CHAPTER VI

METAMORPHISM AND MIGMATISATION

The metamorphic history of the area has been worked out with the help of field data and petrographic studies. The textures, mineralogy and chemistry of the various lithological types discussed in Chapter IV have enabled the author in building-up sequences of metamorphic events that affected the area. The two tectonic units show distinctly diverse metamorphism.

METAMORPHISM IN ALMORA NAPPE

A careful scrutiny of the structure, texture and mineralogy of the various rock types comprising the Almora nappe crystallines in the area, has established the following sequence of metamorphic events:

I. Regional metamorphism of progressive nature that accompanied the main orogenic upheaval and the isoclinal folding (F_1) of the meta-sediments.

II. Retrogressive metamorphism brought about by intense shearing related to the South Almora thrust.

III. Mineralogical and textural changes during the synformal folding (F_2) of the Almora nappe.

Metamorphic Event I

The rocks of the Mukteswar area contain few evidences of load metamorphism prior to the dynamic metamorphism. But Powar (1966), Das (1966) and Desai (1968) have come across enough relicts of a load schistosity in the neighbouring areas. The main metamorphism however, coincided with the isoclinal folding and was so dominant that at most places, the indications of early metamorphism have been more or less completely obliterated.

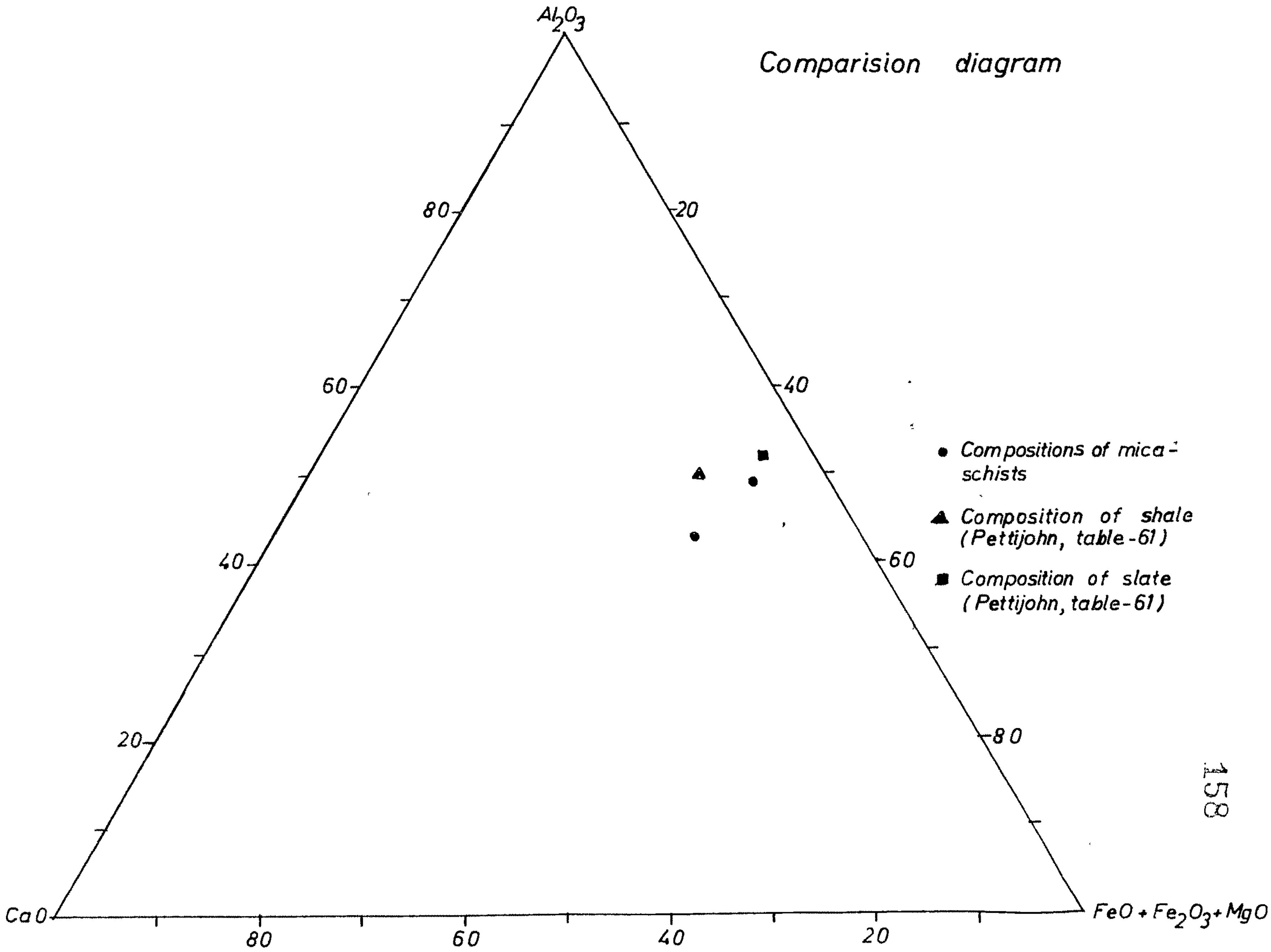
The dynamic metamorphism was of progressive nature, and coincided with the principal deformational episode F_1. Thus, the main foliation (schistosity S_2) of the rocks marks the axial-plane of the isoclinal folding. The metamorphic foliation of schists and gneisses therefore is essentially of the axial plane type and not a product of load metamorphism. The parallelism of the foliation with bedding is due to the isoclinal nature of the F_1 folding.

