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Tectonic deformation of soft-sediment convolute folds

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Abstract

The structures of the Precambrian Ghatsila–Galudih fold belt of eastern India have been studied in great detail but in the absence of suitable strain markers there is no estimate of strain for these rocks. However, tectonically deformed soft-sediment convolute folds are plentiful in these rocks. These spectacular structures morphologically resemble sheath folds but have been produced by tectonic deformation of lobes of soft sediment contortions. An estimate of the magnitude of bulk tectonic strain ($\sqrt{\lambda_3} = 0.31$) across the axial plane cleavage, along with the assumption of no volume change during tectonic deformation, gives us crucial information about the pretectonic shape of the convolutes that can be utilised to determine strain along the *X* and *Y* axes ($\sqrt{\lambda_1} = 2.6$, $\sqrt{\lambda_2} = 1.24$). The shapes of inclusion trails in garnet porphyroblasts within the mica schists indicate that the axis of rotation is parallel to the *Y*-axis of bulk strain. The bulk deformation involves a non-coaxial general flattening, with $\lambda_1 > \lambda_2 > 1 > \lambda_3$, with the vorticity vector approximately parallel to the λ_2 axis.

Keywords: Convolute folds; Strain; Garnet rotation; Vorticity

1. Introduction

Determination of strain in many areas is extremely difficult or impossible if fossils or the commonly used pre-deformational strain markers (e.g. ooids, conglomeratic pebbles, and clastic fragments) are unavailable. Tectonic structures, such as foliations and stretching lineations may give us the orientations of the finite strain axes, *X*, *Y* and *Z*. Line-length changes measured from buckle-folded veins and boudinage structures may give us some information about strain in certain directions. However, in most cases, the data are insufficient, and we need some additional information for strain determination. The aim of this paper is to show that, where deformed convolute folds are plentiful and the structures are well preserved, their geometrical analysis, taken in association with the tectonic structures, may enable us to determine the bulk strain in three dimensions.

The Ghatsila–Galudih fold belt (Fig. 1) is one of the most well studied Precambrian terrains of eastern India. Yet, in the absence of suitable strain markers no attempt has so far been made to estimate strain in these rocks. However, the rocks of this area show a profuse development of tectonically deformed convolute folds. These spectacular structures often resemble sheath folds in morphology but were produced by tectonic deformation of basinal lobes of soft-sediment contortions. Although the structures do not by themselves give us complete information for strain analysis, some of the modifying effects of tectonic strain can be eliminated to give us crucial information concerning the initial, pretectonic shape that can be utilised for strain determination.

The Precambrian metasediments of the Ghatsila–Galudih region (e.g. Dunn and Dey, 1942; Naha, 1956, 1965; Sarkar and Saha, 1962) occur in the central part of the Singbhum anticlinorium. This fold belt (Fig. 1) is bordered by the Dalma syncline in the north and by the Singhbhum Shear Zone (e.g. Dunn and Dey, 1942; Naha, 1965; Mukhopadhyay et al., 1975; Ghosh and Sengupta, 1987a, b, 1990; Mukhopadhyay and Deb, 1995; Sengupta and Ghosh, 1997) in the south. The rocks of the fold belt are dominantly mica schists, with a few beds of quartzite and small isolated bands of hornblende schists. In the neighbourhood of Ghatsila and Galudih the rocks are metamorphosed to epidote–amphibolite facies.

The large-scale structure of the area is revealed by the map-scale closures of plunging folds marked by a few thin quartzite beds occurring within the mica schists (Fig. 2). In the neighbourhood of Galudih the folds show a uniform plunge of about 20° towards 120°. There is a gentle axial depression SE of Galudih. Southwest of Ghatsila the folds plunge at a low angle (about 17°) towards 300°.

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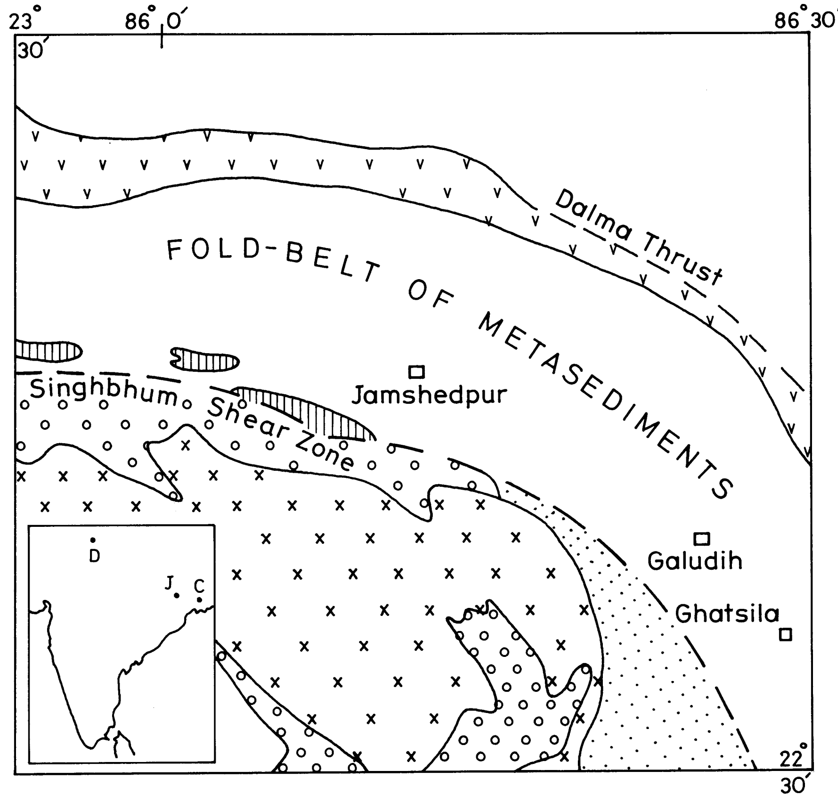

Fig. 1. The Precambrian fold-belt of metasediments lying between the Dalma syncline in the north and the Singbhum Shear Zone in the south. C: Calcutta; J: Jamshedpur; D: Delhi.

