THE ROCK TYPES

A. General Statement:

The different mappable lithological units in this area are recognized by their physical and mineralogical characters. Broadly the units belong to three categories:

(a) Quartzites
(b) Calcareous assemblages
(c) Pelitic assemblages.

Within each mappable unit there are various metamorphic assemblages. The lithological units of the area have been termed by the author after Heron (1917) as 'Alwar quartzites', 'Kushalgarh crystalline limestones', 'Ajabgarh calc-silicates', 'Ajabgarh phyllites and mica-schists' and 'Hornstone breccia'. All these units belong to the 'Delhi System'. The rocks are deformed and metamorphosed. Individual rock types belonging to each unit have been described separately. The emphasis of description is on aspects of metamorphism of the rock types. The assemblages have been considered petrographically and geochemically to evaluate the status and grade of metamorphism and to know the relation between metamorphism and deformation.

The details of deformation have been described separately in Section III of the thesis. However, it will be relevant here to clarify the meanings of terms $S$, $S_1$, $S_2$ and $S_3$ with reference to different rock units because these
terms have been used in the present section during description of rocks.

S - It has been used to denote original bedding of rocks. It is recognized by difference in composition, colour and grain size in layers.

S₁ - It is a bedding-schistosity. This bedding-schistosity is parallel to the limbs and axial-plane of isoclines (F₁). But this schistosity has not been observed to cut across the nose of isoclines. It actually swerves around the hinge and remains parallel to compositional banding. Sometimes it is constricted near the hinge on the convex side of the nose of F₁- folds.

S₂ - It is the dominant cleavage developed throughout the area. Megascopically S₂ is seen as discrete fracture planes in calc-silicate rocks and crystalline limestones. It parallels the axial plane of F₂ - folds. Microscopically it is seen to be accompanied by recrystallized, elongated minerals along this direction; with increase in degree of crystallization the cleavage grades into axial-plane schistosity.

In quartzites the S₂ plane occurs as closely spaced fracture planes which can be traced continuously as cleavage-cum-schistosity in adjacent calc-silicate rocks or crystalline
limestones. In phyllites and mica schists $S_2$ is a fracture cleavage or strain-slip cleavage with restricted recrystallization along this direction.

Except on the limb regions of $F_2$ - folds $S_2$ always makes an angle with $S$ and $S_1$, and can be identified in the field and hand specimens. In the limb regions the angle may be very low and $S_2$, $S_1$ & $S$ appear virtually parallel especially in calcareous metasediments. Even then the identity of $S_2$, distinct from $S_1$ & $S$, can be established by continuous tracing from hinge to limb areas of folds.

$S_3$ - It is developed as axial plane cleavage in relation to $F_3$ folds. It is a fracture cleavage accompanied by restricted crystallization and elongation of minerals in this direction. As $F_2$ and $F_3$ folds occur at high angles, $S_2$ and $S_3$ can be readily identified in the field. $S_3$ has been found to cut across $S$, $S_1$ & $S_2$.

In the study of metamorphism of different rock types the terms $S$, $S_1$, $S_2$ and $S_3$ have been frequently used. Whenever references of crystallization of minerals in relation to these planes have been mentioned, it is implied that observations have been made from rocks which contain these structures established in the field.

B. Sedimentary Features in the Rock Types and Nature of contact among different Rock Types:

A notable aspect of the rocks of this area is the survival of sedimentary features (plate 5) in spite
of deformation and metamorphism. These features are helpful in understanding the stratigraphy and nature of contact among the different rock-types. As the author has made frequent use of these sedimentary structures in detailed mapping for finding directions of younging (Map No. 5) these features have been briefly recorded here.

(a) **Ripple marks** - These are mainly asymmetrical, and few are near symmetrical. The near symmetrical ripples can be used to determine younging direction. Ripple-marks are common in Alwar Quartzites (Fig. 5a) and show flattened crests indicating very shallow water deposition (Tanner, 1962). The ripples have either straight or curved ridges. These have been noted mainly in Talbriksha and Kalachhara localities.

(b) **Current ripple laminations** - These are common in Kushalgarh limestones. The laminae are parallel to the steeper or leeside of the asymmetrical ripples. These are usually formed by advancing ripples (Shrock, 1960). These features help in identifying bedding and younging directions because such internal laminations in currents should point towards current direction.

(c) **Mud-cracks** - These are rarely found in the quartzites (Fig. 5b). The photograph shows casts of mud-cracks indicating subareal conditions during deposition.

(d) **Slump ball** - This is represented by haphazardly arranged balls of calcareous materials. The balls are noted in Kushalgarh limestone and Ajabgarh calc-silicate rocks. Fig. 7b shows slump structures in Kushalgarh black
crystalline limestone. The features may be produced by movement inside a water-saturated calcareous mud due to sliding down a slope which need not be more than a few degrees. They are common in area of rapid sedimentation.

(e) Convolute laminations - These are found in Kushalgarh limestone and Ajabgarh calc-silicate rocks. These are features of irregular folding of layers in the plastic stage and vary in shape from open fold like structure to closed ring-like structure. These have no regular geometrical pattern or shape. Sometimes the convolute laminations are truncated at the top by more regular layers of the rock. Truncated 'tops' indicate right way up and useful for noting the younging direction of rocks.

(f) Load-casts - These are seen in the fine grained bands of Kushalgarh black crystalline limestone. The coarser light coloured bands possibly sagged into fine grained crystalline limestone and produced sole-markings on the under-surface of the overlying layers (cf. Hills, 1966). This feature is also formed by quartzitic bands which sagged within Kushalgarh Limestone.

(g) Flame-structure - This is also a variety of sole-markings (Hills, 1966). The structure is found in Kushalgarh Limestone and Ajabgarh calc-silicate rocks. One layer may sink into underlying layers along saggings of
load casts. The lower layer, if plastic, may be squeezed upward between two adjoining sags to produce flame-like protrusions.

(h) Current bedding - These are common in Alwar quartzites (Fig. 6). The presence of current bedding (deltaic type) has been used to note younging directions of strata in quartzite outcrops around Kalachhara, Katamarha, Indokô chaota, Rekhamala, Bhadar, and Nanglheri.

The fore-set beds are sigmoidal and truncated by top-set beds and gradually merge into bottom-set beds. Wherever truncated tops of fore-set beds, indicating contemporaneous erosion are found, top and bottom of strata could be ascertained. In the quartzites torrential current-bedding occurs and this could not be used to find younging directions.

(i) Channelling - These are seen in Kushalgarh crystalline limestone. This structure is produced by current when limestone beds are scoured out on miniature scale. This leaves a depression which is filled up with later sediments. This feature is different from sagging because the underlying beds are curved around the sag and do not remain straight as in channelling.

Nature of contact among the different rock types:

The junction between Alwar quartzites and Kushalgarh limestones is sharp. Kushalgarh limestones sometimes contain
angular to subrounded blocks or pieces of quartzite and these are aligned in the bedding plane of limestone. Some of these quartzite pieces are even current-bedded with no abnormal change in the younging direction. The consistent younging direction noted in the underlying Alwar quartzites and overlying Kushalgarh limestones, south of Bairawas, indicate that the beds are right way up here. Near Kalachhara current bedding in Alwar quartzites indicates that the beds are right way up but the Kushalgarh limestones structurally underlie the quartzites at this locality. It is likely that a structural discordance occurs between these two rock units here (vide Section III).

The nature of contact between Kushalgarh limestone and Ajabgarh rocks is always gradational. The Kushalgarh crystalline limestone grades through siliceous and argillaceous impure marbles and calc-silicates to Ajabgarh calc-silicate rocks. South of Nanglheri village, this zone of gradation, which is about 25 feet in extent, can be well observed.

The Hornstone breccia occurs in isolated outcrops and its contact with other rock types is not exposed in the area. Structurally the Hornstone breccia occurs above Kushalgarh crystalline limestone.
C. Petrography of the Rock Types:

(1) Alwar quartzites

This rock unit has been metamorphosed along with the other country rocks (Kushalgarh limestone and Ajabgarh rocks) but still retains the original bedding (S). The quartzites are recrystallized and composed mainly of a mosaic of quartz grains with equant shapes.

Lithologically two types of rocks can be recognised:
(a) Pure quartzites, (b) Impure feldspathic quartzites.

(a) Pure quartzites - The rocks are formed of subangular to subrounded granular quartz grains only and they have a planar arrangement parallel to bedding (Fig. 12a,b). In hand specimen they are white in colour and sometimes contain tourmaline and opaque minerals besides quartz.