Evidences of this metamorphism are ideally preserved in those garnet-mica schists and quartz-mica schists which lie above the gneissic bands and are not seriously affected by the subsequent retrogressive metamorphism. The foliation characterised by a parallel orientation of mica and elongated grains of quartz, is seen essentially marking the axial plane of the folded quartzite layers. Merh & Vashi (1965) and Vashi (1966) considered this schistosity to be a primary one, developed from unmetamorphosed sediments during the regional metamorphism that accompanied the isoclinal folding. But Desai (1968) has suggested that the principal schistosity is itself a tightly folded earlier foliation (perhaps a load schistosity). Though in the study area, the author could not get any samples showing relict (crinkled) load schistosity, he did come across some textural evidences to suggest the possibility of a static metamorphism that preceded the main dynamic event. Some mica schists are seen to contain garnet grains which include an earlier garnet in the core. The inner garnet has inclusions which do not show any rotation while the outer one has spiral inclusions of quartz (Plate IV.1B).

The mineral assemblages typically suggest that they are derived by the regional metamorphism of argillaceous sediments. In (Fig.VI.1) the composition of these schists have been depicted in a triangular diagram with the corners represented by Al_2O_3, CaO and (FeO + Fe_2O_3 + MgO) in molecular numbers. For comparison, the composition of average shale and slate listed by Pettijohn (1956,p.344) have also been plotted in this diagram.

Fig.-VI.1.

Comparision diagram



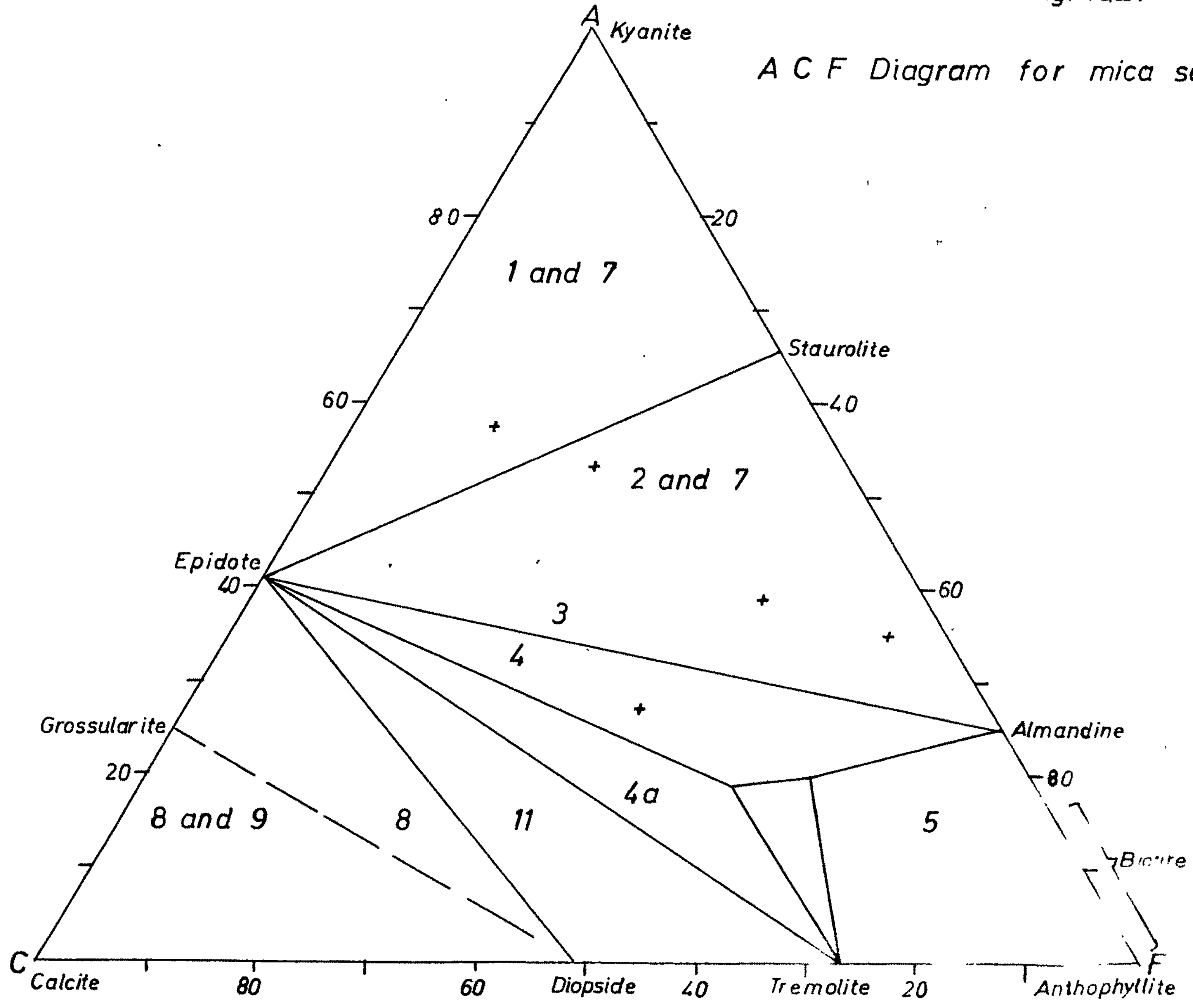
Quartz, biotite, muscovite and garnet are almost always present, while plagioclase, staurolite and kyanite occur occasionally. Wherever chlorite is recorded, it is always a retrograde product after biotite and garnet. The presence of almandine garnet is indicative of a high FeO/MgO ratio. Staurolite and kyanite have also developed but sporadically during this metamorphism. The formation of staurolite perhaps depended upon the original chemical composition of the rock. Turner & Verhoogen (1960) Winkler (1965) and Turner (1968) are of the opinion that staurolite forms in schists that are rich in Al_2O_3, FeO and poor in K_2O. Similarly, the presence of kyanite is indicative of Al_2O_3 rich and K_2O deficient sediments. Obviously, the presence of kyanite and staurolite at a few places only appears to be due to the variation in the composition of the original sediments from place to place.

