CHAPTER VI

METAMORPHISM

GENERAL

Metamorphic history as revealed by the present study is quite interesting. Obviously the metamorphism was impressed upon the rocks during the F_1 and F_2 foldings, and the author, after a careful scrutiny of the structure, texture and mineralogy of the various rock types occurring in the different parts of the study area together with a perusal of the work of Vashi (1966), Desai (1968), Patel (1972) and Munshi (1972), has established the following sequence of metamorphic events:

<u>Event I</u> - The earliest metamorphism of the geosynclinal sediments, perhaps due to vertically directed load, during which the early schistosity (S) was formed, prior to the main upheaval and folding. The mineral assemblages of this metamorphic event are not known.

<u>Event II</u> - Dynamic metamorphism that accompanied the main orogenic upheaval and the isoclinal folding (F_1), during which the existing foliation (S_1) developed in the area. Mineral assemblages indicate moderately high pressure-temperature conditions.

<u>Event III</u> - Retrogressive metamorphism brought about by the Almora thrust and its associated dislocations (This event is not recorded in the study area).

<u>Event IV</u> - Metamorphism that synchronised with the F_2 folding brought about mineralogical and textural changes, giving rise to a new schistosity (S_2) of the nature of crenulation cleavage. New muscovite, biotite, chlorite and garnets were formed.

Metamorphic event I

There are numerous evidences to suggest that the geosynclinal sediments had already undergone some metamorphism before they were subjected to the isoclinal folding, the main orogenic deformation. The author suspects that this early metamorphism could be due to load. As Born (1930) has pointed out, 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." Of course, in the present state, the rocks of the area do not give any indication of the true nature of this metamorphism, but author's traverses in the neighbouring areas have revealed that schistose terrains which do not show isoclinal folding, indicate a schistosity which is parallel to the bedding of the quartzites and calc-silicate bands. If these areas could be taken as those showing the earliest foliation, then it is quite possible that the metamorphism was of the load type. In several thin sections of mica-schists, the author came across relicts of this cleavage, the microfolding of which gave rise to the main schistosity. It is clearly established 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 (Fig.IV.27). The mineralogical evidences are few, as they have been obliterated and thus the author is unable to shed more light on this metamorphic event.

Metamorphic event II

The main event of the regional metamorphism synchronised with the large scale isoclinal (reclined) 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. That this phase of metamorphism was of a "progressive" nature and broadly coincided with the principal deformational episode is clearly established by the fact that the main foliation of the rocks shows axial-plane relationship with the F_1 folds. As most of the folds of this generation - both macroscopic and mesoscopic, are of isoclinal reclined type, the schistosity (= axial-plane cleavage) is almost parallel to the bedding of the quartzites, except near the hinges of the folds. Though subsequent metamorphic changes have partially modified the rocks here and there, the main bulk still indicates the various characteristics of this metamorphic event.

The nature of the metamorphism as revealed by the various rocks of the area has been briefly described below.

The garnet mica-schists that are free from the effects of F_2 crinkling have preserved the impress of this dynamic metamorphism very well. As already mentioned, the main schistosity of these rocks throughout the area is the product of this event. The foliation characterised by a parallel orientation of mica flakes, elongated grains and aggregates of quartz, is seen to be essentially marking the axial-plane of the F_1 folding. This fact is clearly illustrated whenever, the folded quartzite layers or quartzo-felspathic veins are seen in the schists. Vashi (1966) and Merh and Vashi (1965) considered this schistosity to be a primary one having developed directly from the unmetamorphosed sediments. But Desai (1968) in the neighbouring Majkhali area and the author in the present area, have come across good evidences to conclude that the main schistosity (S_1) of the rocks is itself of the nature of a crenulation (? strain-slip) cleavage, having been derived by very tight microfolding of a pre-existing schistosity (S). It is also evident that the 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.

Quartz, biotite, muscovite and garnet are almost always present, while staurolite is occasionally present. Whenever chlorite is recorded, it is always a retrograde product after biotite and garnet. The mineral assemblages and the petro-chemistry of these schists indicate their derivation from graywacke to sub-graywacke sequence (Fig.VI.1, Table VI.1). The presence of almandine garnet is indicative of high FeO/MgO ratio. Staurolite has also developed, but sporadically during this metamorphism. Turner and Verhoogen (1960), Winkler (1967) and Turner (1968) are of the opinion that staurolite forms in schists that are rich in Al_2O_3 and FeO, and poor in K_2O. The sporadic presence of staurolite at a few places only appears to be due to local variation in the composition of the original sediments.

