CHAPTER II

STRUCTURAL CHRONOLOGY IN RELATION TO PROGRESSIVE DEFORMATION
2.1 Introduction

The chronology of the minor structures developed in the area can be worked out and related to the known principal strains in rocks. Considerable research has been done in recent years, especially noteworthy being the work by Treagus and Treagus (1981). Indeed, the orientations of structures which develop in rocks owing to deformation, depend upon the rheologic response of the rocks to the applied stresses and the relationship between geometry of planes, surfaces or lines with respect to the principal axes of the successive finite (and infinitesimal) deformation ellipsoids. Under the same set of forces, different rocks deform to different degrees, and the strain in a given direction within a rock layer would depend on what angle it makes with $\lambda_1$, $\lambda_2$ and $\lambda_3$ axes of the bulk strain. In other words, maximum stretch within a deforming layer may not equal $\lambda_1$ at all since this direction may be at an angle to the maximum principal extension direction $\lambda_1$ of the overall deformation ellipsoid. This is probably the reason why fold hinges bearing no systematic relation to either $\lambda_1$ or $\lambda_2$ may be found in many orogenic belts. Again, the $\lambda_1 \lambda_2$ plane may not coincide at all with the axial plane of a fold and
cleavage slightly postdates the folds, the folds may be transected by the very cleavage with which they are generally related (Borradaile 1978, Duncan 1985).

In other words, the strains within a deforming layer at a given instantaneous stage during the deformation may not possess a systematic relationship with the principal incremental strains. But in general, at the close of deformation, the planes rotate together with nonmaterial line elements within them, so as, to be parallel to the principal strains of the finite deformation ellipsoid (see e.g. Flinn, 1962, 1978). Thus, fold hinges would eventually become parallel to $\lambda_1$ unless they were closer to $\lambda_2$ at the onset of deformation and axial planes may coincide with the regional schistosity, generally (but not necessarily) developed parallel to $\lambda_1 \lambda_2$ planes. In general, principal planes and axes in the material planes rotate at different rates and therefore the finite deformations built up are usually varied and complex.

2.2 Relationship Between Undeformed Layers and First Incremental Deformation Ellipsoid

According to the established rule, one must try and work back to find out (Eulerian mode) what exactly was the attitude of layers, prior to deformation in relation to the $\lambda_1$, $\lambda_2$ and $\lambda_3$ axes of the first instantaneous deformation
ellipsoid. Usually, this is too difficult a process in areas of polyphase folding and polymetamorphic regions, for, the finite strains were built up in a complex manner at different localities. Besides, they must have had varied orientations and magnitude during each of the several tectonometamorphic events.

It is generally believed that the disposition of strata within a basin to be deformed must be horizontal. This generalisation is however not true in most basins. Dips of strata generally are inclined at 30-40° and the strike directions may also vary. If the subhorizontal or gently dipping maximum compression is applied at about 50° to these layers, it is possible for them to further rotate at steeper angles. If such a sequence is deformed with \( \lambda_2 \) in vertical or sub-vertical position (perhaps at deeper crustal levels), it is possible for folds to form with vertically plunging hinges.

2.3 Orientational Variability of \( F_1 \)-Folds and Finite Strains

In the area under investigation hinges of \( F_1 \) folds show variable attitude. In the Barr horizon, \( F_1 \) folds are subvertical with hinges plunging to ESE at 85° or so, down the dip of their axial surfaces (Fig. 2.2, also folded vein Fig. 2.1A). At the eastern extremity, where the Barotiya sequence is cut off by a fault and Nandana banded marble is
Fig. 2.1 - A - A very tight vertical $F_1$ fold traced by a quartzofeldspathic layer to which the regional schistosity is axial planar. About 2 kms north of Barr. Note the boudin-naged thick quartzite layer to the left of the lens cap with one tip of the boudin hidden under the shadow of a cactus.

Fig. 2.1 - B - $F_1$ folds traced by calcareous and pelitic layers in Nandana Marble, about 5 kms ESE of Barr. From the closed outcrop on the horizontal plane and the vertical plane (to which plane of photograph is parallel) it is obvious that the fold hinge plunges moderately towards the observer.
exposed, the enveloping surfaces of minor F₁ folds dip gently to moderately to the NNE or NE or SSW to SW (Fig. 2.1B). Also, folds are not tight structures and not completely isoclinal as in the members of the intervening Barotiya sequence. It may be concluded that the dips of the strata were to the NE or NNE or SW to SSW at the eastern extremity of the major Barotiya ductile shear zone, while they were moderate to steep easterly at the western margin near the Barr "conglomeratic" horizon. The deformation was most intense at the western margin but the entire zone between Barr horizon and Nandana marble (inclusive) was subjected to a fabric parallel up-dip sinistral heterogenous simple shear during latter part of deformation. The initial response was presumably brittle - ductile by dextral sub-horizontal shear, giving rise to brittle - ductile F₁ folds (Fig. 2.2A), nearly vertical or very steeply reclined with hinges plunging in excess of 80° to ESE. The original strike of the zone was nearly NS and hence the original pelitic bands in what is now represented by Nandana marble must have been notherly dipping. The general idea of F₁ folds being recumbent or nearly so, is not favoured here and the variability of F₁ fold axial directions and axial planes (now rotated into subvertical positions) is not as a result of formation of sheath folds (Cobbold and Quinquis 1980). Such situation is indeed encountered in the central part of
Fig. 2.2 - A - F₁ folds in the boudinaged zone of Barr which are formed under brittle regime, the limbs are boudinaged and the fold has a sinistral sense of asymmetry.

