CHAPTER 5

PETROGRAPHY

5.1 INTRODUCTION

Detailed study of the fabric and the structure of the rocks of the area indicates that the rocks have experienced at least three distinct phases of deformation ($D_1$, $D_2$ and $D_3$) and two distinct episodes of polyphase metamorphism ($M_1$ and $M_2$). The first deformation, $D_1$, produced sheared out $F_1$ folds. The $M_1$ metamorphism commenced with progressive type of regional metamorphism, $M_{1a}$, which reached only the greenschist facies limit and was synchronous with $D_1$ deformation. $M_{1a}$ metamorphism was followed by thermal metamorphism, $M_{1b}$ and dislocation - retrograde metamorphism, $M_{1c}$.

The second deformation, $D_2$, produced $F_2$ folds and was also accompanied by polyphase metamorphism, $M_2$. The first phase of this metamorphism was of the progressive type ($M_{2a}$), attaining chlorite grade of greenschist facies. Retrogressive metamorphism ($M_{2b}$) occurred during the waning stage of $D_2$ deformation.

Third deformation, $D_3$, did not produce any significant metamorphic effect.

All aspects of $F_1$, $M_1$ are more intense than $F_2$, $M_2$. While describing the petrography of the rocks of the various
members, the progressive changes which took place in response to the continued rise of temperature and pressure have been recorded. The country rocks have been divided into metapelites, metasemipelites and metapsammites.

5.2 METAPELITES

In these rocks successive stages of advancing metamorphism in the form of mineralogical changes are clearly preserved. The dominant foliated fabric in the rocks is the product of regional metamorphism (M$_{1a}$). This fabric bears witness to the important role of deformation during metamorphism. Progressive metamorphism of the argillaceous rocks has resulted in gradual transition from slate through phyllite to mica schist. The transition was in the nature of increasing grain size side by side with the advent of new minerals.

5.2.1 Slate-Phyllite-Schist

Slate is a low grade metamorphic product of argillaceous rocks characterised by strongly developed foliation throughout the rock except in the immediate contact with Eastern Granite, where slate is peculiarly hornfelsic and lacks foliation. Because of the parallelism of micaceous flakes, the foliation planes of slate, phyllite and schist are sheeny. Slate is greyish-black in colour.
Phyllite is strongly foliated and intermediate in grain size between slate and schist. The bulk of the grains in slate and phyllite is not megascopically recognizable as individuals but at places chlorite defining the mineral lineation is recognizable. The coarser size and abundance of micaeous minerals have given phyllite a characteristic sheeny velvet lustre. The passage among slate, phyllite and schist is so gradual that no sharp line can be marked between slate and phyllite, and phyllite and schist. Schist is light to dark grey, well foliated and fine to medium grained.

In order to establish the relationship between deformation and metamorphism, a brief description of relevant structures, discussed in Chapter 3, is given side by side with the petrographic account. The deformation (D₁) was synchronous with M₁ metamorphism which resulted in the development of axial plane foliation, S₁. At places S₁ coincides with the original bedding, S₀. On the microscopic and mesoscopic scale, S₁ is seen transecting the hinges of P₁ folds (Pl. 11, A). In thin sections, S₁ is marked by thin compositional layering; layers are alternately richer in quartz or in micas. The mica flakes and elongated quartz grains align parallel to the foliation S₁ (Pl. 11, F). On the basis of morphology, three varieties of S₁ have been distinguished, i.e., crenulation cleavage, αS₁, differentiated crenulation cleavage, βS₁, and slaty cleavage γS₁.
All these varieties grade into each other. $\alpha S_1$ is defined by series of parallel microlithons separated by microfaults (Fig. 3.1; Pl. 11, B). It gradually passes into differentiated crenulation cleavage, $\beta S_1$, which consists of alternating domains rich in mica and quartz. Mica rich layers are parallel to the main foliation, $S_1$ (Fig. 3.2, a and b). $\beta S_1$ progressively passes into slaty cleavage, $\gamma S_1$, which is characterised by two distinct domains; one comprising larger silicates which have strong dimensional preferred orientation (Fig. 3.2, e; Pl. 11, D), the other consists of such minerals as quartz and felspar as well as mica and lack preferred orientation. $\alpha S_1$, $\beta S_1$ and $\gamma S_1$ are parallel to the axial planes of $F_1$ fold.

The second deformation, $D_2$, produced another axial plane foliation, $S_2$, which too is expressed as a crenulation cleavage, $\alpha S_2$, in some rocks and differentiated crenulation cleavage $\beta S_2$, in others (Fig. 3.1, f and g; Pl. 11, C). All over the area, $S_1$ and $S_2$ are at an angle to each other, giving rise to prominent intersection lineation. $\alpha S_2$ and $\beta S_2$ are parallel to axial planes of $F_2$ fold.

Under the microscope phyllites are banded, foliated and show lepidoblastic texture. Commonly superimposed over foliation are minute folds and crinkles which are of such small amplitude that they are barely identifiable megascopically.
Since there are no sharp and distinct bands of slate, phyllite and schist, and these rocks merge into one another, the mineralogical aspects of these rocks have been combined together in the petrographic description.

The main constituents of these rocks are quartz, chlorite, muscovite and biotite. Albite, epidote, tourmaline, sphene and oxides of iron form the minor constituents of the rocks. At the contact of the Eastern Granite, metapelites exhibit hornfelsic texture (Pl. 12, B).

**Quartz:** Three generations of quartz, each associated with $M_{1a}$, $M_{1b}$ and $M_{2a}$ metamorphism have been recognized.

Quartz 1 occurs as recrystallized and composite elongated grains lying parallel to the foliation, $S_1$. Segregation of Quartz 1 into augen structures is common. In these structures, quartz again is anhedral but more nearly lenticular than equidimensional.

