CHAPTER 5

MICROFABRICS

In general the term fabric describes individual parts of a tectonite and their orientation and distribution in space. Turner and Weiss (1963) describe the term fabric in the same sense in which Sander (1930) use the term gefuge. They describe it as an internal ordering of both geometric and physical spatial data in aggregates. Hobbs et al., (1976) describe it as the complete spatial and geometrical configuration of all those components that make up the rock. Wenk (1985) defines the term as the sum total of grain shape, grain size and grain configuration. The term microfabric has been used to specify the fabric studies carried out using an optical microscope and/or instruments with higher resolving power.

Fabric studies embody both geometrical or morphological aspects and functional or behavioural aspects (Turner and Weiss, 1963). Of these, the functional aspects are used to correlate directional physical properties to the regular geometry of the matter.

As fabric does not take into account bounding surfaces, its extent is unlimited but implicit in it is the concept of homoginity (Turner and Weiss, 1963). Therefore, to limit the extent of fabric, the term domain is used which specifies a finite three dimensional portion of the body that is statistically homogeneous on the scale of the domain. All the features contributing to the fabric in the domain are known
as fabric elements.
The main objective in undertaking microfabric study is to find out the history of deformation, state of strain in the rocks exposed in the area, physical conditions and microstructural mechanisms responsible for deformation. The present study is divided into four parts. The first part deals with the description of the microstructures. Second part describes the results of crystallographic preferred orientation studies carried out for the C axis of quartz. In the third part kinematic implications of the microstructures are discussed and the last part deals with the state of strain in the rocks exposed in the area.

MICROSTRUCTURES
They describe the shape of individual grains and their spatial relations. Till the early sixties little was known regarding the implications of these structures. Since then lot of experimental work has been done on rocks and minerals (Carter et al., 1964 a, b; Ashbee 1967, 1969, 1970; Hobbs 1968; Griggs et al., 1970; Tullis 1970; Avelalleman and Carter, 1971; Tullis et al., 1973; Dell'angelo & Tullis, 1989). Inferences drawn from the results of these experiments, within the framework provided by metallurgists have provided on insight into the precise meaning of these structures.
It has been understood that thermal and deformational history of a crystal introduces a number of defects into it. The nature of these defects vary with the crystal structure and
its chemical constituents. These defects have a complicated structure and they continuously move through the crystal during its deformation. Such defects have been classified into three types on the basis of their shape. These are: point defects, line defects and planer defects (Hobbs et al., 1976).

Point and line defects in the present study have not been investigated due to the instrumental limitations, but planer defects have certain representatives, that can be observed under the optical microscope (Hobbs et al., 1976). Deformed rocks of the area are studied from the point of view of describing these microstructures and their spatial variations. The following points were taken into consideration while selecting the samples for the present study:

a) They should belong to the same facies of metamorphism,
b) They should be monomineralic (quartz > 95%),
c) Grain size is homogeneous at the scale of observation and
d) Recrystallisation is absent or is in an incipient state.

Quartzite forms a major part of the Larji and Banjar Groups of rocks exposed in the study area. Being a prominent lithologic component and because of its sensitivity to change in the deformation path, it has been used to delineate microstructural domains and evolution of microstructures across the shear zone. Lithologically, quartzites consist of well sorted quartz grains which are about 95 to 80 percent by volume in pure and schistose varieties respectively. Following the classification of Bouchez and Peacher (1981),
the observed microstructures in the quartzites of the study are classified as:

a) Fine grained microtexture,
b) Preserved detrital microtexture,
c) Relict porphyroclastic microtexture, and
d) Elongate mosaic microtexture.

FINE GRAINED MICROTEXTURE: Quartzites with this type of texture are observed in Hurla and Naraul Groups. Bands of these quartzites are generally found alternating with bands of slates (Pl.10a) and they vary in thickness from several mm to few cms. The Contact between quartzite and the slate bands is sharp in nature.
Quartz grains are subpolygonal in shape and less than 100 μm in size. They show irregular to diffuse grain boundaries and shape preferred alignment oblique to the bedding surface. These features are indicative of a dominant dynamic recrystallization component of the deformation.

PRESERVED DETRITAL MICROTEXTURE This texture is observed in quartzites of Naraul Formation. In the field these quartzites are folded along with the rocks of Hurla Formation. They are compact and mostly white in colour. In thin section they show well developed S surfaces, S₁ and S₂, defined by the alignment of sericite flakes and detrital grains of quartz (Pl.10b).
Detrital grains are preserved in the matrix of fine grained quartz and sericite and show slight elongation as a result of deformation. Grains show undulatory extinction and sutured
boundaries. Average ratio of flattening of these relict grains is less than 2 : 1.

