CHAPTER-3

STRUCTURAL GEOLOGY

III.1. INTRODUCTION :

The published work on the structures of Aravallis are by Naha et.al. (1974, 1977, 1984, 1988), Roy (1973, 1978, 1985), Roy et.al. (1971, 1974, 1980, 1981a, 1981b, 1984, 1985a, 1985b), Sharma et.al (1984, 1988).

Detailed work on the study area reveals that the structures of the Jharol group of rocks are more complicated than envisaged by some previous workers. Through the study of satellite images, different tectonic lineaments were deciphered. The study of the structures through image adequetely helped the author to enable to solve structural pattern of the area. The area around Phalasia and Jharol is much more highly deformed and folded as compared to the surrounding area. It is clearly revealed in the geological map of Heron (1953) revealed in the geological map of Heron (1953) and also on the Indian Remote Sensing (IRS) False Colour Composite (FCC) data (Plate- III.1).

Sharma et.al (1988) has carried out some structural study to the North of the present study area around Bagrunda village and has reported four phases of folding in that area.

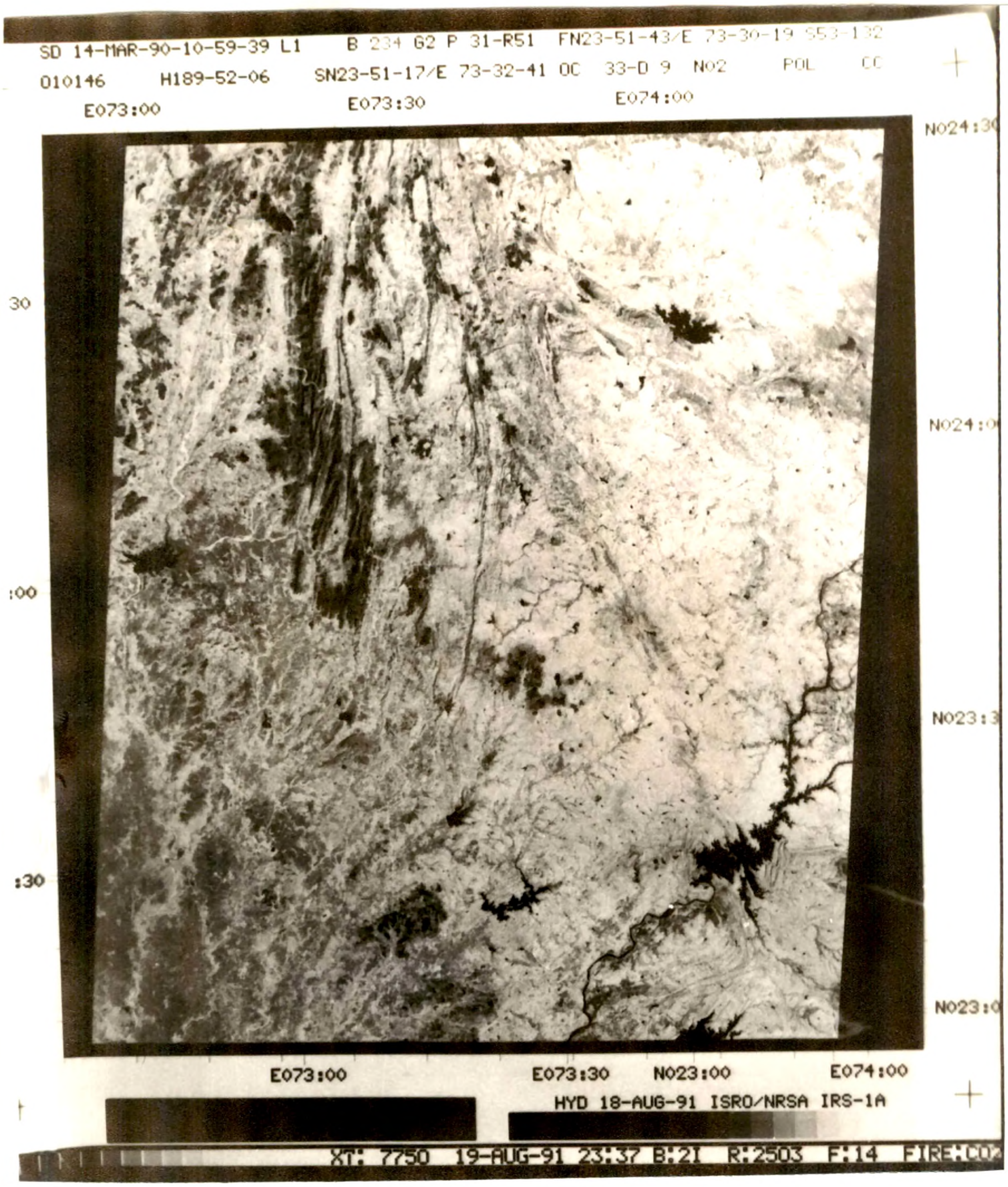


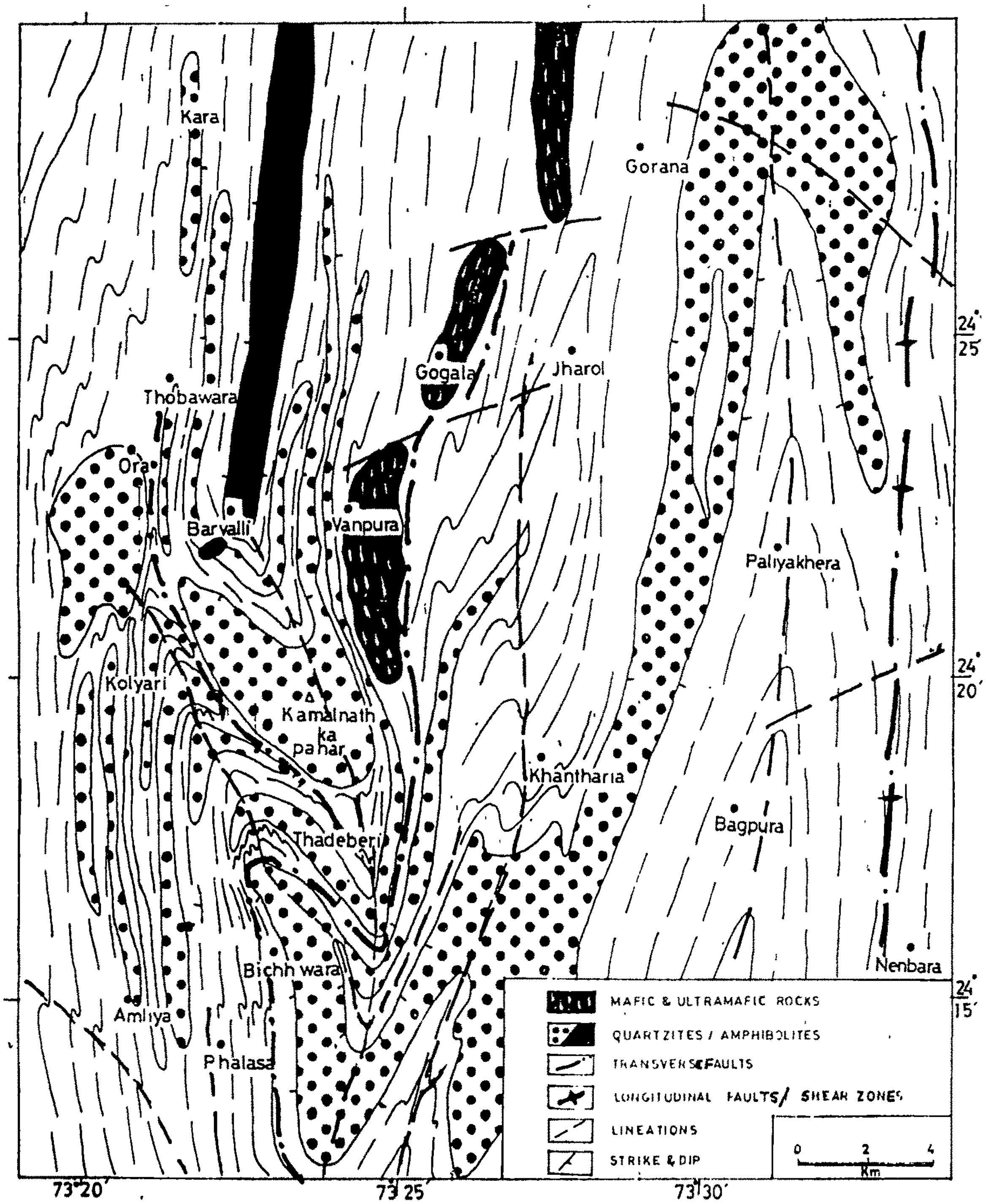
Plate-III-1 :IRS-FCC photo of North eastern Gujarat and Southern Rajasthan.

Besides the above mentioned structural studies; No other work has been done. The correlation of the different structures and structural trends with the tectonic stresses has hitherto been ignored. Besides, no detailed study of shearing in the region has been carried out and the mechanism of deformation which controlled the shearing also remains unclear and unsolved. Therefore, to solve the above problems, the author has carried out a detailed structural investigation of the area around Phalasia and Jharol (Figure-III.1).

III.2. FCC DATA INTERPRETATION :

The IRS-FCC data has proved to be the most helpful in delineating the structural pattern of the area (Figure-III.2). FCC data clearly reveal a complicated zig-zag pattern of folded structures represented by the high quartzite ridges. The low lying areas intervening these quartzite ridges are occupied by the schistose rocks. This statement satisfies Heron's geological map (1953).

The study of Indian Remote-Sensing False Colour Composite images reveals that the structures occurring around Kotra, Phalasia, Jharol and Babalwara area can be divided into two structural domains. The eastern domain (Jharol group) has been tightly folded by more than two phases of folding, whereas, the western domain (Kotra -



STRUCTURAL MAP SHOWING VARIOUS AXIAL TRACES AROUND PHALASIA AND JHAROL AREA, SOUTHERN RAJASTHAN

Figure III.1

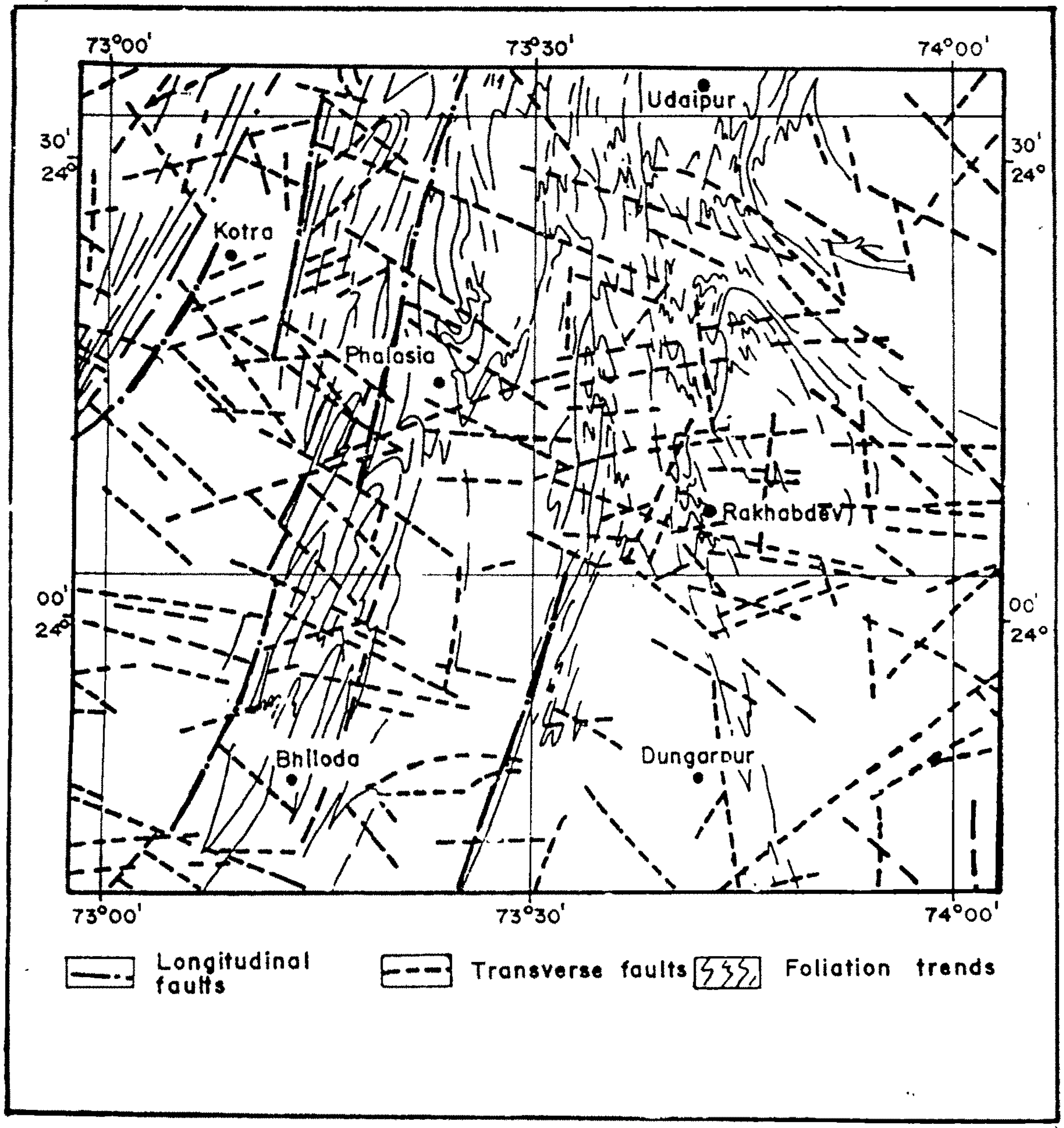


Figure III.2 Tectonic map of phalasia area.

Panarwa sector) shows extremely strong foliations indicating that the rocks have been highly flattened. These contrasting features represent a tectonic contact separating these two structural domains (Figure- III.3). Field observations reveal that the western domain, the Gogunda and Kumbhalgarh, groups, dips beneath the eastern domain (the Jharol group), thus pointing to the structural phenomenon that the older Jharol rocks have been thrusted over the Gogunda rocks along this tectonic junction which is highly sheared and mylonitised.

Planar structures mostly represented by contact planes between linear ridges of quartzites and surrounding schists, foliation planes and fault zones have been traced out. The foliation pattern of the Jharol belt shows complex isoclinal folds between Bicchwara and Jharol villages. Five major longitudinal shear zones in addition to those previously known ones are recognised (Figure- III.1). The Nenbara shear zone exhibits beautiful trallise and rectangular types of drainage pattern which indicates erosional propagation after faulting, shearing and folding and has lead to the formation of linear quartzite ridges as fault escarpment alternated with narrow lowlands comprising soft, easily erodable schistose rocks.

