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Structural pattern in the Precambrian rocks of Sonua-Lotapahar region, North Singhbhum, eastern India

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Abstract. In the western part of the North Singhbhum fold belt near Lotapahar and Sonua the remobilized basement block of Chakradharpur Gneiss is overlain by a metasedimentary assemblage consisting of quartz arenite, conglomerate, slate-phyllite, greywacke with volcanogenic material, volcaniclastic rocks and chert. The rock assemblage suggests an association of volcanism, turbidite deposition and debris flow in the basin. The grade of metamorphism is very low, the common metamorphic minerals being muscovite, chlorite, biotite and stilpnomelane. Three phases of deformation have affected the rocks. The principal D1 structure is a penetrative planar fabric, parallel to or at low angle to bedding. No D1 major fold is observed and the regional importance of this deformation is uncertain. The D2 deformation has given rise to a number of northerly plunging major folds on E–W axial planes. These have nearly reclined geometry and the L_2 lineation is mostly downdip on the S_2 surface, though some variation in pitch is observed. The morphology of D2 planar fabric varies from slaty cleavage/schistosity to crenulation cleavage and solution cleavage. D3 deformation is weak and has given rise to puckers and broad warps on schistosity and bedding. The D2 major folds south of Lotapahar are second order folds in the core of the Ongarbira syncline whose easterly closure is exposed east of the mapped area. Photogeological study suggests that the easterly and westerly closing folds together form a large synclinal sheath fold. There is a continuity of structures from north to south and no mylonite belt is present, though there is attenuation and disruption along the fold limbs. Therefore, the Singhbhum shear zone cannot be extended westwards in the present area. There is no evidence that in this area a discontinuity surface separates two orogenic belts of Archaean and Proterozoic age.

Keywords. North Singhbhum; Singhbhum shear zone; structural geometry; polyphase deformation; volcaniclastic rocks; lithological characteristics; deformation history.

1. Introduction

The Precambrian supracrustal rocks of North Singhbhum form an E–W trending arcuate fold belt characterized by polyphase deformation and metamorphism. It is sandwiched between the Chhotanagpur Gneiss to the north and the Singhbhum Granite to the south. An important tectonic element within this fold belt of Early-Middle Proterozoic age is the Singhbhum shear zone which is a ductile movement zone running parallel to the main tectonic grain within the belt and is situated close to its southern boundary with the older cratonic block of Singhbhum Granite (figure 1). In the traditional interpretation of Dunn (1929) and Dunn and

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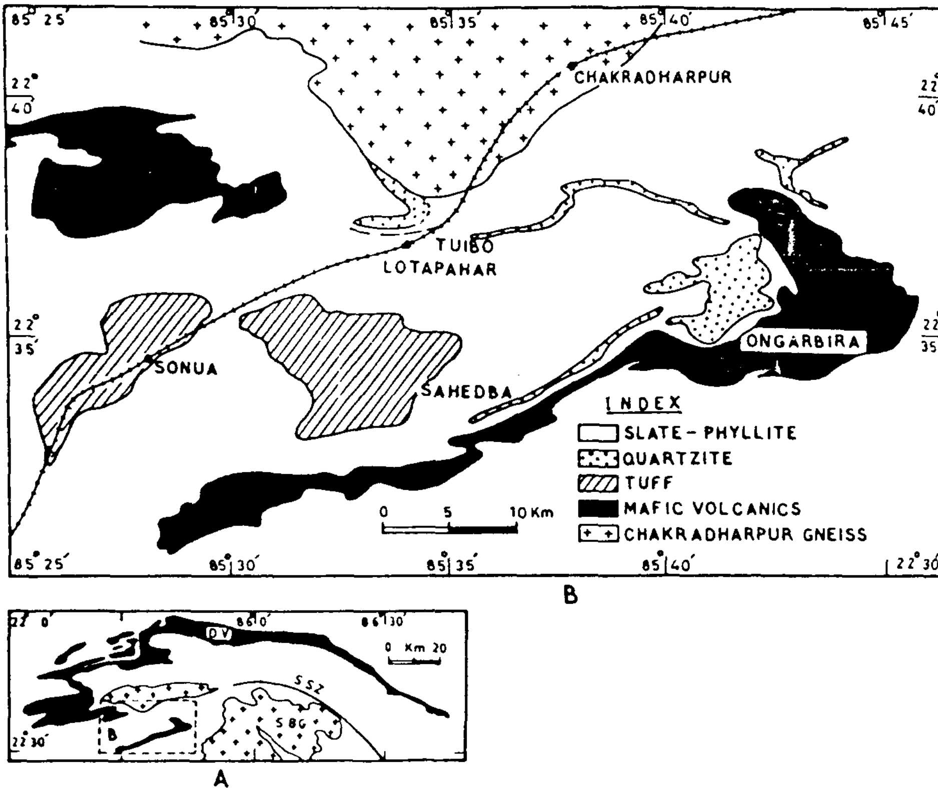

Figure 1. A—Regional map of North Singhbhum fold belt; SBG—Singhbhum Granite; DV—Dalma Volcanics; SSZ—Singhbhum shear zone. Location of area shown in figure is indicated. **B**—Generalized geological map of the western part of the North Singhbhum fold belt (slightly modified from Dunn 1929).

Dey (1942) it is a thrust zone developed on the overturned limb of the Singhbhum anticlinorium, the sense of thrusting being directed from north to south. Sarkar and Saha (1962, 1977, 1983) regarded the shear zone as marking the boundary between the southern Archaean block (iron ore craton) and the northern Proterozoic block (Singhbhum orogenic belt). According to their tectonic model it originated as an intraplate subduction zone along which the southern crustal segment subducted below the northern one.

The Singhbhum shear zone is well demarcated in the eastern and southeastern parts of the fold belt by a narrow zone of mylonites and phyllonites (Mukhopadhyay *et al* 1975; Ghosh and Sengupta 1987). Discontinuous sheets of mylonitized Proterozoic granite (Sarkar *et al* 1986)—the so-called soda granite of Dunn and Dey (1942)—are characteristic of this zone. This mylonite belt peters out westward, a feature first noted by Dunn (1929) and later corroborated by Mukhopadhyay (1984). Dunn's (1964) observation that west of Chakradharpur there is a continuous succession of metasedimentary rocks from north to south is contrary to the interpretation of Sarkar and Saha (op. cit.) that the shear zone also extends to this region, separating the Archaean and Proterozoic geological provinces. The lithological similarity across the supposed western extension of the Singhbhum shear zone was also pointed out by Sarkar and Chakraborti (1982). Hence, the area west of Chakradharpur is critical for deciphering the structural and stratigraphical relation between the northern and southern supracrustal rocks of the North Singhbhum fold belt and the Jamda-Koira Iron Ore basin respectively. This paper presents the results of detailed lithological and structural mapping in two areas around Lotapahar and Sonua, west of Chakradharpur, supplemented by photogeological study of the intervening region, for elucidating the regional structural pattern.

2. Lithological characteristics

Apart from the Chakradharpur Gneiss which has been interpreted as a reworked basement block within the fold belt (Sengupta *et al* 1983), the principal rock types encountered in this region are (figures 2 and 3): (a) quartz arenite-conglomerate, (b) slate-phyllite, (c) chert siliceous slate-greywacke-volcaniclastic rocks.

