CHAPTER 5

METAMORPHISM

5.1 INTRODUCTION

The present chapter is devoted to the study of metamorphism of the rocks belonging to Jutogh and Chail Formations (allochthon) which represent the metamorphites in Arki-Jutogh area. These rocks have suffered metamorphism during the various phases of Himalayan orogeny. During the process of metamorphism, mineralogical transformation (cf. Lyell, 1833) or adjustments took place in response to physico-chemical environments that prevailed during the various phases or episodes of metamorphism.

The rocks of Jutogh and Chail Formations have been repeatedly metamorphosed and as such it is rather difficult to classify them according to zone, grade or facies of metamorphism that these rocks attained during different episodes of metamorphism. However, an endeavour has been made to assign them to grade or facies of metamorphism according to their present mineral assemblages based on the petrographic study (Chapter 4). As this work is mainly confined to the
structural aspects of the rocks and also keeping in view their grade of metamorphism which is low to medium, the chemical analysis of the rocks has not been attempted.

5.2 GRADE AND FACIES OF METAMORPHISM

The study of metamorphites of the area under investigation reveals that the older rocks (Jutogh) which were initially at greater depth display a higher degree of metamorphism than the rocks (Chails) that were at shallower depth (cf. Becke, 1903, 1913; Goldschmidt, 1911, 1912; Grubenmann, 1910; Grubenmann & Niggli, 1924). It is evident that depth of burial, in the slowly subsiding Himalayan geosyncline (Pande, 1967) has played an important role during the metamorphism of these rocks. Therefore pressure and temperature were the main controlling factors for the metamorphic configuration of different rock units of the allochthons (Chapter 4). The mineral assemblages of Jutogh rocks, in general, indicate that they belong to meso-grade of metamorphism while that of Chails to epi-grade (Niggli, 1924).

The metamorphites of the area cannot be classified or mapped strictly according to Barrovian zones of metamorphism (Barrow, 1893, 1912; Tilley, 1925; Harker, 1950). The sharp demarcation of isogrades or establishment of gradual increase
or decrease in metamorphism is not feasible in the Arki-Jutogh area because of the following reasons:

a) The rocks have a polymetamorphic character in which the impacts of earlier episodes have been modified by the later ones.

b) Intense deformation and later cataclasis (thrusting) has resulted in wide retrogression of the progressive metamorphic effects.

c) The presence of large thickness of rocks such as quartzite and less so of marble which invariably show only textural modifications. Therefore, a gradual change in metamorphism in these rocks is not feasible to determine.

d) The metamorphites belong to the allochthonous unit which makes the problem more arduous, for their depth of burial is not possible to ascertain.

The concept of metamorphic facies to designate the mineral assemblages was formulated by Goldschmidt (1911) and Eskola (1914). Eskola (1915) proposed the term "metamorphic facies" to include any association of metamorphic rocks within which there is a constant correlation between
mineral and chemical composition. The concept was further elaborated by Eskola (1920, 1932 and 1939) and advanced by Turner (1948) and Turner and Verhoogen (1960). The main object of facies classification of metamorphic rocks is to have a clear understanding of conditions of metamorphism under which rocks of different composition at a given P and T conditions, acquire a definite set of minerals (Turner, 1948).

During the last decade, the facies were divided into subfacies (Fyfe et al., 1958; Turner and Verhoogen, 1960) to include a wide range of diversification in metamorphic mineral assemblages. This concept of subfacies did not find favour and was criticized as having become both confused and cumbersome (Lambert, 1965). Consequently, Fyfe and Turner (1966) and also Turner (1968) withdrew the concept of subfacies. The use of subfacies has, however, been retained by Kinkler (1967). Fyfe and Turner (1966) proposed the following definition of facies, "a metamorphic facies is a set of metamorphic mineral assemblages repeatedly associated with one another in space and time, such that there is a constant and therefore predictable correspondence between the mineralogy of each rock and its bulk chemical composition".

