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Structural studies in the Pre-Vindhyan rocks of Rajasthan: A summary of work of the last three decades

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Abstract. Multiple deformation in all the Precambrian metamorphic-migmatitic rocks has been reported from Rajasthan during the last three decades. But, whereas the Aravalli Group and the Banded Gneissic Complex show similarity in the style and sequence of structures in all their details, the rocks of the Delhi Group trace a partly independent trend. Isoclinal folds of the first generation (AF_1) in the rocks of the Aravalli Group had gentle westerly plunge prior to later deformations. These folds show reclined, inclined, and upright attitude as a result of coaxial upright folding (AF_{1a}). Superposition of upright folds (AF_2) of varying tightness, with axial plane striking N to NNE, has resulted in interference patterns of diverse types in the scale of maps, and deformation of earlier planar and linear structures in the scale of hand specimens. The structures of the third generation (AF_3) are either open recumbent folds or reclined conjugate folds with axial planes dipping gently towards NE or SW. Structures of the last phase are upright conjugate folds (AF_4) with axial planes striking NNE–SSW and E–W.

The Banded Gneissic Complex (BGC) underlies the Aravalli Group with a conglomerate horizon at the contact, especially in southern Rajasthan. But, for a major part of central and southern Rajasthan, migmatites representing BGC show a structural style and sequence identical with those in the Aravalli Group. Migmatization, broadly synkinematic with the AF_1 folding, suggests extensive remobilization of the basement. Very rare relict fabric athwart to and overprinted by structures of AF_1 generation provide tangible evidence for a basement.

Although the structures of later phases in the rocks of the Delhi Group (DF_3 and DF_4) match with the late-phase structures in the Aravalli Group (AF_3 and AF_4), there is a contrast in the structural history of the early stages in the rocks of the two groups. The folds of the first generation in the Delhi Group (DF_1) were recumbent to reclined with gentle plunge towards N to NNE or S to SSW. These were followed by coaxial upright folds of varying tightness (DF_2). Absence of westerly trending AF_1 folds in the Delhi Group, and extreme variation in plunge of the AF_2 folds in contrast with the fairly constant plunge of the DF_2 folds, provide evidence for an angular unconformity between the Aravalli and the Delhi Groups.

Depending on the importance of flattening attendant with and following buckling during AF_2 deformation, the lineations of AF_1 generation show different patterns. Where the AF_1 lineations are distributed in circular cones around AF_2 axes because of flexural-slip folding in layered rocks with high viscosity contrast, loci of early lineations indicate that the initial orientation of the AF_1 axes were subhorizontal, trending towards N280°.

The orientation of the axial planes of the earlier folds has controlled the development of the later folds. In sectors where the AF_1 axial planes had N–S strike and gentle dips, or E–W strike with gentle to steep dips, nearly E–W horizontal compression during AF_2 deformation resulted in well-developed AF_2 folds. By contrast, where the AF_1 axial planes were striking nearly N–S with steep dips, E–W horizontal compression resulted in tightening (flattening) of the already isoclinal AF_1 folds, and probably boudinage structures in some instances, without the development of any AF_2 folds. A similar situation obtains when DF_4 deformation is superposed on earlier structures. Where the dominant S-planes were subhorizontal, N–S compression during DF_4 deformation resulted in either chevron folds with E–W striking axial plane or conjugate folds with axial plane striking NE and NW. In zones with S-planes striking E–W and dipping steeply, the N–S compression resulted in flattening of the earlier folds without development of DF_4 folds.

Keywords. Multiple deformation; conjugate folds; deformed lineation; Banded Gneissic Complex; Aravalli Group; Delhi Group.

1. Introduction

The pioneering work of Heron (whose definitive interpretation of Rajasthan geology was published in 1953), Gupta (1934), and Gupta and Mukerjee (1938) forms the basic framework of the Precambrian stratigraphy of Rajasthan. These workers proposed a four-fold classification of the Pre-Vindhyan rocks of Rajasthan: (i) Delhi System, (ii) Raialo Series, (iii) Aravalli System and (iv) Banded Gneissic Complex.

