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# SHEAR ZONE STRUCTURES FROM THE MAIN CENTRAL THRUST ZONE OF THE JOSHIMATH AREA, GARHWAL HIMALAYA

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## ABSTRACT

The crystalline rocks of Higher Himalaya are thrust over the meta-sedimentary rocks of Garhwal Group along the Main Central Thrust (MCT). The 8 to 10 km thick MCT zone is characterised by mylonitic rocks at its southern fringe. The study reveals that a progressive ductile shearing (thrusting of MCT) is superimposed on two generations of pre-shearing coaxial folding and is responsible for the development of different shear zone structures and crystallographic fabrics in the crystalline rocks. Various structures arrested in the rocks during different stages of deformations exhibit a compressional and an extensional tectonic regime within the same ductile shear zone. In the MCT zone the ductile shearing is documented by lattice preferred orientation i.e. quartz c-axis pattern which is displayed by well defined single girdle slightly asymmetric with respect to the stretching lineation and foliation. The study also reveals that intra-crystalline creep mechanism was a significant deformation mechanism of the crystalline rocks of the area.

**Key words:** Compressional and extensional structures, Main Central Thrust Zone, Crystallographic fabrics, Mylonitization.

## INTRODUCTION

The Main Central Thrust (MCT) is one of the major intra-continental thrusts in the Himalayan orogenic belt along which considerable amount of post-collision crustal shortening was accommodated (Le Fort, 1975). Originally defined by Heim and Gansser (1939) and Gansser (1964) in the eastern Kumaun Himalaya, the MCT (fig.1) separates the medium to high-grade metamorphic rocks of the Higher Himalayan Crystalline Zone (HHCZ) from the underlying sedimentary and low-grade metamorphic rocks belonging to the Lesser Himalayan Zone (LHZ). Recent studies (Bouchez and Pecher, 1981; Singh and Thakur, 2001; Matcalfe, 1993; Searle, *et al.*, 1993) have revealed that the MCT is not a plane but a several kilometer thick crustal scale ductile shear zone of high strain and has been referred to as Main Central Thrust Zone (MCT zone) (e.g. Pecher, 1977, Arita, 1983; Brunel, 1986; Metcalfe, 1993; Searle *et al.*, 1993; Bhattacharya and Weber, 2004).

During the Tertiary deformation the crystalline rocks were emplaced southwards over the quartzites and limestone of Garhwal Group (Jain, 1971) along the MCT (Heim and Gansser, 1939). Both the underlying (quartzites and limestones) and overlying (crystallines) rocks were mylonitized under ductile deformation conditions and exhibit a wide (8 to 10 km thick) zone of intense shearing (cf. Singh and Thakur, 2001; Metcalfe, 1993). In the area under study the mylonites of the crystalline rocks exhibit different shear zone structures and show variation in crystallographic fabric pattern across the MCT zone. These structures and crystallographic fabrics are used as

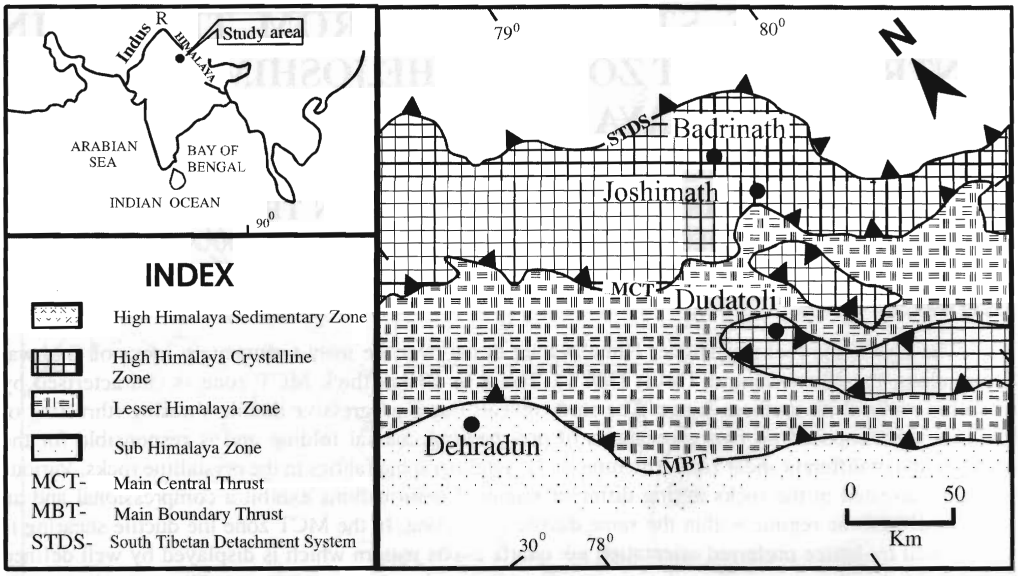

Fig. 1. Regional geological map of the Kumaun Garhwal Himalaya, showing four litho-tectonic zones

kinematic indicators to determine sense of movement in the crystalline rocks of the area. The present work incorporates a study of the shear zone structures, strain and quartz c-axis fabric related to ductile shearing in the crystalline rocks of the MCT Zone around Joshimath. On the basis of petrofabric study the deformation mechanism in the rocks has also been discussed.

