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Research Paper

STRUCTURAL ANALYSIS IN THE CENTRAL SECTOR OF THE NORTH SINGHBHUM FOLD BELT IN AND AROUND SINI, JHARKHAND DISTRICT, BIHAR, INDIA

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The study area is dominantly made up of pelitic, semipelitic schists, amphibolites and quartzite. The metasedimentary sequence has been intruded by granitic rocks in two phases. Signatures of polyphase deformation are clearly discernible in these rocks. The first phase of deformation (D_1) produced schistosity (S_1) with downdip lineation. Mesoscopic isoclinical folds are rarely seen. The second phase deformation (D_2) produced asymmetric folds on S_1 and axial planar crenulations cleavage (S_2). In the northern part S_2 has almost completely obliterated the earlier schistosity and the regional schistosity is here combined (S_1/S_2). The last deformation episode D_3 gently folded S_1 and S_2 on transverse axial planes. Mylonites, ultramylonites and phyllonites are confined to the southern part of the area which represents the western extension of the Singhbhum Shear Zone. Mylonitic foliation within the feldspathic schist and micaceous phyllonite is parallel to S_1. Isolated late stage shear zones occur throughout the area. Evidences suggest that shearing started during D_1 and occurred during different stages in the deformation history. The deformation events comprising D_1, D_2, D_{2A} and ductile shearing are parts of the same deformation cycle with N-S compression combined with simple shear with top-to-the-south sense of movement. Late stage longitudinal compression occurs during D_3.

Keywords: Pressure solution bands, Transposed schistosity, Differentiated crenulation cleavage, Extensional crenulation cleavage, Progressive shearing, Conjugate shear planes

INTRODUCTION

The E-W trending Proterozoic fold belt of North Singhbhum, is flanked to the south by the Archean nucleus of Singhbhum and to the north by the Chhotanagpur Granite Gneiss terrain. A median belt of mafic volcanics (Dalma lavas) subdivides the fold belt into two parts. The present area lies in the central part of the southern section of the fold belt. The Singhbhum Shear Zone which is a more than 100 Km long arcuate belt with northward convexiety passes along the southern flank of the North Singhbhum Fold Belt. This

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Singhbhum Shear Zone (or Copper Belt Thrust) seperates Iron Ore "Stage" and Singhbhum Granite in the south from Chaibasa "Stage" in the north (Dunn and Dey, 1942) (Figure 1). In the recent years it has been proposed that the Indian Peninsular Shield is made up of two blocks, the southern Dharwar-Bastar block and the northern Bundelkhand block. The blocks were amalgamated during mid-Proterozoic and their junction is referred to as the Central Indian Tectonic Zone (CITZ, Radhakrishnan, 1988; Yedekar *et al.*,1990; Jain *et al.*, 1995 and Acharya, 2001). The north Singhbhum fold belt is the eastern continuation of CITZ.

