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ANALYSIS OF FOLDS FROM THE CGGC ROCKS IN SONBHADRA DISTRICT UTTAR PRADESH AND THEIR TECTONIC AND GEOMORPHIC IMPLICATIONS

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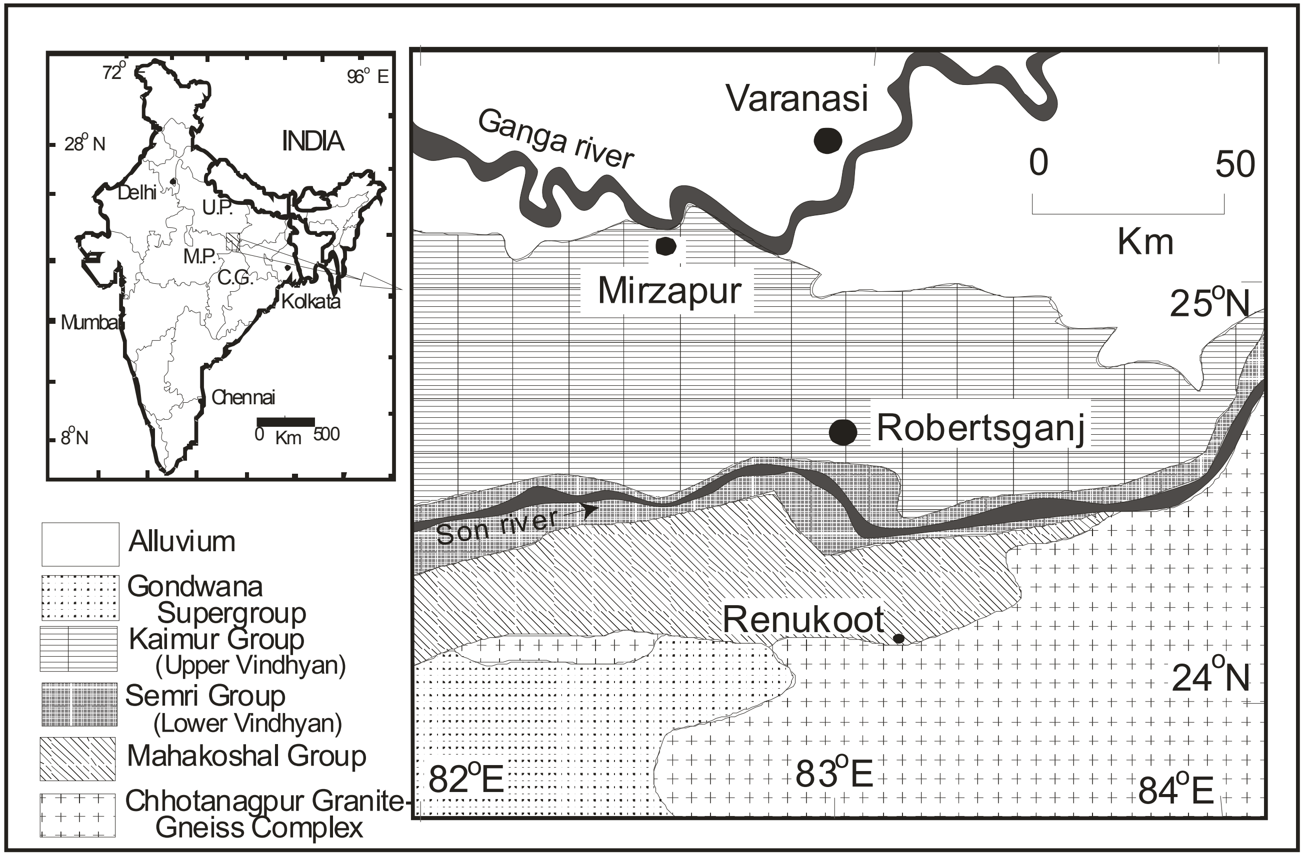
Abstract

The Precambrian rocks exposed in the southern part of Sonbhadra district of Uttar Pradesh rocks form a part of Chhotanagpur plateau of the central part of India. Geologically it belongs to the Chhotanagpur Granite Gneiss Complex (CGGC) which has witnessed multiple tectonic deformations. From the analysis of the folds of this region four deformation phases have been identified for the CGGC rocks. The characteristic fold interference of dome and basin type has rendered the present day topography of the Chhotanagpur plateau which is different from nearby plateaux on other Precambrian rocks in central India.

Introduction

The structural features are the manifestations of the deforming forces that have acted on the rock bodies since their formation. Each rock type possesses different mechanical and physical properties which vary with conditions under which it deforms. Therefore, diverse varieties of structures are displayed by the rocks which constitute the earth's crust. The systematic study of these structures i.e. the structural analysis reveals the deformational histories of the rock bodies in different parts of the crust. Folds are those structures which develop during the ductile deformation of the layered rocks in response to the tectonic forces. Therefore the systematic studies and analysis can reveals many aspects of the tectonic events that the rocks has undergone.