## GEOLOGICAL SETTING

In the area, crystalline rocks occur as a NNE dipping shear zone as typically exposed on the motor road leading to Badrinath. The crystallines immediately in the vicinity of the MCT plane are characterized by the presence of chlorite schists interbedded with quartzites. About 3 km north of Helang (fig.2), the gneisses alternating with schist bands become more prominent. Near Joshimath, the gneisses exhibit augen structure and are characterized by the presence of garnet, and the mica schist becomes biotite rich, and occasionally includes amphibolite bands. Lithotectonic set-up of crystalline rocks around Joshimath have been given by Virdi (1986). Gairola and Srivastava (1987) have described in detail the petrography and mineral assemblages of the metamorphic rocks of Joshimath area. The crystalline rocks in the Joshimath area have been divided into three litho-units (Virdi, 1986): a lower Tapoban Formation followed upwards by Joshimath Formation and Pandukeshwar Formations. The rocks exhibit a progressive increase in grade of metamorphism northward and a well-marked continuity of major structural elements. Effects of mylonitization and shearing are prominent in the lower part of this zone.

### (A) Tapoban Formation

The lowermost unit, named as Tapoban Formation, lies over the Lesser Himalayan sediments of Garhwal Group (Jain, 1971) and is separated by MCT. The general dip of foliation varies from $20^0$ to $60^0$, towards N to NNE direction. The rocks include mica schist, garnetiferous mica schist, thin bands of flaggy quartzites and amphibolites, and exhibit

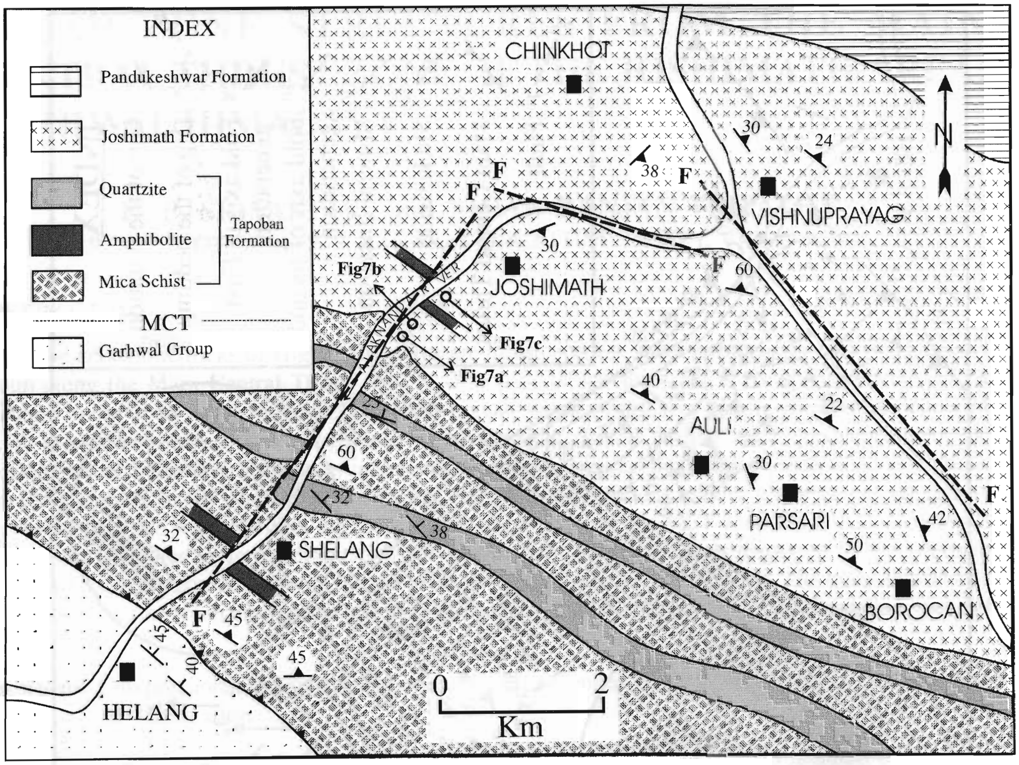

Fig. 2. Geological map of the Joshimath area (modified after, Virdi, 1986)

porphyroclastic and mylonitic textures and structures resulting into an S-L fabric.

