CHAPTER-4

PETROGRAPHY and METAMORPHISM

The region around phalasia and Jharol consists of a varied lithology occurring uniformly over several kilometres. The rock types encountered here are mafic-ultramafic, pelitic and psammitic. In the present study, the petrography and mineralogical composition of the different rocks have been studied based on which the regional metamorphic history of the different rocks and the relationship of metamorphism to the various deformational events has been established.

The various rocks of the study area show a great petrographic diversity which in fact, reflect their complex evolutionary history. Microscopic studies clearly reveal that the rocks have undergone various mineralogical and textural changes during successive periods of deformation and metamorphism. A careful perusal of petrographic characters has enabled the author to throw new light on the geological evolution of the study area. In the following pages, a systematic account of the various microscopic characters of the different rock types belonging to the three main groups, has been given.

IV.A PETROGRAPHY

A.1 MAFIC :

The mafic rocks consist of amphibolites and serpentinites. The serpentinites occur along the fault zone, giving rise to intrusive type of nature to the rocks (Figure-III.1). The minerals present are mostly serpentine with chromite and calcite. (Plate- IV.1).

Amphibolites

Amphibolites of dark greenish colour are characterised by the presence of varying amounts of anthophyllite, hornblende, plagioclase, diopside, garnet, quartz and epidote (Plate-IV.2). The accessory minerals present are sphene, calcite and microcline.

Textural characters :

These rocks are medium to coarse-grained showing gneissic to granoblastic texture. The gneissic texture is characterised by the arrangement of alternate layers of hornblende and plagioclase (Plate-IV.3). Sometimes the rock with higher proportion of hornblende shows a coarse granoblastic texture (plate-IV.4).

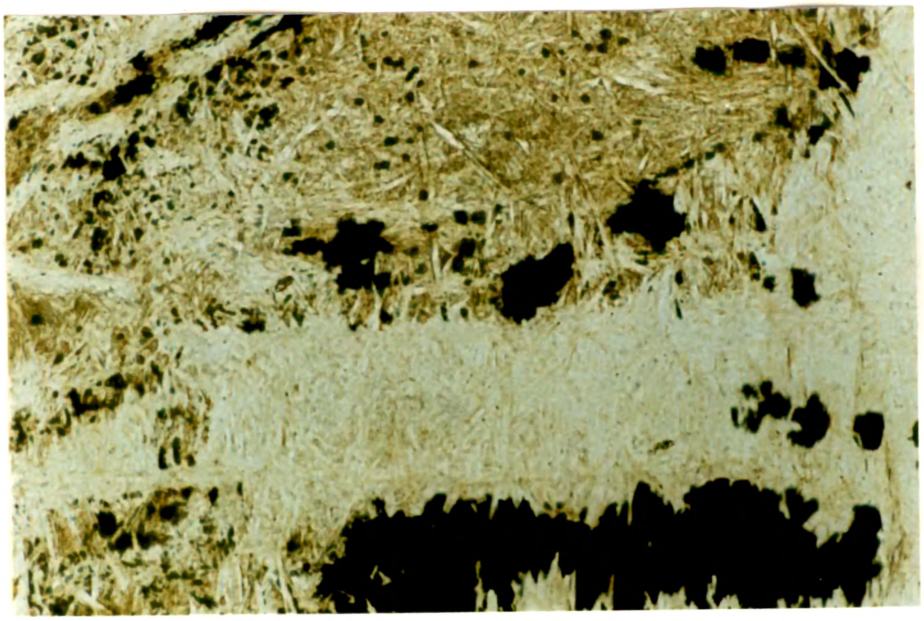


Plate - IV.1 Photomicrograph of serpentinite with chromite (M=20x, XN).

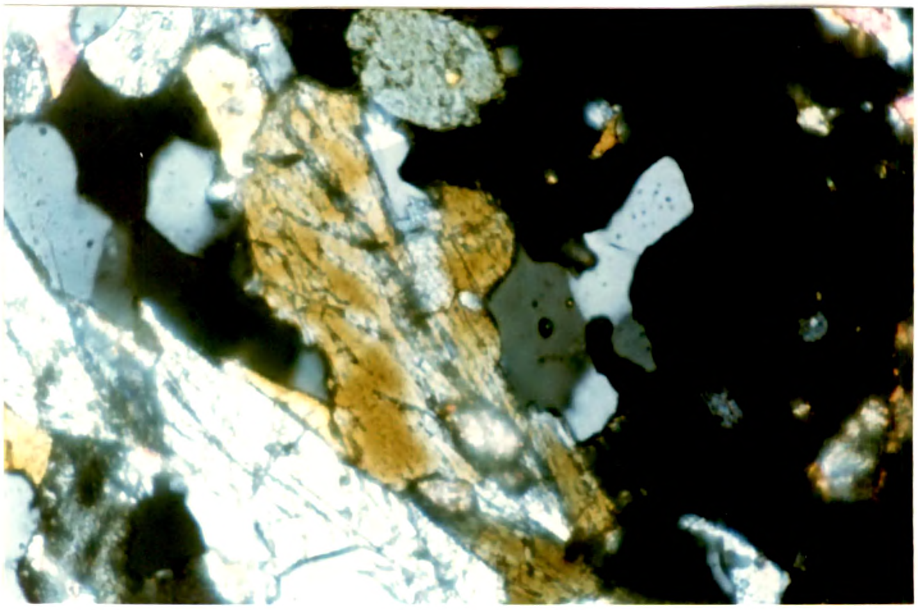


Plate - IV.2 Photomicrograph showing Garnet, epidote and hornblende in amphibolites (M=20x, XN).

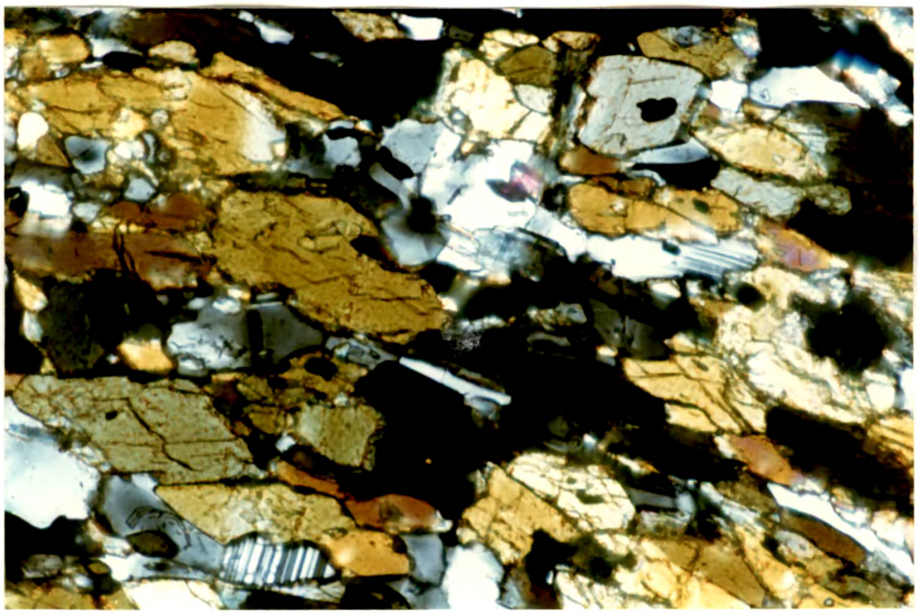


Plate - IV.3 Photomicrograph showing alternate rich layers of plagioclase and hornblende in amphibolites (M=20x, XN).

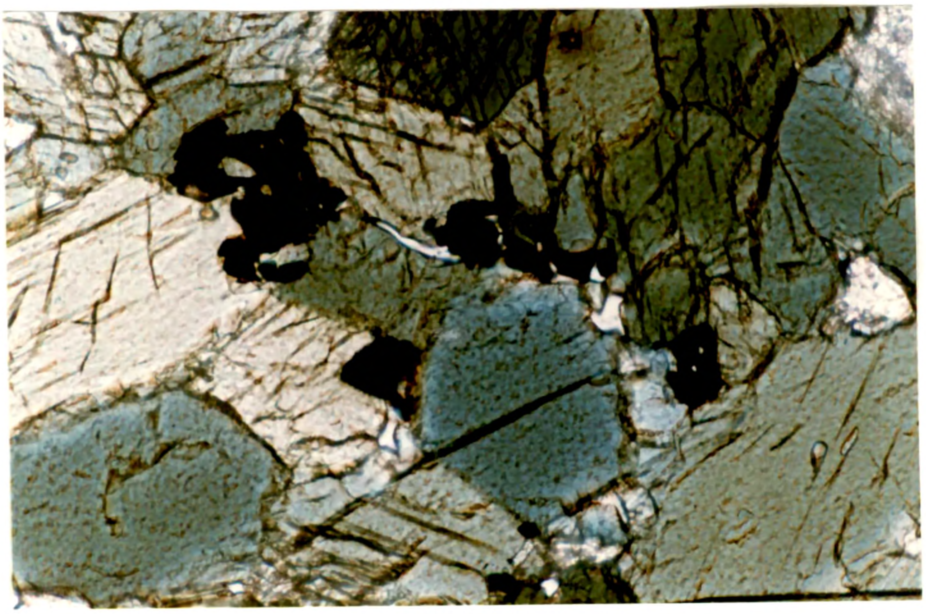


Plate - IV.4 Photomicrograph showing granoblastic structure in amphibolite (M=20x, PPL).