The quartzites in different localities display various structural elements which are briefly noted below:

i) Area south of Nanglheri: The pure quartzites show a lineation formed by cleavage bedding intersection. Long dimensions of quartz grains are here parallel to trace of \( S_2 \) (Fig. 12b). The rock is recrystallized.

ii) Area Talbriksha: The quartz grains here are recrystallized and show sutured margins. They retain slight strained extinction. Tourmaline and opaque minerals occur in layer parallel to bedding (S). The rock as a whole has a
granulose appearance and has no well-defined schistosity; the original bedding is maintained.

iii) Area north of Kalachhara: The quartzites here are recrystallized; quartzes show sutured margins with no strain effect (strained extinction or fracturing not seen).

iv) Area south of Kushalgarh: The rock contains quartz grains showing elongated habit with sutured margins. Some of the grains show strained extinction.

(b) Impure feldspathic quartzite

These are generally grey or pale pink in colour, sometimes streaked and mottled with brown and red stains varying with the amount of iron oxide coating the grains. Besides quartz the rocks consist of microcline, brown biotite, muscovite, tourmaline, apatite, sphene and iron oxides. The texture is granular.

The feldspathic quartzites east of Nanglheri are completely schistose with elongated quartz grains paralleling the bedding-schistosity ($S_1$).

(2) Kushalgarh crystalline limestones

Kushalgarh crystalline limestones show colour bandings - grey, black or pink - one or two inches in thickness. The grey and pink colours persist when the
grain size is coarse and the black colour is usual with fine grained varieties. Sometimes the rock is banded showing a gradation from coarse to fine size. The limestone horizon southeast of Nanglheri on the western limb of the Bairawas antiform (vide Section III) shows lenticular siliceous patches parallel to bedding (Fig. 87). These patches may be original sedimentary lenticles retained in the limestone.

The limestones are usually fine grained, crystalline, granular to schistose. These can be grouped under two types from study of hand specimens -

(a) Black crystalline limestone

(b) Grey and pink crystalline limestone

This variation is based mainly on physical characters but mineralogically there is no general difference among the assemblages of the two types - except that the pink crystalline limestone contains little or no green biotite.

The assemblages recorded in this unit are as follows:

(1) Calcite-biotite-scapolite-muscovite-quartz-sphene-opaque ore.

(2) Calcite-quartz-biotite-tremolite-opaque ore (in pink variety this assemblage is common with the omission of biotite).

(3) Calcite-epidote-chlorite-tremolite-quartz - (opaque ore-biotite-tourmaline-muscovite).
(4) Calcite-biotite-chlorite-(albite/oligoclase-microcline-quartz-epidote and opaque ore).
(5) Calcite-quartz-muscovite-biotite-opaque ore.

The details of mineralogy of the above rock types is shown in Table 1.

Biotite occurring in the above assemblages is green in colour and is either elongated along foliation (Fig. 41) or patchy in nature rendering a hornfelsic appearance to the whole rock. The patchy biotites (Fig. 40) suggest growth of the mineral across its cleavage direction and contrast in appearance with biotites which are elongated parallel to the cleavage of the mineral. The former variety of biotite has a lighter shade in pleochroic scheme while the latter has a deeper one. The elongated biotites have been observed occurring parallel to schistosity $S_2$ (Fig. 33b).

Calcite grains are mostly granular in shape and recrystallized when aligned in the plane of $S_1$ but when these are parallel to $S_2$ the grains are elongated in shape (Fig. 46). Quartz grains are equant in shape and recrystallized along $S_1$. Flattened, elongated recrystallized grains are seen to be parallel to $S_2$.

In the outcrops, northwest of Kushalgarh on both sides of Kushalgarh-Talbriksha road, $S_2$ cleavage is well
Table 1 - Mineralogy of Kushnafish Crystallographic Lithosomes

<table>
<thead>
<tr>
<th>Calcite</th>
<th>Biotite</th>
<th>Muscovite</th>
<th>Scapolite</th>
<th>Epidote</th>
<th>Tremolite</th>
<th>Sphene</th>
</tr>
</thead>
</table>

Note: - Quartzes present is usually clear and may contain few fine dusty opaque inclusions. Chlorite (pleochroic in green shades) and feldspars (albite/oligoclase and microcline) sometimes occur. Opaque ores are common. Percentage of Me in scapolite calculated from graph in "Geochemistry of Scapolites" by D.M. Shaw (1960) in Journal of Petrology, Vol. 1, pp. 218-260.
developed in rocks and constituent minerals are elongated parallel to $S_2$ indicating crystallization along this plane. The calcites, occurring along $S_2$, are elongated lenticular in shape. Other calcite grains in the matrix along $S_1$ are granular in shape.

Southeast of Kushalgarh in the limestone horizons on the southern side of Jaipur - Delhi road the compositional banding and the schistosity in the rock are almost parallel and calcites are extremely elongated (Fig. 30) parallel to this schistosity. In the section perpendicular to it, the rock shows relatively less elongated shape of grains (Fig. 31). This schistosity is $S_2$ as the specimen seen is from the limb of $F_2$ - fold.

In Andoon area (Map 9) the axial plane cleavage $S_3$ associated with $F_3$ is physically prominent throughout, although traces of $S_2$ are noted. Here granular calcites along compositional banding 'S' are recrystallized to emphasize $S_1$. But $S_3$ cuts across it (Fig. 32) and calcites and biotites are elongated parallel to $S_3$. So $S_3$ has a restricted phase of crystallization along it and noted only in the Andoon area (Section III). At this locality $S_3$ cuts across folded $S_2$, displacing the latter and can be distinguished from $S_2$ cleavage.

On the limb of Bairawas antiform (vide Section III) the calcites are elongated parallel to $S_2$. This schistosity ($S_2$) is overlapped by radiating growths of amphiboles askew.
to $S_2$ and patchy biotites cross-cut it. The arrangement of biotite is not only planar but may also be linear. It is interesting that at a particular instance - on the western limb of Bairawas antiform near the hinge - biotites are seen to form lineation (Fig. 33) parallel to $F_2$. The patchy biotites are, however, different in shape and render spotted hornfelsic appearance to the rock (Fig. 40).

A notable feature in some black crystalline limestones is the presence of elliptical concretionary nodules of scapolites which form a lineation (Fig. 86); this lineation is parallel to $F_2$. The scapolites include needle-like biotites.

Feldspars in the crystalline limestones are albite-oligoclase and microcline. Soda feldspars are granular and recrystallized along $S_1$.

Muscovites are few and their distribution is usually random; at places they form incipient porphyroblasts sieved with quartz inclusions. The muscovites sometimes show strained undulose extinction.

Epidotes are usually in the form of equant granular grains occurring along $S_1$.

Chlorites are patchy and irregular in shape.

Patches of opaque ores are present in the limestones. In specimens collected from southeast of Nanglheri, the opaques
are lenticular parallel to $S_1$. At some places they show hexagonal outline (plate 2) but mostly they are irregular in shape.

Blue and green tourmalines are present as non-essential minerals.

A few specimens of the crystalline marble contain actinolitic tremolites. These occur in the form of rosettes composed of radiating clusters of several grains (Fig. 90). Sections prepared in different directions from the same rock specimen indicate that rosettes are three-dimensional, resembling a bunch of flowers or bouquet. In sectional view, under the microscope, the rosettes are seen to be made of several amphibole crystals (Fig. 90). The cluster has an appearance like 'X' with a constriction in the central region; in crossed nicols the amphibole crystals arranged radially from the central region become extinct in a cyclic order from one end of the rosette to the other.

Individual actinolitic tremolites in the form of elongated bladed crystals may occur in a criss-cross arrangement. Rosettes and decussate amphiboles grow across $S_1$. The cleavage $S_2$ is also overlapped by radiating growth of amphiboles askew to $S_2$.

The grain boundary of the actinolitic tremolites is not sharp and fades into chloritic, epidotic, or calcite-quartz-mica bearing matrix of the rock. At places the matrix
materials embay into the grain. The amphiboles contain inclusions of spherical quartz along the middle part of the longitudinal section; these also include decussate grains of biotites.

It has been found that when tremolites are replaced by calcite and green biotite they release iron (plate 2) and the iron-content of the rock in shape of opaque minerals is increased.

(3) Hornstone breccia

The rock consists of abundant angular fragments of pale grey and dark grey quartzite embedded in a fine grained brown matrix which is compact and cherty (Fig. 15a). The angular pieces range in size from fraction of an inch to about six inches in length; although rectangular pieces are common the shape is variable. The arrangement of these pieces is haphazard and no planar or linear structure could be ascertained in the breccia. The rock is devoid of any regular lithological banding.

Under the microscope the angular fragments are seen to be composed of quartz or aggregates of quartz grains. These exhibit strongly developed strained extinction (Fig. 15b). The matrix of the rock consists of fine grained mosaic of recrystallized quartz; few sericitic micas may present. The grains in the matrix are often coated with brownish iron oxide.
Within the limits of the present area there are very few exposures of Hornstone breccia. Moreover, these are isolated and exhibit no contact or relationship with other rock types of the area. Hence the nature and origin of 'Hornstone breccia' and their connection with deformati-
onal history of the area could not be included within the scope of the thesis.