Quartz 2 occurs only in pelitic-hornfelses near the contact of the Eastern Granite. This is the result of thermal metamorphism ($M_{1b}$) in which quartz has recrystallized into granular aggregates with sutured boundaries (Pl. 12, B).

Quartz 3 is found segregated in thin bands bounded by chlorite 2 ($M_{2a}$ metamorphism) and parallel to the axial-plane foliation, $S_2$. The grains of quartz 3 are equidimensional.
measuring in size from 0.01 to 0.03 millimetre on the average, completely recrystallized and polygonal in shape. It contains inclusions of quartz 1 and micas of $M_1$ metamorphism (Fig. 5.1, a). Contacts between quartz and micaceous minerals are often very irregular to hazy because of the growth of micas into the quartz or the filling of quartz into zones between mica lamellae.

Chlorite: It constitutes the major percentage of phyllite and quartz-chlorite-muscovite schist (Table 5.1) and occurs in three varieties.

Chlorite 1 of $M_{1a}$ metamorphism occurs as small highly irregular flakes interleaved with muscovite and aligned parallel to $S_1$. It also appears as bent and crenulated flakes near $P_2$ fold hinges (Fig. 5.1, b). Chlorite 1 is prochlorite and shows bottle green to green colour, feeble pleochroism, indistinct cleavage and weak birefringence ($n_Y - n_\alpha = .006$).

Chlorite 2 ($M_{1c}$) occurs in hornfelses and in quartz-muscovite-biotite schist as altered product of biotite porphyroblasts. At places, pseudomorphs of chlorite 2 after biotite 1 have been observed. Chlorite 2 (penninite) is green, weakly pleochroic and shows 'Berlin blue' interference colours.
Fig. 5.1. Sketches of textures involving porphyroblasts (country rocks): Chl = Chlorite; Qtz = Quartz; Musc = Muscovite; Bt = Biotite.
Chlorite 3 (M$_{2a}$) defines the axial plane foliation, $S_2$, and is superimposed over $S_1$ (Fig. 5.1, c to e). Small flakes and porphyroblasts of prochlorite are pleochroic from light green to green and have weak birefringence ($n_\gamma - n_\alpha = .007$). Cleavage is well developed.

**Biotite:** The assemblage involving biotite is quartz–muscovite–biotite with subordinate amount of albite. Two types can be distinguished.

Biotite 1 (M$_{1a}$) forms small, clear, elongate scales aligned with their cleavages in the foliation $S_1$ and their long dimensions parallel. The margins of the individual flakes are often difficult to define. The flakes are bent because of $F_2$ folding and crenulation (Pl. 11, C). Biotite 1 shows pleochroism with $X =$ yellow, $Y =$ brown and $Z =$ brownish green and strong birefringence ($n_\gamma - n_\alpha = .045$). It alters to chlorite 2 and muscovite 2 and the cleavage planes are crowded with oxides or iron.

Biotite 2 (M$_{1b}$) has been observed superimposed over foliation $S_1$, and is restricted only to hornfelses (Fig. 5.1, f to h; Pl. 12, A). It occurs as large subidioblastic porphyroblasts which cuts across the foliation, $S_1$, without disturbing it and shows helicitic structure (Fig. 5.1, g and h). It is also found occurring along the foliation which may be either due to mimetic crystallization or slight deformation.
accompanying intrusion. Biotite 2 shows pleochroism with X = light brown, Y = Brown and Z = deep reddish brown and strong birefringence \( n_\gamma - n_\alpha = 0.052 \). It also alters to chlorite 2 and muscovite 2.

**Muscovite including sericite:** Typical assemblage in which muscovite dominates is quartz-chlorite-muscovite. Individual flakes are microscopic in size and two varieties have been distinguished.

Muscovite 1 \((M_{1a})\) forms small flakes or aggregates of the same (sericite) segregated into thin bands alternating with quartz-rich and mica-poor bands (Pl. 11, F). Very perfect orientation of the flakes along with chlorite 1 and biotite 1 parallel to \( S_1 \) is characteristic. Frequently, there is sufficient interleaving or overlapping of the flakes so that the limits of the crystals cannot be clearly distinguished from its adjoining grains. The muscovite flakes are curved, crenulated and exhibit wavy extinction wherever they are affected by \( F_2 \) folds. Cleavage is not well marked and cleavage lines are crowded with oxides of iron.

Muscovite 2 is the alteration product of biotite 1 and 2. The mineral shows faint pleochroism from light yellow to colourless. Cleavage planes are marked with iron-oxides and occasionally minute thin needles of biotite which
are in optical continuity with biotite. The grains include the inclusions of quartz and oxides of iron.

**Albite (An_{2-5}):** It occurs in the interstitial spaces as small grains which contain sericite and quartz inclusions. The crystals are rounded to irregular usually roughly equidimensional and show no preferred orientation. Sericitization of feldspar is common.

**Pistacite:** It occurs as light yellowish-green small grains scattered throughout and occasionally as thin continuous streaks.

**Sphene:** It occurs as light brown to colourless irregular grains and alters to leucoxene along the margins.

Other minor constituents include apatite, zircon, opaque oxides of iron and pyrite. Pyrite forms euhedral cubes with typical segregation of quartz in the shadows of these porphyroclasts.