Drainage pattern of a particular shear zone ie.: Nenbara-Kaliawa shear zone is traced out from Toposheet

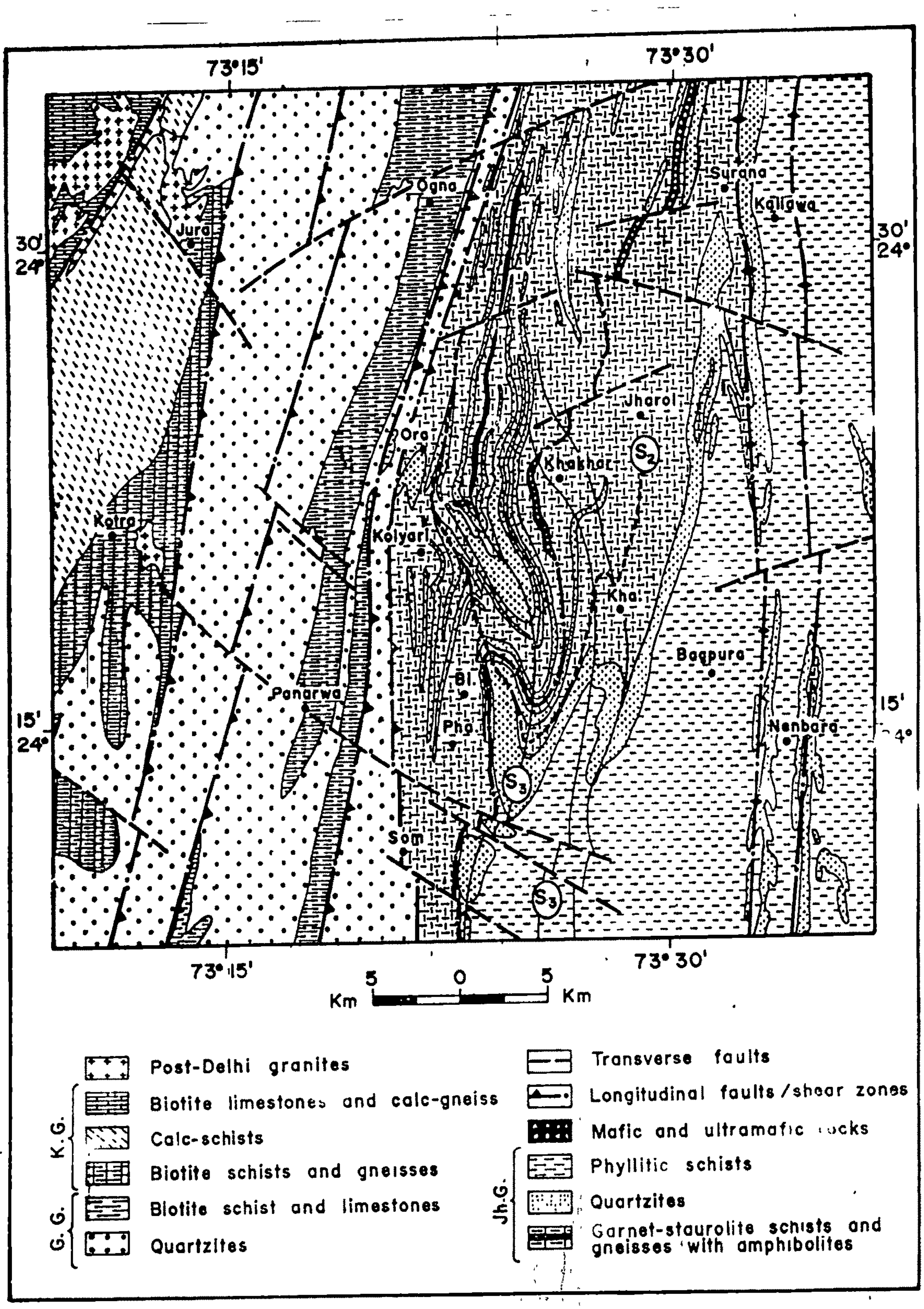
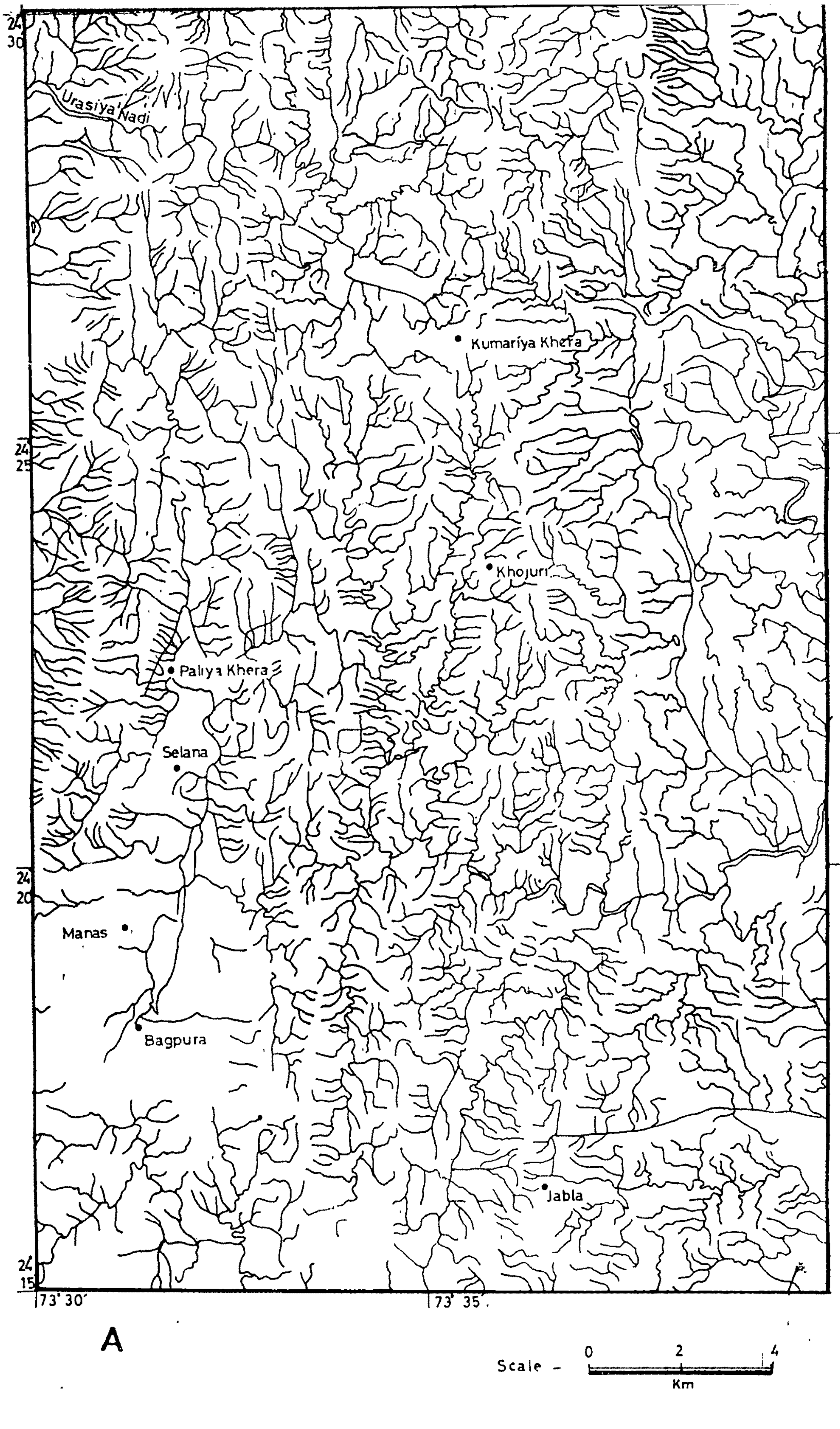


Figure III.3 Geotectonic map of Kotra-Jharol area.

No: 45H/11 and 45H/12 on 1:50,000 scale (Figure- III.4a & b). It is observed that the drainage pattern of this shear zone is fracture controlled. This shear zone must be 30 to 40 km in width. The drainages here are of quaternary phenomenon while the fracture pattern may be of pre-cambrian age but might have been reactivated during Quaternary time. Almost all the fractures are of transverse type. The drainage pattern keeps on changing depending upon the overall erosion of the study area.

Other linear features like segments of streams aligned offsets along several adjacent streams, aligned ends of consecutive ridge spurs, anomalous alignment of groups of continuous ridge crests with very narrow alternate reaches of gullies, aligned tributaries over a long distance, all of which are clearly revealed in the FCC picture of the area. The stereopair of satellite images gives three dimensional picture of the area, thus leading to the accurate measurement of the strike and dip direction and also the amount of dip of the various planar structures. Drury (1990) has interpreted spot data of this area and has found similar features. According to the spot data given by him, it shows a subdued terrain typical of the Jharol phyllites, deforested ridges of thin siliciclastics defining the regional strike and vertical dips. The boundary between pelites and the main ridge may be a ramp on an early low-angled detachment, that has been folded. At lower centre


Urasiya Nadi
Kumariya Khera
Khojuri
Paliya Khera
Selana
Manas
Bagpura
Jabla
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24 25
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24 15
73° 30'
73° 35'
Scale -
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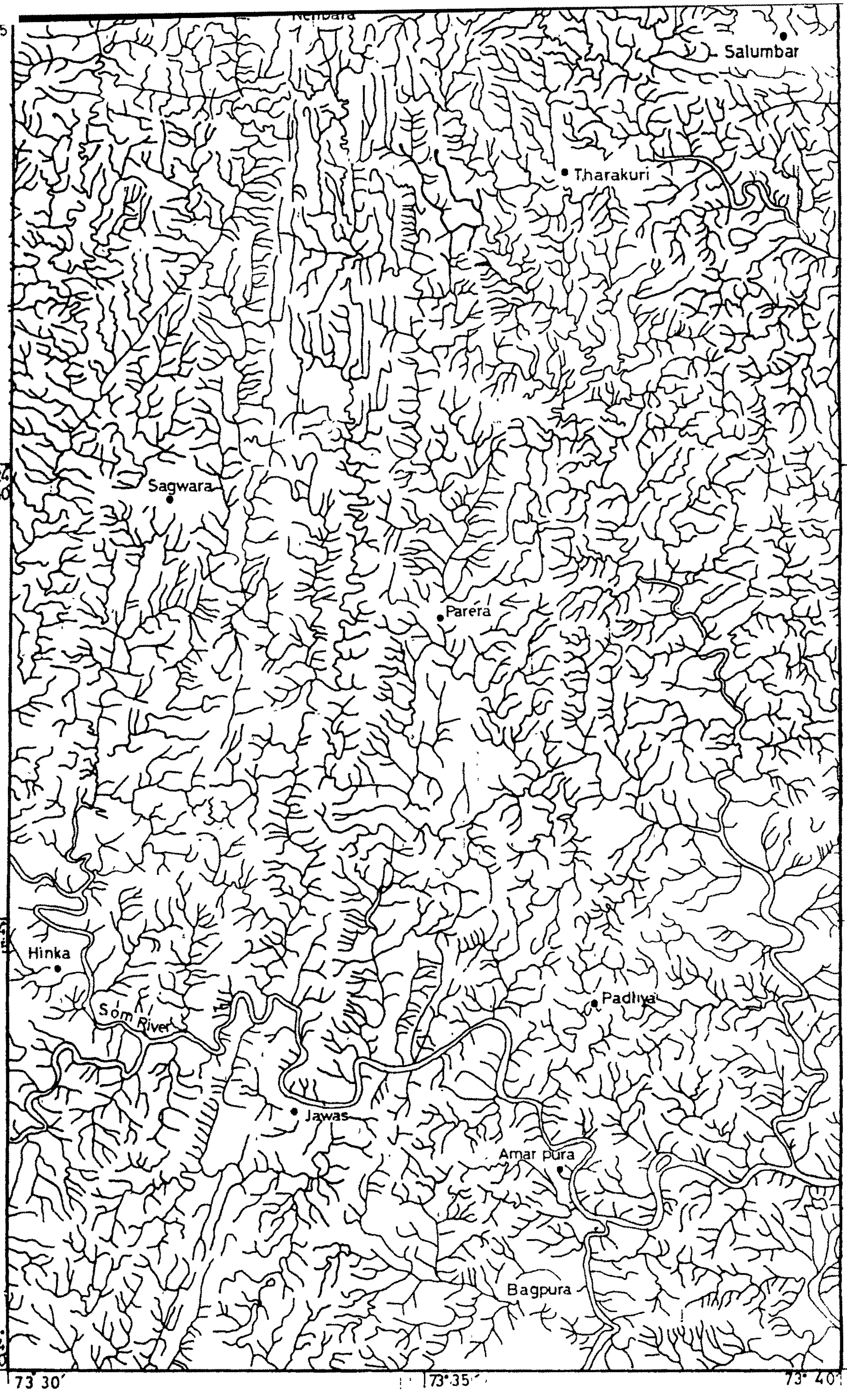
Km

A



B

Scale – 0 2 4 Km

the forested ridges clearly define a major, south plunging synform cored to the south by pelites, with moderate to steep dips on its limbs. It is flanked in the east by a corresponding antiformal closure. The present author recognises this fold closure as the Kamalnath anticlinal fold nose. The IRS-FCC data of the Kamalnath fold also suggest that the axial traces of the early folds have been folded coaxially by the younger folds.

Based on the FCC data - supported by detailed field work, the present author recognises a number of regional dislocations dissecting the study area and its neighbourhood. In all five major longitudinal faults and several transverse and conjugate sets of faults have been observed. Based on the geological map of Heron (1953), these fracture zones can be named as under :-

I - The NNE-SSW trending longitudinal faults :-

a) Rakhabdev - Dungarpur lineament.
b) Kaliawa - Nenbara shear zone.
c) Surana - Bagpura shear zone.
d) Phalasia - Bhiloda fault zone.
e) Kotra fault zone.
f) Sabarmati fault zone.

On going from east to west, it is seen that the various longitudinal faults show its trend towards NNE-SSW.

The eastern most faults, the Kaliawa-Nenbara and Surana-Bagpura trend nearly in N-S direction. The Phalasia-Bhiloda and Kotra faults have been dextrally displaced. The bands of ultramafics have been emplaced along these longitudinal faults and also dislocated by the transverse faults.

The above mentioned faults are major shear zones encountered in the study area. Fracture controlled drainage pattern is observed in many of the above stated shear zones. An example of such drainage pattern of one of the shear zone is illustrated in Figure- III.3a &b. These shear zones, (dislocations) are genetically related to AF_2 and AF_3. Such that both folding and fracturing, represent manifestations of a single stress field characterized by intense compression.

The proper study of the amounts and directions of displacement along these longitudinal fracture zones has shown that these various longitudinal fractures were essentially enclosing the crustal blocks during sub-vertical uplifts of the orogen such that the movement along them has been upward or downward (dip-slip movement, Figure- III.1). But most of the transverse fractures show lateral movement as revealed in (Figure- II.1) to the southeast of Som village, the quartzite blocks have been separated from each other by a set of transverse faults showing dextral sense of movement.

The transverse faults are those faults which are developed later than the longitudinal faults and have been found related to deformational event which gave rise to AF_4 folds due to compressional stresses along NNE-SSW direction. The various WNW-ESE trending faults are all dipping very steeply due SSW and almost all these transverse sets of faults are showing dextral sense of movement. Some of the transverse faults form conjugate sets of faults striking NE-SW to almost E-W and they are intersecting at the angle of 60° to 70° but always less than 90°.

III.3 MESOSCALE STRUCTURES

3.A FIELD OBSERVATIONS :

As mentioned before, the area under study has been highly deformed. Such deformational features like folds, faults and shear indicators are well preserved in all the rock types including amphibolites, serpentinites, gneisses and schists. The schistose rocks occupying the low lying areas are mostly covered by the vegetation but along the road cutting and river sections all structural features are well exposed for the study. Structural investigations have been carried out in detail through critical observation of the outcrops during detailed mapping of the area. The following results are an outcome of extensive fieldwork carried out by the author.

As it is well known that four episodes of folding are encountered in the Aravalli rocks and three episodes of folding are found in the Delhi rocks (Naha et.al.; 1974, 1977, 1984, 1988), Roy (1973, 1978, 1985), Roy et.al.; (1971, 1974, 1980, 1981a, 1981b, 1984, 1985a, 1985b), Sychanthavong and Merh (1981), Sychanthavong (1990). This structural contrast strongly suggests that these rocks really belong to two separate systems, Aravalli and Delhis as proposed earlier by Heron (1953). It is known that, the Aravalli rocks have been involved in the Delhi foldings and AF_1 E-W Aravalli folding is of Pre-Delhi age (Naha et.al., 1984). The Jharol belt rocks, if belong to the Aravalli of Heron, must have imprints of this folding which is markedly absent in the Delhi rocks. According to Sychanthavong and Merh (1981) and Sychanthavong (1978, 1990) the involvement of Aravalli rocks in Delhi folding can be explained by the mechanism of plate tectonics. The $AF_2(=DF_1)$ and $AF_3(=DF_2)$ foldings are coaxial (Figure- III.5) (Plate- III.2) and represent two important tectonic events related to two subsequent subduction zone tectonic processes.