The Sonbhadra district of Uttar Pradesh is constituted of variety of rock formations including those belonging to the Chhotanagpur Granite Gneiss Complex (CGGC), Mahakoshal Group, Vindhyan Supergroup and Gondwana Supergroup (Fig.1) ranging in age from Archaean to Permian. Among these, the CGGC rocks are oldest and exhibit


72°
96° E
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INDIA
Delhi
U.P.
M.P.
C.G.
Kolkata
Mumbai
Chennai
8°N
0 Km 500
Ganga river
Varanasi
0 50 Km
Mirzapur
25°N
Robertsganj
Son river
Renukoot
24°N
82°E
83°E
84°E
Alluvium
Gondwana Supergroup
Kaimur Group (Upper Vindhyan)
Semri Group (Lower Vindhyan)
Mahakoshal Group
Chhotanagpur Granite-Gneiss Complex

evidences of multiple phases of tectonism which have resulted in a complex geology in the region. Studies on the different sectors of the Chhotanagpur Granite Gneiss Complex (Dunn and Dey,1942; Ghose, 1983, 1992; Mazumdar, 1988, Banerji, 1991; Bhattacharya *et al.,* 1992; Ramchandran and Sinha, 1992) (Jain *et al.* 1995; Srivastava, 1996; Srivastava and Gairola, 1997; 1999; Roy and Devrajan, 2000; Acharya and Roy, 2000; Roy *et al*. 2000; Roy and Hanuma Prasad, 2001, 2003; Acharyya 2001, Acharyya and Roy, 2003, Solanki *et al*, 2003; Srivastava and Gairola, 2004; Srivastava *et al*., 2005; Mohan et al 2007; Kumar and Ahmad, 2007; Ramakrishnan and Vaidyanadhan, 2008, Maji *et al*., 2008; Sharma, 2009; Singh and Srivastava, 2011) have reported superposed mesoscopic structures from different areas and revealed about the polyphased deformation with a complex tectonic history of the CGGC rocks.

The different tectonic impulses varying in magnitude and direction have left their imprints in the tectonites of the present area in the forms of the mesoscopic and macroscopic structures which are well documented and preserved as indicators of the tectonic history. Folds are one of those structures which can preserve the records of the stresses and their directions in the rocks in their geometry. In present work therefore the geometry of folds of the multiply deformed CGGC rocks have been studied in detail in order to unravel the intricacies brought about different tectonic episodes in the southern part of Sonbhadra district of Uttar Pradesh. A possible relation of the tectonic and geomorphologic characteristics of the Chhotanagpur plateau in Sonbhadra area has also been sought.

Geological setting

The Chhotanagpur Granite Gneiss Complex is represented by the Dudhi Group rocks in the present area (Mazumdar, 1988; Banerji, 1991). In the Sonbhadra district, the CGGC rocks are exposed in the south of the WNW-ESE striking Son-Narmada South Fault. The rocks of the CGGC are represented by the schist, gneiss, amphibolites with subordinate granite, migmatite and dolerites and marble at few places. These rocks have exhibited metamorphic grade ranging from the biotite zone of the Greenschist facies to the Sillimanite-orthoclase zone of the Upper amphibolite facies with evidences of partial melting (Srivastava, 1996). Complex mesoscopic and macroscopic folds have been observed in almost all foliated rocks of the study area. Therefore the data on folds have been collected from field and analysed in various ways in the present work.

Analysis of mesoscopic folds

The geometrical analysis is the structural geometry which forms the basis for the kinematic and dynamic analyses. Hence the geometrical analysis is the first and foremost task of the structural geologist. The geometrical analysis includes the study of structures, both in the field and the laboratory, which can be studied systematically by considering the scale of the structures and their homogeneity with respect to different domains. On the basis of scale, the structures are classified as microscopic, mesoscopic and macroscopic. In the present investigation the mesoscopic and the macroscopic fabric elements have provided sufficient material for the structural analysis. The structures developed during the initial phases of tectonism have been superimposed by those of the later phases. Sometimes, these superimposed structures have completely obliterated the earlier structures. In general, the tectonites of the present area represent the inherited, imposed and composite structures. Folds are perhaps the most common tectonic structures developed in the deformed rocks. Folds are three dimensional features, formed by a combination of planar and linear structures when a set of S-surfaces becomes curviplanar (Turner and Weiss, 1963).

Mesoscopic folds ranging from a few centimetres to a few metres in amplitude are well developed in almost all rock types in the area under investigation. The geometric elements like the axial plane and fold axis can be easily measured with sufficient accuracy where the folds are plane cylindrical. However when the folds exhibit complex geometry due to superposition, the measurement of data becomes difficult as the fold elements change their orientation from one spot to other. Therefore, validity of the data on this changing fold geometry is restricted to that particular spot on fold where data is measured.

The two-dimensional and three-dimensional study of the folds reveals that ideal plane cylindrical folds on even mesoscopic scale are rare. The planar looking axial planes in profile section become curviplanar when traced along fold hinge line in three dimensions. Thus, majority of folds in present area are non-plane non-cylindrical.

The style and geometry are important features for classifying the folds of different generations (Turner and Weiss, 1963; Ramsay, 1967; Hobbs *et al.,* 1976). In the present work an attempt has been made to study the folds on the basis of style, orientation of fold elements, geometry and shape of the folded layers/surfaces.

Fold Style

Different phases of deformations result into different fold styles, hence, the study of fold profiles and their mutual relationship are important in deciphering the tectonic history of an area. The mesoscopic folds observed in the area belong to isoclinal, tight, close, open, chevron and ptygmatic types. Quite sometimes, these folds are not in their ideal form and are affected by later deformational episodes. These folds, which are developed on some prominent S-surfaces (S_1, S_2, S_3 and S_4), have also shown superposition of one style over another. The study of superposition of folds, leads to conclude that in general, the isoclinal and tight isoclinal folds represent the first phase of folding (F_1), the tight and close folds represent second (F_2) and the open folds are of third generation (F_3). The sharp hinged chevron folds and kink bands are of fourth generation (F_4).

