CHAPTER V

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

Introduction:

The metamorphism of the area has been built with the help of petrographical studies and the field data. The most striking metamorphic feature of the rocks of the Pilkholi area is their showing an apparent metamorphic inversion. It is only on taking into account the existence of the thrust at Upradi, that the true nature of the metamorphic character and the history of the area is understood. In fact, as is already mentioned the area comprises of two distinct tectonic units - an overthrust sheet of older rocks (Chandpurs ?) resting over the younger rocks of Krol Nappe (Nagthats ?).

Taking into account this fact, the metamorphism of the area can best be studied under the following three heads:-

(A) Metamorphism of the rocks of Garhwal Nappe (Chandpurs ?).

(B) Metamorphism of the rocks of Krol Nappe (Nagthats ?).

(C) Metamorphism in relation to the thrust - (phenomena of retrogression and metamorphic convergence).

(A) Metamorphism of the rocks of Garhwal Nappe (Chandpur ?):

The crystalline rocks belonging to this tectonic unit in the present area, disclose a long and varied metamorphic history during which a succession of connected metamorphic episodes affected the rocks. All the rock types discussed in the previous chapter give some clue or the other, about the metamorphism of the area. Especially the pelites are very helpful in reconstructing the metamorphic history. The rocks have passed through a series of different types of regional metamorphism, which played their role in succession both in the geosynclinal stage as well as after or during their upheaval. Obviously the mountain building forces played quite an important role in the metamorphism of the area.

From the preceding petrographic description and textural details of the various rocks, the author has built up the following metamorphic history:

Phase I:

Progressive Metamorphism:

This covers an early phase of regional metamorphism which was almost synchronous with the earliest deformation which folded the area into a big reclined structure. The metamorphic foliation that developed during this event coincided with the axial plane of the fold. Thus the metamorphic foliation (of schists and gneisses) is essentially of the axial plane type, related to the overfolding and not a product of load metamorphism. The parallelism of the foliation with bedding is due to the isoclinal nature of the folds.

Phase II:

Migmatisation:

The 'migmatisation' appears to have closely followed the 'progressive' phase. Porphyritic, augen - bearing and permeation gneisses are in fact, themigmatised derivatives of the pelitic schists and ultimately related to the regional metamorphism. At geosynclinal depths, granitising emanations appear to have invaded the rocks in the core of the fold, their passage facilitated by metamorphic (axial plane) foliation.

Phase III:

Retrogressive Metamorphism:

On account of the continued activity of the deforming stresses, the fold ultimately culminated into a thrust. The differential slipping and shearing in the vicinity of the thrust not only crushed and granulated the schists but also brought down the metamorphic grade. The retrogression is characterised by the development of phyllonites.

I. PROGRESSIVE METAMORPHISM:

The term "Progressive metamorphism" is used to cover an early phase of regional metamorphism to distinguish it from a later phase of diaphthoresis. The progressive phase of regional metamorphism whose effects are well preserved in the rocks, was almost synchronous with the earliest deformation which folded the rocks in Ranikhet area in a big reclined fold. As the main foliation of the rocks lies almost parallel to the axial plane of this fold it is obvious that the metamorphism and deformation were closely connected and proceeded almost hand in hand.

Pressure conditions:

It is now a well established fact that, on account of large scale crustal deformations in regions of active orogeny, geosynclinal sediments are subjected to extreme differential (non-hydrostatic) stresses consisting of either horizontally directed compression or distortional stress (shear). Both these stresses appear to play an important role not only at shallower depths, but even in deepseated metamorphism. Rogues (1952, pp.12-19) has estimated 7000-10000 meter depth for the zone of lower schists containing biotite-garnet-staurolite etc. This could give an idea of the depth at which sediments were metamorphosed in the present case. Directed stresses acting on geosynclinal sediments at deeper levels folded

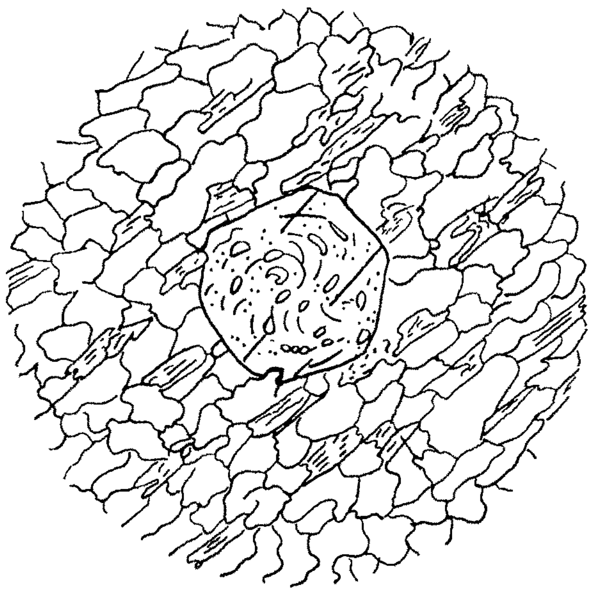


Fig 28

Garnet in mica-schist from Chaubatia showing rotational growth (x 30).

them into a big reclined fold. 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. That the shearing stress played an important role in the metamorphism, is also suggested by the rotated garnets. The 'S' shaped inclusions of quartz in the garnet suggest the rotation of garnets during the growth (Fig.28). The rotation during growth can best be explained by invoking differential slippage in the foliation direction.