The $AF_4(=DF_3)$ folding superimposed almost at right angle on the pre-existing structures have been attributed to continental plate collision between cratonic India and

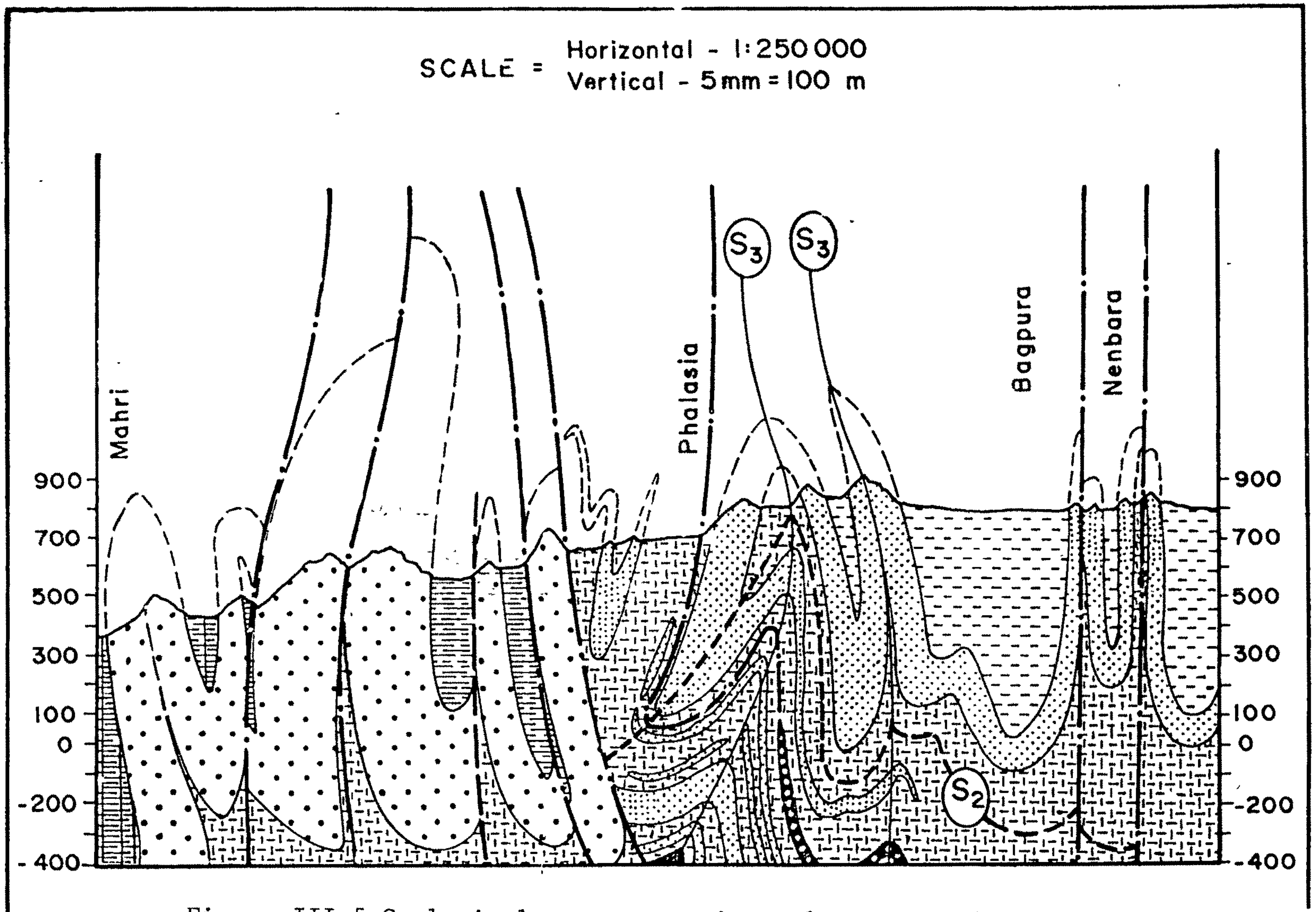


Figure III.5 Geological cross-section along the lattitude 24° 15' showing co-axial F_1 and F_2 folds. S_1-axial trace of F_1 and S_2-axial trace of F_2.

East Africa during the unification of East Gondwana and West Gondwana (Mc Williams, 1981).

Field observations show that refolded folds $AF_2(=DF_1)$ by $AF_3(=DF_2)$ are present in the study area, and these structures have been superimposed by $AF_4(=DF_3)$ cross folding making the early formed two folded structures to become southernly plunging folds. AF_1 folds have not been discovered in the study area although the present author was looking for it throughout her field work. This suggests that, these rocks may be younger than their assigned stratigraphic position as upper Aravalli sequence. It has been recently opined that the thick massive Jharol quartzites (Shamlaji formation) and the overlying non-garnetiferous schists (Bagpura formation), occurring to the west of the Nenbara-Kaliawa shear belt, represent the upper lithounits of the Jharol group and may be equivalent to the Delhi rocks (Sychanthvong and Pratibha Singh, in press).

In all it is found that the Jharol group of rocks are affected by three phases of folding. The axial plane of AF_2 folds are seen cut by the axial plane of AF_3 folds. Both of these episodes of folding were superimposed by a third phase of folding AF_4 which leaves its imprints on the earlier folds in the form of axial traces which cut both the AF_2 and AF_3 linear and planar structures. On account of

Plate-III.2 AF_2 fold hinge has been coaxially refolded by $AF_3 = DF_2$ fold.

Loc: 5 km to the North of Phalasia.

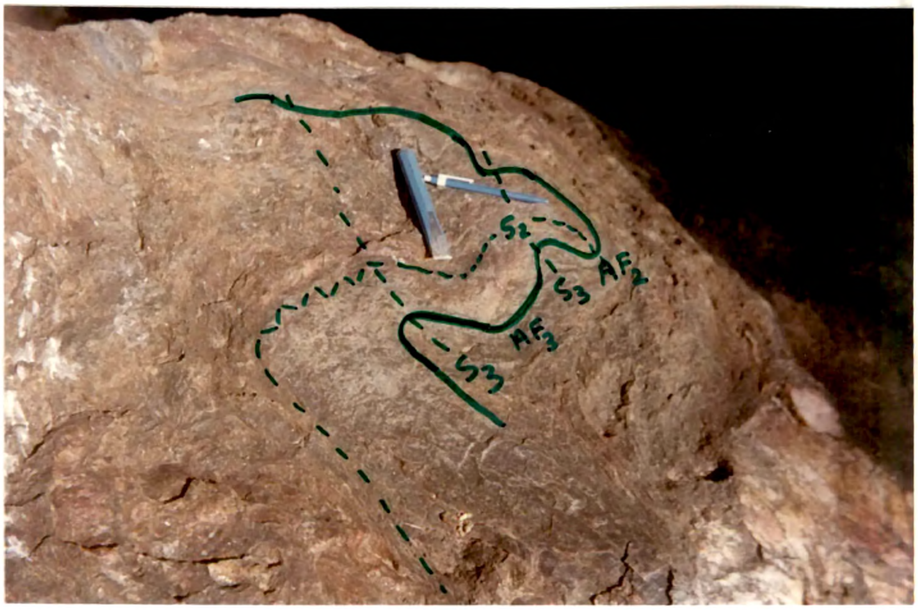


Plate-III.3 AF_2 fold coaxially refolded by AF_3.

Loc: same as plate-III.2.

superimposition of AF_4 on AF_2 and AF_3 the study area has experienced various fold interference patterns on mesoscopic scales and can be summarized in Table-III.1 in comparision with structures recorded in other areasof Rajasthan. This is done in order to understand the overall structural framework of the region imprinted in different rock groups or Supergroups so that, based purely on structural studies , a tentative age correlation of various rock groups or formations can be contemplated.

A.1 - AF_2 FOLD EPISODE (Fold episode-I in Jharol group).

The earliest folding to which the rocks of the study area have been subjected to, is seen as refolded folds generally trending NNE-SSW. The AF_2 trends are directly recognizable through the observation of AS_2 axial plane schistosity trends along which AF_2 axis lies. On account of their involvement in AF_3, these AF_2 folds are very distinctly observed. It is on the basis of such observation that the AF_2 folds could be distinguished from AF_2 folds, as both have identical geometry (Plate-III.3). Mesoscopic AF_2 folds are numerous, always refolded by AF_3 and show diverse orientation of axial planes ranging from sub-horizontal to almost vertical. Isoclinal folds of AF_2 generation are also well preserved in pelitic gneisses exposed around Ora village (PLate-III.4). The axis of these folds trends due NNE-SSW direction and cannot be confused as

Plate-III.4 AF_2 isoclinal fold whose axis is trending due NNE-SSW direction.
Sharma et.al.(1984) confused this as AF_1 folds.
Loc: Ora village.

Plate-III.5 AF_2 - DF_1, recumbent fold in chlorite schist of Jhārol group, showing 'a' lineation across the fold axis.

TABLE- III.1 : MORPHOLOGY & TRENDS OF FOLDS OF DIFFERENT GENERATIONS, IMPRINTED IN VARIOUS ROCK SUPERGROUPS OF SOUTHERN RAJASTHAN

S.N.	Major fold episodes in regional tectonic setting and their approximate age.	Morphology and trends of various folds.	REFERENCES: Aravalli Folds					Delhi Folds.			Vindhyan.		Types of Superposed folds. TYPES			
			Naha & Halyburton 1974, Naha et.al. 1984.	Roy, 1973, 1984.	Raja Rao, 1976.	Powar and Patwardhan, 1984. Sharma et.al., 1988.	M.P. Patel, 1975.	Sychanthavong & Merh, 1981.	Gangopadhay, 1972	Ray, 1974.	Raja Rao, 1976.	Choubey, 1971.	0	I	II	III
1.	Aravalli folding folding. 2500 Ma - 2060 Ma.	Isoclinal & reclined folds E-W.	AF_1	AF_1	$AF_1 F_1$	AF_1	-	-	-	-	-	-				
2.	Second Aravalli folding (F_1 Delhi folding. 1600 Ma - 1400 Ma.	Isoclinal and recumbent folds. NNE - SSW.	AF_2	AF_2	$AF_2 F_2$	AF_2	F_1	DF_1	F_1	F_1	-	-				
3.	Third Aravalli folding. (F_2 Delhi folding). 1200 Ma - 700 Ma.	Doubly plunging and upright folds NNE - SSW.	AF_3	AF_3	$AF_3 F_3$	AF_3	F_2	DF_2	F_2	F_2	F_1	F_1	AF_4 on AF_1		AF_4 on AF_2	AF_3 on AF_2
4.	Fourth Aravalli folding. (F_3 Delhi folding). 900 Ma - 600 Ma.	Northerly overturned in the S^{th}, doubly Plunging and domed in the central & N^{en} region. WNW - ESE.	AF_4	AF_4	$AF_4 F_4$	AF_4	-	DF_3	F_3	F_3	F_2	F_2		AF_4 on AF_3		

AF_1 folds like Sharma et.al. (1984). These folds became isoclinal in nature due to the superposition of AF_4 cross folding. The most prominent planar structures related to AF_2 is the axial plane foliation, developed in schists and gneisses. These planar structures have been involved in AF_3 and AF_4. So far as the linear structures related to AF_2 are concerned, these comprise (a) minor fold axes and cleavage bedding intersections both characterizing 'b' lineation and (b) strain slip lineation developed on bedding planes indicating flexural slip ('a' lineation) found on the surface of the AF_2 recumbent fold hinge (Plate-III.5)

A.2 : AF_3 FOLD EPISODE (Fold episode -II in Jharol group) :

The second phase of folding has been found to be of regional scale as well as local scale coaxial with AF_2 folds. The AF_3 folds and their planar structures have been developed on the AF_2 folds. Since the AF_2 and AF_3 fold axes show identical trends, but their planar structures do not show the same geometry. AS_2 planar structures have been sliced by AS_3 axial plane cleavage forming discrete crenulation cleavage on AS_2. AF_3 folds are revealed throughout the terrain and at most places AF_2 folds are not seen associated. Their strike is also NNE-SSW. Their nature is mostly upright and their axial planes are penetrative through the bedding planes and AS_2 axial plane cleavages (Plate- III.3, Plate- III.6 and Plate- III.26). It has been

Plate-III.6 AF_3 (= DF_2) upright fold in Calc-schist.
Loc: 10 km to the North of Kotra.

Plate-III.7 AF_4 crinkles and puckers in gneisses.
Loc: Ora village.

interpreted and obvious that AF_3 folding is the result of the continuation of the stresses responsible for AF_2 folding, but between these two folding episodes the time gap cannot be precisely determined at the present stage of research..

A.3 AF_4 FOLD EPISODE (Fold episode - III in Jharol group) :

The AF_4 fold episode can be understood only after critical examination of the structural elements related to AF_2 and AF_3 folds. Field studies reveal that the Jharol sequence already folded by AF_2 and AF_3 are superimposed by several WNW-ESE trending folds. These AF_4 folds, beside mesoscopic scale, show crinkles, puckers and kink bands which are better observed on microlevel in the schistose rocks and gneisses (Plate- III.7). AF_4 open folds are observed in quartzites (Plate- III.8).

As less metamorphic changes took place during AF_4 folding, the planar structures related to this folding (AS_4) are restricted to tensional joints and fractures developed across AF_2 and AF_3 fold hinges. The linear structures comprise minor fold axes of puckers and crests of the kink band superimposed over the bedding structure and the earlier formed AS_2 and AS_3 foliations. The AF_4 folding has obviously been generated on account of a strong push form the south against the rigid mass in the north

Plate-III.8 AF_4 open fold in quartzite.

Loc: Kirat village.

(Sychanthavong and Merh, 1981; Sychanthavong, 1990). The superimposition of the AF_4 over AF_2 and AF_3 has resulted in the formation of dome and basin structures (Plate- III.9a & b) or Type-I interference pattern of Ramsay and Huber (1987).

From the above discussed structural characteristics it is found that the trends of the AF_2, AF_3, AF_4 folds and the stresses controlling the generation of these folds are similar to the DF_1, DF_2 and DF_3 Delhi folds respectively of Sychanthavong (1990). The massive as well as foliated amphibolites, garnetiferous gneisses and schists alternated with quartzites, and the non-garnetiferous schsits that form the major lithology of the region do not show any E-W Aravalli folds. Searching for this type of folds, the author has gone out of her study area to the north, east and south but still fail to observe any of such folds in the Jharol belt rocks. Thus, the Jharol belt rocks may not be equivalent to upper Aravalli age. To the northeast, east and southeast of the Rakhabdev lineament, the true Aravalli rocks are exposed and are seen affected by AF_1 folding (Naha and Halyburton, 1974; Naha and Mohanty, 1989; Roy, 1990). This problem will be discussed in detail in Chapter-V where a tectonic model is put forward.

Plate-III.9a Domal structure (sheath fold) developed on account of superposition of AF_4 anticlinal fold on AF_3 anticlinal fold in Schistose rock.

Loc: 5 km North of Phalasia.

Plate-III.9b Basin structure (sheath fold) developed on account of superposition of Af_4 synclinal fold on AF_3 synclinal fold.

Plate-IIII.9a and 9 b are Type-I Interference pattern of Ramsay and Huber (1987).

3.B TYPES OF VEINS DEVELOPED IN SHEAR ZONES :

Veins exists on mesoscale as well as on microscale, which is often helpful in determining the precise relationships between veining and deformation. The historical development of a vein is often complex, as some veins develop before shearing, some develop during shearing while some form after shearing (Ramsay, 1967; Ramsay and Huber, 1987). Critical study of cross-cutting relationship between different vein sets and other structures of the rock like folds and foliations, it is possible to develop the full history of the veins (Barker, 1990). According to Barker (1990), following senses of shear can be recognised based on the development of vein sets in the shear zones (Figure- III.6).

When the rocks are subjected to compression then flexural slipping takes place (Figure- III.7). Due to flexural slipping, space is created between two layers. That space is filled up by quartz material and thus veins are developed, which when further affected by shearing forms conjugate zones of en-echelon quartz veins linked with non-conjugate regional extension veins (Plate- III.10a & b).

Veins developed during simple shear, always tend to form in fractures which is developed perpendicular to the direction of maximum extension and become rotated as shear

Plate-III.10a Laterally displaced quartz veins found in quartzites.

Plate-III.10b Quartz gashes found slightly away from the wakal shear zone, showing initially sinistral local shear movement, which later followed by greater dextral shear movement.