The Banded Gneissic Complex (BGC) was considered to be the oldest group of rocks forming the basement for the successively younger metasedimentary rocks of the Aravalli-Raialo and Delhi Groups. The metasedimentary groups were supposed to be separated from each other by angular unconformities. The Berach Granite (Bundelkhand Gneiss of Gupta 1934; Gupta and Mukerjee 1938; Heron 1953) of the Chitorgarh area was thought to be the basement for the younger metasediments. The unconformities between the BGC and the Aravalli Group, and the Aravalli and the Delhi Groups, were considered to be of regional extent, whereas the unconformity between the Aravalli Group and Raialo Formation was taken to be of local nature. Except for the first one, no conclusive evidence was provided for unconformable relation. On the other hand, a number of workers (Crookshank 1948; Sharma 1953) contended that BGC represents the granitized portions of the Aravalli-Raialo rocks and is not stratigraphically older.

The regional structure of the Aravalli Mountain Chain was considered to be an N- to NNE-trending synclinorium (Heron 1953), with the core occupied by the rocks of the Delhi Group. Although Heron (1953) hinted at some complex structures in certain areas, no explicit statement regarding the details of structures in the different rock units is present. Some conglomerate-quartzite bands within the Aravalli Group were correlated with the Delhi Group and were interpreted as outliers within the rocks of the Aravalli Group (Gupta 1934; Heron 1953). In this paper an attempt has been made to synthesize the structural studies carried out by different workers in the Aravalli region during last three decades, in order to elucidate the basement-cover relations, the stratigraphic relations among the different metasedimentary groups, and the mechanisms of deformation.

2. Sequence of structures in the Banded Gneissic Complex and the Aravalli Group

The earliest attempt to decipher the structural history of the BGC was made by Ghosh and Naha (1962). Through detailed structural mapping of inclusions of resistant metasedimentary bands in a deformed and migmatized terrane around Nathdwara, they found the structures in the metasedimentary enclaves to be accordant with those in the gneissic host. They interpreted the large-scale structure of the BGC here to be stacked up reclined folds plunging SW, with the fold axes varying slightly because of progressive deformation. Subsequent work by Naha *et al* (1966) in the BGC, the Aravalli Group and the Raialo Formation, has shown that all these rock groups maintain an essential unity in a plan of superposed deformation. The earliest structures in these rocks are very tight to isoclinal reclined folds with W to WNW plunging axes. A set of open, upright folds with axial planes striking NNE is superposed on the early structures. The later folds show constant axial trend because of vertical axial planes, but the plunge shows extreme variation from horizontal at the limbs of the early reclined folds to vertical at the hinges. Because of fold interference, hook-shaped folds, eyed folds and irregular dome-and-basins are very common in the scales of hand specimen, outcrop and map throughout the area. Naha *et al* (1967) have shown that the migmatization connected with the formation of the BGC of the Nathdwara-Amet area is synkinematic with the first folding, and the migmatite front transgresses the stratigraphic boundaries in all scales. Both the Aravalli and the Raialo rocks have been migmatized. The conglomerate at Morchana and Mandwara near Rajnagar, considered to provide evidence for an erosional unconformity between the BGC and the Aravalli metasediments, has been found to be a 'tectonic melange' (Naha and Majumdar 1971a). The supposed pebbles represent tectonic inclusions of various shapes, formed by isoclinal folding, stretching and disruption of concordant, pre- to early-kinematic vein quartz and rare pegmatite sheets in the Aravalli mica schist during the first folding (Naha and Majumdar 1971a, b). Therefore, the BGC does not have any separate stratigraphic entity and cannot represent the basement in that area.

Chaudhuri and Mukherjee (1978) have shown that the sequence of structures in the pre-Delhi rocks of the Kishangarh area (considered to be BGC by Heron 1953, and Aravalli Group by Niyogi 1960) is identical with those in the Aravalli-Raialo rocks of the central Rajasthan as reported by Naha *et al* (1966).