MINERALOGY :

In the following pages the mineral assemblages of amphibolites are described.

Hornblende occurs as prismatic crystals, irregular outlines and their parallel and subparallel orientation marks the foliation, sometimes the mineral shows poikiloblastic growth, containing inclusions of plagioclase and quartz. In the coarse hornblende rich varieties, it occurs as large transverse six-sided crystals and broad prismatic blades as observed in plate IV.2 and IV.3. It shows pleochorism from yellowish green to olive green and is identified by its typical amphibole cleavage, parallel to inclined extinction (from o° to 16°). The prismatic sections exhibit one set of cleavage.

Plagioclase observed here is usually clear but at places few grains are interlaced with each other making it difficult for identification. Plagioclase is anhedral to subhedral, somewhat broad and tabular crystals. It is characterized by lamellar twins. Nature of plagioclase is andesine showing 20° extinction angle. Its proportion is always less than that of the hornblende.

Diopside forms anhedral and subhedral grains. Some grains are even elongated, lath shaped with one set of cleavage. It is always subordinate to hornblende and strong birefringence, inclined extinction (42° extinction angle).

Quartz is seen as irregular grains and is confined to the granoblastic mass of the rock. At some places it forms smaller inclusions in hornblende.

Garnet (grossularite) occurs as euhedral and subhedral porphyroblasts and is either colourless or has light yellowish brown tint. It is identified by very high relief. Fractures and cracks are common. Some garnet grains are extremely flattened and stretched.

Anthophyllite is found in subordinate quantities, occurs as ragged and ill-defined prismatic crystals. The mineral is pleochoric from brownish to pale greenish yellow. It shows typical amphibole cleavage and parallel extinction in prismatic sections.

Tremolite, actinolite and epidote are mostly confined to the interstitial spaces between the hornblende and plagioclase crystals.

Calcite and microcline is found in very few thin sections of amphibolites. Saussiritization is also observed.

Sphene, Scapolite and iron ores form the accessory constituents and occur as scattered grains.

A.2 PELITES :

The pelitic rocks occur throughout the study area. Based on their mineralogical composition, these pelitic rocks can be classified into three groups.

(i) Garnet-mica-schists.

(ii) Sillimanite-garnet-gneisses.

(iii) Phyllitic-schists.

The regional metamorphism of the pelitic sediments has given rise to several varieties showing varied mineralogy and texture. Mineralogically, the rocks are composed of quartz, biotite, muscovite, garnet, sillimanite, staurolite, plagioclase, chlorite and orthoclase.

Textural features :

Texturally, the rocks are very interesting. Mostly the rocks show schistose structure, but occasionally gneissic and phyllitic structure (Plate-IV.5 and IV.6).

Schistose structure is confined to varieties which are without feldspars with the presence of feldspar and partial removal of the parallel arrangement of constituent minerals, the rock assumes a gneissic appearance defined by their tendency to lie parallel to the foliation. The rocks also

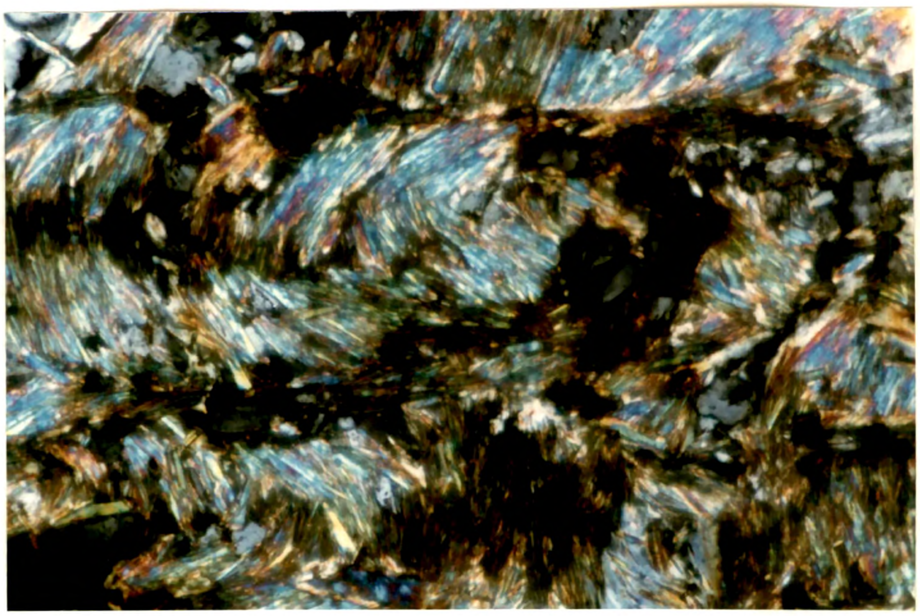


Plate - IV.5 Photomicrograph showing growth of micas along axial plane of AF_3 (M=20x, XN).

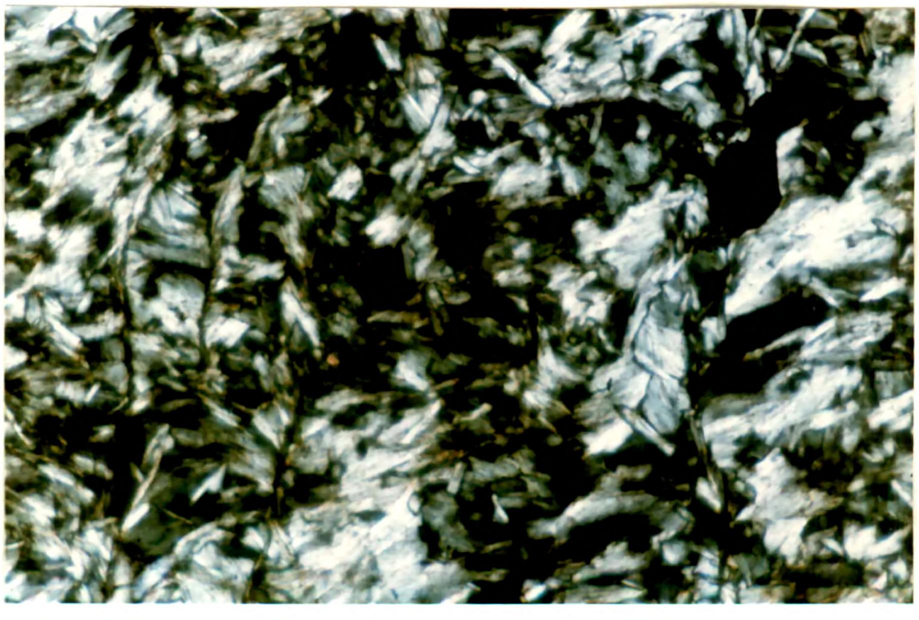


Plate - IV.6 Photomicrograph of chlorite schist (M=20x, PPL).

show porphyroblastic structure on account of the development of large crystals of garnet, biotite and muscovite.

Phyllitic structure is assigned to the low-grade schistose rock, extremely fine grained, highly sheared and mylonitized with chloritic material. The schistosity in these rocks is characterised by the parallelism of mica and chlorite flakes. The minerals present are muscovite, chlorite, quartz and sericite.

MINERALOGY :

Quartz occurs in the form of irregular xenomorphic grains of different sizes. It is either clear or with a few small patches of dust like inclusions. It generally occurs in several sizes, but mostly as elongated bodies parallel to the banding or small irregular grains in the quartz feldspar mosaic. The larger grains mostly show strain effects. The smaller grains occupy interstitial spaces. At times, the mineral shows Bohm lamellae due to post crystalline deformation. The larger grains of quartz show irregular cracks and are occasionally filled with muscovite.

Feldspars comprise of orthoclase and microcline. Most of the feldspar forms untwinned to patchily twinned grains. Microcline is uncommon in these rocks. Orthoclase is identified by its very low relief, right angled cleavages (though not very clear in the present rock sections) and oblique extinction. Its presence was confirmed by staining with sodium cobaltinitrate, the potash feldspar receiving a yellow stain (Nold and Karl, 1967). Feldspars are seen largely altering to sericite. Orthoclase shows rather greater degree of alteration, and the alteration at times, is so pronounced that the sericite forms pseudomorphs after the parent feldspar retains the original shapes and forms.

Sillimanite shows various modes of occurrence. One with basal parting with one set of cleavage found as porphyroblasts and also as fibrolitic aggregates within and around garnet. The sillimanite porphyroblasts lie with their longer axis parallel to the foliation planes. The mineral shows typical cross-fractures. The fibrolitic sillimanite is seen swirling around the garnet and also enclosed within it. In thin section it is observed that the sillimanite is altered to muscovite. The microfolding of the mineral (Plate-IV.7) indicates that the mineral was formed by the metamorphism related to the main foliation (M_1) and its microfolding took place during the super-imposition of later folding (M_2).