(A)

(B)

(C)

(D)

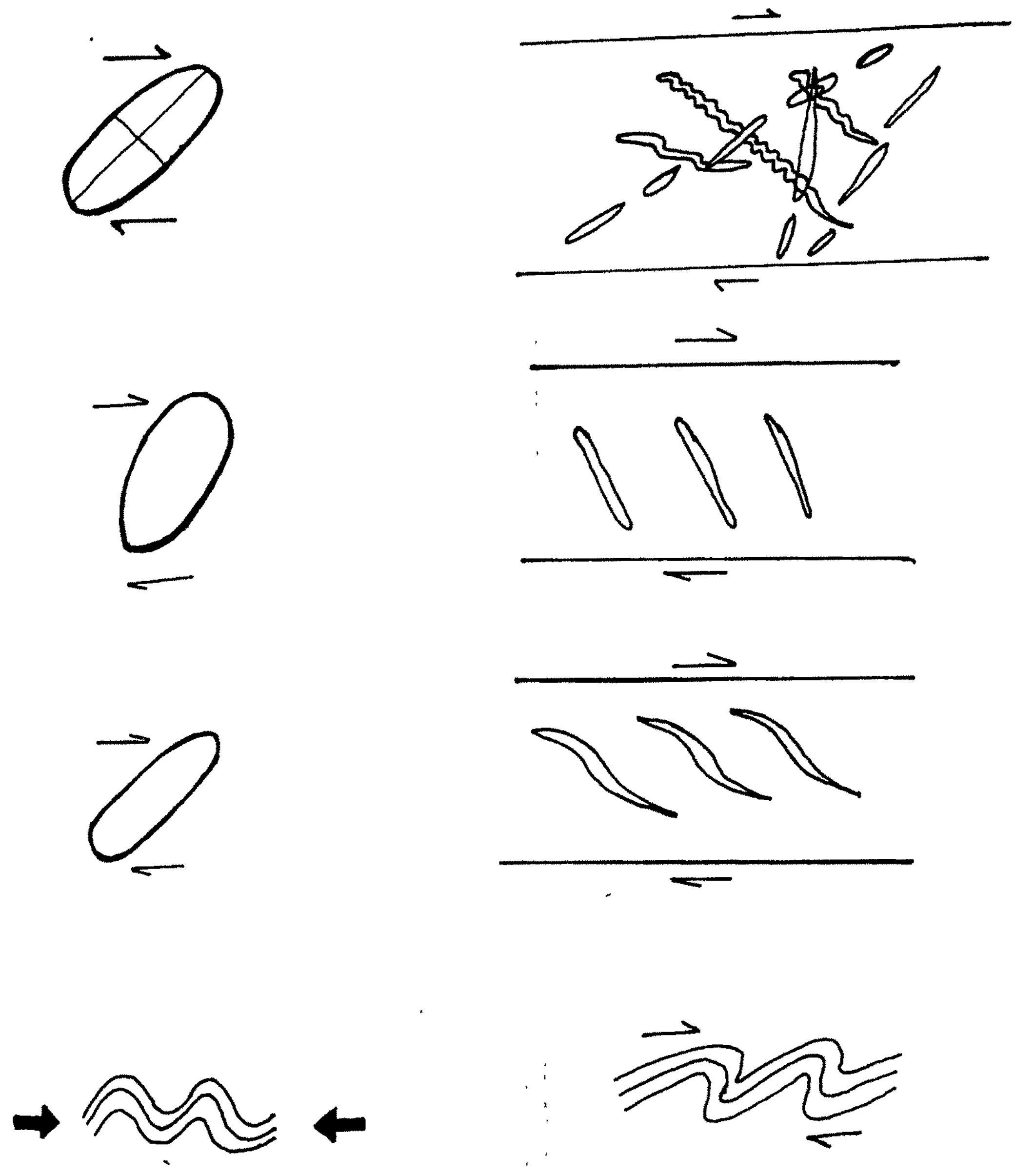


Figure III.6 (A) Schematic illustration of veins deforming during superimposed simple shear, determining simple shear.

(B) & (C) Schematic illustration showing the development of sigmoidal tension gashes.

(D) Development of asymmetrical folds during simple shear (Barker-1990).

(A)

(B)

(C)

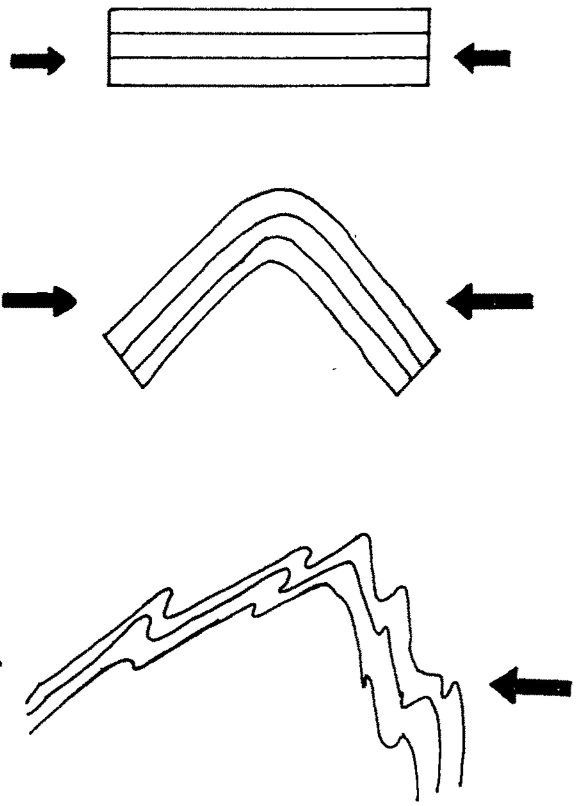


Figure III.7 Veins developed on account of the flexural slip mechanism.

(A) Compression.

(B) When further subjected to compression the veins become folded.

(C) Further compression, veins become tightly folded or even refolded co-axially.

progresses. During rotation the veins attain a sigmoidal trace from which the sense of shear can be determined, Barker (1990); Ramsay and Graham (1970), (Plate- III.11a & b).

Ramsay (1980) has described a process for the development of vein by sequential crack and seal method, by which the quartz or calcite fibres, oriented at a high angle to the vein wall are associated with fibre - parallel trails of inclusions or zones of inclusion bands. The formation of veins by this method is common under low grade comditions. (e.g.: greenschist and sub-greenschist facies; see also, Barker, 1990).

3.C DETERMINATION OF SENSE OF SHEAR :

Shearing is a common phenomenon in orgenic belts. It may occur in intraplate tectonic settings or at plate boundaries and results in the generation of shear zones and shear belts at a local, regional or even global scales. Shear zones originate due to relative displacement along a plane or surface in rocks. They are known to occur in rocks of all ages from the pre-Cambrian to younger rocks. Determining the direction of movement along a shear zone is of fundamental importance in understanding the tectonic framework and tectonic style of deformation in an orogenic belt which can further be critical in tectonic modelling of

Plate-III.11a Uneven development of en-echelon vein system in quartzite.

Plate-III.11b Sigmoidal quartz veins found along the periphery of wakal shear zone, showing dextral shear sense
Loc: 5 km to the west of Manpur village.

a region. So, shear zones, the study of sense of shear and shear sense indicators (kinematic indicators) have drawn considerable attention in recent years. Several shear zones, mylonite zones etc., have been recognized and studied and extensive literature has been published on the criteria used to deduce the sense of shear. The fundamental concepts of deformation resulting on account of shearing have also been well explained (Ramsay and Huber, 1983; Hobbs et.al., 1976; Hanmer and Passchier, 1991) and the types of flow materials forming the shear zones and its resulted structures on mesoscale can be tabulated in Table-III.2. Based on this concept, the present author is attempting to bring out a detailed documentation of available field data encountered in her study area in order to understand the type of shear deformation of the southern Rajasthan region.

Shear zones are made obvious by the presence of weak, pervasive and narrow to wide zones of highly sliced rocks (Plate- 12a,b,c). Several shear planes running parallel to each other can be identified in the field. The sense of movement in shear zones can be determined from the reorientation of pre-existing planar or linear features within the zone (Wheeler, 1987). The presense of closely spaced pegmatitic veins, displaced quartz veins, mylonitic foliation, S-C tectonites, laterally displaced crustal blocks, rotated rigid objects in the field and the presence of displaced phyllosilicates, rotated inclusions are some of

TABLE- III.2 : SHEAR SENSE INDICATORS (KINEMATIC INDICATORS) ON MESOSCALE

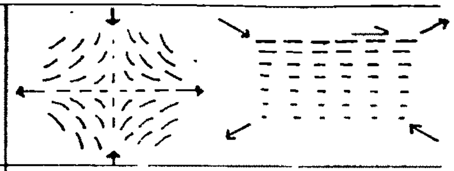
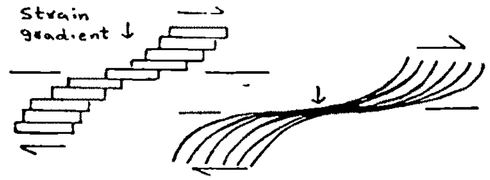
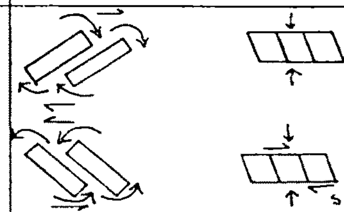
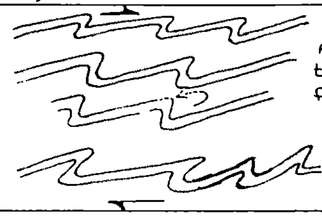
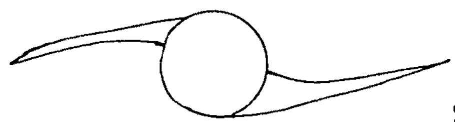
I. Orientation of flow in the field.	Orientation of flow in the field can be explained by the response of deformation of quartz veins with respect to the instantaneous stretching axes of the flow.	
II. Shear plane and shear direction.	- Flow plane is the plane of zero angular velocity towards which most other planes rotate at any instant. - Shear plane is the mean position of the flow plane during progressive deformation. - Shear direction is the mean position of the flow direction.	
III. Tuilage or Tiling.	Tuilage or Tiling structures are grain transected by a set of slip surfaces oriented on high angle to the bulk shear plane and subjected to general shearing flow.	
IV. Fold asymmetry.	Asymmetrical folds such as drag folds, intrafolial folds and sheath folds are useful kinematic indicators.	
V. Porphyroblasts and porphyroclasts rotation.	Rotation of porphyroblasts and porphyroclasts observed in field gives a proper sense of shear.	

Plate-III.12a The great Kotra shear zone (GKSZ), the subduction zone of Sychanthavong and Desai (1977), Sychanthavong and Merh (1981). The Delhi quartzites (Gogunda group) have been sliced into thin shear plates show an oblique deep-slip movement. The eroded portion seen are all schists alternated with quatrzites.
Loc: 5 km to the east of Kotra village.

Plate-III.12b Deep-slip slicken-side in Kotra shear zone.

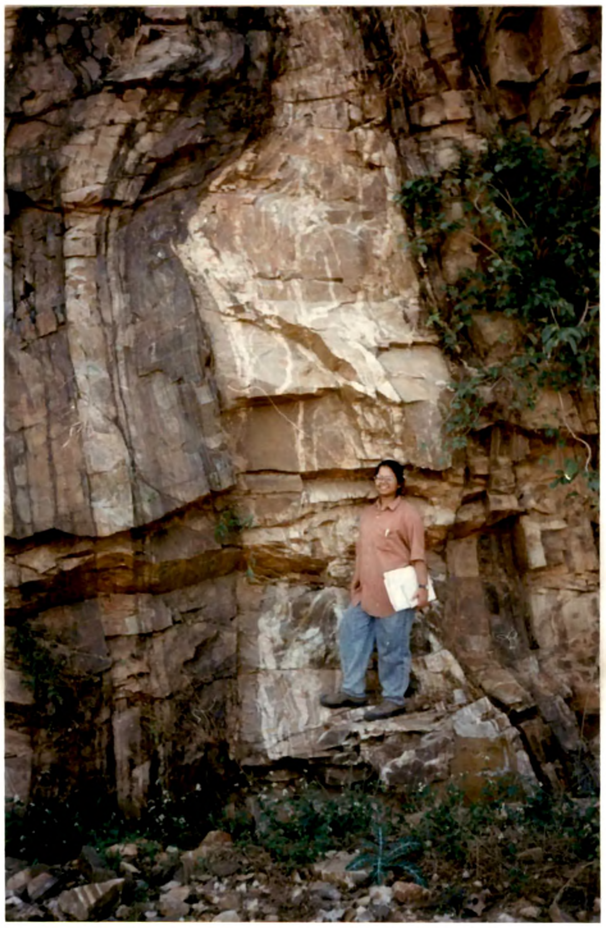


Plate-III.12c Wakal shear zone (WSZ), 5 km to the west of Manpur, developed within the Delhi quartzites. The shear sense is easterly down dip of dextral movement.

the important features that lead to the identification of shear zones, shear belts and shear indicators. The presence of highly sliced schists and quartzites, quartz veins and the laterally displaced quartz veins, sigmoidal quartz, confirm the shear phenomenon in the Jharol group of rocks. This highlights the importance of FCC data as a guide to shear zones prior to visiting the actual sight in the field.

3.D SHEAR SENSE INDICATORS ON MESOSCALE :

Several mesoscopic structures that reveal the sense of shear have been recognised. They are called the "shear sense indicators" - Hanmer and Passchier (1992). These authors have classified the shear sense indicators into several types involving porphyroclasts, porphyroblasts and fold assymmetry formed by rotation of materials.

Rotation of porphyroblasts and porphyroclasts are well distributed in various shear zones of the study area undoubtedly showing shear sense on mesoscale (Plate- III.13, 14, 15, 16, 17).

Assymmetrical folds such as drag folds, intrafolial folds and minor sheath folds are useful Kinematic indicators (Fossen and Rykkelid, 1990; Rykkelid and Fossen, 1992; Hanmer and Passchier, 1991).

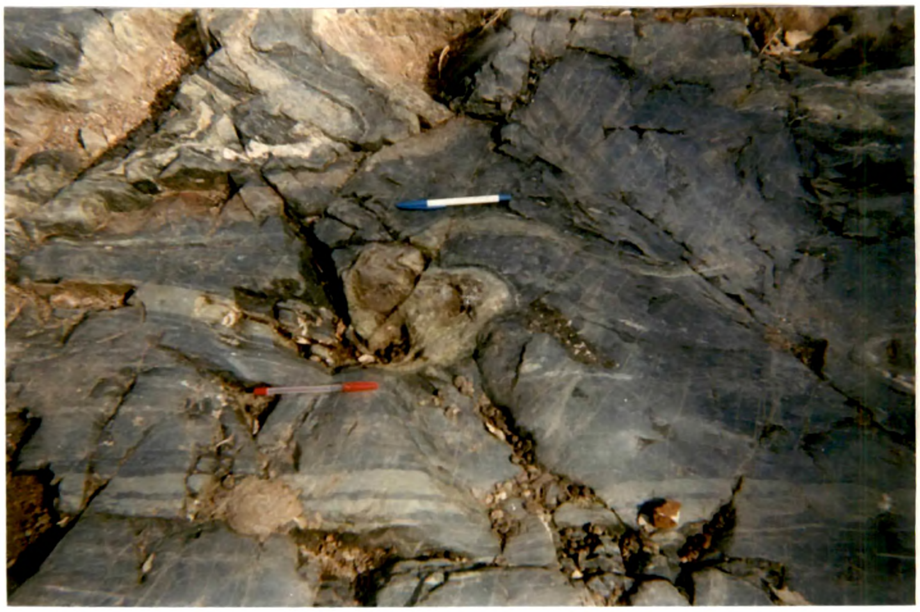


Plate-III.13 Sinistrally rotated porphyroblast of epidote within amphibolites.

Plate-III.14 Rotation of porphyroclast in amphibolitic gneisses, showing sinistral sense of movement. Loc: Kirat village.

Plate-III.15 Rotation of porphyroclast in gneisses showing sinistral sense of movement.
Loc: Ammiwara village.

Plate-III.16 Mylonites showing S-shaped rotated quartzo-feldspathic porphyroclasts with broken tails as well as folded tails.
Loc: Kirat village. 10 km SW of Jharol.

At low shear strains, initially upright folds form which later develop into asymmetrical folds with increasing strain. Their shorter limbs thicken because they lie in the compressional field of the instaneous strain ellipse associated with the shear zone. (Plate- III.18, 19, 20). Non coaxial progressive deformation may result in the formation of shear related folds like intrafolial folds (Plate-III.21). Subsequently with continued shear, overturned folds are generated and shorter limb rotates into the extensional field of the instantaneous strain ellipse thus getting attenuated. This entire phenomenon is characterized by the reduction in the angle between the axial plane of the folds and the bulk flow plane as the shear strain progressively increases, thus revealing the sense of shear (Fossen and Rykkelid, 1990).

Tuilage or tiling structures are grain transected by a set of slip surfaces oriented on high angle to the bulk shear plane and subjected to general shearing flow (Table-III.2).

According to Blumenfeld (1983), Blumenfeld and Bouchez (1988), the geometry might result from forward directed rotation of the slip surfaces in a bulk flow of a given shear sense. If the slip surfaces rotated antithetically, then, the same geometry could result by bulk non-coaxial flow of the opposite sense. Hence, identical result from

Plate-III.17 The porphyroclast of quartzo-feldspathic material showing sinistral sense of movement. One tail of the porphyroclast is detached. All the crinkles seen are of AF_3 generation.

Plate-III.18 Mylonites showing varieties of quartz-feldspathic porphyroclast with as well as without tails or broken tails into boudinaged fragments, giving sinistral sense of shear.
Loc: 1 km east of Ora village.

Plate-III.19 Gneisses showing complex refolded folds of quartzo-feldspathic bands.
Loc: Kirat village.

Plate-III.20 Assymmetrical folds in gneisses giving sinistral sense of movement.
Loc: Kirat village.

AF_2 shear system

AF_3 shear system

Plate-III.21 Intrafolial folds in amphibolites showing sinistral sense of shearing. AF_2 fold coaxially folded by AF_3 during dextral shear deformation. The porphyroclasts developed during AF_2 deformation have been affected by tail detachment during dextral shear superposition. Loc: Barvalli village.