(4) Ajabgarh rocks

The lithological unit above the Kushalgarh crystalline limestone has been described as Ajabgarh rocks (Heron, 1917). This unit comprises of -

a) Calc-silicate rocks

and b) Mica-schists and black phyllites.
Calc-silicate rocks are more resistant to erosion and stand out as small hillocks in the area while mica-schists and phyllites are soft and occupy low ground in the Bairawas valley.

a) Calc-silicate rocks

The various lithological types are -

1) Strongly schistose white marble : calcite-(quartz)

2) Poorly schistose white marble : calcite-tremolite

3) Siliceous marble : calcite-quartz-(tremolite)-green biotite-muscovite-epidote-(opaque ore)

4) Grey tremolite rock : tremolite-(calcite)

5) Talc- rock : Talc-(quartz)-tremolite-(calcite)


Among the non-essential minerals, tourmalines are frequent within the first three types of assemblages mentioned above. They are pleochroic in blue and green shades.

The details of the mineralogy of the rocks are given in Table 2. The relation among some constituent minerals and observed planar structures in the rocks are stated below:

1) Strongly schistose white marble: These are milk-white, compact and schistose rock (Fig. 47). The texture varies from fine grained crystalline mosaic to granoblastic type. It consists mostly of calcite, and little or no quartz. Calcites are usually notably elongated in shape. Quartz grains are also elongated.

The outcrops of Ajabgarh white marbles have been observed on the limbs of $F_2$ folds, that is, Bairawas synform and Bairawas antiform as shown in Map 1. The strongly developed schistosity of the rock is virtually parallel to lithological banding. It is likely that $S_2$, axial plane cleavage of $F_2$ folds, will attain such attitude in these outcrops (Map 1). Even if the rock possessed a previous schistosity ($S_1$ - bedding schistosity) other than $S_2$ its existence is difficult to
<table>
<thead>
<tr>
<th>Calcite</th>
<th>Tremolite</th>
<th>Epidote</th>
<th>Talc.</th>
<th>Biotite</th>
<th>Sphene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relief varying from moderate to low on rotation of microscope stage.</td>
<td>Two sets of cleavages at 124°</td>
<td>R.I. high Variegated interference colour of higher order</td>
<td>R.I. Ny' = 1.648 ± .005</td>
<td>R.I. Ny' = 1.619 ± .004</td>
<td>R.I. - very high Birefringence very high.</td>
</tr>
<tr>
<td>Birefringence high.</td>
<td>1) Colourless, non-pleochroic.</td>
<td>Pleochroic in shades of yellowish green.</td>
<td>Birefringence high</td>
<td>Pleochroism</td>
<td>Birefringence very high.</td>
</tr>
<tr>
<td>Perfect 1011 cleavage.</td>
<td>R.I. N&lt;sub&gt;x&lt;/sub&gt;' = 1.605 ± .005</td>
<td>-2v = 12° (approx.)</td>
<td>Aggregates of fine grained masses.</td>
<td>1) X = pale yellow green</td>
<td>Pleochroic in shades of reddish brown.</td>
</tr>
<tr>
<td>Rhombohedral cleavage parallel lamellar twinning (0001) \ pole of (0112) lamellae = 26°</td>
<td>2) Pleochroic (actinolitic)</td>
<td>Granular habit with poorly developed cleavage.</td>
<td></td>
<td>2) X = pale yellow</td>
<td>Characteristic wedge-shaped for</td>
</tr>
<tr>
<td></td>
<td>X = Pale yellow</td>
<td>Y = Greenish yellow</td>
<td></td>
<td>Y = Z = deep green</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z = Green</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Z \gg Y \gg X$</td>
<td></td>
<td></td>
<td>Extinction st. with cleavage (001).</td>
<td></td>
</tr>
</tbody>
</table>

Note: Quartz present is usually clear and may contain few fine dusty opaque inclusions. Plagioclase (albite/oligoclase) and tourmaline (pleochroic in bluish green shades) are sometimes present. Opaque ores are few. Chemical composition of green biotite has been determined (vide Section II E).
establish because \( S_1 \) will be nearly parallel to \( S_2 \). However, the marble is recrystallized and minerals are dimensionally elongated and flattened along visible schistosity. In other rocks, where \( S_1 \) and \( S_2 \) could be separately established, such elongation of constituent minerals is seen to be strictly confined to \( S_2 \). It is suggested, therefore, that the quartz and calcite grains in the schistose marble are elongated and flattened along \( S_2 \) (Fig. 35). Examinations of thin sections, which are cut normal to schistosity but in different directions from the same specimen, establish the notably flattened shape of minerals especially calcite. In some specimens the flattened grains along \( S_2 \) also suggest elongation nearly parallel to strike of schistosity. But no megascopic lineation is visible in the marbles.

In the calc-silicate and marbles \( S_1 \) has been usually recognized as bedding-schistosity which re-emphasizes \( S \) (original banding in the rock) due to recrystallization of minerals with granular shape.

2) Poorly schistose white marble - Some calcites are elongated parallel to \( S_2 \) and tremolites have grown in a criss-cross fashion in relation to \( S_2 \) (Figs. 9 and 85). The texture is fine grained crystalline.

3) Siliceous marble - These are schistose rocks with schistosity \( S_2 \) nearly parallel to bedding \( S \) or bedding-schistosity \( S_1 \) being on the limbs of \( F_2 \) folds where \( S_2 \) is very close to \( S \) or \( S_1 \) in orientation. Sometimes calcite
is coarse and flattened parallel to $S_2$. East of Nanglheri compositional banding and schistosity are parallel and calcites are lensoidal, elongated parallel to $S_2$. Quartzes are equidimensional and scattered. Tremolites, when present, are criss-cross with respect to $S_2$ (Fig. 38).

Just north of the Bairawas synform in subarea I (vide Section III) cleavage is determined by flattened and elongated calcites. Bedding is virtually parallel to it on the limbs of the synformal hinge. But on the hinge itself grain elongation of calcite parallel to $S_2$ is at an angle to $S$ or bedding. Here bedding is marked by colour banding and heavy mineral layers. The calcites with granular shape emphasize bedding-schistosity $S_1$. Green biotites are patchy and scattered all over the rock rendering a hornfelsic appearance. Muscovite is decussate in relation to bedding-schistosity. Epidotes are few and patchy in nature. Although calcites are flattened and elongated, as seen under the microscope, the rock shows no megascopic lineation.

4) Grey tremolite-marble - The calcites are elongated lenticular in shape in sectional views and found to be flattened parallel to $S_2$. Quartz is equant in shape and recrystallized with sutured margin (Fig. 36). It is recrystallized in the plane of bedding ($S$) to emphasize bedding-schistosity ($S_1$).

The texture is fine grained granoblastic. Tremolites are generally in the plane of schistosity but rosettes occur
at an angle to it. Tremolites in the rosettes may be bent and accompanied by strained extinction.

5) Talc - rocks - Tremolite marbles often grade into talc rock. They have a schistosity parallel to $S_2$ and the grains are flattened parallel to it.

6) Calc-silicate Breccia - These rocks in hand-specimens show angular fragments of calc-silicates embedded in a greenish calc-silicate matrix. But microscopically they show no feature distinctive from the other calc-silicate assemblages described above. They do not have a fixed horizon and are associated with the other calc-silicate assemblages (Fig. 10). There is no evidence of crushing or fracturing in minerals of this recrystallized rock.

7) Amphibole-garbenschiefer - In this rock type the amphiboles render a criss-cross arrangement showing similarity of structure with the garbenschiefer of the type area from Germany (Tyrrell, 1949, p. 272). Hence the rock type is named amphibole-garbenschiefer.

The outcrops of amphibole garbenschiefer occur in the area on the limbs of Bairawas synform where $S_2$ nearly parallels $S_1$, being on the limbs of $F_2$ fold (Map 1).

On the basis of mesoscopic structural elements observed in the garbenschiefer these may be divided into four types -
(a) Amphibole-garbenschiefer with undeformed actinolitic tremolites not lying on the schistosity S<sub>2</sub> (Fig. 83). Mineral assemblage of the rock is tremolite-actinolite-calcite-quartz-sphene-opaque ore-biotite-zircon.

(b) Bouldary nodular amphibole rock with undeformed actinolitic tremolite on the plane of schistosity, S<sub>2</sub> (Fig. 85). Some amphiboles are also decussate in arrangement with respect to S<sub>2</sub>. Mineral assemblage of the rock is tremolite-green biotite-quartz-calcite-sphene-epidote-opaque ore.