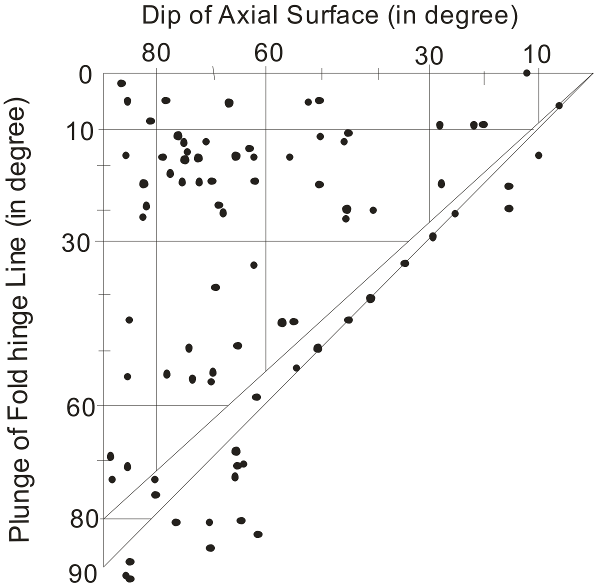
However, it should be kept in mind that all these folds (F_1, F_2, F_3 & F_4) are liable to change their shape and style as well in their multilayered structure due to successive tectonism of the later phases. The variation in the fold style may also be linked with the compositional difference of layers. For example, the thicker quartz layers in a F_2 fold may show an open fold style, while the thinly bedded schist shows the close style. The development of ptygmatic folds on isolated quartz layers is the result of high competence contrast between the layer and matrix, in embedding them.

Orientation of Fold Elements

The attitude of the axial planes and the fold hinge lines are the simplest and chief geometrical devices on the basis of which the orientation of a fold can be understood. In order to express the three dimensional orientation of these elements of folds of the investigated area, Fleuty's (1964) diagram has been used to classify the small plane cylindrical folds (Fig. 2). The plots reveal that there is a wide range of orientation of these elements of folds in the tectonites of the present area and in fact, the plots fall in almost all sectors of the Fleuty diagram. This large variation in the fold orientation may be attributed to the fact that the folds have been modified due to the later phases of deformation. These deformational phases have not only brought about a great diversity in the orientation of fold elements but also affected the cylindricity of the folds. As a result quite a large number of data (Fig. 2) show non cylindricity even in mesoscopic scale and fall outside the diagram. It is evident from Fig. 2 that the steeply inclined - gently plunging folds (17.68%) are the most dominant class in the CGGC rocks followed by reclined folds (14.63%). The non-cylindrical folds (folds outside the limits of Fleuty diagram) are also quite abundant in the area.

Fig. 2

Fleuty diagram showing orientation of fold elements of the study area.