Fig. 2.2 - B - A fine example of F₁ folds whose hinges are curved through 90° (see arrow) and yet this is not the effect of later folding but the inhomogenous flattening particularly resulting from the swapping between λ₁ and λ₂ principal extensions. The folds are refolded by F₄ folds (the accommodation structures). F₁ folds have variable hinge line orientations throughout this outcrop (South of Giri village) but the same degree of tightness ($\sqrt{\lambda_3/\lambda_1} = 0.15$).
the Delhi fold belt, as in the area around Liri (Vaghamay 1989) and recumbent folds abound in Anakhar-Saroth area (Roday 1979). But, in the marginal Barotiya-Sendra sequences, it does not appear that $F_1$ folds evolved as sheath folds under shear regime due to variability of magnitude of displacement vector, but evolved directly as variably oriented folds due principally to original variable attitude of layers, as a result of subhorizontal brittle-ductile shear under high pressure low temperature regime, culminating later into a high temperature high pressure regime. The orientation of the first instantaneous deformation ellipsoid axes were; $\lambda_1$ horizontal NS to NNE, $\lambda_2$ vertical or nearly vertical and $\lambda_3$ subhorizontal E to ENE-WSW. Since the strata were moderately to steeply dipping, the fold hinges rotated towards the $\lambda_2$ direction of the deformation ellipsoid and $F_1$ folds began to amplify in the horizontal direction, with axial planes gradually rotating parallel to $\lambda_1 \lambda_2$ planes. The deformation was not by simple shear alone, it progressed by a complex process of simultaneous pure shear and simple shear increments but must have remained close to plane strain with little extension in the $\lambda_2$ direction. The pegmatite veins intruded along the tensile fractures developed subperpendicular to $\lambda_1$ at the onset of deformation, were folded tightly (but showing less rupture and boudinage) with the same style as those in quartzite
layers. Extensive boudinage occurred since most of the layers quickly crossed over into the overall extensional field of the deformation ellipsoid. Pegmatite veins were folded into both S and Z types, depending upon whether the shear stresses resolved along the layers were positive or negative. Symmetrical folds in pegmatite veins were also developed. Ptygmatic folds developed in pegmatite vein shown in Fig. 3.11B were subjected to computation of the viscosity contrast using the Scherwin-Chapple (1968) equation.

\[
\frac{\mu_1}{\mu_2} = 0.024188 \left[ \frac{Wd}{t} \right]^3 \frac{S^2}{S-1}
\]

... eq. 2.1

in which \( \mu_1/\mu_2 \) is the viscosity ratio between folded layer and matrix, \( Wd \) is the one complete arc length \((2\pi)\), \( t \) the thickness of the layer and \( S \) is the shortening or the ratio \( \left[ \frac{\lambda_1}{\lambda_3} \right]^{1/2} \). The \( \mu_1/\mu_2 \) obtained was 663 under a condition of assumed plane strain, which gives the amplification \( \frac{A}{A_0} \) of more than a million \((\text{given } \lambda d = 1.208)\) which is much above predicted limit of \( A/A_0 = 128 \) of the Scherwin Chapple theory. This is because Scherwin-Chapple theory \((1968,\) is applicable only for low amplitude folds while the amplitude of folds is considerably greater in folds shown in Fig.3.11B than the wavelength. But using the Biot \((1961)\) equation

\[
\frac{\mu_1}{\mu_2} = 0.024188 \left[ \frac{Wd}{t} \right]^3
\]

..... eq. 2.2
the viscosity contrast obtains to be 41.8 which appears to be reasonably acceptable and therefore suggests "explosive amplification". These folds are Z shaped in style and the original layer was therefore oriented at small angle to $\lambda_3$ (Beech 1969, Treagus 1973). Some of the folds in pegmatite veins are strikingly S shaped (Fig. 3.14B, 3.17B). This suggests that the intrusion along the layering was at the onset of deformation. One pegmatite vein near Barr village shows a close to tight fold with subhorizontal plunge and schistosity axial planar to it, this being similar to the situation at Nandana marble at the eastern margin. This pegmatite was intruded as a gently dipping sheet from the main large pegmatite body to the east and therefore the fold hinge developed close to $\lambda_1$ rather than to $\lambda_2$. Boudins were formed with boudin lines parallel to $\lambda_2$. Since the deformation was by a combination of pure shear and simple shear, the deformation path must consist of hyperbolic and straight line segments, the former finally becoming asymptotic to the $\lambda_1$ direction and also the planes of simple shear (only theoretically possible if only simple shear dominant). The deformation path (Fig. 3.52) is thus similar to the one suggested by Ramberg (1975). At the eastern extremity and at places in the intervening area where plunge amounts of $F_1$ folds range between 30° and 35° to NNE or SSW, the story was entirely different. Since the
strata were inclined gently to moderate to the North or NNE or SSW, the hinges of $F_1$ folds got aligned to within $45^\circ$ of $\lambda_1$ direction and generally began rotating towards subhorizontal $\lambda_1$ rather than towards $\lambda_2$. The folds therefore failed to amplify, were arrested at different stages of deformation, depending upon the rheologic properties and amount of extension in $\lambda_2$ direction. They are cut across by tensile fractures and cannot be continuously traced. Some folds are relatively open and plunge to the NNE or NE (or SSW to SW) at gentle to moderate angles. Where pelitic material predominates, axial planar schistosity is developed which has the same attitude as within the boudinaged zone. The hinges of these folds perhaps failed to rotate completely to horizontality, i.e., perpendicular to $\lambda_2$.