(c) Concretionary amphibole garbenschiefer with undeformed actinolitic tremolite aggregates nearly on the schistosity, S<sub>2</sub>. Mineral assemblage of the rock is tremolite-calcite-quartz-green biotite-sphene-opaque ore-epidote-alkali feldspar.

(d) Amphibole garbenschiefer with highly deformed augen-like actinolitic tremolites on schistosity, S<sub>2</sub> (Fig. 25). Mineral assemblage of the rock is calcite-quartz-green biotite-actinolitic tremolite.

The amphibole-garbenschiefer type (a) as described above is a dark black fine-grained rock with a crystalline granular texture. The amphiboles occur in a criss-cross arrangement with respect to S<sub>2</sub> (Fig. 83). The structure is typically maculose grading into hornfelsic (cf. Tyrrell, 1949, p. 272). The amphiboles are crystalloblastic and have
inclusions of sphene and quartz (Fig. 11 and Plate 7, Fig. 1). Tremolite-actinolite crystalloblasts form radiating rosettes. Rosettes are equidimensional. But in some cases their longer dimension parallels S₂. The rock type (a) is not deformed and amphiboles are sieved with inclusions of quartz, sphene and heavy minerals. Pleochroic halo around zircon inclusion in amphibole is noted. Patchy green biotites occur scattered in the rock. Elongated opaque minerals are sometimes parallel to banding, S, which is very close to S₂.

The boudary nodular garbenschiefer type (b) is greyish green in colour with amphiboles occurring as nodules. There is a variety with a greyish white colour and a banding of dark elongated amphiboles parallel to S₂ (Fig. 28). Tremolites occur as lenticular crystalloblasts parallel to cleavage S₂ and also as decussate rosettes with respect to S₂ (Fig. 29). Tremolites are seen to be replaced by carbonates and biotites and black opaque minerals. Crystalloblasts of tremolites are often surrounded by elongated epidotes like a rim and in the pressure shadow zone of tremolite, calcite occurs. Calcites are elongated along S₂ and epidote and biotite are granular. Some spotty green biotites have no definite planar arrangement. Thus there are two sets of green biotites - 1) elongated along schistosity, S₂ and 2) spotty and growing across schistosity, S₂.

From the above discussion it can be suggested that amphibole garbenschiefer type (b) has two notable
characters - a) matrix epidotic (granular defining S₁) or non-epidotic (granular calcite and quartz defining S₁); b) tremolites as radiating rosettes or as oval lenticular crystalloblasts.

The concretionary amphibole garbenschiefer type (c) has ovoid amphibole simulating concretions and are dark grey in colour. These ovoids have their longer dimension parallel to visible schistosity. Although tremolites form radiating rosettes cutting across the schistosity S₂, the rosettes as a unit may be elongated parallel to S₂. Biotites are patchy and irregular, imparting a hornfelsic appearance to the rock or are elongated parallel to S₂. They are sometimes stout and stumpy parallel to S₂ but have their own cleavages across the schistosity.

Garbenschiefer type (d) is a highly deformed rock with a strongly schistose matrix and augen-like amphiboles as crystalloblasts elongated parallel to S₂ (Fig. 26 a,b,c). They sometimes show rosettes of actinolitic tremolites but the rosettes as a whole are elongated in shape parallel to S₂. In the matrix quartz, calcite, and green biotite are recrystallized and remarkably elongated in shape in the direction of the cleavage S₂. These minerals wrap around the augens of amphibole.
b) **Mica-schists and black phyllites**

These pelitic rocks associated with calc-silicate rocks in parallel bands, occur in small outcrops in the Bairawas valley.

The black phyllites are brown black or greenish black in colour, compact and schistose (Fig. 81). Their schistosity is parallel to the lithological banding ‘S’ in the area. The brown staining of the rock is due to iron oxide. Black opaque ores are sometimes lenticular and sometimes porphyroblastic with an elongation parallel to schistosity (Fig. 14). The rock under microscope shows a very fine grained nematoblastic texture. The elongated grains of mica and lenticular opaque ore patches are parallel to S₂ on the limbs of minor F₂ warps. The assemblages are -

1) Quartz-brown biotite-(limonite)-chloritoid-opaque ore.

2) Quartz-green biotite-sericite-opaque ore-calcite-(limonite)-chloritoid.

3) Quartz-green and brown biotite-sericite-opaque ore-calcite-chloritoid-tourmaline.

Green biotites occur in large amounts when calcites are profuse whereas brown biotites dominate when calcite is subordinate.
The details of the mineralogy of the rocks are given in Table 3 under assemblages 1 to 3.

Texturally mica-schists are of two types - coarse grained and fine grained. Mineralogically andalusite is dominant in some mica-schist layers whereas staurolite is dominant in others. The mineralogy of the rock is given in Table 3 under assemblages 4 to 10. The constituent minerals, mainly quartz, biotite, muscovite and opaque ores, define well developed schistosity as well as lineation in the rock. The schistosity and lineation are puckered and bent by F2 folds. S2 usually occurs as 'strain-slip cleavage'; sometimes S2 appears as discrete fracture plane cutting across schistosity. As F1 folds have not been observed in Ajabgarh mica-schists, it is not certain whether the schistosity defined by constituent minerals is S1 or not. Hence the schistosity and lineation have been termed "Structures of Uncertain Age" (vide Section III).

The mica schists are generally greyish brown in colour and show under microscope coarse to fine grained crystalline structure with a prominent schistosity. Irregular developments of spotty biotites render a hornfelsic structure overprinted on the schistose rock. In the description of regional distribution of 'Ajabgarh Series' Heron (1917) occasionally mentioned the occurrence of staurolite, andalusite (including the variety chiastolite) and garnet in Ajabgarh pelitic rocks. Details of the assemblages of this area have been recorded by Gangopadhyay and Sen (1967). The type of assemblages are noted below:
<table>
<thead>
<tr>
<th>Biotite</th>
<th>Sericite</th>
<th>Chloritoid</th>
<th>Other minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.I. - high</td>
<td>R.I. - high</td>
<td>R.I. - high</td>
<td>Quartz usually contains fine opaque black inclusions.</td>
</tr>
<tr>
<td>Birefringence - high</td>
<td>Birefringence - high</td>
<td>Birefringence - low</td>
<td>Tourmaline is pleochroic from colourless to deep bluish shades.</td>
</tr>
<tr>
<td>Pleochroism:</td>
<td>Cleavage poorly</td>
<td>Prismatic sections</td>
<td>Opaque ores are common.</td>
</tr>
<tr>
<td>1) pale green to deep green</td>
<td>developed.</td>
<td>pleochroic from</td>
<td></td>
</tr>
<tr>
<td>2) pale yellow to deep brown</td>
<td>Extinction st.</td>
<td>colourless to yellowish green</td>
<td></td>
</tr>
</tbody>
</table>

**Mineralogy of Ajabgarh mica-schists (assemblages 4 to 10)**

<table>
<thead>
<tr>
<th>Biotite</th>
<th>Muscovite</th>
<th>Garnet</th>
<th>Andalusite</th>
<th>Staurolite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleochroism:</td>
<td>Birefringence - high</td>
<td>R. I. - 1.8202 ± .005</td>
<td>Birefringence low</td>
<td>Birefringence low</td>
</tr>
<tr>
<td>1) pale yellow</td>
<td>Perfect (001)</td>
<td>Dusty inclusions clustered towards the central part of grains.</td>
<td>Birefringence low</td>
<td>Pleochroism</td>
</tr>
<tr>
<td>Y = deep green</td>
<td>cleavage</td>
<td></td>
<td></td>
<td>Colourless, non pleochroic.</td>
</tr>
<tr>
<td>2) pale yellow</td>
<td>Extinction st.</td>
<td></td>
<td></td>
<td>Birefringence moderate.</td>
</tr>
<tr>
<td>Y = Z = deep brown</td>
<td></td>
<td></td>
<td></td>
<td>Extinction st. w -th prismatic ou -line.</td>
</tr>
</tbody>
</table>

Note: Quartz present is clear. Tourmaline (pleochroic from colourless to bluish green), apatite, plagioclase (albite/oligoclase), opaque ores, calcite and epidote are sometimes present. Chlorite may occur as alteration of biotite. Chemical compositions of green and brown biotites, and garnet have been determined (vide Section II E).
Type A. Andalusite dominates:

(1) Andalusite-biotite-muscovite-quartz.
(2) Andalusite-biotite-muscovite-albite/oligoclase-quartz. (Apatite, tourmaline, calcite and opaque ores may occur in small proportions).
(3) Andalusite-biotite-muscovite-sillimanite (?) -quartz. (Apatite, tourmaline and opaque ores may occur in small proportions. Definite identification of sillimanite could not be done. Only a few needle-like grains are present).