A variety of well-preserved soft-sediment deformation structures are exposed in this area (e.g. Naha, 1956; Ghosh and Sengupta, 1985). Among these there is a type of contorted structure, viz. convolute folds (Rossetti, 1999), with a fairly regular wavelength in individual layers. In certain localities, where the convolute folds occur within thick quartzose units, their shapes are little modified by tectonic deformation; in sections perpendicular to the general bedding, they are approximately symmetrical about the perpendicular to the bedding-trace. The morphology of these structures indicates that the convolute folds were initially more or less equidimensional in sections parallel to the general bedding. In most places, however, the morphology of the convolutes (Ghosh and Lahiri, 1983) has been greatly modified by tectonic deformations.

The object of the present study is to make an estimate of strain in the rocks from a detailed analysis of the deformed convolute folds. In addition, since the rocks contain porphyroblasts of garnet with trails of inclusions, the noncoaxial character of the deformation could also be established from the shapes of the inclusion trails. The analysis of deformation of the convolute folds has been made from two domains, i.e. in the stream section near the village Ghikuli southeast of Galudih (Fig. 2) and along the bed of the Subarnarekha River near the ferry point (point P in Fig. 2) SW of Ghatsila. The rocks in these places show a single generation of cleavage that is axial planar to the folds of bedding. The folds are cylindrical in each of these domains, with a uniform orientation of the lines of intersection of bedding and axial planar cleavage. Both these domains occur at the hinge zones of large-scale folds where the cleavage and the general bedding are essentially perpendicular. In both these domains, outcrop faces parallel to the cleavage and perpendicular to the bedding-cleavage intersections (i.e. sections parallel to fold profiles) are plentiful. The cleavage planes in mica schists show a mineral lineation parallel to a well-marked pressure shadow lineation at the peripheries of garnet porphyroblasts. This lineation is essentially at right angles to the trace of bedding on the cleavage. If we take the cleavage plane to be the XY plane of the strain ellipsoid, the pressure shadow lineation would be parallel to the X axis, the fold axis (the bedding-cleavage intersection) would be essentially parallel to the Y axis and the normal to the cleavage would be parallel to the Z axis (Fig. 3a and b).

2. Convolute folds

The soft-sediment convolute folds always have rounded downward-closing lobes of an upper layer penetrating into an underlying layer. Generally, the upper layer is arenaceous and the underlying layer is argillaceous; the difference in composition may be very small. The upward closures of the convolutes are always sharp. The maximum amplitude is shown by the interface between the

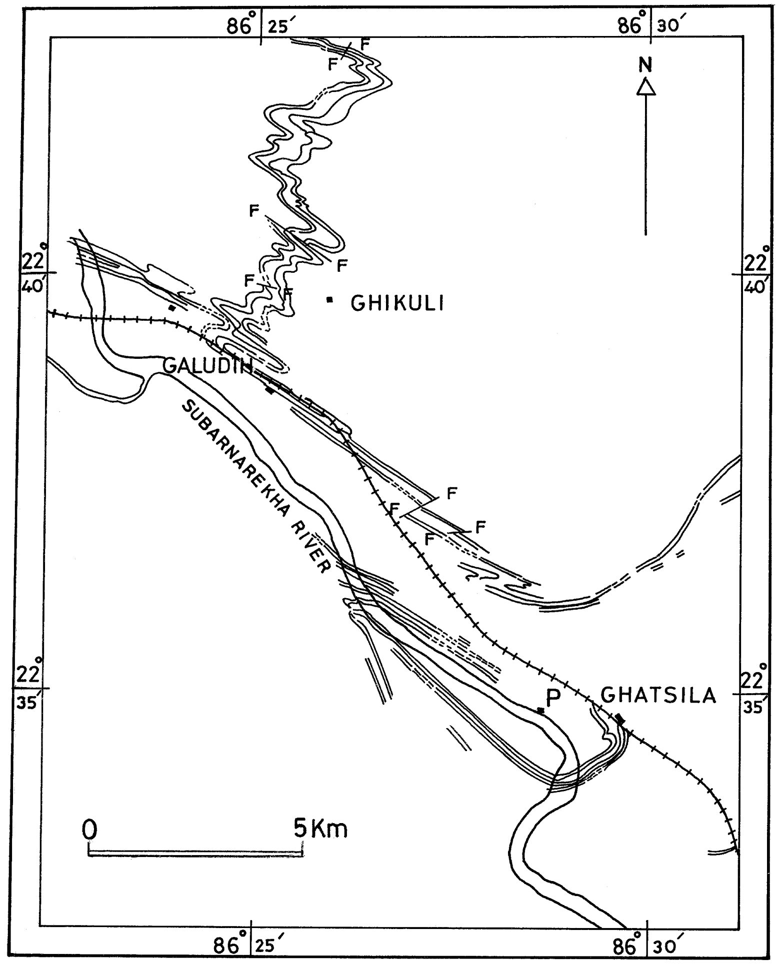

Fig. 2. Map-scale closures of quartzite beds in the Ghatsila–Galudih area.

argillaceous and arenaceous units. Unlike the cylindrical folds of these domains, the convolutes appear in all sections perpendicular to the bedding, indicating thereby that these are in the form of domes and basins. In individual outcrops, the traces of general bedding on the axial planar cleavage are essentially straight. The contorted bedding laminae occur between such straight stripes of the bedding traces on the cleavage.

The convolute folds are similar to what has been described by Allen (1977) as interpenetrative convoluted stratification or interpenetrative contortions. They are also morphologically similar to convolute laminations (Kuenen, 1953; Potter and Pettijohn, 1963; Reineck and Singh, 1975). Different mechanisms have been proposed for the development of such structures. In general, the convolute folds develop by a combination of processes, mostly involving reverse density gradient induced by differential liquefaction associated with different degrees of compaction (Rossetti, 1999). We are, however, interested only in the morphology of a specific type of these structures, i.e. in contortions that have a more or less regular wavelength, that are symmetrical in sections perpendicular to bedding and are initially more or less equidimensional in sections parallel to the bedding.