Sillimanite is identified by its form - both crystals as well as fibres. It shows moderate birefringence, length-slow orientation and biaxial positive figure. The longitudinal sections show parallel extinction and the

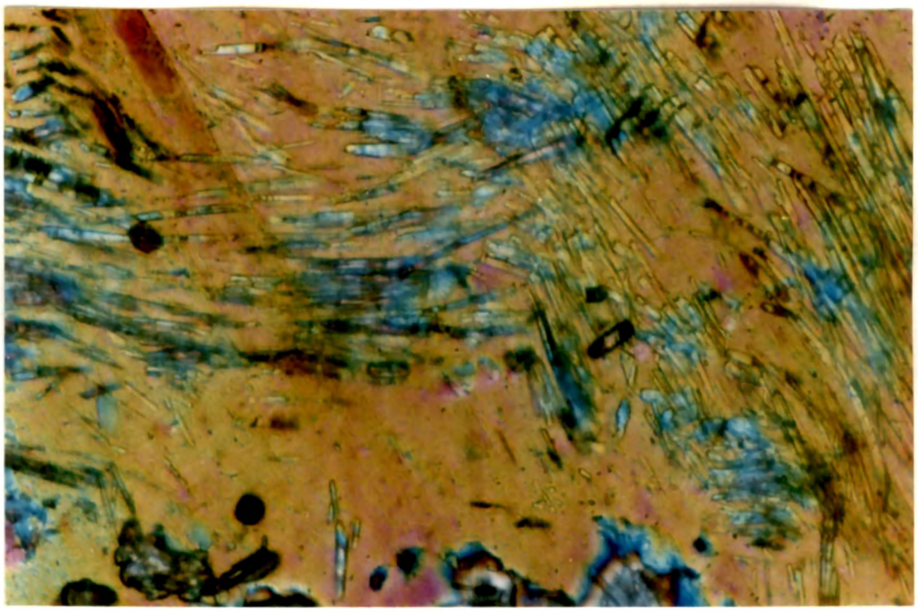


Plate - IV.7 Photomicrograph of sillimanite needles in muscovite (M=20x, XN).

Plate - IV.8 Photograph of AF_2 fold in schistose rock.

cross-sections of the mineral show symmetrical extinction.

Garnet (Almandine) which has characteristic mauvish pink colour in hand specimen, is pale pink to colourless in thin section (Plate-IV.8). It is found present in several habits. It remains completely isotropic under cross nicols. It occurs in different sizes and shapes. Some occur as irregular xenoblastic grains, some as elongate and stretched grains (plate-IV.9 and IV.10). The porphyroblastic garnets are generally irregular and skeletal, and the idioblastic garnets are not very common. Syntectonic garnets are also common. (Plate-IV.11). The porphyroblasts of garnets are seen much cracked, the cracks being either irregularly distributed or transverse to the elongation. It is nearly poikiloporphyroblastic with inclusions of quartz.

Garnet's close association with sillimanite is ideally seen in thin sections. Its grains are seen swirling around by sillimanite mineral. Garnet may be concentrated in bands or scattered throughout the rock and often forms the major constituent by volume.

Staurolite is identified by its light to dark yellow pleochorism and first order grey (order of colour) interference colours. It is observed in the form of small grains as well as euhedral porphyroblasts. They are deformed. The bigger porphyroblasts are crowded with oriented

Plate - IV.9 Photomicrograph of the garnet in the core portion of AF_2 fold of Plate-IV.8. Micas are crystallized along the axial plane of the fold. (M=20x, XN).

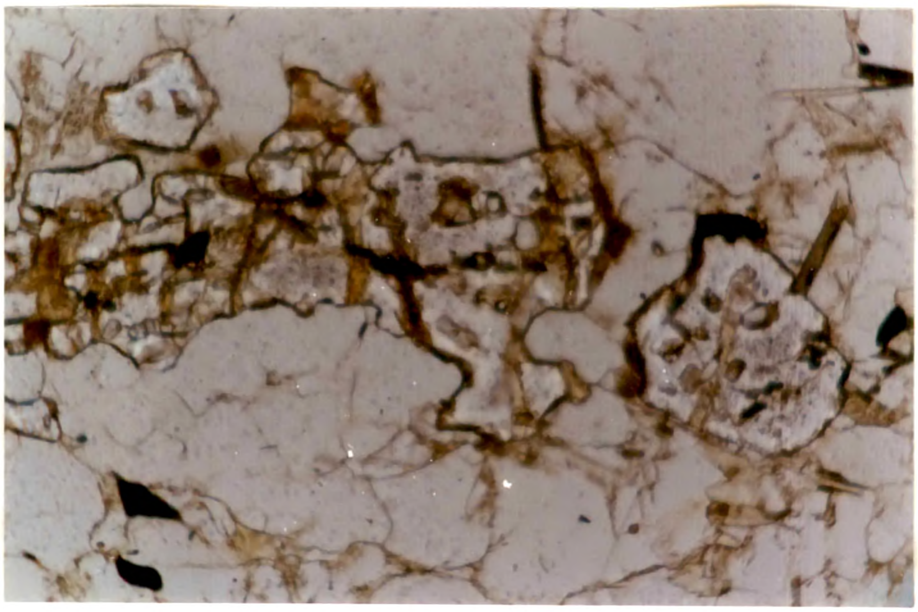


Plate - IV.10 Photomicrograph of elongated garnet in schists (M=20x, XN).

lenticular inclusions, in particular of quartz (Sieve structure) (Heinrich, 1956) undeformed garnets are seen within folded staurolite (Plate-IV.12) and are proving synchronous development of both the grains. Alteration from staurolite to chloritoid (ottrellite) due to retrogression is observed (Plate-IV.13). Quartz veins are transecting the poikilitic staurolite crystals.

Biotite appears in different forms from fine to coarse grained flakes associated with garnet and sillimanite. The smaller grains are confined to the groundmass, and also forms inclusions in other minerals. The coarse grained biotites form porphyroblasts. Their proportion in the rock is quite variable. Parallel orientation of the biotite flakes imparts foliation to the rock. Biotite laths often continue in the same orientation through porphyroblastic garnet. The biotite laths cut across the other porphyroblast minerals and the abundance of biotite may be due to the later generation ie : retrogression. AF_4 crinkles in biotites is observed (plate-IV.14).

The mineral is pleochoric from pale yellow to dark brown. It shows moderate relief, high birefriengence and straight extinction. Darker biotite with very deep brown colour are also seen, and these are indicative of higher iron content.

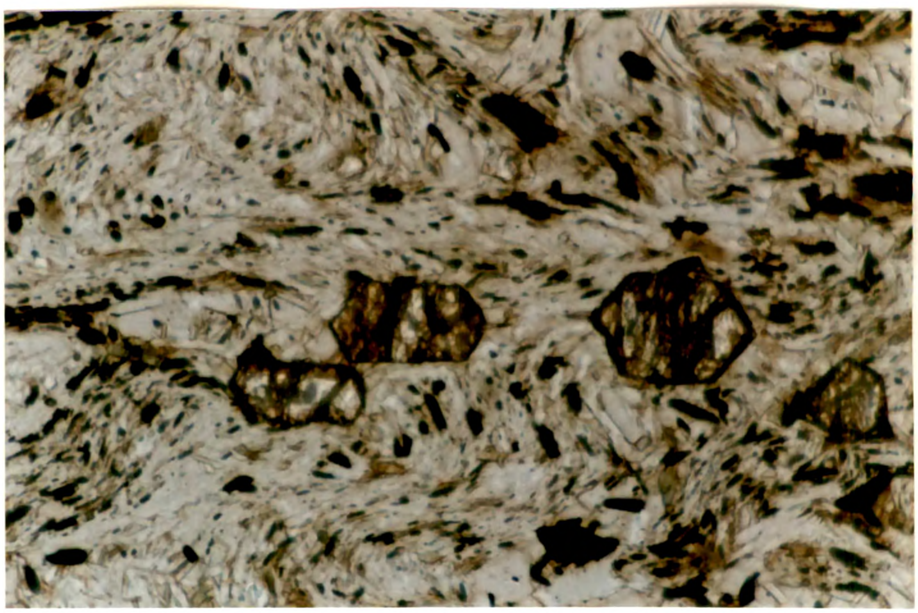


Plate - IV.11 Photomicrograph showing synkinematic growth of garnet (M=20x, XN).

