CHAPTER 4

PETROGRAPHY

4.1 INTRODUCTION

The petrographic characters of the rocks furnish clues to their genesis and their structural and metamorphic history. With this aim in mind, a detailed petrographic study of the rock units of Arki-Jutogh area has been carried out. The modal percentage of minerals of the metamorphites have also been determined and given in Tables 4.1 and 4.2. The order in which the rock types have been described is after Table 3.2 (page 28). The intrusive and metabasic rocks have been dealt separately (Sec. 4.11).

4.2 JUTOGH FORMATION (3a,3b,3c)

The Jutogh Formation can broadly be subdivided into the following petrological units:

- Schists (3a-2, 3a-3, 3a-4, 3b-1, 3c-1 and 3c-2)
- Quartzite (3a-1)
- Marble (3b-2)
- Amphibolite (in 3b-1, 3b-2; described in Sec. 4.11).
4.2.1 Schists

Four varieties of schists are recognised in the Jutogh Formation of the area which are (cf. Table 3.2):

(i) Gametiferous-mica schist (3a-4, 3c-1)
(ii) Quartz-mica schist (3a-3)
(iii) Quartz schist (3a-2, 3c-2)
(iv) Carbonaceous schist (3b-1)

The colour of the rocks varies from light to dark brown, silver grey to bluish black depending on the mineral assemblage of the individual schist. The quartz schist is light grey to yellowish grey while the bluish black colour is restricted to carbonaceous schist. The fine (3b-1) to medium-grained rocks are characterized by a strong foliation or schistosity (S₂). The garnet metacrysts occur in the mica schists in variable proportion and range in size from minute pin-head crystals (3a-4) to pea-size porphyroblasts (3c-1). Graphite is a dominant mineral of carbonaceous schist and the rock soils the finger. Crenulation and intersection lineation is a very common feature of schists (i), (ii) and (iv), while rodding is characteristic of quartz schist (iii).

Under the microscope, the crystalloblastic rocks display a strong foliation (S₂) formed by the preferred orientation of
The main constituents of garnetiferous-mica schist are quartz, muscovite, biotite and garnet with minor constituents of chlorite, magnetite, tourmaline, zircon and apatite. The size and modal percentage of garnet varies from band to band. The ratio between the quartz and the micas is variable; in some samples the quartz predominates over the micas, while in others it is just the reverse. Thus, the lithological bands in the mica schists range from metapelites to metasemipelites. The quartz-mica schist (3a-3) resembles for most of its characters with the garnetiferous-mica schist except that it lacks in porphyroblastic garnet and when present it is sporadic and forms minute grains. Muscovite is occasionally developed in large tabular laths (3a-3). The quartz schist (3a-2,3c-2) is
made up of quartz and varying amounts of biotite and muscovite with minor constituents of tourmaline, epidote, zircon, apatite, iron oxide, chlorite and sometimes garnet. The quartz-rich layers are separated by thin (1 mm) bands of micaceous minerals; micas also occur sometimes uniformly distributed in the rock but showing preferred arrangement (Pl. XIe). With the increase in quartz content (> 80%), the rock passes into schistose quartzite. The carbonaceous schist (3b-1) shows alternate bands of graphitic-rich and semi-pelitic-rich layers with major constituents of graphite, quartz, chlorite (I,II) and muscovite-I, while biotite-I, tourmaline, sphene and iron ore form the minor ones.

Two varieties of quartz have been recognised in the schists. Quartz-I is granular or occurs in small lenticles with subrounded or embayed clear outline, and lies with its longer dimension parallel to the schistosity (S2). It is almost free from inclusions except for a few minute specks of apatite and zircon. Quartz-II represents a completely recrystallised variety. At times, the quartz grains are coalesced and form a large composite augen (Pl. XIId) in which the sutured margins of the grains are more apparent under cross-nicols. These porphyroblasts are wrapped around by the sheaves of mica and chlorite. Occasionally, quartz augen are drawn into elongate, rod-like bodies forming 'ribbon structure' (cf. Spry, 1969; see Pl. XIId). Inclusions of magnetite, muscovite
and chlorite in quartz-II are very common along with apatite and zircon. Wavy extinction and presence of deformational lamellae are characteristic of the mineral.

Biotite is of two generations. The greenish brown biotite-I showing strong pleochroism ($\lambda = \text{light yellow}, \ Y = Z = \text{greenish brown}$) and sometimes pleochroic halos lies parallel to the schistosity ($S_2$) of the rock. It forms contorted and elongated shreds or laths forming sheaves with muscovite-I and chlorite. Biotite-I has altered to chlorite-II and muscovite with the release of minute specks of iron oxide which segregate along the cleavage plane. Brown to greenish brown biotite-II occurring in tabular laths is superimposed over the main schistosity $S_2$ (Pl. XIIc) and shows strong pleochroism ($\lambda = \text{light brown}, \ Y = Z = \text{reddish brown or dark brown}$). The mineral commonly occurs in the mica schists and shows alteration to ferri-muscovite-II and chlorite-III. Magnetite inclusions are common but that of tourmaline are rare.

Muscovite-I associated with biotite-I defines the schistosity in the rock. Muscovite-II occurring as porphyroblasts is superimposed over the schistosity ($S_2$) and contains inclusions. When pale, the mineral shows a faint pleochroism (ferri-muscovite) and represents an alteration product of biotite and contains opaque inclusions. In the carbonaceous
FIG. 4.1

Garnet I, sieved, rotated
Magnetite inclusions
2 mm
Garnet I and Garnet II
(Jutogh, 3c)

Garnet I and Garnet II
(Jutogh, 3c)
schist (3b-2), muscovite-I occurs in tiny flakes and possibly represents the sericite variety of muscovite.

Garnet forms an important constituent of the
garnetiferous-mica schist (3a-4, 3c-1) and varies in size from small metacrysts to porphyroblasts up to 5 mm across. Two forms of garnet (I and II) have been recognised. Garnet-I is syn-tectonic while the garnet-II is post-tectonic F₁ (Figs. 4.1, 4.2; Pl. X).

Garnet-I occurs as seived, fractured and rolled
porphyroblasts. Inclusions of quartz are common along with sericite and some magnetite and they commonly show S- or Z-shaped pattern which implies the rotation of garnet relative to the surrounding material and evinces its syn-tectonic growth (Read, 1948; Turner, 1948; Harker, 1950). The extreme case of rotation of inclusions similar to that of snow-ball garnet (Flett, 1912) has not been observed in the present rocks. The micaceous minerals are wrapped around the garnet porphyroblasts and the pressure shadow zones are filled up by quartz. Garnet-I shows degeneration to chlorite-II and iron oxide in varying degrees. In the shear zones, garnet-I has been highly shattered and dragged along the movement planes (Pl. Xe) where it shows extensive alteration to chlorite. The S₁ generally shows continuity with Sₖ.
FIG. 4.2

A. Syn-tectonic garnet I, rotated. Si-Se continuous.

B. Garnet II, spongy core, superimposed on schistosity (S2)

C. Degeneration of garnet I into chlorite II
The post-tectonic porphyroblastic garnet, superimposed over the schistosity $S_2$ has been designated as Garnet-II. It occurs as a fresh idioblast, sub-idioblast or a xenoblast and frequently forms the outer rim over the garnet-I. Thus the inner part of the garnet is invariably characterized by rotated inclusions (garnet-I) and the outer part is non-spongy (garnet-II). This variety has been called as 'garnet-in-garnet' (Das and Pande, 1963-64). The junction between the core garnet and the peripheral one is often marked by inclusions of iron-oxide (magnetite). The outer garnet is also more pinkish than the inner one. Garnet-II shows fractures and sometimes alteration to deep green chlorite-III.