Shearing stresses played an important role in this metamorphism, as is suggested by the rotated garnets. The 'S' shaped inclusions of quartz suggest the rotation of garnets during their growth (Plate IV.1A).

The minerals of the mica schists, suggest metamorphism up to the "Almandine zone" of Barrow (1912). The author has prepared the ACF diagram of the various rock types (Fig.VI.2) and on the basis of these, the various mineral assemblages have been found to belong to the "Staurolite-almandine sub-facies" of the "Almandine Amphibolite facies" of Turner & Verhoogen (1960, p.552). These rocks are formed under conditions of moderate temperature and pressure and strong deformation.

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 sediments. On account of the crustal movement in the region of active geosyncline, the sediments were subjected to extreme horizontally directed (non-hydro static) compression and shearing. The present metamorphism was thus impressed upon the sediments during large scale isoclinal folding. Structural studies 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, Fig.-VI2.

A C F Diagram for mica schists



fully indicates that shearing stresses augmented the pressure conditions of the amphibolite facies metamorphism. The rotated garnet porphyroblasts with spiral inclusions of quartz are the most conclusive evidence of differential slipping. Jungs & Roque (1952,p.12-19) have estimated 7,000 - 10,000 metres depth for the "zone of lower mica schists" containing biotite-garnet-staurolite etc. A pressure range between 4,000 to 8,000 bars is suggested by Turner & Verhoogen (1960,p.553).

The mineral assemblage of 'Almandine amphibolite facies' indicates a temperature range from 550°C to 750°C according to Turner & Verhoogen (1960, p.553). A moderately high temperature must have combined with above pressure conditions to give rise to the mineral assemblages. It is difficult to understand how such temperatures could be attained in regional metamorphism and several possibilities have been suggested by numerous workers for the source of heat in orogenic evolution. It is not possible to go into the detailed of the problem, and it is considered adequate to state that "The causes of heat generation in the orogenic upheaval are quite obscure and in some way related with the complex process of geosynclinal folding - a large scale equilibriopetal exothermic process" (Ramberg, 1952,p.273).