As a result of subhorizontal shearing, together with component of pure shear during further stages of deformation, a fabric $S_1$, axial planar to subvertical $F_1$ folds, developed and boudins with large amount of separation got aligned parallel to fabric planes. Together with $S_1$ fabric, a subhorizontal mineral lineation developed, consisting of phylosilicates, chiefly muscovite. This lineation, developed perpendicular to hinges of $F_1$ folds, is here termed $L_1'$.

Some of the original curviplanar pegmatite veins, e.g. near Giri village, were folded into complex folds with the
Fig. 2.3 - A - Subvertical $F_1$ folds in the marble band ENE of Giri. Note the incipient development of axial planar cleavage in B besides that the folds in B plunge not vertically but at an amount of 73°.
hinge line of the fold plunging horizontally and then turning through 90° to plunge vertically. This feature therefore typically suggests that the extension occurred to the maximum in both $\lambda_1$ and $\lambda_2$ directions near Giri. The folds in pegmatite veins are isoclinal and subvertical schistosity is axial planar to them. Such complex features were not observed anywhere else except near Giri (Fig. 2.2B).

The shearing continued for some time parallel to foliation planes giving rise to foliation fish (Hammar 1986) and then ceased. That, pure shear component operated during this deformation is substantiated by development of conjugate ductile shears, whose obtuse angle is normal to fabric planes (Ramsey and Allison 1979) and the fabric lies parallel to the walls of the zone (walls consisting of pelitic schists). The shear strain alone cannot produce this feature as $\gamma$ will have to reach a value of infinity.

At some time during the deformation process, there was a swapping between $\lambda_1$ and $\lambda_2$ extensional axes of the deformation ellipsoid. At this stage, foliation parallel sinistral shear developed and already formed boudins were pinched and then pulled apart giving rise to the chocolate tablet boudinage structure (Wegmann 1932). Pinch and Swell structures (Ramberg 1955) are commonly seen on foliation surfaces. The peak of metamorphism was achieved
during the latter part of deformation stage and a down-dip mineral lineation of biotite flakes, quartz blebs, stretched magnetite grains together with syntectonic and post tectonic (post F₁) garnets developed at this stage, the latter more predominantly in the surrounding pelitic schists. The subhorizontally or gently plunging folds began to amplify again and assumed almost a tight to isoclinal fold style. This complex history explains why some folds of F₁ type are nearly upright and others nearly vertical. Upright folds are not F₂ folds since F₂ folds refold the S₁ fabric axial planar to F₁ folds.

2.4 F₂ Folds

Subvertical or steeply reclined F₁ folds are coaxially refolded by F₂ folds, refolding the pre-existing S₁ fabric (Fig. 2.4B, 2.6A), so that the hinges of F₁ and F₂ folds are strictly parallel (type 3 interference of Ramsay 1967) in the Barr area at the margin of the belt. Only the axial planes of F₁ folds are affected. The parallelism between F₁ and F₂ subvertical fold hinges is very striking in the Barr marginal band. Unfortunately, it could not be sufficiently observed anywhere, what sort of relationship exists between F₁ upright to asymmetrical and overturned folds which are gently to moderately plunging and the superposed F₂ folds, presumably, this is coaxial. F₂ folds fold the boudins
Fig. 2.4 - A - Moderately plunging isoclinal $F_1$ folds traced by pegmatic veins within the Barr zone, about 2.5 kms north of Barr fort. The pegmatite veins also show pinch and swell structures. Two such bands are in fact two limbs of a still larger $F_1$ fold whose hinge zone is exposed above the top limit of the photograph. The fabric $S_1$ is axial planar to these folds.

Fig. 2.4 - B - Fabric $S_1$ folded by $F_2$ tight folds (together with boudins) about 1/2 km north of the dam at Giri village. Note very slight axial plane dislocation and Pre-$F_2$ pegmatite on the left hand side. Note the folded boudins above the pen cap and development of incipient crenulation cleavage in the antiformal $F_2$ fold to the right.
and S₁ fabric and are themselves accompanied by an axial planar crenulation cleavage in discrete planes (Fig. 5.6(i)A). The cleavage is formed by the chemical gradients in buckling anisotropic media (Gray and Durney 1979, Durney 1978) and its thermodynamics is given in detail by a theoretical model developed by Durney (1978) in finite amplitude (Chappie 1968) sinusoidal microbuckles. F₂ crenulations are domainal in development and therefore they confirm to type 2 crenulations of Gray (1979). Post F₁ pegmatite veins (those that intervene perhaps the short phase between F₁ and F₂ fold forming events) emplaced along S₁ are folded, sometimes into a chain of low amplitude concentric folds with nearly 1B geometry (Ramsay 1967) together with the boudins and schistosity (Fig. 2.5A). The presence of such pegmatite veins and the boudins, lower the anisotropy of the material (Cobbold et al. 1971) giving rise to sinusoidal buckles. Besides, the boudinage indicates a discontinuity of pre-existing continuous layers and hence, the parameters of low continuity index and low continuity ratio (Roday 1976b) also play a major part in producing the type 1 instability of structures, in a multilayered complex. The folded pegmatite veins also perhaps constitute an anomalous layer of different viscosity from the remaining otherwise more or less statistically homogenous complex. The span of folds is irregular because of interference of folds of different spans propaga-
Fig. 2.5 - A - A pre-$F_2$ pegmatite vein folded into a gentle waveform with anomalous span at one place due to interference of propagating folds along the layering. The quartzite boudins and $S_1$ fabric are also folded. The anisotropy of the complex is low due to pre-existing boudins and the presence of more competent pegmatite vein. These are, therefore, type 1 instability structures of Cobbold et al. (1971). North of the dam at Giri.