### (B) Joshimath Formation

The Joshimath Formation, named after Joshimath overlies the Tapoban Formation and consists of medium to high-grade rocks such as garnetiferous mica schist and gneisses, kyanite gneiss and amphibolites. The strike of the foliation of Joshimath Formation varies from NW-SE to NNW-SSE with northern dips. These rocks exhibit several structural features characteristic of ductile shear zones together with a northward increase in the grade of metamorphism. The rocks also exhibit refolded structures on mesoscopic scale.

### (C) Pandukeshwar Formation

Joshimath Formation grades northward into Pandukeshwar Formation with a decrease in micaceous layers. The rocks are folded into regional isoclinal anticline and the axial trace of which can be traced through Pandukeshwar (beyond the map area-fig. 2) in Alakanada valley (Virdi, 1986). Pandukeshwar Formation is constituted of metapsammite and meta-semipelites represented dominantly by garnet-mica schist and gneisses. The micaceous layers show development of garnet, staurolite, kyanite and sillimanite when studied from south to north indicating a progressive increase in the grade of metamorphism.

## STRUCTURAL FEATURES

The rocks of the area are characterised by well-developed planar and linear (S-L) fabrics. Bedding plane (S1) can be observed as lithological layering and is rarely preserved in

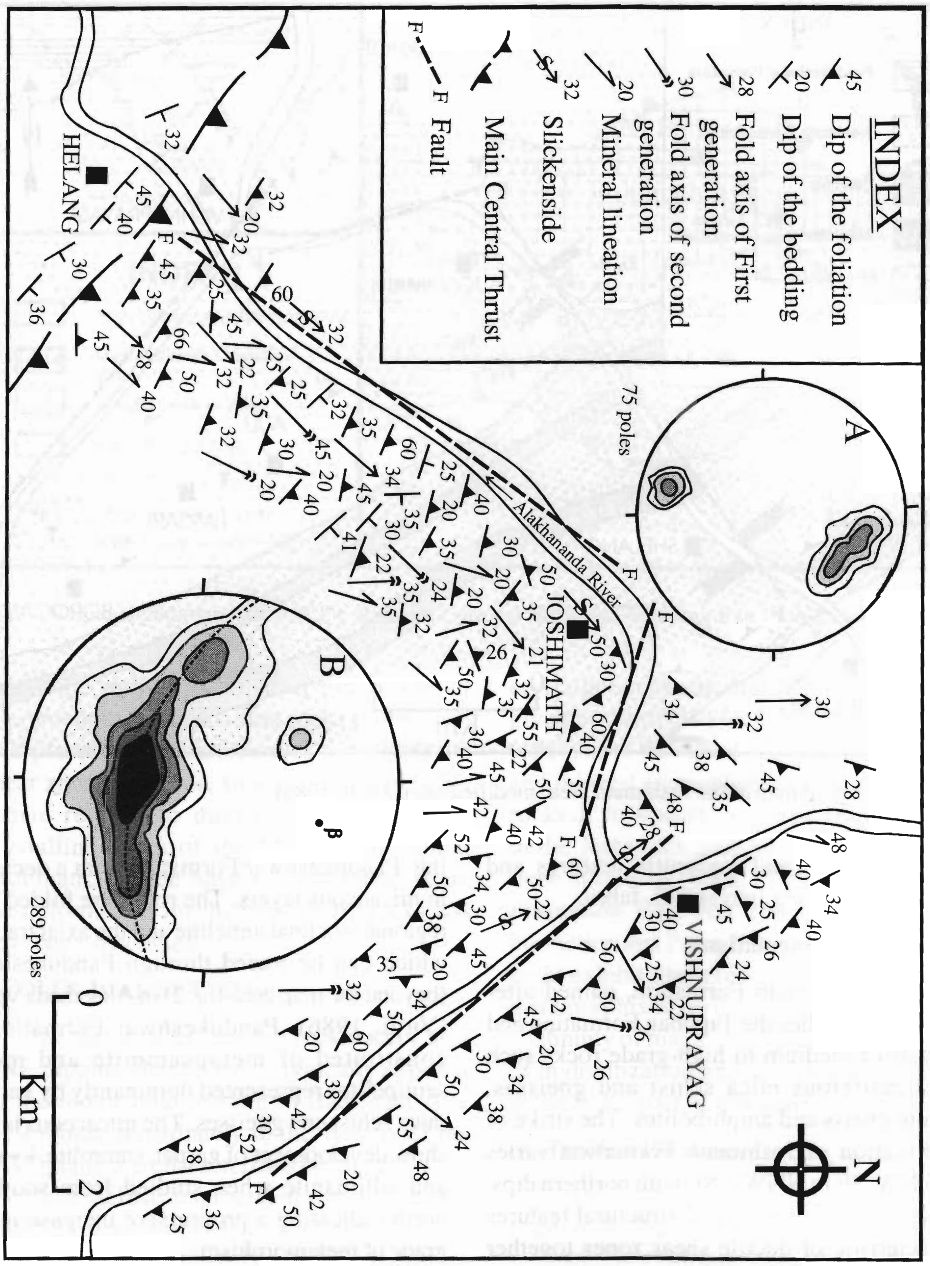

Fig. 3. Structural map of the area around Joshimath, Garhwal Himalaya

Inset-A. Fold axis/mineral lineations plots on lower hemisphere of equal area net Contour intervals: < 1.33, 2.66, > 2.66 % per unit area.

Inset B- Poles to the schistosity plane plotted on the lower hemisphere of equal area net. Contour intervals: 3,6,9,12,15, >15% per unit area.

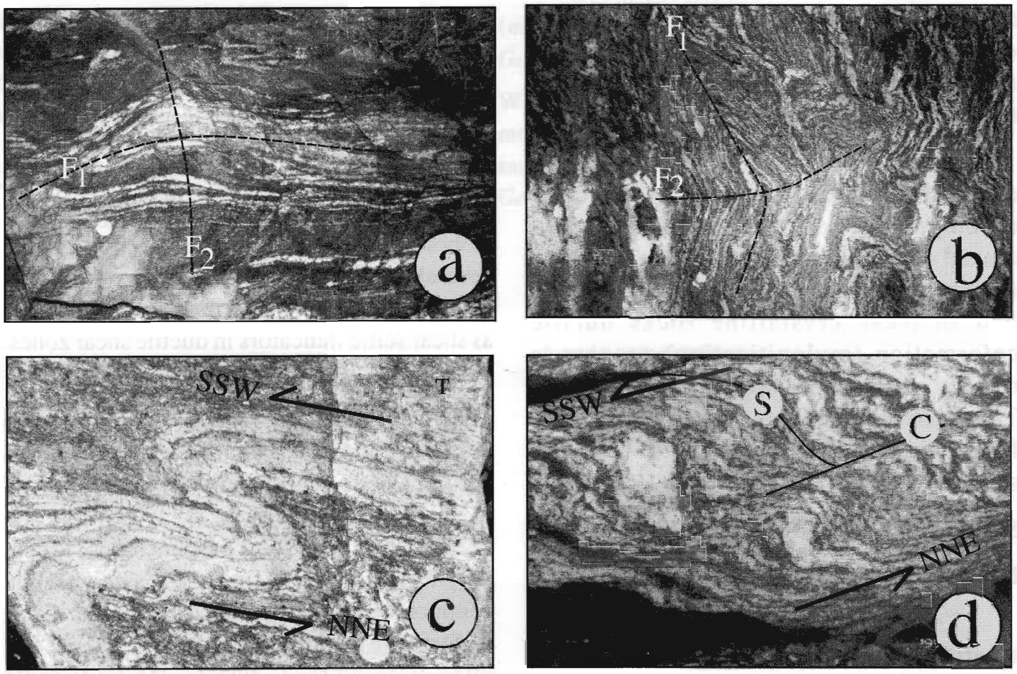

Fig. 4. Field Photographs. (a) Coaxially refolded structure developed in the mica schist of the area. Folding of lithological layering exhibit F1 isoclinal fold. F2 fold is developed on the limbs of F1 fold. Scale: Width of photograph 4.0 meters. (b) Refolded structure developed in the gneisses of the Joshimath Formation. Folding of feldspar layers exhibit F1 isoclinal fold. F2 fold is developed on the limbs of F1 fold, exposed near village Marwari. Scale : width of phtograph 3.0 meters. (c) Lithic layers folded due to shearing in the mylonites, exhibiting a NNE -SSW directed sense of movement. (d) S-C structure developed in the gneisses of the Joshimath Formation.