Plate-III.22 Tuilage or tiling structures found in composite gneisses.

both non-coaxial flow of the opposite sense. Such type of shear indicators are also encountered in the study area and mostly concentrated in shear zones running through gneisses (Plate- III.22).

Along these various shear zones, several oriented samples have been systematically collected for further studies in the laboratory. From such collected samples, each of which have been cut along the preferred direction to prepare thin sections mostly (1) across the strike - parallel to the dip, and (2) across the dip - parallel to the strike; both sections are always cut across the foliation planes. This type of thin section preparation was made in order to detect the sense of shear movement on microscale under microscope. So far the mesoscopic scale structures are concerned, the sense of shear governing the shear deformation of AF_2 folding was dip-slip sinistral type and the same also controlled the AF_3 deformation, but the latter was accompanied by sinistral lateral shear movement. Therefore, most of the AF_2 fold hinges have been twisted and rotated (Plate- III.23). It is expected that microstructures will show more conclusive proofs in terms of shear sense determination. Ofcourse, these data wil be used to interprete the shear deformation of the entire southern Rajasthan region, especially the Jharol belt rocks.

Plate-III.23 Twisted and rotated AF_2 fold hinge of folded quartzite layer embedded in Jharol schist belt exhibiting AF_2 fold hinge down folded vertically by AF_3 folding.

Loc: 5 km to the North of Phalasia.

Plate-III.24 Mylonitised micaceous quartzites on the river bed.
Loc: west of Ora village.

III.4 MICROSCALE STRUCTURES

4.A. MYLONITES AND MYLONITIZATION :

For nearly a centuary ago the word "mylonite" has been named by Charles lapworth (1885) for fine grained well laminated rock. Lapworth describes the rocks in the following way : "The most intense mechanical metamorphism occurs along the grand dislocation (thrust) planes, where the gneisses and pegmatites resting on those planes are crushed, dragged, and ground out into a finely laminated schists (Mylonite - is derived from Greek term "mylon" , a mill) composed of shattered fragments of the original crystals of the rock set in a cement of secondary quartz, the lamination being defined by minute inosculating lines (fluxion lines) of Kaolin or chloritic material and secondary crystals of mica. Since then it is known that the mylonites occupy the zones of high deformation, and are mostly characteristic of ductile shear zones.

Mylonitic rocks are mostly associated with faults or shear zones. Thus may form under the condition of simple shear (Tullis et.al., 1982). If a rock contains 10 to 15 % porphyroclasts and the matrix grain size has less than 0.5 mm diameter then the rock can be called mylonite (Ghosh, 1985). Laminar schistosity, lamination, brecciation and other processes of mechanical transformation of the rocks are confined in these zones (Plotnikov, 1994).

Recently,Ghosh (1985) has defined that mylonites are not considered as cataclastic rock, and the recrystallised textures in mylonites and such rocks were described by him as blastomylonites. The grain size reduction was attributed to cataclasis and the dominant texture was attributed to Post-tectonic recrystallization. Recrystallization process was emphasized by Christie (1963) and the terminology on mylonites was built up on the basis of cataclasis and grain growth by Higgins (1971), Bell and Etheridge (1973) White (1973, 1975, 1976, 1977, 1979). White et.al. (1979, 1990) clearly demonstrate the process of grain refinement in mylonites by syntectonic recrystallization and neomineralization. According to them, the well known mortar structure of mylonites develops by syntectonic recrystallization and not by cataclastic processes.

Based on the above discussed concept the present author has been able to carry out a detailed study of mylonites encountered in the study area. Mesoscopic as well as microscopic observations reveals that most of the rocks like gneisses, garnet mica schist, micaceous quartzites, strongly foliated amphibolites and non-garnetiferous schists of the study area are all sheared to a lesser or greater degree during various episodes of their deformational history. The rocks which occur closer to the major shear zones are highly sheared while those which are farther from the shear zones are little affected by shearing. The micaceous quartzites occurring near Ora ie. near the shear zones are highly sheared and mylonitised (Plate- III.24, 25).

In the case of schistose rocks, the shear planes are more conspicuously seen in the finer non-garnetiferous schists as compared to the gneisses and garnet-mica schists, a characteristic feature which implies the role of depth of the rocks and related P-T conditions in controlling the deformation and related shearing. Thin section studies of these rocks reveal that they are highly crenulated showing S-C fabrics (Plate- III.26). Microstructurally, the C-surfaces appear as thin layers of a re-crystallised, polyminerallic aggregate with a reduced grain size. The S-surface on the other hand are initially oriented at an angle of 45° to the C-surfaces and curve into the C-surfaces such that the angular relationships between the two surfaces define the sense of shear in the rock. According to Ramsay and Graham (1970), in terms of the old rock fabric between the C-surfaces, the S-surfaces are perpendicular to the short axis of the finite strain ellipsoid and hence they mark the planes of finite flattening (Simpson and Schmid, 1983), with progressive deformation, the angle between the C- and S-surfaces decreases and the S-surfaces curve into

Plate-III.25 Highly sheared, mylonitised and sliced, micaceous quartzites.
Loc: East of Ora village.

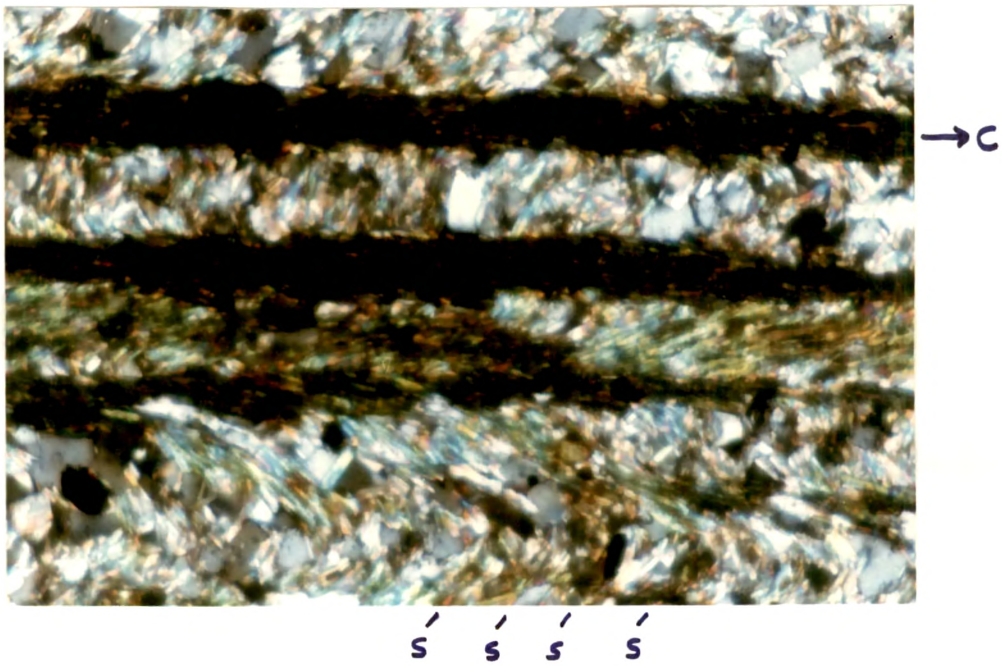


Plate-III.26 Mylonites showing S-C fabrics in the shear zone running through the non-garnetiferous schists. (Magnification - 20x, XN position).

near parallelism with the shear zone boundary.

According to Lister and Snoke (1984), the S-C mylonites have two important properties :

(i) They are usually rocks which mark the locus of a zone of intense non-coaxial deformation and

(ii) during flow the matrix minerals of a mylonite (eg: quartz) deform crystal plastically.

Two effects result because large strains are accomodated by the crystal-plastic behaviour of the matrix minerals of the mylonite.

(i) The matrix minerals undergo extensive dynamic recrystallization normally with the result that reduction in grain size takes place and

(ii) strong patterns of preferred crystallographic orientation typically develop (eg: quartz C-axis fabric).

These characteristics are so widespread that they are almost essential to the definition of a mylonite (Lister and Snoke, 1984). These authors have classified mylonites into two types viz : Type-I and Type-II. The resulted rotational microstructures can be summarized in Table- III.3.

A.1 TYPES OF S-C MYLONITES

There are fundamentally two types of S-C mylonites (Lister and Snoke, 1984).

(a) Type-I S-C mylonites.

(b) Type-II S-C mylonites.

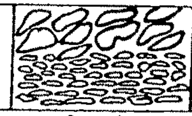
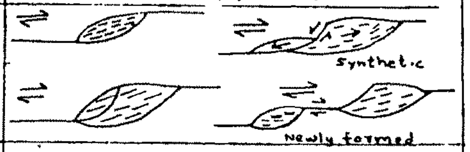
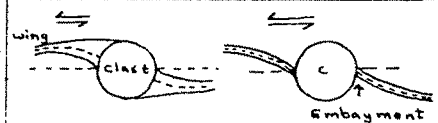
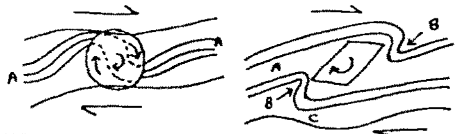
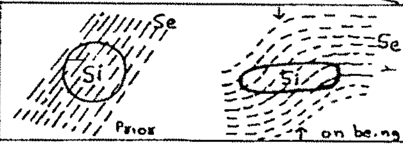
1.a Type-I S-C mylonites :-

In such rocks the mylonite foliation anastomoses in and out of the zones of locally high shear strain in a way which is probably related to fluctuation of the intensity of finite strain (Lister and Snoke. 1984). Type-I S-C mylonites have a wide spread occurrence in granites, granodiorites and augen gneisses subjected to mylonitization in shear zones (Berthe et.al. 1979).

1.b Type-II S-C mylonites :-

The second class of S-C mylonites developed in quartz mica rich rocks subjected to mylonitization during conditions of decreasing pressure and temperature. The most characteristic microstructural feature of type-II S-C mylonites are 'mica fish' produced by boudinage and

TABLE-III.3 : SHEAR SENSE INDICATORS (KINEMATIC INDICATORS) ON MICROSCALE

I.	The Obliquity of elongate recrystallized grains.	The asymmetry of Quartz c-axis fabric with respect to the c-surfaces implies the the sense of shear.	
II.	Cleavage/Schistosity relationship.	C/S fabric develop due to simple (non - coaxial shearing).	
III.	Mica fish.	Microfaulting and microshearing are the main causes of mica fish formation and the antithetic cleavage splits.	
IV.	Rigid objects and associated structures.	Porphyroblasts, Porphyroclasts and their relationship with associated structures - like pressure shadows, wings, foliations and inclusion trails are of kinematic Imp.	
a)	Pressure shadows.	Pressure are symmetrically disposed regions of low strain developed on opposite sides of the rigid object.	
b)	Stiff winged (Porphyroclasts).	They are the product of dynamic recrystallization and are derived from the originally larger clast by a grain size reduction.	
c)	Foliation around rigid objects.	The rigid crystals affected by progressive simple shear, rotates and overgrows the synkinematic growth (domains) and microfolds are formed in the foliations outside the crystals.	
d)	Porphyroblast rotation.	Porphyroblast grow with progressive metamorphism and rotate simultaneous with the growth during non-coaxial progressive deformation.	

microfaulting or microshearing of pre-existing (white) mica grains.

According to Eisbacher (1970) 'mica fish' form commonly in rocks where pre-existing large (white) mica grains are boudinaged by a combination of brittle and crystal-plastic processes (Lister and Snoke, 1984) (Plate- III.27 a and b). The mica fish are usually linked by trails of fragments and when extensively developed these trails, commonly stair-step from one, 'mica fish' to the next. These 'mica fish' can be used to determine the shear sense. (Plate- III.27a). As far as the mechanism of the formation of mica fish is concerned, it can be inferred from micro-structural observations, because the results of microboudinage can still be recognised. The early developmental stages of 'fish' are ocassionally preserved at a stage before the 'fish' has been separated from the host clast by a displacement discontinuity (Plate- III.27b).

Assymmetric 'mica fish' or 'chlorite fish' formed on account of boudinaging of larger mica grains due to non-coaxial deformation are known to occur in Type-II S-C mylonites (Lister and Snoke, 1984). The (001) cleavage of the mica fish is tilted with respect to the shear plane (C-surface or is sub-parallel to it. The acute angle between the C-surface and the (001) cleavage gives the sense of shear.

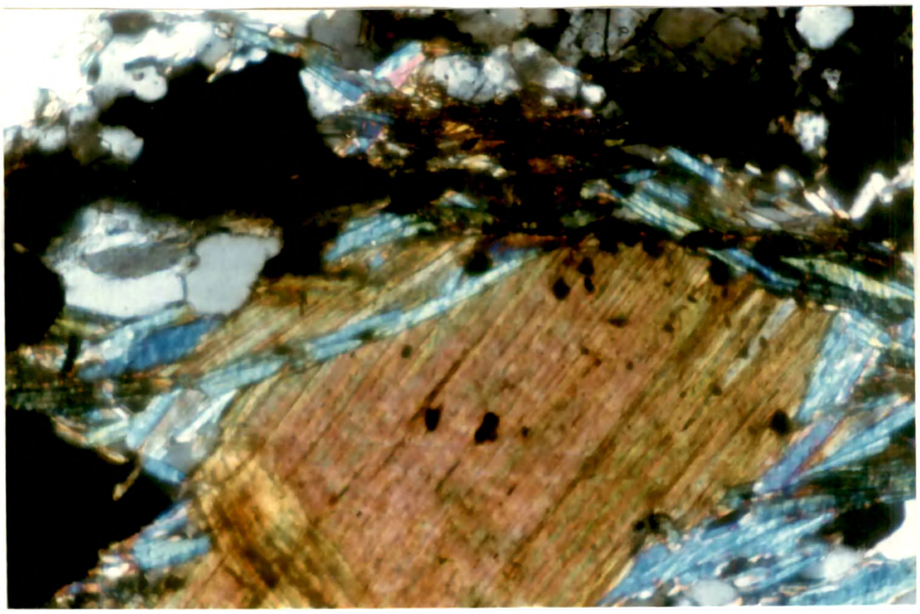


Plate-III.27a Formation of mica-fish by micro-faulting or microshearing from pre-existing mica-grain. The mica-fish shows sinistral sense of movement (M- 20x, XN)

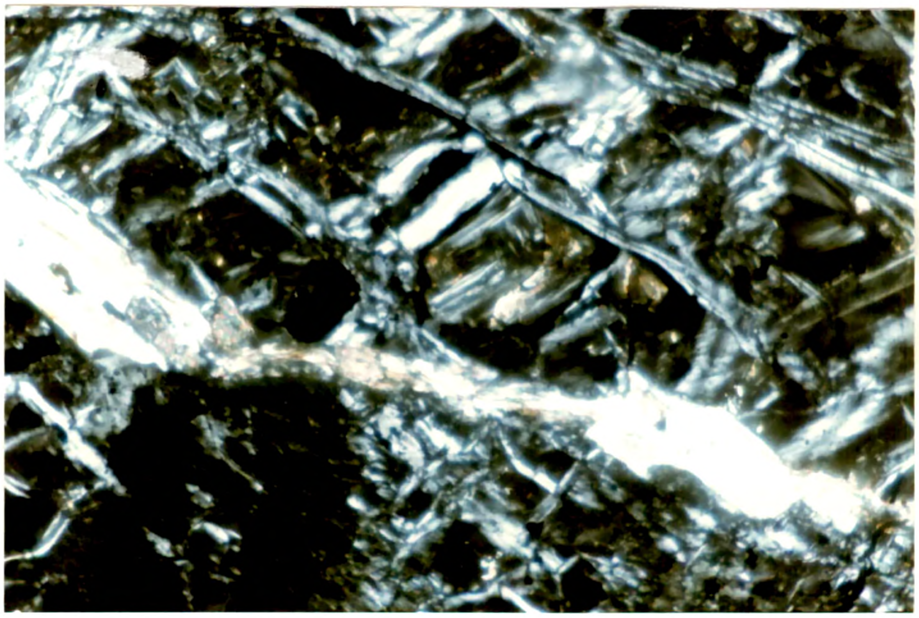


Plate-III.27b Antithetically detached mica-fish in serpentinites. The shear plane has also been serpentinized. The sense of movement is sinistral. (M - 20X, PPL).