It has been observed that individual metamorphic terrain shows a peculiarity in mineral assemblages (Miyashiro,
and thus each metamorphic area is characterized by a definite "facies series" (Miyashiro, 1961). The study of mineral assemblages and their optical characters (Chapter 4) shows that the metamorphites of the area are referable to the following facies (Pyfe and Turner, 1966; Turner, 1968; also see Table 5.1).

1. Greenschist facies
2. Greenschist-amphibolite transitional facies
3. Amphibolite facies

The study of Jutogh and Chail metamorphites from different parts of the Simla Hills (Pilgrim and West, 1928; Kanwar, 1965, 1967; Bisaria, 1970; Bahajan, 1971; Virdi, 1971) shows that these rocks have suffered a kyanite-sillimanite type of metamorphism. This suggests that the metamorphites of the Arki-Jutogh area may be referred to Barrowian type facies series.

In general, the grade of metamorphism increases towards Jutogh town and this area represents the core of a major recumbent fold (F1). It is also notable that the axis of Jutogh Synform (F2) runs through this region. The facies and grade of metamorphism encountered in the area are given in Table 5.1.
### Table 5.1 Relationship between the depth zones, index mineral zones and metamorphic facies in the Arki-Jutogh area.

<table>
<thead>
<tr>
<th>Depth Zones</th>
<th>Mineral Zones</th>
<th>Metamorphic Facies</th>
<th>Assemblages in the Arki-Jutogh Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotite Zone</td>
<td>Chlorite Zone</td>
<td>Green schist Facies</td>
<td>Qtz-chl</td>
</tr>
<tr>
<td>Almandine Zone</td>
<td>Biotite Zone</td>
<td>Epidote-amphibolite Facies</td>
<td>Qtz-chl-mis-ab.</td>
</tr>
<tr>
<td>Biotite Zone</td>
<td>Almandine Zone</td>
<td>Amphibolite Facies</td>
<td>Qtz-chl</td>
</tr>
<tr>
<td>Meso-Zone</td>
<td>Staurolite Zone</td>
<td>Amphibolite Facies</td>
<td>Qtz-chl-mis-ab.</td>
</tr>
</tbody>
</table>

**Abbreviations:** Qtz: Quartz, Cl: Chlorite, Ca: Calcite, Act: Actinolite, Mus: Muscovite.
5.3 GREENSCHIST FACIES

The metamorphites of Chail Formation and in part that of Jutoghs belong to greenschist facies. The Chail Formation exhibits the following mineral assemblages:

**Phyllites**
- Quartz-chlorite-muscovite
- Quartz-chlorite-muscovite-albite

**Schists**
- Quartz-chlorite-muscovite-chloritoid
- Quartz-muscovite-biotite-(chlorite)

The mineral assemblages (1 to 3) belong to the lower part of greenschist facies whereas assemblage (4) belongs to the higher grade (biotite) in the same facies (cf. High pressure greenschist facies group, Zwart, 1967). Production of biotite in (4) may be attributed to the reaction of muscovite and chlorite (Sünkler, 1967, p. 99).

3 Muscovite + 5 Prochlorite →
3 Biotite + Al-rich chlorite + 7 Quartz + 4 H₂O (1)

3 K₁₂ [ (OH)₂/Si₃Al₁₀ ] + 5 (Mg,Fe)₄ [ (OH)₂/Si₂O₈ ]
→ 3 K(Mg,Fe)₃ [ (OH)₂/Si₃Al₁₀ ]
+ 4(Mg,Fe)₄ [ (OH)₂/Si₂O₈ ] + 7 SiO₂ + 4 H₂O
It may be noted that chlorite remains stable along with biotite and muscovite in the above reaction. But in the present assemblage both the chlorite and muscovite are the alteration product of biotite.