the rocks of the area. A lithological layering in the foliated rocks, exhibit tight isoclinal folds of high (3 to 5) wavelength/amplitude ratio (fig. 4a). The foliation (S2) is observed parallel to the axial plane of these isoclinal folds and is very well developed in the rocks of the area. S2 is a continuous cleavage and the fabric varies from slaty cleavage to phyllitic structures to schistosity depending upon the grain size (c.f. Hobbs *et al.*, 1976; Davis, 1984). Foliation and mineral lineations in the rocks are parallel to the foliations and lineations of mylonites developed along the thrust zone. Field evidences clearly indicate that the development and repeated transposition of the fabrics in the crystalline rocks are related to thrust movement. The fold axis exhibits a variation in orientation from NNE to NE direction and is close to the regional direction of stretching lineation (fig.3). The NNE trend of lineations, defined by the stretched mineral lineations and slickensides in the crystalline rocks, are oblique to the dominant strike of foliation and lithological contacts (fig.3) mark the direction of thrust propagation or tectonic transport. Regional foliation is parallel to the lithological boundaries and dips towards northern direction (fig.3). Lineations show a relatively homogeneous distribution pattern plunging either towards NNE or towards SSW directions (inset A in fig.3). The pattern of foliations and lineations are shown in figure 3. Poles to the S-surfaces were plotted on the lower hemisphere of equal area net (inset B in fig.3) and contoured and ß values were obtained which correspond to the observed lineation of the area.

The schists and gneisses of the area exhibit several meso to micro-scale structures, developed due to shearing, indicate non-coaxial deformation of variable intensity. The shear zone structures (discussed later) suggest that in these crystalline rocks ductile deformation (mylonitization) process is responsible for the development of S-L fabrics. This process involves formation of new foliations that obliterate all the previous structures except at few places.

## SMALL SCALE STRUCTURES

### Early structures

The early structures are pre-ductile shearing (before thrusting) and display two generations of coaxial folds (F1 and F2). The F1 isoclinal folds (fig.4a) are gently plunging towards NNE direction with low to moderate amount of plunge and exhibit well-developed axial plane cleavage (S2). The F1 folds are characterised by the fact that earliest recognisable cleavage (S2) is the axial plane of these folds and is the most dominant planar fabric in the area. These F1 folds show all the evidence of buckling (Ramsay, 1967; Hudleston, 1986; Ghosh, 1993). F2 open style fold, develop on the limbs of F1 folds and on S2 surface (figs. 4b and 6a) mainly plunge towards NNE direction. Jain et al. (2002) have considered these structures as Pre-Himalayan structures.

### Structures developed during progressive ductile shearing

During thrusting of crystalline rocks over quartzites and limestones of Garhwal Group (Jain, 1971), the rocks both the side of MCT have been affected by ductile shearing, but the degree of **shearing varies considerably**, and have produced different kinds of shear zone structures. Due to shearing the earlier structures have been reoriented in the NNE to NE direction. The deformational structures observed in the crystalline rocks of the MCT zone can be described in terms pertinent to mylonitic rocks (Bell and Etheridge, 1973; Hobbs *et al.*, 1976). These mylonitic rocks arrest several mesoscopic and microscopic structures at different stages of deformations and are used as shear sense indicators in ductile shear zones.

In the MCT zone of Joshimath area the mineral lineations and stretching lineations are commonly observed and the rocks are accompanied by the S and C surfaces. The S-C penetrative fabric (Berthe *et al.*, 1979, Lister and Snoke, 1984) developed from mesoscopic (fig. 4d ) to microscopic scale (fig. 6d) and is a common feature in mylonites of the area. The S surfaces are mainly striking in WNW-ESE and often cross cut the C surface, the acute angle made between the S and C surface indicate a top to south sense of shear. In the area the angle between the S and C surfaces varies in different localities and traverses. In the localities 2 km north of thrust plane the S-C angle is about 15° and changes to 8° near the thrust plane i.e. near Helang. Further, there is an increase in the development of stretching lineation and decrease in the mineral grain size near the thrust plane has also been observed.

The sub-rounded shape of the porphyroclasts suggests grinding during deformation. Foliations always appear curved around feldspar porphyroclasts. Dynamically recrystallized tails (Simpson and Schmid, 1983) of finer grained quartz, feldspar sericite and chlorite often extend along the foliation in the direction of shear. The porphyroclasts and their tails systematically display a typical retort shape indicating a sinistral sense of shear when the thin section is replaced in its natural orientation in the field. $\sigma$ and $\delta$ type of porphyroclasts (Passchier and Simpson, 1986) of quartz and