Temperature conditions:

The various mineral assemblages indicate that the rocks belong to the "Staurolite-Almandine" sub-facies (Almandine-Amphibolite facies) of Turner and Verhoogen (1960,pp. 545-46). They (1960, p.552) have mentioned that "temperature during this phase of metamorphism must generally be higher in the almandine-amphibiolite facies than in the green schist facies. They conclude that metamorphism in the almandine-amphibolite facies covers a temperature range of perhaps 550°C - 750°C and pressure normally between 4000 and 8000 bars". Thus it is quite reasonable to assume moderately high temperature as it is also evidenced by the abundant development of biotite and garnet in the rocks of the present area. Possibly temperature and stress must have operated in combination to set the above metamorphic conditions.

Ramberg (1952, pp. 272) has pointed out that some heat may be evolved by the intense deformation of the rocks in the orogenic belts. As regionally metamorphosed rocks are born in the intermediate and deeper levels of folded mountains, some metamorphic heat could be generated by differential stresses. But it should however be pointed out that the important source of heat in regional metamorphism lies somewhere else.

The problem that arises thus is about the source of the enormous amount of heat required, to raise the temperature. Deep burial alone does not account for metamorphic temperatures. Turner and Verhoogen (1960, pp. 667-668) have discussed this point and "concluded that during regional metamorphism both the temperature gradient and the upward heat flow are considerably higher than, and perhaps twice or three times as great as, the normal values. Regional metamorphism is not a mere consequence of deep burial, it occurs only when and where heat, and possibly water enter the rocks undergoing metamorphism in abnormal amount".

Magmas, mostly granitic or granodioritic, although they do act as heat sources, are presumably in most cases palingenetic or (? migmatitic). Whatever their mode of origin, they are not the normal constituents of the earth's crust or mantle. To consider them as the main source of heat, does not solve the problem of the ultimate source of temperature rise. The same argument appears to the rise of temperature supposed to be caused by an upward rise of juvenile fluids from deeper level. Here too, we are left with the problem where these fluids came from and why.

Regional metamorphism is typically associated with fold mountain chains. The crust is believed to be thicker ("roots") below a mountain range and this thickening must occur at some stage of orogenesis. If the crust is sufficiently radioactive, (which is not a wrong presumption) its notable thickening would also be conducive to the development of high temperatures, which in turn may give rise to high-grade metamorphism, palingenesis, or start processes of granitisation.

Mineral Assemblages:

Based on the study of various metamorphic mineral assemblages in the different rock types of the area an attempt has been made by the author to derive the original nature of the sediments and also to trace the effect of this metamorphism on various rock types.

Pelites and Semi-pelites:

The pelites and to a certain extent, semi-pelites, being more sensitive to pressure and temperature changes are usually good guides in the study of regional metamorphism. Most of the pelitic and semi-pelitic schists of the present area contain the following mineral assemblages:-

(1) Quartz-biotite-muscovite-garnet-plagioclase.

(2) Quartz-muscovite-biotite-garnet.

(3) Quartz-biotite-plagioclase-clinozoisite.

(4) Quartz-biotite-plagioclase-garnet.

The above assemblages are characteristic of "Almandine-Staurolite sub-facies" of Turner and Verhoogen (1960) and must have been derived from sediments deficient in potash and rich in alumina and silica. The constant presence of biotite suggests that the original sediments were rich in MgO. The presence of almandine suggests a strong preponderence of iron in dioxides.

<u>Psammitic rocks</u>:

The siliceous rocks represent the metamorphosed felspathic sandstones as clearly seen from the following mineral assemblages:-

(1) Quartz-microcline-muscovite-(biotite).

(2) Quartz-plagioclase-biotite-(muscovite)-garnet.

These rocks are rather uninteresting from the point of view of the metamorphic history. Beyond certain point, these rocks tend to show no further mineralogical response to rising temperature during metamorphism. The invariable presence of microcline indicates that the original sediments were rich in potash (Turner 1948,p.84). The quartzites represent highly siliceous sediments while those with garnet might be rich in Mg and Fe. The presence of biotite in quartzite suggests a little argillaceous nature.

The original nature of the psammitic rocks could be of two types:-

(1) Layers of siliceous sandstones interbedded in shales.

(2) Argillaceous sandstones - derived from shales by a gradual increase of quartz content.

Facies:

The rocks of the present area belong to Epi- and Mesozone of Grubenmann (as evidenced by the formation of chlorite, epidote, albite, zoisite, sodic plagioclase, muscovite, biotite and almandine) and "Almandine zone" of Barrow characterised by the wide-spread occurrence of "Pink garnet" in the rocks especially pelites and semi-pelites.

The rocks thus, are obviously a product of medium grade metamorphism. The various mineral assemblages, viz., (i) Quartz-garnet-muscovite-biotite-(plagioclase), and (ii) Quartz-microcline-plagioclase-biotite-muscovite-clinozoisite, indicate that the rocks of the present area belong to the 'Staurolite-Almandine' sub-facies of

'Almandine-Amphibolite' facies of Turner and Verhoogen (1960). This 'Almandine-Staurolite' sub-facies includes the rocks which are thought to be formed under the condition of moderate temperature and strong deformation.

II. MIGMATISATION:

The author's investigations have revealed that the gradual transition of garnetiferous mica schists to coarse felspathic gneisses, ideally exhibits the phenomenon of migmatisation.

The migmatisation which appears to have closely accompanied and followed the regional metamorphism is ultimately associated with obscure plutonic processes at geosynclinal depths. The granitising emanations invaded the rocks in the core of the reclined anticlinal fold, their passage facilitated by the metamorphic (axial plane) foliation. The host rocks viz. schists, in the deepseated core of the fold gradually changed over to gneisses. Thus, the regional metamorphism and migmatisation as shown by the rocks of the Ranikhet-Pilkholi area clearly established that the two phenomena are ultimately interrelated and connected with the orogenic movements, which deformed the geosynclinal sediments; also the migmatisation for the most part was syntectonic.