RELICT PORPHYROCLASTIC MICROTEXTURE Quartzites showing this type of texture belong to Naraul Formation and all the formations of Banjar Group. Quartzites from Naraul Formation are fine grained, compact, and white to dirty white in color. Those from Banjar Group are fine to medium grained, compact, and occur as thin or thick bands alternating with bands of phyllites or metavolcanics.

Quartzites showing relict porphyroclastic microtexture are further subdivided into three division i.e., mild, moderate and strong, depending upon the ratio of recrystallised grains and porphyroclasts. Original grains are usually easy to recognise and mostly contain unrecrystallised core. Ratio of flattening rarely exceeds 5 : 1. Porphyroclasts show wavy extinction deformation lamellae and recrystallised grains at their boundaries.

Mildly deformed porphyroclasts: This type of texture is observed in quartzites from Naraul Formation. Porphyroclasts show sutured grain boundaries and slight recrystallization at the grain boundaries (Pl.10c). Recrystallised grains form less than 25% of the rock.

Moderately deformed porphyroclasts: Quartzites of the Banjar Group show this type of deformational texture. Porphyroclasts are highly elongate, show flattening ratio of 4 : 1 and their margin is rimmed by recrystallised grains (Pl.10d). Two S surfaces, S₁ and S₂, are observed in thin section which are
defined by elongate porphyroclasts, and grain boundaries of dynamically recrystallised grains respectively. Recrystallised grains form 25 - 75% of the rock.

**Strongly deformed porphyroclasts:** Quartzites from Bhalan and Green Bed Formations exhibit this type of deformational texture. Recrystallised grains form more than 75% of the rock (Pl.10e). They show wavy extinction and straight grain boundaries. A few relict porphyroclasts can be recognised which show complete recrystallization in the form of subgrain formation.

**ELONGATE MOSAIC MICROTEXTURE** It is observed in the quartzites of the Manikaran Formation which occur near the contact of Bandal granite. The rock shows granoblastic texture (Pl.10f) and is composed of mosaic of equant, subrounded to elongate clear quartz grains. Grains show almost straight boundaries and meet at triple points and at right angles, in case of quartz-quartz and quartz-mica respectively. Mica occurs as elongated flakes along the quartz grain boundaries. A few highly elongate ribbons of quartz are also observed.

**MICROSTRUCTURAL EVOLUTION**

Various types of mylonites and quartzites described above show a kind of progressive deformation in the area. To carry out deformational fabric studies in detail, the area was systematically sampled along three traverses across the general strike direction and the shear zone. Another set of samples was taken along the shear zone. Oriented samples were cut in XZ and YZ planes, where X parallels lineation and is
assumed to represent the direction of maximum elongation and
XY represents plane of flattening. Framework resulting from
these two fabric elements (XZ &YZ) is used to relate the
quartz fabric. The X, Y and Z axes of the framework are
assumed to parallel X, Y and Z axes of the finite strain
ellipsoid. Microstructures described in the following section
are observed in XY plane.