Chlorite of four generations has been identified, of which, the first formed chlorite-I is generally restricted to low grade rocks while the other three forms occur as altered or degenerated products of biotites and garnets. The pale yellow, faintly pleochroic chlorite-I, occurring as tiny wisps lies parallel to the foliation $S_2$ in phyllites and low grade schists. Chlorite-II occurs as an alteration product of biotite-I and garnet-I and is pale green to green, feebly pleochroic and shows inclusions of ilmenite and magnetite. The mineral occurs interleaved with biotite-I and thus retains the original preferred orientation ($S_2$) of biotite. Chlorite-II also occurs
FIG. 4.3

Mus. I

Biot. I

Musc. II

Tour.

Biot. II

0.5 mm

S2

Chl. III

Chl. IV

0.5 mm

0.5 mm

S3

C. Degeneration of Biotite into Chlorite IV in shear zone

D. Microcrenulation cleavage (Jutogh, 3a)

S1

S2

1 mm

E. Relict micro-current bedding, Banded phyllite (Chailly, 3d)
in thin shreds around or along the fractures in garnet-I as a degenerated product. **Chlorite-III** occurs as porphyroblasts superimposed over the schistosity S₂ and is an alteration product of biotite-II (Pl. XIa). Inclusions of magnetite are very common. The mineral also occurs as small shreds around some of the garnet-II metacrysts. Chlorite-III is slightly pleochroic with X or Y = green, Z = pale green to colourless; 2V = 37°, and is optically -ve. **Chlorite-IV** is formed in the shear zones such as strain-slip cleavage, kink bands etc. and is a product of alteration of biotite-I and -II and marks the foliation S₃ (Fig. 4.3; Pl. XI b). It is greenish in colour and shows faint pleochroism.

The opaque black **graphite**, showing cleavage occurs in flakes or as dusty inclusions in the carbonaceous schist (3b-2) and defines the schistosity (S₀) in the rock.

**Tourmaline** occurs in well developed fine subidioblasts or xenoblasts of prismatic habit that are superimposed over the foliation or lie with their longer axes parallel to it. The mineral is greenish brown in colour, strongly pleochroic and at times exhibits zoning. **Magnetite** occurs as opaque black minute grains or in trails made of fine specks which sometimes mark the relict bedding. It also occurs associated with chlorite generated by the alteration of biotite. **Zircon** and **apatite**
occur mainly as inclusions in quartz and less so in biotite and garnet. Among the other minor constituents are small subidioblastic grains of epidote and sphene.

4.2.2 Quartzite (3a-1)

Grey or greyish white quartzite is fine- to medium-grained. The rock contains a variable proportion of micas and accordingly the quartzite is massive and hard or flaggy (schistose quartzite) in nature. Sometimes the rock is stained with a limonitic coating.

Under the microscope, the rocks exhibit a granoblastic texture with a rude (massive quartzite) or well defined (schistose quartzite) foliation developed by the quartz lenticles and mica flakes. The mica flakes are sometimes disposed randomly in the massive variety. Quartz forms the main constituent of the rock. The other constituents are muscovite, biotite, tourmaline, and magnetite which show similar characters as described for the quartz schist.

4.2.3 Marble (3b-2)

Light grey to dark grey marble is compact and hard. It shows a saccharoidal texture and is often characterized by colour banding showing various shades of white and grey colours. These bands measure 1 to 5 mm in thickness and represent the original sedimentary character (S₀) of the
rock. The marble is tremolite bearing. At times, tremolite occurs in long needles and can easily be recognized without the aid of a hand lens.

In thin sections, the rock shows a granoblastic texture, and a rude foliation formed by calcite. Prismatic crystals of tremolite are sometimes aligned parallel to the foliation (Pl. XIII b). In the darker varieties or bands, a dusty opaque material, perhaps graphite, is disseminated in the carbonate crystals. The rock is composed essentially of calcite with minor constituents of tremolite, actinolite, quartz, diopside, epidote and muscovite.

Calcite occurs as xenoblastic crystals measuring up to 1 mm in size and contains inclusions of quartz, iron oxide and sometimes black graphitic dust. Rhombohedral cleavage with lamellar twinning along the long diagonal of the rhomb are distinct.

Graphite is present as tiny flakes or as dusty inclusions in the rock constituents and forms a dominant minor constituent of dark grey marble. Tremolite is light pale green to colourless and occurs in metacrysts (up to 3 mm) of prismatic habit showing extinction angle 5°-15°. The porphyroblasts are sometimes extensively sieved with granular quartz. Actinolite which is associated with tremolite is

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greenish in colour and shows faint pleochroism with $X =$ colourless, $Y = Z =$ greenish. The pale green to colourless diopside occurring in subidioblastic crystals of prismatic habit shows an extinction angle of $39^\circ$ and two sets of cleavage almost normal to each other. Quartz occurs as granular inclusions in various minerals and also as recrystallized xenoblasts. Epidote is light yellow, feebly pleochroic and occurs in small grains showing anomalous blue interference colour. Muscovite is seen in some sections as tabular crystals superimposed over the carbonate grains.

4.3 CHAIL FORMATION (3d)

The Chail Formation is characterized by the low grade metamorphites which consist of the following petrographical units.

Phyllites (3d-1)
Schists (3d-2, 3d-3, 3d-4)
Quartzite (3d-4)
and Epidiorite (in 3d-1, described in Sec. 4.11)

4.3.1 Phyllites (3d-1)

The phyllites are of two types; sheeny phyllite and banded phyllite. The light to dark grey or bluish grey sheeny phyllite showing marked foliation is often puckered.
foliation plane $S_2$, the trace of bedding schistosity $S_1$ imparts a prominent intersection lineation. Hematite occurs either in specks or in aggregate masses of about 1 mm size elongated in the schistosity plane and producing a mineral lineation (Pl. VIII a) that runs parallel to the intersection lineation. The banded phyllite obviously shows clear bands ($S_1$) and is more indurated as compared to the sheeny phyllite. The width of trace of $S_1$ on $S_2$ measures between 1 mm and 2 cm. The phyllites are at times coated with limonite.

Under the microscope, the rock shows a lepidoblastic fine-grained texture and a strong foliation. It is composed mainly of quartz, muscovite and chlorite with minor constituents of magnetite, hematite, tourmaline and albite. The two $S$-surfaces observed ($S_1$ and $S_2$) in the banded phyllite intersect at an angle of 32°. The banded phyllite shows a slight increase in the grain-size as well (Pl. XV e,f).