Microfaulting and microshearing are the main causes of mica fish formation and also for the antithetic and synthetic cleavage splits (Lister and Snoke, 1984). Mica fish generation is initiated by the formation of a listric normal microfault antithetic to the bulk sense of shear in a large host mica grain. The listric microfault first cuts down through the cleavage and then gradually, curves into parallelism with the cleavage, thus splitting the original single large host grain into two (Plate- III.28). Since the (001) cleavage plane lies in the extensional quadrant of the finite strain ellipsoid of the bulk flow, with continuing deformation, antithetic movement (back rotation of Hanmer and Passchier, 1991) occurs along the 'listric normal microfault'. The (001) cleavage of newly formed segments of mica (ie. the hanging wall of the microlistric fault) rotates with respect to that of the host (foot wall of the microlistric fault). The two segments slide apart and finally synthetic microshearing/microfaulting separates the two originally adjacent segments, thus forming mica fish.

When the above fundamental principles of classification of the S-C mylonites are applied to the rocks of Jharol group, it is found that these can be best classed as "Type-II S-C mylonites". The following micro-structural features observed in the thin sections of rocks support the above described principles.

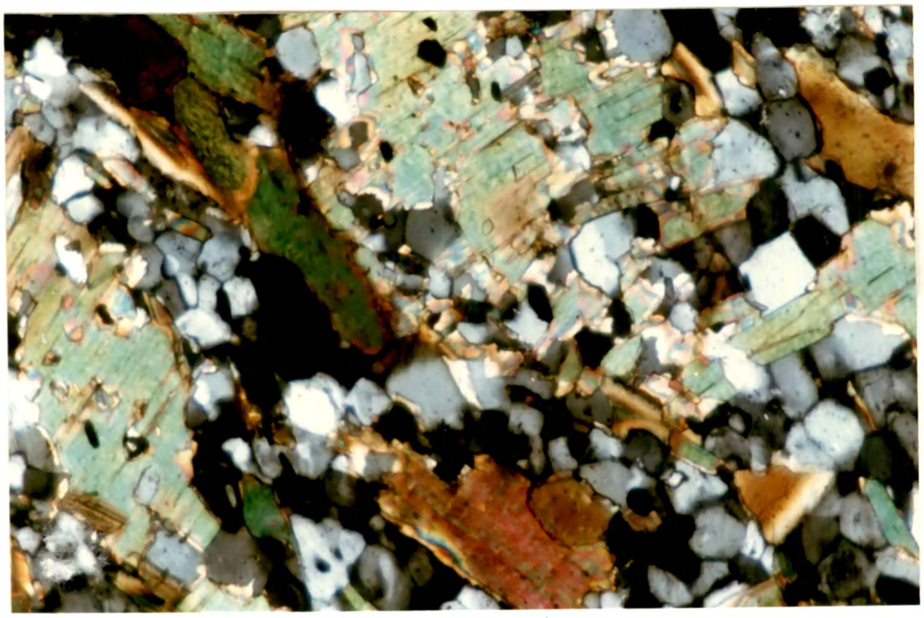


Plate-III.28 Antithetic splitting or pull-apart structure of mica grain. Space created is filled by quartz grains. The grain is sinistrally sheared. (M-20X XN)

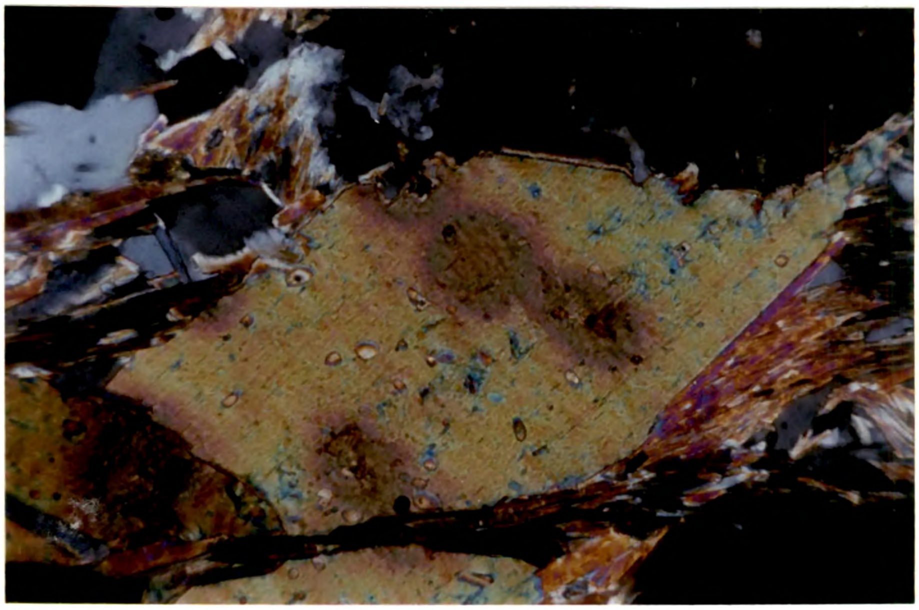


Plate-III.29a Micafish in schist indicating dextral shear sense (M - 50x, XN).

1. The S-C mylonites occurring along the shear zones are extremely rich in quartz and mica which is an important criteria to class them as type-II S-C mylonites.

2. The conspicuous and abundant occurrence of 'mica-fish' is another important microstructural feature which clearly implies that the rocks are indeed Type-II S-C mylonites (Plate- III.29a and b).

Plate-III.30 a, b, c show 'pull apart structures' or antithetic splitting of the mica and staurolite grains. Here the formation of listric normal microfault is seen antithetic to the bulk shear sense, which first cuts down through the cleavage and then curves into parallelism with it. Further continuing deformation leads to the displacement of two segments involved in a single microfault. All these features supplement the conclusion to classify the S-C mylonites under study as Type-II S-C mylonites.

3. The presence of synthetic microfaults (microshears) (Plate-III.30a) is another evidence to call the S-C mylonite along the shear zone as Type-II S-C mylonites.

As revealed in the mesoscale shear structures that the shear sense indicators play an important role in the understanding of shear deformations, and it is expected that the microscale structures must also show a positive and

Plate-III.29b Mica fish in quartz-schist indicating **sinistral** sense of shear. (M - 20x, XN).

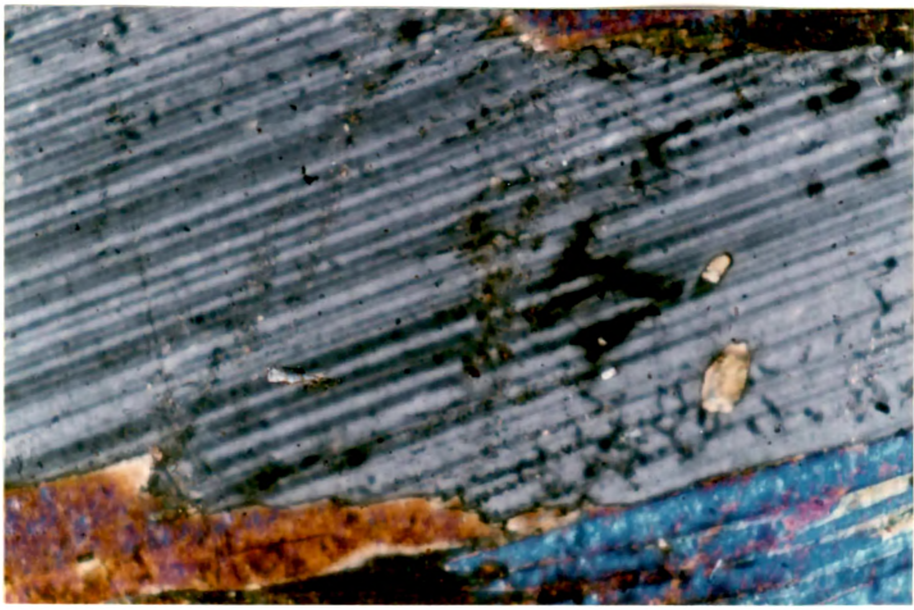


Plate-III.30a Here plagioclase grain is synthetically sheared showing sinistral sense of movement.(M-20x, XN)

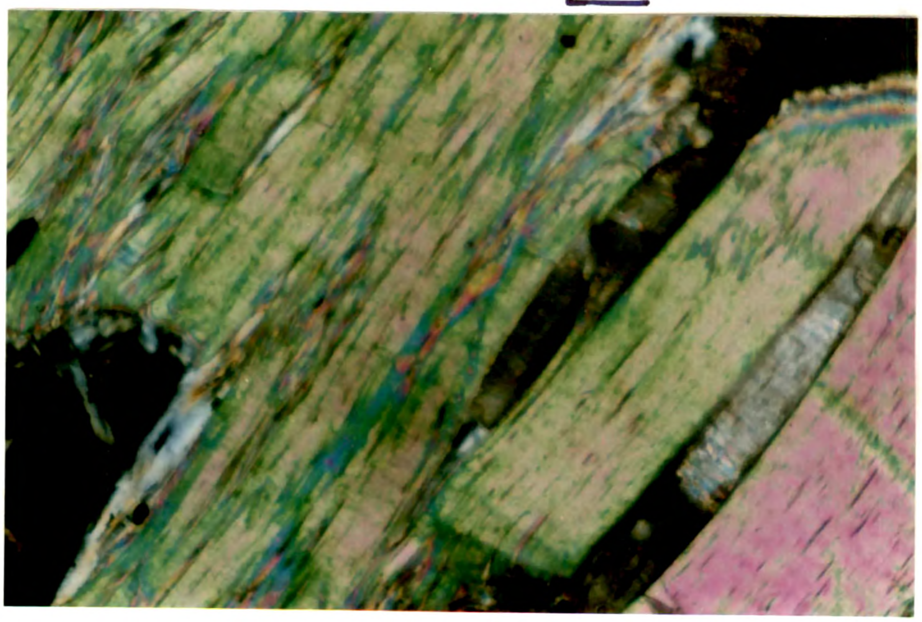


Plate-III.30b Sheared and pull-apart muscovite grain synthetically, filled by calcitic material. The sense of movement is sinistral. (M- 20x, XN).

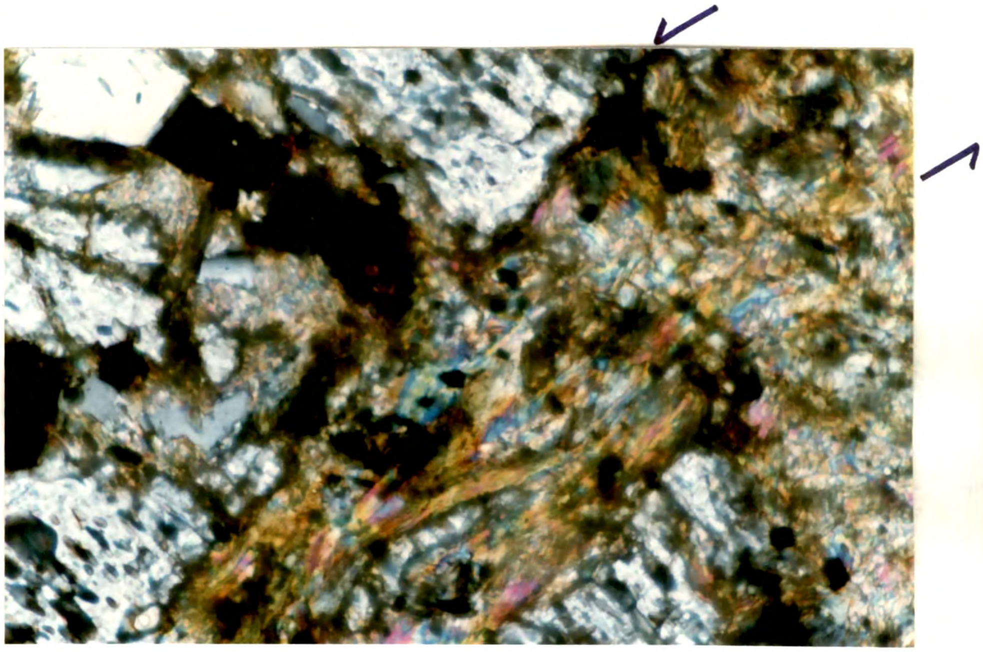


Plate-III.30c Staurolite grain is antithetically sheared and filled up by chloritic material, the altered product of sheared staurolite. The sense of movement is sinistral. (M- 20x, XN).

conclusive method for the study of shear deformation in an orogenic belt. From the study of microscale structures described above, it is illustrated that most shear sense indicators show sinistral shear movement both along the dip and strike during AF_2 and AF_3 deformations. This type of deformation must have been controlled by a large scale horizontal non-coaxial shear movement during the orogenic uplift of the Jharol belt rocks. The detailed discussions on this topic will be in the fifth chapter of this thesis, where, based on these shear movement data, the geological evolution of the Jharol sequence will be treated.

A.2 MYLONITES UNDER SEM

The study of mylonites under scanning electron microscope (SEM) has been carried out by the present author for the first time and few observations are presented here. The type two mylonites described above show interesting feature of shear deformation. Antithetic shear structures are clearly revealed, displayed by the closely packed biotite flakes which have been dextrally antithetically sheared accompanied by microfaulting in the end of the process (Plate-III.31 a and b). This dextral shear sense is different from the main shear sense of sinistral type described above as observed by mesoscale as well as microscale (normal petrological microscope) structures. This dextral shearing must be connected with a body rotation

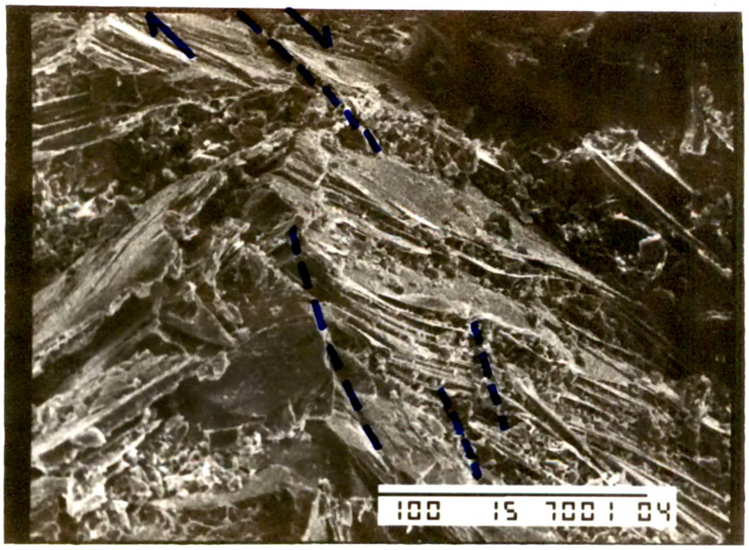


Plate-III.31a SEM microphotograph illustrating the antithetic shear structure of mica flakes showing dextral shear sense (see, arrows for direction of movement). Dashed lines indicate microfaulting accompained by the shearing. (M = 500).
Loc: Kirat village river section.

Plate-III.31b SEM microphotograph illustrating the close-up of the sheared structure shown in 36a above showing microfaulting structure. (see, arrow). (M = 1000).

taken place within a sinistral shear zone. This is true because the sample studied has been taken from the garnetiferous amphibolite gneisses having rotated and flattened garnet porphyroclasts.

The microstructures observed in the schistose rocks, also show dextral shear sense indicated by a very tiny garnet porphyroblast embedded within the mylonitized micaceous media (Plate- III.32). This dextral shear sense is also different from the main sinistral overall shear sense due to rotation of rigid crystals which may rotate clockwise as well as anticlockwise as illustrated in the following sketch (Figure- III. 8). But the overall shear sense of the media is of sinistral type, which can also be seen under SEM. (Plate- III.33). In this photograph, the microfault is revealed showing sinistral shear sense cutting across the mica flakes antithetically (see arrow) with minor displacement. Microtwisting and microcrinkling are also observed. It is concluded that SEM studies of mylonitic rocks are also helpful in determining the sense of shear movement. This presentation is just a selective one, and a detailed account of this study will be presented elsewhere, since it is outside the scope of this thesis.

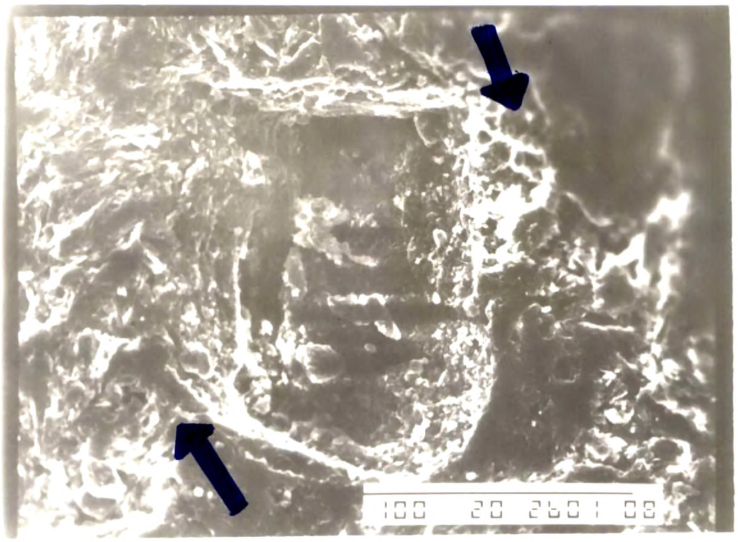


Plate-III.32 SEM microphotograph illustrating a tiny garnet porphyroblast in a mylonitised garnet mica schist showing dextral shear sense.
Loc: 4 km after Bicchwara (Mahipal village).
(M = 3500).