Structural studies by different workers have established a history of polyphase deformation in the rocks of the Aravalli Group in the type area around Udaipur and in adjacent areas (Roy *et al* 1971, 1980, 1988; Roy 1972, 1973, 1985, 1988; Roy and Jain 1974; Roy and Paliwal 1981; Sengupta 1976, 1983; Mukhopadhyay and Sengupta 1979; Mukhopadhyay and Ghosh 1980; Mohanty 1982; Mohanty and Naha 1986; Naha and Mohanty 1988). The earliest folds (AF_1) are isoclinal with well-developed axial planar cleavage (S_1). The axial planes of the AF_1 folds have been involved in coaxial upright folding (AF_{1a}) at some places. The second folds (AF_2) which are upright in nature with NNE–SSW to N–S striking axial planes, vary in tightness from open to isoclinal style. The structures of the third and fourth generations are represented by small-scale conjugate folds and kink-bands. The AF_3 folds show subhorizontal axial planes dipping NE–SW, whereas the AF_4 folds have vertical axial planes striking NNE–SSW and E–W. All the three types of interference patterns of Ramsay (1967), due to overprinting of later folds on the earlier ones, abound in small to intermediate scales, and have controlled the map pattern of the Aravalli rocks in many instances.

(a) Superposition of AF_{1a} folds on AF_1 has resulted in "hook-shaped" pattern (type-3 of Ramsay). (b) Crescent-shaped, mushroom-shaped and omega-shaped patterns (type-2 of Ramsay) have formed because of AF_2 folding of reclined isoclinal AF_1 folds. The early hinges have "mirror-image" disposition about the later axial plane in these patterns. (c) The eyed folds and dome-and-basin structures are common in areas where the AF_2 folds are superimposed on the AF_{1a} folds. In rare instances, interferences of AF_3 and AF_4 folds and of AF_2 and AF_4 folds are seen in dome-and-basin patterns in small scale. Eyed folds on small and large scales, produced by strong flattening during AF_2 deformation of pre-existing (AF_1) axial culminations and depressions, have been observed in the Precambrian marbles of southeastern Rajasthan by Mukhopadhyay and Sengupta (1979).

A large-scale sheath fold involving metasedimentary rocks of doubtful affinity (Delhi/Raialo/Bhilwara) within BGC was reported by Ray (1974b, 1988) from the

Sawar area near Bhilwara. The northern hinge plunges at a moderate angle towards south, whereas the same hinge in the south plunges almost vertically. Ray interpreted this "inversion of fold hinge" as due to superposed deformation.

Detailed structural and stratigraphic work by Naha and Majumdar (1971a, b) and Naha and Halyburton (1977a) in the 'Hammerhead Syncline' and the 'Main Raialo Syncline' in the Kankroli-Rajnagar-Nathdwara sector, where best exposures of the Raialo Formation are present, has shown conformable relation between the Aravalli and the Raialo metasediments. Both the Aravalli and the Raialo rocks have been involved in large-scale folding of two generations: west-trending isoclinal reclined folds have been involved in upright folding on N- to NE-striking axial planes. Locally, small-scale conjugate folds and kink bands of two sets have developed in thinly laminated rocks in the last phases of deformation (Naha and Halyburton 1974a, b, 1977a, b). The first set of conjugate folds (AF_3) are found in zones where (a) the rocks are thinly layered/schistose, with subvertical S-surfaces, (b) the AF_2 folds are isoclinal, and (c) the rocks are mechanically anisotropic. The AF_3 folds have subhorizontal axial planes. The conjugate folds of the later set (AF_4) have vertical axial planes with NNW–SSE and E–W strikes. Determination of the orientation of the principal stress axes from the late phase conjugate folds indicates that the AF_3 folds were induced by a vertical maximum compression and the AF_3 resulted from an NE–SW horizontal maximum compression parallel to the schistosity of the rocks. Therefore, the Raialo rocks in this area do not have any structural or stratigraphic entity, but are considered to be a part of the Aravalli Group.