2.1 *Chakradharpur Gneiss*

The southwestern corner of the Chakradharpur Gneiss body is exposed near Lotapahar where it is a medium-grained leucocratic rock varying in composition from granodiorite to tonalite along with a few basic dykes. The granitic rocks are usually foliated, and the effects of postcrystallization deformation and recrystallization are conspicuous. These include development of deformation bands and deformation lamellae in quartz, deformation of quartz grains into long ribbons, polygonization and subgrain formation in quartz, and bending of twin lamellae and fracturing in feldspar. Thin films of micaceous minerals define the secondary foliation which curves round the grains of quartz and feldspar producing an augen-like texture. We correlate these deformation effects to the deformation events in the supracrustal envelope of the gneisses.

2.2 *Quartz arenite-conglomerate*

Quartz arenite forms an E-W trending band near Lotapahar, which appears to join with the NW-SE trending band along the border of the Chakradharpur Gneiss (figure 2). Another E-W trending band passes through the Tuibo hill east of Lotapahar and this joins up with the Chirubera band further east of the mapped area (figure 1). Quartz is the principal constituent along with a minor amount of muscovite/sericite. In rare instances the rock is an arkose with more than 20% feldspar, mostly plagioclase. In spite of the effects of deformation and recrystallization an original grain-supported fabric is discernible in most of the thin sections. The matrix is fine-grained quartz or quartz-sericite aggregate. Polygonization and subgrain formation in the framework grains, marginal granulation, flattening perpendicular to schistosity and other deformation effects make it impossible to carry out a detailed study of the original texture. In fact, deformation processes have possibly generated some amount of secondary matrix in the rock.

Bedding is generally well-developed and some cross bed sets are also recognized. The latter are of trough to tabular type and a few cm to 50 cm thick. The younging direction in the Lotapahar band is northwards and in the band along the border of the Chakradharpur Gneiss it is southwestwards, away from the gneisses (figure 2).

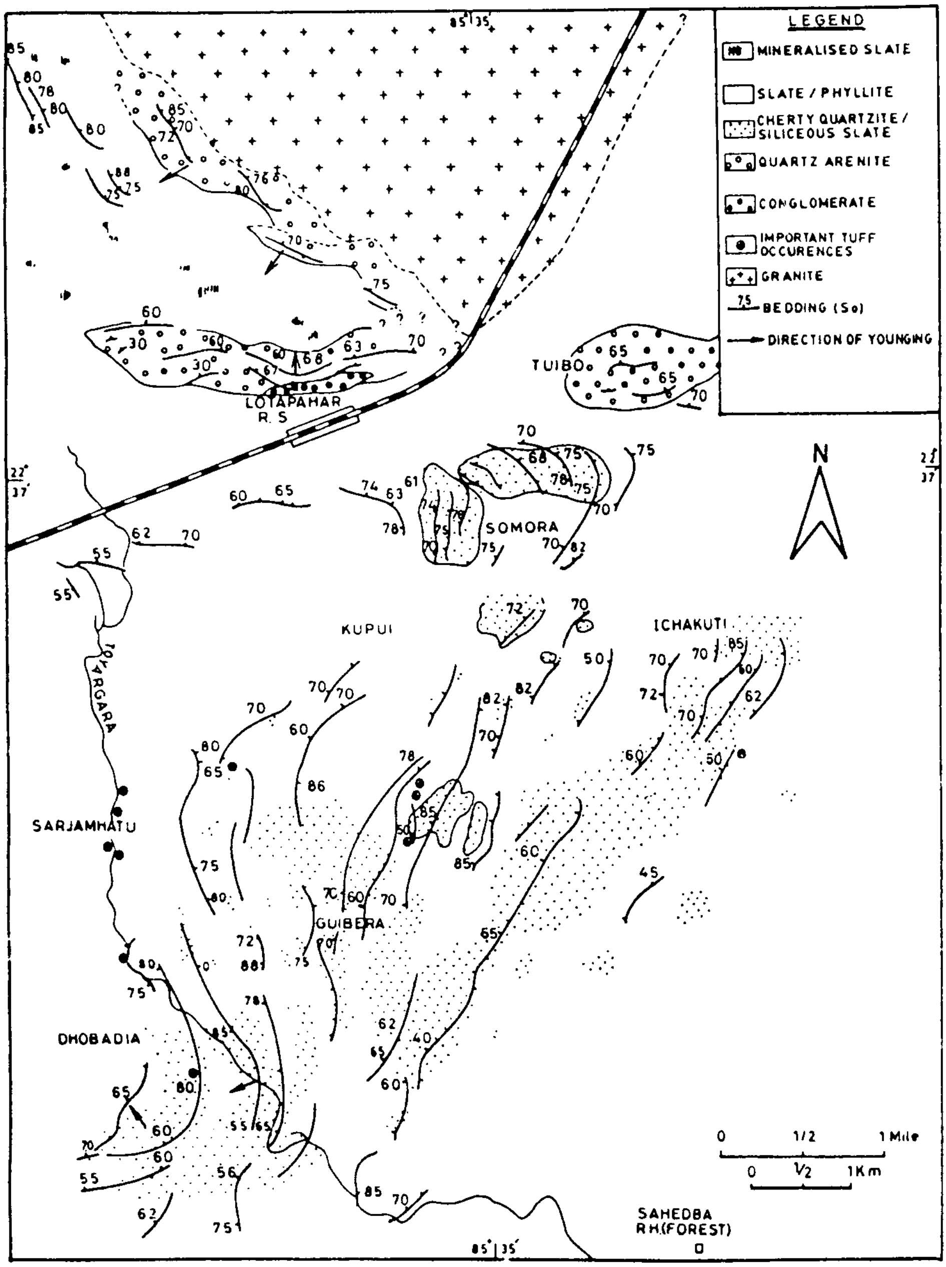

Figure 2. Map showing lithology and bedding orientation near Lotapahar

A schistosity is usually present in the rock, defined by anastomosing films of mica curving round the quartz clasts. The shape of the clasts varies from lenticular, elongated parallel to schistosity, to subspherical, subangular or irregular without any elongation.

Along the base of the Lotapahar hill occurs a lenticular body of polymictic conglomerate. Pebbles of vein quartz, jasper, chert, dolomite and slate are common,