In weakly deformed quartzites of Hurla Formation, quartzite
found near the contact with Aut Formation show dimensional
preferred orientation (Pl.11a,14b). Deformation features are
indicative of slight deformation in the form of wavy
extinction, deformation lamellae (Pl.13b) and mica beards
(Pl.14a) around the quartz grains. These grains are well
sorted and show dominal heterogeneity (Pl.11a) whereas
quartzite in contact with tectonically overlying Naraul
Formation show mortar texture and sutured boundaries
(Pl.11b,e,f). Quartzites from Naraul Formation show great
variation in their textures. Starting in the west i.e. from
the contact with Hurla Formation, it shows slight deformation
in the form of polygonization of cherty material into clear
quartz grains (Pl.11c). Bands of orthoquartzite adjacent to
charity band show sutured grain boundaries without
recrystallization (Pl.11d) and quartz grains show the
development of wavy extinction, cracks and deformation
lamellae. Further eastwards, quartzites show mortar texture
and all variations from slight recrystallization at the grain
boundaries (Pl.11e) to complete recrystallization leading to
the formation of ultramylonite (Pl.9f).
At the contact of Naraul and Bhalan Groups a wide zone of intense deformation is observed. This zone is well developed on the both Hurla-Jhuni and Larji-Sainj road sections and on the slopes of ridge separating Naraul and Chashani villages. Within few meters from Garsa bus stand, in the dip direction, quartzites with slight elongation and recrystallization at grain boundaries are transformed into quartzite with highly flattened grains (Pl.12a). They show slight recrystallization at the grain boundaries, deformation lamellae and wavy extinction. Rock as such look like protomylonite. Further east these elongated ribbons are sheared and break into small fragments and show increase in the proportion of the matrix (Pl.12b). Still further these ribbons reduce to streaks and proportion of matrix increases to 70 - 80% and the rocks show a transitional phase from mylonite to ultramylonite (Pl.12c). Within short distance ultramylonites are noticed (Pl.12e). Further east the rocks show decrease in the intensity of deformation which is apparent from the encounter of reverse order of features described above, particularly decreasing proportion of matrix and angular nature of quartz grains (Pl.12d,f). This zone show the development of some typical microstructures such as variably flattened quartz porphyroclasts (Pl.13a,14c,15c); highly angular fragments in ultrafine matrix (Pl.12d,14d) porphyroclasts showing cracks and fragmentation at margins (Pl.9a,15d). In certain thin sections in otherwise elongated porphyroclasts globular porphyroclasts are found (Pl.15a). Quartzites from Garsa bus
stand to Forest Rest House section, show abrupt increase in the intensity of deformation which has resulted in the development of mylonite-ultramylonite sequence or SC-I mylonites of Lister and Snake (1984). S and C surfaces are defined by porphyroclasts and dynamically recrystallised quartz grains at their boundaries (Pl.12e,13d,e,14e) respectively. Quartz from veins is also dynamically recrystallised and shows identical microstructures to that of the host mylonite (Pl.12e). Even in quartzites showing almost complete recrystallization, a few porphyroclasts are observed (Pl.13d,f) which show flattening, wavy extinction and assymetric pressure shadows. Some of these relict porphyroclasts have been reduced to ribbons. Recrystallised grains are fine to medium, inequidimensional (Pl.13d) and show regular to irregular grain boundaries (Pl.13c,14e). Similar orientation of recrystallised grains (Pl.14e) possibly represents former ribbons. Quartzites from Bhalan and Green Bed Formations show deformation features that indicate gradual decrease in intensity of deformation with respect to that of the rocks of shear zone. But intensity is high as compared to that suffered by quartzites occurring west of shear zone. General texture of these quartzites can be described as mortar texture (Pl.13c). In general proportion of recrystallised grains to porphyroclasts show an increase in the dip direction. Recrystallised grains are granular to elongate with irregular grain boundaries (Pl.13d). Quartz grains from
these quartzites show complete recrystallization. Recrystallised grains are clear equant with straight grain boundaries. Quartz veins in these rocks show pinch and swell structure and recrystallization of quartz in these veins is noticed (Pl.14f).

Quartzite from Manikaran Quartzite Formation show typical equigranular granoblastic texture when pure and relict porphyroclastic texture in case of schistose quartzite (Pl.13e,15f). In case of granoblastic texture quartz grains are clear equant with straight grain boundaries meeting at triple points (Pl.13e). In case of relict porphyroclastic texture both porphyroclast and recrystallised grains show straight contact and grain boundaries form approximate right angle with elongated mica flakes (Pl.15f). Porphyroclasts are highly elongate, average flattening ratio is around 5 : 1 and show cracks which have been healed by recrystallised quartz grains (Pl.15d). They show wavy extinction deformation bands and syntectonic recrystallization (Pl.15b,c). Newly recrystallised grains are cited at deformation band margins (Pl.15b,e) and at porphyroclast margin, which represent areas of high subgrain misorientation. Along with highly elongated aligned porphyroclasts, subrounded to elliptical porphyroclasts are also observed (Pl.15c). Two sets of S surfaces are distinguished in these quartzites. S₁ is defined by parallel alignment of relict porphyroclasts and elongated mica flakes while S₂ is defined by the alignment of reoriented flakes, recrystallised grains and their grain
boundaries (Pl.15c).
Near Bandal granite, schistose quartzites show complete recrystallization which causes elongate mosaic texture (Pl.10f). Recrystallised grains show straight smooth grain boundaries. The grains of quartz meet each other at triple points and at right angles with mica flakes.
From the above described microstructures it is clear that the studied rocks show a progressive increase in the intensity of deformation in the dip direction. At the contact of two groups of rocks there is a narrow shear zone of intense deformation which shows the development of mylonite-ultramylonite sequence. Quartzites from Larji Group show fine grained and preserved detrital microtextures and microstructures which imply low intensity of deformation, whereas that of Banjar Group show relict porphyroclastic and elongate mosaic microtextures and microstructures which indicate comparatively higher intensity of deformation.

CRYSTALLOGRAPHIC PREFERRED ORIENTATION (CPO)
One of the fundamental change resulting from the deformation of rocks is the development of preferred orientation of the crystallographic directions of the constituent minerals. These variations in space can be presented in the form of fabric diagrams. In the last two decades workers from all over the world have been striving to relate these fabric diagrams to the intensity of deformation, mechanisms of deformation, type of strain and physical conditions of deformation (Hobbs et al., 1976; Bouchez and Peacher, 1976;
Lister, 1977; Lister and Williams, 1979; Lister and Hobbs, 1980; Garcia-Celma, 1982; Lister and Dornsiepen, 1982; Passchier, 1983; Tullis, 1977; Tullis et al., 1973; White, 1976). Quartz is one of the most commonly used minerals for this kind of study partly due to its wide spread occurrence and partly because of its relatively simple optical properties. Another tempting feature is the large number of microstructures and related C-axis fabrics shown by this mineral. These features can be used to interrelate atleast some aspects of rock deformation. As C-axis is the only axis that can be determined optically, therefore, in the present study comparison of naturally and experimentally deformed quartzites is restricted to only C-axis fabric.