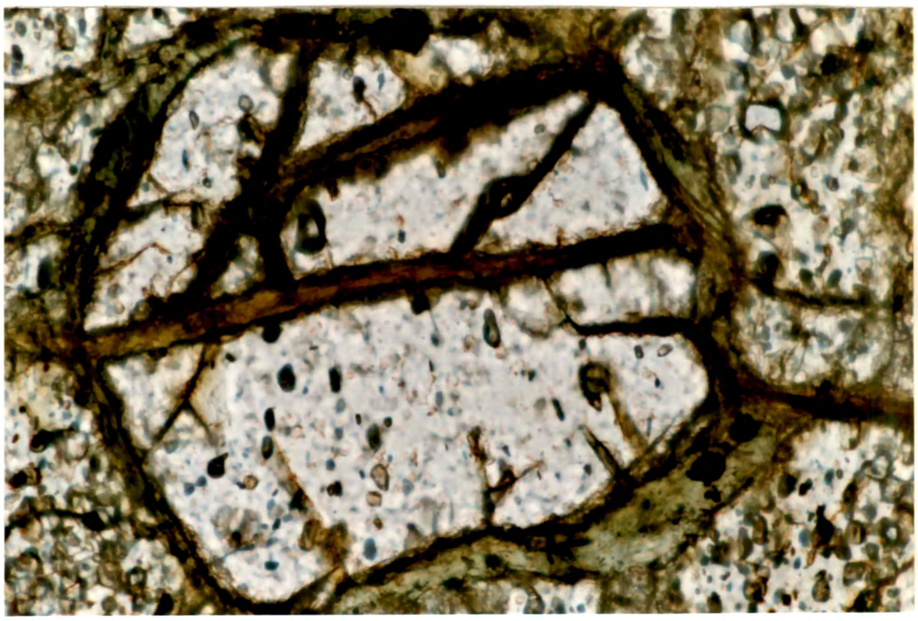


Plate - IV.12 Photomicrograph showing almandine garnet within staurolite (M=20x, PPL).

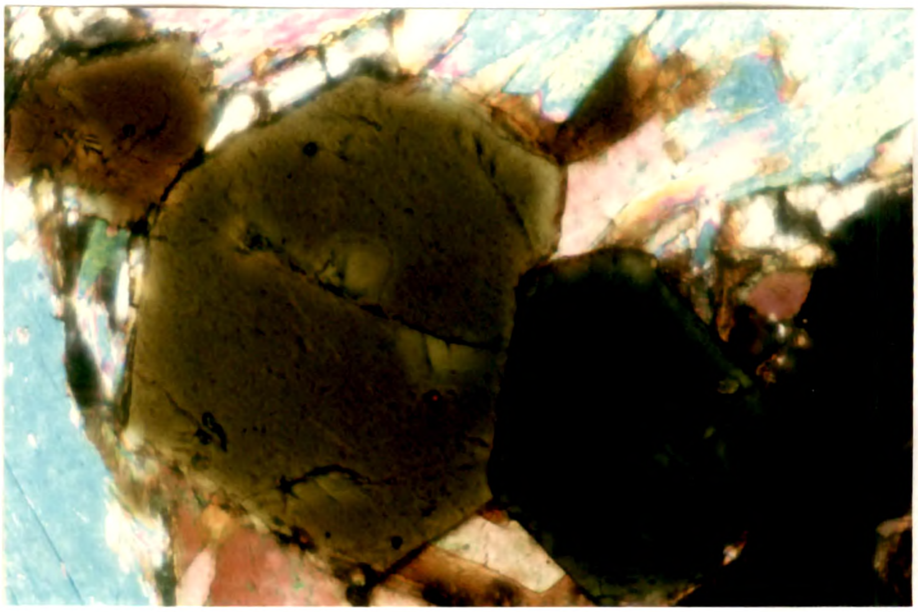


Plate - IV.13 Photomicrograph showing ottrellite in staurolite schist (M=20x, XN).

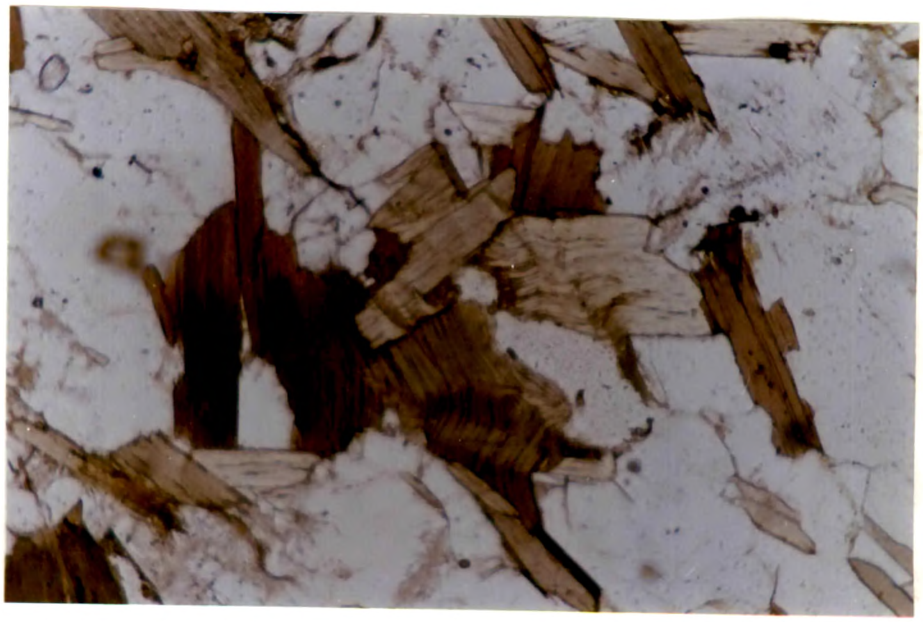


Plate - IV.14 Photomicrograph showing AF_4 crinkles of biotite (M=20x, PPL).

Alteration of biotite to chlorite is quite common. The chlorite shows typical anomalous blue colours.

Muscovite is always present and is found to be dominating the other minerals present. It occurs in several habits. Small flakes, are associated and intergrown with biotite. Such flakes of muscovite are parallel to the foliation. Another mode of occurence is as clusters (1mm to 2mm wide), of tiny flakes with random orientation. These muscovites are obviously the recrystallization products of later origin. Most commonly they are the alteration products of sillimanite and feldspars. The early muscovite which occurs in association with biotite confirms to the foliation, while the late muscovite flakes lie randomly.

Chlorite is a secondary mineral derived from biotite and garnet (Plate-IV.15). It is recognised by its green colour. Some fresh type of chlorites are also observed with very deep greenish blue colour.

Sericite is found mostly as the alteration product of sillimanite and feldspars.

Accessory minerals are apatite, tourmaline and Iron ores. Apatite is present in the form of anhedral grains in the midst of biotite flakes. Tourmaline occurs as tiny grains showing pleochorism from pale yellowish green to dark yellow.

Iron ores are magnetite, chromite and ilmenite, and these form small specks and grains.

A.3 PSAMMITES (Quartzites) :

The quartzites are one of the most conspicuous rock types of the region. The massive quartzites form the thickest single formation in the study area. They are highly sheared and form sinuous ridges throughout the region. They are white in colour and consist of coarse quartz grains and very little amount of mica. Some quartzites show presence of sillimanite in them.

Textural characters :

The rock is medium to coarse grained showing granoblastic texture, with equant grains only slightly interlocking. In some quartzites coarser, anhedral quartz grains or clusters are scattered through a finer-grained matrix.

MINERALOGY :

Quartz is seen as irregular grains. It occurs in several sizes, but mostly as elongated bodies parallel to the banding. The larger grains mostly show strain effects. The larger grains of quartz show irregular cracks and occasionally the cracks are filled with mica.

Micas (muscovite and biotite) appears in different forms from fine to coarse grained flakes. The coarse grained micas form porphyroblasts. Parallel orientation of the micas imparts foliation to the rock.

Sillimanite occurring in quartzites occurs in both modes, with basal parting as well as in fibrolitic aggregates. (plate-IV.16).

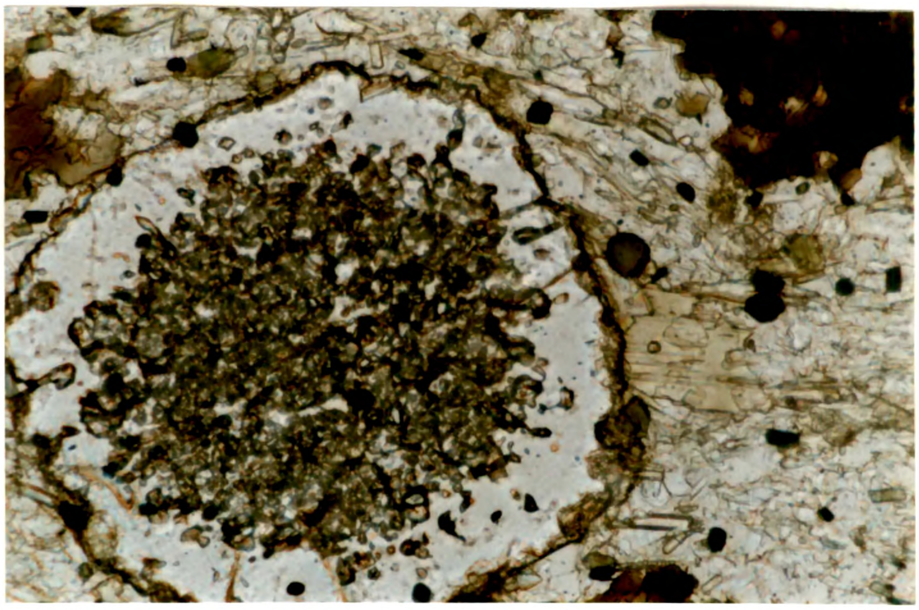


Plate - IV.15 Photomicrograph showing garnet altering to chlorite (M=20x, PPL).