3. Deformation of convolute folds

The geometry of the convolute folds are very different in profile sections of folds and in sections parallel to the axial plane cleavage (Figs. 4a and 5); in the same layer, the wavelengths as well as the wavelength/amplitude ratios of deformed convolute folds are much smaller in profile sections than in cleavage-parallel surfaces. This is because these soft-sediment contortions were flattened parallel to the axial plane cleavages during the folding movement. In all sections at an angle to the cleavage, the trace of the cleavage is approximately parallel to the axial surface trace of the deformed convolutes. This feature is shown in even the weakly deformed convolutes. This confirms that the initial convolute folds were essentially equidimensional in plan view. In sections parallel, or at a low angle, to the bedding, the convolutes appear as oval outcrops with the long axes approximately parallel to the cleavage trace (Figs. 4b and 6a).

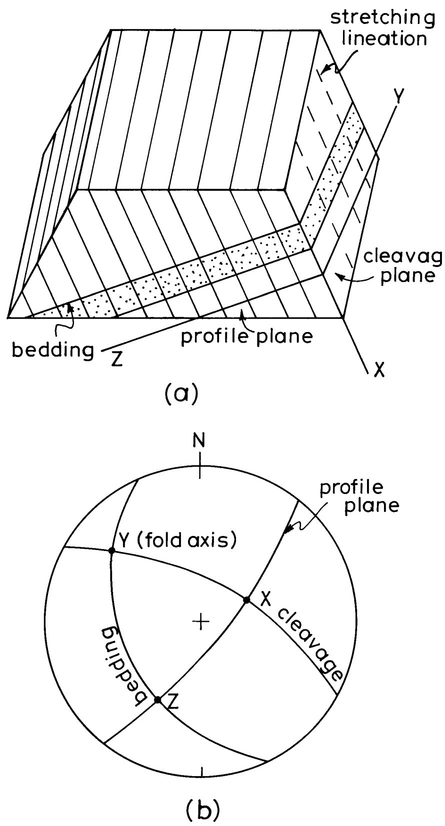

Fig. 3. (a) The direction of maximum stretching marked by the pressure shadow lineation is at a right angle to the trace of bedding on the cleavage surface. Hence the bedding-cleavage intersection is parallel to the *Y*-axis of the strain ellipsoid and the *X*-axis is parallel to the lineation. The *Z*-axis, normal to the cleavage, lies on the profile plane. (b) Stereographic projection showing the geometrical relations of the *X*, *Y* and the *Z*-axes with reference to orientations of the axial planar cleavage, the stretching lineation, the bedding-cleavage intersection and the profile plane at right angles to the bedding-cleavage intersection.

In some places, where the convolutes are larger than the hinge zones of mesoscopic folds, the convolutes themselves become folded. The deformed convolutes may then have crescentic outcrops. Fig. 7 shows a crescentic outcrop of a basinal soft-sediment contortion that has been folded over the hinge of a diastrophic antiformal fold. The bedding laminae of the crescent have been deformed to smaller tectonic folds. On the limbs of the fold the deformed convolutes appear as oval outcrops.

4. Wavelengths of convolute folds

The wavelengths of the convolute folds were measured in those domains where the general orientation of the bedding was more or less at a right angle to the cleavage. This was true for the two domains of outcrops at the ferry point along the Subarnarekha River and near Ghikuli, south-east of Galudih. Both these domains are situated at the hinge zones of large-scale folds; consequently, in sections perpendicular to the bedding-cleavage intersections, the trace of bedding is essentially perpendicular to the cleavage plane, i.e. to the XY plane of the strain ellipsoid. In other words, the trace of bedding on these surfaces is essentially parallel to the Z-axis of the strain ellipsoid. Determination of bulk strain in these rocks has been greatly facilitated by the simple relation of the fold geometry with the principal axes of the strain ellipsoid. The X-axis of the strain ellipsoid is parallel to the well-developed stretching lineation. The bedding-cleavage intersection, perpendicular to the stretching lineation is parallel to the Y-axis. The normal to the cleavage is parallel to the Z-axis. The wavelengths of the deformed convolutes on sections perpendicular to the bedding-cleavage intersections (i.e. on XZ sections) have been designated L_z. The wavelengths of convolutes on the cleavage surfaces have been designated L_y (Fig. 6b).

The convolute folds appear in two types of layers within the mica schists. In one of these the quartz content is only slightly greater than in the host mica schists, and the convolutes are greatly flattened. The shortening of these contorted layers must have taken place essentially by homogeneous strain, and the shortening of these layers should closely approximate the bulk shortening of the mica schist. In the other type of layers the quartz content is distinctly greater, and the flattening of the convolutes on the XZ plane is moderate. L_y and L_z have been measured separately for these two types of layers. For both these sets, each value of L_y or L_z represents an average of two or more waves of convolute folds. An average of 6–10 waves was frequently obtained. In certain places where a large number of waves were exposed in the same layer, an average of 30 waves could be obtained. The average wavelength was obtained by measuring the total length of the layer-trace exposed on the outcrop face (either the cleavage surface or a surface approximately perpendicular to the bedding-cleavage intersection), counting out the number of waves and dividing the total length by the number of waves.

The ratio L_y/L_z is generally larger in the first set of data from the relatively quartz-poor layers than in the second set of data. The first set of data gives an arithmetic mean of 4.04, a standard deviation of 0.62 and a correlation coefficient of 0.98. For the second set of data the arithmetic mean is 2.39, the standard deviation is 0.38 and the correlation coefficient is 0.98. Fig. 8 shows the plots of L_y against L_z for the first set of data. The distribution is linear. The line which best fits the data corresponds to $L_y/L_z = 4.0$. For the second set of data (Fig. 9) the line that best fits the data corresponds to $L_y/L_z = 2.4$.