Heron's thesis about an unconformable relation between the Aravalli and the Raialo rocks of the "main Raialo Syncline" was based on two observations: (a) presence of a supposed gritty quartzite at the base of the Raialo rocks between Balicha and Khamnor; and (b) an overlap between a supposed Raialo marble and Aravalli limestone near Kerowli, southwest of Nathdwara. Naha and Halyburton (1974a) have shown that the gritty appearance of the quartzite band at Sembal is due to segregation of thin quartz veins which were subsequently torn asunder to form tectonic inclusions. Because of lithofacies variation this band grades along strike through calcarenite to marble. Therefore, it cannot be taken as the basal Raialo bed. The supposed angular unconformity/overlap near Kerowli, is in reality the hinge of a large AF_2 fold. The so-called Raialo marble and the Aravalli limestone are thus one and the same unit. Isolated "limestone lenticles" of Heron have been proved to be instructive examples of eyed folds resulting from fold interference. Some of the "lenticles" have also been continuously traced into the supposed main Raialo marble band. All these observations run counter to the angular unconformity/overlap suggested between the Aravalli and Raialo rocks of the "main Raialo syncline".

A conformable relation between the Aravalli Group and the Raialo Formation of the Pur-Banera area has also been demonstrated by Dasgupta (1982) and Naha (unpublished work, 1982).

3. Structural-stratigraphic relations between the Banded Gneissic Complex and the Aravalli Group

Although the relation between the BGC and the adjacent metasediments is debatable in the north and central Rajasthan, the presence of a first-order unconformity separating the BGC from the Aravalli metasediments and volcanics of southern Rajasthan, has been confirmed by several workers in the vicinity of Udaipur (Poddar 1965; Roy and Paliwal 1981; Roy *et al* 1988) and southeast of Udaipur (Roy *et al* 1980; Sengupta 1976; Mohanty and Naha 1986). The BGC-Aravalli boundary in southern Rajasthan is marked by lenticular polymictic conglomerates with boulders and pebbles of granite, quartzite, mica schist, vein-quartz and amphibolite, embedded in feldspathic schist or chlorite schist matrix. The Aravalli rocks which rest on the BGC show a low grade of metamorphism, and at places have retained the detrital character of their sedimentary parentage (Poddar 1965). The unconformity surface is also marked by the presence of high aluminous metasediments (Roy and Paliwal 1981). Preliminary Sm–Nd dating by Macdougall *et al* (1983) indicates that the tonalitic gneisses east of Udaipur may be as old as 3500 m.y. Angular relationship between the foliation in the BGC and stratification in the basal Aravalli rocks have been noted at places (Roy *et al* 1980).

The contact between the supposed basement and the Aravalli metasediments is a gently curved surface in southern Rajasthan as if it was unaffected by intricate fold patterns of the adjacent rocks. The problem becomes more acute when the gneissic foliation as well as the metasedimentary enclaves within the BGC show all the structural patterns traceable in the Aravalli rocks. Microstructural studies indicate that a majority of the quartz and feldspar grains in the BGC are syntectonic with the deformation that produced gneissosity in the rock; only a few grains are involved in deformation. In rare instances, an earlier planar fabric at high angles to the gneissosity and involved in isoclinal folding is found in the BGC (Naha and Mohanty 1988). All these apparently conflicting lines of evidence can be resolved if the BGC in its present state represents a largely remobilized basement.

Although the biotite gneisses and some of the granites intruding into the BGC are demonstrably older than the Aravalli Group, the correlation of the metasedimentary enclaves (marbles and quartzites) still remains a point of controversy. Heron (1953) considered these bands to be Aravalli-Raialo rocks preserved in synclinal cores. Recent workers (Raja Rao 1967; Raja Rao *et al* 1971; Gupta *et al* 1980; Sinha-Roy 1985) have shown that these bands are affected by migmatization at a number of places. Therefore, these metasedimentary rocks are considered by some of these workers to be the oldest rock group in Rajasthan—the Bhilwara Group. The structural features on all scales in these metasedimentary enclaves entirely match with those in the Aravalli metasediments at a number of places (e.g. at Darauli, Palana, and Khemli—Naha and Roy 1983; Bhindar-Chitorgarh-Bhilwara area—Roy *et al* 1981). Some of the amphibolite enclaves within BGC have their chemistry, mineralogy and texture similar to those of the basal Aravalli volcanics (Ahmad and Rajamani 1988). The relationship of these metasedimentary bands with the BGC can be best explained by remobilization of the gneisses (Naha and Roy 1983; Naha and Mohanty 1988).