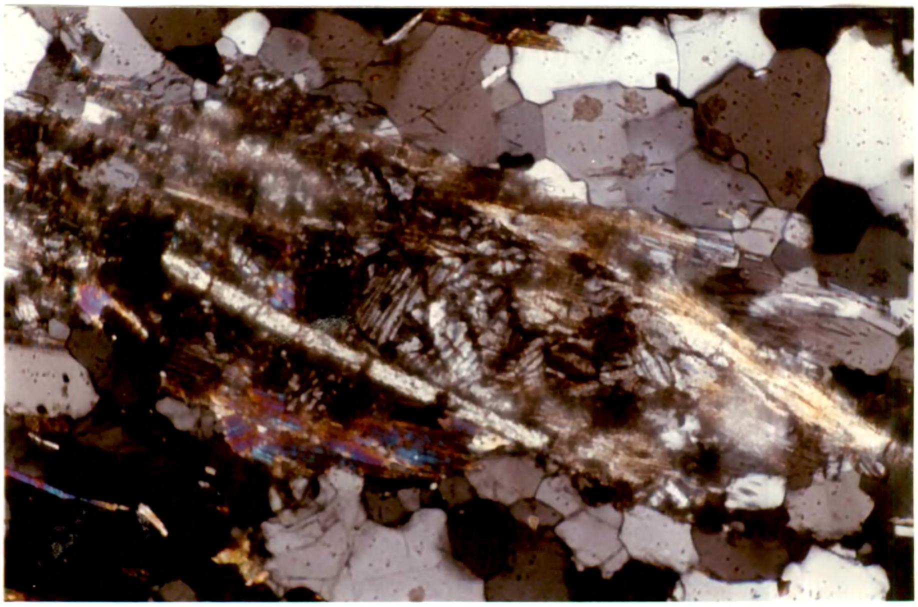


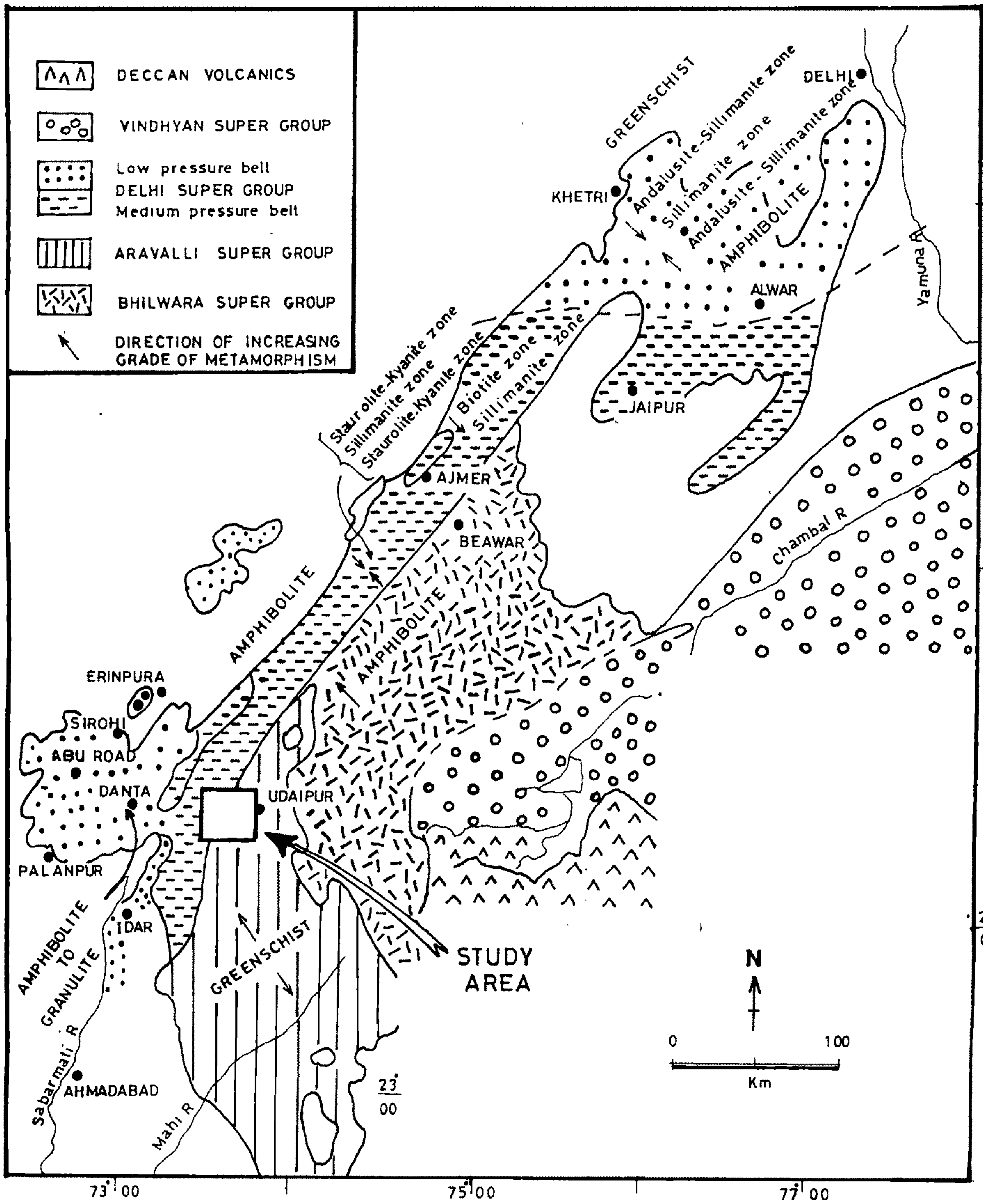
Plate - IV.16 Photomicrograph showing sillimanite in quartzite (M=20x, XN).

IV.B METAMORPHISM

Metamorphically, preCambrians of Rajasthan have been studied only sporadically by some workers (Lal and Shukla, 1975; Sharma and Narayana, 1975; Sharma, 1977, 1983_a, 1983_b, 1983_c; Sharma and Mac Rac, 1981, Sharma et.al; 1987; Desai et.al. 1978; Sychanthavong and Merh, 1981; Gangopadhyay and Sen, 1972, Gangopadhyay and Lahiri, 1983; Sinha-Roy and Mohanty, 1984). The Banded Gneissic complex of rocks have imprints of polymetamorphism ranging in facies from high-rank amphibolite to granulite, while the Aravalli supergroup shows evidences of low-grade green-schist to amphibolite facies, and the Delhi rocks exhibit greenschist to granulite facies, two regional metamorphic events and the late kinematic diapthoresis. Thermal metamorphic effects are recorded only around the granitic intrusions and mafic plutons mostly found in the Banded gneissic complex terrain and in the Delhi tract.

The present account deals with the study of metamorphic rocks, particularly with respect to the mafic and the pelitic rocks, vis-a-vis the deformational episodes. The rocks of Jharol area as seen today, represent a typical polymetamorphic terrain, and their structure, texture and mineralogy point to an interesting metamorphic history. After the critical study of various aspects of these rocks, the following picture of metamorphic evolution has emerged.

MAP OF THE ARAVALLI-DELHI BELT SHOWING DISTRIBUTION OF TYPES AND ZONES OF METAMORPHISM



(After Powar & Patwardhan 1984)

Figure - IV.1

B.1 REGIONAL METAMORPHISM

Regional metamorphism of the rocks of the study area forming a part of Aravalli supergroup had to be carefully delineated and studied, after identifying and separating the metamorphic effects. Systematic metamorphic studies in the Jharol belt rocks have not been attempted and no literature on metamorphic aspects is available. The author had to make a careful scrutiny of the various textural and mineralogical criteria and then work out the metamorphic evolution. The various mineral assemblages of different lithological types, typically indicating the original high-grade regional metamorphism are also summarised. In all, two metamorphic episodes each of which taking place synchronously with folding have been detected, and one retrograde (diapthoresis) metamorphic event accompained by extensive shearing (dislocation metamorphism of Turner and Verhoogen, 1962; Turner, 1968) has also been recognized. The first two metamorphic events termed here as M_1 and M_2 were coeval with AF_2 and AF_3 foldings as evidenced by the internal deformation, (folding and rotation) recrystallization and breakdown of high-grade minerals into low grade mineral assemblages. The later event (M_3) is found only along the major shear zones, where maximum alteration is observed.