Metamorphic event II

The Almora nappe rocks ideally show a case of diapthoresis or retrogression due to dislocation. The South Almora thrust has so affected the mica schists that a progressive down-grading of the metamorphism is recorded in the rocks on approaching the thrust. The isoclinal folding (F_2) that accompanied the progressive metamorphism culminated into the Almora thrust, and the intense shearing caused by the differential slipping along S_1 in the vicinity of the thrust, not only crushed and granulated the schists but also brought down their metamorphic grade. It appears that there was not much of time interval between these two events of metamorphism, and interestingly enough the same differential stresses that brought about important progressive metamorphism were equally responsible for the retrogression. The intense crushing and granulation finally transformed the garnet mica schists into phyllonites. Vashi & Merh (1965,p.32) and Merh & Vashi (1965,p.63) have ideally described the retrogressive effect of the South Almora thrust in the neighbouring area of Uparadi near Ranikhet.

Textural changes during increasing mylonitisation resulted into (i) a progressive decrease of grain size and (ii) development of a strong foliation (Plate IV.6B).

The intensity of differential slipping was so great that the resulting phyllonitic cleavage itself got drag folded and crinkled. Mineralogically, the garnet, biotite and muscovite was most affected. The retrogressive changes could be listed as under:

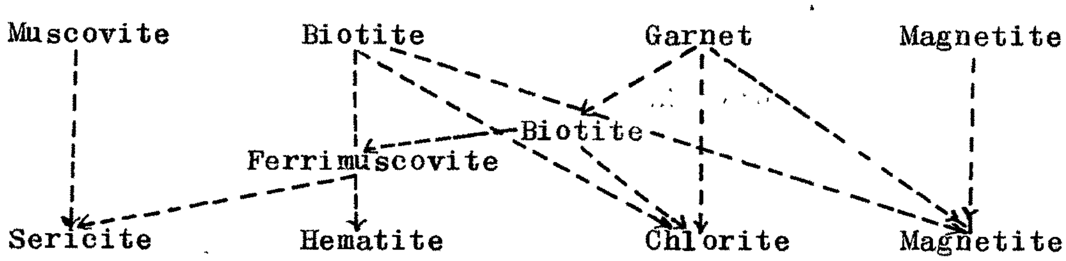
(1) The quartz grains have been finely granulated and arranged in streaks.

(2) The idioblastic garnets have been crushed and increasingly altered to biotite and chlorite with liberation of iron oxide.

(3) Biotite has altered to chlorite and ferri-muscovite with the liberation iron oxide.

(4) Muscovite has changed to streaks of sericite.

Mineralogical changes brought about by the retrogression:



Mineralogically, the phyllonitic rocks belong to the 'Quartz-albite-epidote-sub facies' of 'Greenschist facies' of Turner & Verhoogen (1960,p.537).

Metamorphic event III

At the time of the synformal folding (F_2) of the Almora nappe, some metamorphic changes of progressive nature took place. During this episode, the mica schists developed extensive crinkling and a strain-slip cleavage (S_3).

The microfolding of the schistosity (S_1) and development of a new generation of micas and garnet, are the important features of this metamorphism. During the crinkling caused by the synformal folding F_2 wherever the microfolding was intense, the hinges ruptured and gave rise to a strain-slip cleavage (S_3). The textural and mineralogical changes brought about by this metamorphic event have been listed below:

(1) Bending and breaking of mica flakes and their subsequent recrystallisation as smaller flakes, characterising the F_2 fold style.

(2) Growth of new micas along the ruptured microfold hinges. To this category belong the muscovite and biotite porphyroblasts seen growing oblique to the main foliation (S_1), even in the absence of distinct crinkling.

(3) Formation of a new garnet, which is idiomorphic, and shows very clear evidence of static growth mostly in the hinge areas of the microfolds. Quite often such garnets contain within them rotated garnets of earlier (F_1) origin (Plate IV.2B).

It is strikingly obvious that during this metamorphism a complete recrystallisation of all minerals took place and thus most of them are fresh and free from strain effect and alteration. The textural and mineralogical changes, clearly indicate that these were brought about by an upgrading in the metamorphic conditions, during the synformal folding of the Almora nappe.

MIGMATISATION IN ALMORA NAPPE

The two gneissic bands occurring within the garnet-mica schists are of migmatitic origin. This migmatisation preceded, synchronised with and even outlasted the main orogenic events, and it is so obvious that the deformation, regional metamorphism and migmatisation formed an integral part of the orogeny. Migmatisation generally takes place in same environment as that of high grade regional metamorphism, and most migmatites form under conditions of amphibolite facies. Stress may play an indirect part in facilitating the passage of the emanations by providing tectonic planes.

The transformation of mica schists to gneisses was brought about mainly by the increasing metasomatic action of emanations rich in alkalies. The chemical data has shown that the transformation of the meta-sediments into gneisses involved considerable enrichment in alkalies and some increase in Al_2O_3 and SiO_2, the addition having taken place in three stages sodic, potassic and sodic.