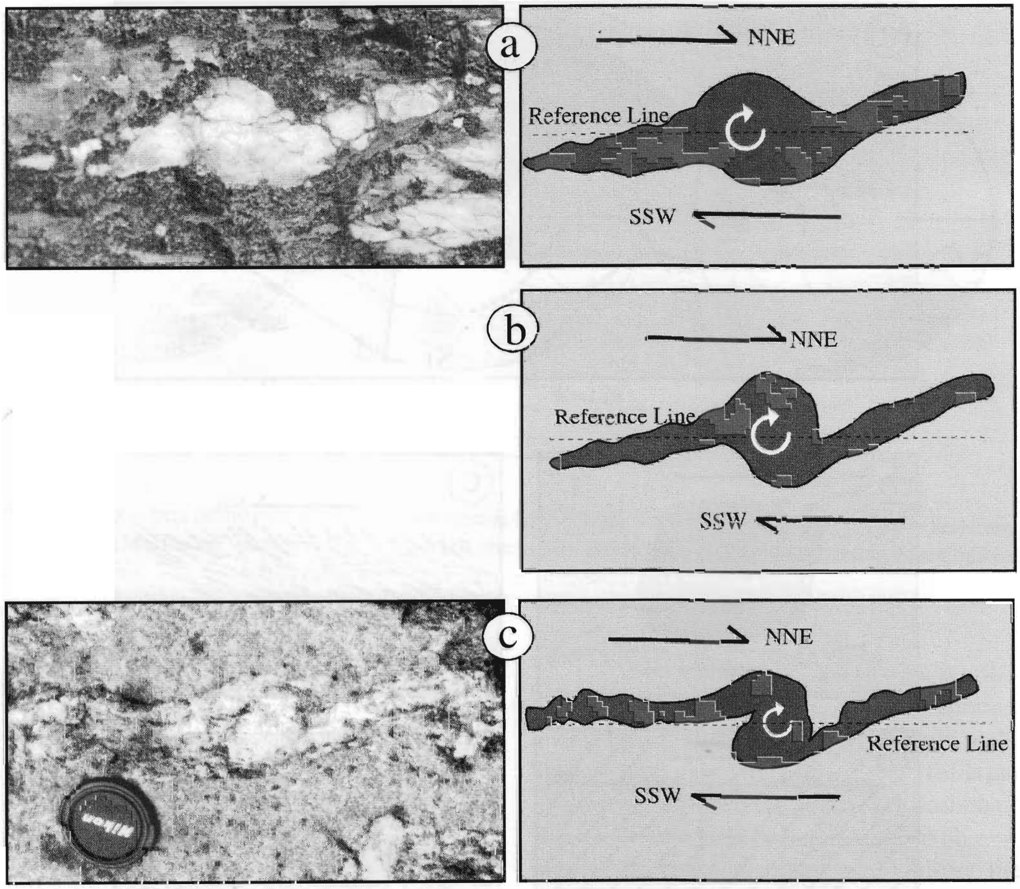

Fig. 5. Progressive development of δ type of feldspar porphyroclasts in the gneissic rocks of the area. Fig. a, b, and c shows progressive rotation with progressive shearing.

feldspars were observed in the area under study. However, σ-type of porphyroclasts (fig.6g) are much more common than δ type. Figures 5a, b and c demonstrate the progressive development of δ type of feldspar porphyroclasts in the mica schist of the area. The change in shape of these mantled grains are due to non-coaxial flow within neighboring matrix, giving rise to incipient rolling structures (Van Den Driessche and Brun, 1987). Sigmoidal inclusions of quartz (Schoneveld, 1977) in garnet (fig.6b) have also been used as a kinematic indicator and, suggest a NNE ward rotation in the area under study.

The other structures such as asymmetric boudins (Hanmer, 1986) of quartz and feldspar, sigmoidal foliations (fig.6c) at different scales (Ramsay and Graham, 1970), book-shelf structure (fig.6f), and 'mica fish' (Lister and Snoke, 1984) (fig.6e) have also been noticed. At few places folded mylonitic layerings (Simpson, 1986) have also been observed (fig.4c). It mainly develops in mylonitic rocks due to heterogeneous deformation and causes local perturbation in flow. These perturbations may amplify into asymmetric mesoscopic folds and their vergence is consistent with sense of shear (Simpson, 1986) in the rocks. All these