In the past considerable work has been done on the granite and gneissic rocks of the Himalayas and variety of views have been put forward from time to time. The early workers viz., McMahon, Wadia, Pilgrim and West(1936), Auden(1933) and Middlemiss were obviously convinced of these gneisses and granites being of igneous origin. But lately a number of workers viz., Petermisch (1949), Pande (1963), Das (1963), Gupta (1961) and other have started believing that the granitic rocks could be of metasomatic origin. According to Petermisch (1949), "the origin of banded gneiss of Nanga Parbat is due to permeation of felspathic material along active foliation planes. According to him degree of metamorphism and granitisation are systematically linked. However, Nautiyal (1940) and Malhotra (1950) working on the granites of Almora and Sihaidevi respectively, have preferred to consider these rocks as of magmatic origin. But on going through their works, the author found that most of the criteria on which they concluded the igneous origin, could very well be utilised to support the metasomatic origin. The author's investigations indicate that the gneissic rocks of the present area are of metasomatic origin.

Regarding the age of the Himalayan granites and gneisses, McMahon (1883), Grieshbach (1891), Auden (1933), Hayden (1934), West (1936), Sarkar (1965) and others have described them to belong to the following three periods:-

(i) Late Palaeozoic granites.

(ii) Early Tertiary gneissose granites.

(iii) Biotite-, Hornblende-, and Tourmaline granites of late cretaceous or early Tertiary age.

Wadia describes the gneisses of Nanga Parbat and Gilgit as post Dogra and favours post Carboniferous age for the biotite granite of Pir Panjal. In Himalayas, there are granites of more than one age. Perhaps Pande (1963) was the first to consider the gneissic rocks of Kumaon to be migmatites and of Tertiary age. Sarkar (1964) too has found that the granitic rocks and the metamorphism of the associated rocks could be dated as lower Oligocene. He has assigned their age on the Ar/K radioactive dating of the muscovite samples from Ranikhet and Almora. The gneissic rocks of the present area too show evidence of migmatitic origin and closely connected with the Himalayan orogeny and this has led the author to believe that the gneisses originated syntectonically and are possibly of Tertiary age. The pre-tectonic granites described by different workers in other parts of Himalaya have not been found in the present area.

Granitisation and Migmatisation:

Geologists differ in their opinion regarding the origin of granitic rocks. The various views and hypotheses put forward for the origin of granitic rocks can be broadly grouped under the two main schools of thoughts, one belonging to Magmatist school and the other to Transformist school. Magmatists believe that the granitic rocks are formed from the magma by its consolidation or crystallisation. But further they differ regarding the origin of magma and its source. The transformist believe that granitic rocks are produced by metasomatic processes which did not lead to the dissolution of the solid framework. Transformists however, differ in their opinion as to whether this transformation is "Wet" or "Dry". Considerable confusion has arisen out of varied definitions of transitional or similar processes put forth by several authors. An acceptable definition which the author considers quite suitable is due to McGregor who describes the granitisation as "the process by which solid rocks are converted to rocks of granitic character"; and "includes all such processes as palingenesis, permeation, migmatisation, injection and assimilation" (McGregor and Gilbert 1949, pp.194).

Read (1957, p.88) defines granitisation as "the process by which solid rocks are converted to rocks of granitic character without passing through a magmatic stage". According to him, "Migmatisation is the final product of the regional metamorphism. Regionally metamorphosed rocks at depth or at the core are the migmatites". According to him (p.359) regional metamorphism and granitisation are genetically connected. Once granitisation has begun in the 'Sial', it will proceed with the evolution of the orogenic belt. Chemical mobility is followed by mechanical mobility, the basement becomes reactivated, anatexis and related processes contribute their quota, and the terms of the Granite Series appear in orderly progression.

Evidence of migmatisation in Ranikhet-Pilkholi area:

The author has come across ample evidence to suggest the migmatitic origin of the gneissic rocks of the area investigated. In the following lines, he has summarised the various criteria that he has taken into account to arrive at the above conclusions:

1. Field Criteria:

(i) The gradational contact of gneisses with country rocks:

The gneissic rocks of the present area show gradual contact with the schists. They occur as a narrow band which gradually merges on both sides into schists by the gradual decrease in the felspar content. If it would have been granitic intrusion, it would have shown sharp junction with the host rocks.

(ii) The gradual increase in the size of felspars:

The gradual increase in size of the felspars from very small lenticles to augens and porphyro-blasts indicate increasing felspathisation. It is very strikingly convincing phenomenon to note that small felspar centres which mark the beginning of the process, gradually tend to grow in size, forcing apart or cutting the foliae, and ultimately growing as porphyroblasts lying at all angles.

(iii) Identical nature of foliation:

The identical nature of the foliation of gneisses and that of neighbouring schistose rocks indicate that they are the result of migmatisation. Had it been an intrusive granite it would have disturbed the schistosity of the neighbouring schists. The coincidence of schistosity and foliation can not be explained by intrusive contact.

(iv) <u>Absence of features caused by forceful injection:</u>

No evidence of forceful injection is recorded anywhere in the area. There is complete absence of brecciated contacts and xenoliths etc.

(v) <u>Resister</u>:

The thin bands of quartzite occurs as caps with a sharp junction over the gneissic band. These siliceous rocks resist migmatisation and obviously acted as barriers, not allowing felspathic solutions to permeate through them. Read and Watson(1962,pp.564) write that "Pure quartzites are chemically remote from the granites. They are made up of almost one single component, silica, and felspathisation cannot take place without considerable influx of material. Highly siliceous rocks are therefore resisters which tend to retain their original characters against migmatisation."

(vi) Variation in grain size:

It is observed in the field that the band of gneissic rocks is bordered by the felspathic schists - a narrow zone between schists and migmatites. The felspathic schists gradually develop augens and ultimately the felspars grow as porphyroblasts in median part of the band. With the gradual passage of felspathic schists to porphyroblastic gneiss there is a progressive increase of grain size of the rock.