The author has not been able to study the graphitic schists in detail. The streaks of graphitic dust

Fig. VI. 1.

Diagram after Butler
(1965, P.180)

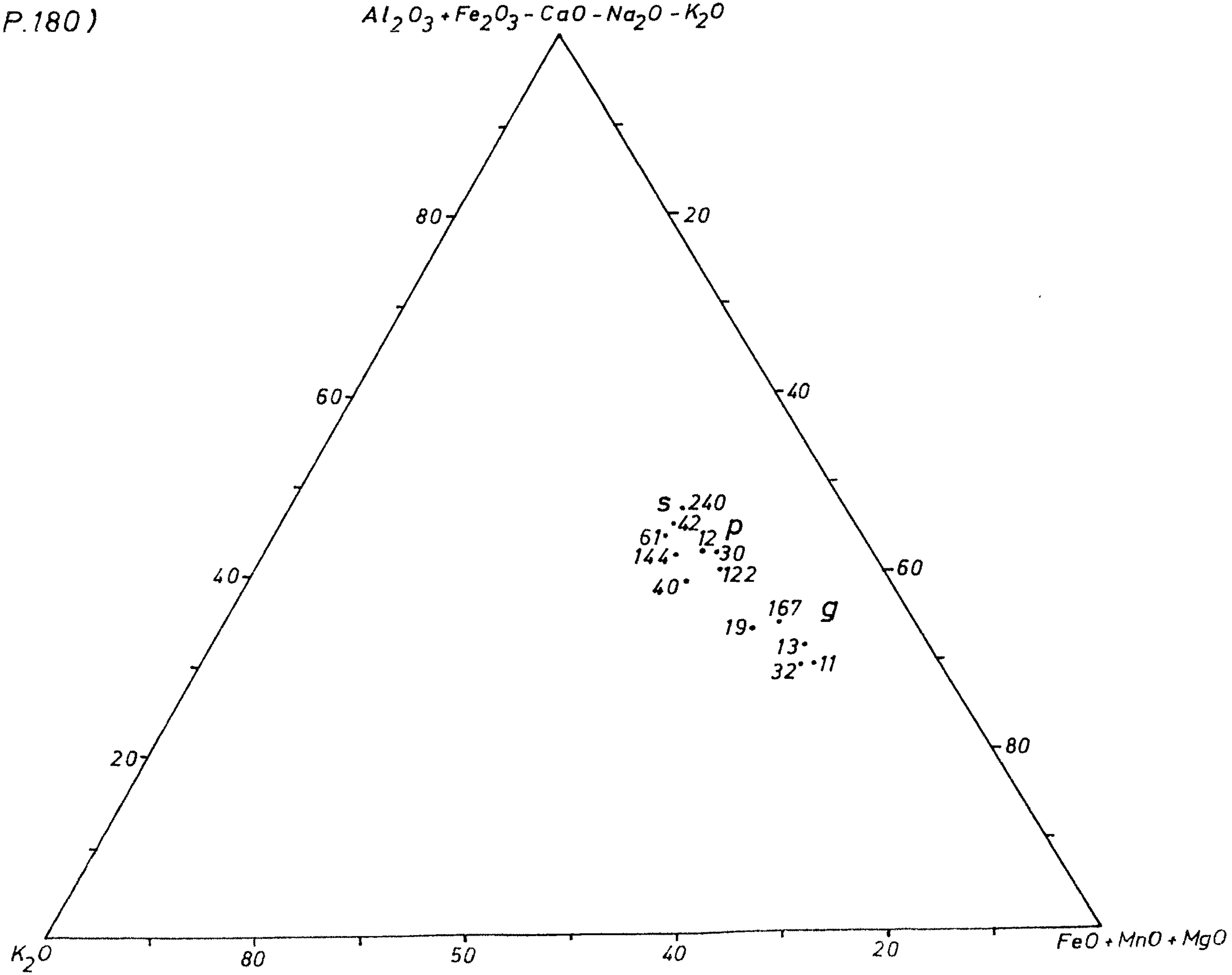

TABLE VI.1

Chemical analyses of mica-schists

Rock type	Garnet mica-schist									Quartzose mica-schist			
Sp.no.	32	13	11	12	30	112	167	240	144	19	40	42	61
SiO_2	64.36	63.26	63.01	61.47	64.89	61.35	63.16	62.18	64.59	67.21	69.11	69.40	71.85
TiO_2	00.92	00.89	00.91	00.82	00.51	00.89	00.78	00.92	00.63	00.43	00.69	01.01	00.76
Al_2O_3	16.05	16.28	15.92	20.17	18.50	19.42	17.25	18.62	18.05	16.52	16.05	17.23	16.00
Fe_2O_3	02.74	02.98	02.59	03.21	03.12	03.12	03.02	04.32	02.92	02.48	01.90	01.59	01.08
FeO	05.82	05.56	05.70	04.50	04.53	04.65	04.92	04.12	04.05	03.90	02.84	02.01	02.52
MnO	02.05	02.11	01.99	00.30	00.32	00.42	01.95	00.26	00.29	00.37	01.98	01.50	00.98
MgO	01.01	01.00	00.95	01.62	01.12	01.60	00.88	01.02	00.58	00.52	00.71	00.65	00.60
CaO	01.90	02.01	01.69	01.90	02.34	01.80	02.65	01.52	01.28	01.82	01.55	01.20	01.01
Na_2O	02.00	02.00	02.49	02.00	02.08	02.25	02.23	02.32	03.09	02.69	01.31	02.05	01.91
K_2O	03.10	02.84	02.67	03.90	03.02	03.65	02.73	03.50	03.64	03.98	03.79	03.08	03.24
P_2O_5	00.05	00.07	00.08	00.03	00.02	00.05	00.10	00.05	00.07	00.05	00.09	00.08	00.05
Total	100.05	100.02	100.01	99.92	100.45	99.20	99.37	98.83	99.19	99.97	100.89	100.81	97.10

AKF values (For Butler's diagram)

Al_2O_3+ Fe_2O_3- CaO- Na_2O- K_2O	29.81	31.64	29.68	42.85	42.28	40.25	34.39	46.66	42.35	33.72	39.02	45.72	44,26
K	12.94	11.71	11.79	11.83	14.54	15.53	12.96	16.02	19.38	15.51	19.55	16.58	18.58
F	57.25	56.65	58.53	41.32	43.18	44.24	52.65	37.32	38.27	50.77	41.43	37.70	37.16

ACF values

A	39.28	40.91	39.01	50.70	49.63	48.19	42.95	54.23	51.96	46.41	48.88	56.56	54.69
C	12.16	12.59	11.36	11.89	15.18	11.60	16.49	10.84	11.27	16.32	13.00	10.60	09.95