I.A. PROGRESSIVE METAMORPHISM

(Lower to Upper Amphibolite facies)

Mineral Assemblages :

(A) Staurolite - almandine subfacies :

I Ultramafic Rocks :

Serpentine - Calcite

II Mafic Member :

1. Hornblende - Plagioclase - almandine - epidote (-Quartz)
2. Hornblende - Plagioclase - epidote (-quartz).
3. Hornblende - Plagioclase - (diopside).
4. Anthophyllite - Hornblende - Almandine.
5. Anthophyllite - tremolite.
6. Diopside - epidote (-Plagioclase - quartz).
7. Diopside - grossularite (-quartz).

III Pelitic Member :

1. Quartz - staurolite - almandine - muscovite - plagioclase (-Biotite).
2. Quartz - almandine - muscovite - biotite - plagioclase (-epidote).

(B) Sillimanite - almandine - muscovite subfacies / Sillimanite - almandine - orthoclase subfacies

Staurolite + quartz $\rightleftharpoons$ Sillimanite + almandine + H_2O.

I. Mafic Member (Para amphibolites) :

1. Hornblende - plagioclase (-diopside - quartz).

2. Hornblende - Plagioclase - almandine (-quartz).

II <u>Pelitic Member</u> :

1. Quartz - sillimanite - muscovite - almandine - Plagioclase (-biotite).
2. Quartz - almandine - muscovite - biotite - plagioclase.

III <u>Migmatitic Gneisses</u> :

1. Quartz - sillimanite - almandine - orthoclase - (Plagioclase - biotite).
2. Quartz - orthoclase - microcline - plagioclase - almandine - biotite.
3. Quartz - orthoclase - microcline - plagioclase - biotite.

IV <u>Psammitic Member</u> :

1. Sillimanite - biotite - muscovite - quartz.
2. Biotite - muscovite - quartz.

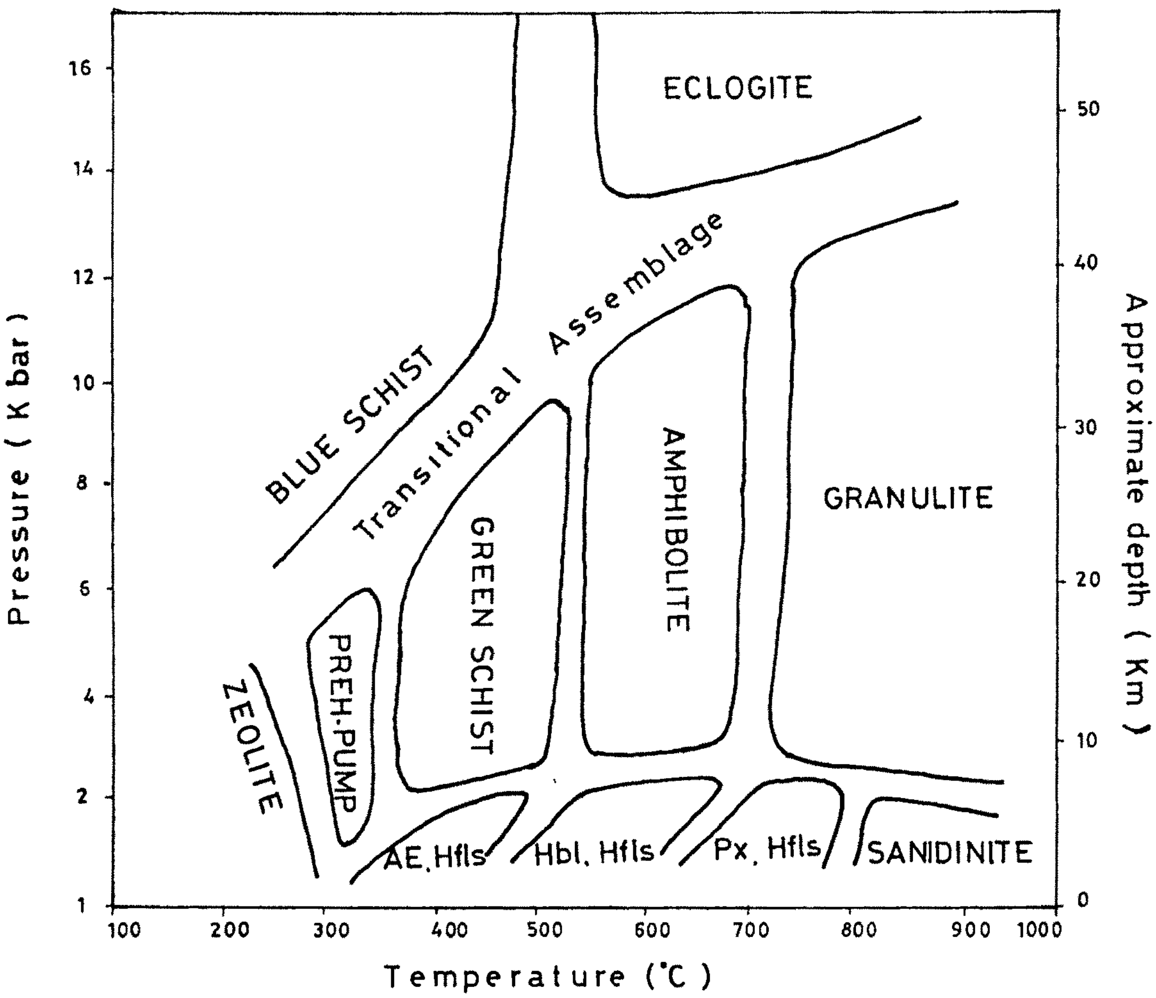
It may be mentioned that no cordierite and andalusite have been recorded anywhere in pelitic rocks alluded to above.

A.1 METAMORPHIC FACIES and ASSEMBLAGES

The above mentioned assemblages typically indicate medium to high grade of regional metamorphism corresponding to the "sillimanite zone" of Barrow. The presence of sillimanite in the gneissic rocks, together with the potash feldspar, is a clear indication of metamorphism under high temperature and pressure conditions. The author has preferred to assign the amphibolite facies to these rocks on the basis of following considerations :

1. Widespread occurrence of typical para-amphibolites derived from the metamorphism of Calc-magnesian rich sediments. The prevalence of green hornblende and occasional anthophyllite also rules out the granulite facies (Turner and Verhoogen, 1960).
2. The présence of sphene in the amphibolitic rocks is indicative of metamorphism lower than that charactersing the granulite facies. Turner and Verhoogen (1960, P.555) have pointedly mentioned that the sphene is invariably absent in the rocks of granulite facies. Eskola (1957) has mentioned that sphene does not occur in granulite facies.

In the amphibolite facies the non-aluminous amphiboles occurring in calcareous rocks become unstable and the pyroxene diopside is then prominent (Bhaskar Rao, 1986; Winkler, 1975 ; Miyashiro, 1973). On the basis of mineral assemblages present in the various lithological units, it can be summarised that while amphiboles have been derived from calc-magnesian sediments, the schists and gneisses appear to have been derived from pelitic sediments.



(After Bruce W. Yardley, 1989)

Figure - IV.2 Pressure - Temperature diagram showing the fields of the various metamorphic facies.

Hfls = hornfels
AE = albite - epidote
HBL = Hornblende
PX = Pyroxene
Preh-Pump = Prehnite-pumpellyite

3. Frequent presence of muscovite and extensive sericitisation of sillimanite, as in the present case, can be explained as under (Turner and Verhoogen, 1960, P.552).

"The mineral assemblages of the sillimanite zone - in fact assemblages of high-grade facies in general, tend to be complicated and partially obscured by reactions taking place in response to

(i) Falling temperature (during unloading) &
(ii) fluctuations in water pressure connected with melting and freezing of granitic magmatic component in migmatite area. So sillimanite, muscovite and potash feldspar may be associated in one rock; and textural evidence may indicate partial replacement of early mica by sillimanite, after the peak temperature of metamorphism. This mixing of facies in no way invalidates recognition of the sillimanite - almandine - muscovite and sillimanite-almandine-orthoclase subfacies as separate entities in provinces where the high grade assemblages have remained unmodified during unloading following the peak of metamorphism".

Turner (1968) has, of late revised his ideas on metamorphic facies and has recommended abandonment of the concept of subfacies. He has reverted back to Eskola, and has included all the medium to high grade metamorphic assemblages into Amphibolite facies, which covers a complete span of successive zones of progressive regional metamorphism characterized by almandine, staurolite, kyanite and sillimanite.

According to the revised views of Turner (op cit), the present assemblages could be referred to the Sillimanite isograd of amphibolite facies.

The mineral assemblages of pelitic and mafic rocks of the study area could be assigned to 'staurolite-almandine' subfacies and 'sillimanite-almandine-muscovite' subfacies of almandine amphibolite facies of Turner and Verhoogen (1962) and to Amphibolite facies of Miyashiro (1973).

The conditions of metamorphism characterising the mineral assemblages of the area following Turner and Verhoogen (1960, PP.533), cover a temperature range of 550°C to 750°C and pressure normally between 4000 bars to 8000 bars.