Fig. 2.5 - B - Pre-$F_2$ pegmatite layers and $F_1$ folds traced by pegmatite layers folded coaxially about $F_2$ folds in the reservoir of the dam at Giri. The hook-shaped pattern is noticeable in the bottom centre of the photograph (thin quartzite layers folded) with $F_1$ closure to the left hand side.
ting along the layering thus producing zones of anomalous span folds (Watkinson 1978, Watkinson and Cobbold 1978, Ramsay and Huber 1987). For all practical purposes, looking at the striking parallelism between hinges of subvertical \( F_1 \) and \( F_2 \) folds, it appears that \( F_1 \) and \( F_2 \) were formed in quick succession.

The configuration of the deformation ellipsoid during the generation of \( F_2 \) buckles of dominal extent appears to be similar to the late phase of the \( F_1 \) deformation, with \( \lambda_2 \) and \( \lambda_3 \) horizontal and \( \lambda_1 \) vertical. One significant effect of \( F_2 \) deformation has been, as pointed out by Murty and Bhargava (1972), a dextral shear couple on the left hand side limbs of vertical antiforms which drag the tips of the well separated boudins and give them a shape of "fish" or "cuttlebones" on the schistosity planes.

Minor \( F_2 \) folds are rather sporadically developed and only a few exposures were seen near Barr. The frequency of appearance however, increases to the north-east along the horizon, being maximum at Giri. The axial planes of \( F_2 \) folds are subvertical at places, slightly oblique to the fabric \( S_1 \) and at still others entirely parallel. This discrepancy might be attributed to the original changes in schistosity attitude and refraction of stresses across layering and schistosity. \( F_2 \) folds can be distinguished from \( F_4 \) sinusoidal buckles, by
Fig. 2.6 - A - $S_1$ fabric and $F_1$ folds folded coaxially by $F_2$ folds near Barr village.

Fig. 2.6 - B - A single set of sinistral kink bands of $F_4$ generation affecting $S_1$ near Megardha.
simply the trend of the axial surfaces of the two and by the "brittle" kinking associated invariably with the latter. F₂ major fold forms the principal map pattern in the Barotiya sequence and plunges gently to SSW. It is a major antiform and the Barr zone forms the slightly inverted limb of this major S shaped tight F₂ fold with Nandana marble forming the eastern limb. The fault to the east brings the Sendra Complex directly into juxtaposition with the Barotiya sequence antiformal fold. The pre-F₂ sequence folded by F₁ folding contains a large number of S folds (F₁). Therefore the Barr conglomeratic rock forms a younger unit than the Barotiya sequence.

2.5 F₃ Fold Structures and Orientation of Principal Compressive Stresses

F₃ folds are gravity induced and such folds were first described by Roberts (1971) from the Trondheim region of Norway. Roberts argued that the folds develop because of the gravitational settling of the deformed pile under its own weight. Hence the maximum principal compressive stress σ₃ is always oriented vertically in the direction of the earth's gravitational field. In case of Trondheim region, Roberts (1971), showed that since the layering and schistosity were steeply inclined, σ₃ direction subvertically produced triclinic set of single kink bands. While the kink-bands were single and sinistral at Meraker on the eastern flank of
the diaperically spread nappe structure, they were single kink bands of dextral symmetry developed on the western flank. Again, following the thesis of Cobbold et al. (1971), the $F_3$ folds can develop as sinusoidal buckles, recumbent to reclined, quite open in relatively less anisotropic material and as conjugate or single kink bands in perfectly anisotropic material. Whether single kink-bands develop in preference to conjugate one is naturally controlled by the shear and compressive modulii (Blot 1965). This again in turn is dependent upon the angle between the principal strains of the related deformation ellipsoid and orientation of layering. Speaking more generally, $\sigma_3 \wedge S_1$ or $\sigma_3 \wedge S_2$ would determine the result. The symmetry of the kink bands may be of a high order (orthorhombic) or as low as triclinic. Fig. 2.7B shows sinusoidal rather disharmonic $F_3$ folds in calc gneiss/amphibolite formation to the north west of the Midway Motel at Barr while Fig. 2.7A shows a single set of $F_3$ dextral kink bands on subvertical schistosity SSW of Barr. The distinct dextral displacement along the kink planes observed suggests "brittle" kinking (Johnson and Honea 1974).

$F_3$ folds of this kind have been recorded from nearly the entire Aravalli Range in Rajasthan, and near Udaipur. Roy (1973) showed these to be associated with excellent crenulations subhorizontally disposed together with a discrete crenulation cleavage. Roday (1978) reported similar
Fig. 2.7 - A - A single set of F₃ (dextral) kink bands developed as a result of gravitational settling of the deformed pile. Locality SSW of Barr.