CPO results in deformed mineral aggregates with or without recrystallization. In the later CPO is the direct consequence of internal deformation mechanisms (Price, 1985) these are employed by each grain to accommodate an imposed external strain, without involving large amount of diffusion, grain boundary sliding or loss of cohesion. Such deformations are termed plastic and involve dislocation glide or twinning mechanisms. In rocks where recrystallization occurs while the deformation is continuing, the observed fabrics are akin to those of rocks which do not show significant recrystallization (Price, 1985). White (1976) and Lister and Price (1978) are of the opinion that even if recrystallization processes operate, dislocation glide remains the principal reorientation mechanism.

Quartz crystal is predominantly composed of covalent bonds in
three dimensional framework; consequently it lacks easy glide planes. The absence of easy glide planes is responsible for high yield strength even at high temperatures. However if water is present as traces, the quartz show anomalous weakening and can achieve large plastic strain although the exact mechanisms of this transformation are not known (Paterson and Kekulawal, 1979). Experimental and electron microscope studies have revealed that the dislocation plays a major role in the deformation of quartzite. The most commonly reported slip systems involve either the basal plane $c = (0001)$, the prism $m = (1010)$, the $+ve$ rhomb $r = (1011)$ or $-ve$ rhomb $z = (0111)$ as slip planes and $a$-axis, $c$-axis or vector sum of $c + a$ as slip directions (Christie et al., 1969 a, b; Hobbs et al., 1972; Twiss, 1974; Blacic, 1975; Morrison Smith et al., 1976). There are uncertainties regarding the relative importance of activity on each slip system and relation of slip system to physical conditions and impurity content. Nevertheless, the available information regarding these slip systems in the framework of Taylor-Bishop-Hill theory has been utilised by Lister and his coworkers (e.g. Lister, 1977; Lister and Williams, 1979; Lister and Hobbs, 1980) to carry out computer simulation studies. They have presented a number of alternative predictions of the type of fabric at given strains under the operation of different combinations of slip systems. To compare the measured fabric with appropriate theoretically predicted fabric, it is necessary to determine the strain that rock containing the
fabric have accumulated. However, in the studied area it was only possible to find out strain in some of the samples selected for CPO study. Even in those samples, correlation is only approximate because of the following constraints, as pointed out by Price (1985):

a) Non coaxial component of strain is difficult to detect,

b) Nature of strain path may change during deformation,

c) Imposed strain may not be homogeneous on the grain scale (almost always true and cannot be avoided) and

d) Final shape of deformed grains may not reflect the total imposed strain if grain boundary sliding is significant or if original grains were not approximately spherical.

To minimise the approximation of correlation between natural and experimental fabrics, samples chosen for LPO study were:

a) Almost monomineralic (quartz > 95%),

b) They showed certain typical microstructures,

c) Susceptible to strain analysis and

d) Related to the shear zone spatially.

Fabric diagrams for different samples are shown in figure 16(a-f). These diagrams represent lower hemisphere equal projections and horizontal line shows the lineation direction and the trace of foliation containing lineation. Dark areas represent areas of maximum concentration. Abbreviation attached with the diagrams: 571,200: sample number and number of measurements. Almost all the fabric diagrams show symmetric or asymmetric Type 1 girdles of Lister and Williams (1979). They show YZ girdle, which depict variation of symmetry with respect to foliation plane. Moreover, mostly
multiple maxima are observed. Concentration of these maxima occur either around Z axis or Y axis. In one fabric diagram (5712) along with the YZ girdle, maxima is also observed around X axis. In another fabric diagram (186) along all the axes vacancy fields are observed. The XY girdle observed in the fabric diagrams can be correlated with the similar girdle predicted by model A or B quartzites of Lister and Williams (1979). But it is known that at low temperatures and higher strain rates crustal rocks tend to deform by brittle rather than ductile mechanisms. Therefore, all the fabric diagrams except those which belong to the rocks of ductile shear zone are correlated to the theoretical fabrics of model B. On the other hand those belonging to the shear zone are correlated with the theoretical fabrics of model A.

