CHAPTER VI

M E T A M O R P H I S M

SEQUENCE OF METAMORPHIC EVENTS:

The rocks of the Majkhali area reveal an interesting metamorphic history. The metamorphism of the area has been built up with the help of petrographic studies and the field data. The various lithological types discussed in the previous chapters (III and V) help in building up a succession of connected metamorphic events that affected the area. The rocks have passed through a series of different types of regional metamorphism including granitisation, which initiated in the early geosynclinal stage and culminated with the final upheaval. Obviously the mountain-building forces played quite an important role in the metamorphism of the area.

A careful scrutiny of the structure, texture and mineralogy of the various rock types occurring in the different parts, has established the following sequence of metamorphic events.

I. The earliest metamorphism of the geosynclinal sediments due to vertically directed load, prior to the main upheaval and folding.

II. Regional metamorphism that accompanied the main orogenic upheaval and the isoclinal folding (F_1) of the metasediments.

III. Retrogressive changes brought about by intense shearing along some dislocation planes.

IV. Mineralogical and textural changes during the synformal folding (F_2) of the Almora Nappe.

V. Late hydrothermal changes.

The study has further revealed that the process of migmatisation was intimately connected with the regional metamorphism, and the migmatisation at deeper levels began prior to the main folding, continued during the upheaval, and perhaps outlasted it.

METAMORPHIC EVENT I:

There are evidences to conclude that the geosynclinal sediments had already undergone some metamorphism before they were subjected to the isoclinal folding, the main orogenic deformation. Though mineralogical evidences are few, the preservation of the early schistosity (S), itself intensely folded during (F_1), clearly establishes that the existing schistosity (S_1) of the rocks is not a primary one, but has been derived by the tight folding of an earlier schistosity, thus the S_1 is seen to be of the nature of a cleavage, produced due to microfolding of S. The relicts of this early schistosity are frequent, though scattered, but adequate enough to suggest a prefolding metamorphism.

The author considers that this earliest phase of metamorphism could be a phenomenon connected with the load of the overlying sediments. As Born (1930) has pointed out that the "sediments of deeply sinking geosynclines normally undergo epizonal load metamorphism prior to the folding and in deformational metamorphism which normally accompanies folding, the imprint of load metamorphism may become obliterated or rendered too obscure, to be recognised". The structural evidence in favour of the existence of this early metamorphism is discussed in the Chapter IV.

Under the effect of load, the geosynclinal sediments undergo mineralogical and textural changes, the most striking structural phenomenon being the parallelism between the original bedding and the metamorphic schistosity. According to Milch, Daly and others (Turner and Verhoogen, 1960, p.662) , load metamorphism mainly consists of chemical reconstitution under vertically directed load at temperatures conditioned mainly by depth, and the resulting schistosity develops on account of the "flattening" in the plane normal to the applied load or from mimetic crystallisation of mica and amphiboles with their long axes in the surfaces of maximum ease of growth afforded by sedimentary bedding.

In the study area, the load schistosity (S) is only sparsely preserved, having been obliterated by the subsequent deformations and metamorphism.

METAMORPHIC EVENT II :

The main event of the regional metamorphism synchronised with the large scale isoclinal folding(F_1) of the rocks, and the existing metamorphic characters - structural, textural and mineralogical, to a large extent were impressed upon during this event. This phase of metamorphism was of "progressive" nature. That this metamorphism broadly coincided with the principal deformational episode is clearly established by the fact that the main foliation of the rocks is almost parallel to the axial plane of the isoclinal folding. Though subsequent metamorphic changes have considerably modified the rocks here and there, the main bulk of the rocks still indicate the various characteristics of this metamorphic event.