The various stages of mineralogical changes leading to the transformation of schists to gneisses, could be summarised as under:

I. Appearance of plagioclase in the groundmass.

II. Increase in the total plagioclase content and also its size.

III. Increase of quartz and plagioclase content; plagioclase becoming porphyroblastic; appearance of microcline in the groundmass.

IV. Increase of muscovite and microcline content; microcline replacing plagioclase porphyroblasts.

V. Appearance of orthoclase porphyroblasts; plagioclase porphyroblasts considerably replaced by microcline; decrease of biotite content.

VI. Formation of quartz-plagioclase rims round orthoclase porphyroblasts.

Evidences of Migmatisation

Megascopic:

The contact of the gneisses with the flanking schists is transitional, and with a gradual increase of felspar content, the schists imperceptibly pass into gneisses. Not only the amount of the felspars goes up, but their size too increases. The gradual increase in the grain size of the rock as a whole and of the felspars in particular, clearly indicates a metasomatic origin.

Further, the presence of relict schist bands, and layers of quartzite inside the gneisses, typically illustrates the phenomenon of "ghost stratigraphy", and demonstrates that the framework of the host rock remained coherent throughout the transformation.

Microscopic:

Thin sections reveal a perfect gradual transformation of schists into gneisses through various transitional stages of increasing felspathisation. The metasomatic growth of the felspar porphyroblasts is fully established on the basis of the following textural criteria:-

(i) The felspar augens and porphyroblasts show a steady and gradual increase in size,with increasing felspar content of the rock.

(ii) The augens and porphyroblasts contain abundant inclusions of muscovite, biotite and quartz.

(iii) The gradual replacement of plagioclase by microcline, is a clear indication of the metasomatic action. It is obvious that the process of migmatisation consisted of two main metasomatic phases - an early sodic phase followed by a late potassic. The replacement of plagioclase by microcline has imparted to several felspar grains - "perthitic" or "anti-perthitic" appearance, depending on the degree of replacement. The perthites suggest an advanced stage of replacement, while the anti-perthites indicate the early stage. In all cases, the inter-growth is of patchy and irregular type.

(iv) In the replacement of plagioclase by microcline, a peculiar rounded effect is produced on the plagioclase, which is bounded by a series of curves, often lobe shaped with their convex side facing the microcline (Cheng 1943 p.139). The attack on felspar by quartz is more in the nature of corrosion than replacement, the characteristic contact line between them being a series of curves with their convex sides facing the attacked mineral.

(v) The replacement phenomenon between the plagioclase and microcline, has at many places given rise to typical myrmekitic texture. The characteristic intergrowth of plagioclase and vermicular quartz is quite commonly recorded near the contacts of the two varieties of felspars, where plagioclase is seen being replaced by microcline and vice-versa. Development of myrmekite by such replacement, has been suggested by a number of workers.

(vi) Well formed garnets in gneisses, indicate that the enclosing rocks were derived from originally garnetiferous mica schists.

Chemical criteria:

The chemical data also supports migmatisation (Table VI.1). The variation diagrams (Fig.VI.3) showing the percentage of SiO_2, Al_2O_3, FeO, TiO_2, MgO, CaO, Na_2O and K_2O in the various varieties from mica schists to porphyroblastic gneiss, reveal the trend of chemical changes. SiO_2 shows a small but gradual increase. Al_2O_3 more or less remains constant. Fe_2O_3, FeO, MgO and TiO_2 show a decline. CaO at first increases and then its content goes down with the increase of K_2O. ~~dominates~~. Thus, it can be concluded that the migmatisation was brought about mainly by addition of alkalies.

Probable mechanism of migmatisation:

In most migmatites, the introduced component migrates from outside into the host to combine with the pre-existing material; it may be supplied by a nearby body of granitic magma, or may rise from much deeper levels. The introduced material may migrate as a quartzo-felspathic melt or it may take the form of a diffuse system of ions which migrates through the pore fluids. Though the migmatising emanations could belong to any of the above categories, and migmatites could originate in various ways, it is now generally agreed