Fig. 2.7 - B - F₃ sinusoidal folds in calc gneiss about 2 kms NW of the Midway Motel at Barr. The axial planes are gently dipping towards the observer, albeit obliquely. Note the gently dipping fracture cleavage axial planar to folds, disharmonic nature, and box-shaped geometry at some places.
structures with excellent subhorizontal crenulations from the basement of the Delhi supergroup rocks, east of Badnor. Roday (1978) related the variation in the attitude of axial planes of these folds to the doming up of strata during the first phase of the Delhi orogenic cycle. Similar structures were reported by Bhola and Vardarajan (1981) from the Mohindergarh region of Delhi rocks in Haryana, by Biswal (1988) from Banaskantha region of Northern Gujarat, by Naha and Halybuton (1974) from the famous Nathdwara Amet sector, the area of Hammer - head syncline of Heron (1953). Pahuja (1973) has reported such structures from Bhim-Todgarh area, Patel (1970) from the Gurach area north of Udaipur and Bhargava (1972) from the area to the east of Ajmer city. The total shortening involved in the development of these structures, as Vaghmarey (1989) has shown does not exceed 25 per cent. The principal mechanism is by inter-layer slip, unaccompanied by any within layer deformation. It is interesting to note that such F3 structures are more prevalent in the supracrustal rocks near their contacts with the Banded basement gneissic complex. Murty (per. com. to Roday 1980) is of the opinion that F3 structures, as far as the area to the north of Udaipur is concerned were presumably formed by constraint on the amplification of upright F2 structures in that area and are therefore a result of constrictional deformation (Flinn 1962). As far as this area is concerned,
it may be a sound hypothesis but, where \( F_2 \) folds are not upright and are amplifying in horizontal direction, this model of constrictional deformation becomes unacceptable. In this case, the constrictional deformation of the kind conceived by Murty would give rise to \( F_4 \) folds, described later in this chapter. The axial planes of the sinusoidal \( F_3 \) folds generally strike EW and dip gently to the north or south at angles not exceeding 20°. Where steeper inclinations are observed, it appears to be the effect of superposed \( F_4 \) folds. At places, where \( F_3 \) folds are developed as single conjugate kink bands, the complementary kink planes generally strike NNW and NNE and dip gently to the ENE and WNW respectively intersecting into a gently dipping \( \sigma_2 \), the intermediate principal compressive stress whose orientation lies parallel to the axis of the orogen.

Sinusoidal \( F_3 \) folds are recumbent with subhorizontal axial planes or very open reclined folds, with hinges plunging gently to NNE or SSW, down the dip of their axial surfaces.

Fig. 2.8 shows the equal area schmidt projection for some \( F_3 \) conjugate kink bands measured in the area. \( \sigma_3 \) is steep or subvertical and both \( \sigma_1 \) and \( \sigma_2 \) are horizontal. The conjugate folds have a low order symmetry but symmetry of high order orthorhombic was seen at the western part of the Nandana marble band in Barr-Beawar road cutting, not far from Jhala ki Chauki.
\( \sigma_3 = \bullet \quad \sigma_2 = \circ \quad \sigma_1 = \square \)

Mean symmetry of \( F_3 \) kink bands is nearly orthorhombic

FIG 2.8
2.6 *F*<sub>4</sub> *Folds*

The last of the fold forming phases, here designated *F*<sub>4</sub>, are by far very predominant and are accommodation structures formed by constraint on the propagation of an orogen parallel to its trend. Because subvertical schistosity predominates in the region, *F*<sub>4</sub> structures are generally developed as conjugate kink bands (Fig. 2.10B) and less commonly as single kink bands or as structures intermediate between sinusoidal folds and conjugate kink bands (Fig. 2.9A). While the *F*<sub>1</sub> related cleavage *S*<sub>1</sub> is the most pervasive fabric which forms the regional schistosity, the *F*<sub>2</sub> related fabric *S*<sub>2</sub> is only dominantly pervasive and only in the form of discrete planes (Fig. 5.6(i)A). It is also seen to pass into a fanning fracture cleavage in case of some of the *F*<sub>2</sub> folds in relatively more competent rocks. *F*<sub>3</sub> folds hardly even produce a pervasive fabric and *F*<sub>4</sub> folds again do not give rise to any pervasive fabric. In other words, the deformation intensity has been gradually decreasing from *F*<sub>1</sub> to *F*<sub>4</sub>. So is the case with metamorphic gradients, the peak of the metamorphism was achieved towards the end of *F*<sub>1</sub> folding. The garnet growth is not seen entirely after *F*<sub>2</sub> folding and the late non-stress thermal peak has had regressive effects on the pre-existing garnets, such as chloritization of garnet, staurolite broken up into islands etc., also polygonization of *S*<sub>1</sub> fabric at some places.
Fig. 2.10 - A - $F_1$ fold traced by a layer in pegmatite and overlying quartzite. The hinge dips steeply away from the observer. The fabric $S_1$ is axial planar to these folds. About $\frac{1}{2}$ km south of Giri village.

Fig. 2.10 - B - $F_4$ conjugate kink bands developed on $S_1$ fabric. The obtuse angle between two conjugate axial planes faces the direction of maximum shortening in rocks. Note that the presence of boudins renders low anisotropy to the rock, hinders interlayer slip and perfect conjugate kink-bands are therefore not developed. Near Biranthia - north of temple.
Fig. 2.9 - A - Schistosity $S_1$ folded by $F_4$ folds in felsic volcanics about 4 kms SE of Barr. Note that the folds are intermediate between conjugate kink-bands and sinusoidal buckles owing to relatively lower anisotropy (which may be due to mylonitic foliation with porphyroclasts of felspar).

Fig. 2.9 - B - Very gentle $F$ sinusoidal folds seen on a plane at acute angle of 5$^\circ$ to $S_1$ foliation. The downdip stretching lineation reverses its direction of pitch as a result of $F_3$ folding. North of dam at Giri.
The kink planes developed during $F_4$ folding are generally steep or subvertical and have a directional stability in ENE direction, the complementary set trending in azimuth $N310^\circ$ on the average. $\sigma_3$ therefore bisects the obtuse angle between the conjugate kink-bands and $\sigma_2$ is close to vertical. The symmetry at most of the places is close to monoclinic but becomes lower at some places where fabric has changed orientation due to the effect of $F_2$ folding. Normal kink bands are found (Cosgrove 1976) together with extensional crenulations (Platt and Vissers 1980) in such places where $S_1$ has apparently changed the attitude due to $F_2$ folding effect. Fig. 2.11 shows the attitude of the principal compressive stress axes $\sigma_3$, $\sigma_2$ and $\sigma_1$ for some of the conjugate kink bands of $F_4$ generation fold event in the area.