Fabric diagrams of all the quartzites of Larji Group fall in both constrictive as well as in general flattening fields; but the rocks whose fabric corresponds to flattening field, occur in the vicinity of shear zone. Fabric diagrams of the Banjar Group rocks fall in the field of axial shortening and general flattening. Change in the intensity of deformation is reflected by the corresponding change in the width of the girdle.

Model A fabrics represent a family of yield surface configurations that give rise to a point maxima of C axis which is parallel to Z for progressive symmetric shortening (Lister and Hobbs, 1980). Tullis et al., (1973) have obtained similar fabrics for experimentally deformed quartzite at low
temperature or faster strain rates. These fabrics are also common in nature in most of the observed fabrics as suggested earlier. The essential characteristics of this model is that Basal $\langle a \rangle$ system dominate over $-\text{ve rhomb } \langle c+a \rangle$ and prism $\langle a \rangle$ contributes in a minor way. The fabric concentration of C axis at high angle to Z indicates the activity of prism $\langle a \rangle$ glide (Lister and Hobbs, 1980).

Model quartzite B is represented by a family of yield surfaces that give rise to 25 small circle girdle of C axes around Z for progressive axially symmetric shortening. This model is characterized by relatively soft basal $\langle a \rangle$ and hard $\text{+ve and -ve rhomb } \langle c+a \rangle$ systems (Lister and Hobbs, 1980). Prism $\langle a \rangle$ systems are also included but their activity is negligible.

Comparison of observed fabrics to the model quartzite fabrics developed under coaxial and noncoaxial deformation suggest that the rocks of Larji Group have suffered deformation mostly in the constrictive field. The rocks of shear zone and as well as those of Banjar Group indicate deformation as a result of flattening and axial shortening. Moreover a change in the mechanism of deformation from basal $\langle a \rangle$ to rhomb $\langle c+a \rangle$ is suggested in the shear zone. Fabrics of rocks from the shear zone are also indicative of higher strain state. Another important point of difference between the fabrics of rocks of the two groups is the presence of assymetric YZ girdle with respect to foliation plane in the Banjar Group. This indicate non-coaxial component of deformation in these rocks.
Ductile shear zones are deep seated equivalents of brittle faults (Ramsay, 1986). These zones usually lack unequivocal offset marker layers for the determination of sense of shear (Simpson, 1986). Various microstructures that can be used to determine the sense of shear in these zones are known as kinematic indicator. Hanmer (1986) has defined kinematic indicator as a structure, whose geometry is indicative of the progressive rotation of the principal axes of finite strain with respect to the principal axes of kinematic framework and/or the shear plane of the deformation. Various examples of kinematic indicators have been provided by Simpson and Schmid (1983), Simpson (1986) and Passchier and Simpson (1986). In the following portion description of various kinematic indicators, that are observed in the area is given. Following Simpson (1986) all observations are made in XZ section i.e. section perpendicular to the foliation and parallel to the maximum stretch direction.

S-C STRUCTURE: C surface is a very small scale ductile shear zone that forms within a much wider non-coaxial flow regime. They are subparallel to each other and occur evenly spaced across the outcrop (Pl.3e) and S planes are observed curling along these planes. In plate 3e it represents left lateral shear sense.

Simpson (1986) suggested that the term shear band be used in the case where the relative age of the two foliations is uncertain or when one of them is demonstrably of different
origin. The S-C mylonite should be restricted to those cases where synchronous or nearly so development of S planes (schistosity) and C planes (shear-planes) can be demonstrated. Berthe et al. (1979) also consider that synchronous development is important, but Lister and Snoke (1987) suggested that, it need not be adhered to. Thus in the present description, these structures are not differentiated and S-C structures of quartz mylonites occurring in the area are used to find out the shear sense and angle between S and C planes is used to delineate the extent of shear zone (Fig.4). Shear sense and S & C planes observed in thin section of rock samples from different outcrops in the studied area are presented in the form of a map. Simpso (1986) points out that these structures prove to be one of the most reliable indicator provided they occur in single well developed sets. Similar structures have been used by Platt and Vissers (1980), White et al. (1980) and Law et al. (1984) to find out the sense of shear in non-coaxially deformed rocks of larger dimensions.

ASSYMMETRIC PORPHYROCLASTS: These structures have been subdivided into two types namely type and type (Passchier and Simpson 1986). They are highly reliable as long as reference plane can be drawn through them (Simpson 1986). Relict porphyroclasts of quartz are common in the fine grained mylonites of the area. They are microscopic in nature and under the microscope show narrow mantle and elongated tail of recrystallised quartz grains. All the porphyroclasts selected for such study show monoclinic symmetry with respect
to the reference plane drawn through them after Simpson (1986). Observed symmetry also indicates the non coaxial nature of the deformation. All the porphyroclasts observed in the thin section are of type and indicate sinistral shear sense (Pl.19b,c,d,f; 20a,b,c).