Hietanen (1967, p. 196) gives another equation for the formation of biotite when iron is available:

\[
\text{Chlorite + Muscovite + Hematite} \rightarrow \text{Biotite} + \text{H}_{2}\text{O} + \text{CO}_2 \quad \ldots \quad (ii)
\]

The chloritoid, a constituent mineral of assemblage (3) quartz-chlorite-muscovite-chloritoid, is of restricted occurrence, analogous to staurolite in the amphibolite facies. The special chemical factors governing the origin of chloritoid are of a large Fe/Mg ratio, a relatively high Al content (Turner, 1968) and simultaneously low K, Na and Ca content (Hoschek, 1967 vide Winkler, 1967). Hoschek (op. cit.) further suggests that the above mentioned bulk chemistry required for the formation of chloritoid, is seldom realized in the rocks and this leads to the general absence of chloritoid from metamorphic assemblages.

Chloritoid in the area (assemblage 3) occurs in association with muscovite and chlorite and not with biotite. It has been said that the mineral is restricted to chlorite
zone and does not reach the realm of Miotite zone (Williamson, 1953; Snelling, 1957). Barth (1962, p. 315) states that the position regarding chloritoid is uncertain and it is possible that it requires special conditions for its development, perhaps higher temperature than in the usual greenschist facies and special pressure conditions. Turner (1968, p. 270) and Winkler (1967, p. 95) have placed the mineral in the chlorite zone of greenschist facies.

In the assemblage (3), the chloritoid shows post-tectonic development over the schistosity $S_2$ (Petrography, Chapter 4). It is sometimes helicitic with micaceous inclusions and shows $S_4$ continuous with $S_e$. This leads to suggest that the chloritoid is not syn-tectonic but developed later perhaps during episode IV of metamorphic history (Sec. 5.7).

The assemblages of Jutosh metamorphites which belong to the greenschist facies are:

- Carbonaceous Schist: Quartz-muscovite-chlorite-graphite (5)
- Marble: Calcite-actinolite (-tremolite)-quartz-(graphite) (6)

The assemblage (5) of carbonaceous schist consisting of chlorite and minor amount of biotite belongs to the lower
part of greenschist facies. Chlorite occurs as alteration product of biotite. Likewise, in assemblage (6), the actinolite - tremolite show their correspondence to the greenschist facies. The tremolite develops in the marble by decarbonation reactions with or without water. Bowen (1940) gives the following reactions when the role of water is negligible:

\[
3 \text{Dolomite} + 4 \text{Quartz} \rightarrow \text{Tremolite} + 2 \text{Calcite} + 4\text{CO}_2
\]  

\[\text{... (iii)}\]

When role of water is taken into account, the following reaction takes place according to Tilley (1943):

\[
3 \text{Dolomite} + 4 \text{Quartz} + 6\text{H}_2\text{O} \\
\rightarrow \text{Talc} + 3 \text{Calcite} + 3 \text{CO}_2
\]  

\[\text{... (iv)}\]

Regarding the sequence of steps of reactions (iii) and (iv) there prevails some disagreement. It depends upon many factors controlling the reaction and has been discussed at length by Turner (1967). It may be mentioned here that talc has not been observed in the marble of Jutogh (assemblage 6). It, therefore, implies that metamorphism of impure limestone occurred in water deficient conditions.

The en-diorite (foliated variety) and some ortho-amphibolites occurring in the area show the development of
hornblende, chlorite, epidote, actinolite and plagioclase with metastable relicts of augite and belong to greenschist facies.

It may be mentioned here that assemblages (5) and (6) of carbonaceous schist and marble respectively, belonging to greenschist facies are found to occur near the Jutogh Thrust where the Jutoghs have come in contact with the Chails. These rocks (carbonaceous schist and marble) are also repeated near Jutogh town due to recumbent folding and show a higher degree of metamorphism as indicated by the presence of biotite porphyroblasts in carbonaceous schist and diopside in the marble. The biotite porphyroblasts and diopside are partly altered to chlorite and tremolite respectively. Further, it seems that the development of chlorite in the assemblages (5) and (6) is the result of degeneration of biotite, and not due to progressive regional metamorphism.