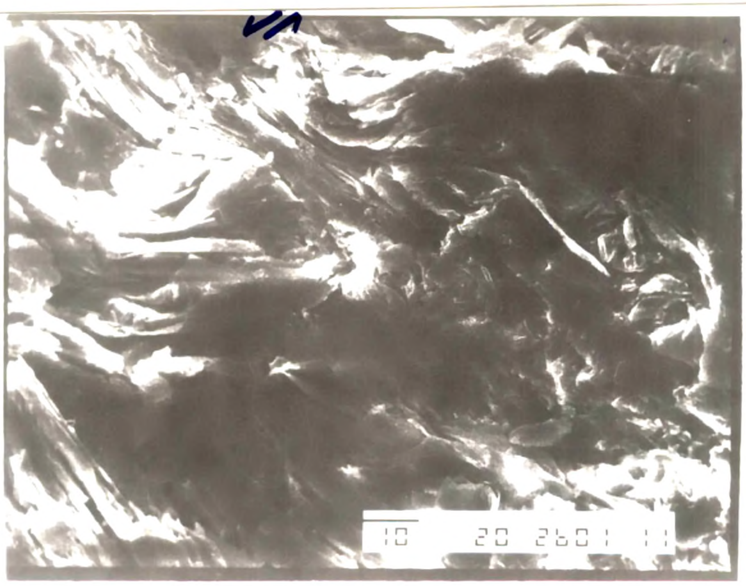


Plate-III.33 SEM microphotograph illustrating microshear structure in a micaceous mylonitic rock. It shows a sinistral shear sense with several microcrinkles (M = 1000).
Loc: 4 km after Bichhwara (Mahipal vilage).

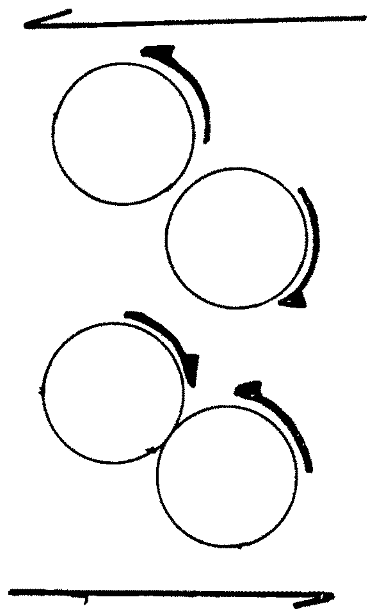


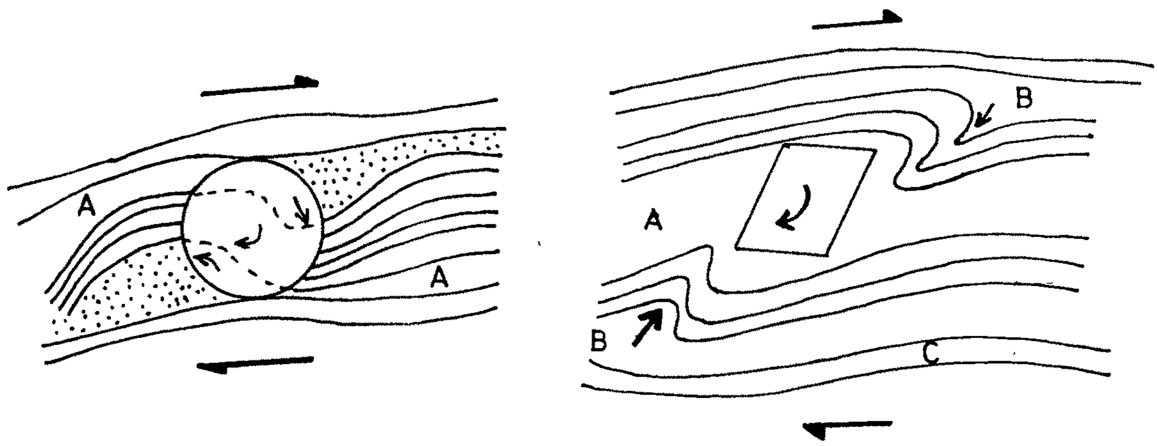
Figure III.8 The movement of the border grains are governed by the main shear which is sinistral, and the inner grains have been rotated on account of the movement of the adjacent grains.

4.B - FOLIATIONS AROUND RIGID CRYSTALS

B.1 - MICROFOLDS AROUND RIGID CRYSTALS :-

Rigid crystals (like garnet) are bordered by two domains-quartz rich domains (pressure-shadows) and mica rich domains (Schoneveld, 1977). When rigid crystals are subjected to progressive simple shear (without a shortening component perpendicular to the foliation) than it rotates. Simultaneously, the crystal overgrows (synkinematic growth) the domains mentioned above. Microfolds are formed in the foliation outside the growing crystal. Taking a reference point in the core of the microfold and looking towards the point of maximum curvature of the foliation, the direction of rotation of the grain can be deduced which gives the shear sense. The spacing of the pre-existing foliation planes adjacent to the rotating grains is also a useful guide to the rotation direction (Simpson and Schmid, 1983). For a rigid object rotating in a clockwise direction, the pre-existing foliation planes on the upper left hand side and the lower right hand side have a closer spacing. This implies a dextral sense of shear. (Figure-III.9a & b).

More recently, a similar method has also been applied to determine the local sense of shear in felsic volcanic rocks (Vernon, 1987). When a flow-layered felsic volcanic



(A) (B)

Figure - 9

Analogy between the use of microfolds adjacent to porphyrobalsts in metamorphic rocks and phenocrysts in volcanic rocks to determine the sense of shear.

(a) Rotated, porphyroblastic garnet model modified after Schoneveld (1977). The foliation outside the garnet forms a small microfold at the point of entry into the grain. Arrows indicate the direction of rotation of the grain. Pressure shadows are stippled. Point A shows the tendency of the pre-existing foliation on upper left hand and lower right hand side to closely space together in clockwise rotation (After Simpson & Schmid, 1983. Fig.4B, p.1283)

(b) Schematic diagram showing the various microstuctural features ideally developed around a phenocryst in a relatively uniform groundmass undergoing progressive simple shear. Compression of the flow layers occurs at A, expansion occurs at B, and deflection away from the phenocryst occurs at C. Small arrows show the direction of closure of the microfolds, the sense of relative rotation of the phenocryst and the overall sense of shear. (After Vernon, 1987; Fig.3, pp.129).

rock consisting of phenocrysts or globules undergoes non-axial deformation, the planar flow layering gets disturbed and forms asymmetrical microfolds in the adjacent ground mass. These asy mmetrical microfolds are analogous to the microfolds that occur around rotated rigid objects in metamorphic rocks. The direction of closure of the microfolds gives the sense of rotation indicating the sense of shear. These types of structures are extremely numerous in the study area, and the presentation here is only selective one.

As in Figure-III.10 the assymmetrical microfolds is observed around the garnet porphyroblasts. Crinkling of micas are seen adjacent to the garnets. Around the larger garnet porphyroblast the layering of quartz is preserved as a deformed pressure shadow quartz domain. All the quartz grains are recrystallized and entering the garnet grains. The sense of movement of the earlier pure shear feature is sinistral although it has been affected by severe simple shear deformation in the advanced stages of orogenic uplift.

In Figure-III.11 two generations of garnet is observed. The synkinematic ones are seen overgrown on the pre-existing foliation and with further deformation they became rotated, stretched and elongated. The older ones are still preserving their euhedral shape but are highly

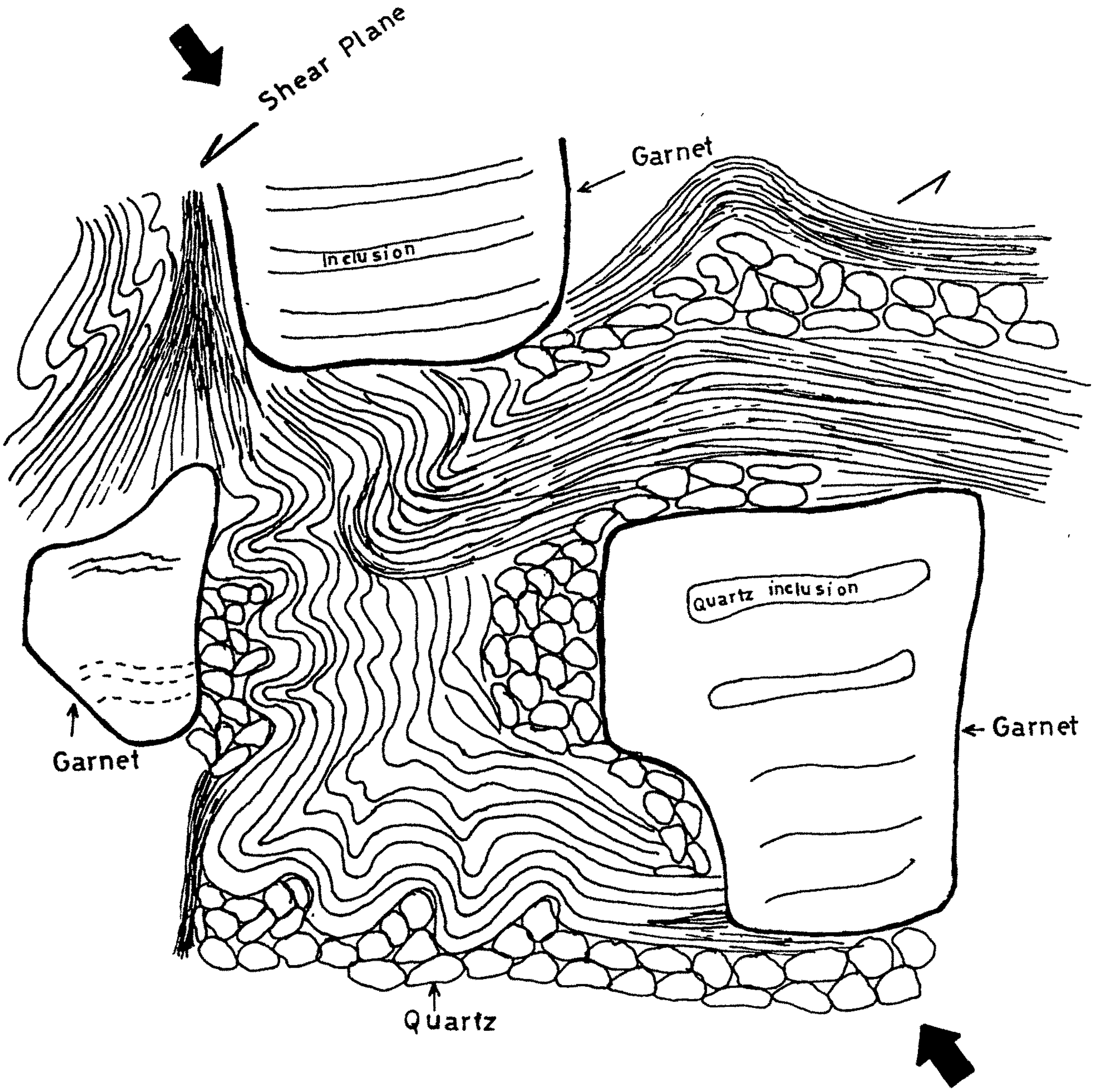


Figure III.10 Microscopic sketch showing sinistral shear sense locally developed due to pure shear deformation which later on changed into simple shear. This is few of such features survived after the area has undergone simple shear deformation.

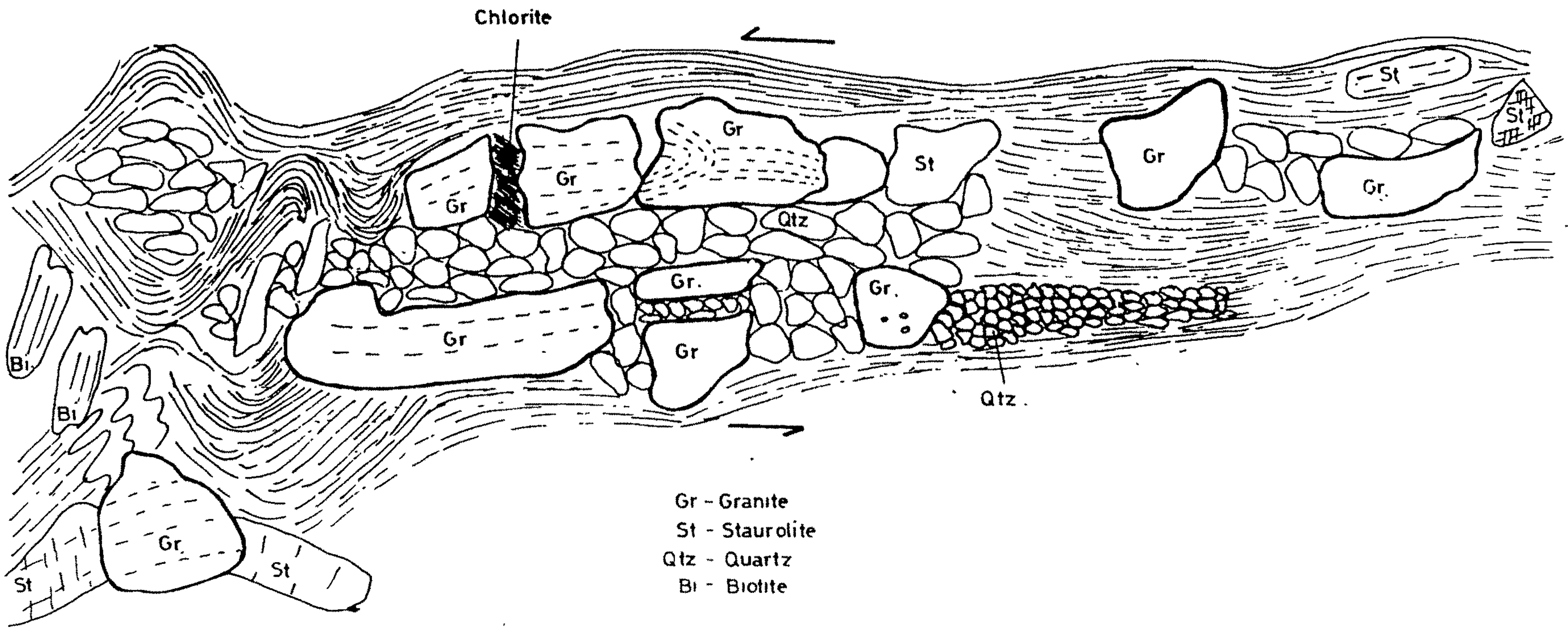


Figure III.11 Microscopic sketch illustrating two generations of garnet grains, pre-kinematic and synkinematic growths.

fractured. Inclusions of quartz in garnet are running parallel to the trend of the lineation indicating that the pre-Kinematic garnet porphyroblasts were formed during pure shear deformation during the initial stages of AF_2 folding. Inclusions of quartz in staurolites are highly folded along with the surrounding muscovite and biotite to form microfolds of crinkle types.

B.2 PORPHYROBLAST ROTATION :

Porphyroblasts are coarse crystals embedded in a fine-grained matrix in metamorphic rocks is known since many decades ago, but the use of porphyroblasts in the study of shear deformation has been taken up quite recently. They grow with progressive metamorphism and have been considered to rotate simultaneously with growth during non-coaxial progressive deformation (Schoneveld, 1977; Powell and Vernon, 1979; Ramsay and Huber, 1987; Visser and Mancktelow, 1992; Passchier et.al., 1992). More recently new a concept postulating the non-rotation of porphyroblast with respect to geographical co-ordinates during non-coaxial deformation has evolved (Bell and Johnson, 1989; Johnson, 1990a; Johnson, 1990b; Bell and Johnson, 1992; Johnson, 1992, Bell et.al. 1992). This has resulted in a debate on porphyroblast rotation/non-rotation (Passchier et.al., 1992; Bell et.al., 1992). Though debatable and controversial, the use of porphyroblasts in shear sense studies is worth discussing.