5. Determination of bulk shortening from buckle-folded veins

The ratio of wavelength to arclength of folded layers can give us an estimate of bulk shortening (in terms of stretch)

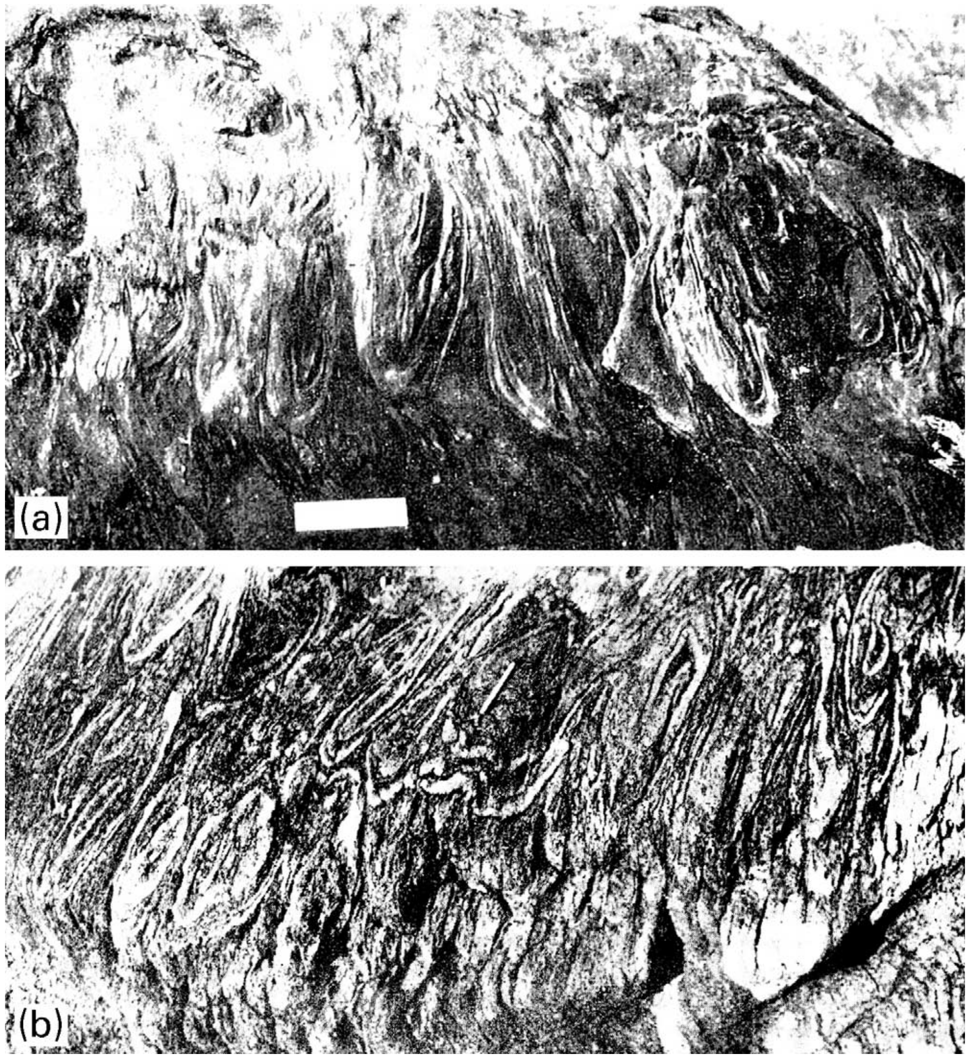

Fig. 4. (a) Deformed convolute folds with small wavelength/amplitude ratios in a section normal to the bedding-cleavage intersection. (b) Oval sections of deformed lobes of convolute folds on a surface at a low angle to the general bedding.

only if the buckle-folds are produced almost entirely by external rotation, and layer-parallel homogeneous strain is negligible. The mesoscopic folds of thin (a few centimetres to a few decimetres in thickness) beds of quartzite generally

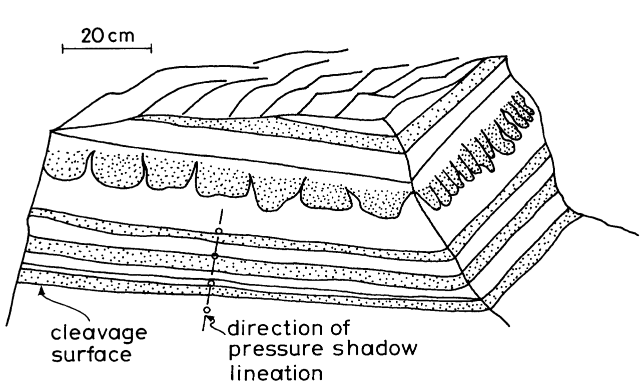

Fig. 5. Trace of convolutes on the cleavage surface. Note that the wavelength/amplitude ratios are much larger than in Fig. 4a.

show a cleavage; consequently, they must have undergone some layer-parallel strain during buckle folding. Hence their wavelength/arclength ratios (of an average of 0.40) cannot be utilised to measure the bulk shortening of the enveloping mica schists. However, in sections at right angles to the bedding-cleavage intersections we find in some places buckle-folded thin quartz veins of a few millimetres in thickness. The veins themselves do not show any cleavage and have the geometry of parallel folds. It is reasonable to assume that the shortening of these veins took place essentially by buckle shortening without significant homogeneous strain. This assumption implies that the bulk stretch of the rocks normal to the cleavage is given by the ratio of wavelength to arclength of the folded veins. The average wavelength/arclength ratios were measured in those veins that are approximately perpendicular to the trace of cleavage in the host mica schists. The average ratio of wavelength to arclength is 0.31.