Type B. Staurolite dominates:

(1) Staurolite-garnet-andalusite-muscovite-biotite-quartz.
(2) Staurolite-garnet-andalusite-muscovite-biotite-albite/oligoclase-quartz.
(3) Staurolite-garnet-muscovite-biotite-quartz (Apatite, calcite, tourmaline and opaque ores may occur in small proportions).

Type C. Garnet dominates:

(1) Garnet-chlorite-muscovite-biotite-quartz (Epidotes, calcite and opaque ores may occur in small proportions).

The above pelitic assemblages can be well observed in an outcrop about 1\frac{1}{2} miles north of Bairawas. The pelitic
bands here alternate with those of garbenschiefer. This selected outcrop has been mapped separately to record the nature of occurrence of these rock types (Map 11).

In the pelitic assemblages above when there is a scarcity of green biotites in the rock, epidotes are present. Green biotites are profuse when calcites are associated with it. Biotites are only locally chloritised. Sometimes opaque minerals (some are ilmenite) occur as porphyroblast (Plate II).

The following features of andalusite in the andalusite-rich schists deserve special mention –

(i) Andalusite varies from microscopic dimension (Fig. 76) to the size of small pigeon eggs (Fig. 77). The observed range of microscopic dimension is 0.1 mm. to 2.5 mm. It is crystalloblastic and contains inclusions of quartz, biotite and opaque ores.

(ii) Andalusite of moderate sizes (0.2 cm. - 0.5 cm.) is seen as numerous light coloured spots or patches (Fig. 76) in hand specimens. When the mineral is developed on this scale the rocks display a spotted appearance.

(iii) Andalusite of large size is ellipsoidal, egg-like in shape (Fig. 79). Each ellipsoidal grain is a single individual andalusite with inclusions of quartz, biotite, muscovite, garnet and opaque ore. The greatest, mean and least
dimension axes of 20 grains have been measured and the average size is estimated to be 3.11 cm. x 2.81 cm. 2.33 cm. The uniformity in size of andalusite with this habit and their abundance in the schists are notable.

The pelitic schists in some bands are also characterised by the presence of large crystals of staurolite (2 cm. - 5 cm.) and numerous small sized garnets (0.1 mm. - 2 mm.). Wherever andalusite is observed in these schists it is of microscopic dimensions. Staurolite, andalusite and garnets are porphyroblastic; garnet may occur as inclusions in both staurolite and andalusite. It has been observed that when garnets occur alone and not in association with staurolite or andalusite they are smaller (0.2 mm. - 0.5 mm.) in size than when they (0.8 mm. - 1.5 mm.) are associated with staurolite and andalusite. The garnets when present in the assemblage containing andalusite and staurolite have two types of occurrences as mentioned earlier - 1) as inclusions within staurolite crystal (Fig. 18) and 2) as independent crystals (Fig. 17).

The first type shows sizes ranging from 0.2 mm. - 1.2 mm. while the latter shows a range between 0.3 mm. - 1.5 mm. Garnets are subidioblastic to idioblastic with dusty grey or clear inclusions concentrated in the middle part of the grain. Garnets are granular in habit and cut across the
Staurolites are subidioblastic to idioblastic (Fig. 80). They are pleochroic from colourless to golden yellow. The crystals are sieved with quartz inclusions and also include brown mica. In none of the specimens examined, staurolite includes andalusite or vice versa. The brown biotite inclusions in andalusite are of a lighter shade than the brown biotite in the matrix.

Biotites occur in the schists in the following manner:

a) long-needle-like along schistosity in the matrix, b) elongated stumpy stout crystals along schistosity with their own cleavage across it (Plate 7, Fig. 2), c) long needle like decussate crystals within porphyroblasts of andalusite (Plate II).

Biotites in the matrix are generally parallel to schistosity (Fig. 23) and folded with it but some are askew to it. Patchy green biotites are present in an irregular fashion. Muscovite is usually found within andalusite porphyroblasts in decussate arrangement. In the matrix of the schists they align themselves parallel to schistosity and are folded with it.

Green chlorites have three modes of occurrence:

1. Elongated at an angle to schistosity.
2. Porphyroblastic and with inclusions of biotite and chlorite, producing sieve structure (Plate II).
3. Parallel to the axial plane of conjugate pucker (F2 - fold) in the schists.
There are a few, very fine needle-like crystals in the rock as observed under the microscope. These are colourless and show moderate birefringence, straight extinction and high refractive index. The mineral is tentatively suggested to be sillimanite although specific identification could not be done.

Quartz shows three types of occurrence:

(a) recrystallized granular without any strain effect.
(b) bent along with conjugate pucker, \( F_2 \), and exhibiting a cross fracture paralleling the trace of strain-slip cleavage, \( S_2 \).
(c) elongated parallel to schistosity.

Garnet, staurolite and andalusite show the following relations to microstructures:

(1) Garnets cut across / . They show a fracture plane parallel to the trace of strain-slip cleavage, \( S_2 \) and are sometimes disrupted along it (Figs. 19 and 84). Sometimes the schistosity, which is folded on \( F_2 \) axis, seems to swerve around garnets (Fig. 16). Inclusions of quartz, zircon etc. in the garnet have no definite arrangement while quartz in the matrix is parallel to schistosity. Garnets at the hinge and limb of the \( F_2 \) puckers retain their equidimensional shape (Fig. 21).
(2) Staurolites occur as porphyroblasts; schistosity. curves around the crystals (Figs. 16 and 80a). They have inclusions of brown mica and quartz in a pattern crudely continuous with the existing schistosity in the rock. Crystals of garnet are often included in staurolite (Fig. 80b). The mica-schist shows a crude banding at high angle to schistosity. Observations in the field indicate that this banding is not bedding of the rock and is likely to have developed due to segregation of biotite and quartz feldspar during recrystallization.

(3) Andalusites contain inclusions of biotite and muscovite which may be decussate in arrangement or may form a trail continuous with trace of schistosity in the rock (Plate II).

D. Relation between deformation and metamorphism in the rock types.

General petrographic description and grain growth in different rock types have been stated in previous pages. The following account attempts to summarise deductions regarding the time relationship between deformation and crystallization. At least three deformational episodes have been detected in the area (vide Section III). Each episode is accompanied by some degree of metamorphism. Crystallization of metamorphic
minerals can be dated in relation to recognized phases of deformation. In all available samples of rocks such relationships are not apparent; only in rocks where structures such as folds, cleavages are reflected on microscopic scale their thin sections were studied to find relationship between crystallization and deformation.

Zwart (1963) and Johnson (1962, 1963) have shown how relationship between crystallization and deformation can be deduced from microscopic study of thin section of metamorphic rocks. The same techniques have been used by the present author.

The salient features observed in samples of different lithological units are stated below.

(i) **Alwar quartzites** -

In the quartzites the trace of the close-spaced fracture, which can be traced as $S_2$ cleavage in adjacent calc-silicate rocks, intersects the bedding and the intersection gives a lineation as observed in subarea II (vide Section III). In the rock the quartz grains are recrystallized, flattened and elongated parallel to $S_2$ which is the axial plane cleavage of $F_2$ folds (Fig. 12). It is suggested that the quartzites were at least partially recrystallized during $F_2$ phase of folding.
(ii) Kushalgarh crystalline limestones -

Selection of samples has been made with knowledge of the following data:

(a) $S_2$ is dominant on the western limb of Bairawas antiform ($F_2$).
(b) $S_1$ and $S_2$ are both developed northwest of Kushalgarh and south of Kushalgarh.
(c) $S_1$, $S_2$ and $S_3$ are developed northeast of Andoon.

In the crystalline limestone, which occurs east of Nanglheri village, $S$ is defined by compositional banding. The calcite, quartz and biotite have recrystallized to emphasize bedding-schistosity, $S_1$. There is, however, no marked elongation and flattening of minerals along $S_1$. These granular calcites, quartzes and slightly elongated biotites are possibly developed during either $F_1$ or post-$F_1$ phase of folding.

In specimens containing $F_2$ and associated cleavage, $S_2$, calcite, biotite and quartz grains are remarkably flattened and elongated along $S_2$. Such flattening and elongation of minerals can be traced from hinge to limb areas of $F_2$ folds. The dimensionally elongated minerals along $S_2$ contrast with the same of equidimensional habit along $S_1$. The generation of elongated calcites, quartzes and micas along $S_2$ is suggested to be contemporaneous with $F_2$ phase of folding. Some scapolite grains indicating a linear arrangement parallel to $F_2$ axis, occur on $S_2$ and are also assigned to the time of $F_2$ folding.
To the south of Kushalgarh on the southern side of Delhi-Jaipur Road the schistosity in the rock has been marked by elongation of calcite and green biotites. The specimen examined is from the limb of F\textsubscript{2} fold where S\textsubscript{2} parallels S. S\textsubscript{2} is visibly recognized and elongation of grains is seen parallel to it. The matrix is granular and recrystallized to emphasize S\textsubscript{1}, parallel to S, which in this case is incidentally parallel to S\textsubscript{2}. But there is no elongated grains of calcite and biotite in the matrix (Figs. 30, 31).