Quartz occurs in fine lenticular grains (quartz-I) measuring 0.04 mm in size or in small augen (quartz-II) of 0.1 mm size lying with their longer dimension parallel to the foliation. Tiny flakes of muscovite-I (sericite) occurs with light green, slightly pleochroic chlorite-I. Pale white muscovite-II (ferri-muscovite) showing feeble pleochroism is sometimes seen in the banded phyllite and is superimposed over
the foliation $S_2$. Magnetite occurs in small crystals or as trains of inclusions which lie parallel to the foliation. Hematite is seen in minute specks or films. It sometimes forms augen (0.5 - 1.5 mm in length) which are stretched in the plane of schistosity (Pl. XV b) and mark the mineral lineation in the sheeny phyllite. Minute crystals of yellowish brown, pleochroic tourmaline are superimposed on the foliation. A few grains of plagioclase felspar (albite) showing lamellar twinning and an extinction angle of $6^\circ$-$8^\circ$ along the twin lamellae are observed in the banded phyllite.

The rocks encountered near the thrust zone (Chail Thrust) have attained a mylonitic or phyllonitic character due to intense shearing (Pl. XIV b,c,e).

4.3.2 Schists (3d-2, 3d-3, 3d-4)

The following petrographical varieties of schists occur in the Chail Formation.

(i) Chlorite schist (3d-2)
(ii) Chloritoid-chlorite schist (3d-2)
(iii) Biotite-chlorite schist (3d-3)
and (iv) Quartz schist (3d-4)

The schists generally occur in light to dark grey and greenish
grey (i), bluish green (ii), greenish brown (iii) or greyish white (iv) colours and show specks of iron ore disseminated in them. The rocks (i to iii) exhibit silvery lustre and sometimes crenulation lineation. Near the thrust zone, these rocks are highly sheared and are rendered phyllonitic. The essential constituents can be recognised with a hand lens. The quartz schist (iv) is banded and shows alternate quartz-rich and metapelitic-rich bands. This imparts a flaggy nature to the rock. Joints and secondary quartz veins are common in it.

Under the microscope, the schists exhibit a strong foliation ($S_2$) developed by the preferred orientation of flaky minerals and the quartz lenticles. The earlier schistosity ($S_1$) is sometimes discernible in the rocks. The phyllonitic varieties show a mylonitic texture in which the quartz augen are enclosed in a fine-grained groundmass of sericite and chlorite; the rock is strongly foliated (Pl. XIV c,e). The common constituents of the schists are quartz, chlorite and muscovite and are seen in variable amounts. The chloritoid is restricted to the assemblage (3d-2-ii) only and biotite to the (3d-3-iii) and (3d-4-iv). The quartz schist shows quartz-rich bands measuring up to 5 mm thick which are delineated by thin (up to 2 mm) metapelitic or metasemipelitic layers formed of muscovite, chlorite and a small amount of biotite. Among
the minor constituents of the schists are tourmaline, magnetite, zircon and sphene.

Quartz occurs as small lenticular grains (quartz-I) or as recrystallised porphyroblasts (quartz-II) measuring 0.2 mm to 1 mm in length and contains inclusions of muscovite and chlorite. Wavy extinction is typical and the mineral sometimes shows ribbon structure. Chlorite-I occurs in minute flakes which are generally segregated and appear as streaks under cross-nicols. The mineral shows a light bottle green colour and is feebly pleochroic. Chlorite-II degenerated from biotite-I is sometimes observed in (3d-3-iii) and contains opaque inclusions. Muscovite-I occurs in slightly pale or clear flakes (1 mm long) and imparts a strong foliation to the rock. Slightly pale and feebly pleochroic muscovite-II (ferri-muscovite) superimposed over the schistosity represents an alteration product of biotite-II (in 3d-3-iii). Biotite-I is pale brown, pleochroic and lies parallel to the foliation (Sg). Biotite-II occurs as porphyroblasts that are superimposed over the schistosity. The mineral is deep brown in colour and shows a strong pleochroism (cf. schists of Jutoghs, Sec. 4.2.1). Bluish green chloritoid occurring in tabular laths shows a faint pleochroism and hour class structure. Polysynthetic twinning is common. The crystals showing minute micaceous and opaque inclusions are
superimposed over the schistosity ($S_2$). $S_1$ and $S_0$ are seen continuous which evinces its post-tectonic growth (Chapter 5).

Among the minor constituents, tourmaline occurs in small subidioblastic crystals and is strongly pleochroic. A few crystals of sphene (in 3d-2-1) show a deep green colour and the characteristic form. Zircon and magnetite occur in minute granular form or as inclusions.

4.3.3 Quartzite (3d-4)

Milk white to cream coloured, compact and hard quartzite is more or less homogeneous and invariably forms boudins in the metapelitic country rock (Pl. IIId). It often shows numerous fractures which are filled up by silica.

Under the microscope, the rock shows a granoblastic texture formed by completely recrystallised quartz grains which at times, form quartz augen. Wavy extinction is typical. Two sets of fractures healed up by silica are seen intersecting each other at an angle of 52° (Pl. XVa). The massive quartzite is made up chiefly of quartz with a very small amount of tiny flakes of chlorite, muscovite, iron ore and tourmaline. The rock shows a rude foliation and a streaky character due to intense shearing. The schistose quartzite shows an increase in the micaceous constituents (Table 4.2) and a better development of foliation ($S_0$).
4.4 JAUASAR FORMATION (2d)

The Jaunsar Formation is represented by the following rock types:

- Pebbly quartzite (2d-1)
- Grey sandstone (2d-2)
- Dark slaty shale (2d-3).

4.4.1 Pebbly Quartzite (2d-1)

Yellowish or brownish white rock is essentially a coarse rudite formed of pebbles and granules of quartzite/quartz tightly packed in an argillaceous and arenaceous matrix. The rock is well indurated and is generally stained brown on the weathered surface.

Under the microscope, the major constituents of the rock, the granules and pebbles, are seen cemented with arenaceous and argillaceous matrix. The rock fragments, plagioclase, felspar, hematite and tourmaline (Pl. XVI c) occur in small amounts.

The pebbles and granules of quartz/quartzite are rounded and are of varying dimensions up to 7 mm across. Most of them are composite pebbles showing sutured contacts and wavy extinction. Quartz grains of fine to coarse sand grade occurring in the matrix are subrounded and show wavy
extinction. Authigenic quartz is not uncommon. Inclusions of hematite, zircon and apatite are also seen in them. The argillaceous constituent of the matrix is composed of fine flakes of sericite and chlorite with some clay.

The rock fragments are few, generally of slaty or phyllitic nature and of fine to coarse sand size. The plagioclase felspar occurs in few clear grains which show lamellar twininning and an extinction angle of 6°-10° along the twin lamellae. Small grains of hematite and tourmaline also occur.

4.4.2 **Grey Sandstone** (Cd-2)

Grey to dark grey, medium-grained sandstone is hard, massive and micaceous. Near the Chail thrust, the rock has acquired a foliated structure.