In the staurolite-almandine subfacies ,staurolite and almandine is associated with micas but there is absence of potash feldspar; the common micas which occur here are red-brown biotite and muscovite . Presence of staurolite shows that the pelitic rocks are rich in Al_2O_3, Iron oxides and deficient in K_2O (Turner and Verhoogen, 1962).

Pelites in the lower temperature part of the amphibolite facies contain muscovite, biotite, almandine and staurolite. In the higher temperature part, muscovite is decomposed by reaction with quartz; and sillimanite is formed and at the same time staurolite disappears. At the highest part of temperature biotite and almandine are stable.

Staurolite almandine subfacies corresponds to the lowest grade of metamorphism within the amphibolite facies. The reactions that mark the progressive metamorphism of pelitic rocks beyond the staurolite zone are:-

1. Staurolite + quartz $\rightleftharpoons$ Sillimanite + almandine + H_2O
2. Muscovite + quartz $\rightleftharpoons$ Sillimanite + orthoclase + H_2O

So the sequence of progressive metamorphism is from the staurolite - almandine subfacies to the sillimanite - almandine - muscovite and sillimanite - almandine - orthoclase subfacies is as observed in the above figure. This subfacies points to an increasing temperature leading to the following mineralogical reactions.

Kyanite $\rightleftharpoons$ Sillimanite

Muscovite + quartz $\rightleftharpoons$ Sillimanite + orthoclase + H_2O

So here, sillimanite, muscovite and potash feldspar are associated in one rock; and textural evidences indicate

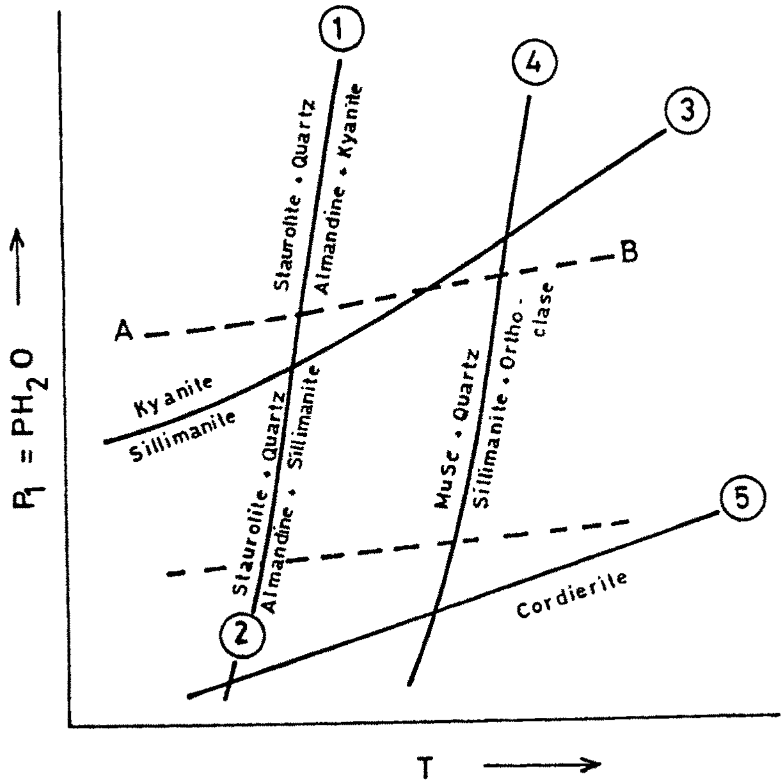


Figure - IV.3 Hypothetical curves of univariant equilibrium for reactions leading to appearance of sillimanite in almandine-amphibolite facies of Turner and Verhoogen, 1962.

partial replacement of early mica by sillimanite or late 'sericitization' of sillimanite after the peak temperature of metamorphism.

A.2 MIGMATISATION :

The schistose rocks when traced in the study area gradually merge into migmatitic gneisses. The terrain shows a progressive increase in feldspar content and grade into foliated prophyroblastic gneisses, with following textural and mineralogical changes:

Textural Changes :

(i) The transition is marked by a progressive coarsening of the overall texture in schists and amphibolites.

(ii) The biotites progressively show better parallelism on going towards migmatitic gneisses.

(iii) The potash feldspar and the plagioclase gradually shows increase in grain size and tend to develop first as sub-augens, then as augens and finally as well-formed porphyroblasts.

Mineralogical Changes :

(i) Progressive increase of potash feldspar characterises the most important mineralogical change. The feldspar enrichment takes place both in the main mass of the

Rock as well as in the porphyroblasts.

(ii) Alteration of garnet to biotite.

(iii) Appearance of Sillimanite.

CAUSE AND MECHANISM OF MIGMATIZATION :

Obviously the intruding potassic material metasomatically transformed the pre-existing schists into migmatitic gneisses. The transformation was brought about by alkali emanations (potassic) material given out obviously by granitic material.

An interesting feature of these migmatitic rocks is that they are alternating with the schistose, psammitic and the mafic rocks. However this phenomenon of metamorphism and metasomatism is more or less synchronous with regional metamorphic event and closely followed by metasomatic, but with considerable overlapping (Patel, 1971).

I.B. RETROGRESSIVE METAMORPHISM

At the later stage of metamorphism conversion of amphibolite facies (Hornblende-andesine-biotite) to greenschist facies (Chlorite - actinolite - albite - epidote - sericite) is observed in a zone of strong differential movement and formation of talc-magnesite schists from serpentine rocks has also taken place (Turner and Verhoogen 1962, P.486-487). It can be easily diagonised where partially destroyed relicts of the high temperature assemblage persist in association with low-temperature minerals. Relict garnets and staurolite mantled with chlorite along with muscovite-chlorite-quartz in schists is observed. Some strongly deformed rocks of phyllitic nature lack the relict minerals but are really the products of retrogressive (late kinematic) metamorphism.

MINERAL ASSEMBLAGES :

I. Mafic Member :

1. Chlorite - tremolite.
2. Talc - tremolite (- chlorite - quartz).
3. Talc - serpentine - tremolite.
4. Talc - magnesite (- dolomite).
5. Talc - actinolite - chlorite (- quartz).
6. Serpentine (- talc - actinolite).
7. Hornblende - albite - epidote - almandine (- biotite - quartz).
8. Hornblende - (tremolite - chlorite - almandine).
9. Talc - tremolite - chlorite.

II. Pelitic Member :

1. Quartz - muscovite - chlorite - albite (- epidote - tourmaline).

2. Biotite - muscovite - quartz (- albite - epidote).
3. Muscovite - chloritoid - quartz (- albite - epidote).
4. Muscovite - chloritoid - chlorite - quartz (- albite - epidote).
5. Biotite - muscovite - chlorite - quartz (- albite - epidote).
6. Biotite - muscovite - almandine - quartz - albite (- epidote).
7. Muscovite - chloritoid - almandine - quartz (- albite - epidote - chlorite).
8. Muscovite - chloritoid - quartz (- chlorite).

III. Psammitic Member :

1. Quartz - muscovite - biotite - sillimanite.
2. Quartz - muscovite - biotite.

The retrogression from amphibolite to greenschist facies (the alteration of higher grade minerals to lower grade one) involve hydration which is due to decrease in temperature and increase in PH_2O or both for e.g:alteration of biotite or garnet to chlorite, feldspar to sericite, olivine to serpentine, hornblende to epidote. These secondary minerals are forming fibrous fringes around, inclusions within and pseudomorphs of the primary minerals.

Chlorite here is a secondary altered product from biotite and hornblende, especially the rocks which has been subjected to late kinematic deformation and fracturing. So there is every possibility that chlorite is an alteration product in the metamorphic rocks of the study area.

DISCUSSION AND CONCLUSION :

In the amphibolites exposed around Barvalli village, diopside co-exists with hornblende and plagioclase and indicate higher metamorphic grade, with occasional appearance of sphene. This is the indication of M_2 metamorphic assemblage having higher temperature conditions. The survival of M_1 metamorphic assemblages is observed in the amphibolites of Mohmad Phalasia area where hornblende - epidote - alblte - quartz amphibolites are exposed and the garnet amphibolite gneisses at Kirat village. They are extremely flattened and strongly foliated with flattened and stretched garnet crystals. Wherever the amphibolites are sheared during later movement, they are seen to have been altered into hornblende chlorite schist. With sphene, exposed at Jhanjhar village and are closely associated with massive amphibolites. The associated ultramafic rocks (serpentinites) have also been metamorphosed and recrystallised into asbestos bearing chlorite schists with chromite.

The above lying pelitic gneisses and schists with thin bands and lenses of quartzites also show similar responses of metamorphic history.