It can be suggested from above observations that calcite, quartz and green biotite in Kushalgarh crystalline limestone crystallized in two periods related to two phases of deformation: firstly, during or after F\textsubscript{1} folding and secondly, during or after F\textsubscript{2} folding.

In outcrop of Kushalgarh crystalline limestones north of Andoon four planar structures, S, S\textsubscript{1}, S\textsubscript{2} and S\textsubscript{3} are present. S\textsubscript{3} cuts across S\textsubscript{2} and can be distinguished from the latter (vide Section III & Fig. 103). In thin section prepared from sample of rock with S\textsubscript{3} it has been observed that some calcite, quartz and green biotite are recrystallized and aligned along S\textsubscript{3} with notable elongated shape (Fig. 32). Parallel to lithological banding recrystallized granular quartz, calcite and green biotite occur, emphasizing bedding-schistosity, S\textsubscript{1}. It is suggested that there is a very limited phase of crystallization of calcite, quartz and green biotite along S\textsubscript{3} during or after F\textsubscript{3} phase of folding.
(iii) **Aiabgarh rocks**:

Samples for study comprise of -

(a) Calc-silicates with amphibole rosettes, patchy biotite and elongated calcite showing relationship to $S_1$ and $S_2$.

(b) Amphibole garbenschiefer with amphibole rosettes lying on $S_2$; with radiating rosettes not lying on $S_2$; with deformed augen-like amphiboles, and (c) Mica-schists with mica, quartz, andalusite, staurolite and garnet, showing relationship to $S_1$, $S_2$ and $F_2$ folds.

In the calc-silicate rocks calcite, quartz and biotite are recrystallized along $S$ to emphasize bedding-schistosity, $S_1$. In rocks, where $S_2$ is strongly developed, post-crystalline deformation of granular calcite and quartz in the matrix is visible. In the same rocks lenticular, elongated and flattened calcite and quartz have recrystallized along $S_2$.

Amphiboles occur generally along cleavage, $S_2$, but the petal-like rosettes of amphiboles cut across $S_2$ (Fig. 29). The crystallization of amphiboles is suggested to be during or after $F_2$ folding.

The patchy biotites do not conform to the elongated arrangement of calcites parallel to $S_2$ and they are overprinted
on $S_2$, suggesting that their growth post-dates $S_2$. The textural study of the rocks, therefore, indicates that there are at least two generations of biotites, calcites and quartzes - one prior to $F_2$ folding and another during or after $F_2$ folding.

The specimens of amphibole garbenschiefer disclose three types of relationships of amphiboles with respect to $S_2$. Some grains are ellipsoidal with direction of elongation parallel to $S_2$ (Fig. 28). Radiating rosettes of amphiboles, however, show an angular relation to $S_2$; the cleavage is cut across by amphibole crystals (Fig. 29). It suggests that these amphiboles post-date $S_2$.

The deformed auge-shaped amphiboles are elongated parallel to cleavage $S_2$ (Fig. 25). These amphiboles may occur as aggregates with radial arrangement; the aggregates as a whole are elongated in shape parallel to trace of $S_2$. In the same rock biotites, calcites and quartz are recrystallized, free of strain and remarkably elongated in shape in the plane of $S_2$. There is no recrystallized quartz and calcite; quartz and biotite with granular texture are observed when $S_1$ is present in the rock.

In the garbenschiefer biotites are texturally two types: one is elongated parallel to $S_2$ and another patchy, nearly equant occurring across $S_2$. 
(iv) Mica schists

In these rocks the schistosity is defined by flattened and elongated mica and quartz (Figs. 20, 23). Opaque porphyroblastic ores are also seen to be elongated along schistosity (Fig. 22). The schistosity has an attitude strikingly similar to bedding-schistosity of adjacent Ajabgarh calc-rocks. So this mica growth may be S₁ or mimetic after S₁. The schistosity and lineation defined by elongated grains of mica and quartz are distorted by puckering on F₂ axis (Fig. 21). The axis of puckering is at high angle to mineral lineation. The two micas, biotite and muscovite, and quartz grains are twisted around the hinges of F₂ puckers. Strong strain shadows have developed in mica and quartz. Cleavages of micas are bent. Some quartz grains show fracture in conformity with strain-slip cleavage (S₂) of the rock (Fig. 19). Thus the lineated minerals have suffered post-crystalline deformation during F₂ folding.

Some stout, stumpy and inequidimensional biotites are elongated along schistosity. But the cleavage trace of biotite is at an acute angle to the schistosity (Fig. 24). Probably when the schistosity was generated, these biotites originally had not been in the alignment of the plane and the deforming force rotated the grains until they came in the schistosity plane when further rotation was prohibited. The result is that the biotites show a dimensional
elongation parallel to trace of schistosity but no lattice orientation (cf. Zwart, 1963). Rocks containing biotites with cleavage across foliation have been cut on different faces to examine the shape of the biotites three-dimensionally. From these data, Fig. 45 is drawn, giving the possible position of stumpy mica in the rocks before rotation.

If the micas shown in RB₂ are rotated, they would give figures like RB₁, RB₂ and RB₃ with cleavages lying mostly across the foliation (Fig. 45).

The chlorites contain biotites and quartz as inclusions and themselves appear as crystalloblasts (Plate II). At places biotite changes into chlorite. The elongation of the chlorites is aligned in the direction of schistosity.

Garnets cut across the schistosity and at places, the schistosity swerves around them. In rock specimens folded on F₂ axes, disrupted garnet is seen with the plane of fracture through garnet parallel to strain slip cleavage S₂ (Fig. 84). Thus F₂ has deformed garnets. Garnets have pressure shadow of quartz in the rim possibly due to the release of strain in the waxing stages of deformation.

Andalusites show two types of relationship with the schistosity:

a) Schistosity continuous through it

and b) Schistosity curving around the crystal (Plate II).
The patchy nature of andalusite indicates that it might have nucleated at several places and during subsequent movement segregated to form incipient porphyroblasts (Kretz, 1966). From the relation with schistosity it is suggested that it has started to grow after the initiation of schistosity and included the latter. The swerving around of schistosity is due to its flattening during growth (Zwart, 1962).

Andalusite includes garnet and thus post-dates the crystallization of garnet.

Staurolite occurs as subidioblastic crystals and includes garnet. Thus it post-dates garnet. No other relationship to elucidate its time of crystallization is available.

The relationship between deformation and crystallization in terms of recognized episodes of deformation of the area has been summerized in Table 4.
<table>
<thead>
<tr>
<th>Minerals</th>
<th>$F_{1}/S_{1}$</th>
<th>$F_{2}/S_{2}$</th>
<th>$F_{3}/S_{3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Syn</td>
<td>Post</td>
</tr>
<tr>
<td>Ajabgarh Micaschists</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garnet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Andalusite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biotite</td>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Amphibole</td>
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</tr>
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<td>Ajabgarh calc-silicate</td>
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<tr>
<td>Quartz</td>
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<td>Biotite</td>
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</tr>
<tr>
<td>Amphibole</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

- Elongated habit
- Patchy
- Granular habit
- Flattened and Elongated habit
- Green variety
- Ellipsoidal habit
- Rosettes
E. Status and grade of metamorphism with note on geochemistry.

The rock types, which lend clue to the status and grade of metamorphism, belong to the Kushalgarh crystalline limestones and Ajabgarh rocks. The metamorphic assemblages can be broadly divided into two categories:

I. Calcareous,
and II. Pelitic.

For the purpose of discussion in this section these have been further subdivided into groups according to specific mineral assemblages.

I. Calcareous assemblages

(1) Kushalgarh crystalline limestones: The main groups are -
   (a) Calcite-quartz-biotite-tremolite-opaque ore.
   (b) Calcite-biotite-scapolite-quartz-sphene-opaque ore.
   (c) Calcite-epidote-chlorite-tremolite-quartz-opaque ore-
       biotite-tourmaline-muscovite.
   (d) Calcite-biotite-chlorite-albite/oligoclase-
       microcline-quartz-epidote-opaque ore.
   (e) Calcite-quartz-muscovite-biotite-opaque ore.