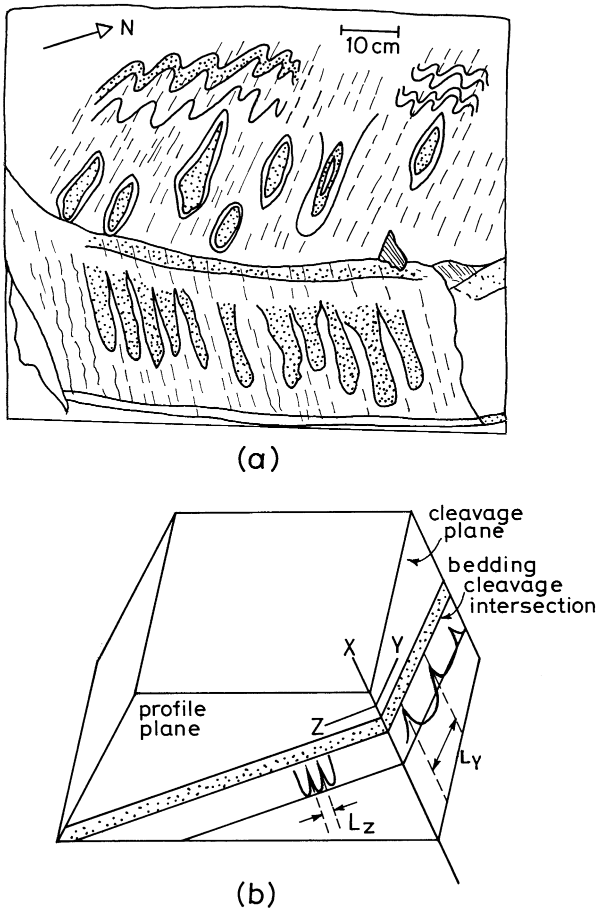

Fig. 6. (a) Oval outcrops of deformed convolute folds on a surface sub-parallel to the bedding. The long axes of the ovals are parallel to the cleavage-trace and to the traces of axial planes of mesoscopic diastrophic folds. (b) The wavelengths of convolutes L_y and L_z parallel to the *Y*- and the *Z*-axes of bulk strain.

6. Determination of bulk three-dimensional strain

The bulk three-dimensional strain was determined under the following assumptions:

1. The bulk stretch normal to the axial planar cleavage is 0.31 obtained from the average ratio of wavelength to arclength of the buckle-folded veins as described above.
2. The convolute folds of set 1 (Figs. 4a and 8) were deformed almost entirely by homogeneous strain, and, consequently, the wavelengths of the convolutes along the *Z*-direction (the cleavage-normal) were shortened by the bulk stretch of 0.31.
3. The volume remained constant during the tectonic deformation.

Let the wavelength of an initial convolute be L_o in both the *Y* and the *Z* directions, and let the wavelength of the deformed convolutes be L_y and L_z. Then:

$$\sqrt{\lambda_2} = L_y/L_o \text{ and } \sqrt{\lambda_3} = L_z/L_o = 0.31 \quad (1)$$

where λ_2 and λ_3 are the quadratic elongations along the *Y* and the *Z* directions. Therefore,

$$\sqrt{\lambda_2}/\sqrt{\lambda_3} = (L_y/L_o)/(L_z/L_o) = L_y/L_z \quad (2)$$

Since the mean value of L_y/L_z is 4.0 for the deformed contvolute folds of the first set of data,

$$\sqrt{\lambda_2}/\sqrt{\lambda_3} = 4.0 \quad (3)$$

From Eqs. (1) and (3) we then have:

$$\sqrt{\lambda_2} = 0.31 \times 4.0 = 1.24$$

For volume-constant deformation,

$$\sqrt{\lambda_1} = 1/(\sqrt{\lambda_2}\sqrt{\lambda_3}) = 2.6$$

Thus, we have, for the bulk three-dimensional strain:

$$\sqrt{\lambda_1} = 2.60$$

$$\sqrt{\lambda_2} = 1.24$$

$$\sqrt{\lambda_3} = 0.31$$

Since $\sqrt{\lambda_2} > 1$, the deformation is a general flattening, with a small extension parallel to the fold axis and a much larger extension perpendicular to the fold axis on the cleavage plane. This is in conformity with occurrence of quartz veins (Fig. 10b) showing pinch-and-swell structure on outcrop faces sub-parallel to the fold axis and at a high angle to the cleavage. The value of $\sqrt{\lambda_2} = 1.24$ is also in agreement with the development of pinch-and-swell structures in a band of metabasic rock (Fig. 10a), which cuts across the folded bedding laminae of mica schist on a subhorizontal surface near the ferry point of the Subarnarekha River. The trend of the metabasic band makes a low angle (17°) with the bedding-cleavage intersection in the adjoining mica schists.

7. Noncoaxial nature of bulk deformation

In non-coaxial bulk deformation, equidimensional rigid objects rotate relative to the instantaneous stretching axis (ISA) in the deforming matrix (e.g. Hanmer and Passchier, 1991; Ghosh, 1993, pp. 196–216; Passchier and Trouw, 1996, p. 176; Williams and Jiang, 1999). With progressive deformation the foliation also rotates with respect to the ISA. The rates of rotation of the porphyroblast and of the foliation are different. S- and Z-shaped trails of inclusion (S_i) develop in a syntectonic porphyroblast because of this difference in the rates of rotation of the porphyroblast and of the external foliation (S_e) relative to the fixed orientation of the ISA in the matrix. The foliation may trace the changing orientation of the *XY* plane or it may rotate passively after its initiation parallel to the *XY* plane. In either case, the rate of rotation of the foliation decreases with progressive deformation, and at any stage of deformation, this rate is smaller than that of the rigid porphyroblast. Consequently, in a section perpendicular to the rotation axis, an S-shaped S_i