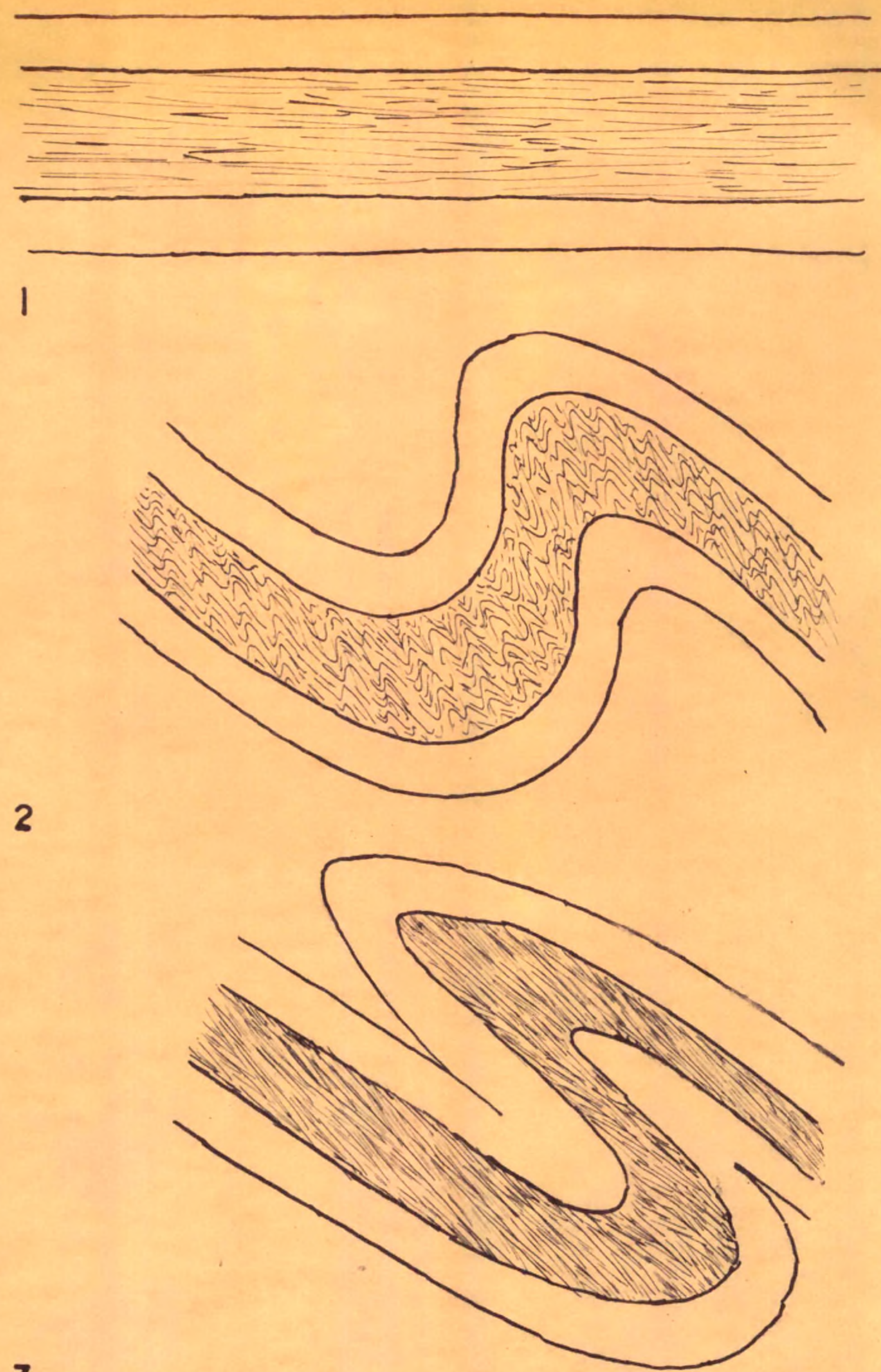
The nature of the metamorphism and its effects on the various rocks of the area, have been briefly described below:-

<u>Pelitic and Semipelitic schists</u>: The imprint of this metamorphism is ideally preserved in those garnet mica schists and siliceous mica schists which have not been serously affected by the subsequent dislocation metamorphism or by the late folding (F_2). In other words, the pelites and semipelites from such places where shearing or crinkling is less intense, still preserve the impress of this regional metamorphism. As already mentioned, the main schistosity of these rocks throughout the Almora Nappe, is the product of this event. The foliation, mainly characterised by a parallel orientation of mica flakes and elongated grains and aggregates of quartz, is seen to be essentially marking the axial plane of the isoclinal folding. This fact is clearly illustrated wherever, the folded psammitic layers or quartzofelspathic veins are seen in the schists. Vashi (1966) and Merh & Vashi (1965) considered this schistosity to be a primary one having developed directly during the metamorphism of the sediments that accompanied the isoclinal folding.