Under the microscope, the rock shows subangular to subrounded quartz grains (over 50 %) of coarse silt to medium sand grade and embedded in an argillaceous paste of sericitic and clayey matrix impregnated at times with carbonaceous matter (Pl. XVIa). It occasionally contains ferruginous contamination. The rock near the Chail thrust, in thin sections, shows some development of preferred orientation of elongate and equant quartz grains and flaky minerals (Pl. XVIb). According to Williams, Turner and Gilbert (1955, p. 205), the term semi-schist
has been used for cataclasites representing a transitional stage in the development of schist from a greywacke, sandstone or tuff. Considering the preferred orientation of flaky minerals and elongated quartz grains, the rock near the Chail Thrust probably represents a semi-schist or a very low grade metasemipelite.

Among the minor constituents are a few grains of fresh plagioclase felspar showing an extinction angle of 5°-15° along the twin plane, granular hematite and flakes of muscovite and biotite. Muscovite occurs in clear flakes and dominates over the brownish pleochroic biotite.

4.4.3 Dark Slaty Shale (2d-3)

Greenish or brownish grey in colour, indurated and thinly laminated shale shows a marked bedding fissility which imparts it a slaty look. The rock is highly puckered and is traversed by numerous veins of quartz.

Under the microscope, the rock shows 0.2 to 2.0 mm thick laminae showing a variation in colour, mineral composition and grain size. The major mineral constituents are quartz, sericite and chlorite with small amounts of biotite, plagioclase, carbonaceous material and iron oxide (Pl. XIVa).
Quartz occurs in subangular to subrounded grains of average 0.04 mm size and forms about 50% of the constituents in the argillaceous-rich laminae while in the quartz-rich laminae it is over 60% of the lamina.

In quartz-rich layers, the matrix is dominantly carbonaceous and produces a mesh-like structure. Secondary enlargement of quartz is frequent. The microscopic veins are filled up with chalcedonic quartz.

The matrix composed of fine sericitic and chloritic material is impregnated with carbonaceous matter with some ferruginous contaminations. The minerals are aligned with their longer dimensions parallel to the lamination. At places, or near the shear zones, the tiny flakes are slightly rotated or make a high angle with the bedding. This gives rise to the development of incipient cleavage on microscopic scale (cf. Pls. XVIIa; XVIIIc).

Biotite occurs in small pale brown lamellar flakes lying parallel to the lamination. Muscovite occurring in clear flakes dominates over the biotite in proportion.

The other minor minerals are fresh plagioclase feldspars showing an extinction angle of 2°-24° along the twin lamellae, and hematite occurring in fine specks or grains.
4.5 ARKI FORMATION

Arki Formation comprises the following rock types:

- Laminated shales (2a-5, 2a-3)
- Fine sandstone (2a-5), siltstone and silty shale (2a-1)
- Limestones (2a-4, 2a-2)
- and Orthoquartzite (2a-1).

4.5.1 Laminated Shales (2a-5, 2a-3)

Brown, greyish brown, grey or black, thinly laminated shales are characterized by bedding fissility. They lack any development of cleavage recognisable in the hand specimen.

Under the microscope, the shales show silt-size quartz grains mixed with argillaceous matrix and variable proportions of ferruginous, calcareous and/or carbonaceous matter. Based on the predominant constituent of the matrix, the rock may be designated as argillaceous, carbonaceous, ferruginous or calcareous shale. Further, these varieties of shale merge into each other. The laminae are 0.1 mm to 7 mm thick. Tiny flaky minerals (sericite and chlorite) are invariably arranged parallel to the bedding. Near the movement zones, quartz shows recrystallization along the shear planes and at places the minute argillaceous flakes are seen rotated at a low (25°) to high
angle (70°) to the bedding to produce an incipient development of cleavage (Pl. XVIIIe).

Subangular to subrounded silt-size quartz grains show normal or wavy extinction and occur in variable proportions in the laminae. In the argillaceous shale, quartz forms 40-50% of the rock. The argillaceous matrix commonly contains ferruginous matter and seldom carbonate matter. The carbonaceous shale shows carbonaceous matter occurring in aggregates or thin lenses (Pl.XXc) or scattered in the laminae. The ferruginous shale shows quartz grains coated with iron pigment and forming 50% of the rock. Some of the laminae rich in ferruginous content contain up to 75% quartz. The calcareous shale resembles the other types except that the matrix is rich in carbonate mud and the quartz content is reduced to 30-40%.

The secondary quartz that fills the fractures is sometimes coated with iron oxide and contains inclusions of iron ore and matrix. The accessory constituents are hematite specks, tourmaline and plagioclase feldspar with extinction angle of 4°-8° along the twin trace.

4.5.2 Fine Sandstone, Siltstone and Silty Shale (2a-5, 2a-1)

Grey, dark grey or brownish yellow in colour and
occasionally stained with iron oxide the fine sandstone, siltstone and silty shale are micaceous and well indurated. The bedding may be marked by colour variation or is poorly preserved in sandstone and siltstone. In the silty shale, the bedding is distinct and the rock sometimes shows bedding fissility. Small folds are common in these rocks.

In thin sections, the rock shows quartz grains occurring in an argillaceous matrix occasionally contaminated to variable extent with ferruginous pigment. Carbonaceous content is sometimes observed in the fine sandstone (Pl. XX d). Laminae (0.30 mm thick) are common in the shale; sometimes micro-cross-lamination is also seen.

Quartz occurs in subangular to subrounded grains generally coated with limonite and shows wavy ophtormal extinction. In fine sandstone it forms 60% or more of the rock and the grains (0.1 to 0.2 mm) are fairly sorted and tightly packed. At places fusion of grains results in sutured boundaries. In the shale and siltstone, the quartz occurs in various dimensions within the silt grade and reaches up to 0.1 mm in size. Some of the quartz grains, in the rocks under description, show their edges replaced by sericite flakes to produce a hazy look when viewed under medium or high power objective.
The matrix composed of clayey paste of chloritic and sericitic material fills the voids between the quartz grains. The fine flaky constituents of the matrix are generally aligned parallel to the bedding. Muscovite occurs in flakes of 0.1 - 0.2 mm in length. The ferruginous content occurs from accessory contamination to appreciable amount so that the rock is essentially ferruginous. The shales generally show alternate layers rich in ferruginous content. The grey coloured rocks contain negligible ferruginous matter.

Among the accessory constituents, hematite occurs as small angular grains which are sometimes segregated into small bodies not exceeding 0.15 mm in size. Few grains of fresh plagioclase feldspar show lamellar twinning and extinction angle of 10° along the twin plane. Zircon and greenish brown, pleochroic tourmaline occur in minute subrounded grains.

4.5.3 Limestones (2a-2, 2a-4)

The Arkı limestone is of three types viz., laminated limestone (2a-4), Massive limestone (2a-4, 2a-2) and Oolitic and pisolithic limestone (2a-4, Mainly 2a-2).

Laminated and massive Limestone

The limestones show various shades of grey and yellowish grey and occur as finely laminated (2a-4), bedded or massive
(2a-4, 2a-2). The laminae or beds vary in thickness and are delineated by colour difference or by textural variation. At places, the limestone is cherty, and the yellow coloured variety is ferruginous. The massive limestone at places shows well preserved algal stromatolites.