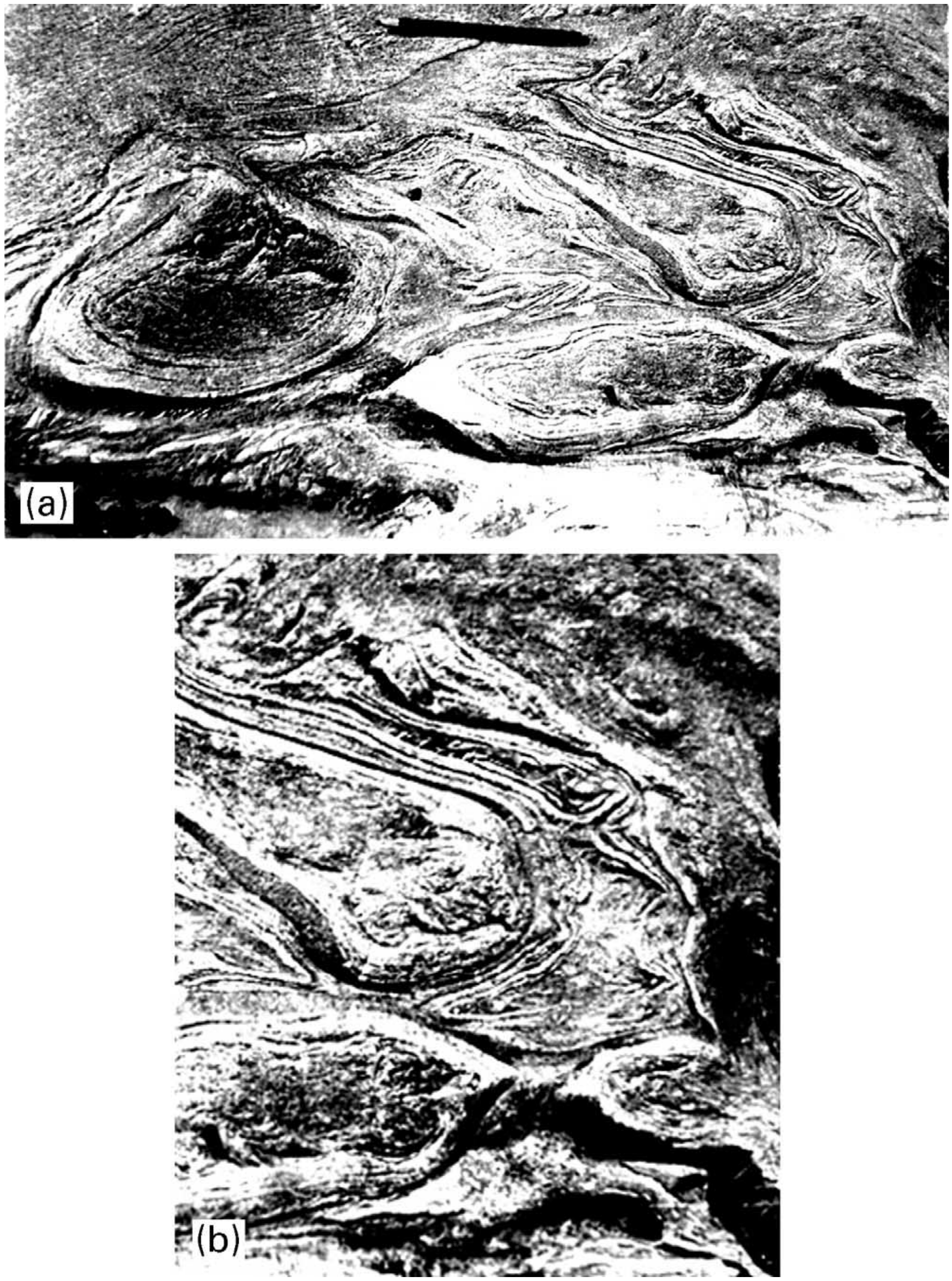

Fig. 7. (a) Soft-sediment contortions folded over a tectonic fold. On the fold limbs the convolutes appear as oval outcrops but over the hinge of the mesoscopic fold the outcrop of the convolute appears as a crescent. (b) Details of the crescentic outcrop shown in (a).

may be produced when the porphyroblast rotates in a sinistral sense and a Z-shaped S_i may be produced when it rotates in a dextral sense. In a single-phase of deformation, the rotation axis of a nearly spherical porphyroblast is parallel to the vorticity vector in the deforming matrix. The sense of rotation of the porphyroblast is the same as the sense of vorticity.

As pointed out by Ramsay (1962), S- or Z-shaped S_i may also form in a syntectonic equidimensional porphyroblast during rotation of a pre-existing foliation by a later coaxial deformation in which eqidimensinal porphyroblast does not rotate at all. This possibility can be ruled out in areas that have undergone a single phase of deformation.

The bulk deformation history of the Ghatsila–Galudih area was not coaxial. This is clearly indicated by the trails of inclusions in paratectonic porphyroblasts of garnet in mica–schists. Thin sections of mica–schists of this area frequently show S- or Z-shaped trails of inclusions in porphyroblasts of garnet (Naha, 1965); occurrence of such trails of inclusions indicate paracrystalline rotation of the garnet.

In order to determine the orientation of the axis of

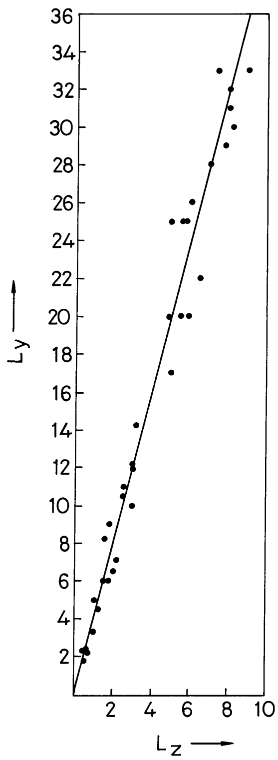

Fig. 8. Plot of L_y against L_z (in centimetres) for convolute folds in quartz-poor layers.

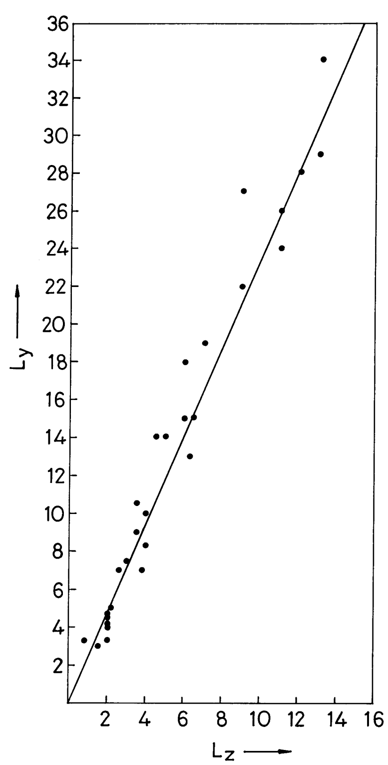

Fig. 9. Plot of L_y against L_z (in centimetres) for convolute folds in quartz-rich layers.