The present study, however, has led the author to conclude that the main schistosity (S_1) of the rocks is itself of the nature of a (? strain-slip) cleavage, having been derived by a very tight microfolding of a pre-existing schistosity (S). In some semipelites, the oblique relation between S and S_1 is clearly made out under the microscope (Fig. 25). It is also evident that this schistosity developed under considerable shearing stress. The elongated patches of quartz grains and the rotation of garnet during growth, amply prove differential slipping of the matrix during metamorphism.

The mineral assemblages typically suggest that they are derived by the regional metamorphism of argillaceous sediments. Quartz, biotite and muscovite are almost always present, while garnet and plagioclase may be present or absent. Broadly speaking these mineral assemblages could be assigned to Almandine zone of Barrow. Whenever chlorite is recorded, it is always a retrograde product after biotite. The relative proportions of quartz and micas, decide whether a rock could be called a pelite or a semipelite. Pelitic schists represent highly argillaceous material while the semipelitic types indicate derivation from sandy shales. In case of semipelites which consist of alternating micaceous and

Fig. 25



Development of S_1 from S

siliceous layers, it is evident that the original mass consisted of rapidly alternating shales and sandstones. Sediments were on the whole restricted in potash content and rich in alumina and silica. The constant presence of biotite suggests that the original sediments were rich in MgO. The presence of almandine is indicative of a high FeO/MgO ratio. Considering the mineralogy and the chemistry of these rocks, the likelihood of the original sediments having a graywacke affinity cannot be ruled out.

Graphite schists: The foliation characterised by the streaks of graphite in these rocks, coincides with S_1 and is obviously a product of isoclinal folding. It is likely that the original sediments that gave rise to these graphitic rocks, consisted of argillaceous material with some carbonaceous content. The author is here tempted to putforth an altogether different mode of origin for the graphite. Some workers (Bose, 1959 and K. Rao and M. Rao, 1965) have suggested that limestones under suitable conditions, metasomatically react with siliceous emanations from the granitic source, and form calcareous silicates of suitable composition. The CO_2 on entering the nearby rocks undergoes reduction (deoxidation) releasing carbon in the process. This mode of origin cannot be ruled out because granitisation had already commenced prior to the folding and metamorphism, and there were ample calcareous layers in argillaceous sediments. Close occurrence of calc-silicate bands and the graphite schists also points out towards the possibility of graphite forming at the expense of $CaCO_3$.

Psammitic rocks: Psammitic rocks are/of the nature of flaggy quartzites. The white compact variety is made up of quartz with some muscovite and microcline. Obviously the presence of microcline indicates that the original sediments were somewhat rich in potash (? arkosic to some extent). The grey and foliated variety somewhat richer in biotite, are quite often garnetiferous. These rocks appear to be the siliceous derivatives of the pelites. The biotite, muscovite and garnet indicate a fair proportion of the argillaceous sediments. For the purposes of metamorphic studies, these psammitic rocks are less interesting, as they do not show much response to the increasing grade of metamorphism.

<u>Calc-silicate rocks</u>: The calc-silicate bands occurring in pelites and semipelites represent somewhat calcareous and magnesian argillaceous sandstones. The presence of clinozoisite, zoisite and tremolite-actinolite typically suggest a medium grade of metamorphism.

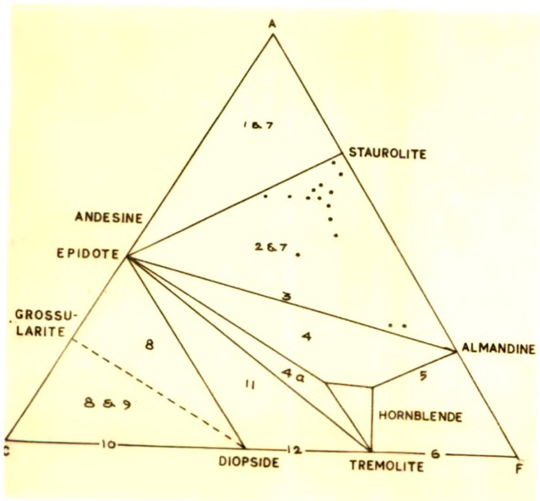
<u>Metamorphic grade and facies</u>:

The petrography of the rocks, indicates a medium grade of regional metamorphism, and on the basis of the mineral assemblages in pelites, semipelites and calc-silicate bands, the rocks could be assigned to the "Almandine zone". The author has prepared the ACF and AKF diagrams of the various rock types (~~Plate 22,~~ Plates 24 to 27) and on the basis of these, the various mineral assemblages have been found to belong to the "Staurolite-Almandine subfacies" of "Almandine-amphibolite facies" of Turner and Verhoogen (1960,p.552). These rocks are formed under conditions of moderate temperature and strong deformation.

<u>Pressure and temperature conditions</u>:

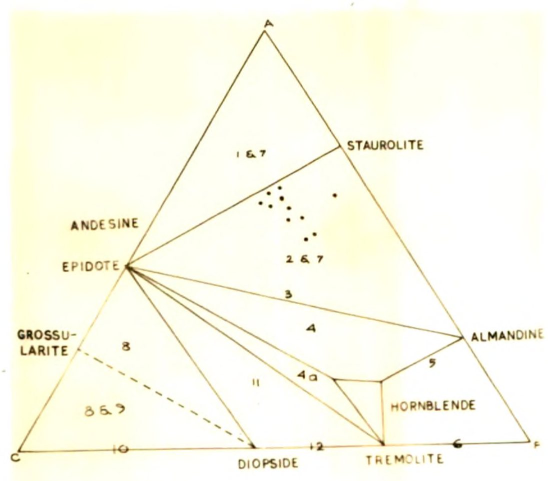
<u>Pressure conditions</u>: The regional metamorphism of the "progressive" type responsible for the development of the above mineral assemblages, constituted an integral