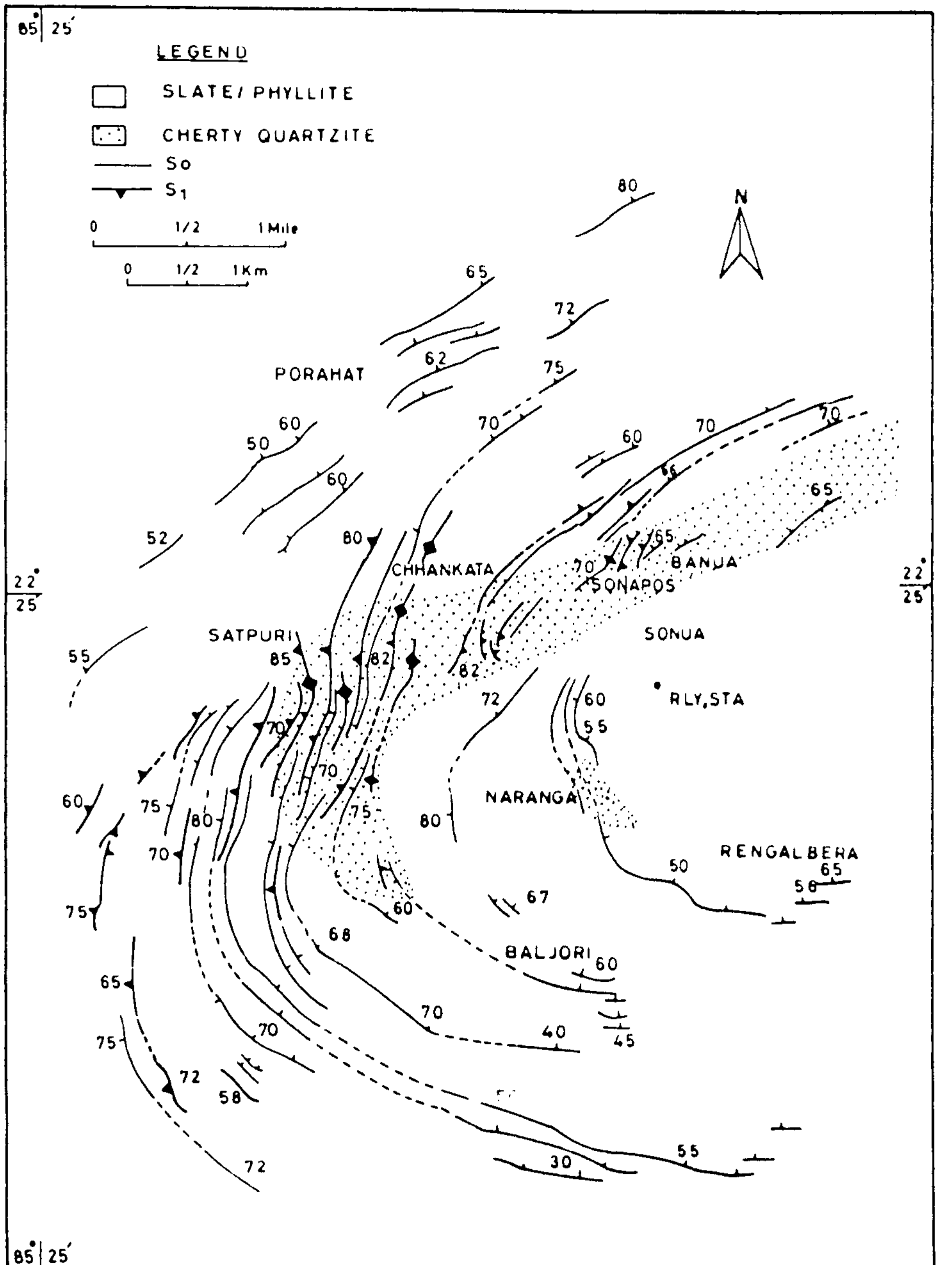

Figure 3. Map showing lithology and orientation of bedding and first schistosity near Sonua.

all of them elongated parallel to schistosity. The conglomerate is coarsest at the base with the common clast size ranging from a few mm to 20 cm. Towards north the clast size decreases and the conglomerate grades into quartz arenite. This is consistent with the northward younging direction deduced from cross bedding.

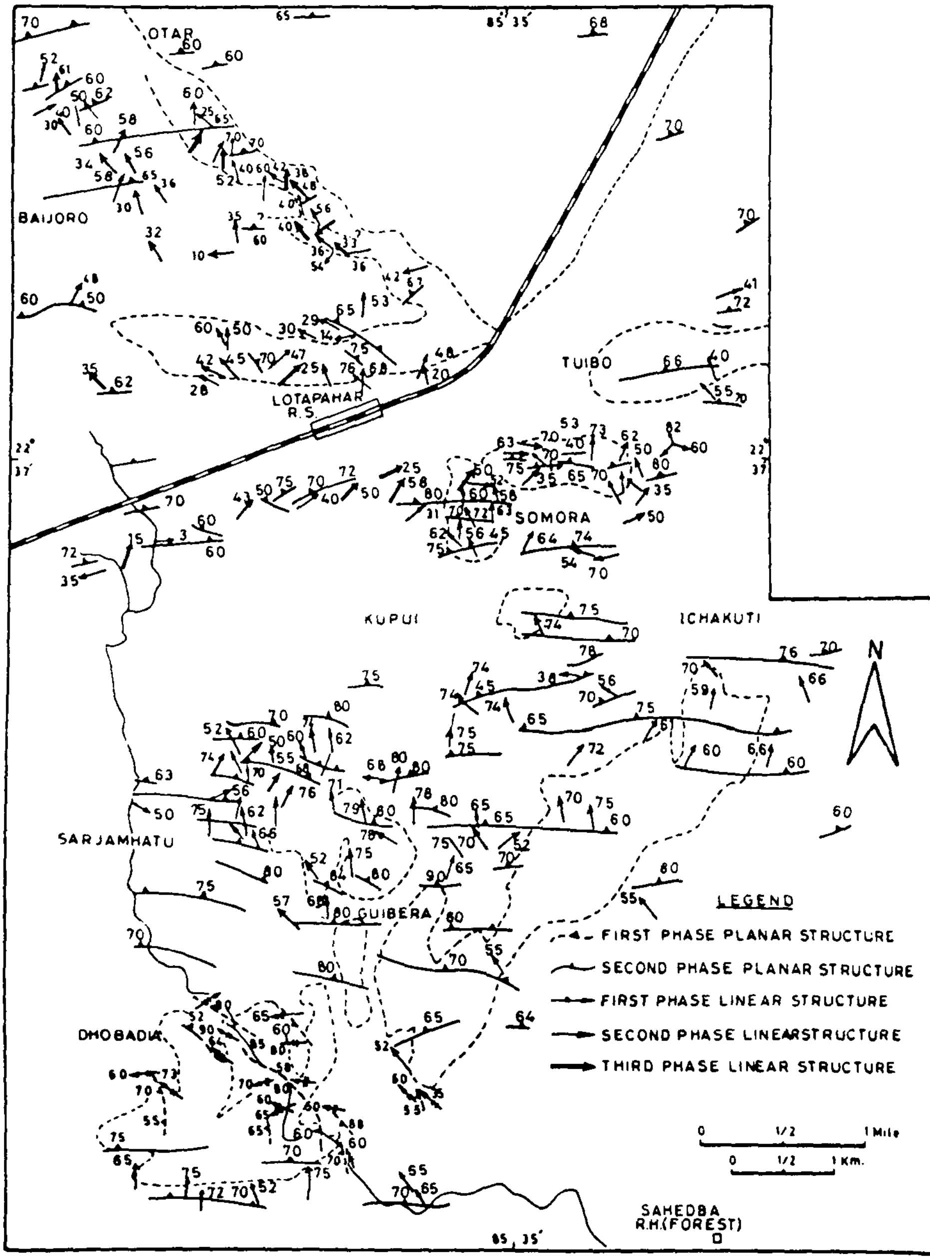

Figure 4. Map showing orientation of secondary planar and linear structures near Lotapahar.

2.3 *Slate-phyllite*

Pelitic and semipelitic rocks make up a major part of the supracrustal sequence in the area. Finely-banded phyllitic rocks, which may be ferruginous or carbonaceous, occur north of Lotapahar and at several localities near Sonua. The rocks are greenish, deep reddish or black in colour, depending on the presence of chloritic, ferruginous