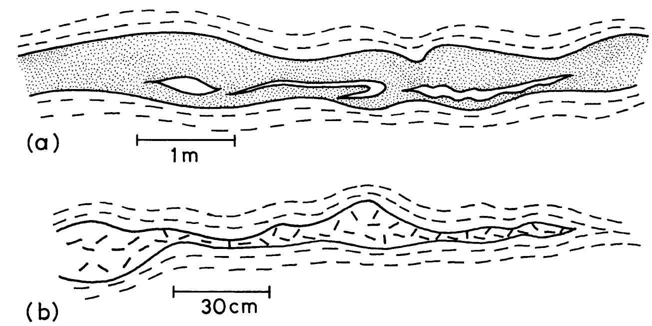

Fig. 10. (a) Pinch-and-swell structure in a metabasic band occurring within the mica schists at the ferry point of the Subarnarekha River. The surface on which the pinch-and-swell structure is shown is at a very low angle with the bedding-cleavage intersection. (b) Pinch-and-swell structure in a quartz vein on an outcrop-face subparallel to the fold axis. Ferry point, Subarnarekha River.

rotation of the porphyroblasts, three sets of thin sections were made from oriented specimens of mica–schists of the ferry point outcrops where garnet porphyroblasts are plentiful. The three sets of thin sections are: (a) parallel to the stretching lineation and perpendicular to the cleavage, (b) perpendicular to the lineation, and (c) parallel to the cleavage. These three sets of planes are parallel to the *XZ*, *YZ* and *XY* planes of the strain ellipsoid, respectively.

Since the rocks of the two domains considered here have not undergone superposed deformations, it is likely that there was a single axis of rotation for a porphyroblast of garnet and that the rotation axis lies on the schistosity plane (Rosenfeld, 1970, pp. 55–56).

The patterns of inclusion trails were different in the three sets of differently oriented thin sections (Fig. 11). In sections parallel to the stretching lineation and perpendicular to the cleavage, the inclusion trails showed S- or Z-shaped patterns. The patterns are S-shaped, indicating a counterclockwise rotation of the garnet, in the reference frame of the ISA and the geographical coordinates (Williams and Jiang, 1999), when looking in a northerly direction, i.e. down the plunge of the fold axis (Fig. 12a). The patterns are Z-shaped, indicating a clockwise rotation, when looking in a southerly direction (Figs. 11a and 12b).

S- or Z-shaped trails of inclusions do not occur in sections parallel to the schistosity (Fig. 11b) and in sections perpendicular to the stretching lineation (Fig. 11c). In sections parallel to the schistosity the inclusion trails are more or less straight in the central part and show a gentle outward convexity on either side, with approximate mirror symmetry (Fig. 11b). The central trails are at right angles to the stretching lineation. Such trails of inclusions in sections parallel to the schistosity could develop in syntectonic garnet only if the trails of inclusions are parallel to the rotation axis (Powell and Treagus 1967, 1970; Rosenfeld, 1970). Since the trails of inclusions occur on the schistosity (*XY*-plane) and are perpendicular to the stretching lineation (*X*-axis), the rotation axis coincides with the *Y*-axis of the strain ellipsoid.

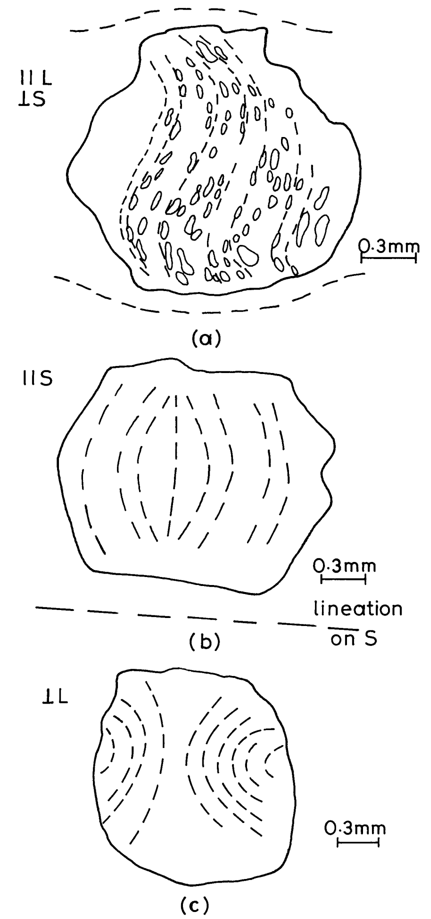

Fig. 11. Trails of inclusions in garnet porphyroblast in differently oriented thin sections from mica schists at ferry point. (a) Z-shaped trails of inclusions in a section parallel to the lineation and perpendicular to the schistosity. (b) Section parallel to the schistosity. The straight segment of the inclusion trails is essentially perpendicular to the lineation. On either side the trails show outward convexity. (c) Section perpendicular to the lineation. Trails showing outward concave pattern.

In sections perpendicular to the stretching lineation (i.e. parallel to the *YZ*-plane) the trails of inclusions are curved, concave outward on either side, with more or less straight segments (parallel to cleavage-trace and the *Y*-axis) in between (Fig. 11c).

The following points indicate that the curved trails of inclusions truly indicate paracrystalline rotation and are not helicitic structures:

1. There is only a single generation of schistosity in this area, and that schistosity, axial planar to the folds of bedding in all scales, is the earliest schistosity.
2. In the two domains considered here, the schistosity is either straight or shows very weak warping, the wavelengths of which are many times greater than the curved forms of S_i trails. The prophyroblasts of garnet are a few millimetres in diameter, while the warps on the schistosity are in the scale of a few centimetres to a few decimetres.

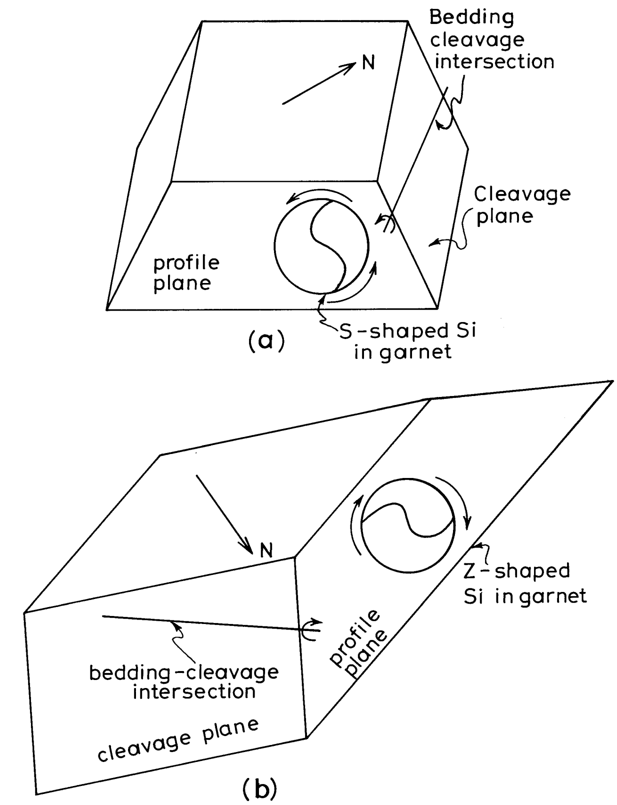

Fig. 12. (a) S-shaped inclusion trails indicating counterclockwise rotation on transverse sections, looking northwesterly. (b) Z-shaped inclusion trails indicating clockwise rotation on transverse section, looking southeasterly.

