CHAPTER IX

SUMMARY AND SYNTHESIS
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9.1 Fold Structures

It has been shown that the variability of attitude of hinges and axial planes of $F_1$ folds, but particularly the former, observed in the area, is in part due to the effect of subsequent fold forming events and partly due to the inherent changes in the orientation of primary layers in sedimentary rocks, in different parts of the basin with respect to the first instantaneous strain ellipsoid principal axes. The regional schistosity which is axial planar to $F_1$ folds is formed late during deformation history but it does not transect the $F_1$ fold limbs. The orientation of hinges of $F_1$ folds is shown to be dependent upon the fact, whether initial layers were close to $\lambda_1$ or to $\lambda_2$ axes of the successive incremental deformation ellipsoids. The variability of attitude of hinges of $F_1$ folds is not attributed to the original formation of these as sheath folds under shear regime.

$F_2$ folds associated with discrete crênulation cleavage, fold the regional schistosity, axial planar to $F_1$ folds and are coaxial with $F_1$ folds as in the Barr to Giri area. It is also possible that these have been obliquely superimposed on $F_1$ folds producing oblique mushrooms, as in the central part of the Barotiya Sequence.
The $F_1$ minor folds in the area are of S type and suggest that the Barr horizon lies above the Barotiya Sequence. The present observation of the Barr horizon underlying the Barotiya zone is because of $F_2$ folding since $F_2$ folds have rotated the early structures, and the Barr horizon forms the inverted limb of the major $F_2$ fold in the sequence from Barr to Nandna.

Gravity induced $F_3$ folds are observed in the area, as also the accommodation structures, $F_4$. These involve far less shortening than the $F_1$ or $F_2$ folds which form the principal map pattern. They are developed as sinusoidal folds or conjugate kink-bands or intermediate structures depending upon the anisotropy of the multilayered complex. While $\sigma_3$ was vertically oriented during the formation of $F_3$ structures, it was subhorizontal during the formation of $F_4$ structures and acted in NNE-SSW direction. The degree of symmetry of conjugate kink-bands depends upon the angle between $\sigma_3$ and orientation of S-planes involved in previous fold forming events.

Cleavage-bedding intersections and boudin lines are parallel to $F_1$ fold hinges and steadily plunge steeply to ESE in the Barr zone; which was a zone of sandstones and shales of considerable initial thickness but now represent a much narrowed zone at the flank of the Delhi fold belt.
9.2 Strain Analysis - Boudinage Theory

The strain analysis assuming this to be a zone of double boudinage due to the swapping between \( \lambda_1 \) and \( \lambda_2 \) extensional strains, has been attempted. Thus it has been concluded that the Barr horizon represents a zone of double boudinage or chocolate tablet boudins with an early brittle to brittle-ductile phase (\( \lambda_1 \) and \( \lambda_3 \) horizontal, \( \lambda_2 \) vertical) of clockwise HSS, culminating into a more ductile one, when foliation developed, together with shearing parallel to foliation planes producing the asymmetrical pull-aparts, which help to deduce the sense of shear.

The presently observed fantastic shapes of boudins are a result of stretching down the plane of fabric by longitudinal strain, together with sinistral up-dip HSS, which occurred after the swapping between \( \lambda_1 \) and \( \lambda_2 \) (\( \lambda_1 \) vertical or nearly so, \( \lambda_2 \) and \( \lambda_3 \) in horizontal plane). Part of the shape variation may be related to the effect of superposed \( F_2 \) folds (which have sometimes been referred to in this text as \( F_1' \) folds).

The overall deformation computed from boudinage in two orthogonal sections or, on a single plane oblique to \( \lambda_1 \), \( \lambda_2 \) and \( \lambda_3 \) (i.e. oblique to the two orthogonal lineations and a pole to foliation plane) suggests that the overall deformation is close to plane strain at or near Barr with higher value of \( k \). But, the deformation gradually becomes
more and more oblate towards Giri, where the values of \( k \) are of much lower order. Similar feature is noticed towards south of Barr where the lowest values of \( k \) are observed near Megardha. The studies were not extended beyond Megardha.

A method devised allows the values of \((1 + e)\), to be computed from pinch and swell structures on the fabric planes and the other two planes normal to fabric and mutually perpendicular.

A mathematical method to attempt determination of the finite strains from the direction cosines of a normal to a plane oblique to \( \lambda_1, \lambda_2 \) and \( \lambda_3 \) is being developed and would be published after review by eminent scientist in the field.

