19.b). It shows first order interference colour and undulatory extinction. It also fills microfractures traversing hornblende. In schistose amphibolites, it is recrystallized to form bigger grains elongated parallel to the foliation of the rock (Plate 18.b). Sometimes, thin quartz-rich bands alternate with hornblende-rich bands.

Biotite though not so abundant is often present in the form of flakes and shreds arranged parallel to the foliation plane. It shows pleochroism from light yellow to deep brown. It is intimately associated with hornblende of which it is an alteration product.

Sphene forms small drop-like granules with specks of black ilmenite in their core which are often aggregated together. Rutile, occasionally, occurs as slender needles in the biotite.

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