3. In any one thin section, perpendicular to the schistosity and parallel to the stretching lineation, the trails of inclusions in the garnet porphyroblasts are either all S-shaped or all Z-shaped.

The occurrence of rotated porphyroblasts of garnet clearly indicates that the deformation was noncoaxial. The bulk deformation therefore involves a noncoaxial general flattening type of strain, with $\lambda_1 > \lambda_2 > 1 > \lambda_3$.

8. Summary and conclusions

In the absence of common strain markers, tectonically deformed soft-sediment convolute folds, along with other structural features can be utilised to determine the principal strains. This method is well suited for the two domains of the Ghatsila–Galudih area where the direction of maximum stretching (*X*-axis of bulk strain) is clearly marked by the pressure shadow lineation and where the trace of bedding on the axial planar cleavage is essentially parallel to the *Y*-axis. In plan view the convolute folds were initially more or less equidimensional. After deformation the wavelengths (L_z) of the convolutes in the *Z*-direction were greatly reduced. For any particular layer, L_y, the wavelength in the *Y* direction, is distinctly greater than L_z. Since the initial wavelength (L_o) in

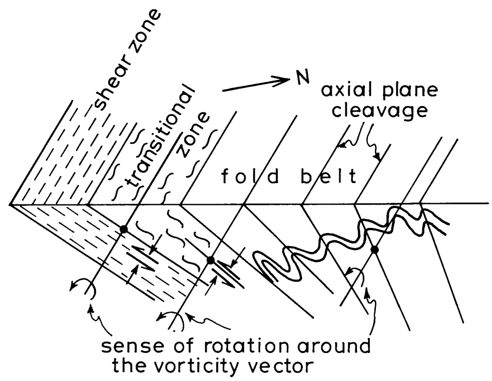

Fig. 13. Schematic diagram showing relative positions of the Singbhum Shear Zone, the transitional zone and the fold belt. The sense of rotation around the vorticity vector is the same in all the three domains.

the Y and the Z directions was the same, the ratio of the deformed waves L_y/L_z is equal to the stretch ratio $\sqrt{\lambda_2}/\sqrt{\lambda_3}$. Measurement of L_y and L_z in a large number of layers indicated that the data could be separated in two sets, i.e. from relatively quartz-poor and quartz-rich layers. The plots of L_y against L_z show a linear distribution for each set. For the first set of data the arithmetic mean of L_y/L_z is four. Even for constant-volume deformation, this value of L_y/L_z, by itself, does not give us the principal stretches unless it can be assumed that the fold axis is a direction of no strain. This assumption is ruled out by occurrence of pinch-and-swell structures at very low angles to the fold axis. However, an independent estimate of the stretch along the Z direction ($\sqrt{\lambda_3} = 0.31$) can be obtained from the average ratio of wavelength to arclength of buckle folded thin quartz veins. Under the assumption that there was no volume change during the period of tectonic deformation, the principal stretches are calculated as $\sqrt{\lambda_1} = 2.60$, $\sqrt{\lambda_2} = 1.24$ and $\sqrt{\lambda_3} = 0.31$.

The deformation was noncoaxial. This is indicated by frequent occurrence of garnet porphyroblasts that had undergone paracrystalline rotation. At the ferry point in Ghatsila, the sense of rotation is counterclockwise (with S-shaped trails of inclusions in thin sections) when looking northward down the plunge of the fold axis. The pattern of inclusion-trails in garnet in cleavage-parallel thin sections indicates that the rotation axis lies on the cleavage plane more or less at right angles to the stretching lineation. In other words, the rotation axis is essentially parallel to the Y-axis of bulk strain. The bulk deformation is therefore a noncoaxial deformation of general flattening type with $\sqrt{\lambda_1} > \sqrt{\lambda_2} > 1 > \sqrt{\lambda_3}$ and with the vorticity vector parallel to the $\sqrt{\lambda_2}$ direction.

The fold belt of the Ghatsila–Galudih area lies to the north of the mylonite belt of the Singbhum Shear Zone (SSZ) (Fig. 1). There is a transitional zone in between, immediately to the north of the SSZ, where the structure and the structural history are similar to those of the SSZ but rocks are not mylonitic (Ghosh and Sengupta, 1990). The structures of the northern fold-belt and of the SSZ were produced in the course of a single continuous deformation, although the intensity of deformation increases from the fold-belt, through the transitional zone, to the SSZ. Within the fold-belt, from northeast to southwest, the folds become progressively tighter and more overturned towards southwest. The SSZ, as well as the transitional zone, show a strong noncoaxial deformation in a flattening field, with a subhorizontal vorticity vector and the displacement vector at the zone-boundary lying on a vertical plane that is perpendicular to the vorticity vector. Hence, in spite of the thrusting sense of movement, the deformation in the SSZ is in the nature of transpression. The up-dip shearing movement in the shear zone has a subhorizontal vorticity vector with a counterclockwise sense of rotation while looking towards northwest. In accordance with the earlier conclusion that the structures of the fold-belt and the shear zone were produced in a single continuous process, the results of the present analysis show that the deformation in the fold-belt in the Ghatsila–Galudih region, although much less intense than in the SSZ, is also noncoaxial and lies within a flattening field. The orientation of the vorticity vector and the sense of rotation around it are also similar to those of the SSZ (Fig. 13).

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