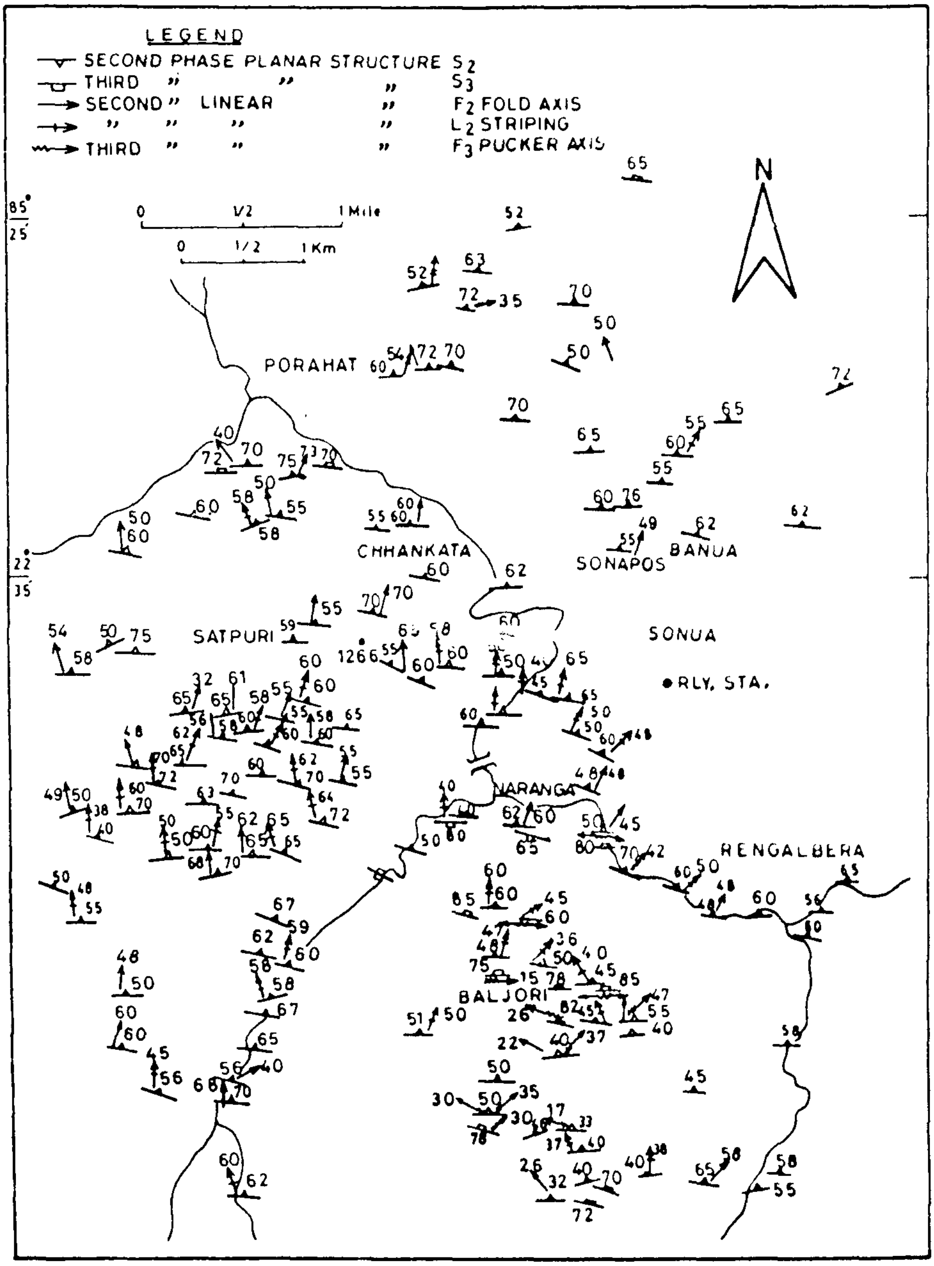

Figure 5. Map showing orientation of D2 and D3 planar and linear structures near Sonua

or carbonaceous material. Carbonate-bearing phyllite is found near Rengalbera, south of Sonua. Under microscope, clasts of quartz and occasionally tabular or irregular altered feldspar are seen embedded in a schistose matrix. Euhedral pyrite crystals are also present; around these simple symmetrical pressure shadows of fibrous quartz have formed. The phyllosilicates are chlorite, muscovite-sericite and rarely biotite. Fine-grained clayey minerals which cannot be resolved under microscope are also present at places. At several localities quartz veinlets containing stilpnomelane are found. North of Lotapahar iron impregnation in the slates has given rise to well-developed rectangular or polygonal boxworks. This may be related to the presence of Lotapahar fault (Dunn 1929).

2.4 *Chert—siliceous slate—greywacke—volcaniclastic rocks*

These occur as variants within slate-phyllite. Formational boundaries cannot be mapped in the field. Figures 2 and 3 show the patches where such rocks are well-developed. It is to be noted that the boundaries of these patches do not represent definite lithological boundaries.

South of Lotapahar and also near Sonua fine-grained rocks, which in the field appear to be chert or siliceous slate, occur. A fine lamination is usually present and penecontemporaneous fold structures, slumps, local truncation of laminae and channelling are sometimes seen. Under microscope the rocks are seen to be made up of fine-grained microcrystalline quartz and fine flakes of sericite and chlorite. Sometimes the micaceous minerals do not show any preferred orientation, but a secondary planar fabric is defined by the presence of discontinuous, anastomosing solution planes, marked by the concentration of opaque granules. The relative proportion of quartz and phyllosilicates varies from one outcrop to another defining a continuous spectrum of rock types, chert and slate-phyllite being the two end members. The rocks are often pervaded by closely-spaced quartz veinlets. As we shall discuss later, some of these rocks probably represent very fine-grained volcaniclastic accumulation (ash beds).

Within both siliceous and micaceous rocks some bands and patches that are rich in relatively coarse detrital grains and rock fragments are observed. The matrix may be siliceous or micaceous (fine-grained schistose or a structureless sericitic paste). In some rocks a considerable amount of epidote-zoisite is present in the matrix in the form of lenticular streaks.

The proportion of matrix in these rocks usually varies from 70% to 80%. The size of the detrital clasts varies from fine silt to coarse sand. Highly elongated rock fragments, some of them more than 15 mm long, are occasionally seen. The detrital grains show poor sorting. The size frequency distribution of clasts in two groups of samples is shown in figure 6.

The detrital grains are mostly of quartz and fairly unaltered feldspar. Some of them are highly angular; embayed margins are occasionally seen. The quartz grains usually show effects of strain, like undulose extinction and formation of subgrains. In some rocks a large number of fragments of a fine-grained material are seen. These are made up of aggregate of epidote-zoisite, phyllosilicates and a little quartz. Extremely fine grain size and nearly isotropic fabric of both the fragments and the surrounding matrix make their distinction difficult. Some rock fragments of volcanic material display a relict flow structure. Such fragments are highly elongated, bent, wispy and flame-like in shape. These are probably devitrified glass. Other types of rock fragments include granite, fine-grained quartzite and slate-phyllite. The proportion of clasts of different composition in a few samples is given in table 1.

These rocks may be termed as metagreywackes. While many of the fragments betray their volcanogenic affiliation, the presence of granite, coarse perthite, quartzite, slate and phyllite fragments indicates the presence of different rock types in the provenance.

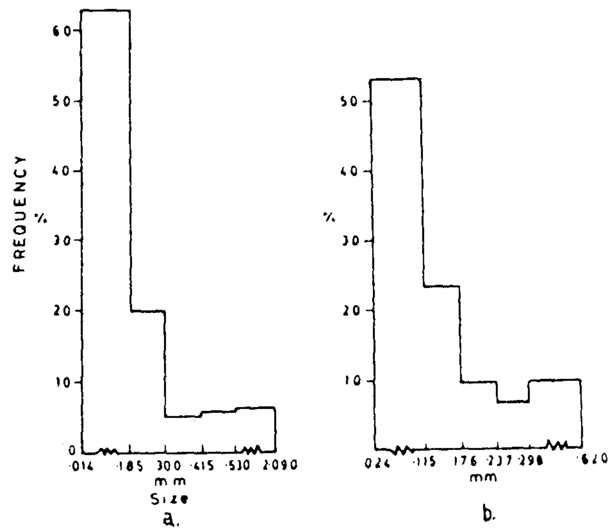

Figure 6. Size frequency distribution of clasts in two groups of samples of metagreywacke volcaniclastic rocks from south of L[illegible].