5.2.2 Pelitic Hornfelses

All along the contact of the Eastern Granite, dark grey, fine-grained dense rock is encountered. The rock is typically hard and breaks into blocks. Under microscope, the rock shows typical hornfelsic texture containing an aphanitic groundmass of slaty and phyllitic character with porphyroblasts of biotite 2 superimposed over S1. This
biotite replaces chlorite 1 of the regional muscovite-chlorite phyllites. The growth of the porphyroblasts appears to have been static in character but it was followed by a further flattening across the foliation, as is shown by micas of the matrix which sweep around these porphyroblasts (Fig. 5.1, h) and grains of epidote (Pl. 12, D) which otherwise are superimposed on $S_1$. There is a complete recrystallization of the fine grained foliated slate to compact hornfelsic mosaic with destruction of foliation (Pl. 12, B). Whenever the foliation is observed, it is inherited from the parent rock (Pl. 12, C). Reduction in grain size is common because polygonization of strained crystals produce granular aggregate of unstrained ones. Randomly oriented porphyroblasts have a post-tectonic relationship to $S_1$ foliation. Breaking down of biotite 2 porphyroblasts has yielded chlorite 2. This change is associated with $M_{1c}$ metamorphism.

Albite usually forms xenoblastic grains confined to the matrix. Epidote and tourmaline occur as the accessories.

Since the rocks exhibit low grade of metamorphism and are fine grained, it has not been possible to work out the modal percentage of the minerals. However, the relative abundance of minerals in metapelites has been given in the
### Table 5.1: Relative abundance of minerals in metapelites.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Sample</th>
<th>10</th>
<th>12</th>
<th>18</th>
<th>24</th>
<th>8</th>
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<tbody>
<tr>
<td>Quartz</td>
<td></td>
<td>xxx</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
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<td>-</td>
<td>-</td>
<td>*</td>
<td>xxx</td>
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</tr>
<tr>
<td>Albite</td>
<td></td>
<td>*</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Accessories</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

10: Slate, 12: Phyllite, 18: Chlorite schist, 24: Chlorite-biotite schist, 8: Pelitic hornfels

- XXX = Abundant
- XX = Common
- X = Present
- * = Present in traces
- - = Absent

### 5.3 METASEMIPELITES AND METAPAMMITES

These are represented by quartzites which occur as thin bands or ribs interbanded with metapelites of the Salin Member. Two types of quartzite, i.e., schistose quartzite and massive quartzite, have been distinguished.
5.3.1 Schistose Quartzite

It is fine to medium grained and greyish white in colour. S\textsubscript{1} foliation is developed and defined by thin streaks of metapelitic material running parallel to the same.

Under the microscope, quartzite has developed granoblastic elongate texture with no sign of original grains and this is probably due to the growth of new quartz crystals at the expense of the old grains. It is composed essentially of quartz, muscovite and biotite with minor amounts of chlorite, tourmaline, sphene, feldspar, zircon and oxides of iron.

Quartz: The quartz crystals tend to be flat and elongate with their long and mean dimensions giving a foliation which is parallel to the axial surfaces of F\textsubscript{1} folds. Usually the grain boundaries are not straight but irregular and sutured. Most of the quartz grains show wavy extinction.

Biotite and muscovite: These are concentrated along selected thin zones. Micaeous segregation has resulted in films composed of small ill-defined flakes. Muscovite and biotite, however, exhibit alike optical character as described for metapelites.
The minor constituents include zircon, apatite and oxides of iron.

5.3.2 Massive Quartzite

Light green, generally massive quartzite lacks foliation. Under the microscope, the rock exhibits a typical granoblastic polygonal texture without any marked elongation of minerals and foliated character. It is composed almost entirely of quartz with minor amounts of micas, feldspar, sphene, oxides of iron and tourmaline.

Quartz: It is equigranular with xenoblastic grains. The grain boundaries are commonly smooth and meet in triple-points. It shows an undulose extinction and deformation lamellae.

Micas: Chlorite and sericite are very common minor minerals. They are disseminated throughout the rock with a tendency to align in streaks. Flakes are large, often bent around quartz grains and are seen penetrating the quartz grains.

The accessory minerals are disseminated throughout the section without any marked orientation.

The relative abundance of minerals in metapsammites and metasemipelites is given in table 5.2.
Table 5.2: Relative abundance of minerals in metapsammites and metasemipelites.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Minerals</th>
<th>22</th>
<th>29</th>
</tr>
</thead>
<tbody>
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<td>Quartz</td>
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<tr>
<td>Micas</td>
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</tr>
<tr>
<td>Albite</td>
<td>x</td>
<td>*</td>
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<tr>
<td>Accessories</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

22: Schistose quartzite
29: Massive quartzite

22 : Schistose quartzite
xxx = Abundant
29 : Massive quartzite
xx = Common
x = Present
* = Traces

5.4 MINERAL PARAGENESIS

The metapelite exhibit the following mineral assemblages:

A. Slate and phyllite:
   i) Quartz-chlorite-sericite
   ii) Quartz-chlorite-sericite-albite-epidote

B. Mica schist:
   iii) Quartz-muscovite-chlorite-epidote
   iv) Quartz-muscovite-biotite-albite-epidote.
The first two assemblages correspond to the lowermost part of the greenschist facies and the last two assemblages to the upper-middle part of the greenschist facies of Barrovian-type (Winkler, 1967 and Turner, 1968). The assemblages (i), (ii) and (iii) also correspond to the chlorite zone and assemblage (iv) to the biotite zone of Barrow (1893) and Tilley (1925).

The following mineral assemblage has been recognized in the pelitic hornfelses:

Quartz-muscovite-biotite ± albite ± epidote

This assemblage corresponds to the albite-epidote-hornfels facies of contact metamorphism (Winkler, 1967; Turner, 1968).

All these mineral assemblages suggest that metamorphism and emplacement of the granitic bodies have taken place in the epizone (Becke, 1908; Grubenmann and Niggli, 1924). Since chloritoid does not appear in the mineral assemblage, it is deduced that the original sediments were poor in alumina and iron and rich in potash.

