CHAPTER VII

M I G M A T I S A T I O N

GENERAL:

The various gneissic bands occurring in the Majkhali area, have been recognised as migmatized derivatives of pelitic and semipelitic schists. This migmatisation preceded, synchronised with, and even outlasted the main orogenic events and it is obvious that the deformation, regional metamorphism and migmatisation, formed an inter-related sequence of orogenic events.

In the study area, the phenomenon of migmatisation ideally exhibits the gradual transition of garnetiferous mica schists to coarse felspathic gneisses.

The quartzo-felspathic material of these migmatites appears to have been generated more or less insitu, formed essentially in the solid by metamorphic and metasomatic changes. Permeation by incoming emanations caused metasomatic alterations in the host. The granitic parts of the rock could also have derived some of their substance from the host by the process of metamorphic differentiation.

Migmatisation generally takes place in the same environments as that of high grade regional metamorphism. Many migmatites are formed under conditions of "amphibolite-almandine" facies. Stress may play an indirect part in facilitating the passage of migmatising emanations by providing tectonic planes.

The transformation of pelitic schists to gneisses, has obviously been brought about mainly by the increasing metasomatic action of emanations rich in alkalies. The chemical analyses have shown that the transformation of metasediments into gneisses, involved enrichment of alkalies and a slight increase in the Al_2O_3 and SiO_2. It is also seen that the process of migmatisation consisted of an early sodic phase and a late potassic phase. The mineralogical changes leading to the transformation of garnet mica schists into migmatitic gneisses can be summarised below.

Stage A: Increase in the amount and size of plagioclase felspars.

Stage B: Increase in the amount of microcline and gradual replacement of plagioclase by microcline.

Stage C: Increase in the quartz content.

Stage D: Increase in muscovite content.

Stage E: Decrease in biotite content. Recrystallisation of biotite into bigger flakes of reddish brown colour.

EVIDENCE OF MIGMATISATION:

The author has recorded ample evidences in favour of the migmatitic origin of the gneissic bands. In the following lines, the various criteria for migmatisation have been summarised:

I. Field criteria:

Field evidences that clearly indicate the gradual transformation of schists into gneisses are as under:

(i) Nature of gneiss-schist contact: The contact of the migmatites with the surrounding schists is transitional. With a gradual increase of felspar content, the schists imperceptibly pass into gneisses. There is no discordance in the foliations of the schists and gneisses - both being identical. In the field, it is very clearly seen that the schists have changed over to gneisses by increasing metasomatic growth of felspars.

(ii) Felspar content: The transition of schists to gneisses, has been caused mainly by the increasing felspar (and quartz) contents. The felspar content is seen gradually increasing towards the median portions of the gneissic band. Not only the amount of felspar goes up, but the size of the felspar grains too increases. Right near the schists, the felspars occur as small grains uniformly scattered along the foliation. On going away, these felspars grow bigger, some of them tend to become augen shaped. With increasing felspathisation, the rock is seen to be coarse gneissic, with numerous big felspars, imparting a porphyroblastic appearance to the gneiss. This cannot be explained by any other mechanism except gradual addition of felspathic material by metasomatism. The gradual increase in the grain size of the rock as a whole and of the felspars in particular, clearly indicates metasomatic growth.

(iii) Ghost stratigraphy: There are numerous discontinuous layers of relict schists and quartzites inside the migmatitic bands. The trends of these 'skialiths' are identical with those of the surrounding host rocks, and demonstrate that the framework of the host rocks remained coherent throughout their transformation. The presence of such relicts are hard to explain unless the enclosing gneiss represents the metasomatised sediments.

II. Microscopic criteria:

Replacement origin of gneisses is very well substantiated by a number of textural and mineralogical evidences seen under the microscope. These have been briefly discussed below:

1. Perfect gradation from schists to gneisses: Thin sections ideally reveal a perfect transformation of garnet mica schists into porphyroblastic gneisses through various transitional stages showing gradual increase in the felspar (and quartz) content. Schists are seen passing into gneisses in the following order:

(i) Garnet mica schists changing over to felspathic schists with the appearance of tiny grains of plagioclase along the foliation.

(ii) With the increase in the content and size of the felspars (plagioclase), the rock passes into permeation gneiss. This is accompanied by an increase in the overall grain size of the rock.

(iii) These permeation gneisses give place to augen gneisses with the growth of a few felspars as distinct augens. At this stage microcline appears in the groundmass and is occasionally seen replacing the plagioclase or forming independent augens.