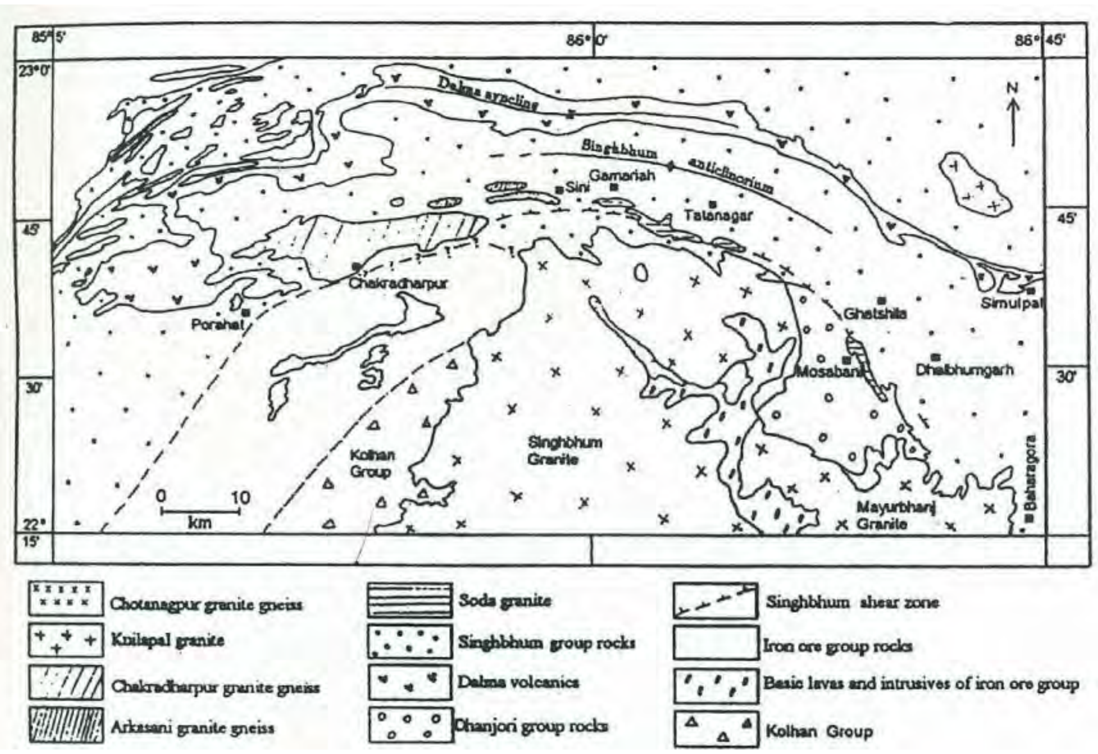
METHODS OF STUDY

Mapping was done on 1:25,000 scale using an enlarged copy of the Survey of India Toposheet as base map. Altitudes of various planar and linear structures were measured and the relations between different structural elements were studied both in hand specimen and thin section. Structural and lithological maps were prepared.

Lithology

The area (latitudes 22^{0}46'N and 22^{0}51'N and longitudes 85^{0}54'E and 86^{0}3'E) (Figure 2) covers a part of the Singhbhum Shear Zone and an area north of it within the Proterozoic fold belt of North Singhbhum and is located near the small township of Sini and Gamaria, Singhbhum District, Jharkhand. The principal rock types encountered in Sini area are quartzite, mica schist and phyllite. Amphibolites (both massive and schistose varieties) are present as discontinuous lenses. Massive granite and granophyres are found in the

Figure 1: Geological Map of Proterozoic Fold Belt of North Singhbhum



Source: Modified from Dunn and Dey (1942)

Figure 2: Location Map of Study Area

southern part of Sini area. Very fine grained feldspathic schist is also present along the banks of Sona Nadi, it is a granitic ultramylonite. Dolerite occur as lenses.

STRUCTURAL ELEMENTS

Planar Structures

Bedding (S_0)

Bedding is found in quartzite and they are marked by colour and compositional banding. The thickness of these bands varies from a few mm to a few cm. Bedding is usually not recognizable in the mica schists. In some semipelitic schists and tourmalinite compositional layers define bedding. In most instances bedding is parallel to the regional schistosity due to isoclinal nature of the first folds and they cross cut each other only near the hinges of the mesoscopic first folds on bedding.

Schistosity (S_1)

It is the dominant planar element in most of the rock types in the southern and central parts of the area. Megascopically, schistosity is defined by parallel arrangement of muscovite, biotite and sometimes chlorite. In thin sections the flaky minerals form thin laminae, which at places show an anastomosing pattern enclosing long, lenticular quartzose domains (Hobbs *et al.*, 1976; and Borradaile *et al.*, 1982).

An interesting structure is found in the banded semipelitic rocks near Charakpathar. Here quartzose and micaceous layers in banded semipelite is cut across by an oblique set of compositional bands defined by regularly spaced thin micaceous laminae separating quartzose domains. It is inferred that this secondary banding originated at relatively low grade of metamorphism by a process of solution transfer associated with the formation of differentiated crenulation cleavage (Gray, 1977a and 1979) parallel to the axial planes of folds on a primary fabric parallel to bedding. Subsequent recrystalization during higher grade metamorphism obliterated the traces of earlier crenulated fabric and we now observe a regular secondary banding cutting across the primary compositional bands (bedding). Such pressure solution bands accompanying the formation of crenulated cleavage has been described by Ramsay and Huber (1987, p. 439) as tectonically formed striping or banding. This secondary banding, a first generation structure (S_1) is parallel to the schistosity of the adjacent mica-schist.

Mylonitic Foliation (S_1)