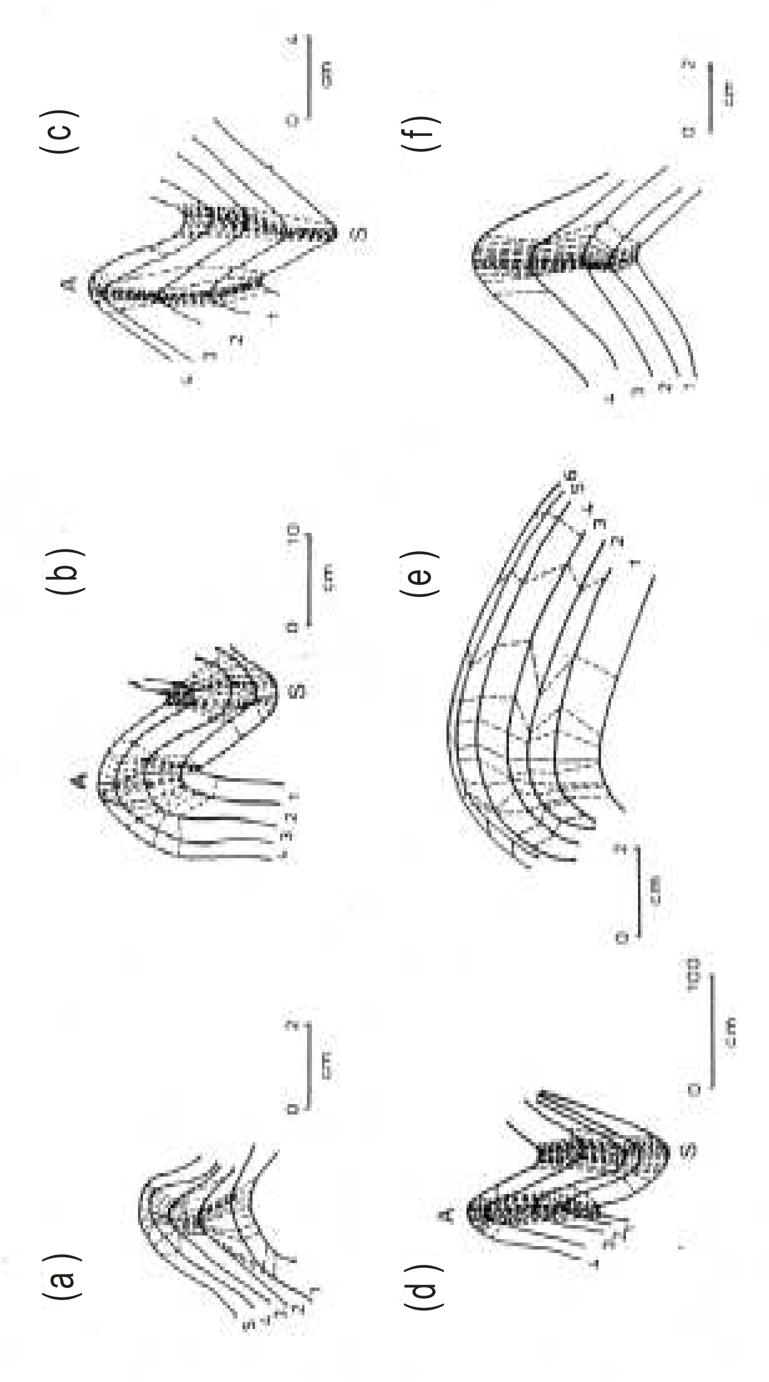
Fold Profile Geometry

The development of a geometrical classification of the folded layer is based on dip isogon pattern, variation of the relative orthogonal and axial surface-parallel thicknesses on the profile section (Ramsay, 1967; Hudelston, 1973; Ramsay and Huber, 1987). Such a classification plays an important role in the study of fold morphology and in elucidating the principal folding mechanism (Ramsay, 1967). It is also possible to study the changes in the shape of different folded layers on the fold profile. The shape of any one layer in the folded structure depends on the relationship of bounding surfaces of the layer and in particular, the relative rates of change of the inclination of these bounding surfaces. Therefore, study of several profile sections of the fold will not only give a better idea about fold morphology in three dimensions, but also help in understanding the possible mechanism involved in its evolution.

The geometrical classification of fold morphology is also significant in terms of strain (Hobbs, 1971). Elliott (1965) gave the concept of `dip isogon' as the curve joining points of equal dip (α) on adjacent folded surfaces on the fold profiles. The dip isogons form a series of continuous curved lines on the profile section and exhibit a pattern which may range from strongly convergent to strongly divergent from outer arc towards inner arc of the fold. Ramsay (1967) divided the folds into three fundamental classes on the basis of patterns of the isogons. However, he has also taken into account the thickness parameters (t'_α and T'_α) into this classification and divided the folds into 1A (strongly convergent dip isogons), 1B (parallel fold), 1C (weakly convergent isogons), Class 2 (parallel isogons) and class 3 (Divergent isogons). According to Ramsay (1967), the folds of class 1A and 3 indicate differential compression in their evolution while class 1B and 1C suggest a flexure-slip mechanism, and class 2 suggests a slip mechanism in the fold formation.

The thickness parameters, which involves measurement of data on the orthogonal distance (called as orthogonal thickness `t') and along the axial surface (`T') between the tangents drawn at equal dip angle (α) on the fold profile, were introduced by Ramsay (1967). He (1967) utilised the ratios t'_α ($= t_\alpha/t_o$) and T'_α ($=T_\alpha/T_o$) and the dip angle α for graphically classifying the folds (Ramsay 1967; Ramsay and Huber, 1987). Although the fold classes recognised by t'_α/α and T'_α/α plots are same as recognised by dip isogon patterns, but the importance of thickness based classification is more over the other, which is based merely on the visual interpretation. The thickness parameters are sensitive to even slight change in the fold geometry. Zagorčev (1993) modified the classification of Ramsay (1967) by a further subdivision of 1A into 1A1, 1A2 & 1A3 and class 3 into 3A, 3B & 3C subclasses.

For the geometrical classification of the folds of the area, tracings of the profiles are used, which have been taken either directly from the field, field photographs or hand specimen folds. Care was taken in each case so that the profile sections (Fig. 3) under analysis, as far as possible, were perpendicular to the fold hinge. Dip isogons drawn at 10^o interval on the profile sections of the folds of the study area have been given in Fig.3.