PLATE 24



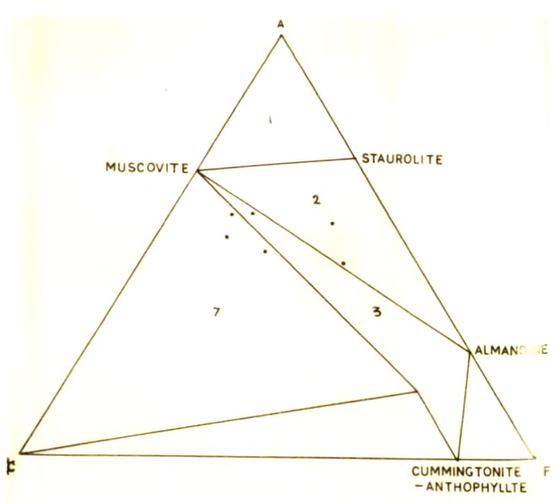
ACF Diagram for pelites and semipelites

PLATE 25A



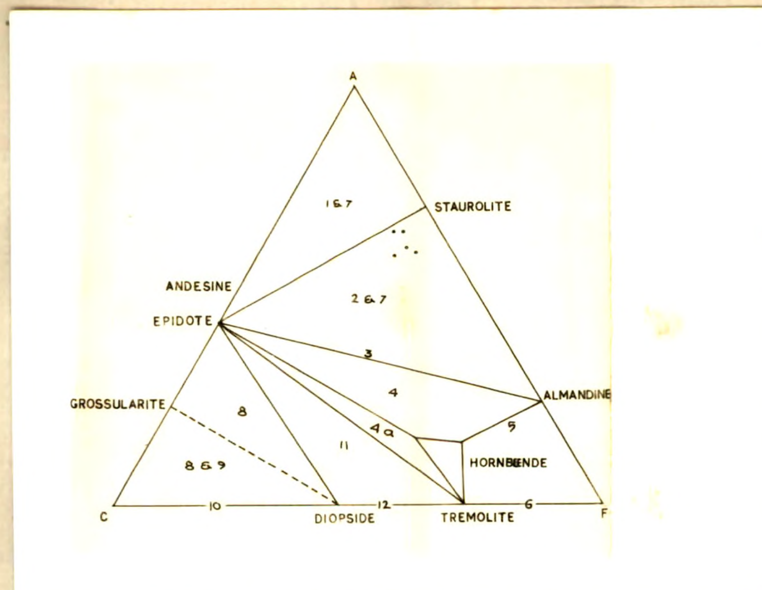
ACF Diagram for migmatites

PLATE 25B



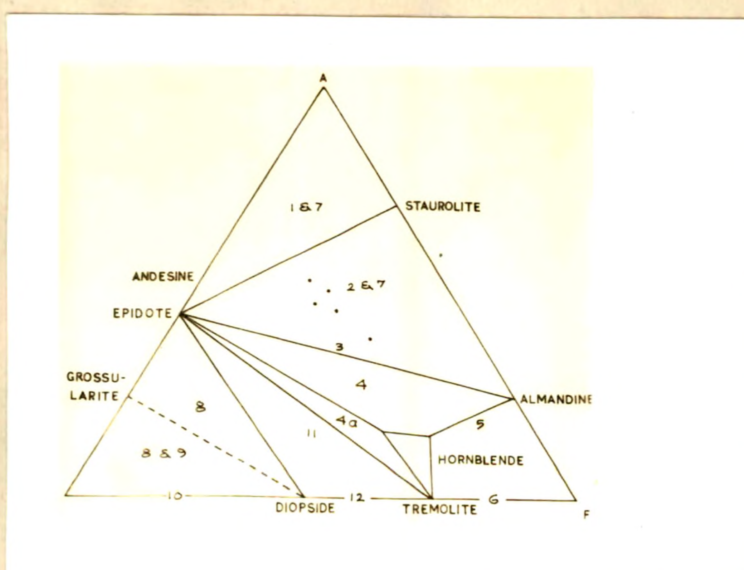
AKF Diagram for migmatites

PLATE 26A



ACF Diagram for psammites

PLATE 26B



ACF Diagram for calc-silicate rocks

part of the orogenic upheaval of the geosynclinal sediments. While the earliest metamorphism (Event I) might have taken place on account of the confining load of the overlying sediments in a sinking geosynclinal basin, their subsequent metamorphism appear to have taken place simultaneously with the main deformation. The present metamorphism was impressed upon the sediments (or to be precise metasediments) during the large scale isoclinal folding. Due to large scale crustal deformation in this region of active orogeny, the geosynclinal sediments were subjected to extreme differential (non-hydrostatic) stresses consisting of tangentially directed compression and shearing. Structural studies have revealed that the process of isoclinal folding ultimately culminated into the thrust (Almora Thrust), and thus the element of strong shearing was all along dominant during the metamorphic transformation. It is clear that the various minerals grew under considerable shearing stress. The growth of mica flakes slightly oblique to the main bedding foliation (S) (feebly preserved in some semipelites only) is indicative of shear. Elongated aggregates of interlocking quartz grains - recrystallised also indicate crushing and recrystallisation. The most conclusive evidence of the differential slipping of the matrix is shown by the spiral inclusions of quartz inside the garnet porphyroblasts. It is thus reasonable to conclude that directed stresses acting on geosynclinal sediments at deeper levels folded them into several reclined isoclinal folds, and the metamorphism that accompanied the deformation gave rise to mineral assemblages that characterise moderately high pressure and temperature. The co-existence of medium plagioclase with epidote in some rocks indicate high load pressure augmented by shearing stress. The depth at which the metamorphism might have taken place, could be 7000 to 10,000 metres, the mineral assemblages characterising the "zone of lower mica schist" (Jungs and Roque, 1952,p. 12-19). A pressure range between 4000 to 8000 bars is suggested by Turner and Verhoogen (1960, p. 553).

Temperature conditions: According to Turner and Verhoogen (1960, p.553), the mineral assemblages of "Almandine-amphibolite" facies indicate a temperature range from 550° to 750°C.

The question as to how such high temperatures are attained in regional metamorphism, is yet to be fully answered. It is difficult to prove that the temperature rise is a consequence of depth of burial and the normal geothermal gradient. Several possible alternatives have been suggested for the source of heat in orogenic evolution: (1) Heat may be introduced by intruded orogenic magmas, either early swarms of diabase or syn- and late orogenic quartzo-felspathic melts. (2) Heat may be evolved by the intense mechanical shearing and deformation of the rocks in orogenic belts. (3) Radioactive decay in the thickened sial in orogenies. (4) Exothermic chemical reactions may play a part. (5) Convection currents in the substratum may displace hot portions of the substratum towards the zones of geosynclines and folded mountains. (6) The net effect of the complex process of folded mountain formation may be exothermic, because this geologic event is a large scale equilibriopetal process (Ramberg, 1945; Van Bemmelan, 1949), aiming at an establishment of thermodynamic and mechanical equilibrium out of the non-equilibrial situation which precedes and causes the orogeny.