The scattered development of sillimanite significantly points to metamorphic temperature being slightly above 700°C, at least locally. Sometime in the course of metamorphic history probably during M_2. The overall mineral assemblages provide some interesting features. Staurolite is seen to co-exist with garnet and biotite in absence of andalusite, sillimanite, kyanite and instead chloritoids are present. wherever sillimanite is present, andalusite, kyanite and staurolite are not seen. In all cases micas are abundant. These mineral associations are difficult to visualise and are explained by the experimental model of Richardson (1968, 1969) and a superimposition of successive metamorphic events with varying P/T conditions has to be invoked. Obviously, with the imprinting of M_2 and M_3 on M_1, while some minerals have survived, the others were replaced by new minerals. Such adjustments of stability limits of mineral phases from time to time depending on the pressure and temperature conditions during successive metamorphism, have been discussed in great detail by Sheyer and Solfort (1968_a, 1968_b, 1970).

In the schists around Kirat, Ora and Amliya - staurolite is seen co-existing with biotite and rotated garnet. They are seen to overgrow on the tiny pre-existing garnet crystal nucleii, which in turn co-exists with biotite and muscovite. Staurolite is seen rotated and folded along with garnet. Staurolite is seen altered into ottrellite during later metamorphic episode. The embedded quartzite layer also show similar metamorphic responses. The biotite quartzites consist of sillimanite - biotite - muscovite - quartz assemblage, developed oblique to the pre-existing foliation made up of quartz and biotite. Since the rock is extremely rich in quartz, only two metamorphic imprints can be recognized.

In garnet mica schist around Bichhwara and Jharol villages, similar responses are observed. The second generation of garnet crystals are seen to overgrow the pre-existing schistosity indicating synkinematic M_2 metamorphism. At Bichhwara fold nose, such garnet crystals are seen overgrown on the crenulation cleavages of AF_3 generation of folds. They are seen co-existing with the recrystallized biotite and quartz grains preferredly oriented along the AF_3 crenulation cleavages. At other places, sillimanite co-exists with these minerals. Along the shear zone, chloritisation is observed altered from biotite.

The Bagpura formation also shows identical metamorphic imprints. The first metamorphic foliation, develped during AF_2 folding, consists of folded tiny flakes of biotite and muscovite with some aggregates of quartz crystals. The later mineral assemblages are coarse biotite flakes co-existing with quartz overgrown on the tiny closely spaced early foliation mostly crystallized parallel to AF_3 axial plane cleavages. Chlorite crystals are quite fresh and found as alteration products of both the earlier biotite crystals. They are more prominent along the shear zone.

In general the preCambrian terrains, all over the world, are generally characterised by polymetamorphic history. In most cases however the superimposition is that of a retrogressive type caused either by the dislocation metamorphism (Read, 1957, PP.296-297). or by hydrothermal solutions. Migmatisation of high grade metamorphic rocks could also be included as a phenomenon of polymetamorphism. The facies change, has been attributed by Cooray (1962) due to the role of water. Thus, it is quite obvious that most common agents of downgrading are hydrothermal solutions, whatever may be their source.

The study area however, belongs to a rather rarer category of polymetamorphic terrains where a late retrogressive (diapthoresis) metamorphism of greenschist facies has been inferred with an early high-grade regional metamorphism of lower to upper amphibolite facies.

The metamorphic history of the area comprising a sequence of several metamorphic and metasomatic changes, summarised in the table - presents a metamorphic picture, which is complex but interesting one. The enclosed sketch map-shows an approximate classification of Jharol area based on their polymetamorphic characters.

While concluding this discussion on the various aspects of the regional metamorphism of the Aravalli rocks, the author would like to mention that sillimanite bearing gneisses indicating a high grade of metamorphism have always posed a problem regarding their facies limits.

TABLE- IV.1 :

MINERALS RECORDED AND METAMORPHIC FACIES IN THE JHAROL GROUP OF ROCKS

ROCKS	MINERALS RECORDED	METAMORPHIC FACIES: AF_2 & AF_3 ULTRAMAFIC AND AMPHIBOLITES (PROGRESSIVE)	METAMORPHIC FACIES: AF_4 GREENSCHIST (RETROGRESSIVE)
Mafic	Hornblende	-------	
	Diopside	-------	
	Plagioclase	-------------	-------------
	Chlorite		-------
	Tremolite		-------
	Actinolite		-------
	Quartz	-------------	-------------
	Anthophyllite	-------	
	Epidote		-------
	Sphene		-------
	Calcite		-------
	Microcline	-------	
	Garnet	-------	
Pelitic	Biotite	-------	-------
	Muscovite	-------	-------
	Almandine	-------	
	Chlorite		-------
	Quartz	-------------	-------------
	Staurolite	-------	
	Sillimanite	-------	
	Plagioclase	-------	
	Orthoclase	-------	
	Sericite		-------

TABLE- IV.2 :

RELATIONSHIP BETWEEN METAMORPHISM AND DEFORMATION

MINERAL	DEFORMATION		
	AF_2	AF_3	AF_4
	M_1	M_2	M_3
Hornblende	-------	-------	
Diopside		-------	
Garnet	-------	-------	
Plagioclase	-------	-------	
Biotite	-------	-------	-------
Muscovite	-------	-------	
Staurolite	-------	-------	
Ottrelite			-------
Sillimanite		-------	
Chlorite		-------	-------
Quartz	--------	--------	-------
Sericte			-------

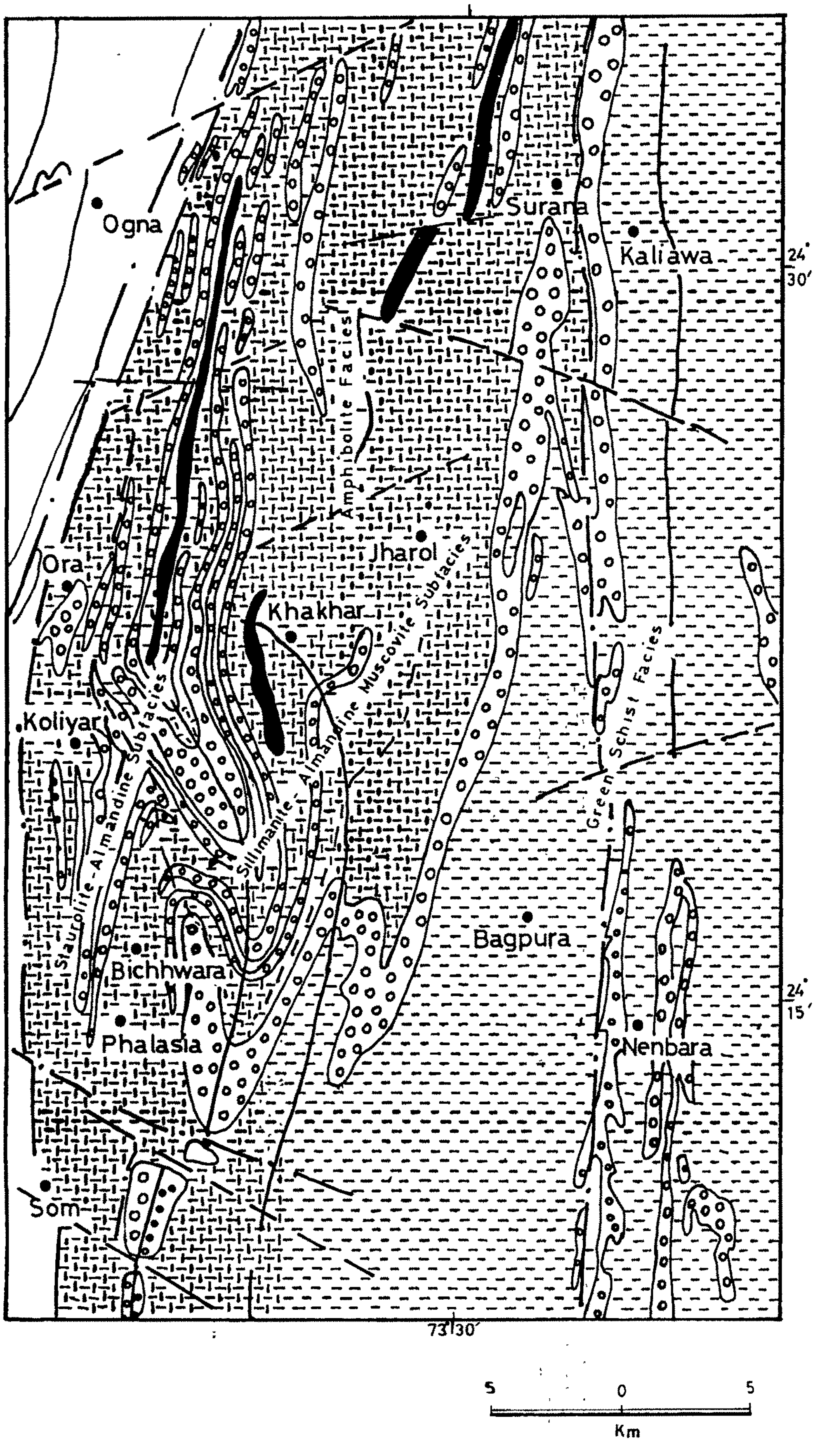


Figure - IV.4 Sketch map showing polymetamorphism of Jharol group of rocks.