There has been considerable difference in opinion as to whether $F_3$ structures predate $F_4$ or were developed at the end of the orogenic events. Probably the best way is to find out the areas of superposition of $F_4$ on $F_3$ folds. In the Kharwa-Liri-Shamgarh area, Vaghmarey (1989) has shown that $F_3$ sinusoidal folds have at places a steeper inclination than the average and he has interpreted this as the effect of $F_4$ folding. In fact, in a single outcrop, he observed $F_3$ and $F_4$ both developed in the felspathic schist east of Shamgarh Anticline. He found that where
F4 CONJUGATE KINK-BANDS - ORIENTATIONS OF $\sigma_3, \sigma_2$ AND $\sigma_1$ PRINCIPAL COMPRESSIVE STRESSES.
NOTE THAT SYMMETRY VARIES FROM ORTHORHOMBIC TO MONOCLINIC.

FIG 2.11
F₃ folds are developed, F₄ folds do not generally tend to develop in highly anisotropic material and F₃ and F₄ are indeed mutually exclusive. At other places he found the steeply dipping F₄ kink plane cross-cutting a gently dipping F₃ kink plane. In general, it may be concluded that F₃ folds are earlier and F₄ most certainly post date F₃. Slight dislocation of F₃ related kink planes along the F₄ related kink planes (in case of "brittle" kinking) as in the case of the felspathic quartz schist at the eastern margin of the Delhi-basin in Shamgarh area (Vaghmarey 1989), clearly suggests that F₄ folds most certainly postdate F₃.

2.7 Fold Interference Patterns

Successive sets of folds of different generations produce interference patterns as those described by Ramsay (1962, 1967, Ramsay and Huber 1987).

The type zero pattern (Ramsay and Huber 1987) may be said to be related exclusively to the single episode of F₁ deformation due to inhomogenous flattening. Domical shapes may be produced but these are not related to the interference between two sets of folds of different generations, but to a single episode of inhomogenous flattening due to heterogeneous simple shear, varying in different parts of the fold, giving rise to structures that may look like periclines, but are not by definition periclines.
The overprinting of \( F_2 \) on \( F_1 \) folds is purely coaxial at some places and therefore the interference between the two is of type 3 pattern giving rise to hook shaped patterns (Ramsay 1962, 1967). However, where \( F_2 \) folds are upright, their superposition on \( F_1 \) folds produces type 2 pattern (Ramsay 1962, 1967, Ramsay and Huber 1987). The former pattern gives rise to the Z on Z type minor refolded folds in the Barr horizon proper, particularly near the village Giri where \( F_2 \) folds are developed in abundance.

The interference between sinusoidal \( F_3 \) and sinusoidal \( F_4 \) structures produces dome and basin or type 1 pattern of interference (Ramsay 1962, 1967), but the domes and basins are developed on subvertical schistosity surfaces, since the flow direction of both the sets lies perpendicular to the fabric planes. In other words, the schistosity is shortened in one episode vertically, giving subhorizontal "corrugations" and then subhorizontally, thus refolding these corrugations. \( F_3 \) and \( F_4 \) sets are at high angle to each other. The domical and doubly plunging sinusoidal folds are generally aligned in \( F_4 \) axial direction owing to the greater intensity of deformation during the generation of \( F_4 \) structures.

The superposition of \( F_3 \) folds on \( F_1 \) folds produces mushroom shaped (type 2 of Ramsay 1962, 1967) pattern of interference, \( F_3 \) folds folding the hinges as well as axial
planes of $F_1$ folds, however, gently. Because of the mild intensity of $F_3$ folds, the umbrellas of the mushrooms are rather widely extended. This pattern also results by superposition of $F_3$ on $F_2$ folds (where $F_1$ and $F_2$ are coaxial) and this pattern can only be seen on subvertical ESE trending vertical tensile fractures which produce large gaps between the seemingly continuous ridge. Because $F_3$ folds are rather domainal and because of their paucity of development, especially as sinusoidal buckles, this pattern, though theoretically possible, is rarely seen in the field. In fact it can be better seen in subvertical sections slightly oblique to tensile ESE trending deep fractures, but such sections are rarely encountered in the field.

2.8 Inheritance of Original Ductile Shears Into Late Stage Faults

A unique phenomenon associated with $F_4$ folds, that is seen in the region, is the original kink planes turning into planes of shear with reversal of displacement sense so that the acute angle between them faces the direction of maximum shortening in rocks. This feature suggests that towards the end of the orogenic movements, the rocks pass into more brittle state and original weak zones such as the $F_4$ associated kink planes turn into shear fractures with noticeable displacement along them. Probably, this feature further substantiates that the $F_4$ accommodation
Fig. 2.13 - A - Dislocation of a thick pegmatite vein dextrally in the road - cutting near Barr, on way to Beawar. This suggests development of foliation parallel shear at some stage during deformation process.