(iv) The augen gneisses ultimately end up as coarse-foliated porphyroblastic gneisses, wherein the augens have developed into discrete porphyroblasts, many of them cutting across the foliation. The porphyroblasts of plagioclase show almost invariable replacement by microcline, and all stages of replacement are recognised (Fig. 24).

2. Nature of the felspar porphyroblasts: It has been already mentioned above that the "porphyroblasts" of plagioclase and microcline, are the products of increasing felspathisation, the latter gradually replacing the former. That these felspars grew metasomatically is clearly established on the basis of following textural features:

(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 metasomatic phases - an early sodic followed by a late potassic. The replacement of plagioclase by microcline has imparted to several felspar grains - a "perthitic" or "antiperthitic" appearance, depending on the degree of replacement. The perthites suggest an advanced stage of replacement, while the antiperthites indicate the early stage. In all cases the intergrowth is of patchy and irregular type.

3. Textural relations: The migmatisation has not only changed the chemical and mineralogical composition of the metasediments, but has also imparted a number of textural changes. A number of textural features described below clearly indicate the dominant role of replacement:

(i) Sutured texture: The most striking feature is that of the "sutured relationship" between (a) plagioclase and microcline, and (b) plagioclase and quartz.

In the replacement of plagioclase by microcline, a peculiar rounded effect is produced on the plagioclase, which 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.

(ii) The replacement phenomenon between the plagioclase and microcline, has at many places given rise to typical myrmekitic texture (Plate 28). The characteristic intergrowth of plagiolcase and vermicular quartz is quite commonly recorded near the contacts of the two varieties of felspars, where plagioclase is seen being replaced by microcline. Development of myrmekite by replacement, has been suggested by a number of workers. Drescher-Kaden (1948, p. 102) is of the opinion that the same solutions which form the orthoclase of the granites and granitised rocks corrode plagioclase along 'smekal defects' and deposit silica. Osterwald (1955, p. 317) believes that the Bighorn myrmekite was formed during the replacement of plagioclase by potash felspar through introduction of silica from outside the system. That myrmekite can be formed by replacement of plagioclase by microcline is also suggested by Agrawal (1957), Bose (1959), Cannon (1962), Chatterji (1965), Gangopadhyaya (1959), Snook (1965).

4. Presence of garnet: Well formed garnets in gneisses, occasionally present, indicate that the enclosing rocks were derived from originally garnetiferous mica schists.

III. Chemical criteria:

The chemical analyses of a few selected rocks - representing various stages of migmatisation, when plotted on a number of diagrams, give an idea of the chemical changes undergone by the rocks during the migmatisation. Facts that emerge out of this chemical study, fully support the various textural, structural and mineralogical evidences of migmatisation discussed earlier in this chapter.

Variation diagrams: The trends of the percentage of SiO_2, Al_2O_3, Fe_2O_3, FeO, TiO_2, MgO, CaO, Na_2O and K_2O from garnet mica schist to porphyroblastic gneiss very clearly reveal the chemical changes that were brought about by migmatisation. It is seen that SiO_2 shows a gradual increase, though the addition is not very significantly high. Al_2O_3 more or less remains constant. Fe_2O_3 shows a marked decline in percentage, and so behave the FeO, MgO and TiO_2 contents. CaO significantly shows an increase in the early stages, but steadily decreases later on. Na_2O continues to show an increase except in the porphyroblastic stage, when it is gradually being replaced by K_2O. K_2O naturally, in the initial stages shows a decline in the percentage, but subsequently rises in content steadily. In the early stages of migmatisation, plagioclase is the first to appear, and this results in the increase of Na_2O and CaO and decrease of K_2O. With the appearance of microcline and its gradual replacement of plagioclase, the Na_2O and CaO show a decline.

From the variation trends (Fig. 26) it can be seen that there is a limited increase of SiO_2, insignificant addition of Al_2O_3 and mostly the transformation has been brought about by soda followed by potash (Table I).

QLM values: QLM values calculated from the analyses of 4 representative migmatitic rocks (Table II), when plotted on Von Wolff's diagram (Fig. 27), reveal that with increasing migmatisation, the free quartz(Q) percentage shows steady decrease while those of leucocratic mineral increased. This indicates that during the transformation, there was only a very limited external supply of silica and appreciable addition of alkalies, and thus the free quartz of the schists was taken up in the formation of felspars.