F	48.56	46.50	49.63	37.41	35.19	40.21	40.56	34.53	36.77	37.27	38.12	32.84	35.36

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characterises the S_1 foliation and in some sections, its derivation from S is also seen. Under the circumstances, either the graphitic material represents carbonaceous material in the original sediments or it originated by obscure metasomatic processes from the $CaCO_3$ of the associated calcareous sediments. If the latter origin is valid, this transformation must have taken place prior to the F_1 folding.

The flaggy quartzites containing muscovite, biotite and potash felspars suggest the original sediments to be rather arkosic.

The regional metamorphism of the progressive type responsible for the development of the above mineral assemblages, constituted an integral part of the orogenic upheaval of the geosynclinal metasediments. On account of the crustal movement in the region of active geosyncline, the sediments were subjected to extreme horizontally directed (non-hydrostatic) compression and shearing. The present metamorphism was thus impressed upon the sediments during large scale isoclinal folding. Structural studies in the neighbouring areas by Vashi (1966) and Patel (1972), have revealed that the process of isoclinal folding ultimately culminated into the Almora thrust and thus the two structural events i.e. isoclinal folding (F_1) and the thrusting comprised two stages of a continuous deformational episode. This fact taken together with the evidence of slipping and rotation during metamorphism, fully indicates that shearing stresses augmented the pressure conditions of the amphibolite facies metamorphism (Turner and Verhoogen, 1962). The rotated garnet porphyroblasts with spiral inclusions of quartz are the most conclusive evidence of differential slipping.