In thin sections, the laminated limestone shows a distinct, but a small variation in texture in the alternate laminae both of which being formed of cryptocrystalline calcite. The massive limestone exhibits a calcilutitic texture and generally shows 5 mm thick layers. The laminae or layers in the rocks are defined by textural difference, graded bedding (Pl. XIX f) or by limonitic or cherty traces lying along the bedding. However, thin cherty streaks are also seen traversing the bedding. Dolomitization has occurred on a minor scale and the subhedral to euhedral dolomite rhombs show twin lamellae parallel to the short diagonal of the rhomb. Sometimes, quartz grains are aligned along the bedding and form laminae not exceeding 0.1 mm in the laminated limestone. The massive limestone contains detrital quartz grains of 0.05 - 0.1 mm size. Secondary enlargement of quartz is also observed. A few grains of hematite are sometimes seen along with quartz. Chlorite flakes (0.1 mm) also occur in small amount.

Stromatolitic limestone shows 1-2 mm thick layers.
composed of cryptocrystalline to microcrystalline calcite and quartz grains impregnated with carbonaceous material to produce a mesh-like structure. Only a few subrounded quartz grains of fine sand grade are contaminated in the layers. The laminae are defined by the variation in the carbonaceous content and texture. The dolomitization has occurred on a minor scale.

Oolitic and pisolitic limestone

Light to dark grey or brownish yellow limestone is formed of allochems of oolites, pisolites, pellets and carbonate fragments (intraclasts) mixed in various proportions and embedded in the carbonate mud. The allochems occur in various dimensions. Sometimes they do not exceed 2 mm in size and the rock is essentially an oolitic limestone. With the increase in size (seen up to 3 cm) of allochems, the rock passes into a pisolitic limestone.

Under the microscope, the rock shows carbonate allochems loosely packed in the carbonate mud contaminated with quartz grains. The rock has undergone chertification and dolomitization (see below). Numerous veins and fractures traverse the allochems and have displaced them on a microscopic scale (Fig. 4.4 b,d).
FIG. 4.4

a  Chertification and dolomitization in carbonate oolith (Arki, 2a-4)

Dol.
Chert

b  Deformed carbonate pisolite (Arki, 2a-4)

Calcite vein showing displacement

C  Pene-contemporaneous deformation in pisolite (Arki 2a-4)

Chert

2 mm

D  Oolitic limestone (2a-4) with core of coarser calcite embedded in carbonate material with quartz grains.

Oolitic limestone (2a-4) with core of coarser calcite embedded in carbonate material with quartz grains.
The oolites and pisolites range in size from less than 0.5 mm to 2 mm and 2 mm to 5 mm respectively and are characterized by concentric layering of cryptocrystalline (or lutitic) carbonate. They generally show multi-layered concentric structure. In rocks where pellets are abundant, concentric layering in the oolites (and pisolites) is seen restricted and in such cases they exhibit one (superficial oolite) or two carbonate layers. Some of the pisolites show spherulitic cross under the cross-nicols. Composite pisolites are not uncommon and sometimes the layers are contaminated with tiny clastic quartz grains. The nuclei of oolite and pisolite are generally formed of aggregate of cryptocrystalline mud or clear microcrystalline calcite. Less commonly clastic quartz and rarely a rock fragment forms the nucleus. In pisolites the carbonate core sometimes shows bedding on a microscopic scale. Some of the layers show pene-contemporaneous folding (Pl. XIXe). The pellets form bodies of cryptocrystalline carbonate which resemble in shape with oolite or pisolite but unlike them lack any concentric layering. Some of the pellets do show one discontinuous or irregular layer enveloping the main carbonate body. The carbonate fragments show very irregular shape and attain a maximum size of 3 cm; some of them show bedding structure.
Two important phenomena of replacement of carbonate (calcite) by chert and by dolomite are worth mentioning. In the chertification, calcite has been replaced by microcrystalline quartz. The replacement is generally in part but in extreme cases the whole oolitic (or pisolithic) body or intraclast is replaced by silica. The oolitic structure is retained during the replacement (Pl. XIXb). The concentric layers are replaced by fibrous cryptocrystalline silica while the core is replaced by an aggregate of silica. Preferential replacement of some oolitic layers is also observed. Dolomitization follows the chertification and is evinced by the subhedral to euhedral rhombohedra of dolomite replacing both the cryptocrystalline silica and the carbonate material (Fig. 4.4a; Pl. XIXc). The dolomite crystals are of 0.01 - 2.00 mm in size and are distinguished from calcite by their form and twinning. The replacement has also occurred in the core of the intraclasts through microscopic veins and fractures. The extent of dolomitization varies and is up to 15%.

4.5.4 Orthoquartzite (2a-1)

White or greyish yellow, fine- to medium-grained compact and hard quartzite shows less marked bedding. The specimens are generally slickensided and ripple marked.
Fracture surfaces of the rock are generally coated with limonite.

In thin section, the rock shows fairly sorted quartz grains of fine to medium sand grade which are tightly packed with chert and negligible argillaceous matrix (Pl. XXb).

Quartz occurs as subangular to subrounded grains of 0.2 to 0.7 mm in size and exhibits straight or wavy extinction. The grains occasionally contain inclusions of zircon and apatite. Secondary enlargement of quartz is common, grains have fused to form sutured boundaries. In some sections, the grains are coated with a brownish film of iron oxide. Chart is seen in small patches of 0.5 to 2 mm thick and 6 mm in length, filling the voids between the grains.

Among the minor flaky constituents are light green slightly pleochroic chlorite, greenish brown and pleochroic biotite, and clear sericite. Among others are small grains of zircon, iron ore and subrounded brownish green tourmaline.

4.6 SHERPUR FORMATION

It consists of massive limestone (2f-1) and bedded limestone (2f-2). Except for bedding, both the varieties of limestone appear alike. The grey and compact limestone is
traversed by numerous calcite veins and is dolomitized. Thin (up to 1 mm) cherty streaks are present in the limestone and the rock is invariably stained with pale yellow colour due to leaching of iron oxide. Near the thrust zone (Sherpur Thrust), the rock is powdery and also highly recrystallized.

Under the microscope, the rock is seen composed of aggregate of micro- to crypto-crystalline interlocking crystals of calcite which are embedded in aphanocrystalline calcite mass. Secondary veins are filled with spary calcite. The limestone shows, in some sections (lower part of the formation), a high degree of dolomitization (Pl. XVIIIa). Near the thrust zone, the limestone shows intense shearing (Pl. XVIII a) and recrystallization. The calcite crystals are up to 5 cm across and show bent cleavage traces (Pl. XVIII c).

Thin streaks of chert often define the bedding. A few grains of quartz are also contaminated in the calcareous mass. Small grains of iron ore are sometimes observed in the rock.

4.7 SIMLA FORMATION (2b, 2c)

The Simla Formation consists of the following rock units:
Shales: Laminated (2b-4), Variegated (2b-3) and Needle (2c-1) shales.

Siltstones: Greyish brown, grey or purple siltstone (2b-4, 2b-2, 2c-3).