Fig. 2.13 - B - A series of curviplanar sinistral faults affecting chert layers of the Barotiya sequence. The faults are intimately related to overall ductile sinistral shearing during F₂ episode or towards late phases of F₂ episode of deformation. Note the drag along the longest of these faults. A complementary dextral fault (also curviplanar) dislocates the principal member (near the fountainpen).
Fig. 2.12 - A - A series of dextral antithetic faults affecting the Nandana marble that displace a quartz vein progressively to the right. Note that the fault plane traces appear curvilinear on horizontal surface because of change in the mechanical properties of the rock, from the place where quartz vein exists and away from it. The overall trace of a given fault has therefore a sigmoidal geometry suggesting a weaker section of the rock near the place where quartz vein is intruded. South of Jhala Ki Chauki.

Fig. 2.12 - B - An original sinistral ductile shear zone of very small width culminating into a sinistral fault at the end of deformation but still inheriting the attitude of the initial ductile shear. A complementary ductile dextral shear exists below the lens cap at a very acute angle to the fabric $S_1$. Locality - River bed near Biranthia.
structures were the last to develop in the region and therefore postdate $F_3$ folding, a point that has raised a controversy that remains to arrive at a consensus. Fig. 2.12B is example of such a sinistral fault.

2.9 Structural Analysis

Since the thrust of the present work is on the determination of finite strain in the Barr "conglomeratic" zone, the structural analysis, by making conventional equal area schmidt plots by dividing the area into various domains in which the folding could be considered for practical purposes to be statistically cylindrical, was not attempted. Besides the Barotiyana sequence seems to have a singularly uniform structural style and this precludes demonstration of spatial relationship of minor structures by making equal area plots. But the data collected was nevertheless plotted by considering only three domains, the western domain, the central domain and the eastern domain, which predominantly consists of Sendra granitic complex and repetition of part of the Barotiyana sequence east of the Nandana fault. However, the boundaries between these domains are not given in structural map, they could be taken as arbitrary since controlled by zigzag lines.

2.9.1 Western Domain

This includes the Barr conglomeratic horizon and the surrounding garnetiferous pelitic schists. Fig. 2.14A shows
the poles to boudinaged veins, which were once continuous. The offset boudin centres were joined in horizontal planes and pitch of boudins in subvertical ESE sections was noted. This facilitated the exact attitude of a boudinaged vein or bedding, So, to be known. The pole to the best fit girdle to the poles defines $\beta F_1$ of the western region of the area and in particular the Barr horizon. $\beta F_1$ plunge in $122^\circ$ at $83^\circ$. plunges of stretching lineations (plus Symbols) are also plotted in this figure which cluster to an amazing high degree around $\beta F_1$. Thus, stretching lineations are parallel to $F_1$ fold hinges.

Fig. 2.14B shows the minor axes of $F_1$ folds. They show some diversity due to inhomogenous flattening and therefore the folds of $F_1$ generation in pegmatite veins were also considered. The subhorizontal $L_1'$ lineations are also shown which are developed in the direction of amplification of $F_1$ folds. The $L_1$ and $L_1'$ lineations therefore maintain a perfect orthogonality. Where $L_1'$ departs from horizontality, the $L_1$ stretching lineation departs from its down dip orientation. This is again suggestive of these orthogonal lineations to be developed during a single episode of deformation, though with slight time lag.

Fig. 2.14C shows the poles to $S_1$ in the Western domain. Three girdles can be drawn, out of which one is perhaps the most prominent and its pole defines $\beta F_2$ or $\beta F_1$. Measurement
of plunge of hinges of F₂ fold near Geti, cluster around ΒF₂. Another girdle can be drawn that defines ΒF₄ due to both sinusoidal F₄ folds and conjugate F₄ kink bands. Some of the poles to schistosity fall closer to the central region of the diagram. This suggests gentle attitude of schistosity where F₃ structures are developed. This pole to the possible, rather ill defined third girdle defines ΒF₃. A comparison between this point and σ₂ positions in Fig. 2.11 confirms that this pole must define ΒF₃ and σ₂ is gently plunging or subhorizontal and possesses trend parallel to the orogen.

Fig. 2.14D shows the axes of F₄ kinks plotted on the schmidt net. It will be noticed by comparison that the kink axes fall into two groups and the bisector between these two groups of kink axes more or less defines the ΒF₄ in figure.

2.9.2 Central Domain

An examination of the structural map shows that the geometry of major F₁ folds and congruous S and Z F₁ folds is not very different from that in the western domain. F₂ folds on mappable scale are more abundant however in the amphibolites and calc gneisses between Birnanthia and Barr and to the east of Barr. Again the major mappable F₁ fold east of Jhala Ki Chauki, showing limb and axial plane
dislocation, is an $F_1$ fold of steeply reclined type with $F_1$ hinge and related lineations pitching down the plane of schistosity.

Some of the mappable $F_4$ folds exist to the ENE of Barr, and $F_2$ folds in this part of the area have their hinges plunging to the SSW at gentle angles between $25^\circ$ and $40^\circ$. Sendra granitic bodies are sympathetically emplaced along the regional schistosity. Probably Sendra granite was emplaced late kinematically with reference to $F_1$. The isotopic chronologic date based on Rb/Sr ratio for this granite obtained by Choudhry et al. (1984) is 800 Ma; thus suggesting its late kinematic emplacement with respect to the Delhi orogenic cycle.

Fig. 2.15A shows the poles to bedding, principally in Nandana marble and chert bands in this domain. Two girdles can be drawn, one defining $\beta F_1$ pole and the other defining $\beta F_1'$ or $\beta F_2$ fold. The respective lineations are close to these points.