But it will be seen that most of the suggested sources are considered inadequate or untenable. As regards the possibility of heat introduced by intruded hot magmas, on many considerations, this assumption is found invalid. "Field and thermodynamic data are in disharmony with the assumption that regional metamorphism is a huge 'contact' reaction zone around hot magmatic melts" (Ramberg, 1952, p.273). According to several theories of folded mountain formation, there is no reason to believe that intrusion of magmas in orogenic zones is the driving force of orogenies. Perhaps the sequence is other way round, the events of orogenic evolution create magmas. During the evolution of orogenies, the temperature rises, and at the peak of the temperature rise, quartzo-felspathic melts occur by refusion of parts of the crust. Thus, there are no reasons for believing that regional metamorphism is chiefly caused by the heat liberated from intruded melts.

Heat generated by the intense mechanical shearing and deformation, or radioactive decay in the thickened sial, does contribute somewhat to the elevated regional temperature in orogenies. But they are certainly not the dominant causes of the rise of temperature.

The author believes that the causes of the heat generation in the orogenic upheaval are quite obscure and in someway related with the complex process of geosynclinal folding - a large scale equilibriopetal exothermic process (Ramberg, 1945; Van Bemmelen, 1949). As Ramberg (1952, p.273) has suitably explained, "it is very likely that the whole sequence of geological processes which result in the folding and rise of folded mountain ranges is a large scale event which proceeds spontaneously, tending to create a stable situation out of the unstable state of affairs of the geosynclinal stage. In the urge of nature to achieve stable equilibrium throughout the parts of the crust (and substratum) which are occupied by the geosyncline, displacement of matter on a small and large scale is crucial. Thus rock matter is displaced mechanically by faulting, folding and plastic creep or flow of solid rocks and flowage of molten magmas. We know also that another kind of material transport is operating, namely, the diffusional migration creating metasomatism and growth of petroblastic rocks in the solid state. This latter kind of material displacement is intense and large scale in deeper sections of folded mountains. During such a lively chemical exchange of rock-making matter, it is inevitable that significant heat effects occur. Since granitization and allied metasomatism largely mean consolidation of enery-rich or activated atomistic particles "at countless points throughout the rock", it is fair to assume that the net effect will be positive. That is, granitization and other kinds of metasomatic replacements should contribute much to the heat required to account for not only the elevated temperature in regional metamorphism but also refusion of acidic magmas.

METAMORPHIC EVENT III:

Retrogressive metamorphism: The progressive phase of regional metamorphism discussed above was followed by a retrogressive metamorphism. Retrograde metamorphism is usually attributed to strong differential stresses aided by hydrothermal solutions. Deformation possibly acts as 'catalytic agent' and triggers off the process of retrogression.

Downgraded rocks are encountered at a few places forming narrow zones of phyllonitic rocks.

At a number of places in the study area, such differential slipping accompanying shearing has not only crushed and granulated the rocks but has also brought down the metamorphic grade, giving rise to narrow zones of phyllonitic rocks.

<u>Textural and mineralogical changes:</u> Texturally, these phyllonitic rocks show intense crushing and granulation resulting into a marked diminution in grainsize and a very strong foliation. Minerals, most affected are biotite, muscovite and garnet. As a result of the retrogressive changes:-