Table 1. Modal analysis of metagreywacke volcaniclastic rocks.

	South of Lotapahar	
	1	2
Quartz	15·14	9·24
Feldspar	4·52	4·62
Rock fragments	5·82	3·46
Matrix	74·52	82·68

Relative proportion of components in the framework grains

	Lotapahar	Sonua
Quartz : feldspar : rock fragments	60:17:23	49:48:3
	53:27:20	

From the texture they are interpreted to represent some form of sediment gravity flow deposit. Some of these rocks in which the fragments are mostly of volcanogenic material may also be volcaniclastic sediments (tuffs).

Interbanded with these rocks are some thin beds of fine-grained quartzite which show profuse current ripple lamination and cross-bedding on a small scale. The rocks with matrix-supported coarser detrital grains and associated layers of cross-laminated fine sand and siltstone may represent Bouma A and C divisions of turbidite sequence, the fine-grained micaceous and siliceous background rocks being normal basinal sediments.

Apart from quartz, feldspar, muscovite and chlorite, stilpnomelane is a characteristic constituent of these rocks. It occurs either as individual needles, closely associated with thin veinlets of quartz or as radiating sheafs distributed throughout the fine-grained matrix. Epidote-zoisite is an important constituent in some rocks. Other minerals like pumpelleyite and amphibole are rarely seen.

Similar association of shale-greywacke with volcanogenic material and extensive cherty rocks has been reported from rocks of all ages including Precambrian (Walker and Pettijohn 1971; Fisher and Schiminke 1984; Paris *et al* 1985; Gibson and Towe 1971; Lowman and Bloxam 1981; Niem 1977). Cherty rocks in these sequences are often regarded to be related to volcanism in various ways. In view of the extensive presence of submarine lava flows in the fold belt (e.g., the Dalma Volcanics and the Ongarbira Volcanics, Bose and Chakraborti 1981, Gupta *et al* 1981), and the presence of volcanogenic detritus in the greywackes of this area, such a correlation seems to be valid here also. The fine-grained cherty rocks of this area might have formed from silica exhalation from submarine volcanoes; alternatively, convection of sea water through the volcano-sedimentary pile might have led to extensive silicification of fine-grained rocks (Paris *et al* 1985), or they might have formed through alteration of volcanic ash (Gibson and Towe 1971; Wise *et al* 1973).

A detailed sedimentological study of the rocks was beyond the scope of the present work, but these preliminary observations have brought into light several interesting features about the association of volcanism, turbidite deposition and debris flow in the basin. A thorough sedimentological study of these rocks is sure to bring into light many new facts which would be of utmost importance in working out the relation between sedimentation and tectonism, and in understanding the mode of evolution of the basin.

3. Deformation history

Three phases of tectonic activity (D1, D2 and D3) have affected the rocks of this region. The most prominent deformational structure is an approximately E–W striking schistosity/slaty cleavage which is axial planar to a group of major and minor folds having reclined geometry. Striping and mineral lineation parallel to the fold axes show high values of pitch on the schistosity (figures 4 and 5). Structures of this generation (D2) are ubiquitous; however, the presence of a penetrative planar fabric, parallel or at low angle to bedding and crenulated by D2 folds (figure 7), suggests the existence of an earlier (D1) deformational phase. Where this earlier planar fabric is well-defined by the parallelism of phyllosilicates the D2 planar structure takes the form of crenulation cleavage rather than of schistosity or slaty cleavage (Figure 7).

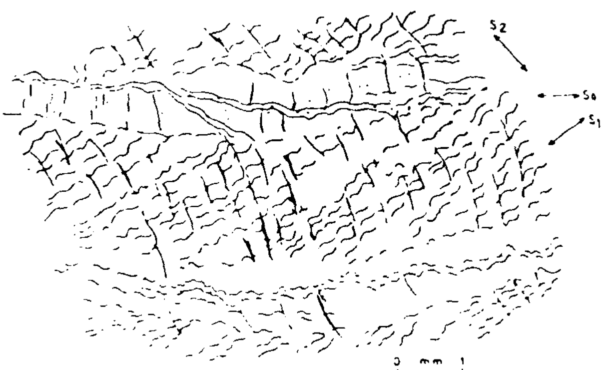

Figure 7. Sketch of a thin section of banded semipelite from north of Lotapahar showing relation of S_0, S_1, and S_2.

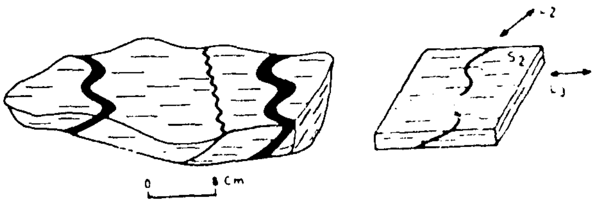

Figure 8. Sketch of a hand specimen from Baljori near Sonua, showing S_2, L_2, and L_3. Relationship is schematically shown in the right hand diagram.

While the D2 deformation has produced a number of mappable folds no major fold related to D1 could be recognized in this region. Hence the regional importance of D1 remains uncertain.

A weak third phase of deformation (D3) has produced puckers on the schistosity as well as small folds and kinks, sometimes of a conjugate nature. An interesting effect of the third deformation is illustrated in figure 8. Here the D2 schistosity surface (S_2) remains essentially planar, but D3 has produced minute crinkles which appear as a lineation (L_3) on this surface. An earlier lineation (L_2) defined by the intersection of quartzose bands on the schistosity is folded with axial traces parallel to L_3. Hence, superficially the structure resembles folded lineation on an unfolded surface. However, this is not really so, and the observed features reflect the differing responses of the different planar structures during D3. Because of very fine planar anisotropy the schistosity surface is microscopically crinkled, so that megascopically the surface appears unfolded, while the oblique thicker quartzose bands developed folds of larger wavelength and amplitude; hence the L_2 intersection lineation is folded. It may be noted that the axes of the D3 folds on the quartzite layers do not lie on the schistosity surface, but are at an angle to it, and an oblique section across these folds is seen on the schistosity surface.

4. Structural geometry

4.1 *First phase structures*

The commonly observed effect of the first deformation is the development of a penetrative planar fabric (S_1). Though this is frequently parallel to bedding (S_0), it is not a primary or diagenetic feature as indicated by the occasional non-parallelism between S_0 and S_1 and by the metamorphic recrystallization of minerals like chlorite, muscovite/sericite, and rarely biotite parallel to it. At two localities, Banua near Sonua and Dhobadia south of Lotapahar, where the angular relation between S_0 and S_1 is clearly observed, the attitude of the line of intersection between them is statistically computed. The vector means of S_0 and S_1 are calculated (Loudon 1964) and the line of intersection between the two mean planes is determined. At Banua the computed L_1 plunges 44° towards 300° and at Dhobadia it plunges 58° towards 280°. However, such computations could not be carried out at other localities, and hence it has not been possible to determine the regional orientation of L_1 or the geometry of its deformation by D2 folds.

D1 minor folds are very rarely observed. A few are found in the chert and phyllite near Sonua. Some isoclinal folds found in the quartzite north of Lotapahar probably belong to this episode.

In the chert near Sonua S_1 appears as a set of closely-spaced persistent quartz veinlets, a fraction of a mm to 1 mm thick. These are crenulated by D2 folds. Such veinlets are usually absent in the phyllites and slates in which S_1 is a schistosity defined by parallel alignment of phyllosilicates. In these rocks the phyllosilicates are of two types: (a) very fine grains forming a mesh without any distinct alignment, and (b) larger well-defined flakes with parallel alignment. The former are probably clastic or diagenetic grains, while the latter are recrystallized and of metamorphic origin. In the banded slates and phyllites from north of Lotapahar S_1 planes show 'refraction' while passing from the quartzose to the micaceous layers. In the former it is distinctly oblique to S_0, but on approaching the micaceous layers it is curved, eventually becoming parallel to S_0 (figure 7).