Sandstones: Lithic greywacke (2b-1), Quartz wacke (2b-1, 2c-2).

4.7.1 **Shales** (2b-4, 2b-3, 2c-1)

**Laminated Shale (2b-4)**

The grey, dark grey or brownish rock is finely laminated. The laminae impart a remarkable bedding fissility to the rock and gives a false appearance of rock cleavage. The specimens show small, open puckers belonging to $F_3$ generation of folds.

Under the microscope, the rock shows characteristic laminations generally between 0.2 and 2 mm in thickness and rarely reaching up to 5 mm in cross-section. The laminae are composed mainly of paste of clayey sericitic and chloritic material, sometimes ferruginous, in which are studded quartz grains of silt or fine sand grade. The quartz grains occur in various fashions —they may be distributed homogeneously in the laminae or may show concentrations at the base to produce
micro-graded bedding or they may form alternate arenaceous-rich laminae (Pl. XVII a) in which case the rock may be called as 'Lamnite' (Augustin, 1963).

Quartz measuring up to 0.1 mm occurs in subangular to subrounded grains and varies in amount from accessory occurrence in argillaceous-rich layers to as much as 60% in the arenaceous-rich layers and accordingly grains show very loose to tight packing in the laminae. Secondary enlargement of grains is common. Inclusions of sericite, zircon and apatite are common.

The argillaceous matrix generally predominates over quartz grains of silt grade. The platy minerals are aligned parallel to the bedding to produce bedding fissility. Sometimes these flakes are aligned at an angle to the lamination to produce incipient cleavage (cf. Pl. XVIII e). The matrix in some shales is contaminated with ferruginous matter which occurs more dominantly in alternate layers.

Among the accessory constituents are tiny grains of hematite, fresh plagioclase grains of silt grade and showing an extinction angle of 4°-9° along the twin plane, zircon and a few subrounded and equant rock fragments of phyllite or slate of fine silt grade.
Variegated and Needle Shales (2b-3, 2c-1)

Light brown, yellow, bluish grey or green shales (2b-3) show thick laminations marked by colour variation. Green or purplish needle shales (2c-1) are friable and micaceous and lack bedding fissility.

Under the microscope, the variegated shales resemble the laminated shale (2b-4) except that the laminae or beds in the latter are 5 mm to 2 cm thick. The needle shales are rather silty, micaceous and lack lamination. Quartz forms about 50% of the rock in argillaceous matrix contaminated with ferruginous and carbonaceous matter. The ferruginous content is abundant in the purple needle shale. Sericite or muscovite forms an important minor constituent along with others described above in laminated shale (2b-4).

4.7.2 Siltstones (2b-4, 2b-2, 2c-3)

Greyish brown, grey, yellowish grey or purple and micaceous siltstones are well indurated. They exhibit sedimentary structures such as sole marks and cross-bedding and lack bedding fissility. Calcareous siltstones give effervescence with the acid and the ferruginous varieties are coated with limonitic film.
In thin section, the rock is composed of about 50% quartz grains up to silt grade which are loosely packed in sericite-rich argillaceous matrix.

Angular to subangular or subrounded quartz up to 0.1 mm in size occurs in triangular or equant grains and contains occasionally apatite inclusions. Some of the grains have their margins replaced by fine flakes of sericite. Quartz grains show both wavy or normal extinction; fracturing is common. Some chert in small aggregates is also seen.

In calcareous siltstones the matrix is clay-carbonate mud in which calcareous and argillaceous constituents occur sometimes in equal amounts. The carbonaceous contamination in the matrix is about 5%. The ferruginous matter is occasionally contaminated; in purple siltstone it occurs in an appreciable amount.

Hematite, among minor constituents, occurs in tiny grains and granular aggregates; muscovite occurs in small flakes (0.1 mm); a few grains of plagioclase felspar in clear grains show an extinction angle between 5° and 8° along the twin plane; zircon grains have thick boundaries, high relief and characteristic shape; brownish green tourmaline occurs in subrounded to rounded grains.
4.7.3 Sandstones (2b-1, 2c-2)

The sandstones of Simla Formation belong to two categories, lithic greywacke (2b-1) and quartz-wacke (2b-1, 2c-2).

Lithic Greywacke (2b-1)

Grey of various shades, greenish, purplish brown or bluish in colour, fine- to medium- or coarse-grained rock is micaceous and sometimes ferruginous. The coarse-grained varieties are generally massive and show microbreccia texture. Bedding is more distinct in the finer-grained varieties. Cross-lamination or cross-bedding is common.

Under the microscope, the rock is composed of quartz grains (50-60%) with rock fragments (20-25%) studded in a sericite-chloritic-rich clay matrix contaminated occasionally with ferruginous and carbonaceous contents. Tourmaline, micas, zircon, plagioclase felspar and chloritoid form the accessory constituents.

Quartz occurs in angular to subrounded grains that are poorly sorted and range in size from 0.1 to 0.5 mm. The equant, triangular or subcircular quartz grains show wavy or normal extinction. Overgrowth is common and the grains are sometimes interlocking and have sutured contacts which betray
the sedimentary parentage. Inclusions of zircon, apatite and sericite are common. The rock fragments which are elongated or equant, are represented by subangular to subrounded fragments of phyllite, carbonaceous slate, ferruginous shale or slate. Kinking of S-surface is common in the rock fragments.

Of the minor constituents, mica (especially muscovite) and tourmaline are ubiquitous. Muscovite occurs in clear flakes, biotite exhibits greenish brown colour and tourmaline occurs in subrounded, yellowish brown grains. Among others, zircon occurs in small grains of characteristic habit; hematite is seen in minute grains and streaks; chloritoid of bottle green colour shows twinning and hour-glass structure. Subrounded or subangular grains of plagioclase felspars occur only in small amount, but in some sections, they exceptionally form more than 5% of the rock. The grains are fresh, show lamellar twinning and an extinction angle between 3° and 25° along the twin lamellae.

Quartz-wacke (2b-1,2c-2)

Greyish or brownish green, yellowish grey or purple, indurated and massive quartz-wacke is medium-grained and micaeous. It displays a microbreccia texture and commonly shows small scale cross-bedding. Near the Chail thrust the
rock (2c-2) is highly crushed and sheared along the weak planes.

Microscopically the rock is similar to lithic greywacke except that the rock fragments have been reduced to small amount (up to 5%) and the clay matrix has attained a higher proportion. The rock consists of unsorted grains of quartz (55-60%), generally up to medium sand grade (0.1 - 0.5 mm), loosely packed in a sericite-chlorite-rich argillaceous matrix. Rock fragments are few, with accessory minerals of muscovite, biotite, tourmaline, zircon, hematite and chloritoid.

Thin sections of the rock occurring near the Chail thrust (north of Jamlog) show the quartz grains and other constituents lying parallel or subparallel in a preferred direction (cf. Pl. XVI b). They have, perhaps, rotated in the matrix under the impact of stresses generated during thrusting.

4.8 KAKARA FORMATION (la)

The three rock types that constitute the Kakara Formation in the present area are: Brown shale and siltstone (la-1), Grey limestone (la-2) and Laterite (la-3).