The equidimensional porphyroblasts of garnet, staurolite, albite etc., have been considered very useful for the determination of sense of shear. Porphyroblasts can be considered analogous to a ball bearing which rotates when subjected to non-coaxial deformation. They are believed to grow synkinematically, thus overgrowing the foliation originally constituted of quartz and phyllosilicates (in schistose rocks). The phyllosilicates usually get transformed to a composition identical to the host crystal/porphyroblast, while the quartz grains form inclusion trails within the porphyroblasts. This foliation within the porphyroblasts is termed Si while that found outside is termed Se (Spry, 1969; Barker, 1990). By matching the inclusion trails inside the porphyroblasts (Si) with the foliation outside (Se), the sense of rotation (ie: the sense of shear) can be determined (Plate- III.34). Such porphyroblast geometries that show a continuous Si-Se foliation with an oblique relationship between Si and Se, are considered to be developed on account of rigid body rotation in a non-coaxial flow regime, wherein the foliation is fixed to the flow plane and the rigid object rotates with respect to it. Thus Si rotates with respect to Se. However, if the foliation is not fixed to the flow plane ie: the foliation itself has an oblique relationship with the flow plane, than the rigid object as well as the external foliation, rotate with respect to one another (Plate- III.35). Thus Si and Se rotate relatively, Ramsay (1962) suggested that porphyroblast geometry similar to that mentioned above, may form by rotation of foliation with repect to a stationary spherical object during coaxial (pure shear) progressive deformation (Passchier et.al, 1992). Accordingly, Se would rotate with respect to a stationary Si, thus resulting in the development of an oblique relationship between Si and Se and also flattening the porphyroblast (Figure- III.12).

Stretching and flattening of garnet grain is observed on a larger scale in Jharol group of rocks. Flattening, pull apart and slight rotation of the garnet grain is observed (Plate- III.36). In this case, the growth of garnet grain was synkinematically taking place followed by flattening in the later stage of deformation (Zwart, 1960; Toteu and Macaudiere, 1984). Movement was still continuous after the crystallization of garnet resulting the micas to have been deformed and the garnet grain almost entered in the mica, ultimately leading to split of the mica grain (Figure- III.13, Plate- III.37).

The study of porphyroblast rotation also proved useful in the study of shear deformation as discussed above. The sense of movement involving the rotation of garnet in the Jharol rocks follows the main shear sense revealed by

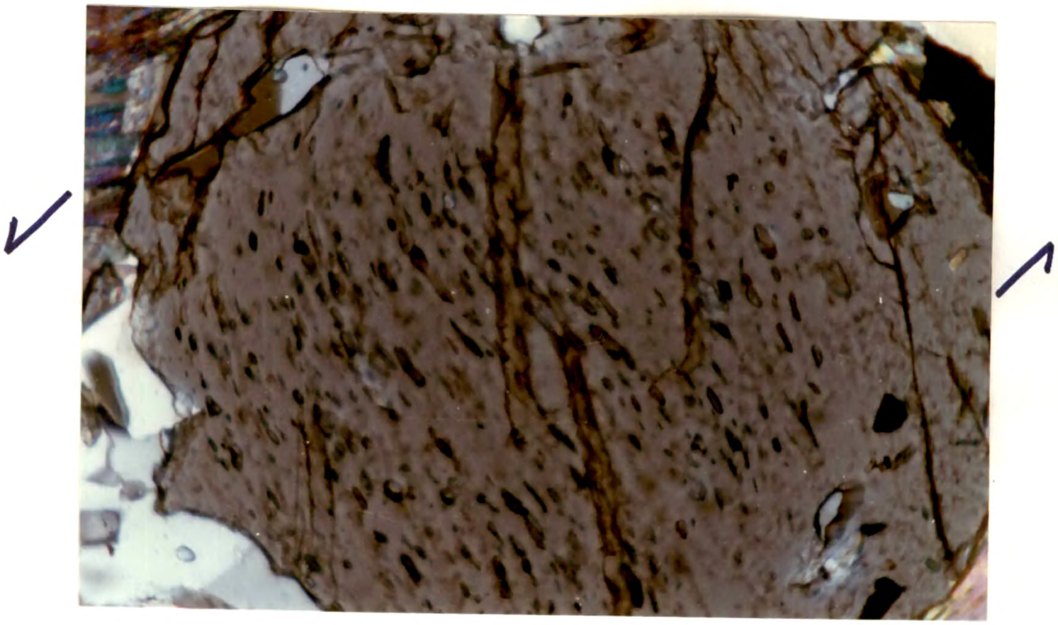


Plate-III.34 Rotated garnet. Inclusions of quartz are perpendicular to the main foliation. The rotation of garnet porphyroblast is sinistrally observed. (M : 20x at 45° cross nical position).

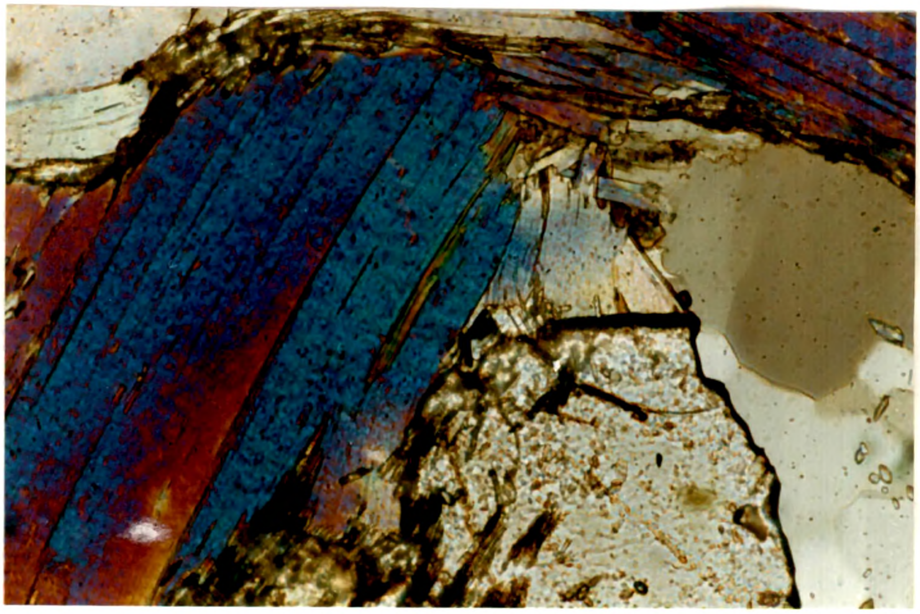


Plate-III.35 Clockwise (dextral movement) rotation of garnet grain pushing the muscovite grain to rotate and inject into another grain. Here, Si and Se rotate relative to each other. (M : 20x, at 45° cross nicol position).

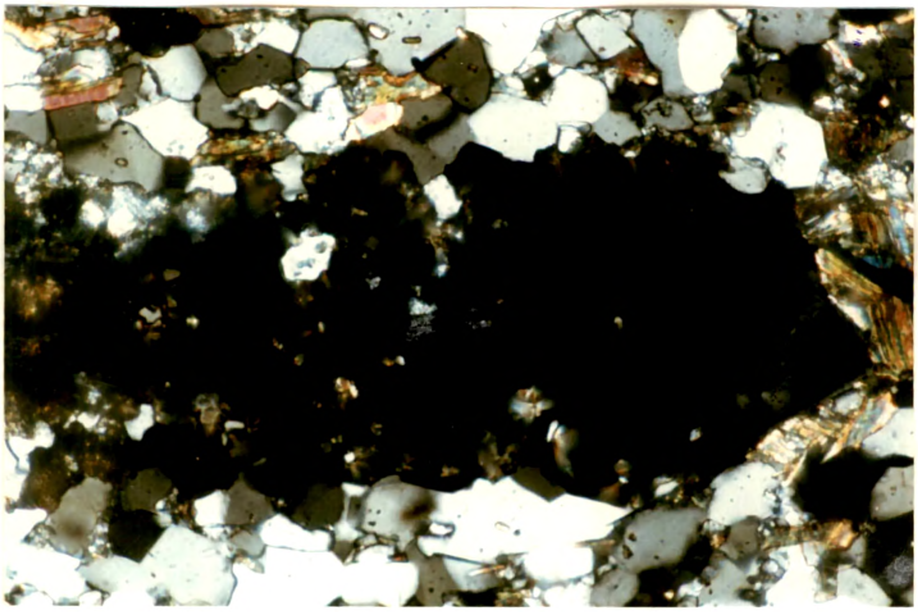
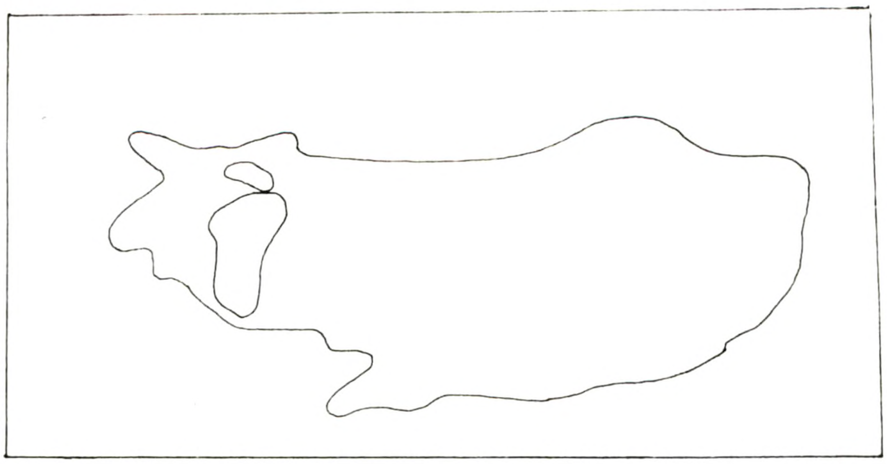


Plate-III.36 Flattening of garnet porphyroblast in sheared garnet mica schist.



:Sketch of above photograph.

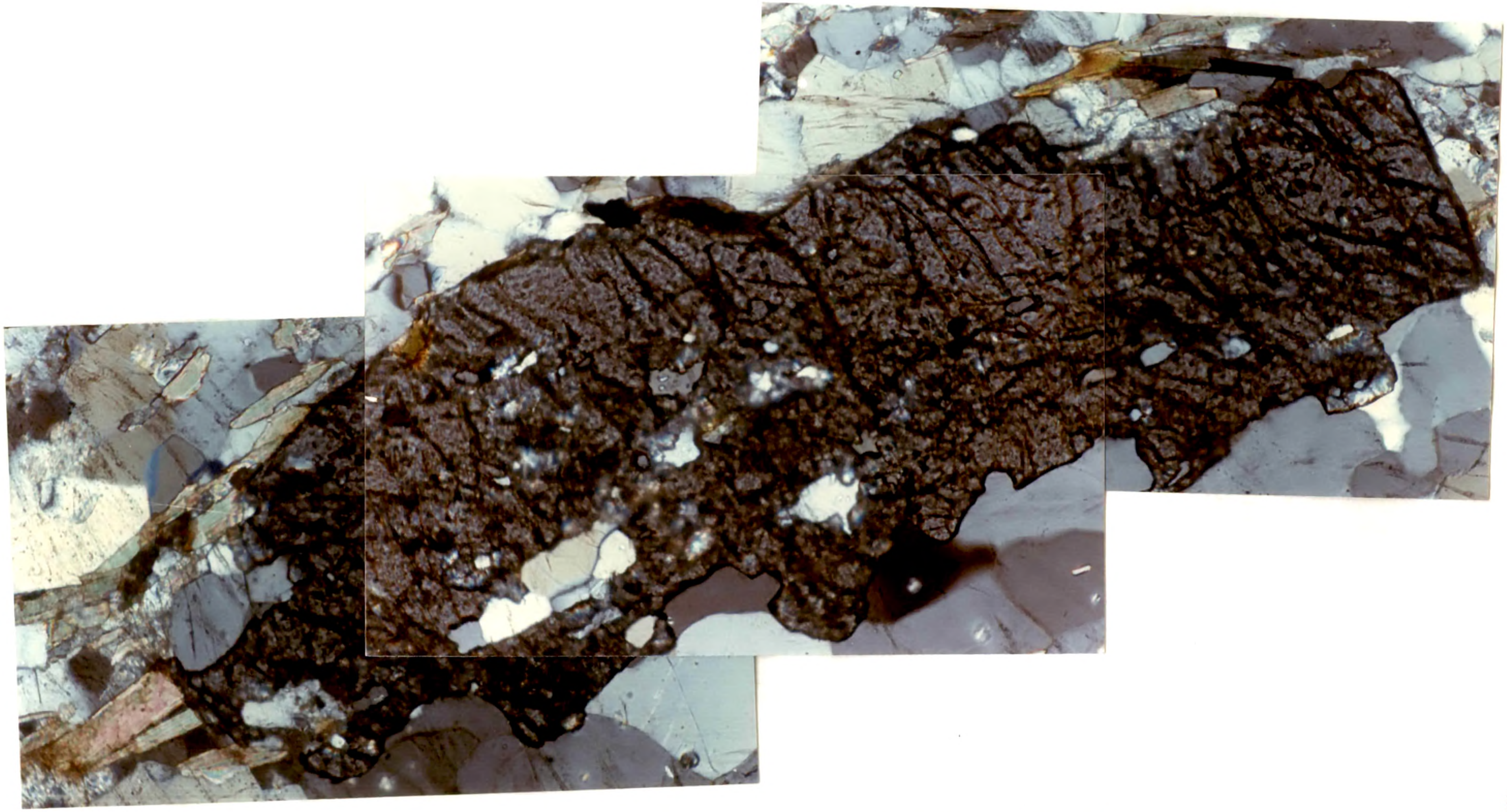


Plate-III.37 Stretched garnet in gneisses along the shear plane developed at low angle oblique to the main foliation (M : 20x, at 45° cross nical position)

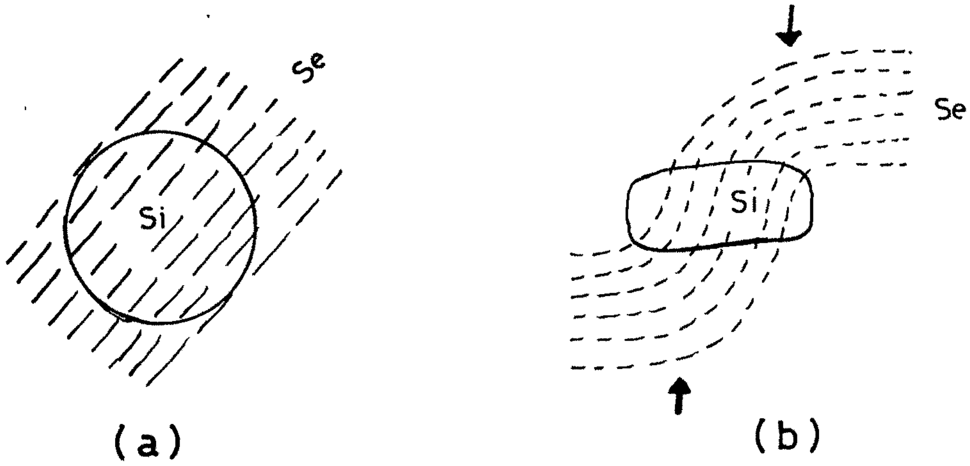


Figure III.12 Rotation of S_e with respect to stationary S_i due to coaxial deformation.

(a) Prior to coaxial deformation.

(b) on being subjected to coaxial deformation.

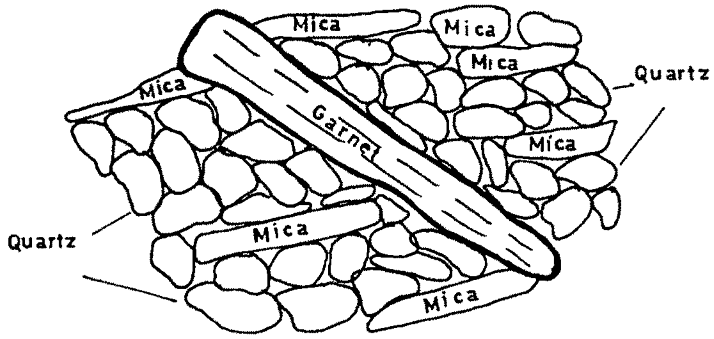


Figure III.13 Microscopic sketch showing stretched garnet porphyroblast splitting the mica flakes in garnet-mica-schist.

mesoscale structures confirming that the Jharol rocks have been deformed mainly by simple shear mechanism. All these findings are useful in the construction of tectonic model governing the deformational folding and metamorphism of the Jharol region as a whole. These deformational characteristics, metamorphic changes and the model controlling the deformation will be discussed in length in the following two chapters (Chapter- IV and V).