(a)
1
2
3
4
5
0
cm
2
(b)
A
S
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2
3
4
0
cm
10
(c)
A
S
1
2
3
4
0
cm
4
(d)
A
S
1
2
3
4
0
cm
100
(e)
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(f)
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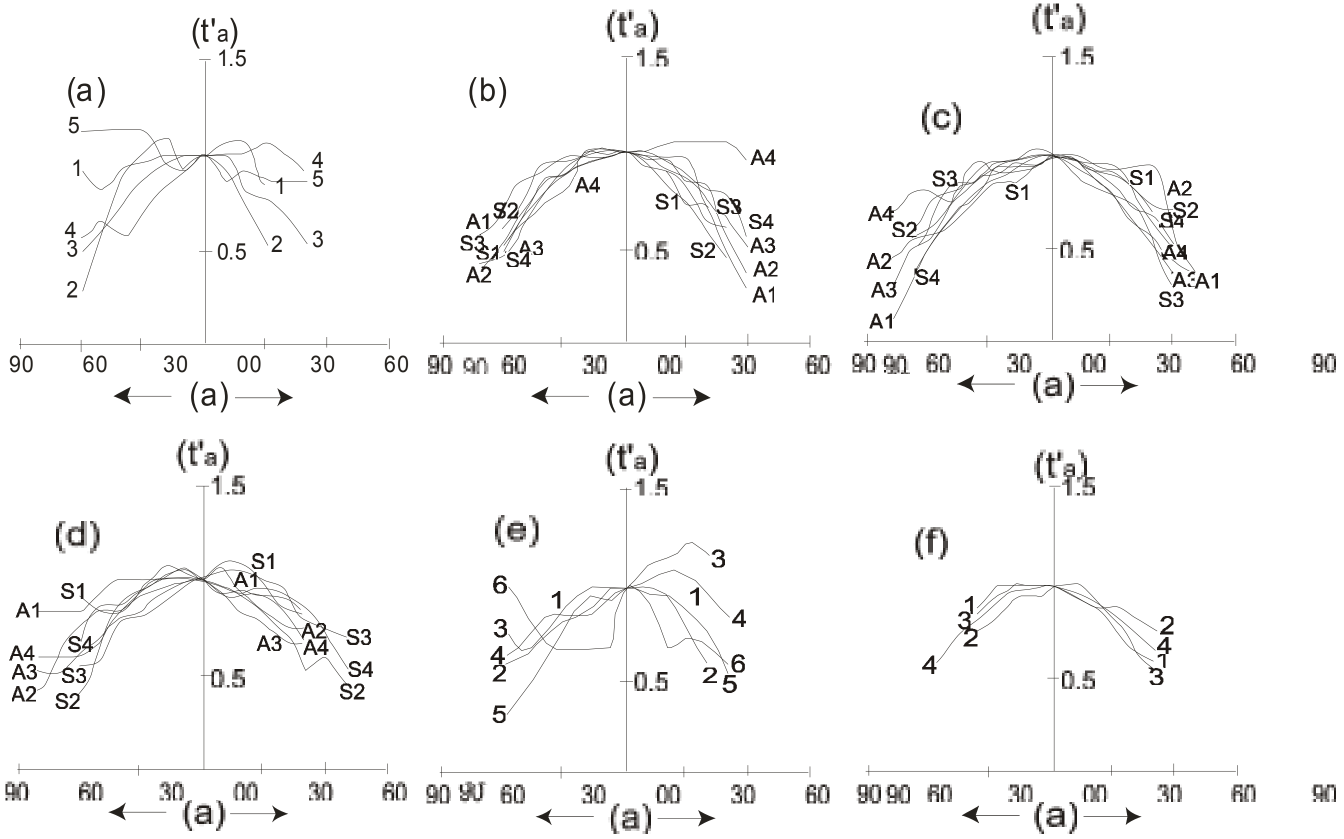
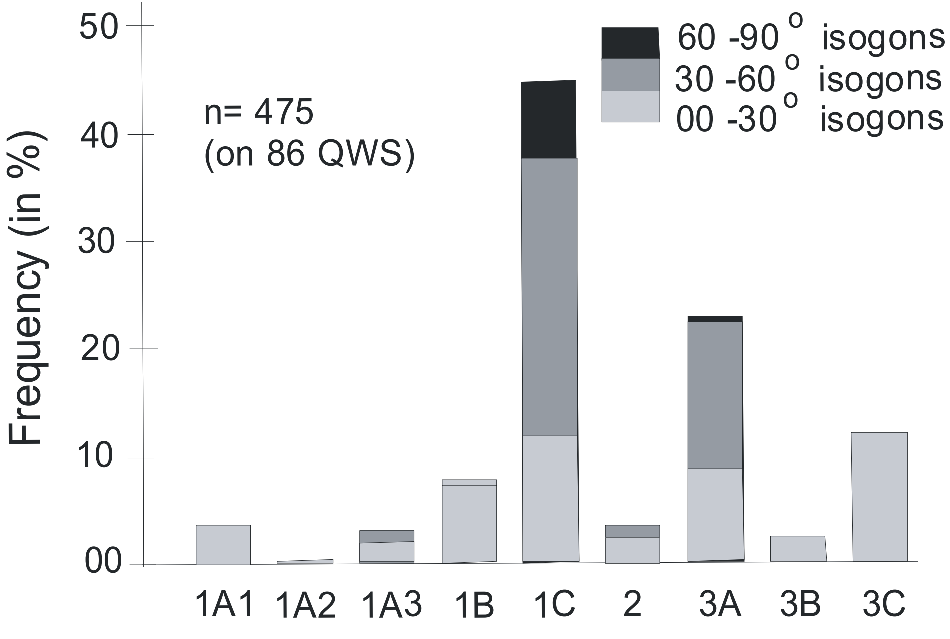

(a)
(b)
(c)
(d)
(e)
(f)
(t'a)
1.5
0.5
90
60
30
00
30
60
90
(a)
A1
A2
A3
A4
S1
S2
S3
S4
1
2
3
4
5
6

Although the patterns of the isogons from outer arc towards inner arc, even in a quarter wave sector of the fold (single or multilayered) is not definite, yet it can be noticed that most of the times, the isogons show a weakly convergent nature, and thus, such folds belong to 1C class of Ramsay (1967). However, strongly convergent, parallel and divergent patterns of isogons are also present and hence, the folds also belong to 1A, 1B, 2 and 3 types. The changing pattern of isogons in a multilayer sequence or even in single layer is possibly due to mechanical anisotropy and compositional difference of the layers.

The thickness parameters on the profile section of these folds have been measured along the dip isogons as described by Ramsay and Huber (1987). The orthogonal thickness ratios t'_α (= t_α/t_o) were calculated from those data. The t'_α value against change of angle (α) has been plotted for each fold to represent the variation in geometry of each layer of folds with change in α values. In these graphs (Fig. 4) the left limbs of the folds have been plotted on the left side of the graph and the right limbs on the right hand side. Thus, the t'_α vs α plots, which have been joined by a free hand curve, not only describe the change in geometry of the individual layer or layers but also give a good visual interpretation of the symmetry of these changes in the left and right limbs of the fold.