The minerals of metapelites are distributed in accordance with the increasing grade of metamorphism from slate to schist. Quartz, chlorite, albite and iron oxide develop from recrystallization of respective detrital
constituents of argillaceous sediments. Grains of clastic origin are absent from the assemblage. Quartz starts appearing in little lenticles/streaks conforming the general parallel orientation. In slates, chlorite appears in patches and knots which gradually develops into larger flakes in phyllite and schist. It has been observed that muscovite and chlorite have recrystallized in phyllite and chlorite schist without any mutual reaction. Along with chlorite, sericite also makes its appearance. The amount of chlorite decreases rapidly when biotite appears with the increase in grade of metamorphism and since biotite has not been encountered occurring as pseudomorphs after any particular mineral, it can be concluded that biotite must have formed at the expense of stress minerals like chlorite, muscovite and iron oxides. Biotite appears first as numerous minute scales in transitional stage from chlorite-zone to biotite-zone and then figures as porphyroblasts in typical biotite-schist. Muscovite and chlorite seem to react with each other with the rising temperature to form biotite. The following reaction has been considered to be pertinent:

\[
3 \text{Muscovite} + 5 \text{prochlorite} \rightarrow 3 \text{biotite}
+ 4 \text{Al-rich chlorite} + 7 \text{Quartz} + 4 \text{H}_2\text{O}
\]
Since the newly generated chlorite phase is not met within thin sections, it can be concluded that the temperature range for greenschist facies was not exceeded (Winkler, 1967).

In hornfelses, amount of sericite and chlorite decreases whereas biotite increases. The biotite 2 is riddled with numerous inclusions of quartz, sericite, chlorite and iron oxides, and is also superimposed over S1. It must have developed from chlorite, sericite and iron oxides which were in stable phases before the emplacement of the granitic bodies. Biotite 2 and albite have been converted into chlorite and sericite during the subsequent retrograde metamorphism.

The table 5.3 shows the stability range of different minerals in the metasedimentaries.

Table 5.3: Stability range of different minerals.

<table>
<thead>
<tr>
<th>Rocks</th>
<th>Metamorphic facies</th>
<th>Green schist facies</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Chlorite</td>
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<tr>
<td>Mineral zones</td>
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<td>Metapelites, meta-</td>
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<td>semipelites and</td>
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<td>Albite</td>
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<tr>
<td></td>
<td>Epidote</td>
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<td></td>
<td>Iron ores</td>
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<td>Pelitic hornfelses</td>
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<tr>
<td>Biotite</td>
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Albite-epidote hornfels facies
While mapping the granitic bodies, the author broadly classified the Eastern Granite into foliated components (1A, 1B) and nonfoliated component (2). Component 1A has developed along the periphery of the granite mass and shows acute mylonitization. The foliation in component 1A is intense and it gradually becomes less prominent in component 1B, away from the border. Component 1B is also foliated but the mylonitic fabric is less marked. The central component is nonfoliated and intrudes into the foliated components.

Following modifications of Streckeisen's (1967) igneous rock classification (as in Hyndman, 1972), QFA diagram was constructed on the basis of recalculated modal volume percent. Plots of the components 1A, 1B and the Western Granite fall in the field of Granodiorites and that of the Component 2 in the field of Granite (Fig. 5.2).

5.5.1 Western Granite

The rock is well foliated and mylonitised. It is fine grained at both the contacts and the grain-size gradually increases towards the central part, which is porphyritic in nature. The mylonite banding is defined mainly by a compositional layering so that the mica-rich
Fig. 5.2, Q(Quartz) — P(Plagioclase) — A(Alkali feldspar) diagram for the Eastern and the Western Granites (after STRECKEISEN, 1967)

Eastern Granite:
- Component 1 A = +
- Component 1 B = o
- Component 2 = •
- Microgranite = Q

Western Granite = Δ
layers, about 1 milimetre thick, alternate with layers rich in quartz and feldspars. The banding is somewhat irregular, presumably due to the heterogeneities created by the large feldspar grains. A prominent lineation is developed throughout the granite and is defined by elongate aggregates of mica and elongate quartz and feldspar grains which have been elongated in the plane of mylonite banding. Quartz crystals however show much greater elongation without fractures whereas the individual feldspar lenses tend to break up into fragmental trains which are mesoscopically expressed as mineral lineation.

Microscopic features of mylonitized granodiorite, in three mutually perpendicular sections of each sample (ab, bc and ac) have been summarized in figure 5.3. Thin section study has revealed that the rock is composed of finely divided granulated quartz, orthoclase perthite, microcline, plagioclase, biotite, muscovite and magnetite. In addition to minerals mentioned above, pseudotachylyte has also been observed only near the western border of the Western Granite.

Feldspar: Feldspar includes the porphyroclasts of perthite, microcline and oligoclase. Observations made on crystals visible in three mutually perpendicular planes (ab, bc and ac) indicate that feldspar porphyroclasts are
Fig. 5.3. Block diagram, based on thin section study, shows the relationship among mylonite banding, shear fractures and lineation.
dimensionally flattened with the longer dimensions parallel to the banding and the shortest roughly perpendicular to it. This pattern of orientation is also seen in small porphyroclasts (Fig. 5.3; Pl. 13, A and B).

Feldspar grains are surrounded by swirls of quartz and mica (Pl. 13, C). The external boundaries of the feldspar grains are well rounded, suggesting grinding during deformation (Pl. 13, D). The ductile material, surrounding separated fragments of feldspar grains, often flows into the gaps between them (Fig. 5.4, a; Pl. 13, A). Commonly the feldspar porphyroclasts have trails which are made up of recrystallized aggregate of quartz and broken feldspar grains (Fig. 5.4, b). The trails extend out along the banding from the porphyroclasts, tapering gradually. The banding curves around the porphyroclasts and their pressure shadows (Fig. 5.4, d; Pl. 13, C).