(vii) Ghost stratigraphy (Relicts of the host rocks):

Relicts of host rocks - generally the ribs of quartzites and occasionaly schists are recorded at several places. About half a furlong to the south of Ranikhet Dakbungalow and also at the quarry near Jhuladevi,relicts of the host rocks (schists) are found in migmatites. These occur more or less in the form of thin ribs surrounded by felspathic rock, migmatites. It is remarkable to note that these relicts contain pods of felspar, similar to those of migmatites. These remnants are otherwise in conformity with the foliation of the adjacent migmatite and do not show any disturbance. All these characters strongly favour the view that they are the remnants of the original rocks left untransformed by the process of felspathisation.

2. Petrographic criteria:

(i) Sutured texture:

Porphyroblastic quartz and felspars generally show intricate sutured outlines. Such texture has been explained by many as due to metasomatic replacement (Gilluly 1933, Read 1931, Cheng 1943, Pande 1957).

(ii) Perfect gradation from schists to gneisses:

Even under the microscope it is noticed that the specimens collected across the strike of the contact from the schists to the central part of the migmatite band, show a very gradual change with increasing development of plagioclase and potash felspars. This perfact gradation from schists to gneisses with increasing quartz and felspar content indicate metasomatism.

(iii) Gradual increase in size of plagioclase porphyroblasts:

The plagioclase first makes its appearance as a slightly bigger grain than the rest of the mass, lying along the foliation. Then its size is seen to gradually increase. The borders of the porphyroblasts are highly sutured and partly include the adjoining micas and quartz. With further increase in size and content, it forms regular augens, and finally as big porphyroblasts lying across the foliation.

(iv) Gradual replacement of plagioclase by microcline:

All stages of the replacement of plagioclase by potash felspar can be traced. This is a very clear indication of replacement.

(v) Absence of perthites:

Igneous granites typically contain perthites. Absence of these in the gneisses of Ranikhet supports their non-magmatic origin.

(vi) Presence of Garnet:

The presence of garnet porphyroblasts in migmatites clearly indicates that the gneisses were originally garnetiferous mica schists.

(vii) Inclusions of quartz and mica:

In igneous granites, the sequence of crystallisation is such that inclusions of micas and felspars are more likely in quartz, as the latter is the last to crystallise. But in the present case, the augens or porphyroblasts of plagioclase and garnet contain abundant inclusion of pre-existing quartz and mica.

(viii) The selvages of biotite around the augens and porphyroblasts:

It is common to see selvages of biotite and muscovite recrystallised (minerals of the host rock) around the porphyroblasts (Read & Watson, p.535).

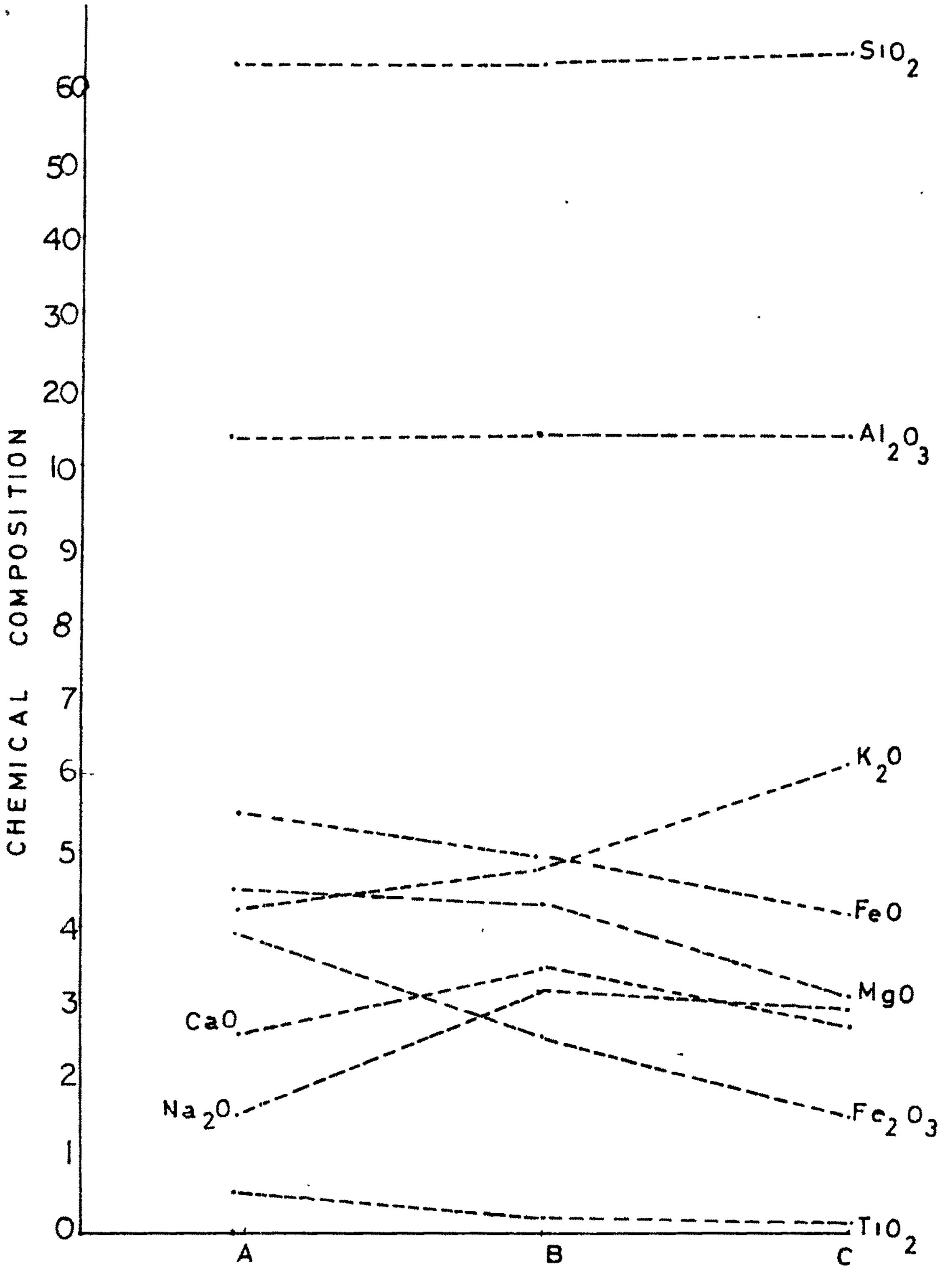
3. Chemical Criteria:

(i) The chemical data too support the views held by the author. Representative samples of mica schists (A), augen gneiss (B), and porphyroblastic gneiss (C) were chemically analysed.

	Garnet mica schist (A)	Augen gneiss (B)	Porphyroblastic gneiss (C)
SiO_2	62.9	63.61	65.23
Al_2O_3	14.06	14.75	15.42
Fe_2O_3	3.96	2.56	1.51
FeO	5.62	4.96	4.28
CaO	2.61	3.43	2.70
MgO	4.52	4.36	3.01
K_2O	4.28	4.81	5.18
Na_2O	1.80	3.19	2.97
TiO_2	0.52	0.15	0.086
P_2O_5	0.014	0.18	0.052
MnO	0.004	0.007	0.003
Total	100.288	100.517	100.441

Fig 29

VARIATION GRAPH BASED ON DISTANCE vs. CHEMICAL COMPOSITION.



Discussion:

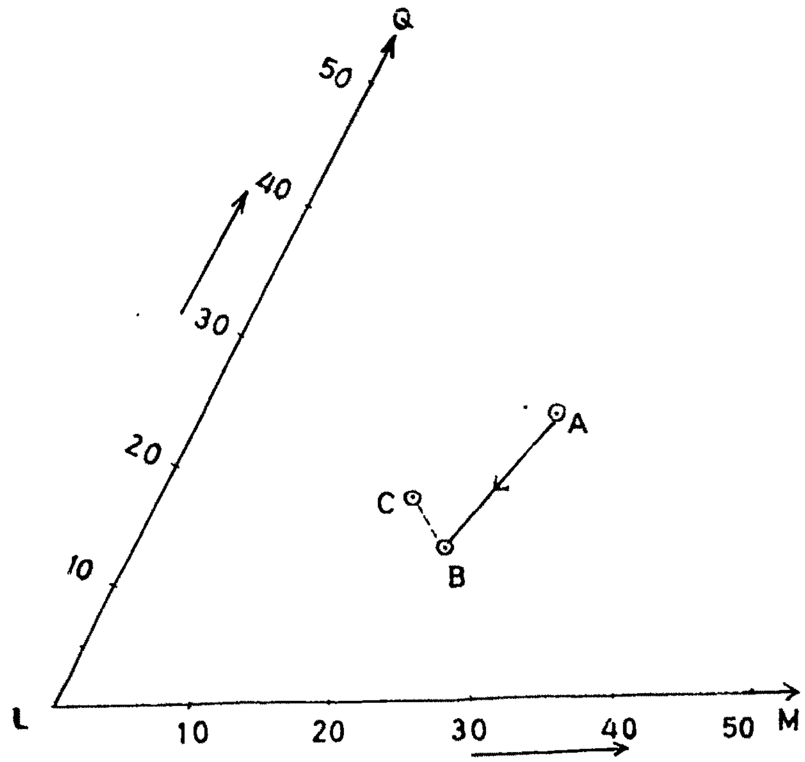
From the study of the graph (Fig. 29) plotted from the above chemical analyses, it is clearly seen that there is an increase of Alumina and Silica towards porphyroblastic gneiss and moderately higher concentration of potasium, sodium and calcium is observed with decrease in percentage of iron, magnessium and titanium oxides. Maximum Na_2O and CaO is seen in augen variety. Possible inference that can be drawn from these observations is that, granitisation process has resulted in the expulsion of ferromagnesian elements i.e. FeO, TiO_2, Fe_2O_3, MgO etc. with resulting increase in alkali metals and SiO_2 in porphyroblastic gneiss. It is interesting to note that while potash shows a steady rise, the soda percentage declines in the porphyroblastic type. This is due to the replacement of soda by potash.

(ii) Q.L.M. Values:

The following are the values of Q.L.M. (after von Wolff) obtained from the chemical analysis done by the author.

Fig 30

von Wolff's Q-L-M Diagram



	Garnet-mica Schist A	Augen Gneiss B	Porphyroblastic Gneiss C
Q	22.60	11.23	15.84
L	52.41	66.64	66.03
M	25.00	22.20	17.66

The above values obtained have been plotted on the triangular diagram (Fig.30). From this diagram, it is clear that garnet-mica schist (represented by A) has in the first stage been converted into Augen gneiss (represented by B) by a process of felspathization and desilication. In the subsequent stage of alteration, the augen gneiss gave rise to porphyroblastic gneiss (represented by C) by a process of granitisation involving addition of silica and decrease of mafic constituents. This result supports the author's views regarding the progressive granitisation of garnet-mica schist through augen gneiss to a final stage of porphyroblastic gneiss as indicated in the discussion on field evidences.

Conclusion:

All the above mentioned evidence clearly point out that the gneissic rocks are in fact migmatites, of metasomatic origin. In general the original schistose structure can thus be clearly seen in all gradations to schist. This indicates the control of schistosity over granitisation.