Fig. 5

Frequency of different fold types of the study area as per classification of Zagorčev (1993).



The t'_α vs α plots of folds of the study area (Fig.4) suggest that majority of the layers are not restricted to any particular class of Zagorčev (1993) and they show change in their geometry from one class to another. Therefore, in order to find the most abundant class of folds, the t'_α vs α curves have been statistically analysed. Such an analysis has been done on the basis of relative lengths of each of these curves falling in the zones of various fold classes of Zagorčev (1993). A total of 475 isogons data have been studied on 86 quarter wave sectors of the folds. The frequency in terms of percentage of the different classes of the folds is shown with the help of bar diagram in Fig.5. Each bar thus represented, is divided into 3 sectors (Fig. 5) each of which represent the relative abundance of that particular class of fold between 0-30°, 30-60° and 60-90° dip isogons.

Fig. 5 reveals that the folds of the area although belong to all the 9 classes i.e. 1A1, 1A2, 1A3, 1B, 1C, 2, 3A, 3B and 3C of Zagorčev (1993), yet the frequency of class 1C is the most dominant followed by 3A. Besides these, other noticeable classes are 1B and 3C. It is also to be noted that while the major parts of 1C and 3A classes of area comes from isogons beyond 30°, particularly from between 30-60°, many other fold classes like 1A1, 1A2, 1B, 3B and 3C more or less restrict themselves within 0-30° isogon lines. The isogons beyond 60°are present only in 1C and 3A classes. The greater abundance of 1C class of folds in the present area suggests that the folds have been subjected to flattening strain after their formation.

Analysis of macroscopic folds

The term macroscopic structure is applied to the structures of large dimensions which cannot be studied in a single outcrop. The geometry and orientation of such large scale structures can be established by the interpretations based on a detailed study of mesoscopic structures. The mesoscopic structures give clear indication that the present area has undergone repeated folding and faulting.

Analysis of macroscopic folding is usually focused upon the most prominent S-surface, generally some kind of lithologic layering in the tectonites. Where more than one S-surface has been folded macroscopically, each should be investigated (Turner and Weiss, 1963). The object of analysis is to determine the pattern of preferred orientation of the most prominent S-surface in each of several domains homogeneous with respect to that S-surface. In the study area, though there is a wide variety of rock types and some of which could provide macroscopic bands, yet a clear picture of the different folding pattern does not emerge from the geological map (Fig.1) or satellite imageries. Therefore, in order to obtain a clear picture of the macroscopic structures, it was essential to analyse the S-surfaces statistically, in different segments (called as subarea) of the area, which have been demarcated on the basis of homogeneity of the fold.

To analyse the data statistically, the poles to the S-surfaces were plotted on the lower hemisphere of the equal area net. The plots were contoured to obtain best fit girdle and consequently, the ß-axis. In the present area, like many other metamorphic terrains, the original bedding planes are more or less completely obliterated. Therefore, first generation of macroscopic folds can not be analysed directly. However the second generation folds which are developed in the area have been analysed with the help of S_2 surfaces, which includes the schistosity and gneissosity of the rocks of the area.

Second Generation Folds

To analyse macroscopic folds on S_1 and S_2, the area has been studied by dividing it into 20 subareas. In the present work, best possible efforts were made to identify the subareas which are statistically homogenous with respect to a particular prominent fold of that domain, but it was not possible everywhere to obtain subareas having a single girdle for poles to S_2. This is perhaps due to strong interference of folds of different generations. The inferred macroscopic fold axis of second generation ($ß_2$), thus obtained in different subarea are given in Table 1.

Table 1

Orientation of inferred macroscopic fold axes ($ß_2$) in different subareas of the study area.

Subarea No	Plunge of $ß_2$	Subarea No	Plunge of $ß_2$	Subarea	Plunge of $ß_2$
I	30/128,0/90-270	VIII	5/105	XV	60/290, 50/225
II	30/33	IX	65/342,60/165	XVI	20/210
III	78/346, 8/253	X	50/175,30/125	XVII	35/275
IV	8/60,70/295	XI	80/290, 18/93	XVIII	28/60
V	70/345,8/255	XII	50/205	XIX	14/238
VI	14/92,38/120	XIII	72/170	XX	70/270,5/57
VII	12/253,65/146	XIV	15/90,0/60-240		

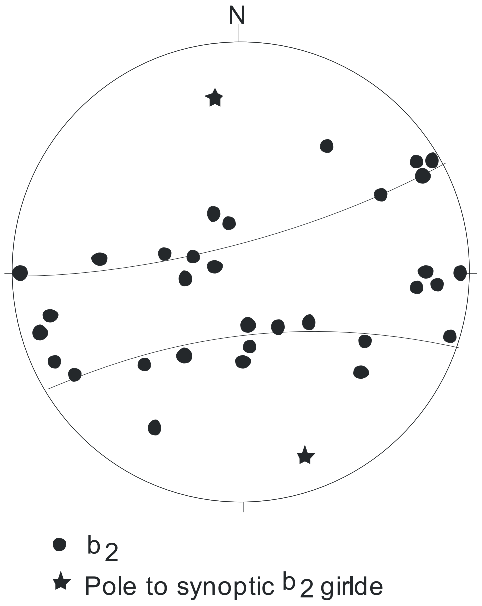
The data of $ß_2$ in the subareas (Table1) show that only 8 out of 20 subareas could be obtained to have a statistical homogeneity with respect to only one π-S girdle. In fact the interference of folds is so pronounced that it has resulted in more or less dome and basin structures (type 1 interference pattern of Ramsay, 1967). Bhattacharya *et al.* (1992) also report the dome and basin structures in the CGGC near villages Nawatola in Sonbhadra district. In the present area, in fact, the $ß_2$ values of the subarea are indicative of the most dominant trend of the fold in that particular domain. A synoptic $ß_2$ diagram has been prepared (Fig.6), in which occurrence of $ß_2$ along two small circle girdles (poles to which are 23^o/N07^oW and 14^o/S18^oE) suggest that, the F_2 folds in the CGGC are formed by flexure-slip mechanism.