Larger feldspar porphyroclasts are generally split open by shear fractures, lying at high angle to the banding (Fig. 5.4, c and d; Pl. 13, A and C). These fractures are in-filled by quartz grains. Banding bisects the obtuse angle between the intersecting fractures (Fig. 5.3). At places, displacement between fractured portions of the porphyroclasts has been observed. Pinched-out forms are also exhibited by small porphyroclasts. The elongation of
Fig. 5.4. Camera Lucida diagrams for Western Granite.
feldspar grains is always in the plane of banding. The feldspar porphyroclasts show undulose extinction and twisted twin planes (Pl. 13, E). These porphyroclasts are set in a fine grained aggregate of quartz showing mortar texture. Microcline is sericitized or made opaque by tiny inclusions oriented in different directions. Banding is wrapped around these porphyroclasts, thus indicating pre-tectonic origin of the feldspars. The oligoclase grains are mostly twinned on albite, albite-ala and albite-periclino laws. The anorthite content varies from An$_{15}$ to An$_{20}$.

**Quartz:** It is recrystallized and occurs in thin, straight sided bands parallel to the mylonite banding. The bands swirl around the relict porphyroclasts of feldspar (Fig. 5.3). These quartz rich bands are free from strain effects. The minute quartz grains show sutured boundaries against one another. Slivers of quartz show a regular arrangement in small domains, and if traced along banding, they tend to die out and at places have imparted foliation to the rock (Fig. 5.3; Fig. 5.4, e).

Quartz also forms fine grained, recrystallized aggregates in the matrix where it is often accompanied by feldspar and mica. Quartz grains show mortar texture. Long, lenticular quartz porphyroclasts with signs of deformation are set in a fine grained aggregate of quartz. The recryst-
tallized quartz grains are generally strain-free and some have boundaries meeting at 120 degrees. At places, quartz and mica appear to have flowed in the fractures present in feldspars, hence modifying the boundaries and fracture traces of feldspar porphyroclasts (Fig. 5.3).

**Mica:** Porphyroclasts of biotite have been bent and twisted into lenticular form (Fig. 5.4, f) and often altered to chlorite and iron oxide. Muscovite is kinked, pulled apart and scattered. Tiny flakes of biotite and chlorite impart foliation and lineation to the rock. With increasing amount of crushed matrix, minute flakes of biotite and iron oxide swirl around the relict lenticular porphyroclasts. Biotite flakes occur both as inclusion in feldspars and along the grain boundaries of quartz. Sericite occurs in all the sections, and is plentiful in some slices. It is drawn out into strings, and 'meanders' about the porphyroclasts of feldspars.

**Pseudotachylyte:** It has been observed locally near the western border of the granodiorite. It occurs in the form of bands generally parallel to the foliation planes while in few cases cut them at an angle. These bands consist of nearly isotropic base highly charged with fragments of crushed minerals.
Leucoxene: It has been drawn out into strings in which the fragments of magnetite are entangled.

Table 5.4 gives the modal analyses of the principal varieties of the Western Granite.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Samples 1</th>
<th>Samples 2</th>
<th>Samples 3</th>
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<td>02.65</td>
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</table>

1. : Average of 4 samples, i.e., 48, 46, 43 and 41 (Samples near the western border).
2. : Average of 3 samples, i.e., 40, 39 and 37 (Samples from the centre).
3. : Average of 4 samples, i.e., 36, 33, 32 and 31 (Samples near the eastern border).

5.5.2 Eastern Granite

5.5.2.a Granodiorites (Components 1A and 1B)

The most conspicuous feature of the rocks of the
component 1A is their pronounced foliation. The crystals of feldspar are seen whose edges have been crushed until the resultant crystals are augen shaped and frequently have trails of crushed feldspar extending out from either end (Pl. 14, A). The phenocrysts show evidence of shearing strain by strain shadows and microfaults even when the groundmass of the rock is quite devoid of cataclastic structures. The rock is composed of medium-grained crystal aggregates which wander irregularly in swirls between the larger crystals, and yet are oriented into streaks which give the rock a definite foliation. The larger grains, occurring either as individual crystals or in groups more or less isolated in the fine to medium-grained matrix, show evidence of intense shearing. They are cracked, bent and deformed, show wavy extinction, abundance of microfaults and their edges are commonly surrounded by angular fragments rubbed off by mechanical movement.

However, the streaky matrix in which the larger crystals are imbedded is characterised by an almost complete absence of strain effects, and is not composed merely of a mylonitic paste. At places, broken up and granulated material has been recrystallized into quartz-feldspar-biotite aggregate. The veinlets made up largely of feldspar and quartz, containing biotite and
other minerals, wander irregularly between the large cracks within them (Pl. 14, B to E). This material also penetrates or sometimes grades gradually into the fine-grained matrix. Microcline in these veinlets has irregular outlines with quartz grains.

The outer component 1A passes gradually into an inner component 1B which is much more uniform petrographically. It is markedly porphyritic. Foliation in component 1B is well marked but not as conspicuous as in the rocks of the component 1A. Under the microscope no essential difference in mineral composition from the rocks of the component 1A can be observed, but there is gradual decrease of features due to cataclasis/protoclasis and recrystallization, and corresponding decrease in the intensity of foliation.

The major minerals of the granodiorite are orthoclase, plagioclase, quartz, microcline and biotite. Epidote, chlorite, muscovite, sphene, magnetite, apatite and zircon are the accessories present.