The process and stages of migmatisation:

The migmatisation is closely connected with regional metamorphism at geosynclinal depth. The rocks which now occupy the core of the fold represent the sediments from the deeper levels, which were nearest to the theatre of granitisation. These were granitised easily by the migmatising emanations rising from depth. The passage of such rising emanations was facilitated by the development of metamorphic (axial plane) foliation, which acted as "privilaged paths". Migmatisation appears to have immediately followed the folding and the metamorphism of the rocks, and possibly formed a later phase of the same orogenic event. Thus the schists in the core of the fold gradually changed over to gneisses.

Petrographic study of the rocks reveal that the process of migmatisation consisted of an early sodic phase which gave rise to plagioclase porphyroblasts in the augen and porphyroblastic variety. This sodic phase was followed by a potassic phase which is evidenced by the replacement of plagioclase by microcline in the above varieties.

This scheme of progressive alkali increase agrees with that proposed by Lapadu - Hargues(1945) who found that regional metamorphism leading to granitisation consists of a progressive calc-alkali influx combined with an iron-magnesia migrating into lower grade zones. He found that with increasing grade, there is an influx of alkalies from deeper zones. In the lower grades, there is an accession of soda; in higher grades, the accession of alkalies continues with potash dominant - both alkalies come from a deep source - the soda moving the farther.

The migmatisation is first recorded in the feslpathic schists with the appearance of abundent plagioclase in the groundmass, and then as augens and finally as well formed (very often idiomorphic) porphyroblasts. The potassic emanations appear to have followed the sodic ones, and show increasing activity from augen bearing to porphyroblastic variety of gneisses. All gradual stages of replacement of plagioclase by potash felspar are observed in the gneissic rocks of this area (Fig. 22). In the augen gneisses the microcline is seen in the ground mass only, but with its increasing content in the porphyroblastic variety, a number of plagioclase porphyroblasts are seen in various stages of gradual replacement by microcline. Broadly speaking the deformation (reclined folding) and migmatisation almost coincided, though some post folding migmatisation cannot be ruled out. Read and Watson (1962, pp. 567-69) have mentioned that "Migmatites are developed in regions of moderate or high temperature where the country rocks are invaded by active emanations..... Near the base of the crust in the orogenic regions, temperature may become so high that partial liquifaction takes place. A fluid containing the most easily mobilised components gather in all interstices and partings, and this fluid may be forced by orogenic pressures to move upward into new regions where it reacts with the country rocks to produce migmatites..... The migmatisation material consists of granitic fluids or of the active components Si, Na and K diffusing as ions ". About the stages (p. 562) "The first sign of migmatisation in pelitic schists is generally shown by the development of eyes and irregular streaks of coarse quartzo feldspathic material, or of ovoid feldspar porphyroblasts lying in the plane of schistosity. At the margins of feldspathic areas the minerals of host rocks often recrystallise to produce selvage of large micas, sometime associated with garnet. As migmatisation proceeds, felspar appears in the groundmass of the host and the quartzo felspathic folia multiply to produce a gneissose texture. The original schistosity may give place to a less regular foliation."

From the above field and petrographical evidence and discussion, the following sequence of events would be suggested:-

(i) Due to isoclinal folding, deeper portions of the geosynclinal sediments were lifted up in the core of the fold.

(ii) Principal foliation of the metamorphic rock coincided with the axial plane direction of this early folding.

(iii) These deepseated rocks, nearest to the theatre of granitisation seem to have been easily affected by the migmatising emanations from depth which rose along the foliations. Migmatisation might have thus immediately followed the folding.

(iv) As shown by the thin sections of these migmatised rocks, the sodic emanations were followed by the potassic, the former travelled farther.

It also becomes quite clear that the migmatisation and the formation of gneissic rocks closely followed the upheaval, deformation and metamorphism of the sediments, and formed an integral part of the main orogenic event.

III. <u>RETROGRESSIVE METAMORPHISM</u>:

The rocks of the Pilkholi area afford an excellent example of the retrogressive metamorphism, a case of metamorphic down-grading caused by a dislocation (S. Almora thrust). On account of the continued activity of the deforming stresses, the rocks ultimately ruptured and the Ranikhet overfold culminated in the thrust. The differential slipping and shearing in the vicinity of the thrust not only crushed and grannulated the schists but also brought down the metamorphic grade.

Due to retrogression the garnet mica schists ultimately end up as sericite-chlorite phyllites (phyllonites) in the vicinity of the thrust. Thus deformation is seen to play an important role in the retrogression in the present area.

"Retrogressive metamorphism- (diaphthoresis) - the mineralogical readjustment of high temperature metamorphic assemblages to a lower temperature, is generally attributed to strong deformation or to hydrothermal activity subsequent to the main stage of metamorphism" (Turner and Verhoogen 1960,p. 486). The criteria establishing retrogressive metamorphism are almost entirely mineralogical. The interpretation of retrogressive phenomena is based on the assumption that, over the lower range of metamorphic temperatures, metamorphic reactions proceed at an appreciable rate only when accelerated by strong deformation or by a passage of a wave of aqueous or other pore fluids. The two factors i.e. deformation and hydrothermal solutions, then could be regarded as "Catalytic" agents responsible for the retrogression. Which of the two above discussed factors, is more effective is a matter of some disagreement. Schwartz and Todd (1941, p.188) consider that retrogression is mainly due to the attack of hydrothermal solutions on so called high grade minerals. Turner (1948, p.302) on the other hand thinks that Schwartz and Todd have emphasized unduly the role of aqueous solutions in this process. He agrees more with Knopf's (1931, p.7) statement that "If adjustment to the new pressure-temperature field is to take place, the instigating force or trigger of the reaction must be furnished by a strong differential movement of the constituent parts before or together with the diaphthoresis". Read (1934) also placed emphasis on the deformation. According to Turner (1948,p.303) the aqueous solutions generally play minor role only. Downgrading of metamorphism is usually attributed to strong differential stresses aided by hydrothermal solution. Deformation possibly acts as 'Catalytic agent' and triggers off the process of retrogression. Slipping and shearing along pre-existing metamorphic foliation are very often seen to cause retrogression.