The general characteristics of greenschist facies that have been followed above are after Turner (1968). The greenschist facies includes the common products of low grade regional metamorphism represented by completely recrystallised, usually well foliated rocks in the Carrovan zones of chlorite and biotite. The greenschist facies rocks have the characteristic minerals — albite, white micas, biotite (restricted to higher grade), prochlorite with a relatively
high Fe$^{2+}$/Fe$^{3+}$ ratios, epidote, dolomite (in silica deficient rocks) and in magnesian rocks talc and antigorite. The principal white mica is muscovite (the 2K polymorph), characteristically having a phengitic character. Chloritoid is found in rocks high in ferrous iron and in aluminium.

5.4 GREENSCHIST-AMPHIBOLITE TRANSITIONAL FACIES

The term "greenschist-amphibolite transitional facies" has been retained in the present work because the rocks belonging to this subfacies show a distinct recognizable unit in the present area.

The following mineral assemblages of Jutogh metamorphites belong to transitional facies (of Turner, 1968):-

Quartz-muscovite-biotite ... (7)
and Quartz-biotite-muscovite(- garnet) .. (8)

In the assemblages (7) and (8), incipient or little development of almandine is seen. The first appearance of garnet qualifies the assemblages to be placed equivalent to the greenschist-amphibolite transitional facies. The assemblage (7) represents a quartz schist in which foliation is strongly developed, while assemblage (8) is a mica schist showing tiny crystals of almandine. Chlorite is seen
associated with micas in some sections (as an alteration product of biotite).

The boundary between the greenschist and amphibolite facies is represented by assemblages of both the upper greenschist facies and the lower amphibolite facies. Such assemblages are referred to as 'Greenschist-amphibolite transitional facies'. It is equivalent to epidote-almandine-amphibolite facies of Eskola (1939) and Turner (1943), and quartz-albite-epidote-almandine subfacies of greenschist facies of Turner and Verhoogen (1960, p. 533) and Winkler (1967, p. 95).

According to Turner (1968, p. 303, 304), the geological evidence suggests that the transition from the greenschist to amphibolite facies represents a P-T field in which a number of the critical equilibrium curves are indeed closely spaced and do intersect each other. This is the explanation suggested by Turner (1968) for the observed differences in the field sequence in which certain critical minerals, notably almandine, plagioclase and hornblende, appear in transitional facies in different individual terrains (Turner, 1968). The biotite becomes frequent and almandine makes its first appearance to remain stable throughout the whole range of metamorphism.
5.5 AMPHIBOLITE FACIES

The Jutogh metamorphites occurring around Jutogh hill, are characterized by the following assemblages of amphibolite facies:

- Garnetiferous-mica schist: Quartz-almandine-biotite-muscovite ... (9)
- Marble: Calcite-diopside-quartz-(-tremolite) ... (10)
- Amphibolite: Hornblende-plagioclase-epidote-garnet ... (11)

The Jutogh metapelites and metasemipelites of the area, especially of the Mica Schist Member, show a prolific development of almandine with the assemblage (9), quartz-almandine-biotite-muscovite. In this assemblage staurolite has not been observed but specific compositional requirements for its development do not debar the assemblage to be included in the amphibolite facies. The almandine garnet attains a pea-size and is very abundant. Beyond the almandine isograd in the Barrovian zonal sequence, regionally metamorphosed rocks enter the amphibolite facies (Turner, 1968). Turner and Verhoogen (1960) proposed the following assemblages for low temperature amphibolite facies corresponding to staurolite zone in the
Barrovian zonal sequence:

Quartz-staurolite-almandine-muscovite-plagioclase-
epidote

and Quartz-almandine-muscovite-biotite-plagioclase
(- epidote)

These assemblages closely resemble the assemblage (9) of Jutoghs and thus the latter's inclusion into amphibolite facies is justified. The mineral staurolite, depending on chemical composition of original sediments, is restricted in its occurrence and its absence does not disqualify the assemblage (9) of Jutoghs for its correspondence to the lower amphibolite facies. The development of staurolite in metamorphites is controlled by the chemical composition of the original rock as is the case with chloritoid. Such a restricted composition may not be realized in the rocks (Hoschek, 1967).