(2) Ajabgarh calc-silicate rocks: The main groups are -
   (a) Calcite-tremolite-actinolite-quartz-biotite-
       muscovite-epidote-opaque ore-(sphene)-(alkali feldspar).
   (b) Talc-tremolite-(quartz)-(calcite).
In the amphibolite facies (lower part) involving calcareous/magnesian sediments, with excess of SiO₂ and K₂O, amphibole always occurs if the rock composition permits. Generally anorthite comes into the assemblage. But when the lower temperature range of the facies is in existing condition, epidote is stable. Here in these assemblages anorthite is not found while epidote persists according to the above condition (Barth, 1962).

In Ajabgarh calc-silicate rocks, talc, calcite, and tremolite occur together. Under the conditions of greenschist facies the calcite-talc association is held as low-temperature modification of the pure magnesium-tremolite. However, in tremolite, part of magnesia may be replaced by iron (actinolite) whereas talc is unstable to take iron into solution. Considering actinolite as a solid solution of two-components, Ca₂ Mg₅ Si₈ O₂₂ (OH)₂ and Ca₂ Fe₅ Si₈ O₂₂ (OH)₂ - the magnesian component at low temperature breaks up into calcite and talc but the ferrous component remains stable.

Thus calcite + talc + quartz $\rightarrow$ x Ca₂ Mg₅ Si₈ O₂₂ (OH)₂ + y Ca₂ Fe₅ Si₈ O₂₂ (OH)₂

Greenschist facies $\leftarrow$ Higher facies Barth (1962).

The above reaction indicates that the association of calcite, talc, actinolitic tremolite does not necessarily mean lack of chemical adjustments in metasediments of the present area (Barth 1962).
Scapolite paragenesis needs a possible explanation when occurring with calcite and quartz. The presence of $\text{CO}_2$ normally prevents the formation of scapolite in the quartz-calcite bearing limestones. But with increasing $\text{CO}_2$ pressure only the scapolites approaching the extremal composition (60% Me), remain stable in the marble. According to Korzhinskii's hypothesis (1940) the $\text{CO}_2$ pressure depends directly on the depth and for this reason, marbles of the deep seated complexes are likely to contain scapolites with narrower range of composition than the marbles of shallower complexes (Marakushev 1964). The composition of scapolite in Archaean marble rocks vary generally from $\text{Me}^{57}$ to $\text{Me}^{64}$ (Marakushev 1964). This observation fits in with the scapolite formed in the metasediments here.

Scapolite in Kushalgarh crystalline limestone -

\[
\begin{align*}
\text{R.I.} & \quad N_o = 1.585 \pm 0.0005 \\
& \quad N_e = 1.583 \pm 0.0005 \\
& \quad M_e = 59\% (n_m = 1.564)
\end{align*}
\]

The amphibolite facies has been experimentally found to attain temperature around 500°C (Turner and Verhoogen, 1965; Turner, 1968). In the larger parts of the facies quartz-calcite association is stable. Thus the conditions of amphibolite facies is the most feasible pressure-temperature condition attained by the calcareous assemblages in this area.
II. Pelitic assemblages

1) *Ajabgarh phyllites*: The assemblage is -
   Quartz-brown biotite-chloritoid-opaque ore-(calcite)-(tourmaline).

2) *Ajabgarh mica schists*: The main groups are -
   **Type A.**
   1) Andalusite-biotite-muscovite-quartz
   2) Andalusite-biotite-muscovite-albite/oligoclase-quartz
      (Apatite tourmaline, calcite and opaque ore may occur in small proportions).
   3) Andalusite-biotite-muscovite-sillimanite(?)quartz
      (Apatite, tourmaline and opaque ores may occur in small proportions).

   **Type B.**
   1) Staurolite-garnet-andalusite-muscovite-biotite-quartz
   2) Staurolite-garnet-andalusite-muscovite-biotite-albite/oligoclase-quartz
   3) Staurolite-garnet-muscovite-biotite-quartz
      (Apatite, calcite, tourmaline, opaque ores may occur in small proportions).

   **Type C.**
   1) Garnet-chlorite-muscovite-biotite-quartz
      (Epidotes, calcite and opaque ores may occur in small proportions).
Chemical analyses of rocks and minerals from Ajabgarh mica-schists
(Analysis by the author at the Mineralogisk-Geologisk
Museum, Oslo).

Mineral: Green biotite  Location: Nodular calcareous rock associated with mica schists in Subarea - XIII (Map11).

Chemical Analysis:

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Wt. %</th>
<th>Molecular %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>10.23</td>
<td>49.01</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09</td>
<td>2.35</td>
</tr>
<tr>
<td>CaO</td>
<td>1.19</td>
<td>4.11</td>
</tr>
<tr>
<td>FeO</td>
<td>17.01</td>
<td>45.09</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.19</td>
<td>x</td>
</tr>
</tbody>
</table>

Mineral: Brown biotite  Location: Mica schist Easternband in Subarea XIII (Map11)

Chemical Analysis:

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Wt. %</th>
<th>Molecular %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>8.86</td>
<td>43.13</td>
</tr>
<tr>
<td>MnO</td>
<td>0.04</td>
<td>0.19</td>
</tr>
<tr>
<td>CaO</td>
<td>0.85</td>
<td>1.96</td>
</tr>
<tr>
<td>FeO</td>
<td>20.46</td>
<td>54.90</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.11</td>
<td>x</td>
</tr>
</tbody>
</table>

For comparison with the above results the chemical analysis of a Green biotite from Ajabgarh calcareous assemblage is given below:

R.I: \[ N'y = 1.6197 \pm 0.004 \]
<table>
<thead>
<tr>
<th>Oxides</th>
<th>Wt. %</th>
<th>Molecular %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>10.41</td>
<td>49.05</td>
</tr>
<tr>
<td>MnO</td>
<td>0.06</td>
<td>1.32</td>
</tr>
<tr>
<td>CaO</td>
<td>1.21</td>
<td>3.77</td>
</tr>
<tr>
<td>FeO</td>
<td>17.07</td>
<td>45.28</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>2.90</td>
<td>x</td>
</tr>
</tbody>
</table>

The results of chemical analysis of six samples of Ajabgarh mica-schists are stated in Table 5.
Table 5 (Samples from area shown in Map II)

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Sp.no.1 Type A (2)</th>
<th>Sp.no.3 Type A (3)</th>
<th>Sp.no.2 Type B (1)</th>
<th>Sp.no.4 Type A (2)</th>
<th>Sp.no.5 Type A (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wt.%</td>
<td>Mol. %</td>
<td>Wt.%</td>
<td>Mol. %</td>
<td>Wt.%</td>
</tr>
<tr>
<td>SiO₂</td>
<td>57.36</td>
<td>x</td>
<td>58.31</td>
<td>x</td>
<td>57.51</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.09</td>
<td>x</td>
<td>1.13</td>
<td>x</td>
<td>1.06</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.01</td>
<td>0.56</td>
<td>3.91</td>
<td>1.16</td>
<td>3.56</td>
</tr>
<tr>
<td>FeO</td>
<td>5.77</td>
<td>4.54</td>
<td>6.14</td>
<td>4.65</td>
<td>5.64</td>
</tr>
<tr>
<td>MgO</td>
<td>3.13</td>
<td>4.43</td>
<td>3.08</td>
<td>23.25</td>
<td>3.12</td>
</tr>
<tr>
<td>MnO</td>
<td>0.54</td>
<td>0.52</td>
<td>0.63</td>
<td>4.96</td>
<td>0.54</td>
</tr>
<tr>
<td>CaO</td>
<td>1.80</td>
<td>1.76</td>
<td>1.77</td>
<td>x</td>
<td>1.76</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.74</td>
<td>6.25</td>
<td>0.68</td>
<td>5.81</td>
<td>0.69</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.35</td>
<td>1.70</td>
<td>3.31</td>
<td>1.74</td>
<td>3.24</td>
</tr>
</tbody>
</table>

Sp. no. 1. Type A (2) Samples collected from Sp. nos. 4, 5, 6 Type A Eastern band Map II
Sp. no. 3. Type A (3) Western band Map II
Sp. no. 2. Type B (2) Western band Map II

Analysed by the author (R. Sen) using X-ray fluorescence spectrograph, Flame Photometer and Atomic Absorption (for MgO) at the Mineralogist-Geologisk Museum, Oslo.

Type A (1) (Page 59) these rocks with andalusites varying in size from patchy no. (4), small crystal (no.5), big ellipsoidal crystals embedded in the rock no. (6) are analysed. Type A (2) = no. 1, T.A. (3) = no. 3, Type B (2) = no. 2, Type A (1) = nos. 4, 5, 4-6.
Result of chemical analysis of garnet from Ajabgarh mica-schist, Type B.