Petrographic details of the retrogressive change have already been discussed in the previous chapter. It will be evident from these descriptions that the retrogressive changes have been preserved best in the pelitic and semi-pelitic rocks. Psammatic rocks do not seem to have been affected by the retrogression. The author proposes to discuss below its various aspects in a general way.

(1) <u>Textural and Mineralogical changes</u>:

Texturally the rocks tend to show crushing and grannulation, a gradual diminution of grain size and stronger foliation. The foliation is seen folding. This drag folding has been caused by the slipping along the foliation itself.

Mineralogically, the garnets, biotite and muscovites are seen most affected. On account of crushing along planes of slipping:

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

(ii) Plagioclase content has been diminished.

(iii) The idioblastic garnets show alteration to chlorite and biotite. This alteration is more common along cracks and sides and they are sometimes seen alter to haematite. Fragments of garnets lie along the foliation and are seen altering to chlorite.

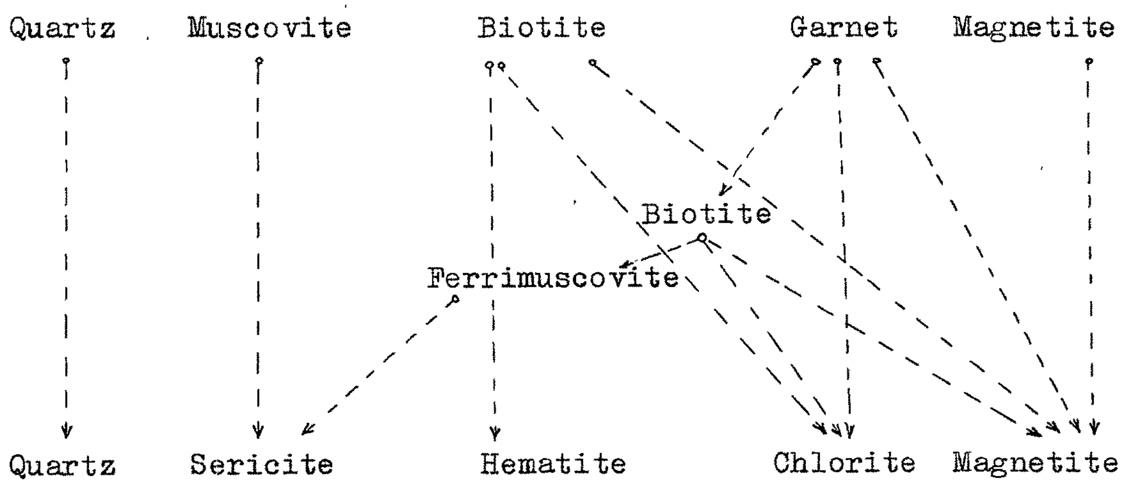
(iv) The biotite is seen altering to chlorite.

(v) Biotite is also seen changing to ferri-muscovite with the liberation of iron oxide.

(vi) Abundant tiny grains of magnetite scattered all over in the phyllonite are obviously a bye-product of the degeneration of garnets and biotites.

(vii) Muscovite has changed to streaks of sericite.

Mineralogical changes brought about by the retrogression:



(2) Cause of the retrogressive metamorphism:

Retrogression is attributed to strong differential stresses usually aided by hydrothermal solutions. In the present case, the differential stresses have played a dominant role during the entire metamorphic history. During the early stages of the orogeny, the differential stresses coincided both the progressive metamorphism. The same stresses - which caused the overfold to culminate into the thrust were equally effective in the diaphthoresis that accompanied the dislocation. It is thus interesting to note that shearing stress is equally important in bringing about metamorphism as well as decreasing the metamorphic grade. Slipping along the foliation at the time of the thrusting would be the prime cause of retrogressive metamorphism in the area.

(3) Date of the retrogressive metamorphism:

Retrogression appears to have followed immediately the progressive phase, and formed an integral part of the regional metamorphism. It is seen that the deformation which accompanied the progressive phase of regional metamorphism and migmatisation, continued to be effective during the retrogressive phase and was its main cause. With the increasing intensity of the deforming stresses, the fold gradually passed into the thrust. Thus it can be inferred with fair amount of certainty that there was a very little time interval between these two phases of regional metamorphism.