An interesting structural feature is observed in an exposure near Banua, north of Sonua. Here S_0 which is nearly parallel to S_2 remains planar while the oblique S_1 is folded with axial planes parallel to S_0 (figure 9). This is due to the fact that S_0 being nearly parallel to S_2 is perpendicular to D2 compression and is unfolded, while the oblique S_1 by virtue of its falling in the zone of shortening of D2 strain ellipsoid (Ramsay 1967) gets folded.

Near Baljori and Naranga south of Sonua, irregular, dentate and discontinuous planes defined by granules of opaque minerals are found in the thin sections and hand specimens of some rocks. These are oblique or subparallel to S_0 and are crenulated with axial planes parallel to S_2. These represent solution planes formed during the D1 deformation.

4.2 *Second phase structures*

4.2a *Minor structures*: The most commonly observed structures in this region belong to the second phase of deformation. S_2 is conspicuous in slates and phyllites and is

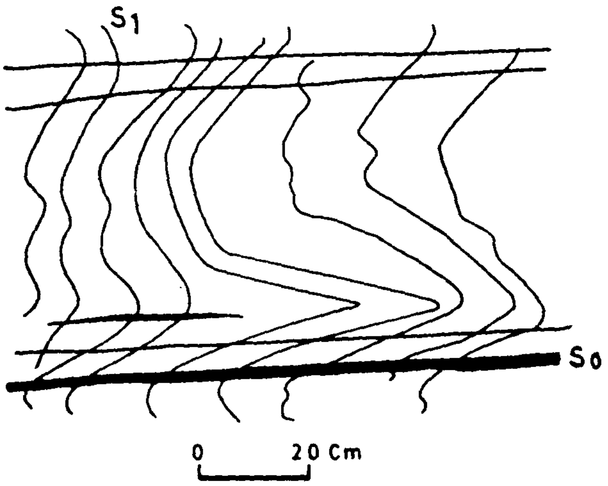

Figure 9. S_0 parallel to S_2 unfolded while oblique S_1 is folded with axial plane parallel to S_0, near Sonua (sketched from a photograph).

less well-developed in cherty quartzite. From microscopic study the following morphological types are recognized: (a) slaty cleavage/schistosity without domainal fabric, (b) slaty cleavage/schistosity with domainal fabric, (c) crenulation cleavage of both zonal and discrete types, (d) discrete solution planes. The pervasive slaty cleavage without any domainal fabric is defined by flakes of muscovite/sericite, chlorite and needle-shaped opaques. In some cherty quartzites and siliceous slates there is a planar fabric defined by flattened quartz grains, lenticular streaks of epidote-zoisite and parallelism of flaky minerals; in others the fine-grained matrix is without any planar structure.

In the more quartzose semipelitic types, banded phyllites, greywackes and tuffs a domainal fabric is well-developed. Thin films of micaceous minerals curve round the clasts and show reticulate, anastomosing patterns enclosing trapezoidal or elliptical domains. The average spacing of the micaceous planes varies from 0·1 to 0·2 mm. The quartz clasts often have irregular, angular shape, while the clasts of fine-grained rock are flattened normal to S_2. The quartz grains show undulose extinction, deformation bands and deformation lamellae indicating that they have been deformed by intragranular dislocation processes, while the optically unstrained flattened grains in the matrix indicate deformation by intergrain diffusion (Kerrich *et al* 1977). Fibrous growth of quartz or phyllosilicates against porphyroclasts also points to diffusion transfer during deformation. In the quartzitic rocks near Lotapahar S_2 appears as discrete micaceous films or laminae curving round the deformed framework grains of quartz which may or may not show an elongation. Some massive quartzites are devoid of any secondary planar fabric.

Solution planes are commonly observed in these low grade rocks. They appear as thin dark sinuous lines whose spacing usually varies from 0·03 to 0·05 mm in the micaceous parts and 0·1 to 0·3 in the quartzose parts. Dark brown limonitic material, opaque granules or fine flaky minerals are concentrated along these planes. Biotite and stilpnomelane are also occasionally present. Solution planes may be associated with slaty cleavage, or more commonly with crenulation cleavage, or they may be present in rocks which do not show any other planar anisotropy. Some rocks exhibit evidence of extensive solution activity. Quartzose beds are disrupted or offset along such planes and sometimes thick pressure solution seams wrap round completely detached squarish blocks of quartzose material. Following Cobbold (1977) we term these as P bands—differential displacements being normal to the pressure solution seam margins.

In banded slates and phyllites what appears as S_2 slaty cleavage in hand specimens turns out to be crenulation cleavage under microscope (figure 7). The earlier crenulated fabric may be parallel or at a low angle to bedding. The crenulation cleavage may be of discrete or zonal type (Gray 1977). Flakes of chlorite, muscovite/sericite, and rarely biotite are parallel to the crenulation cleavage, especially when it is of discrete type. In banded rocks the crenulation cleavage usually stops at the boundary of the quartzose bands, but a few solution planes may penetrate well into the latter. In symmetrical folds the average spacing of the crenulation cleavage surfaces varies from 0·1 to 0·2 mm; in asymmetrical folds the spacing varies from 0·05 to 0·1 mm.

Metamorphic differentiation accompanying the development of crenulation cleavage has often given rise to secondary compositional bands (quartzose and micaceous) parallel to the crenulation cleavage. Progressive development of this mineralogical differentiation may be traced from an incipient development of these bands to pervasive development which may completely mask the original bedding.

The morphology of S_2 appears to be controlled by the nature of the original fabric in the rock and the intensity of deformation. The different morphological types may be observed even within a single thin section.

S_2 may show the phenomenon of refraction, making a higher angle with S_0 in the more quartzose layers. Sometimes quartz veins parallel to schistosity are confined to such quartzose layers producing a structure similar to ladder veins. These are best interpreted as due to dilatation consequent upon slight movement on oblique curved S_2 planes (Ramsay 1967, p. 407).

Offset of beds along S_2 is occasionally observed. This may be due to collapse as a result of solution along cleavage planes (Hobbs *et al* 1976) or due to slip along S_2 as a result of non-coaxial deformation (cf. Dietrich and Carter 1969).

The downdip lineation on S_2 appears to be parallel to the direction of maximum elongation during D2, but enough markers are not present to permit a systematic determination of the strain values. Shortening measurements from intersecting folded quartz veins in samples from near Sonua yield a value of $Z:Y = 1:3$. An earlier work by Mukherjee and Roy (1960) on Lotapahar conglomerate gave an average value of $X:Y:Z = 7:4:1$. Wherever fibrous growth of minerals are found against quartz clasts or pyrite grains they are straight, indicating irrotational strain during the development of S_2.

Minor folds of second generation are found in the banded semipelitic rocks. They have S, Z or M shapes, being congruous to the D2 major folds. These are buckle folds modified by flattening and often attain a nearly similar geometry (class 2, Ramsay 1967).

4.2b *Major structures:* Mappable folds of second phase are present both near Sonua and Lotapahar. Near Sonua the major fold is a westerly closing, northerly plunging reclined fold (figure 3). The fold is overturned with both the limbs dipping northerly, the strike of bedding is ENE-WSW on the northern limb, N–S on the hinge zone and E–W on the southern limb. The orientation parameters determined from equal area projection diagrams in three sectors covering the two limbs and the hinge zone are given in table 2. As representative examples, the data from the northern limb are plotted in figures 10a, b, c. In each sector S_0 and S_1 poles show a maximum with spread along a great circle. S_2 poles and L_2 each show a maximum. L_2 is subparallel to β which has nearly the same orientation in all the sectors. Thus the whole area is homoaxial with respect to D2 fold axis. The pitch of the fold axis on the axial plane

Table 2. Orientation parameters for the Sonua fold.