4. Structural patterns in the Delhi Group

Detailed structural studies in the rocks of the Delhi Group have been carried out by a number of workers (Dasgupta 1964, 1968; Mitra 1970; Sen 1971; Gangopadhyay and Chatterjee 1971; Gangopadhyay 1972; Gangopadhyay and Das 1974; Ray 1974a, 1976; Gangopadhyay and Sen 1975; Roday 1977, 1979; Mukhopadhyay and

Dasgupta 1978; Gangopadhyay and Pyne 1980; Bholà and Varadarajan 1981; Bhola and Sabarwal 1982; Ray 1983; Gangopadhyay and Lahiri 1984; Naha *et al* 1984, 1987, 1988; Sengupta 1984; Das 1988). Structures of four generations (DF_1–DF_4) are decipherable in the Delhi rocks. Structures of the first two generations are ubiquitous in all scales, and the structures of last two phases have developed in some sectors. The DF_1 folds are very tight to isoclinal with a pervasive axial planar cleavage (S_1). These folds have affected the stratification planes only. The folds of the second generation (DF_2) have developed on stratification as well as S_1. These folds range from open to isoclinal style, with vertical axial planes striking NNE–SSW to NE–SW. A crenulation cleavage (S_2) has developed parallel to the axial planes of these folds. The DF_2 folds are strictly coaxial with the DF_1 folds. Both the DF_1 and DF_2 folds show all the characteristics of buckle folding. The upright DF_2 folds with NE–SW striking axial planes must have developed by a horizontal NW–SE compressive strain acting on subhorizontal layering. The folds of the third generation (DF_3) are kink folds with subhorizontal axial planes. These folds have affected axial surfaces of DF_1 and DF_2 folds and the S_1 and S_2 cleavages. At places the DF_3 folds have conjugate axial planes striking NE–SW and NW–SE. The DF_3 folds were formed by vertical compression. The folds of the last generation (DF_4) are upright chevron folds with NW–SE striking axial planes. Locally conjugate DF_4 folds with N–S and E–W striking axial planes have developed. The DF_4 structures have been caused by a horizontal compression in an NE–SW direction.

The Delhi rocks have been intruded by acidic igneous rocks of two phases. The earliest granites are found in the Alwar sub-basin and the Khetri area. These granites give an Rb–Sr age of 1600 Ma (Choudhary *et al* 1984). The younger granites are 850–750 Ma in age (Choudhary *et al* 1984) and more widespread along the Aravalli range and west of it. These granites are syn- to post-DF_2 in age (Gangopadhyay and Lahiri 1986).

Gangopadhyay and Mukhopadhyay (1987) have traced the effect of diapiric intrusion of younger granites on the structures of the Delhi rocks. According to them, the reorientation of the folds of the second generation from NNE or NE strike to N strike has resulted from rotation and distortion of the existing tectonic structures by two granitic plutons.

Along the eastern margin of the Delhi belt, the Delhi and the pre-Delhi rock groups show variable relationship at different places. According to Heron (1953), the contact is an angular unconformity modified by thrusting. Naha *et al* (1966) observed that the AF_1 folds of the pre-Delhi rocks are absent in the rocks of the Delhi Group, and that the AF_2 folds in the Aravalli rocks are more tight near the contact with the Delhi rocks. A structural discordance between the rocks of the Delhi and Aravalli Groups was, therefore, suggested by these workers. Subsequently Naha *et al* (1984) have shown that there is a remarkable identity in the later phases of the deformational history of the Delhi and the pre-Delhi groups (DF_3–DF_4 and AF_3–AF_4 respectively). The earlier stages of the structural history of the two groups are, however, significantly different. The EW-trending reclined AF_1 folds are absent in the Delhi rocks, and the NNE-trending folds of the second generation in the pre-Delhi groups are upright, whereas the corresponding structures in the Delhi rocks are of two phases—recumbent folds, followed by coaxial upright folds. It is also significant that the DF_1 and DF_2 linear structures show a constancy in trend and plunge (gently NE or SW) where they are not affected by subsequent deformation. But the NNE- to NE-trending

AF_2 linear structures show an extreme variation in plunge from horizontal to vertical, maintaining a constant trend, even where they are unaffected by later movement. This is because the subvertical axial planes of the NNE- to NE-trending AF_2 folds were superposed on the limbs and hinges of westerly-trending tight to isoclinal AF_1 folds resulting in extreme variation in plunge, whereas the NNE- to NE-trending upright DF_2 folds affected NNE-trending recumbent DF_1 folds, coaxially. These differences in the earlier phases of the structural evolution of the two groups therefore indicate that the DF_1 and DF_2 deformations of the Delhi rocks with NNE to NE trend were accommodated in the AF_2 structures of the pre-Delhi rocks; the AF_1 structures of the pre-Delhi rocks are absent in the rocks of the Delhi Group because of the presence of an angular unconformity between the Delhi and the pre-Delhi rocks.