4.8.1 Laterite (la-3)

The rock is purplish brown in colour and characteristically pisolithic showing pisolites over 5 mm in diameter. The
Pisolites are circular to oval in cross sections and are closely packed and cemented by brown ferruginous matter.

Under the microscope, the rock shows a light pale brown to deep brown colour. The pisolites measure up to 6.0 mm and are composed of limonitic and bauxitic matter. The rock is isotropic under cross-nicols. The bauxite is of clasticite variety, pale brown in thin section, isotropic and forms contraction cracks (Pl. XX e) due to shrinkage. The limonite is brown to deep brown isotropic and is generally concentrated dominantly on the outer part of the concentric layers of pisolite. A few grains of quartz occur in the inner core of pisolites. The matrix which fills the voids between the pisolites is of the same composition as that of pisolites.

4.8.2 Grey Limestone (la-2)

Grey or brownish grey in colour and compact limestone shows comminuted fossil debris in carbonate-rich matrix. The fossil fragments seen on the rock surface measure up to 5 cm in length. The rock is traversed by numerous calcite veins.

Under the microscope, two varieties of limestone are distinguished, viz., fossiliferous limestone and fossiliferous phosphatic limestone. The latter is brownish grey in hand specimen. The two types of limestone have the same
microscopic characters except the collophane constituent.

In thin section, the rock is seen composed of cryptocrystalline carbonate mud in which are embedded shell fragments forming 15-20% of the rock. Among the minor constituents are collophane and quartz. Where the shell fragments are comparatively abundant, the proportion of collophane and quartz also increases. Quartz in such cases forms up to 10-15% of the rock. The rock is traversed by numerous veins filled with sparry calcite. Dolomitization has occurred on a small scale in some carbonate intraclasts and shell fragments.

The shells or rock fragments generally exhibit a coarser texture than the cryptocrystalline carbonate in which they are embedded. Some of the shells show a brown film of collophane around their margins.

The collophane occurs in light to dark brown colour in bodies of 1 mm in size and is isotropic under cross-nicols. It is also seen along some fossil fragments. The bulk sample of phosphatic limestone contains 2 to 4 per cent of P2O5 (Srikantia and Sharma, 1970). Subangular grains of quartz 0.05 mm in size occur associated with fossil fragments. Only a few quartz grains occur in the carbonate mud where fossil
fragments are absent. Small grains of hematite occur as a minor constituent.

4.8.3 Brown Shale and Siltstone (1e-1)

The brown, greenish greyish or bluish brown shale and siltstone are indurated and sandy or silty in nature. The bedding is not very distinct. The brown shales are phosphatic.

Under the microscope, rock is seen composed of silt grade quartz grains mixed in a paste of fine matrix. Among the accessory minerals are collophane, hematite, epidote and glauconite.

Insular to subrounded grains of quartz up to 0.04 mm in size occur in varying amount forming 40-50% of the rock. The fine argillaceous matrix is composed of sericite and clayey minerals that lie almost parallel to bedding where the bedding is marked by lamination. It is generally contaminated with calcareous, carbonaceous or ferruginous matter. The ferruginous matter becomes more dominant in the brown shales. The carbonaceous matter occurs in finely divided grains or in aggregates of 0.2 mm size.

Collophane occurs in small nodules or aggregates.
showing brown to deep brown colour and measuring up to 0.5 cm across. It is isotropic under cross-nicols. Among the other minor constituents are light green epidote, chlorite, a few grains of bladed-like feldspar showing extinction angle of 0°-15° along the twin lamellae, zircon and chloritoid.

4.0 SIKATU FORMATION

The SIKATU Formation is represented by (i) Shale and siltstone (1b-1) and (ii) Shelly limestone (1b-2).

4.0.1 Shale and Siltstone (1b-1)

Greenish grey, olive green or purple shales and siltstones are well indurated and show close jointing. Minute, shining, micaeous flakes can be recognised in the hand specimen. The greyish green shale sometimes contains broken fragments of shells and foraminifera.

Under the microscope, the rock shows quartz grains embedded in an argillaceous and calcareous matrix. Fractures or joints are filled with calcareous or ferruginous (purple shale) matter. The fossil fragments occur in the greyish green shales that also contain a semi-crystalline carbonate associated with argillaceous matrix.
Well sorted grains of quartz of silt grade, subrounded or subangular form 40% of the greenish grey rocks. These grains are cemented together by calcareous matter. In the ferruginous varieties, however, quartz content reaches up to 50%. Broken shells, composed of cryptocrystalline carbonate are seen in calcareous shale and form 10-15% of the rock.

Tiny flakes of muscovite and minute grains or granular aggregates of hematite form minor constituents of the rock.

4.9.3 Shelly Limestone (1b-2)

The shelly limestone is brownish grey to bluish grey in colour, hard and compact and shows a good preservation of foraminifera with some broken shell fragments.

Under the microscope, the rock shows several entire foraminifera tests, embedded in a calcareous ground mass which contains much comminuted fossil debris and detrital quartz grains. At times, hematite in the form of thin films imparts a light reddish brown colour to the rock.

Most of the foraminifera tests are complete and show details of internal chambers and have undergone slight obliteration at places. The chambers are filled with cryptocrystalline calcite. The tests attain a maximum
diameter of 3 mm and show conspicuously spherulitic cross when viewed under the cross-nicols (Pl. XXI b). This cross apparently moves with changing interference colours when the stage is rotated.

A few pellets composed of crypto-crystalline (lutitic) calcite and up to 1.5 mm in length, occur embedded in the matrix. They are oval in shape and lack any concentric layering. Broken shells, perhaps of molluscs occur in elongate thin fragments composed of crypto-crystalline carbonate. Some of the fossil fragments show compositional layering.

Quartz occurs as subangular to subrounded equant grains. The mineral is uniformly distributed in the matrix and is detrital.

The argillaceous matter occurs as minor constituent and is composed of sericitic-clayey matrix. Tiny grains of hematite conspicuously occur in granular form.

4.10 DAGSHAI FORMATION

The Dagshai Formation is constituted of (i) Purple shale and clay (lc-1), (ii) Purple, grey sandstone (lc-2) and (iii) White quartzite (lc-1).
4.10.1 Shale and Clay (lc-1)

Bright purple or brown coloured rock is friable and lacks bedding.

In thin section, the rock shows a purplish brown colour. It is difficult to identify the minerals due to their fine size. However, quartz grains (0.02 mm) and minute flakes of sericite are easily recognised. The clayey matrix is mixed up completely with iron oxide.

4.10.2 Sandstone (lc-2)

The purple or grey and medium-grained sandstone is characterized by grey or greyish black rock fragments which impart a mottled appearance to the rock. Iron oxide forms the cementing material.

Under the microscope, the rock is seen composed of quartz, rock fragments and a few grains of plagioclase felspars that are studded in argillaceous and ferruginous matrix. At places the cement is purely ferruginous (hematite). The higher percentage of rock fragments over that of feldspars classifies the rock as lithic sandstone.