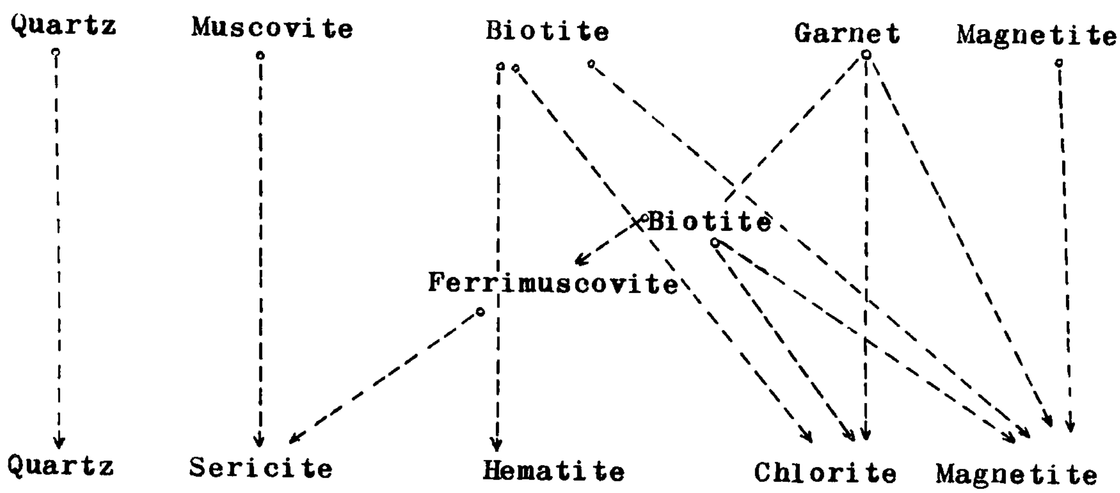
(i) The quartz grains have been finely granulated and often arranged in streaks.

(ii) Plagioclase has disappeared.

(iii) Garnets have been partially destroyed, altering to chlorite.

(iv) Biotite is altered to chlorite and muscovite (sericite) with liberation of iron ores.

Mineralogical changes brought about by the retrogression:



Causes of retrogressive metamorphism: In the present case, the differential stresses have played a dominant role throughout the progressive as well as the retrogressive stages of the regional metamorphism. The deforming stresses which operated during the "progressive" phase continued to be active and ultimately the process of isoclinal folding culminated into the Almora Thrust. It was during this thrusting that a large number of scattered dislocation planes developed parallel to the thrust, and the resultant crushing along these shear planes gave rise to narrow bands of retrograde assemblages. The same stresses which caused the isoclinal folding and the progressive metamorphism, when culminated into the thrust, became the prime cause of retrogression. Vashi (1966) has ideally described the retrogressive effect of the South Almora Thrust. In Upradi area, he found that the rocks in the vicinity of the thrust show interesting metamorphic changes. He found that the thrust has been responsible for the downgrading of the metamorphism of the rocks of the overthrust sheet, characterised by a gradual retrogression of garnet mica schists to sericite-chlorite phyllites near the thrust. In the present case, the retrogression is mainly confined to shear zones only and is rather abrupt and sharp.

<u>Date of retrogressive metamorphism</u>: Retrogression appears to have followed immediately the progressive phase. The progressive phase synchronised with the

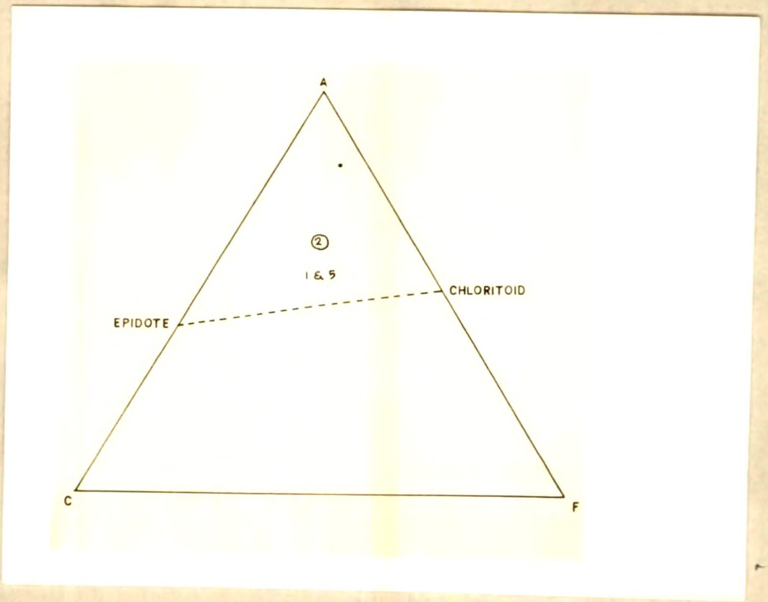
overfolding, while the retrogression was brought about by the intense shearing when the folds culminated into the thrust. Thus it can be inferred with certainty that the time interval between the two metamorphic events was not much and formed an integral part of one single metamorphic cycle.