Third Generation Folds

The Macroscopic analysis of earlier formed folds suggests that the rocks of the present area have undergone later episodes of deformation. This can also be inferred by the differing orientations of ß$_2$ in different subareas (Fig.6). Therefore, to analyse the macroscopic folds of third generation, new subareas were demarcated this time, on the basis of orientation of axial planes (S_3) of the F_2 folds. On the basis of S_3, the area has been subdivided into 6 subareas (Fig. 7) to obtain the orientation of macroscopic fold axis of third generation (ß$_3$). These plots are shown over the satellite image of southern part of Sonbhadra district of Uttar Pradesh in which Chhotanagpur Granite Gneiss Complex (CGGC) rocks are exposed. In all the subareas the S_3 data are scattered along two great circle girdles which suggests that there is strong interference of folds of third generation over the previous ones. The third generation folds have not only affected and rotated the earlier formed folds, but they themselves are affected by the fold geometries of earlier folds. The careful observation reveals that there is always presence of a NW –SE striking great circle in all the subareas. This suggests that the F_3 fold axis trend was perpendicular to the above strike. However, the F_3 fold axis may plunge NE or SW because of the interference of previously formed folds. The synoptic ß$_3$ diagram (Fig. 8) which has been prepared by plotting of all the 12 ß$_3$ poles from all subareas show in Fig. 7. This diagram (Fig. 8) reveals that the ß$_3$ plots are scattered along two girdles (Fig.8), in which one is vertical with NE-SW strike (may be a small circle girdle) and the other great circle girdle strikes N62^{o} E and dips 62^{o} northerly. This may indicate that the F_3 folds in CGGC were formed by slip as well as flexure-slip mechanism.

Fig. 6

Synoptic β_2 diagram for the study area.



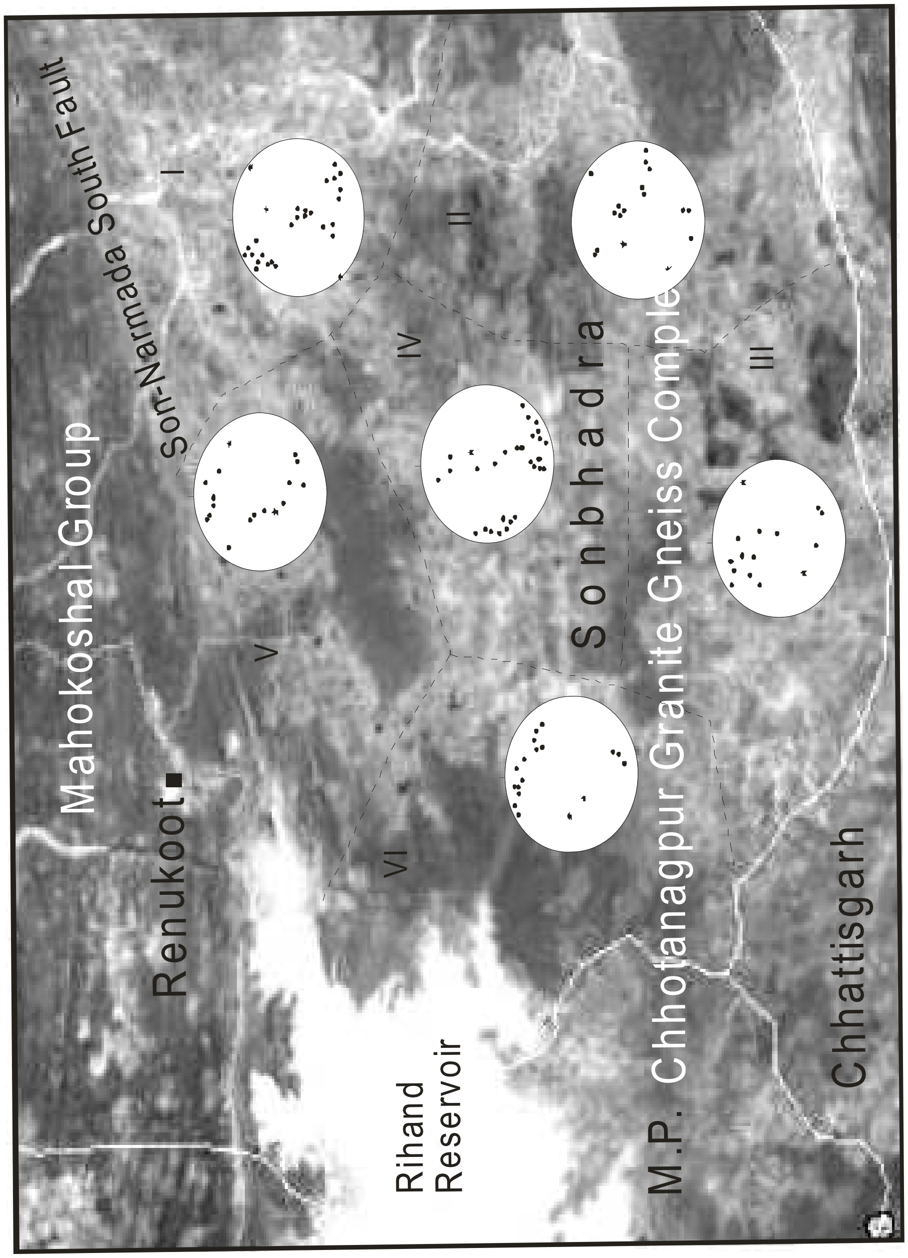
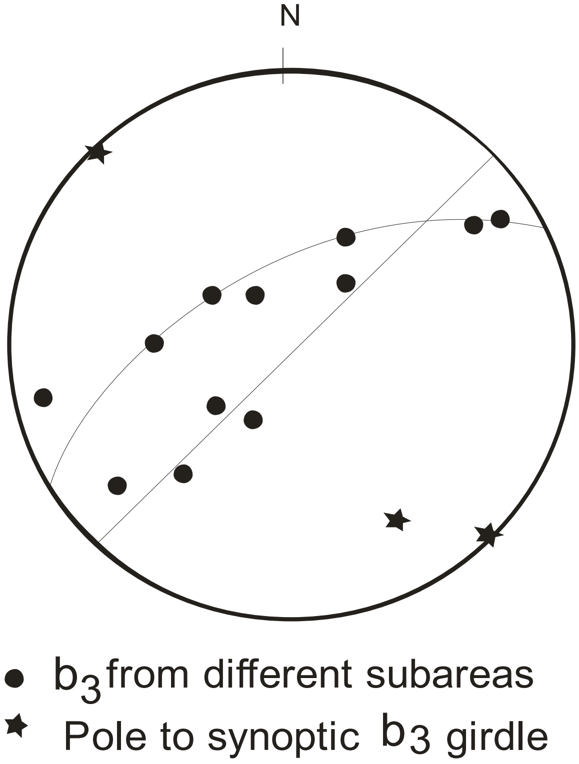