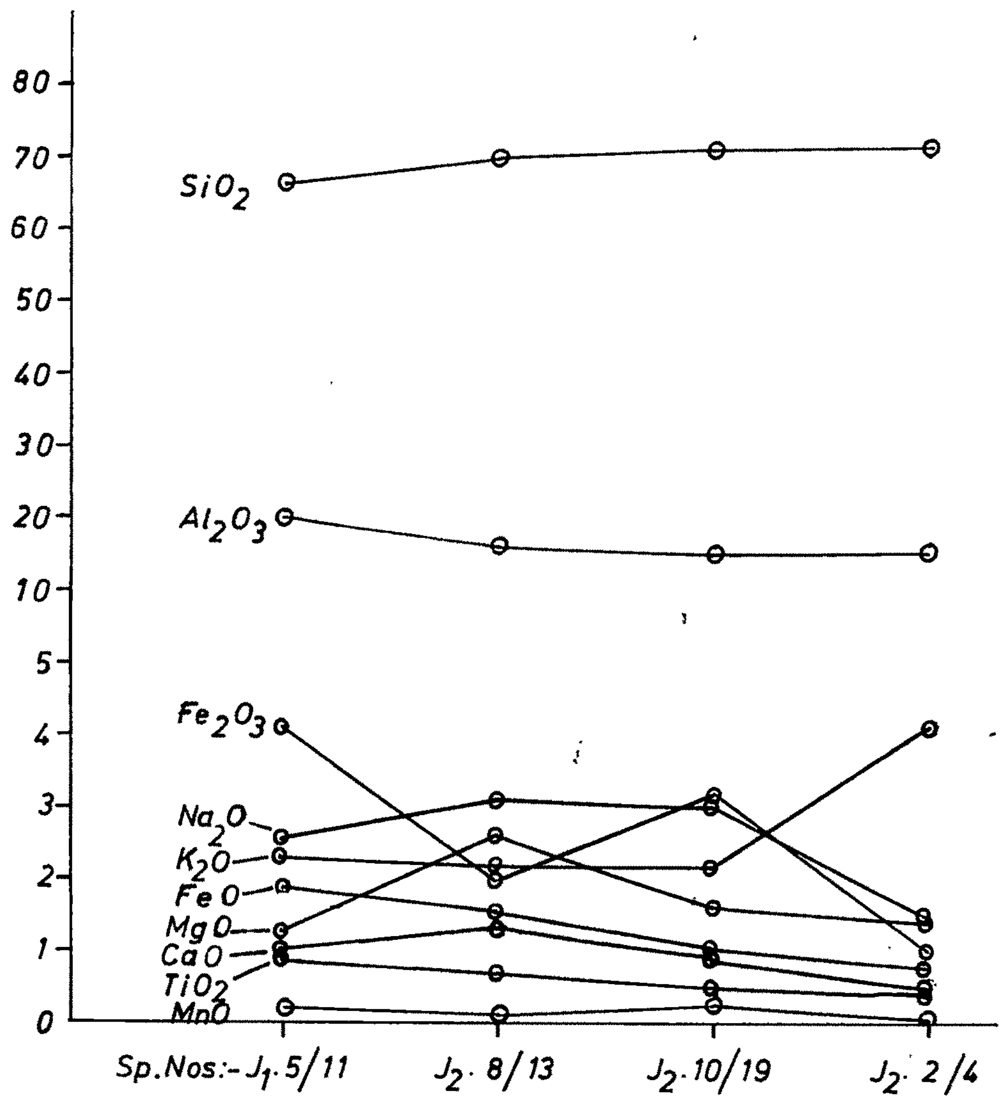
TABLE VI.1

	Mica schist	Permeation gneiss (J_2 8/13)	Augen gneiss (J_2 10/19)	Porphyroblastic gneiss (J_2 2/4)
SiO_2	66.08	70.02	70.90	72.74
Al_2O_3	20.08	16.50	15.75	15.95
TiO_2	0.92	0.70	0.50	0.40
Fe_2O_3	4.17	2.00	3.20	1.00
FeO	1.92	1.59	1.02	0.82
Na_2O	2.59	3.12	3.07	1.50
K_2O	2.37	2.12	2.12	4.12
CaO	1.00	1.30	0.91	0.50
MgO	1.33	2.62	1.62	1.40
MnO	0.16	0.10	0.18	0.09
P_2O_5	0.06	0.03	0.02	-
Total	100.68	100.10	99.29	98.52

Analyst: J.P.Patel

Fig.—VI.3.

Variation diagram for migmatites.



that large scale migmatisation is brought about without injection of any igneous melt.

Whether the circulation of hydrothermal solutions or long distance ionic diffusion in a stationary medium, is the main factor in migmatisation, is highly problematic. Many geologists think water to beessential for the transportation of ions. Read (1948, p. 15) believed in efficacy of hydrothermal solutions and felt that at high temperatures, molecular diffusion could bring about changes in solid rocks on a rather limited scale only. But recent views favour "dry transformation" by ionic diffusion in solid state without water. Perrin (1954,p.451) considers that ions can move for long distance causing granitisation. Reynolds (1947,p.409-11) has suggested following three possible ways in which ions may migrate through a solid (crystalline) medium:

(1) Through spaces in the lattice, if the lattice is sufficiently open and the migrating ions are of appropriate size.