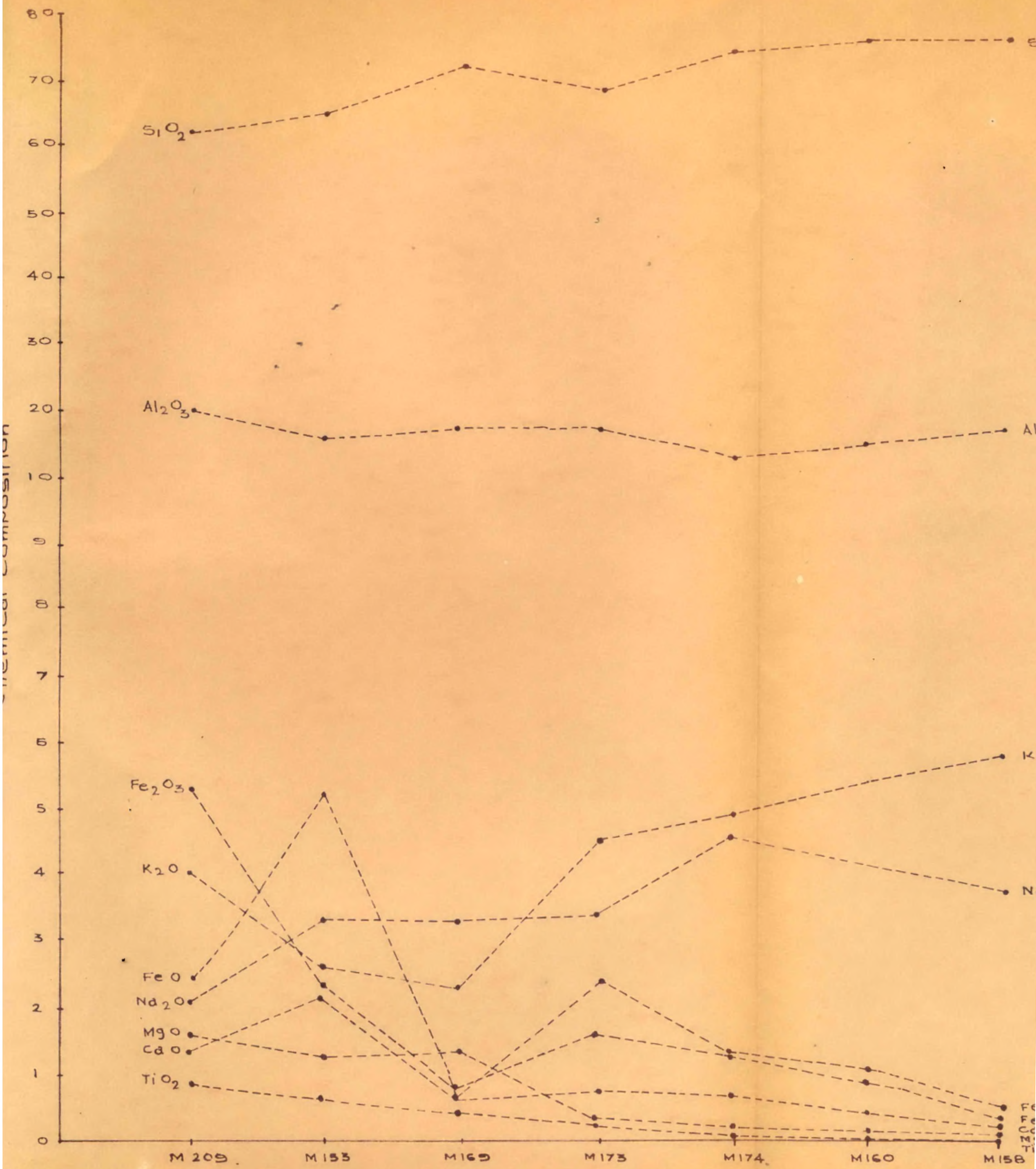
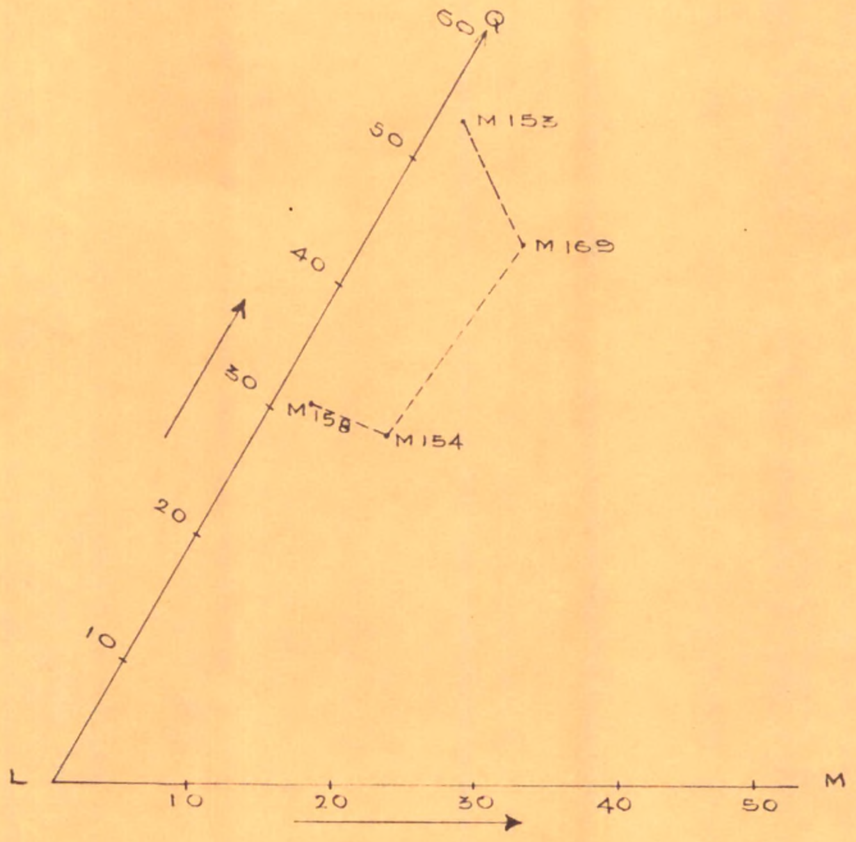