Quartz forms angular to subrounded grains measuring up to 1 mm across and constitutes 50-55% of the rock.
Inclusions of iron and apatite are common. It shows undulose or straight extinction. Subangular to subrounded rock fragments of grey shale or slate, quartzite and mica schist form about 15-20% of the rock. On an average, the rock fragments measure 0.1 mm to little over 1 mm. Plagioclase felspar occurs as fresh or slightly altered subrounded grains of about 0.5 mm size and form 2-3% of the rock.

4.10.3 Quartzite (1c-3)

The rock is generally white in colour or sometimes purplish or creamish white, medium-grained, hard and compact. Quartz grains forming the main constituent of the rock are recognisable in the hand specimen. Quartzite is of two types, (i) orthoquartzite, and (ii) protoquartzite. The former is white in colour, whereas the latter has a purplish or creamish colour.

Under the microscope, the orthoquartzite is characterized by a mosaic of quartz grains that are fused together. The cement where present occurs in small amounts as reorganized argillaceous matrix. Authigenic quartz is also present in small amount. The angular to subrounded, well sorted and distorted grains of quartz are of 0.3 mm in average size and contain inclusions of zircon and rutile. The minor constituents are pale brown, subrounded tourmaline, specks of
magnetite and hematite; and a few grains of epidote which show pleochroism in shades of green.

The protoquartzite shows in thin section fine to medium sand-sized grains of quartz embedded in a ferruginous cement contaminated with argillaceous matrix. The quartz forms 75-80% of the rock and is subangular to subrounded with an average size of 0.2 mm. Most of the grains are clear, with a few inclusions of zircon or rutile and show generally normal extinction. The grains are coated with iron oxide film. The rock fragments (up to 5%) of slates or schists occur in subangular to subrounded grains. The other minor constituents are tourmaline, magnetite, hematite, epidote and ilmenite.

4.11 INTRUSIVE AND METABASIC ROCKS

The intrusive and metabasic (including para-amphibolite) rocks are represented by amphibolites (3b), epidiorite (3d) and dolerite (2a) and they occur in the Jutogh, Chail and Arki Formations respectively.

4.11.1 Ortho-amphibolite (in 3b)

Medium- to fine-grained, deep green to brownish green rock shows a prominent schistosity marked by preferred orientation of hornblende prisms.
Under the microscope, the rock is characterized by granoblastic texture and is composed of hornblende, plagioclase and quartz with epidote, sphene, apatite, chlorite, biotite and magnetite as minor constituents.

**Hornblende** forms the major constituent of the rock and occurs as pale green elongated grains and laths which show a preferred orientation ($S_0$). The mineral is pleochroic ($X = $ pale green, $Y = $ bottle green and $Z = $ bluish green) with birefringence $0.024$, $2V = 65^\circ-71^\circ$ and $Z\Delta c = 15^\circ$ to $17^\circ$. Cleavage is well marked and is seen in one or two sets in longitudinal and transverse sections respectively. The metacrysts are sieved and contain inclusions of quartz, felspar, epidote and magnetite. The mineral alters to chlorite and epidote.

**Quartz** forms an important constituent with hornblende and plagioclase. It occurs in grains or as porphyroblasts which show sutured margins and undulose extinction. **Plagioclase** occurs in small laths which are occasionally parallel to the foliation. Twinning is seen in some laths on albite law. The anorthite content in the plagioclase varies from 24-30 %.

4.11.2 Para- amphibolite (in 3b)

Dark greenish grey to brownish grey, medium-to coarse-
Grained para-amphibolite shows a marked foliation developed by preferred orientation of hornblende prisms. Well developed and pinkish crystals of garnet up to 7 mm across are studded in the rock.

Under the microscope, the medium- to coarse-grained rock is composed of hornblende and garnet porphyroblasts which are set in a ground mass (Pl. XIII e).

Hornblende occurs as long, sieved porphyroblasts (Pl. XIII d) with inclusions of quartz, sphene and apatite and shows a preferred orientation (S0). The mineral is pleochroic (X = brownish green, Y = brownish, Z = pale green) and shows alteration to chlorite.

Quartz occurs in small grains or is segregated to form small augen. The grains are sutured, interlocking and generally show undulose extinction. Garnet is an important constituent and occurs as idioblasts up to 7 mm across. The mineral is fractured along which it alters to chlorite. Minute inclusions of quartz and magnetite are common.

The minor constituents are plagioclase, sphene, epidote, zircon, chlorite, biotite and oxide of iron.
4.11.3 Epidiorite (in 3d)

Dark green to greyish green rock is fine- to medium-grained and shows a marked variation in grain-size and texture from the core to the periphery of the metabasic body. On this basis, two types of metabasics have been recognised, viz., the foliated variety that occurs near the periphery and the non-foliated variety that occurs in the core of the metabasic body.

Under the microscope, the foliated epidiorite is characterized by a rude foliation marked by the preferred arrangement of chlorite and hornblende needles. The non-foliated and massive epidiorite shows blasto-ophitic texture. In the foliated variety, hornblende, plagioclase and chlorite are the dominant minerals whereas plagioclase, hornblende and augite form the main constituents of the massive variety which has also retained the original texture. Among the minor constituents are quartz, biotite, sphenite, epidote, ilmenite and iron ore.

The laths of plagioclase are surrounded by mafic minerals to produce ophitic texture. Twinning is common on albite law. The anorthite content in the plagioclase varies from An$_{25}$ to An$_{45}$ from the peripheral to the central part of the
metabasic body. The mineral is cloudy and dusty with opaque minerals.

**Hornblende** occurs as prismatic or irregular grains of hornblende showing one set of cleavage in longitudinal section and a marked pleochroism (X = pale green, Y = yellowish green and Z = brownish green) and extinction angle 23° to 27°. The mineral also occurs as an alteration product of augite (uralitization). Inclusions of quartz, biotite and chlorite are common. Light green to bottle green and slightly pleochroic chlorite forms a major constituent in the foliated variety.

**Augite** occurs in the massive variety while it has been replaced by chlorite and hornblende in the foliated variety. It produces a blasto-ophitic texture with laths of plagioclase. The extinction angle of augite varies between 40° and 45° and 2V is about 60°.

4.11.4 **Dolerite** (in 2a)

Greenish black and medium- to fine-grained rock is composed essentially of felspars and mafic minerals which are partly altered.

Under the microscope, the rock exhibits ophitic texture and consists essentially of plagioclase felspar, pyroxene (augite) and olivine with epidote, chlorite, iron
oxide and serpentine as accessory constituents.

The plagioclase felspar is subhedral and exhibits intergrowth. The mineral is kaolinitized with the development of epidote minerals especially clinozoisite. The mineral shows bent twin lamellae and also fractures which are filled with limonite and hematite. Anorthite content varies from 40–60%.

Augite and granular olivine (in subordinate amount) constitute the mafic minerals. They are mostly altered to serpentine, magnetite and chlorite. Some relicts of olivine are also observed. Augite shows two sets of cleavage in transverse section and one in longitudinal section with \( 2V = 58^\circ \), optically +ve; extinction angle 41° to 45° and moderate birefringence (0.022).

Ilmenite with leucoxenic border at times gives rise to leucoxenic sphene. The other accessory constituents are epidote, iron oxide and serpentine.