Garnet may be formed by the following reaction:

$$(\text{Mg, Fe, Mn})_9 \text{Al}_3\text{Si}_{18}\text{O}_{22}(\text{OH})_2 + 4 \text{SiO}_2$$

Chlorite Quartz

$\rightarrow 3 (\text{Mg, Fe, Mn})_3 \text{Al}_2\text{Si}_3\text{O}_{22} + \text{H}_2\text{O}$$

Almandine

...... (v)

and also by:
The assemblage (9), quartz-almandine-biotite-muscovite, of Jutoghs is associated with marble and metabasics (assemblages 10, 11) which undoubtedly belong to the amphibolite facies. This further supports the contention of the author in considering the assemblage (9) as equivalent to the lower amphibolite facies. The marble and amphibolite are represented by calcite-diopside-quartz (-tremolite) (10) and hornblende-plagioclase-epidote-garnet (11) assemblages respectively. The appearance of diopside in marble (10) and plagioclase of An$_{30}$ variety in amphibolite (11) clearly demonstrate their correspondence to the amphibolite facies.

Diopside may be formed by the following reaction (Bowen, 1940):

\[
\text{Tremolite} + 2 \text{Calcite} + 2 \text{Quartz} \\
\rightarrow 3 \text{Diopside} + 2 \text{CO}_2 \\
\text{..... (vii)}
\]

5.6 PRESSURE AND TEMPERATURE CONDITIONS DURING METAMORPHISM

The greenschist facies as used in this section also includes the greenschist-amphibolite transitional facies. It
may also be pointed out that the rocks we are dealing with (Jutoghs and Chails) are polymetamorphosed and were not under a particular set of pressure and temperature conditions during the various metamorphic episodes they witnessed, instead they were under a variable P & T conditions. Therefore, P and T conditions that are deciphered in the following pages are related to the highest degree of P and T values they achieved (episode IV, Sec. 5.7).

Fyfe et al. (1958) have shown that a possible range compatible with experimental data on the stability of greenschist minerals, and taking into account the general lack of metamorphism in many deeply filled geosynclines is 300° to 500°C and \( P_{H_2O} \) equal to 3 to 8 Kb. Barth (1962) has given a temperature range of 100°-400°C for the greenschist facies. Winkler (1967) concludes that experimental work performed under near natural conditions indicate a range of 400°-550°C and 1-5 Kb for greenschist facies, above which it gives way to the amphibolite facies. Velde (1964) has shown that appearance of chlorite facies minerals commence in the vicinity of 300°C (cf. Fyfe et al., 1958). Considering the mineral assemblages of the greenschist facies of the Arki-Jutoghs area, which they now exhibit, it may be suggested that the rocks in question underwent metamorphism under a temperature of 300°-500°C and a pressure of a few Kb.
METAMORPHIC FACIES IN RELATION TO $P_t$ (=$P_{H2O}$) AND $T$. ALL BOUNDARIES GRADATIONAL.

(after Turner 1968)
The amphibolite facies covers a temperature range of 550° to 750°C and pressure normally between 4 and 8 Kb (Turner and Verhoogen, 1960). Turner (1968, p. 131) suggests a temperature of over 500°C and $P_{H_2O}$ of a few Kb for the beginning of development of amphibolite facies. Winkler (1967) gives a temperature of 550°C for the beginning of amphibolite facies.

For the formation of lower amphibolite facies, as is the case we are dealing with in the Arki-Jutogh area, it may be suggested from the above data that the metamorphism of the Jutoghs occurred at or a slightly higher temperature than 550°C and a pressure over 5 Kb.

The P and T conditions of metamorphic facies in general are depicted in Fig. 5.1.