PRESSURE SHADOW: Pyrite crystals in quartz mylonites show the development of pressure shadows. The asymmetry in these structures has been shown as a highly reliable indicator of shear sense (Takagi and Ito, 1988). Asymmetric nature of these shadows (Fig.20d) indicate sinistral shear sense as well as non-coaxial nature of deformation.

DISPLACED BROKEN GRAINS: Displaced grains of mica (Fig19a,e) and broken grains of pyrite are also observed in the thin sections of the quartz mylonites. As recommended by Simpson (1986) only those grains are chosen that make high (50° - 130°) or low (≤20° or > 160°) angle to the flow plane are used as indicators. All of them indicate sinistral shear sense.

GRAIN SHAPE PREFERRED ORIENTATION: In quartz mylonites along with an early foliation, a secondary foliation is also observed, due to the alignment of elongate dynamically recrystallised quartz grains. These structures are sensitive to slight changes in incremental strain so they indicate shear sense of last increment only (Simpson 1986). This type of structures are also described as Type-II S-C mylonites by Lister and Snoke (1984). Such mylonites noticed in the quartzites of Banjar Group indicate sinistral shear sense.
CRYSTALLOGRAPHIC PREFERRED ORIENTATION (CPO): Development and description of CPO in the quartz mylonites of the area has been dealt in detail in the earlier portion of this chapter. In order to determine the sense of shear, asymmetry of CPO with respect to the main foliation is used. It is based on the fact that in quartz grains plastically deformed by slip on basal (0001) planes in the $<a>$ direction in combination with rhomb or prism slip in the $<a>$ direction, resultant C-axis pattern is usually Type I or Type II girdle. This girdle is oblique to the foliation plane in the sense that is the same as the shear sense in the rock, in case of rocks involving non-coaxial deformation.

There are few difficulties associated with the use of fabric diagrams for natural rocks. Fabric might have originated from the operation of different combinations of slip systems and slip directions which is difficult to interpret (Passchier, 1983); it may be symmetric even in the zones of high shear strain (Law et al., 1984) and even asymmetric patterns may give incorrect shear sense when compared to other criteria (Bouchez and Peacher, 1976; Carreras et al., 1977). So CPO has been used as a kinematic indicator within the above limitations. 46 quartzite samples were studied for the purpose. Fabric diagrams for most of them are shown in figure 16 and c-axis fabric diagrams represented by fabric skeltons are shown in figure 17. Almost all of these diagrams belong to Type I of Lister and Hobbs (1980). Fabric diagrams showing above mentioned asymmetric relation mostly belong to Banjar
Formation and indicate left lateral shear sense.
On the basis of shear sense indicated by various indicators it is suggested that Banjar unit has undergone deformation with non-coaxial component with left lateral shear sense. In the shear zone in one section cut at right angles to bedding (i.e. YZ Section), also sinistral sense of shear is observed which suggests that Banjar Group deformed under the action of a shear couple. Both the movements might have occurred at the same time or one might have succeeded the other.

FINITE STRAIN
Finite strain studies were carried out by using deformed grains and aggregate of grains. The reference frame for orientation of axes of strain ellipsoid is assumed to be parallel to that defined for foliation. Foliation represent XY plane of strain ellipsoid (X > Y > Z) and lineation in the foliation define the direction of maximum elongation (X). The study was carried out in two mutually perpendicular thin sections (XZ and YZ) as well as on the outcrop. In the former measurements were made from the enlarged photographs of the thin sections while in the latter, XZ and YZ surfaces were recognised on the outcrop and long and short axes of the ellipse were measured there only.

Ramsay and Huber (1983) have reviewed the techniques for determining strain from deformed objects. They have pointed out the compromise one has to make between accuracy and tediousness in the technique involved. They also pointed out that for many geological investigations results obtained by
quicker methods are perfectly adequate. So strain estimates for deformed objects were made using Fry and Inverse Surfor Wheel methods. Fry method devised by Fry (1979) provides a graphical solution to the centre to centre method. Inverse Surfor Wheel method devised by Panozzo (1986) also provides graphical solution but is based on the deformation of the grain boundary surfaces.

FRY METHOD: In this method strain is measured by redistribution of locatable points using the way, joins or tie lines between the points change their length. Centres of about 60 grains in the photograph of each thin section were chosen for the study, which is considered as an appropriate population to define the shape of strain ellipse (Ramsay and Huber, 1983). Various steps involved are as follows:

i) On the photograph centres of all the grains were marked,

ii) Than a transparent overlay with a marked central reference point was used to trace the position of all the points related to one point,

iii) This process was repeated for each and every selected grain centre by moving the overlay, keeping a constant azimuth.