(2) From one lattice point to another within the crystal mesh. This type of diffusion occurs when the atoms in a crystal are in a state of rapid thermal vibrations.

At a certain temperatures, these variations become so large that ions may break away and wander through lattices.

(3) Through zones of atomic disorder. Lattices are composed of minute blocks which are not perfectly aligned. These mosaic structures give rise to atomic disorder at the junctions of mosaic units. Atomic disorder is also found along the boundaries of closely packed crystal grains. Orogenic stresses create pronounced atomic disorder.

The migmatites of the study area suggest that the quartzo-felspathic material, introduced into the schists, was not of the nature of a granitic melt, as there are few evidences to show any injection of a molten material. On the other hand, various criteria point towards a gradual metasomatic alteration of schists into gneisses, the transformation having been brought about by the passage through solid rocks, of a stream of inter-changing constituents. It appears that in bringing about the migmatisation, hydrothermal solutions played a rather subordinate role. The absence of sericitization and chloritization during this transformation indicates the paucity of water. The various textural and mineralogical features of the gneisses point to the possibility of metasomatism brought about by the mechanism of solid diffusion without much water.

The important controlling factors in solid diffusion are temperature and pressure. Heat results in increased diffusion. Stresses promote solid diffusion because they decrease pore space. Shearing distorts the crystal lattice and so promotes ionic migration. Obviously, in a region of active orogeny, where sediments have been subjected to high temperatures and different types of stresses, ideal conditions would exist for initiating such processes. Thus regional metamorphism and migmatisation form a connected sequence of events closely related to the orogeny.

The nature of the ultimate source of the emanations, though undoubtedly being in the deepseated parts of the geosyncline, is yet to be properly understood. Some believe that sources of granitising emanations are the palingenetic granitic magma, while others suggest a chemical "squeezing" of K, Na, Si, O at deeper levels and their subsequent upward migration. Whatever may be the ultimate source of the migmatising emanations, it is almost universally agreed that the downwarping of the sialic crust forming the roots of the fold mountains, on touching the hot simatic substratum leads to the generation of granitising emanations. Whether it is wholesale melting, selective fusion or ionic dissociation is a matter of conjecture.

Migmatisation in relation to various deformational episodes:

The gneissic bands of the study area do not reveal much about the time relationship between migmatisation and deformation. But taking into account the field and petrographic data from the present area, and the information available in the works of Vashi (1966) and Desai (1968) on similar rocks of Ranikhet and Majkhali areas respectively, the author has been able to build a fairly complete picture of the migmatisation sequence in relation to deformational events.

Migmatisation was initiated before the main folding (F_1): Desai (1968) has very clearly shown a folded gneissic band in Majkhali area and the folded shape of the band is due to F_1. Further the gneissic bands of the study area are supposed to be tight isoclinal fold cores and if it is so, it implies that the gneisses existed prior to F_1 folding. Perhaps this earliest phase was mainly sodic.

Migmatisation continued to be effective during the main isoclinal folding (F_1): On account of this folding, the deepseated migmatised sediments were lifted up as anticlinal fold cores, and these are now seen forming narrow gneissic bands in schists. The foliation (=axial plane) in the gneisses developed during the folding, and the large scale growth of felspars along the foliation as discrete grains and augens, illustrate an easy passage of emanations along the axial-plane foliation. The dominant emanations were soda rich, but some potassic ones also appear to have started coming in.

Migmatisation continued during Almora thrust and outlasted the second folding (F_2): Porphyroblasts cutting and growing across the schistosity indicate their origin after F_1. Quite a few of these porphyroblasts are seen deformed by the Almora thrust, so it is obvious that such felspars grew after F_1 and before Almora thrust. Most of the porphyroblasts are of potash felspar (orthoclase and microcline) replacing plagioclase. On the other hand, there are some porphyroblasts, which have grown even after the second folding (F_2). These are orthoclase changing to microcline. Thus, potash metasomatism continued to be operative even after the F_2 folding. An interesting phenomenon observed in this connection is that the pre-Almora thrust porphyroblasts frequently contain a discontinuous rim of oligoclase quartz, and this sodic rim is free from thrust effect. Thus, it is evident that the final stage of the migmatisation process consisted of a sodic phase, which was definitely post-thrusting, and perhaps even post F_2.