Mahokoshal Group
Son-Narmada South Fault
Renukoot
Rihand Reservoir
I
II
III
IV
V
VI
S o n b h a d r a
M.P. Chhotanagpur Granite Gneiss Comple
Chhattisgarh

Fig. 8

Synoptic β_3 diagram for the study area.



Tectonic and Geomorphic Implications

The superposed folding is a common phenomenon found in many low- to medium-grade metamorphic terrains of the world. The superposed folding in the rocks of Chhotanagpur Granite Gneiss Complex (Ghose, 1983, Sarkar, 1988; Banerji, 1991) has been recognised by many workers. The folding episodes that have acted multiply in these rocks have resulted into complex geology of the region. In the present area a maximum of 3 sets superposed folding has been observed in single outcrop. Based on superposition patterns as observed on the mesoscopic and macroscopic scales, following conclusions are drawn for developmental sequence of the folds of the CGGC rocks occurring in the Sonbhadra district of Uttar Pradesh.

The tight isoclinal to isoclinal folds developed during the first phase of folding (F_1) on bedding plane (S_1). The bedding plane is completely obliterated however, isoclinal folding representing F_1 folding have also been observed in the amphibolites and a few quartz bands in gneiss. The schistosity (S_2) developed parallel to the axial plane of these folds. During the second phase of folding (F_2) tight to close folds developed on the limbs of F_1 folds and S_2 planes. The second phase of folding caused rotation of S_1 and S_2 along the axial plane of the second generation fold (S_3). The F_1 and F_2 which are the most dominant folding episodes were followed by a mild folding episode F_3 when open folds developed. The chevron and kink bands which show sharp and acute hinges are found characteristically in the thinly foliated rocks.

They have been recognised as F_4 folds in the present study, which are more developed near fault zones. The interference between F_2 and F_3 folds has resulted in the development of domes and basins which are numerous in numbers. As a result when we observe the terrain in satellite imageries we do not see any prominent ridges or valleys in the area unlike the adjacent deformed Mahakoshal Group of rocks (Fig.6). Rather the topography is developed in such a way that numerous small hillocks or isolated mounds are observed in the area that represent the domal parts many a times, as residual hills with radial patterns of drainages.

Similarly, the basinal part is represented by ponds or reservoirs. The domes are developed where the anticlinal axis of one fold has interference with antilclinal axis of another fold. The basins are similarly, results of the interference of synclinal axes of the two folds. The interference of anticlines of one fold and syncline of another fold has resulted into retardation of amplitudes of both the folds waves and as a result the ground becomes flatter.

This way the development of Chhotanagpur plateau can be understood which is having numerous hillocks. This way the Chhotanagpur plateau is different from the undeformed Upper Vindhyan plateau lying in nearby areas in the same region in central India.

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Fig. 1 Location map of study area.

Fig. 3
Dip isogons on the profile sections of the representative folds of the study area.

Fig. 4 Orthogonal thickness parameter t'_α versus dip angle α plots for folds shown in fig.3. The left and right quarter wave sectors of the folds are plotted on the left and right of the t'_α axis respectively. A and S represent antiform and synform respectively and 1, 2, 3 etc. are the layer numbers.

Fig.7
π-S_3 diagram in different subareas of the study
area placed over the Landsat image.