Plagioclases: They occur as big phenocrysts and tend to be subhedral and euhedral. Untwinned grains predominate over the twinned grains. Plagioclase grains are mostly twinned on albite, albite-ala and albite pericline laws. The anorthite content varies from 13% to
Normal zoning is observed (Fig. 5.5, a; Pl. 15, A and B) in a few phenocrysts. The compositional variation from the core to the boundary is An 25 to An 18. Sometimes, oscillatory zoning has also been observed. Zones are completely parallel to each other and to the core. The oldest stages of plagioclase frequently show broken, subsequently healed and corroded forms. The zoning, however, has invariably been destroyed due to the development of twinning (Pl. 15, C). This is evidenced by the growth of coarser and irregular twin lamellae, sericitization and variation in extinction position.

Plagioclases have lobed borders with quartz. Rounded quartz inclusions and biotite inclusions are common. Some of the plagioclase plates are anteperthitic. The plagioclase grains are seen in various stages of replacement by microcline (Fig. 5.5, b; Pl. 15, D).

The plagioclase inclusions are often arranged in parallel zones in microcline (Fig. 5.5, c). The plagioclase are oriented with their largest faces, mostly (010). Clouding of plagioclase, vermicular inclusions of quartz (myrmekite) as well as saussuritization with the development of sericite and albite are commonly marked (Pl. 14, F; Pl. 15, B and E). Paragenetically the plagioclases are
Fig. 5.5. Granite textures: (a)-zoned plagioclase; (b)-microcline (M) replacing plagioclase (P); (c)-plagioclase (P) arranged in parallel zones in microcline (M); (d)-albite vein (A) and quartz vein (Q) along fracture in plagioclase; (e,f)-myrmekite in plagioclase (P) in contact with microcline (M); (g) hypidiomorphic inner part of orthoclase (HI) surrounded by xenomorphic outer part (XO) Scale = 0.7 mm.
of two generations. The early formed grains are characterized by their large size, clouding, sericitization, high An content, while the latter ones are fresh and occur as small grains of albite (An$_3$ to An$_5$). Such grains have developed mainly at the boundaries of plagioclase grains. Bent and broken plagioclases are sometimes seen in contact with quartz and microcline which show no sign of strain (Fig. 5.5, d).

**Quartz:** Two types of quartz have been distinguished. Idiomorphic quartz has been identified in the forms of hexagonal crystals and rounded forms occurring as inclusions in other minerals (Pl. 16, A and B). Xenomorphic quartz is the main variety present in the granodiorites. It forms irregular masses filling the interstitial spaces between the older minerals.

Many of the inclusions are irregularly arranged in the idiomorphic quartz grains. Cores of the quartz grains are rich in inclusions, but rims are virtually free. Inclusions appear to be of accicular mineral, with a high refringence, probably rutile.

**Potash feldspars:** In component 1A, finely cross-hatched microcline occurs interstitial to plagioclase and quartz. In component 1B, the microcline plates attain porphyritic dimensions. These plates have irregular
margins and inclusions of plagioclase, rounded quartz and biotite. The plagioclase inclusions are altered, corroded and sometimes show relict twinning lamellae. All these indicate that microcline is the latest mineral to form. Well twinned microclines show a 'blocky' type of extinction. The -2V of the microcline varies from 78 to 82 degrees.

Plagioclase grains often develop myrmekitic borders against microcline (Fig. 5.5, e and f; Pl. 15, E and F). Sometimes small plagioclase grains bordering or included in microclines are wholly myrmekitized. They occur in lobed and irregular patterns. Rods and spindles of quartz in myrmekite are slender, elongate and tend to concentrate away from the plagioclase. They are either perpendicular to the plagioclase surface or tend to converge towards plagioclase.

Most of the microclines are perthitic in nature. Microclination of plagioclase has caused obliteration of twin lamellae, development of sieve structure in the plagioclases resulting in the formation of patchy microcline perthite.

Albitization mainly occurs at the boundary of the plagioclase and potash feldspar. It has resulted in the development of intergranular 'albite rims' around older plagioclase.
Among the different types of perthite, the rod type perthites are the most common. The spindles in these perthites are grouped towards the centre of microcline and they do not extend into the host from the margins. This aspect of the perthites plus their definite orientation indicate that they are plutonic perthites and they were formed by the soda component present in solid solution in potash feldspar (Alling, 1938; Emmons, 1953a and b). The plagioclase inclusions have zonal distribution in microcline crystals and are oriented with their longest dimensions parallel to the crystal faces of microcline.

At places orthoclase phenocrysts show hypidiomorphic inner part and a xenomorphic outer part rich in inclusions of quartz (Fig. 5.5, g; Pl. 16, B). The outermost xenomorphic parts obviously grow into the older granitic fabric partially replacing them.

**Biotite:** It forms independent flakes, with ragged edges, or fine grained, irregular and discontinuous fringes. They are pleochroic from yellow to brown. Some stray epidote grains are present in biotite clusters. It is also present in the plagioclase as an alteration product especially at the junction of plagioclase and microcline.
Sometimes biotite flakes contain cross muscovite inclusions in them. Biotite often shows resorption effects and alters to pale green chlorite.

**Accessories:** The accessory minerals exhibit more or less idiomorphic forms. Apatite is subhedral to euhedral with rectilinear sides. This is also present as tiny needles in plagioclase and biotite. Acicular apatite crystals exhibit skeletal features. Zircon is occasionally present. Observations on thin sections only, indicate that the form of the zircons does not vary. Zircon occurs as inclusions in apatite. When it is present in the biotite flakes, pleochroic haloes are seen around them. A few sections contain acicular brown iron mineral showing pleochroism in different shades and often they coalesce to form elongate, irregular, grains.

Table 5.5 gives the modal analyses of the granodiorites (components 1A and 1B) of the Eastern Granite.
Table 5.5: Modal analyses (Vol. %) of granodiorites (Eastern Granite).