Fig 26 VARIATION GRAPH BASED ON DISTANCE VS. CHEMICAL COMPOSITION

Fig 27



Von Wolff's QLM diagram

TABLE I

	Garnet mica schist	Felspathic schist	Permeation gneiss	Augen gneiss		Porphyroblastic gneiss	
Wt. %	M 209	M 153	M 169	M 173	M 174	M 160	M 158
SiO_2	61.42	66.45	71.76	67.94	72.14	73.20	74.48
Al_2O_3	20.17	15.97	16.75	17.16	16.56	12.50	13.50
TiO_2	0.92	0.72	0.52	0.63	0.64	0.42	0.52
Fe_2O_3	5.26	2.30	0.99	1.85	1.39	1.30	0.58
FeO	2.40	5.26	0.72	2.39	1.76	1.48	0.59
Na_2O	2.11	3.30	3.29	4.49	3.16	4.60	2.28
K_2O	3.99	2.96	2.27	3.27	2.56	4.90	5.98
CaO	1.42	2.24	0.56	0.84	0.98	0.50	0.66
MgO	1.67	1.32	1.01	0.31	0.40	0.20	0.52
MnO	0.35	0.07	0.57	0.67	0.57	0.20	0.47
P_2O_5	0.03	0.03	0.09	0.06	0.04	-	0.09
Total	100.04	100.62	99.93	100.61	100.20	99.90	99.67

TABLE II

Wt. %	Felspathic schist M 153	Permeation gneiss M 169	Augen gneiss M 154	Porphyro-blastic gneiss M 158
SiO_2	66.45	71.76	73.89	74.48
Al_2O_3	15.97	16.75	12.46	13.50
TiO_2	0.72	0.52	0.55	0.52
Fe_2O_3	2.30	0.99	0.60	0.58
FeO	5.26	0.72	4.04	0.59
Na_2O	3.30	3.29	2.95	2.28
K_2O	2.96	2.27	3.37	5.98
CaO	2.24	0.56	0.98	0.66
MgO	1.32	1.01	0.30	0.52
MnO	0.07	0.57	0.57	0.67
P_2O_5	0.03	0.09	0.09	0.09
Total	100.62	99.93	100.04	99.87
Q	28	53	42	36
L	63	45	47	59
M	9	2	11	5

Alkali-Alumina Ratios: In the following Table III, ratios between the alkalies and the alumina in the four representative rocks (Table IV) showing different stages of migmatisation, have been given.