A distinct structural and metamorphic break between the Delhi and the pre-Delhi Groups has also been reported from an area around Badnor by Mukhopadhyay and Dasgupta (1978). They have shown that the deposition of the rocks of the Delhi Group started after the folding of the first generation in the pre-Delhi rocks. The contact between the Delhi and the pre-Delhi rocks near Hira-ka-Baria, southeast of Beawar was studied by Chattopadhyay and Mukhopadhyay (1985). Both the rock groups show identical structural pattern. The schistosity within the rocks of the Delhi and pre-Delhi Groups is parallel near the contact, but it shows different orientations within the pre-Delhi rocks away from the contact. They interpreted that: (a) the crystallization of granites within pre-Delhi Group precedes the first deformation in the Delhi Group, and (b) the parallelism of planar fabrics in both the groups is a result of reorientation of pre-Delhi structures during the Delhi orogeny.

5. Patterns of deformed early lineations over later folds

The early (AF_1) lineations show diverse patterns over later (AF_2) folds (Naha *et al* 1966, 1969; Naha and Halyburton 1977b; Mukhopadhyay and Sengupta 1979; Mukhopadhyay and Ghosh 1980; Ghosh and Chatterjee 1985; Sharma *et al* 1988). The early lineations in competent units with little or no post-buckle flattening show a small-circle pattern of distribution in stereogram. A great-circle distribution pattern is found in folds which are 'similar' in form; and an irregular distribution of early lineations subtending variable angles with the AF_2 axes is observed in layers with a wide range of competence (Naha and Halyburton 1977b). By plotting the intersections of the loci of the AF_1 lineations showing small-circle pattern, Naha and Halyburton (1977b) obtained a maximum at 09°/N281°. This indicates that the AF_1 fold axes had a gentle westerly plunge prior to AF_2 folding.

Mukhopadhyay and Ghosh (1980) recognized three principal morphological types of deformed early lineation. Ghosh and Chatterjee (1985) elaborated this classification on the basis of the nature of variation of the angle between the early lineations and the later fold axis and identified six major types:

Type 1: $L_1 \wedge F_2$ is constant.

Type 2: $L_1 \wedge F_2$ is minimum at the hinge and increases away from it on both limbs. The sense of curvature of L_1 is opposite on the two limbs.

Type 3: $L_1 \wedge F_2$ increases from one line of inflection of the fold to the other and maintains the same sense of curvature every where.

Type 4: $L_1 \wedge F_2$ is 90° at the hinge only and shows a mirror symmetry about the hinge line on the unrolled form surface. The sense of curvature is the same every where.

Type 5: $L_1 \wedge F_2$ is a maximum at the hinge and decreases on either side. The sense of curvature is opposite on the two limbs.

Type 6: Complex patterns characterized by variable $L_1 \wedge F_2$ along the fold axis.

Mukhopadhyay and Ghosh (1980) and Ghosh and Chatterjee (1985) have shown that an association of different types of deformed lineation patterns occur in an area because of the flattening undergone by rocks of different competences and/or because of the non-synchronous development of small folds at different parts of a larger fold. From theoretical analysis of deformed lineation patterns, Ghosh and Chatterjee (1985) concluded that the X-axis of bulk strain during AF_2 deformation was either subhorizontal or gently plunging and with a N to NNE trend, and that the early (AF_1) lineations were initially very close to the subhorizontal Z-axis of bulk deformation trending W to WNW.