<table>
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5.5.2. Granites (component 2)

Coarse grained, porphyritic and leucocratic granites are found in the central part of the Eastern Granite. In thin sections the granites show hypidiomorphic to allotriomorphic textures. These rocks are characterised by the simple mineral assemblage: microcline, quartz, plagioclase, muscovite, biotite, tourmaline, epidote, apatite, ores and zircon, in approximate descending order of abundance. A subordinate amount of biotite and rare occurrence of magnetite is characteristic of the component 2.
Potash feldspars: These include microcline and orthoclase. Generally two distinct habits of microcline are recognised as (i) porphyritic tabular crystals (-2V = 78°) containing the inclusions of plagioclase, biotite and rounded quartz, and (ii) mantling the plagioclase grains having irregular and patchy development at the margins. Perthite occurs in good amount. Orthoclase occurs as subhedral phenocrysts containing the inclusions of plagioclase and biotite.

Plagioclase: Oligoclase occurs as irregular plates. The anorthite content ranges from 18% to 20%. Twinning is mostly after albite, albite-ala, albite-periclase, manebach laws. The rest of the characters are the same as in granodiorites except that these do not show any strain effects.

Quartz: In most of the sections, the characters of quartz grains are the same as in granodiorites. In some of the sections, quartz grains are found invading plagioclase grains giving rise to peculiar intergrowths of quartz and plagioclase. The quartz is xenomorphic and is generally strain free.

Muscovite: It occurs as thin to broad laths. Small flakes are seen included in plagioclase crystals. At places these micas are found to grow along the cleavage planes of biotite and the latter is very subordinate in amount as compared to muscovite.
Tourmaline: It occurs as anhedral to subhedral prismatic grains. It is bluish gray to yellowish gray in colour. The birefringence is masked by the body colour. The refractive indices as determined by the immersion method are: $e = 1.615 \pm 0.002$; $w = 1.634 \pm 0.002$.

Zircon, apatite, sericite, sphene, iron ore and occasionally epidote are accessory minerals.

Table 5.6 gives the modal analyses of the rocks of the component 2.

Table 5.6: Modal analyses (Vol. %) granites (Eastern Granite).

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5.5.3 Mineral Paragenetic Sequence

The present mineral composition of the granodiorites and granites and their typical fabric are not the result of a single petrogenetic act. They result from a sequence of processes as admitted by Niggli (1938, 1942) and Drescher-Kaden (1948). It has been possible to distinguish the following two stages of crystallization in these granodiorites and granites: (i) the magmatic crystallization of the main mineral content and (ii) the postmagmatic crystallization characterized by the partial replacement of the main minerals by younger ones stable at lower temperature (Mehnert, 1968).

5.5.3a The magmatic crystallization

From the petrographic description, it is obvious that accessories like apatite, rutile, zircon and magnetite, etc., were first to be formed since these exhibit more or less idiomorphic forms and occur as inclusions in all the other minerals. Moorhouse (1956) pointed out that the distinctive idiomorphism is not necessarily due to early crystallization; the same mineral species also occur in late or even post magmatic stages. Apatite is found as inclusions in biotite and in turn contains zircon inclusions. From this it is deduced that zircon crystallized before apatite and that both of them crystallized before biotite.
Next minerals to crystallize were idiomorphic quartz and biotite which occur as inclusions in the plagioclase phenocrysts. Since no inclusions of idiomorphic quartz have been encountered in biotite or vice versa, the relative position of this quartz and biotite is difficult to fix.

The next mineral to appear was plagioclase which occurs as big phenocrysts in granodiorites and granites. Normal zoning in the plagioclase crystals is conclusively explained by Bowen’s diagram of crystallization of plagioclases from a melt through cooling. It is agreed that normal zoning is explained by incomplete reaction between the crystal and the surrounding melt (Greenwood and McTaggart, 1957; Vance, 1962; Mehnert, 1968).

The plagioclase inclusions are arranged in parallel zones in microcline hence it is clear that the crystals of plagioclase were suspended in potash feldspar rich melt and that the melt was sufficiently mobile so as to allow the free movement of these crystals. Turbulence related to magmatic flow might have been helpful to bring about the requisite motion.

The clouding in plagioclase phenocrysts is faint and patchy in distribution and is due to the concentration
of minute granules and rods of some opaque minerals, probably iron ore.

Potash feldspars were next to crystallize in the magmatic stage as these contain inclusions of other minerals mostly corroded plagioclase, idiomorphic quartz and biotite flakes.

The order of crystallization described above is comparable to Rosenbusch's (1882, 1898) order of crystallization which is well suited for the early stages of magmatic crystallization.

5.5.3.b Post magmatic crystallization

While most of the other minerals appear to have been active at relatively late stages in the evolution of the mineral fabric, plagioclase and the accessories seem to have been relatively stable since their initial crystallization. For example, bent or broken plagioclases are sometimes seen in contact with quartz and microcline which show no signs of strain.

Microcline also appears to be relatively late in origin, enclosing quartz, biotite, and plagioclase crystals, occasionally in zones parallel to the outer edges, and replacing plagioclase. It is commonly
microperthitic with patchy grid twinning and as usual, is separated from adjacent plagioclases by myrmekitic intergrowths or albite rims or both.

Finely intergranular albite crystallize, relatively late, in low temperature conditions. Albition has resulted in the development of albite rims around older plagioclases. Regarding the origin of solutions producing albite rims, either they could represent resolved parts of already solidified rock or an addition from outside by differentiated solutions enriched in alkali as visualized by Mehnert (1968).