TABLE III

Ratio	Garnet mica schist M 142	Felspathic schist M 153	Augen gneiss M 154	Porphyroblastic gneiss M 158
K_2O/Al_2O_3	0.15	0.25	0.27	0.34
Na_2O/Al_2O_3	0.10	0.33	0.23	0.19
$\frac{K_2O + Na_2O}{Al_2O_3}$	0.26	0.58	0.50	0.53

TABLE IV

Wt. %				
SiO_2	62.11	66.45	73.89	74.48
Al_2O_3	21.01	15.97	12.46	13.50
TiO_2	0.88	0.72	0.55	0.52
Fe_2O_3	4.75	2.30	0.60	0.58
FeO	1.11	5.26	4.04	0.59
Na_2O	3.27	3.30	2.95	2.28
K_2O	3.24	2.96	3.37	5.98
CaO	1.21	2.24	0.98	0.66
MgO	1.62	1.32	0.60	0.52
MnO	0.35	0.07	0.57	0.47
P_2O_5	0.03	0.03	0.09	0.09
Total	99.58	100.62	100.04	99.67

From the Table III it becomes clear that the K_2O/Al_2O_3 ratio steadily increases, indicating progressive enrichment in potash. Similarly the total alkalies ($Na_2O + K_2O$) also show a similar increase. On the other hand, Na_2O/Al_2O_3 ratio shows first a little rise and then with increasing migmatisation shows a gradual decline towards augenbearing and porphyroblastic varieties. This decline of soda-alumina ratio is another indication of the increased replacement of soda by potash.

$K_2O:Na_2O$ mols: The mol values for K_2O and Na_2O of the analyses of 5 representative migmatitic rocks (Table V) when plotted on standard diagrams prepared by Marmo (1955), ideally show that while augen bearing varieties fall within synkinematic field, the porphyroblastic gneisses (richer in microcline) lie in the late kinematic field (Fig. 28).

Niggli values: Niggli values of Si and Al for the two augen bearing varieties (Table VI) when plotted on standard diagrams of Marmo (1955) again confirm their synkinematic origin (Fig. 29).

Fig 28

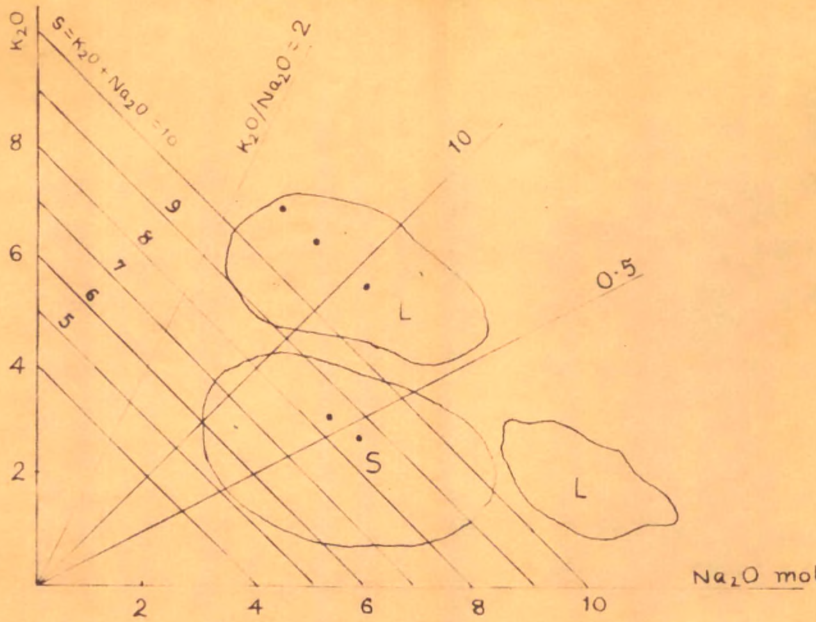


Diagram based on variation in alkalies in Majkhali migmatites (Marmo)