5.7 METAMORPHIC HISTORY

The metamorphic history of the rocks under consideration is deciphered from a detailed study of their field, mesoscopic and microscopic characters. The results reveal that the metamorphites of the Chail and Jutogh Formations have witnessed five major episodes of metamorphism. The imprints of these episodes are recorded in the rocks by growth of new minerals.
over the earlier ones, retrogression of metamorphic minerals and the relation of the minerals with the structures produced during a metamorphic episode. Thus the mineral assemblage formed during one episode became unstable in the following one and was adjusted to P and T environments by the growth of new stable minerals. These changes were spread over a great span of geological time and are related to Himalayan orogeny. In the following pages an attempt has been made to unravel the various episodes of metamorphic history of the rocks under investigation. A summary of metamorphic history is also given in a tabular form (Table 5.2) for ready reference.

5.7.1 Episode-I

The first episode of metamorphism in the area pertains to an early metamorphism of controversial nature and age. Although opinions prevail (Pilgrim and West, 1928) regarding the early metamorphism especially of Jutoghs, yet there are no concrete evidences to confirm the exact time when the rocks were metamorphosed. The Caldonian or Hercynian orogenies (cf. Pande, 1967; Pande and Saxena, 1968; and Fuchs, 1968), if at all have affected these rocks, their imprints have been lost during the much stronger metamorphism of later episodes II and IV (see below).
Table 5.2 Metamorphic history of the Jutogh and Chail Formations of Arki-Jutogh Area

<table>
<thead>
<tr>
<th>Metamorphic Episodes</th>
<th>Minerals Developed</th>
<th>Related Planar Structure</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Episode-I</strong></td>
<td>Quartz-I</td>
<td>Bedding schistosity $S_1$</td>
<td>Early foliation (bedding schistosity $S_1$)</td>
</tr>
<tr>
<td>Early (Load ?) Metamorphism (Time and place controversial)</td>
<td>Chlorite-I, Muscovite-I (probably)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Episode-II</strong></td>
<td>Quartz-II</td>
<td>Main foliation or schistosity $S_2$</td>
<td>Appearance of Biotite-I, Garnet-I. Main impact on mineral assemblages, adjustments and penetrative axial plane fabric $S_2$.</td>
</tr>
<tr>
<td>Regional progressive metamorphism and intense tectonism</td>
<td>Muscovite-I, Biotite-I, Garnet-I</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Episode-III</strong></td>
<td>Chlorite-II, Ferrimuscovite-I</td>
<td>-</td>
<td>Widespread retrogression and degeneration of high grade minerals biotite-I and garnet-I to chlorite-II and ferrimuscovite-I.</td>
</tr>
<tr>
<td>Interphase retrogression between episodes II and IV</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Contd......
### Episode-IV

| IVa Geothermal metamorphism | Porphyroblasts of Biotite-II, Garnet-II, Chloritoid | Degeneration of biotite-II and garnet-II to chlorite-III, Biotite also alters to F.M.-II. Chlorite-III and F.M.-II are superimposed on S₂; S₁ and Sₑ continuous. |
| IVb Hydrothermal metamorphism | Chlorite-III, Ferrimuscovite-II | Degeneration of biotite-II and garnet-II to chlorite-III, Biotite also alters to F.M.-II. Chlorite-III and F.M.-II are superimposed on S₂; S₁ and Sₑ continuous. |

### Episode-V

| Va Thrusting and Diaphthoresis | Chlorite-IV | Crenulation cleavage | Diaphthoresis and mylonitization with production of phyllonites in metamorphites. |
| Vb Late cataclasis | Chlorite-IV | Crenulation cleavage and fracture cleavage | Production of chlorite-IV along crenulation cleavage S₃ in Va and Vb. |
Many workers (e.g. Pande et al. 1963; Das and Pande, 1964-65; Kumar, 1968; Mahajan, 1971; Virdi, 1971) have expressed that early metamorphism and/or load metamorphism have given rise to bedding schistosity. The metamorphism brought about by deep burial of sediments (vertically directed pressure) and rise in temperature constitutes load or static metamorphism (Daly, 1917) or burial metamorphism (Winkler, 1967). Turner (1948), however, expressed doubts if the load could alone bring about any significant metamorphic changes in the rocks.