The various mineral assemblages of mica-schists, quartzose mica-schists and flaggy quartzites, and their intermediate varieties, suggest that the original sediments represented a graywacke-sub-graywacke-arkose sequence. Desai and Merh (1971) by chemical study of the rocks of Majkhali area concluded that they were metamorphosed equivalents of the two sequences, viz. Sandstone-shale and Arkose-graywacke. They felt that the psammitic and pelitic sediments of this area were formed under conditions in which mechanical sorting into arenaceous and argillaceous (possibly mainly micaceous) fractions was highly effective. They assigned the "Staurolite-almandine sub-facies" of "Almandine-amphibolite facies" to the regionally metamorphic rocks.

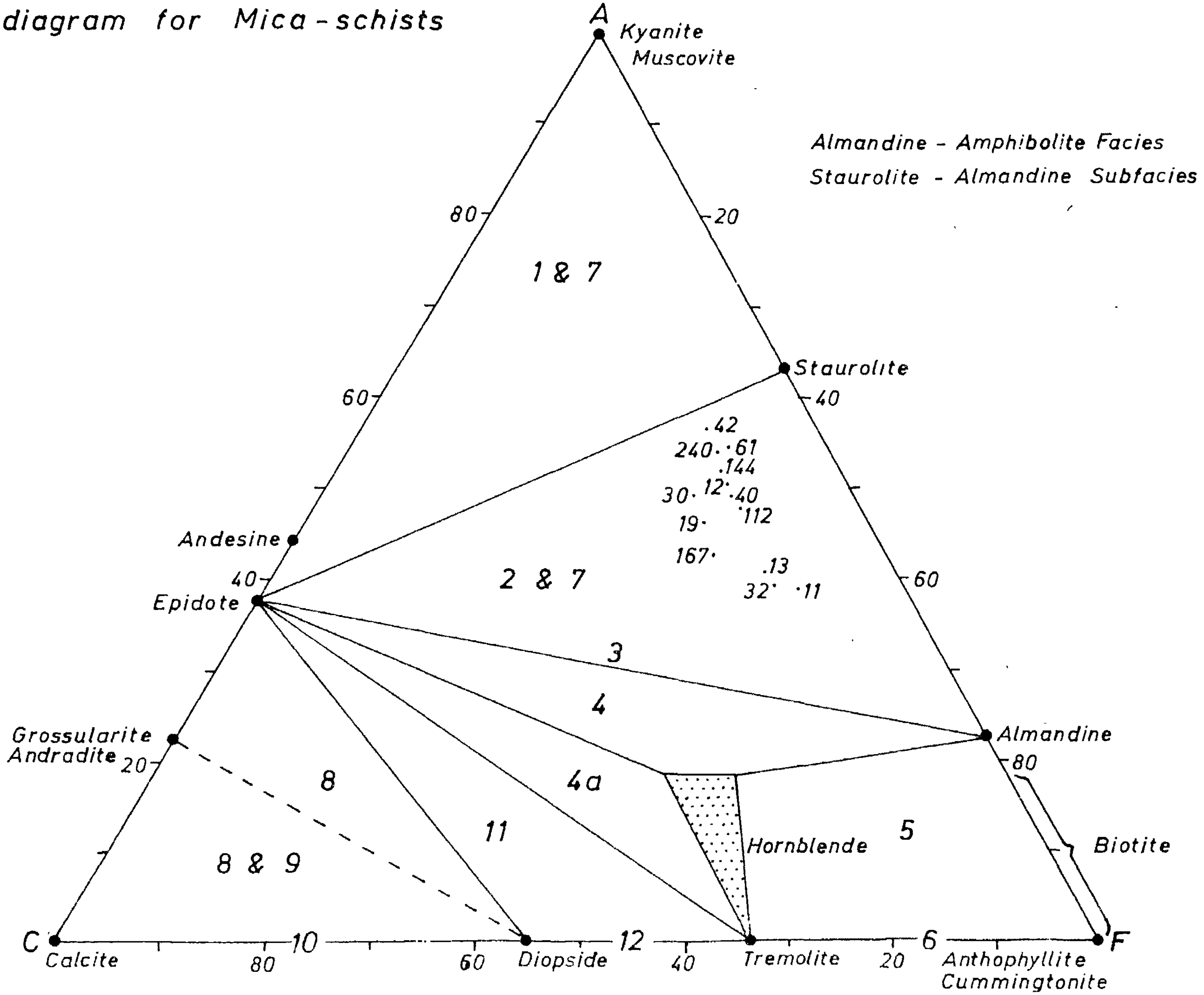
The minerals of the mica-schists of the Almora area also suggest metamorphism upto the "Almandine" and "Staurolite" zones of the Amphibolite facies of Turner (1968). The author has prepared the ACF diagram (Fig.VI.2, Table VI.1) of the various types of schists which show that the rocks belong to the staurolite-almandine sub-facies of the amphibolite facies of Turner and Verhoogen (1962, p.546). These rocks are formed under conditions of moderate temperature, pressure and strong deformation.