S - Synkinematic Field
L - Latekinematic Field

Fig 29

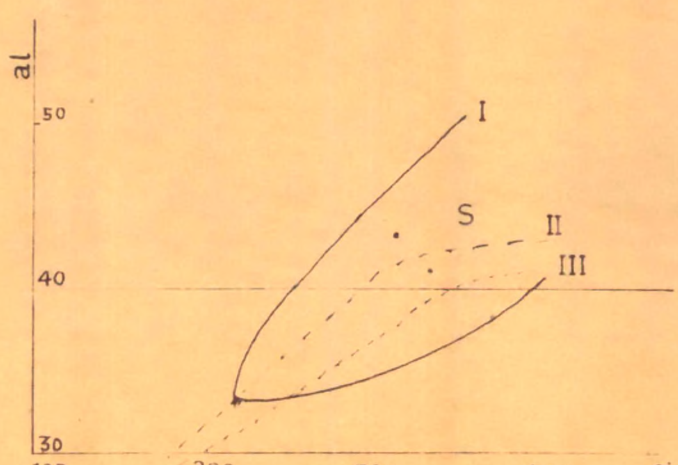


Diagram for synkinematic migmatites of Majkhali area (Marmo)

TABLE V

Wt.%	Augen gneiss		Porphyroblastic gneiss		
	M 154	M 157	M 158	M 160	K 17
SiO_2	73.89	66.58	74.48	73.20	74.45
Al_2O_3	12.46	16.10	13.50	12.50	14.11
TiO_2	0.55	0.62	0.52	0.42	0.69
Fe_2O_3	0.60	4.62	0.58	1.30	0.11
FeO	4.04	2.19	0.59	1.48	0.39
Na_2O	2.95	3.18	2.28	4.60	4.11
K_2O	3.37	3.43	5.98	4.90	5.24
CaO	0.98	2.24	0.66	0.50	0.52
MgO	0.60	0.71	0.52	0.20	0.35
MnO	0.57	0.50	0.47	0.20	0.25
P_2O_5	0.09	0.09	0.09	-	0.02
Total	100.04	100.36	99.67	99.90	100.24
K_2O	3.5	3.4	6.4	7.4	6.6
Na_2O	6.4	5.5	5.6	5.2	5.5

TABLE VI

Wt.%	Augen gneiss	
	M 154	M 157
SiO_2	73.89	66.58
Al_2O_3	12.46	16.10
TiO_2	0.55	0.62
Fe_2O_3	0.60	4.62
FeO	4.04	2.19
Na_2O	2.95	3.18
K_2O	3.37	3.43
CaO	0.98	2.24
MgO	0.60	0.71
MnO	0.57	0.50
P_2O_5	0.09	0.09
Total	100.04	100.36
Si	325	300
Al	42	44

The above chemical criteria, when considered together present the following picture of the process of migmatisation:

(1) The schists have been gradually transformed into gneisses, mainly by the addition of alkalies.

(2) The transformation started with addition of soda, which was soon followed by potash.

(3) Potash gradually replaced soda.

(4) There was only a limited increase in silica and negligible addition of alumina.

(5) The mafic content (MgO, FeO, Fe_2O_3, TiO_2) on the whole decreased.

(6) The migmatisation was mainly synkinematic.

MECHANISM AND CAUSES 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 aqueous solution of broadly granitic composition which reacts with the host rock, or it may take the form of a diffuse system of ions which migrates through the porefluids. Though the migmatising emanations could belong to any of the above categories, and migmatites could originate in various ways, it is now generally agreed 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 be essential for the transportation of ions. Read (1948, p.15) believed 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, pp. 409-411) has suggested three possible ways in which ions may migrate through a solid (crystalline) medium.

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

(ii) 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 vibrations become so large that ions may break away and wander through lattices.

(iii) 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 pelitic 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 interchanging constituents. It appears that in bringing about the migmatisation, hydrothermal solutions played rather a subordinate role. The absence of sericitization and chloritization during this transformation clearly 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, the 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.