Fig. 2.15B shows the poles to $S_1$ fabric planes in the area. They define three girdles, on $\beta F_1$ due to the parallelism between $S_0$ and $S_1$ plunging to the ESE steeply, $\beta F_2$ plunging south at $80^\circ$, thus slightly departing from the orientation in the western domain. The third girdle defines $\beta F_1'$. The disparity between $F_1$ and $F_1'$ has been explained
322 Poles to So F₂ axes
0.31-1.55-4.65 % per 1 % area

453 Poles to S₁
0.22-1.103-2.2-3.311 % per 1 % area

258 Poles to S₁
0.387-1.938-4.651 % per 1 % area

FIG 2-15
in section 2.4 in terms of the progressive deformation and finite strain. The 4th girdle defines $\beta F_4$; the fifth girdle defines $\beta F_3$; the last two being related to sinusoidal $F_4$ and $F_3$ folds respectively.

2.9.3 Eastern Domain

A large part of the eastern domain is occupied by Sendra granitic complex. Fig. 2.15C shows poles to $S_0$ in cherts, fabric $S_1$ in country rocks and granite. Two girdles are prominent, the most prominent one defines $\beta F_4$ plunging to the SE steeply and the less prominent yields a pole $\beta F_2$ plunging to the south, steeply to moderately. Part of the fabric variation that defines $\beta F_4$ may not be related to $F_4$ folding at all but to the oval granitic bosses whose boundaries tend to swerve the schistosity to assume a different trend which fortuitously coincides with $\beta F_4$.

2.10 Granite Emplacement

The geological and the structural map (Figs. 2.16 and 2.17 in pouch) and field studies reveal that granite emplacement has occurred by stoping and wedging and not by diapirism, although, the oval outcrops suggests granitic masses to have risen by their own buoyancy in the meshcrystal phase. Further, the xenoliths of country rocks within granites, maintain a structural concordance with the overall set up in the host rocks. It therefore is plausible to
believe that granite emplacement took place by magmatic wedging and stoping, rather than by diapirism. Further, there is no zonation within the granites and the granite bosses are uniformly of the same composition. A perfect isochron is obtained by Choudhry et al. (1984) which is generally uncommon for diapiric granites. The only exception to this appears to be the schistosity and chert bands, amphibolite bands swerving and the oval granitic body to the east, which is typical of granite diapiric bodies (Stephansson and Johnson 1976). It is possible that part of the granite may have risen as a crystal mesh melt phase, typical of diapirism.

2.11 Minor Faults

Minor faults abound in the area are systematically related to the Barr boudinaged zone and the entire ductile shear zone between the Barr horizon and the Nandana marble. No outcrop of Sendra granite is found to the west of Nandana fault. The ductile shear zone can more properly be called ductile deformation zone after Mitra (1978). The ductile deformation zone contains structures that suggest a complex deformation history with changing principal stresses and varying displacement vectors. The Nandana fault was originally strike slip dextral (Fig. 2.12A) as suggested by observations on outcrop scale but it was later turned into a high angle reverse fault, during the emplacement of Sendra granites.
Minor faults within the Barr zone proper are related intimately to the ductile shears and show variations of thermal regime, spatially during the progress of deformation. Since these faults are directly related to the discussions on strain aspects of the zone, they will be described in the chapter on strain analysis.

2.12 Principal Conclusions

This account sums up the structural chronology in relation to the progressive deformation. As mentioned, shown in details, the $F_1$ folds which are accompanied by the dominant $S_1$ fabric, are systematically related to the infinitesimal and finite strain. The strain has been consistently of the flattening type, perhaps passing from near plane strain to flattening type. That the folds $F_1$ were formed by flattening strain ($1 > k > 0$, Flinn 1962) alone and not constrictional, is substantiated by the following observations -

(i) The fold hinges are contained in the $XY$ plane (the fabric is assumed to have been parallel to $XY$ or $\lambda_1 \lambda_2$ plane at the close of deformation). In constrictional strain ($\alpha > k > 1$, Flinn 1962), fold axes are oblique to $XY$ or $\lambda_1 \lambda_2$ plane of the finite deformation ellipsoid.

(ii) Folds are generally cylindrical where unaffected by inhomogenous flattening. No periclinal $F_1$ folds are found.
(iii) The cleavage is axial planar to $F_1$ folds and nowhere are the transected folds (Barraidale 1978, Duncan 1985) encountered.

(iv) Cleavage bedding intersections and boudin lines are parallel to $F_1$ fold hinges. Even though the axial direction of $F_1$ folds varies depending upon whether they are closer to $\lambda_1$ or to $\lambda_2$, the cleavage bedding intersections do not lie athwart to fold hinges.

In the light of structural chronology in relation to fold forming events, it is difficult to agree with Sychanthawong et al. (1989) that the downdip stretching lineations are unrelated to any of the fold forming events. Indeed, the down dip stretching lineation which developed late during $F_1$ episode, does parallel the hinges of sub-vertical $F_1$ folds.

It may be stated at the end that the total shortening involved in the generation of $F_1$ structures was maximum of all fold forming events. This being of the order of 60% on the average. The total $(1 + e_3)$ values for $F_2$, $F_3$ and $F_4$ were respectively 0.55, 0.78 and 0.73. Thus, with the exception of $F_4$ folds, the shortening involved in the formation of the orogen has been steadily decreasing from $F_1$ to $F_4$ in the order of the values of $(\lambda_3)^{1/2}$ increasing 0.4 ($F_1$), 0.55 ($F_2$), 0.78 ($F_3$) and 0.73 ($F_4$).
Since $F_1$ and $F_2$ events occurred in quick succession, part of the shortening during $F_1$ of the order of 60% in ESE, WNW direction, may also include that produced during the generation of $F_2$ structures, $F_1$ and $F_2$ being coaxial, at the western margin but at variance in the central and eastern parts of the area investigated.