6. Control of the attitudes of early planar structures on the development and orientation of later folds

The axial planes of the early folds with related cleavage show wide variation in orientation because of later deformations. The variable orientation of the S-surfaces (S_1) in relation to the maximum compressive strain direction during later deformations lends an added significance to the localized nature of the later folds (cf. Naha *et al* 1984, 1987, 1988; Naha and Mohanty 1988). Experimental studies (Paterson and Weiss 1962, 1966; Weiss 1969; Anderson 1974; Gay and Weiss 1974) have shown that (i) when the initial angle (α) between the S-surface and the maximum compressive stress direction lies between 0° and 25°, conjugate folds develop due to compression; (ii) if α is more than 25° but less than 45°, one set of kinks develops; and (iii) α greater than 45° leads to the development of boudinage structures.

Naha and Mohanty (1988) have shown that the AF_2 folds are characteristically present in sectors where the S-surfaces have E–W strike with gentle to steep dips, and N–S strike with gentle dips. These folds are absent in sectors where the S-planes show N–S strike and steep dips. This localized nature of the AF_2 folds becomes meaningful when we remember that the E–W or ESE–WNW maximum compression direction during AF_2 acted on S-surfaces (S_1) with variable orientation because of AF_{1a} folding. Where AF_1 axial planes were striking EW or nearly N–S with gentle dips, the E–W compression resulted in the formation of the AF_2 buckle folds. On the other hand, where AF_1 axial planes were striking N–S with steep dips (caused by basement configuration and/or AF_{1a} folding), the AF_1 folds were further flattened and probably boudinaged without development of AF_2 folds (Type 0 of Ramsay and Huber 1987).

The AF_4 folds developed by a N–S horizontal compression acting on diversely oriented S-surfaces. Therefore, these folds also show localized development like AF_2 folds. In sectors with steep S-surfaces striking nearly E–W, the AF_4 folds are absent because conditions were unfavourable for their development (σ_1 was nearly normal to the S-surface). On the other hand, these folds show conjugate sets in sectors with S-surfaces striking nearly N–S, whereas one set of axial plane orientation dominates in sectors with NNW–SSE to NW–SE strikes.

The strike of the axial planes of DF_4 folds is also dependent on the orientation of the S-surfaces (Naha *et al* 1984, 1987, 1988). Naha *et al* (1984, 1988) have shown that in the Khetri area, conjugate DF_4 folds with axial planes striking NE and NW or chevron folds with axial planes striking E–W, have developed in sectors with dominant S-surfaces either subhorizontal or striking N–S with steep dips. Only one of the conjugate sets of DF_4 folds has developed in areas where S-surfaces are steep with strikes either NE–SW or NW–SE. In zones where the S-surfaces strike E–W with steep dips, the DF_4 folds are absent. In the Todgrah area, the DF_4 structures also show three sets of axial planes: N–S and E–W striking conjugate sets and the chevron folds with axial planes striking NW–SE (Naha *et al* 1984, 1987).

7. Conclusions

Structural studies carried out in the Precambrian metamorphic terranes of Rajasthan have thrown light on the following aspects: (a) regional structural patterns and deformational histories of the Banded Gneissic Complex, Aravalli (including Raialo) and Delhi Groups; (b) stratigraphic relations among the different rock groups as gleaned from the structural data; (c) the nature of the basement and its response during the deformational episodes in the cover rocks; (d) details of superposed deformation including the behaviour of early fold hinges and lineations during later folding, leading to an understanding of the mechanism of deformation; and (e) control of early planar structures in the development and orientation of later folds.

The Precambrian metamorphic-migmatitic rocks of Rajasthan have undergone four phases of deformation. An erosional unconformity between the BGC and the Aravalli rocks is present in southern Rajasthan. Identical structural patterns in the supposed basement and in the cover rocks indicate large-scale remobilization of the basement during the early phases of deformation of the cover sequence. The rocks of the Raialo Formation in central Rajasthan, showing a structural similarity with that of the Aravalli rocks, do not have separate stratigraphic entity in this area. The rocks of the Delhi and Aravalli Groups show considerable contrast in their structural history during early phases, but these have identical structures of later phases. This difference is considered to be the result of an angular unconformity between the two groups.

The orientation of the axial planes of the earlier folds in relation to the strain patterns during later deformations, has controlled the development of the later folds. Therefore, the localized development or the absence of later folds in some sectors should not be construed as a result of localized strain.

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