The metamorphites of the area, especially the fine-grained ones, sometimes show a rudimentary early foliation (S<sub>1</sub>). This early foliation (S<sub>1</sub>) may possibly represent the bedding schistosity and thus a relict structure of effects of episode-I. Possibly quartz-I, chlorite-I were formed during this phase.

5.7.2 Episode-II

The second episode is the most powerful in the metamorphic history of the Jutogh and Chail metamorphites and it is during this episode that the rocks acquired their most dominant features which were modified by later episodes. This episode is marked by dynamothermal metamorphism and intense tectonism. The rocks developed metamorphic assemblages of
low- to medium-grade (greenschist-amphibolite facies) with the production of a strong cleavage ($S_2$) and formation of quartz-II, muscovite-I, biotite-I and garnet-I.

The strong foliation ($S_2$) developed during this episode is essentially an axial-plane schistosity belonging to $F_1$ fold structures (recumbent or reclined folds). The rotated inclusions in garnet and axial-plane schistosity with lineations testify that metamorphism and tectonism were synchronous in nature. Thus, this episode (II) represents a low to moderate temperature and high pressure metamorphism. The first phase of Himalayan orogeny was accompanied with this episode of regional metamorphism.

Not only the Jutoghs (as advocated by Pilgrim and West, 1928) but both the Jutogh and Chail Formations underwent recumbent folding and associated regional metamorphism. This is based on the fact that both the formations exhibit the same structural and metamorphic features (see Chapters 4 and 6).

During the episode-II the basic rocks developed a foliation ($S_2$) accompanied by degeneration of pyroxene to hornblende and actinolite (uralitization) and more basic plagioclases into oligoclase-andesine and epidote (saussuritization).
5.7.3 **Episode-III**

Following the regional metamorphism and recumbent folding ($F_1$), the rocks were subjected to widespread regional retrogression. It is believed that the Himalayan geosynclinal sediments were uplifted above the zone of plastic deformation, and with the decrease in temperature and release of stresses, the degeneration of biotite-I and garnet-I into chlorite-II and iron oxide took place (Figs. 4.2, 4.3; Pl. X c,d). The biotite-I which defined the foliation ($S_2$) degenerated into chlorite-II and ferri-muscovite-I which lies parallel to $S_2$ along with magnetite and relics of biotite.

This episode represents an interphase retrogression between the episodes II and IV (described below).

5.7.4 **Episode-IV**

The episode-IV represents a phase of static metamorphism of geothermal (IVa) nature followed by a hydrothermal phase (IVb). The partial recrystallization of earlier metamorphic assemblage with least effect of stress marks the geothermal metamorphism. The new minerals that were produced and superimposed on the main foliation ($S_2$) include garnet-II, biotite-II and chloritoid.
Garnet-II occurs as porphyroblasts superimposed on the foliation ($S_2$) in which $S_i$ and $S_e$ are continuous (cf. Saxena, 1964). It also occurs as overgrown on garnet-I to produce zoned or 'garnet-in-garnet' structure (Das and Pande, 1963-64) which are indicative of polymetamorphic nature of the rock containing them (Rast, 1965; Roy, 1965; Saxena and Janardhan, 1967; and Hietanen, 1968). Biotite-II occurs as small idioblastic flakes or as porphyroblasts (Fig. 4.3) superimposed over the foliation ($S_2$). Flakes or porphyroblasts of biotite-II have no preferred arrangement and thus do not form any planar fabric whatsoever.

The chloritoid occurring in the assemblage quartz-chlorite-muscovite-chloritoid of Chail Formation is superimposed over the schistosity $S_2$. It is sometimes helicitic with micaceous inclusions and shows $S_i$ continuous with $S_e$. This leads to suggest that chloritoid is not syn-tectonic. It seems that the mineral developed during the episode-IVa of metamorphism.