METAMORPHISM IN KROL NAPPE

Metamorphically too, the rocks of the Krol nappe are quite different from those of the Almora nappe, and just as the structural history of the Krol nappe comprises events which have little effects on Almora nappe, the metamorphic evolution of the former has also followed quite a different course. The salient features of the metamorphism of the Krol nappe are summarised as under:-

I. Progressive metamorphism that synchronised with the Almora thrust movement.

II. Progressive metamorphism that accompanied the development of the Bhowali anticline during F_2 folding.

III. Retrogressive metamorphism due to Ramgarh thrust.

IV. Late hydrothermal changes.

An important feature of the metamorphism of the Krol nappe is that the various events have not affected the various metamorphic rocks all over, but their imprints are seen in one or the other part individually. Of the four events, first has mainly affected the rocks above the Ramgarh group, while the effects of the second, which was quite insignificant, are confined to the metabasalts below the Titoli quartzites. The third retrogressive event is the most prominent, and its effects are well recorded in the Ramgarh group. The last and the fourth event mainly comprising hydrothermal changes, is confined to the mafic rocks only.

Metamorphic Event I

This metamorphic event of a progressive nature, is related to the differential slipping that was caused by the Almora thrust movement. The slipping took place, perhaps along the bedding planes and it was confined mostly to softer layers (original shales etc.). Thus, they show a development of strong shear cleavage obliterating the sedimentary structures while the quartzites and limestones have retained their original structures to a considerable extent. Unlike the Almora nappe in whose rocks the Almora thrust caused a retrogression, its effects on the Krol nappe, were of progressive nature. In fact, the metamorphic effects of Almora thrust on the rocks above and below the dislocation, ideally illustrate the phenomenon of 'metamorphic convergence' of Read (1957,p.297).

Broadly speaking, the rocks lying above the limestones, show a progressively increasing metamorphism on proceeding nearer to the South Almora thrust. As already stated, quartzites show little response to this metamorphism, but the argillaceous layers are seen to change over from almost slaty chloritic phyllites to coarser biotite phyllites, indicating an increase in metamorphic grade.

On the basis of the mineral assemblages of the chlorite-, muscovite-, and biotite-phyllites, the rocks have been broadly assigned to the green-schist facies. It is obvious that the increasing metamorphism towards the South Almora thrust was responsible for a transition from Quartz-albite-muscovite-chlorite-sub-facies (Chlorite zone) to Quartz-albite-chlorite-biotite sub-facies (Biotite zone).

The actual pressure and temperature conditions that give rise to green schist facies are not fully known, and as Turner & Verhoogen (1962, p.534-35) have rightly written, "the estimates of temperature and pressure of low-grade regional metamorphism are little better than a guess..... The low temperature limit of the green-schist facies is determined largely by reaction kinetics. Under the accelerating stimulus of deformation and pore-fluids, at some range of temperature which may be in the vicinity of 300°C, the velocities of a number of reactions become appreciable and metamorphism sets in."

Metamorphic Event II

It is during this metamorphism that the basalts, underlying the Titoli quartzites, got foliated and slightly metamorphosed. The deformation was due to the flexural slip that accompanied the development of the Bhowali anticline during F_2 folding.

Metamorphic Event III

This event of metamorphic changes, brought about by the Ramgarh thrust, was essentially of retrogression. Downgrading of metamorphic assemblages along thrust and shear zones, has been referred to as 'dislocation metamorphism'. The textural and mineralogical changes that accompanied the intense differential slipping during the development of the Ramgarh dislocation, provide an excellent example of dislocation metamorphism.

The shearing and the retrogression is confined to the Ramgarh group only, and the effects of extensive mylonitisation are very well exhibited by the granitic rocks. Details of the textural and mineralogical changes have been already given while describing the petrography of these rocks. Based on the field and microscopic evidences, the retrogressive metamorphism can be summarised as under:-

Textural changes:

With increasing nearness to the Ramgarh thrust, the felspar and quartz porphyroclasts show a progressive decrease in size, and passing through an intermediate 'augen' shape finally end up as altered and granulated streaks. The rock as a whole tends to become finegrained and increasingly foliated.

Mineralogical changes:

The quartz grains show granulation and stretching into streaky aggregates. Felspars show progressive alteration to sericite, which is finally seen as thin streaks. Biotite is changed over to streaky chlorite. Secondary minerals derived as alteration products, other than the above minerals, are epidote, calcite and quartz.

Metamorphic Event IV

This last event is a late one and of rather minor importance. To this, are related the hydrothermal changes mainly seen in the epidiorites. Considering the undeformed nature of the epidiorite sills, they are undoubtedly younger than the last major deformational episode of Ramgarh thrusting. But their extensive alteration indicates action of hydrothermal solutions at some date after their emplacement. The changes brought about by the hydrothermal solutions mainly consist of large-scale alteration of pyroxenes to hornblende and chlorite, and partial saussuritisation of plagioclase.

The actual source of the emanations are not known. It is quite possible that the solutions were released from the igneous source itself, thus providing a case of autometasomatism. But then this is just a guess only, and more work is required to say anything definite on the subject.