Microstructural studies suggest that the so called pebbles or bouldins show layering of quartz rich layers and phyllosilicates in the thin section scale, with regular pinch and swell structures. The quartz grains and grain aggregates are deformed, elongated, show strain shadows and extremely well defined tensile cracks, subperpendicular to the long axes of quartz grains. The tear drop shapes are observed in the thin section as well, together with lozenzes, asymmetrical pressure shadows, C and S surfaces etc. The magnetite grains contain pressure shadows filled with quartz and dimensional orientation together with tear-drop shapes.
The folded pegmatite veins were restored to the original orientation by removal of finite strain at any given place, by a simple procedure. The shear strain effects were not removed. The study suggests that these are initially emplaced in the presently observed maximum shortening direction. This might cloud a little the conclusion that the overall deformation history is non-coaxial. But, since shear strain is not removed, the method is taken to be valid.

The boudinaged folded veins were also subjected to strain removal. It is found that they were emplaced close to the presently computed cone of lines of no finite longitudinal strain, but were emplaced in the contractional field, folded, passed on into extensional field and unfolded or ruptured. They were presumably emplaced along Luder bands, oblique to the tensile fractures. The exclusively boudinaged veins were intruded along the fabric planes at late stages during the history of deformation and are associated with ductile shears.

By removal of strain, it has been found that the Barr zone had an initial thickness (or width in horizontal plane) about 2 to 3 times greater, and the length of this zone was about a third or nearly 40% of the presently observed length. The original attitude of the zone was presumably close to NS.

The k values and the lengths of longest axes of boudins appear to be systematically related, and the relation-
ship between the two appears to be direct. As $k$ values increase, the length of longest axes of boudins also increase. However, the relationship between $\nu$ values and lengths of longest axes of boudins bear an inverse relationship. This is also true of the relationship between $\xi_S$ and lengths of longest axes of boudins, down the plane of schistosity.

The deformation path on the Flinn graph (1962) shows a prominent kink and a non-coaxial strain history, transgressing the curves of $V$ and $V^X$. The knick points in the deformation paths for each group of data suggest the deformation attained at the time of swapping between $\lambda_1$ and $\lambda_2$ extensional strains.

The orientations of the traces of cones of lines of no finite longitudinal strain and with $\lambda_1$ and $\lambda_2$ have been computed. It is found that the angle gradually decreases as the deformation becomes more and more oblate. The orientations of the planes of maximum shear strain have been computed and it has been found that foliation was not parallel to $\lambda_1 \lambda_2$ plane at any time during the history of deformation, as foliation parallel shear is observed at places. The orientations of the planes of maximum or minimum shear strain obviously do not coincide with the traces of the cones of lines of no finite longitudinal strain in any of the principal planes. The angle between
\( \lambda_1 \lambda_2 \) planes and those of maximum shear strain at the end of deformation process has been computed. The values are least where the deformation is highly oblate.

The progressive deformation consists of simultaneous pure and simple shear (similar to the one suggested by Ramberg 1975) before the swapping between principal extensions. Subsequent to this, the updip sinistral shearing occurred along the foliation planes and longitudinal strain occurred too.

It has been attempted to bring out the simple shear part of deformation using Burns and Spry (1969) diagram but, this is supported from the observations on minor structures in the field as well. The Barr perturbation zone has been shown to be one of \( P^--S^- \) type in the initial stage of deformation and \( P^-S^+ \) in the latter part (Cobbold 1977a, 1977b) by computation of the values of negative dilation using the method given by Schwerdtner (1982). The dilation \((-\Delta)\) is about 6% near Barr to the highest of 22% near Giri but, these values cannot be taken to be fool proof since wall rock strain was calculated by the method after Talbot (1970).

The offset ratio of boudins \( F/b \) gives values lower than one predicted for ideal simple plane shear (Ghosh and Ramberg 1976) due to the component of pure shear.

The study of asymmetrical pull-aparts and foliation fish (Hamner 1986) together with existence of C and S bands
(Berthe et al. 1979) suggests foliation parallel dextral shear to have operated. This is suggested from the other shear, criteria as well (Simpson and Schmid 1983, Capais et al. 1987). The pure shear component is suggested by the presence of conjugate ductile shears (Ramsay and Allison 1979) and extensional crenulations and internal boudinage (Platt and Vissers 1980).