This exercise results in certain pattern of points around central reference point. For all samples central reference point is surrounded by a vacant region followed by high concentration of points, which is followed by a region of low concentration. The region of high concentration is elliptical in form and is used for finding out the axis of strain ellipse. Results obtained are presented in table 3, and
graphically presented in the form of Flinn, and Logarithmic plots in the figures 18 & 19 respectively.

For these results to be valid it is assumed that undeformed fabric was isotropic anticlustered. Likely source of error in this method is the crucial step of fitting an ellipse into the vacancy field left between the point clusters. All possible precautions are taken to minimise the error involved in this step.

INVERSE SURFOR WHEEL METHOD: It is a simple method devised by Panozzo (1986) to find out two dimensional strain. It is based on the probability of intersection of deformed lines on a given traverse. To find out the shape of strain ellipsoid in three dimension, measurements were made in XY and YZ sections of the sample. Various steps involved in the process are as follows:

i) Fabric outline is drawn from the photograph of oriented thin section and a reference direction with a point centre is chosen,

ii) The centre of the inverse surfor wheel is placed on point centre with set of parallel lines on the wheel in the direction of reference direction,

iii) The number of intersections of the set of parallel lines with the fabric outline is counted for 18 orientations turning the wheel counterclockwise,

iv) The number of intersections (n) are plotted as a function of orientation,

v) Best fit curve is found for all points and
vi) Minimum and maximum values $n_{\text{min}}$ and $n_{\text{max}}$ of the curve and $\theta_{\text{min}}$ at which minimum occurs are determined. The ratio $n_{\text{min}} / n_{\text{max}}$ represents the ratio $\sqrt{\lambda_2} / \sqrt{\lambda_1}$ of the strain ellipse and $\theta_{\text{min}}$ represents orientation $\theta$ of the long axis. Results obtained are presented in table 3, and graphically shown as Flinn and Logarithmic plots in figures 18 & 19 respectively. Reliability of the results is based on the following assumptions:

i) Initial state possessed random orientation of surfaces and random anticluster distribution of centre points.

ii) Effect of all active deformation processes is such that grain boundaries can be regarded as passive markers.

Crucial steps and likely source of error in this method is fitting a smooth curve through the points of $n/\theta$ plot. Otherwise reliability of results obtained by this method is apparent from similarity of results with those obtained by regular Surfor Wheel method (Panozzo, 1986), which involves digitisation of points and computer and is highly accurate.

In a few thin sections deformed porphyroblasts whose original outline could be marked were used to determine the axis of strain ellipsoid. For one outcrop deformed quartz-carbonate lenses were used to find out the axis of strain ellipsoid. In the above mentioned study it is assumed that the initial shape of the porphyroblast was spherical. In case of deformed porphyroblasts measurements were made from photomicrographs of the respective sections, whereas in case of quartz-carbonate lenses, measurements were made at the outcrop. Results of this study are presented in table 3 and as Flinn.
Progressive Deformation
Quartzites from the studied area, particularly those from Banjar Group contain euhedral pyrite crystals with pressure shadows. Analysis of these pressure shadows can be used to evaluate part of deformation subsequent to mineral growth (Ramsay and Druny, 1977; Ramsay and Huber, 1983). Because these euhedral pyrites often originate after diagenesis, perhaps during the course of low grade metamorphism accompanying a tectonic deformation (Ramsay and Huber, 1983), they can not be used to determine the total strain.

For the purpose of evaluation of progressive deformation pressure shadows were identified as displacement controlled and face controlled depending upon fibre-crystal geometries. Of these, geometry in the case of former and suture line in the case of latter were used to trace out the progressive strain history.

For the evaluation of incremental strain history, fibre orientation, length of fibre between chosen angular interval and maximum diameter of the resistant object in the mean direction of fibre sector were recorded from enlarged photomicrographs. Technique used is similar to one described in Ramsay and Druny (1977). Calculations were carried out on the basis of rigid fibre model, which assumes that for any particular incremental fibre length, any previously deformed fibres are undeformable and act in a rigid way like that of central resistant object (Ramsay and Huber, 1983). In case of
coaxial incremental deformation nth increment is given by

$$e_n = \frac{\delta_n}{I + \delta_1 + \delta_2 + \ldots + \delta_{n-1}}$$

and total finite elongation is given by

$$e = \frac{\delta_1 + \delta_2 + \ldots + \delta_n}{l}$$

In case of noncoaxial increments nth increment is given by

$$e_n = \frac{\delta_n}{I + \sum_{i=1}^{n-1} \delta_i \cos \phi_i}$$

where
- $l$ -- radius
- $\delta_n$ -- length of the incremental fibre
- $e$ -- incremental strain
- $\phi$ -- angle between an early formed fibre and direction of later increment.

On the basis of data obtained from the above mentioned study, strain increments for various samples are plotted on the map as shown in figure 20.