The lack of foliation or random growth of minerals developed in episode-IV and the absence of any disturbance caused to foliation ($S_2$), show that pressure played a very passive role during this episode (IVa) of metamorphism. Thus it is suggested that the metamorphism of episode IVa was
essentially of geothermal nature which neither disturbed the earlier planar fabric nor imposed any other on it. The widespread migmatization in the Jutogh and Chail Formations in other areas such as Narkanda (Virdi, 1971) may belong to this episode. It is probable that the heat required for geothermal metamorphism was supplied by magmatic body (Pande, 1967; Pande and Saxena, 1968).

The episode IVb pertains to hydrothermal alteration of minerals. Thus biotite-II and garnet-II porphyroblasts are altered completely or partly to chlorite-III. The chlorite-III porphyroblasts are superimposed on the foliation $S_2$ in which $S_1$ and $S_6$ are seen continuous (Fig. 4.3; Pl. XI a). Likewise ferrimuscovite-II occurs as interleaved with reddish brown biotite-II. The former occurs as an alteration product of biotite-II.

5.7.5 Episode-V

This episode represents dislocation metamorphism in which the stress played a dominant role. The episode may be subdivided into two: Va - in which large scale thrusting took place and Vb - pertaining to late cataclasis.

The rocks in the area were subjected to intense thrusting in Post-Oligocene (i.e. Post-Dagshais) in which
Jutogh and Chail metamorphites moved as one unit to rest over the parautochthon. During these movements, a general slipping between the beds prevailed (cf. Auden, 1934). There developed zones of retrogression or diaphthoresis along intense movements (cf. Becke, 1909, vide Knopf, 1931) in the rocks which resulted in mylonitization and retrogression of biotite and garnet to chlorite-IV. According to Schwartz and Todd (1941), ".....the change from biotite to chlorite is often cited as a retrograde change. This requires abundant water as shown by the following comparison":

\[ K_2(OH)_4 \cdot (Mg,Fe)_6 \cdot (AlSi_3O_{10})_2 = (OH)_{16} \cdot Al_{4}Mg_{10}Si_{6}O_{22} \]

<table>
<thead>
<tr>
<th></th>
<th>Biotite</th>
<th>Chlorite</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O</td>
<td>4.5</td>
<td>12.19</td>
</tr>
</tbody>
</table>

Similarly a change from garnet to chlorite, oligoclase to sericite also require an increase in H2O content. However, Turner (1948) expressed that hydrothermal solutions play a limited role in such transformations.

Thus the decline in temperature and release of stresses with some hydrothermal activity must have been the governing factors for widespread diaphthoresis. These changes are synchronous with phase-II of tectonic history (Chapter 7).
### Table 5.3 Mineral paragenetic sequence in metamorphites of Arki-Jutogh Area

<table>
<thead>
<tr>
<th>Rock Formation</th>
<th>Metamorphic Facies</th>
<th>Greenschist Facies</th>
<th>Transitional Facies</th>
<th>Lr. Amphibolite Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mineral Zones</td>
<td>Chlorite Zone</td>
<td>Biotite Zone</td>
<td>Staurolite Zone on</td>
</tr>
<tr>
<td></td>
<td>Minerals of the area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metapelites, metamorphic and carbonaceous schist.</td>
<td>Graphite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marble</td>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chlorite</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Muscovite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biotite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Garnet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Epidote</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Iron ores</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chail Formation</td>
<td>Calcite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tremolite-actinolite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diopside</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metapelites and metamorphites</td>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chlorite</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Muscovite</td>
<td></td>
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<tr>
<td></td>
<td>Chloritoid</td>
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<tr>
<td></td>
<td>Biotite</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Iron ores</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The late cataclasis includes the structures formed in the rocks after F3 folding and are referred to as late F3 (or late phase III tectonic) structures. They include strain-slip or crenulation cleavage (S3), shear planes along which development of chlorite has been observed (Pl. XI b,c). This has also been designated as chlorite-IV.