	S_0 max. Strike	S_0 max. Dip	S_1 max. Strike	S_1 max. Dip	S_2 max. Strike	S_2 max. Dip	β_{S_0} Plunge	β_{S_1} Plunge	L_2 max. Plunge
N. Limb	65	60 N	50	60 N	96	56 N	60 → 14	57 → 3	60 → 10
S. Limb	90	58 N		-	98	47 N	59 → 5 50 → 57	- -	46 → 10
Hinge Zone	133 40	66 N 68 N	Parallel to S_0		96	56 N	60 → 0	60 → 0	58 → 7

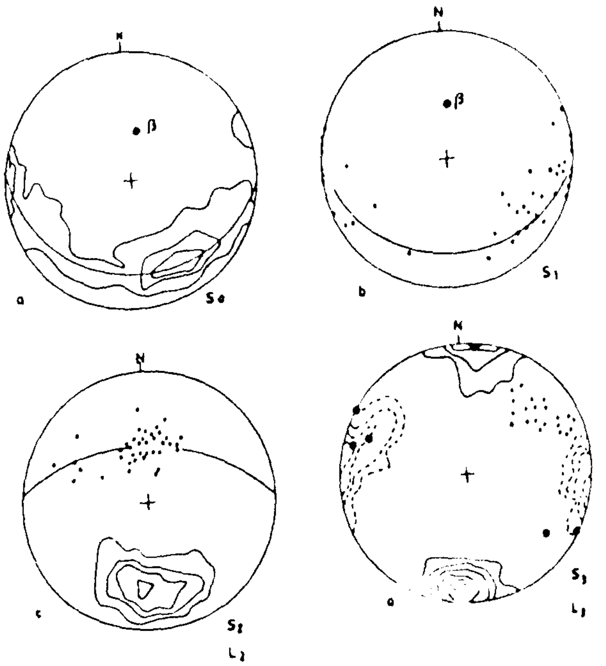

Figure 10. Equal area plots of structural data from the Sonua fold. **a.** $^{129}S_0$ from northern limb. **b.** S_1 from northern limb; **c** $^{125}S_2$ (contoured) and $^{18}L_2$ (dots) from northern limb. **d.** two sets of D_3 planar (47 and 84 contoured) and (4 and 20) linear structures (dots) from southern limb. Contours at 1%-5%-10%-20%-30% per 1% area.

is 80–90° indicating the reclined nature of the fold. On the southern limb the effect of D3 folding is significant and is responsible for the distribution of S_0 poles on another girdle. It may be noted that on the northern limb a small angle is observed between the S_0 and S_1 maxima and the slight difference in the orientation of β_{S_0} and β_{S_1} may reflect the nonparallelism of the two planes. On the hinge zone and on the southern limb S_0 and S_1 are subparallel. This variation matches with the pattern described by Ramsay (1967) for folding of two nonparallel planes by flexure flow; on one limb the initial angle increases and it decreases continuously across the hinge to the other limb.

South of Lotapahar the bedding plane attitudes define a number of easterly and westerly closing folds (figure 2). The direction of younging determined from cross-lamination indicates that the easterly closing folds are synclines and the westerly closing folds are anticlines. The three well-defined folds are, from north to south: (a) Somora syncline (b) Sarjamhatu anticline and (c) Dhobadia syncline. The orientation parameters determined from the equal area projection diagrams from the different sectors covering the three folds are given in table 3. In each sector S_2 shows a well-defined maximum; S_0 shows two maxima with a spread along an approximate great circle. The two maxima correspond to the two limbs of the folds. L_2 shows a maximum with a spread along a great circle that coincides with the mean orientation of S_2. The L_2 maximum is close to β_{S_0}, but the two are not always strictly coincident, which probably suggests a slight deviation of the cleavage from the axial plane. The pitch of β_{S_0} on the mean S_2 plane varies from 65° to 75°; hence the folds are not

Table 3. Orientation parameters in the Lotapahar region.

	S_0 max. Strike	Dip	S_2 max. Strike	Dip	β_{S_0} Plunge	L_2 max. Plunge
Somora Syncline	22	70 W	265	70 N	67 →325	70 →350
	268	72 N			70 →35 (A)	
					70 →272 (B)	
Sarjamhatu Anticline	16	72 W	282	70 N	68 →329	72 →334
	332	90				
Dhobadia Syncline	344	64 W	292	70 N	56 →334	54 →315
	26	58 W				
Lotapahar Syncline	262	60 N	276	60 N	60 →358	55 →340
	130	70 NE				
	155	74 NE	270	55 N		48 →350

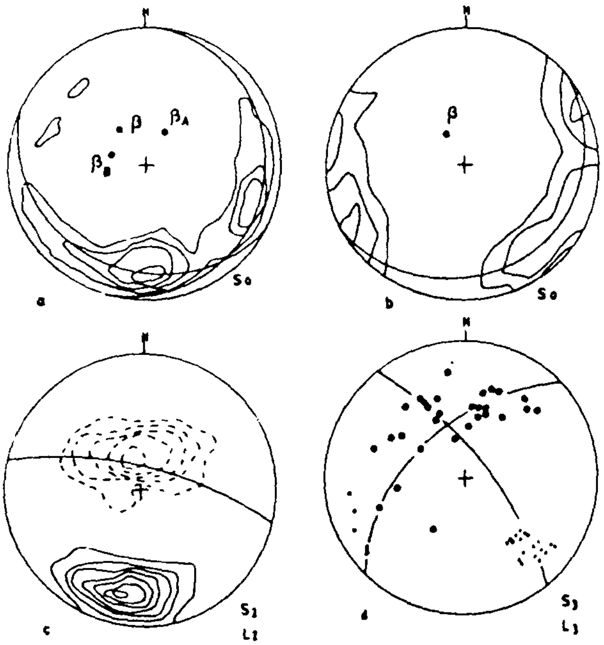

Figure 11. **a**. 668 S_0 from Somora syncline. **b**. 297 S_0 from Sarjamhatu anticline. **c**. 267 S_2 (solid contours) and 188 L_2 (dashed contours) from Sarjamhatu anticline. **d**. two sets of D3 planar (small dots) and linear (large dots) structures from Lotapahar syncline. All contours at 1%-3%-5%-10%-15%-20%-25% per 1% area.

strictly reclined. Some variation of S_2 poles is seen in each sector as a result of fanning and refraction (figure 11c). The plots from the Somora syncline show an interesting feature (figure 11a). The S_0 poles do not lie on a single great circle which indicates noncylindrical nature of the folding. The two maxima give the average attitudes of bedding on the two limbs and their line of intersection may be taken to indicate the overall attitude of the Somora fold axis (β_{S_0}) which plunges 67° towards 325°. Small scale folds are present on the limbs and these have caused the distribution of poles on two different great circles for the two limbs (figure 11a). The corresponding βs ($\beta_{S_{0(A)}}$ and $\beta_{S_{0(B)}}$) plunge 70° towards 272° and 70° towards 35° (table 3). Thus, the smaller folds on the limbs are not coaxial with the larger fold and the axes of the smaller folds define a chevron pattern (Ramsay and Sturt 1973) over the large fold.