Phyllonitic rocks can be said to belong to "Quartz-albite-epidote-biotite-subfacies" of "Greenschist facies" of Turner and Verhoogen (1960, p.537). These rocks are retrograde rocks derived from "Almandine-Amphibolite facies" during thrusting (Almora Thrust) (Plate 27).

METAMORPHIC EVENT IV:

Some metamorphic changes coincided with the synformal folding of the Almora Nappe. During this tectonic episode, the rocks (mainly micaceous) of the area developed extensive crinkling, and strain-slip cleavage (S_2). The textural and mineralogical changes brought about during this metamorphic event, have been summarised below.

PLATE 27



ACF Diagram for phyllonitic rock

Textural changes: Extensive microfolding of the schistosity (S_1) is the most striking phenomena. The pelites and semipelites ideally show the effects of this deformation and metamorphism. Depending on the intensity of the deforming stresses, the type of microfolding also varies from place to place. With intense folding, the chevron type microfolds in pelites have broken along the hinges giving rise to cleavage of axial plane type.

In some pelites and semipelites, the deformation has straightaway resulted into a large number of closely spaced shear planes, the slipping along which has given rise to characteristic microfold of the drag type. Less intense stresses have thrown the schistosity into gentle microfolds and puckers. During this microfolding, considerable recrystallisation has taken place. Broadly, following textural changes have been recorded:-

(1) Crushing and granulation of bigger quartz grains, then recrystallization as elongated aggregates of small grains with a tendency to collect on the bends of the microfolds. Some

differential slipping appears to have taken place during this microfolding also, but without any obvious retrogressive change.

(2) Bending and breaking of the mica flakes and then subsequent recrystallization as smaller flakes, characterising the fold pattern.

(3) Growth of elongated mica flakes, single or as tufts along the axial plane of the microfolds.

(4) In less intensely folded rocks (where only gentle puckers have developed) large porphyroblasts of biotite have grown oblique to the main schistosity, very often marking the late axial plane (S_2).

Mineralogical changes: It is interesting to note that during the microfolding, though the rocks were subjected to considerable differential slipping at most places, there has been little retrogression. On the other hand, mineralogically the changes have been somewhat of the 'progressive' nature. Various mineralogical changes brought about by this metamorphism are listed as under:-

(1) Recrystallization of broken quartz grains and mica flakes.

(2) Formation of a new biotite as porphyroblasts. These biotite porphyroblasts have grown during the microfolding.

(3) Formation of new garnet. This garnet appears to have grown during or subsequent to the microfolding. This is very clear from the fact that the fold trends cut across uninterrupted through these late garnet grains. The fold patterns of quartz and magnetite inclusions inside these garnets are identical and in continuation with the folds in the surrounding matrix, and it is quite obvious that these garnets have grown in a static matrix. Some grains along the limbs of the fold show helicoid pattern of inclusions, and it is possible that these garnets also grew during the late microfolding.

Metamorphic conditions: The above mentioned textural and mineralogical changes, clearly indicate that these were brought about by metamorphic conditions - characterised by fairly dominant differential stresses and moderately high temperature. During the synformal folding, the temperature of the rocks of the Almora Nappe must have been considerably raised. While the stresses were due to the folding, the rise in temperature might have been mainly a function of the second phase of orogeny, augmented by the granitization process.

METAMORPHIC EVENT V:

Hydrothermal changes: Pelites and semipelites show some retrogressive changes, mainly brought about by hydrothermal action. Of course, the changes are not widespread. These changes mainly mineralogical, are summarized below:-

(1) Alteration of garnet and biotite to chlorite in pelitic and semipelitic schists.

(2) Alteration of amphibole to biotite and garnet to zoisite in calc-silicate rocks.

These mineralogical changes appear to have taken place, after the main orogenic activity and deformation ceased to be effective. It is apparent that these transformations took place without any shearing, the cause of these changes being mainly late hydrothermal solutions, perhaps connected with the emplacement of late granites, in the neighbourhood.