The peculiar quartz/feldspar intergrowth (myrmekite) was first described by Michel Lévy (1874) and later by Becke (1908) and Sederholm (1916). Becke (1908) interpreted the intergrowth as a replacement phenomenon of the surrounding potash feldspar by growing plagioclase. In the area under study, the reverse is true, that is, potash feldspar replaces plagioclase.

A careful review of the numerous petrographic occurrences of myrmekite was given by Drescher-Kaden (1948). According to him, the same solutions which give rise to the orthoclase of granites, corrode plagioclase. The solutions deposit silica while the removed cations
The investigations of Oarman and Tuttle (1963) indicated a solid solution series between NaAlSi$_5$O$_8$ and CaAl$_2$Si$_6$O$_{16}$, the so-called 'myrmekite molecule'. At lower temperatures the solid solution dissolves and three phases form: two feldspar and quartz. Shelley's (1964) theory does not require circulating solutions but a certain amount of stress during myrmekite formation is necessary. The quartz forming the myrmekite fabric can also be explained by exsolution from alkali feldspar in response to a lowering of temperature (Hubbard, 1966). If an origin by simultaneous crystallization of two components of myrmekite is accepted, the thickness of quartz stems and their distance from each other is an approximate measure of the width of migration of mobile components during crystallization.

Drescher-Kaden's (1948) theory explains the origin of myrmekites in the area well, for which the evidence comes from the progressive enrichment of microcline in the granodiorites (component 1B) near the borders of the component 2.

Quartz was clearly active at late stages, as indicated by its frequent veining of plagioclase and microcline, by the occasional presence of serrated edges suggesting grain boundary migration, and by the widespread

fill empty spaces in the lattice of plagioclase.
occurrence of undulose and patchy extinction.

Further evidence of late mineralogical changes is provided by the sericitization of plagioclase and the occurrence of sericite along the cleavage planes in microcline.

Granodiorites of the Western and the Eastern Granite (component 1A) show well developed mylonite banding which wind around resistant feldspar crystals. This banding is marked chiefly by quartz and by minute laths of mica, some of which are clearly shreds torn off larger crystals. The feldspar augen commonly have trails or shadow zones, occupied by small granules of the larger crystals. Although the mineral alignment here is dominantly of protoclastic effect, there is much evidence of mineral activity even at the late stage in the evolution of the granitic bodies. Thus many of the aligned micas are fresh and undeformed, the microclines are more perthitic and exhibit better grid twinning than in the component 2 of the Eastern Granite, and myrmekite and coarse antiperthite are more prevalent here.

Thus, the overall picture is one of early crystallization overlapped by later crystallization, accompanied by falling temperatures.
5.5.4 Minor Intrusives

Granodiorites and granites are cut by light coloured rocks richer in quartz, alkali feldspars, muscovite and pneumatolytic minerals. These are pegmatites, aplites, microgranites and quartz veins. Pegmatites have been divided on the basis of field relationship into two, early and later, the former intrude granodiorites only and the latter, both granites and granodiorites.

5.5.4a Pegmatites

These occur in the form of small dykes. The most striking textural feature of pegmatites is their extraordinary coarseness of grain. The development of graphic intergrowths of quartz and microcline - perthite have generally been observed which is due to the simultaneous crystallization of these minerals.

Early pegmatites are of granodioritic composition and later are of granitic composition. However, pegmatites are richer in microcline than the host granites. Microcline and microcline-perthite are the dominant constituent of pegmatites; these are associated with quartz and muscovite. Among the abundant and varied accessory minerals are those normally occurring in granites, together with
tourmaline which is regarded as 'pneumatolytic'.
Plagioclase (An\textsubscript{12}) is present. Stray grains of epidote and flakes of biotite are also seen. In thin sections tourmaline is found as a subordinate accessory in anhedral to subhedral prismatic grains. It is bluish gray to yellowish gray in colour. Birefringence is masked by the body colour. The mineral is distinguished by its uniaxial negative and length-fast character, presence of irregular cross fractures and mottled appearance.

Late pegmatites of grinitic composition at places show a very distinctive primary zoning. Following zones have been observed from the contact towards the centre of the pegmatite bodies:

1. Aplitic border zone,
2. Zone of graphic intergrowth of quartz/microcline,
3. Zone of microcline phenocrysts and
4. Core of quartz.

In earlier pegmatites the effects of strain and crushing are usually exhibited by undulatory extinction of the quartz, by bending and faulting of the twin lamellae of the feldspars, by crumpling of micas and by granulation of crystal borders. The later pegmatites do not show these characters.
5.5.4.b Aplites

These are light coloured - white to buff. In hand specimens they represent a remarkably even and fine-grained saccharoidal texture, which, under the microscope, is seen to be micrographic. The aplites are composed principally of quartz, alkali feldspar (chiefly microcline and microcline-perthite) and sodic plagioclase. The mineralogical composition varies according to the type of granite with which the aplites are associated. The proportion of quartz varies, but in some varieties this mineral predominates, indicating a passage to quartz veins. The accessory minerals include zircon, tourmaline, epidote and allanite. Microcline crystals are often characterized by (001) cleavages. $-2V = 79^\circ$ to $82^\circ$. Quartz and plagioclase inclusions in microcline are common. Plagioclase is fresh and twinned (An$_{17-20}$). Tourmaline occurs as needles and the needles freely penetrate into secondary quartz, a mosaic of which forms the general background of the sections.

5.5.4.c Microgranites

These are massive and dark gray in colour. Microgranites contain K-feldspars, oligoclase and xenomorphic quartz with shining flakes of oriented muscovite and subordinate tourmaline. They are also very poor, almost lacking in such mafic minerals as biotite, magnetite, etc.
Table 5.7 gives the modal analyses of microgranites.

Table 5.7: Modal analyses (Vol. %) of microgranites

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