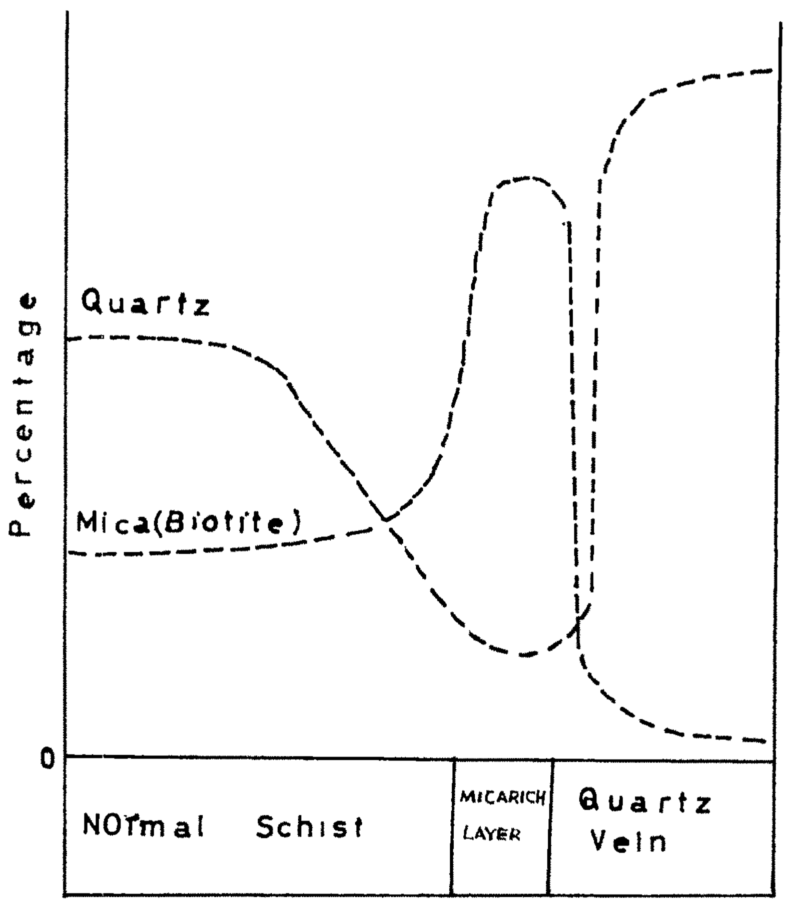
Quartz Veins:

The widespread occurrence of veins or strings of quartz and in the metamorphic rocks of the area is recorded.

It is seen that these veins and strings in the area have identical orientation over large distances and are obviously due to segregation or sweating of quartz along shear planes. It has been found that these veins are mainly composed of coarse grained milky white quartz. The contact zone between quartz veins and neighbouring schists is found to be

Fig 31

GRAPH SHOWING BIOTITE QUARTZ RELATION NEAR QUARTZ VEIN



(Based on Chapman)

very poor in quartz and rich in mica proportion (Chapman 1950, Fig. 31). Obviously the quartz veins are the products of metamorphic differentiation. Role of shearing stress in metamorphic differentiation is noteworthy.

(B) Metamorphism of the rocks of Krol Nappe:

To the south of the Upradi thrust, below the Garhwal Nappe, lies the Bajina series (Krol Nappe) consisting mainly of alternating layers of slaty-phyllites and quartzites. They show a slight decrease in metamorphic grade when traced away from the thrust.

As discussed in earlier chapters, within the limits of the area investigated, the rocks of the underlying Krol Nappe constitute an upper - psammitic group consisting of phyllites, and quartzites and a lower calcareous group - crystalline dolomitic limestone. The various rock types have already been discussed in detail in Chapters III & IV and the description gives a fairly good hints about their metamorphism. Pelites as usual are very helpful in tracing the metamorphic history.

On the whole, the rocks show low grade metamorphism. The metamorphic grade is as high as of chlorite zone. The various mineral assemblages indicate that the rocks belong to quartz-albite-chlorite sub-facies (green schist facies) of Turner and Verhoogen (1960, pp. 530-31).

Mineral assemblages:

A study of the various metamorphic mineral assemblages throws some light on the original nature of the sediments.

(i) Pelites:

The following mineral assemblages have been traced by the author:

(a) Quartz-chlorite-sericite

(b) Quartz-sericite-chlorite

(c) Quartz-(sericite)-(chlorite)-plagioclase.

(ii) Psammites:

The siliceous rocks represent the metamorphosed felspathic sandstone.

The common mineral assemblages are:

(a) Quartz-sericite-plagioclase.

(b) Quartz-plagioclase-microcline-(± biotite).

(iii) Calcareous rocks:

The calcareous rocks are seen to consist of calcite-dolomite-quartz. This suggests that original calcareous sediments must be rich in Mg and some silica.

The above assemblages clearly suggest that the sediments consisted of a lower calcareous portion, fairly rich in Mg and having SiO_2 as dominant impurity. Beds overlying the limestones, constituted a group of psammites and pelites interbedded. The psammitic portion contains argillaceous impurities and some sodic material. The pelitic layers obviously were derived from normal argillaceous constitutents. The absence of epidote possibly suggests lack of CaO.

Obviously the rocks of Krol nappe show a fairly low grade of metamorphism. The presence of oligoclase could be taken as an indication of a metamorphic grade, a little higher than that of the green schist facies.

Nature of Foliation:

In the quartzites, and limestones the sedimentary bedding is clearly seen at many places. Occasionally, current bedding is also recorded. The interbedded argillaceous layers have a well defined slaty cleavage, which for the most part is parallel to the bedding.

The slaty cleavage however becomes almost phyllitic in the vicinity of the thrust which indicates a slight increase in metamorphic grade. It is not possible for the author to say anything definite about the nature and genesis of this metamorphic foliation.

(C) The phenomenon of Metamorphic Convergence:

The area, when traversed from north to south, shows an apparent metamorphically inverted sequence which is characterised by the occurrence of slate and slaty phyllite at the bottom, overlain successively by phyllonites, chlorite-schists, garnet-mica schists and gneisses respectively. As the investigations reveal, the area affords an example of metamorphic convergence and not of metamorphic inversion. The Upradi thrust has metamorphically joined the two tectonically distinct units.

The differential slipping and shearing that accompanied the thrust, not only crushed and granulated the rocks of the overthrust sheet but also brought down its metamorphic grade which is characterised by the gradual retrogression of garnet-mica schist to sericite-chlorite-phyllite (phyllonites) near the thrust. The thrust also affected the underlying rocks of the Krol nappe by causing a slight increase in the metamorphism in the vicinity of thrust. The slaty rocks become more phyllitic towards the thrust. Thus the area affords a good example of Read's 'Metamorphic Convergence'.