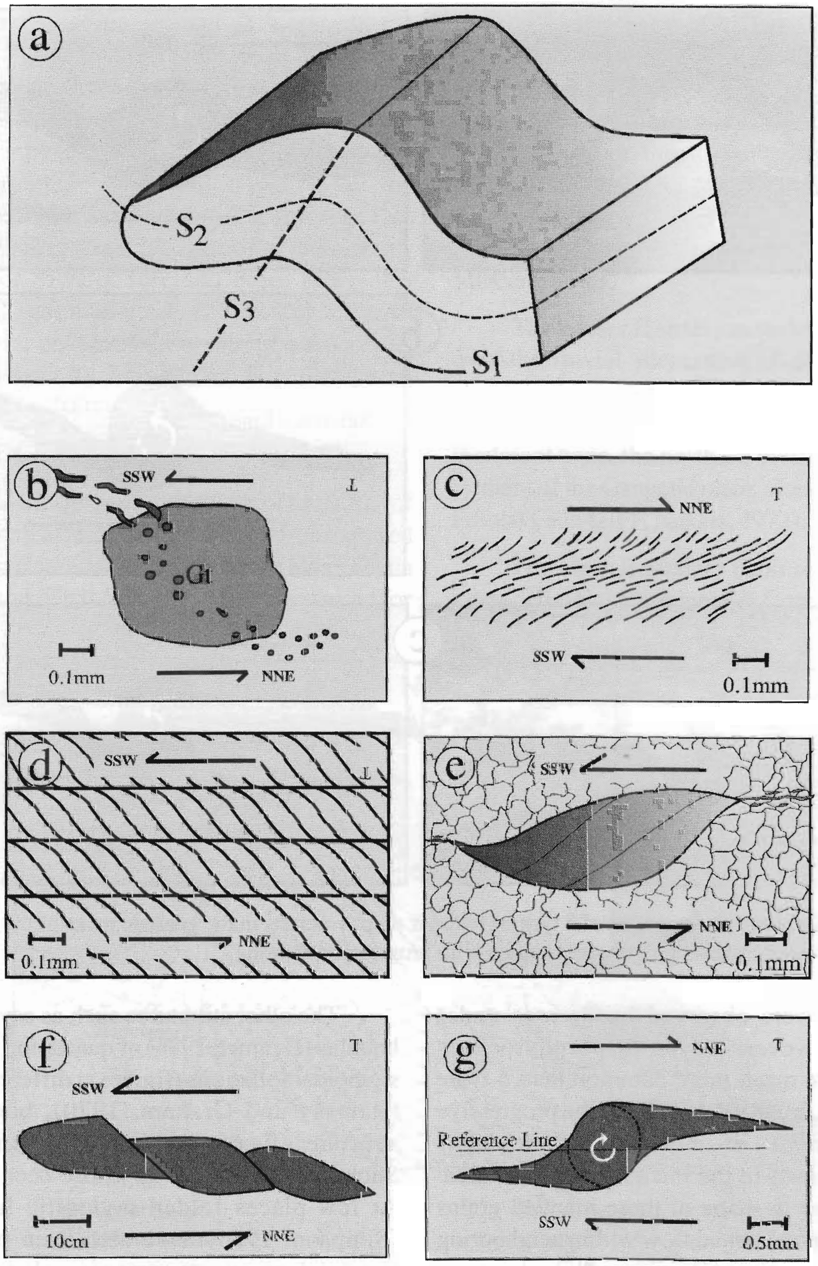

Fig. 6.(a) Hand sketch of a refolded structure exhibiting folding of bedding (S1) results into S2 as axial plane of F1 fold. The S2 refolded into S3 as axial plane of F2 fold. (b) Rotated garnet with quartz inclusions in gneisses of Joshimath Formation, (c) Sigmoidal foliation in mica schist (d) S-C structure in mica schist (e) mica flakes developed in quartzites inter-bedded with mica schist of Tapoban Formation (f) Book self structure developed in the feldspars of gneisses (g) σ-type of porphyroclasts in gneisses

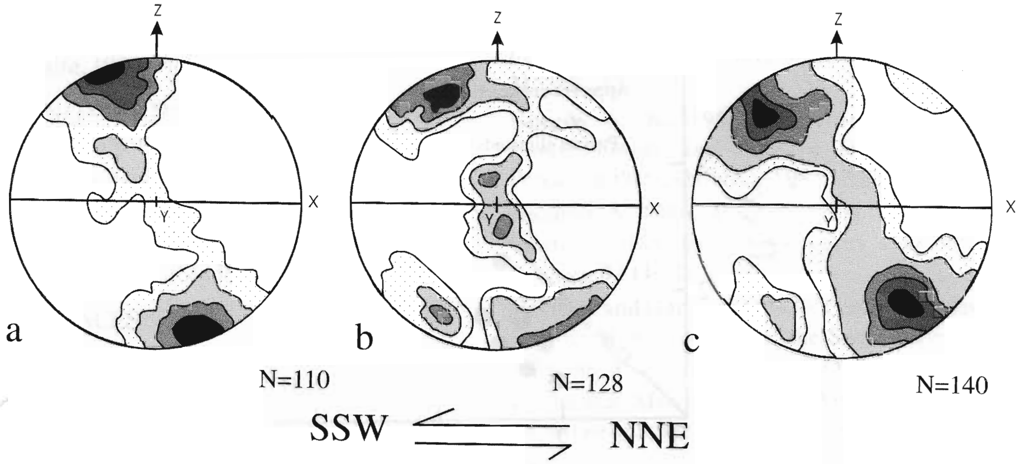

Fig.7: Quartz c-axis fabric plotted on the lower hemisphere of equal area projection, from the three locations of the MCT zone (shown in fig.2), from the gneisses of the Joshimath Formation of the area. Contour intervals: 2, 4, 6, >6% per unit area. N is number of measurements.

mesoscopic and microscopic structures of Joshimath area suggest a top to south directed sense of shear.