Garnet:

R.I. = 1.302 ± .005

Chemical Analysis:

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Wt. %</th>
<th>Molecular %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>6.02</td>
<td>20.83</td>
</tr>
<tr>
<td>CaO</td>
<td>0.65</td>
<td>18.27</td>
</tr>
<tr>
<td>MnO</td>
<td>2.01</td>
<td>3.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(unusually high)</td>
</tr>
<tr>
<td>FeO</td>
<td>32.01</td>
<td>61.11</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.62</td>
<td>x</td>
</tr>
</tbody>
</table>

Discussion on Ajabgarh mica-schists and phyllites:

In the pelitic rocks belonging to the amphibolite facies, with excess silica and deficient in $K_2O$ andalusite is present along with other minerals. Thus the occurrence of andalusite in Eastern pelitic bands (Type A) is explained. But the association of andalusite-garnet-staurolite, and of andalusite-sillimanite (?) (if occurrence of sillimanite is accepted) need explanation.

The presence of chloritoid in the phyllites may indicate the lower temperature range of epidote-amphibolite subfacies (Barth, 1962). The association of staurolite, andalusite and garnet in the mica schist calls for explanation.
It has been recently found that the occurrence of andalusite and its association with staurolite and garnet are not uncommon in environments of regional metamorphism, especially when pressure is deficient and need not be interpreted as of local significance only (Winkler, 1967). As these minerals are found all over Alwar district, Rajasthan, India (Map 15) it can be suggested here that their occurrence is regional and not local. Heron (1917) mentioned the occurrence of these minerals from Ajabgarh pelites from several localities in Alwar district, Gangopadhyay (1967) suggested that this association indicates that Alwar Dt. witnesses metamorphism under high temperature and low pressure conditions.

The above pelitic associations belong to the 'Intermediate Facies Series' of Winkler (1967). Chloritoid can be observed in some rocks in this facies series (as in Bosost area reported by Zwart 1958, 1960, 1962, 1963) as has been found in the present area in phyllites; it is to be expected in the Abukoma type (Miyashiro, 1961) if proper chemical composition is present.

The pelitic associations marked as Types (A), (B) & (C) (Refer to Page 59) in Kushalgarh area are peculiar in themselves and not exactly identical with any of these facies type described from Bosost, Buchan, Abukoma, Eastern Pyrenees, Northern Hampshire, Barrovia, Michigan and Idaho (Heitanen, 1967).
The assemblages here (Refer Page 59) are intermediate between Abukoma (Japan type of Heitanen, 1967) type and Barrovian type. The amphibolite facies may begin at approximately the same temperatures here as in other areas above. But the subdivision of the facies on the basis of upper stability limit of staurolite in the common paragenesis and the upper stability limit of muscovite in the presence of quartz cannot be possibly applied here as no transition in minerals is seen and there is no transition from andalusite to sillimanite as found in other areas. On the other hand, they occur together if the identification of sillimanite is accepted. Almandine garnet contains larger than normal (see analyses Page 63) amount of spessartine molecules. If in the original bulk composition, Mn was present in large amount it could go into garnet and form a stable structure without having a tendency to be replaced. So it does not necessarily mean a lower temperature condition (Atherton, 1968).

Andalusite starts to crystallise in the low-pressure in the biotite zone but the presence of garnet indicates a higher pressure in the present area. Staurolite has an upper stability limit in the Andalusite zone in the low pressure; so the presence of staurolite and andalusite together does not pose a problem. But according to experimental investigations by Winkler (1967) and Althaus (1967) (using the same laboratory and apparatus by the present authors and their results should have same significance), sillimanite and andalusite should not
occur together without a change over. Sillimanite occurs only at pressures close to the triple point. But little is known about the stability of andalusite and sillimanite occurring together without a change over.

In Heitanen's diagram (1967), the lines representing pressure-temperature conditions of different facies of regional metamorphism do not coincide with the assemblages here. But it can be suggested that the assemblage reached a condition in the present area near the cotectic line of andalusite and sillimanite (if its occurrence is accepted) and thus both are found to occur together. Schimazu (1966) suggested that when dynamic stress in a non-hydrostatic field is considered instead of hydrostatic pressure (which is only considered in experimental investigations) involving the aluminium silicates, instead of a triple point it is possible to have a zone in which the equilibrium of andalusite-sillimanite exists (Fig. 6). In this condition the number of variants in the phase rule becomes 7 instead of 2, i.e., \( p = c + \frac{2}{3} - f \) becomes \( p = c + 7 - f \), thus the phase rule ceases to be applicable under the circumstances.

Note on geochemistry:

The bulk compositions of the rocks (given in Table 5') are plotted on an AKF diagram and also on \( \text{Al}_2\text{O}_3-\text{MgO-FeO} \) diagram (Plate 6). In the latter, the position from chemical analyses of the two biotites and the garnet are also plotted.
Molecular percentages are plotted following Eskola's rule (Barth, 1962). But the bulk compositions show strange positions with respect to their mineral paragenesis (discussed in the following pages).

It is to be mentioned first that there is no K-feldspar in the assemblages. The AKF diagram also shows plots in a field outside the range of K-feldspar. So the rocks are deficient in K-feldspars.

Samples analysed (nos. 1, 2, 3, 4, 5 and 6 in Table 5) give the following reactions:

(a) Staurolite + quartz ⇌ almandine + andalusite + H₂O
(b) Almandine + K-feldspar ⇌ biotite + muscovite + quartz

Quartz from (b) again goes into (a) to be used up for completion of reaction. If the quantity of quartz is not enough, staurolite is not used up completely. So the reaction (a) is incomplete giving an assemblage of sample 2. So staurolite-almandine-andalusite-quartz are associated together.

The almandine of reaction (a) reacts with K-feldspar in the sediments first to produce biotite, muscovite and quartz. As K-feldspar reacts first with garnet, andalusite is left out which crystallises later to give an assemblage of sample no. 2. The reaction (b) partially progresses to release quartz but is also incomplete because of less of K₂O content. Thus all the minerals participating in the reaction are found in the assemblage of Sample no. 2.
In samples (1), (4), (5) and (6) there was enough K$_2$O to convert all garnets to muscovite and biotite so only andalusite is found with biotite-muscovite-quartz in the assemblages. The reaction (b) is complete in this case. But as said earlier, andalusite was left out of the reaction from (a) and crystallised to form andalusite in the assemblage of samples (1), (4), (5) and (6).

All the K-feldspars (being deficient originally) are used up in the reaction (b) and hence K-feldspar is not found in the rock.

Sample no. 3 indicates the position of bulk-composition around andalusite and sillimanite cotectic line. If the presence of sillimanite is accepted, it might be due to variation of pressure locally.

From the triple-point diagram of Clark (1957) it is noted that considering the assemblages of samples nos. 1, 4, 5, and 6, almandine is not suitable at lower pressures than the line A. It breaks up into biotite and muscovite but andalusite is stable. So it exists and there is no almandine with it.

The bulk-compositions of nos. 1, 2, 3, 4, 5 and 6 when plotted on Al$_2$O$_3$ - MgO - FeO diagram with the minerals, they give difference from normal paragenesis because of heterogeneity of original concentration particularly heterogeneous distribution of K-feldspar.
It is suggested that concentration of Al₂O₃ was different in different bands originally before reaction. K₂O was also heterogeneously distributed. And if the system was closed with respect to CO₂ and H₂O, there is little possibility of migration of alkalis and volatile matter. Naturally Al₂O₃ cannot be much diffused because it is heavier. So the latter is concentrated to give rise to patches where there is lower concentration and big crystals where there is higher concentration.

In the Barrovian type of metamorphism (Heitanen, 1967), staurolite and kyanite are found but no wollastonite. So the system is closed against CO₂ and pressure is therefore very high. But in the Abukoma type (Miyashiro, 1961), there is andalusite in the assemblage. So the type of metamorphism involved in the present area with no kyanite is intermediate between Barrovian and Abukoma type. But here there is no wollastonite as in Barrovian type. Hence the reaction -

Calcite + quartz ⇌ wollastonite + CO₂

did not occur with a high CO₂ pressure and the system was closed. The CO₂ pressure was likely to be high and this condition did not allow the operation of the above reaction. So wollastonite is not found in the Ajabgarh calc-silicate rocks associated with pelitic schists.
This high $\text{CO}_2$-pressure condition also fits in with the scapolite paragenesis of the calc-magnesian sediments (Page 58) discussed earlier.

From the above discussions it can be suggested that the pelitic assemblage in this area lies somewhere between Andalusite subfacies (low pressure Órjarvi region, Eskola, 1915), and Sillimanite subfacies (pressure variable and high temperature) lying within the amphibolite facies (Schimazu, 1966).

Thus in the $F_1$ phase of folding, the calcareous assemblages reached equilibrium in the lower amphibolite facies but in the $F_2$ phase all the assemblages were in the upper amphibolite facies. In the later part of $F_3$ phase of folding, possibly when the strain was releasing, biotites were locally changed into chlorite.