North of Lotapahar no fold closure is exposed, but the existence of a synclinal fold is inferred from the change in the bedding strike from E–W to NW–SE, the reversal in the direction of younging in the E–W striking and NW–SE striking quartzite bands (figure 2) and the reversal in the acute angle relation between S_0 and S_2. The pitch of β_{S_0} and L_2 maximum on mean S_2 is nearly 90° and the Lotapahar syncline is of reclined nature.

It may be mentioned that the structural continuity between the two easterly closing folds, the Lotapahar syncline and the Somora syncline, could not be established because of the lack of exposure in the intervening region. It is probable that the westerly closing fold between the two synclines is disrupted by a fault — the Lotapahar fault of Dunn (1929).

4.3 *Third phase structures*

D3 minor folds and crenulations are sporadically developed throughout the region. Locally a cleavage has developed parallel to the axial planes. D3 structures are well-developed on the southern limb of the Sonua fold. Here they are responsible for the distribution of S_0 poles on a second girdle (table 2). Puckers and open asymmetrical folds are developed on S_2. They have E–W striking, steeply dipping axial planes and gently plunging axes (figure 10d). The axes of a second set of puckers and broad warps on schistosity and bedding plunge moderately towards northeast, and their axial planes dip steeply towards NW or SE (figure 10d).

Near Lotapahar the axial planes of D3 puckers belong to two sets: NE–SW strike with steep northwesterly dip and NW–SE strike with steep northeasterly dip. The axes are highly variable (figure 11d).

5. Regional structurai pattern

The major structures at both Sonua and Lotapahar are D2 folds on E–W axial planes. The folds are nearly reclined, but there is some variation in the pitch of lineation on the D2 schistosity surface. The generalized strike of bedding over the whole region, based on photogeologic study and field mapping, is shown in figure 12. East of the mapped area a prominent easterly closing fold is defined by the Ongarbira volcanics (figure 1; Dunn 1929; Sarkar and Srivastava 1982). The quartzite at Tuibo joins up with that at Sahedba (figures 2 and 12) over the closure of this fold (figure 1). The Somora syncline, Sarjamhatu anticline and Dhobadia syncline south of Lotapahar (figure 2) are second-order folds developed in the core of the large Ongarbira fold. The bedding strikes suggest that the southern limb of this fold continues westward upto Sonua defining there a westerly closing fold (figure 12). Thus the Sonua fold and the Ongarbira fold appear to form together a large synclinal "eyed fold". Of course this is to be confirmed by more detailed study in the area between Sonua and Lotapahar.

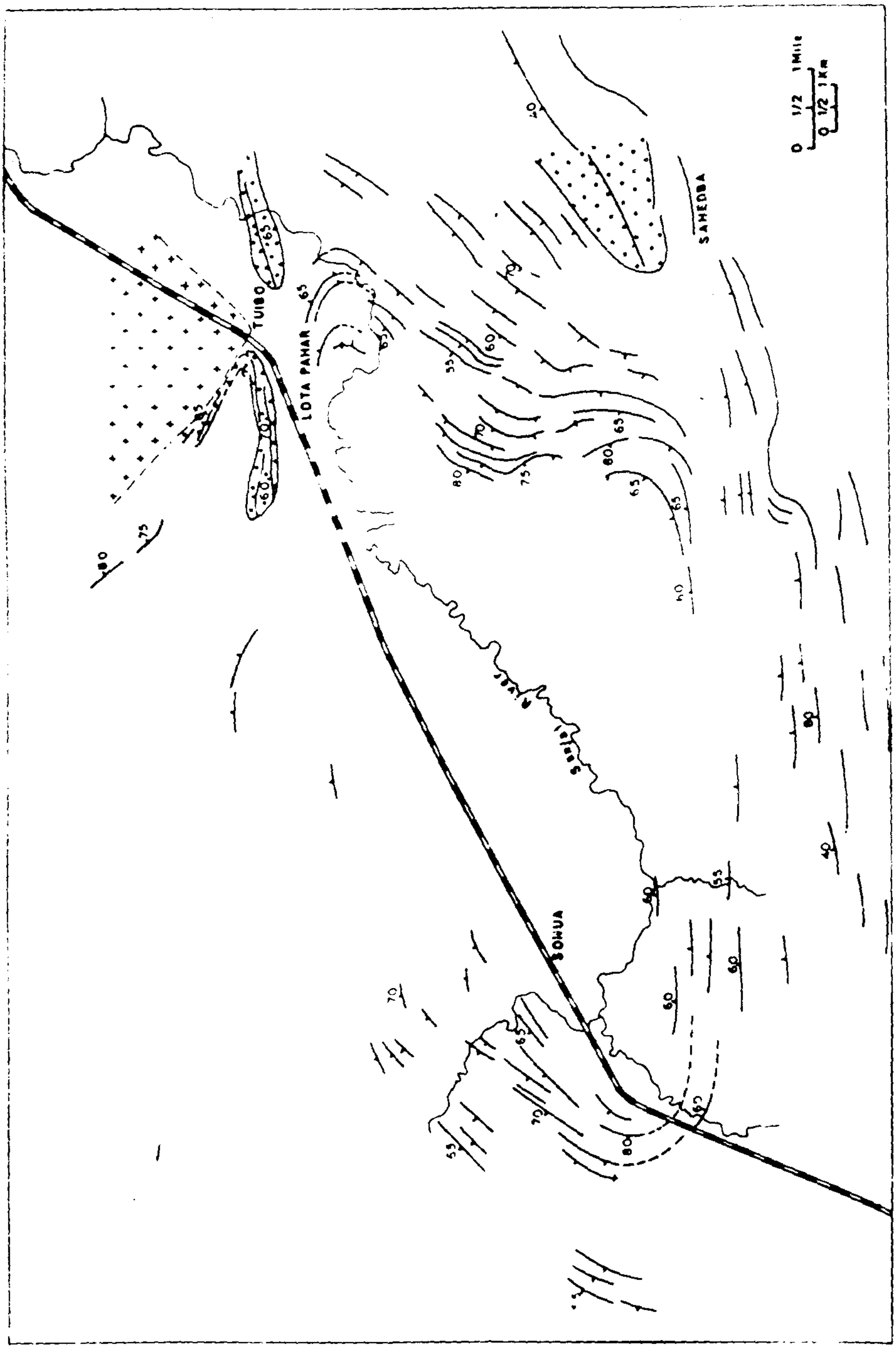

Figure 12. Trend map of bedding in the Lotapahar-Sonua region based on photogeological study with field check.

In the western part of the North Singhbhum fold belt the presence of a series of major folds on E–W axial planes is clearly demonstrated by the tortuous outcrop pattern of the Dalma volcanics (figure 1; Dunn 1929). The major folds in the area under study belong to the same set and form an integral part of the overall pattern of alternate easterly and westerly closures (Sarkar and Chakraborty 1982). As in the present area, such folds at Sonapet and Tebo-Hesadi, north of Lotapahar, are shown to be second generation structures (Bhattacharya 1966; Sarkar and Bhattacharya 1978). However, the presence of D1 major folds in western Singhbhum is yet to be demonstrated and hence the regional importance of the first deformation is uncertain.

No mylonite belt is located within the mapped area and there is a structural continuity from north to south. Therefore, the Singhbhum shear zone cannot be extended westward in this area. The Dalma volcanics and Ongarbira volcanics occupy comparable structural horizons. The continuity between them is lost as a result of attenuation and faulting on the fold limbs. The uniformity of the structural pattern indicates that the North Singhbhum fold belt extends at least up to the southern boundary of the area in figure 12. Though there are faults, within the limits of the area mapped no discontinuity surface that separates two orogenic belts of Archaean and Proterozoic age exists (cf. Sarkar and Saha 1977).

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