### Quartz c-axis preferred orientation

To study the quartz c-axis fabric in shear zones (Lister and Williams, 1979; Law, 1990) three thin sections of quartz rich rocks of Joshimath Formation (location shown in fig.2) were prepared along the XZ (parallel to stretching lineation) plane and studied under universal stage. Data were plotted (fig.7a, b, and c) by the method suggested by Turner and Weiss, (1963) on the lower hemisphere of equal area net and contoured. The c-axis plots are highly asymmetric with respect to foliation and stretching lineation (fig.7). The girdle containing the point maxima is oblique to the foliation plane and its normal is expected to track the bulk shortening direction of the non-coaxial deformation (Etchecopar, 1977). In all samples studied the fabric asymmetry is consistent with the overall sense of regional shear deformation.

## FINITE STRAIN ESTIMATION

Assuming negligible ductility contrast and homogeneous deformation on grain scale, strain analysis of deformed feldspar porphyroclasts from the gneisses of Joshimath Formation were carried out. In order to observe maximum changes taken place along the extension of bulk tectonic transport direction and perpendicular to it; two thin sections of each of the gneissic rocks were prepared along XY and YZ planes. Under the microscope, length of the long axis, short axis, and the angle of orientation $\phi$ of longer axis with respect to a reference line i.e. schistosity are recorded for each of the elliptical particle. The shape of each particle has been recorded as Rf= long axis/ short axis of ellipse, and plotted on the Rf/$\phi$ plot (Lisle, 1985). The strain ratios (Rs) obtained from the XY and YZ plane of different samples from Lisle (1985) graph, have been plotted on the Flinn (1965) graph. Most of the data fall in the apparent flattening field, i.e. they represent oblate ellipsoids (fig. 8).

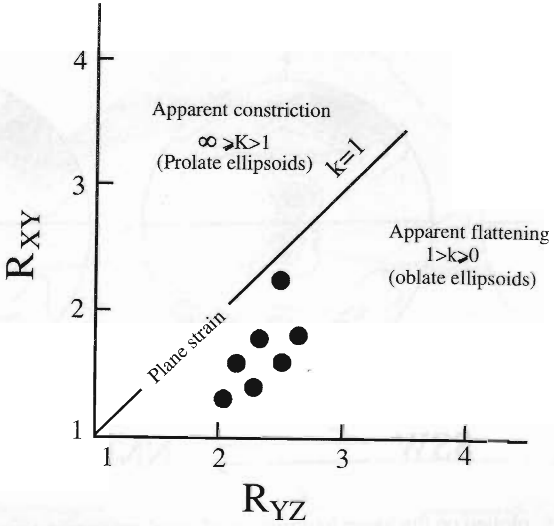

Fig. 8: Flinn plot where shape of ellipsoid is obtained from the feldspar porphyroclasts of gneisses.

## DISCUSSION AND CONCLUSIONS

In the crystalline rocks of Alaknanda valley the structures such as different types of folds on mylonitic foliations, and several generations of mylonitic foliations marks their development in compressional tectonic regime, whereas the structures such as extensional crenulation cleavage, boudins and rotated porphyroclasts exhibit extensional imprints within the overall compressional regime. The structures observed in both (extensionl and contractional) tectonic regimes exhibit a top to the south sense of movement. The direction of shear obtained from stretching lineations and slickensides (fig. 3) consistently indicate a top to south directed sense of movement and suggests that this area has experienced ductile shearing. It is possible that during progressive non-coaxial deformation the layers caught up in the zone of contraction (<45° with respect to bulk shortening direction) underwent folding, whereas the layers in zone of elongation (>45°) got extended. Similar observation have also been made by Mukhopadhyay *et al.* (1997) from Chur area of western Himalaya, and Patel *et al.* (1993) from Zanskar area of NW Himalaya. The NNE trend of F1 and F2 folds, suggests rotation of early structures during progressive thrusting.

The quartz c-axis fabrics are highly asymmetric with respect to structural framework in the gneisses of the area. If we consider the PT conditions, as derived from the metamorphic assemblage obtained from garnet-biotite pair from the pelitic schists, gneisses and amphibolites as 640°C (Gairola and Ackermand, 1988) together with the characteristic of quartz c-axis fabric, it can be stated that intra-crystalline creep was an important mechanism of deformation under moderate temperature conditions.

Thus, the different shear zone structures/ microstructures and quartz c-axis fabric developed during the emplacement of crystalline rocks over the quartzite of Garhwal Group along MCT plane, exhibit non-coaxial deformation regime and demonstrate SSW directed sense of shear which is in accordance with the northward movement of Indian plate (Metcalfe, 1993).

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