Jungs and Roques (1952, p.12-19) have estimated 7000 - 10000 meters depth for the "zone of lower mica-schists" containing biotite, garnet, staurolite etc. A pressure range between 4000 to 8000 bars is suggested by Turner and Verhoogen (1962, p.553).

The mineral assemblage of amphibolite facies indicate a temperature range from 450°C to 650°C according to Turner (1968, p.366). A moderately high temperature must have combined with above pressure conditions to give rise to the mineral assemblages. Such complex pressure and temperature conditions develop only in active orogenic belts. High pressures and temperatures can be possible in such areas, where pressures are augmented by movement of rock masses and the heat is in some way related with

Fig. VI. 2.

ACF diagram for Mica-schists



the complex process of geosynclinal folding which Ramberg (1952, p.273) has called as "a large scale equilibriopetal exothermic process."

Metamorphic event III

In between the two events of metamorphic changes II and IV of progressive types, in the areas adjacent to the two flanks of the Almora thrust (viz., N Almora and S Almora thrusts), a major retrogressive event intervened. In the Almora area, the effects of this retrogressive metamorphism, which was essentially related to the Almora thrust movement are however not recorded. But Vashi and Merh (1965), Vashi (1966), Desai (1968), Patel (1972) and Munshi (1972) in their investigations in other parts of the Almora nappe, have discussed this metamorphic event at length. The differential stresses which caused the isoclinal folding (F_1) culminated into the Almora thrust, and it was during the slipping along this dislocation that extensive retrograde changes were brought about in the garnet mica-schists. On account of this, the rocks above the South Almora and North Almora thrusts show metamorphic inversion of garnet mica-schists to phyllonites. In Majkhali area, Desai (1968) came across numerous shear zones developed parallel to the thrust, along which narrow bands of retrograde chlorite and sericite rich fine grained phyllonitic rocks have developed. As the study area is right in the middle of the Almora nappe synform, somewhat distant from the thrusts, the retrogression caused by the dislocation is not so well marked, and the mineral assemblages and the textures do not show any significant record of the metamorphic downgrading.

Metamorphic event IV

This event of progressive metamorphism coincided with the synformal folding of the Almora nappe. It was during this event that the schistosity was extensively crinkled, and associated with this textural change, several new minerals developed.

Textural changes brought about during this event, comprise the development of a sporadic crenulation cleavage (S_2). Depending on the intensity and tightness of the microfolds, the mica flakes show rupture along the hinges, giving rise to an axial-plane type crenulation (=? strain-slip) cleavage. Less intense deformation have simply thrown the schistosity into gentle microfolds. Irrespective of the fact whether the hinges of microfolds have broken or not, the most prevalent textural feature is the granulation and recrystallisation brought about by a flexural-slip mechanism. This is so evident from the streaky aggregates of relatively finer grained quartz following the flexures, with a tendency to collect in the bends of the microfolds.

Mineralogical changes that accompanied this microfolding event, clearly indicate an upgrading, and could be listed as under:

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

(2) Formation of new muscovite, biotite and chlorite porphyroblasts. These porphyroblasts have grown during the microfolding and either lie along the S_2 cleavage or oblique to S_1.

(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 inclusions inside these garnets are identical to and in continuation with the folds in the surrounding maxtrix. It is thus quite obvious that these garnets have grown in a static matrix.

The above mentioned textural and mineralogical changes, clearly indicate that these were brought about by metamorphic conditions - characterised by fairly high pressures, dominant differential stresses and moderately high temperature. During the synformal folding at some depth, 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.

Late retrogressive changes

The thin sections have revealed that occasionally garnets show some alteration to chlorite. Stray cases of biotite changing to chlorite are also noted. All these changes appear to be of hydrothermal nature brought about much after the main metamorphic events, and are perhaps related to the late hydrothermal activity of the granitic rocks.