**MECHANISMS INVOLVED IN MICROSTRUCTURAL DEVELOPMENT**

Since 1960 lots of experimental work has been carried out on rocks and minerals. Products of these experiments along with naturally deformed rocks have been studied extensively from the point of view of microstructures and CPO using optical and electron microscope, universal stage and X-ray texture goniometer. CPO studies for deformed rocks have also been carried out using computer simulation methods. These studies have succeeded in relating the development of particular
microstructures and CPO to certain microstructural mechanisms operative under a set of physical conditions. In the light of these interrelations microstructures and CPO observed in the deformed rock of the area have been discussed in the following portion.

Quartzites from Hurla Formation show the development of microstructures such as wavy extinction and deformation bands which indicate deformation at low temperatures or faster strain rate (Tullis et al., 1973), accomplished with the help of intragranular slip. Fabric diagrams for these quartzites show the development of broad YZ girdle suggesting low strain conditions. Moreover resemblance of these diagrams with those of model A quartzites (Lister and Hobbs, 1980) suggest that the deformation took place in the constrictive field with the help of predominant basal slip mechanisms.

Quartzites in and around the shear zone show the development of various microstructures such as wavy extinction, deformation bands, deformation lamellae and the development of subgrains in recrystallised grains. All these structures indicate recovery, continued recovery and further recovery stages of White's (1973) scheme of deformation mechanisms. These processes indicate slow deformation of wet quartz at moderate and high temperatures. These three stages of recovery show progressive development along the dip direction. Highly elongated grains (P1, 12α) without recrystallization and fracturing indicate ductile behaviour of the rocks in the shear zone, whereas surrounding rocks.
show textures that are indicative of brittle ductile mode of deformation. Fabric diagrams for these quartzites show symmetric or asymmetric YZ girdle pattern. These fabrics fall in the flattening field of Flinn and Logarithmic graph (Fig. 18 & 19) and indicate high state of strain. The observed YZ girdles can be correlated with the similar fabrics developed in model A and model B quartzites. As the fabrics of model A and model B correspond to brittle and ductile mode of deformation respectively (Price, 1985), fabrics of the quartzites from the shear zone which show features of ductile deformation have been correlated with those of model B, and fabrics of the quartzites from the vicinity of the shear zone are correlated with those of the model A. As a consequence a shift in the deformation mechanism from basal slip to rhomb \(<c+a>\) slip system in the shear zone is observed.

Microstructures of these quartzites show striking similarity with those observed by Tullis et al. (1973) in experimentally deformed quartzites. Plate 12a shows highly elongated porphyroblast with small inequant recrystallised grains scattered along the grain boundaries of the porphyroblast. These porphyroblasts show wavy extinction and deformation bands. Plate 12c shows more flattened nature of the porphyroblast. The recrystallised grains are numerous though smaller than those observed in plate 12a and occur along the deformation bands and grain boundaries. Plate 12b shows relatively undeformed porphyroblasts as augen or ribbons, and recrystallised grains account for more than 50% of the rock.
These three specimens are almost similar to the three specimens of plate 5 of Tullis et al. (1973), as far as microstructures are concerned. From this similarity it can be inferred that deformation took place under the dominance of recovery and recrystallization processes. and figures 12.a,c and b show progressive increase in the state of strain. Moreover in their experiment representative samples were deformed at 700°C and 10^-7/ sec strain rate. Quartzites of Manikaran Quartzite Formation show granoblastic texture, which suggests dominance of grain boundary migration and higher strain rate at moderate to higher temperature. CPO for these quartzites show broad YZ girdle which correspond to fabric of flattening field under low strain conditions. Fabric for one quartzite sample of this formation is random in nature (Fig.16,186), suggesting almost undeformed state of the rock.

It can be, therefore, concluded that from Hurla to Jhuni, microstructures indicate a progressive increase in temperature of deformation, and along the shear zone, inferred from geological mapping, microstructures indicative of higher strain state are observed which further confirm its existence.
Fig. 16a Quartz c-axis fabrics
Fig. 16b Quartz c-axis fabrics
Fig. 16c Quartz c-axis fabrics
Fig. 16d Quartz c-axis fabrics
Fig. 16e Quartz c-axis fabrics
Fig. 16: Quartz c-axis fabrics
Fig. 17 Variation in the fabric skeleton in the Naraul area.
Fig. 18 Flinn graph for the shape of strain ellipsoid (a) data obtained by Fry method (b) data obtained by Inverse Surfor Wheel method.
Fig. 19. Logarithmic graph for the shape of strain ellipsoid (a) data obtained by Fry method (b) data obtained by Inverse Surfor Wheel method.
Fig. 20 Incremental strain directions in the Naraul area.
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- Fry method, b - Inverse surf or wheel method, c - Others