Though the migration of quartzo-felspathic matter in a granitisation zone may extend in almost any direction, depending upon the particular conditions which control the driving free-energy gradients(Ramberg, 1952, p.261) of the movable material, there seems little doubt that the average direction of motion of granitic matter is upward from deeper portions of the geosyncline to relatively shallower levels. Granitic minerals - quartz, alkali felspars and micas have low densities and hence are thermodynamically most stable in the shallower zones. For this reason the above minerals, or minerals containing same elements as quartz, felspar, and micas (Si, Na, K, Al, O, H) will tend to disintegrate when pushed to deeper levels, and following the demands of thermodynamics, these elements must migrate upward until they get consolidated in the quartz and alkali felspar lattices in the zone of granitisation. "At higher temperature in deep orogenic zones, minerals tend to 'evaporate' (Frenkel, 1946) and the movable constituents will creep toward shallower depths under continuous consolidation. Because the most mobile constituents are those which build granites, quartz and felspar will preferably be displaced upward by this process also. To compensate for the upward diffusion current, the whole 'crust' sinks bodily through the swarm of slowly rising atoms, ions and molecules. In part, the calco-ferro-magnesian elements are also migrating chemically downward. In any case, the net result will be that granodioritic matter is rising and calco-ferromagnesian matter is sinking in the evolving folded zones, thereby minimizing the thermodynamic instability which causes the orogenic evolution. In other words, we may take the view that the energy potential gradient which drives the orogeny is the same as that which drives the granitisation and other kinds of large scale metasomatism. Thus it is so evident that folding, thrusting, and plastic flow of the rocks, as well as their recrystallisation and metasomatism, together with their local refusion, are all visible proofs of the exhaustion of the giant energy potential gradient which stands behind the whole phenomenon of orogeny" (Ramberg, 1952,pp.261-262).

The author would however, like to point out in the end that the mode of origin of the migmatites suggested by him, should be considered only tentative and valid for the rocks of the study area only. It is not his intention to make a generalised statement to include the origin of the gneisses and granites of the Almora region as a whole. Possibility of various other modes of the formation of migmatites in the adjoining areas cannot be ruled out, and he feels that each area has to be investigated on its own merit. An overall picture of the origin of migmatites (and granites) of the entire region can be obtained only after the various areas have been systematically studied.

MIGMATISATION IN RELATION TO THE VARIOUS DEFORMATIONAL EPISODES:

Deformation, regional metamorphism and granitisation - all these form integral part of orogeny and in any area of folded or uplifted geosyncline, a close relationship is seen to exist between deformation and regional metamorphism at one end, and between granitisation and regional metamorphism at the other. In the present case also, the study has amply revealed a synchronisation between various deformational and metamorphic episodes. The metamorphism in turn is seen connected with the migmatisation. Various stages of migmatisation and their relation to the fold episodes have been briefly summarised below:

(1) Migmatisation was initiated before the main folding (= F_1). This is clear from the folded

migmatitic band in the NE corner of the area. The folded shape of the band is due to F_1, the foliation having been impressed during the folding, and cutting across, marking the axial plane direction of the folding. The author believes that the earliest phase of migmatisation was initiated before the folding set in, and was confined for the deeper parts of the sinking geosyncline. This migmatisation broadly synchronised with the load metamorphism of the geosynclinal sediments. Perhaps this earliest phase was mainly a sodic phase.

(2) Migmatisation continued to be effective during the main isoclinal folding (F_1): The foliation (= axial plane) impressed on the gneisses developed during the folding. On account of this folding, the deepseated migmatised sediments were lifted up as anticlinal fold cores, and these are now seen forming a number of bands in the pelitic schists. 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 fluids also appear to have started rising.

(3) Migmatisation outlasted the folding (F_1): Both sodic and potassic emanations, one after the other, continued to play their effective role, transforming the augens into discrete porphyroblasts. These porphyroblasts, occasionally idoblastic, very often have grown across the foliation, without disturbing the foliation trend. The inclusions inside the porphyroblasts suggest a static and late kinematic growth. During this phase, potash appears to have dominated over the soda, and large scale replacement of plagioclase by microcline is recorded.

(4) The relationship between the last phases of migmatisation and the synformal folding (F_2) is not clear. A faint crinkling of the foliation on F_2 occasionally recorded, suggests that the migmatisation had practically come to a close, when the second folding(F_2) affected the rocks. Further data will only reveal the exact time relationship between the two.

For the time being, it is adequate to conclude that migmatisation and regional metamorphism synchronised with the main orogenic upheaval, and could be broadly considered as synkinematic.

Table showing the time relation between structure, metamorphism and migmatisation in Majkhali area

	Deformation	Metamorphism	Migmatisation
1.	Confining pressure (Vertically directed)	Load	Early migmatisation (? sodic)
2.	First folding (isoclinal)	Progressive (Staurolite-Almandine sub facies)	Main bulk of migmatisation-soda followed by potash.
3.	Shearing due to thrusting	Retrogressive -phyllonitic rocks along shear zones -(Green schist facies)	-
4.	Second folding (E-W synformal)	Progressive-Biotite porphyroblasts, new garnet	-
5.	Third folding	-	-