Approximate orientational changes of principal strain axes from the beginning to the end of deformation have been shown schematically on the equal area projection, chiefly on the basis of computations of finite strain and naturally observed minor structures.

The examination of the fabric planes, of which a large number of photographs have been produced in this thesis, clearly suggests that the original boudins were further stretched under the influence of predominantly highly ductile deformation. These do not appear to be pebbles but boudins that were stretched after the swapping between $\lambda_1$ and $\lambda_2$ principal extensions.

9.3 Strain Analysis - Pebble Theory

Although the presence of this unit as a true sedimentary conglomerate has been questioned on the basis of many observations, the strain analysis was also attempted, treating the double boudins as pebbles. Since the $2\theta$ is low, the harmonic means (Lisle 1979) of pebble axial ratios were
obtained for the analysis in preference to the Rf/γ technique of Dunnet (1969). It was found that the values of H do not properly reflect the changes in finite strain from one locality to another in agreement with natural observations. The value of k obtained to be close to 0.5 with slight departures which is not correct since the deformation is more oblate. The mean RfH (Roday and Katpatal, in press) given by

$$\overline{RfH} = \frac{1}{2}(\overline{Rf} + H) - (H + \overline{Rf})^{-1}$$

was used to compute the finite strain and this gave results comparable to those obtained by the boudinage theory. The initial shapes of pebbles were computed from the harmonic means and the deformation paths for each group of lithologies were computed for each of the 79 localities. The analysis was also done by using Hossack (1968) diagram derived from Nadai (1963). The initial shapes in case of a third of the localities are prolate, suggesting the boudinage rather than the pebble theory. The orientation fluctuation parameters were evaluated in relation to shape ratios and equations were derived to obtain finite strain from the orientation fluctuation parameters alone. A triangular deformation plot is suggested based on the fluctuation of 2α, 2β and 2γ alone, which gives values comparable to that of the shape ratios.

The extreme shapes of boudins with long axes measuring 150 cms, intermediate axes about 25 cms and the shortest axes
only a couple of cm's suggests the rupture of original thin quartzose layers. The pinching of the horizon near kalakot as suggested by Heron (1953) is shown to be a lateral as well as vertical variation (across the stratigraphic column). Since, lithologic boundaries are shown to lie oblique to the boundaries of the Barr deformed zone, the shapes of the pebbles suggest rupture at many places rather than original pebbles being assumed fantastic shapes. The extremely small fluctuation of pebble axial orientations in case of this horizon does not permit the relationship between p, q and r with b, k and a to be perfectly studied. However, this attempt has been made.

As the schistosity developed very late during the history of deformation, it does not "wrap" around the boudins or pebbles, to the extent that would be expected if the schistosity began forming at the time, the rupture began. At many places, it is observed that the so-called pebbles can be seen to have belonged to a layer that is folded under brittle to brittle-ductile phase of deformation. The pebble concentration is very large, sometimes reaching 90%. To have such a large concentration together with such extreme shapes, one has to invoke the boudinage theory. The 20° is extremely small which also suggests double boudinage rather than the pebble deformation. The model given in this thesis through chapters II and IV and principal conclusions drawn appear to be more realistic.
9.4 **Shape Analysis**

The shape analysis of the three dimensional pebbles (?) or boulders has been attempted on the basis of their departures from the true ellipsoidal shapes in terms of the values of exponent n for each of the four quadrants in case of two dimensional shape analysis. Ten shapes based on the values of n for four quadrants have been categorised and the mechanism is suggested. For three dimensional deformation the $R_v$ has been computed. A procedure for construction of ideal shapes for a family of Super- or subellipses has been outlined, and some ideal shapes produced. But the ideal shapes would depart if the lengths of the three axes of pebbles vary. The $R_v$ for three dimensional ellipsoidal bodies have been computed using the concept of revolution after Spiegel (1968).

9.5 **Plate Tectonic Models**

A review from the existing literature and data at hand, a plate tectonic model for the area has been built. The model suggests strong support for the Island arc type evolution and is basically similar to the concept given by Sinha Roy (1988).

9.6 **Neotectonic Study**

Based on the remotely sensed data and field observations, the recent tectonic activity in the area has been
worked out. This activity is principally restricted to ENE trending lineaments with sinistral sense. The neotectonic activity can be tied up with the existing seismic data and the present plate tectonic set-up at the Iranian-Indian plate boundary.

The mineralization of scheelite and Wolframite has been studied in Calc Silicate bodies and skarns. Not much emphasis is however laid on this aspect.