In the southern part of the area, the extremely fine grained feldspathic schist represents an ultramylonite derived from a granitic protolith. The main foliation is defined by parallelism of tiny flakes of mica and chlorite as well as very thin micaceous or chloritic laminae within an ultramylonitic matrix. Within feldspathic schists exposed along Sona Nadi and Sanjay Nadi (in the southern part of the study area) a regular colour banding is found (Figures 3). Lighter bands are ultramylonitic and composed of fine-grained quartz and feldspar, whereas darker bands are made up of muscovite, biotite and chlorite flakes. A banded migmatite could have been the protolith of this banded mylonite. Alternatively, the distributed mafic and felsic minerals in the original granite could have become concentrated in bands during deformation as a result of contrasted, ductility (Passchier et al, 1990, p. 26-34, Ramsay and Huber, 1987, p 591). In the less deformed granitic rocks an augen structure is developed and lenticular quartzo-feldspathic augen are wrapped around by anastomosing micaceous laminae. With greater intensity of deformation the rock is converted to a finely foliated quartzo-feldspathic rock with only a few tiny porphyroclasts. The mylonitic foliation in both the feldspathic schist (ultramylonite) and the less deformed granite has a very strong nearly downdip stretching lineation. The mylonites show isoclinals/tight early folds of reclined nature as well later asymmetric folds with gentle to steep plunges. The foliation in phyllonites is also grouped under mylonitic foliation. Characteristically the phyllonitic foliation is of composite nature with sigmoidal S and C planes (S-C fabric) (Figure 4). Typically the angle between the two planes is 20°-30°. The movement planes are defined by micaceous/chloritic laminae and the S-planes by small phyllosilicate flakes. Often the C-surfaces ramps up to a higher level giving rise to sigmoidal shape. Such ramps are subparallel to the S-fabric defined by small phyllosilicate flakes. Asymmetric tails against porphyroblasts or lenticular aggregates are common. The phyllonitic foliation is cut across by later shear planes (C'-planes, Berthe *et al.*, 1979). The foliation in the mylonites and phyllonites is parallel to the schistosity in the

Figure 3: Ultramylonite with Alternate Quartzo-Feldspathic and Chlorite-Biotite Bands Near Sona Nadi, Southern Part of the Area

Figure 4: S-C Fabric in Phyllonite, Occassional Dragging of the Oblique Flakes Along the Movement Surfaces South of Sini

neighbouring rocks; hence these are all grouped together as S_1.

Crenulation Cleavage/Transposed Schistosity (S_2)

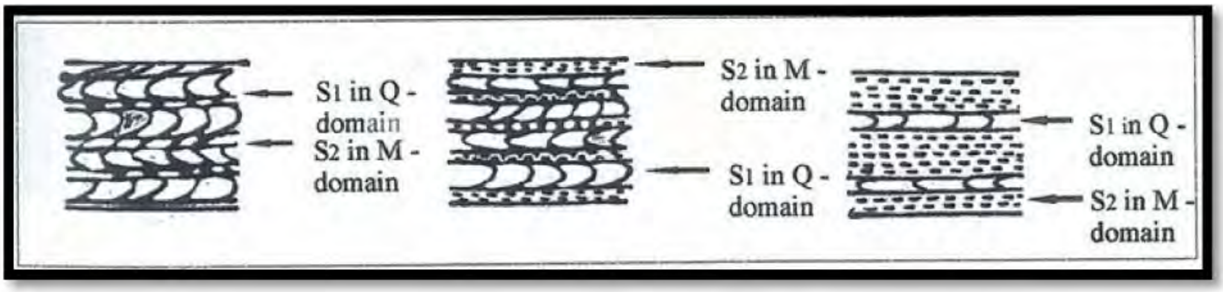
In the southern part of the area the schistosity is folded and crenulation cleavage parallel to the axial planes of the folds is well developed in mica schists. Both discrete and zonal crenulation cleavages (Gray, 1977b) are observed. In some banded rocks the cleavage appears as discrete planes in the quartzose bands (Figure 5) while in the micaceous bands it is of zonal nature. Some mica flakes have recrystallised parallel to the crenulation cleavage. In the northern part of the area near Sini Pahar, Charakpathar and Khadan Hills the main foliation in the meta-pelitic rocks apparently appears to be a schistosity, and its formation is accompanied by metamorphic differentiation that has given rise to a few mm thick siliceous bands separated by thin micaceous laminae. These correspond to M-domains or cleavage domains and QF-domains or microlithons (Davies, 1996). However, careful examination reveals that the fabric is a differentiated crenululation cleavage, and folded early schistosity is clearly recognizable within the quartzose domains. S_1 can sometimes be traced continuosly across the domain boundary. In micaceous bands the S_1 mica flakes are folded and an axial planar S_2 fabric has developed. At many places S_2 has almost completely transposed the earlier schistosity (S_1), but isolated first fold hinges (Figure 6) defined by earlier mica flakes are still present, their axial planes being parallel to the main foliation (S_2)

Figure 5: Discrete Crenulation Cleavage in Quartzose Band in Banded Toumalinite, Kukudungri, Northern Part of the Area

In some thin sections within M-domains relict earlier mica is present as isolated transverse flakes truncated by S_2-parallel flakes. Similar features are also seen at Kukudungri. It is, therefore, concluded that the main planar fabric

Figure 6: S_2 Tranposing S_1, Isolated Relict Hinge of D_2 Fold Defined by S_1 Mica, Sini Pahar

Figure 7: Stages in the Development of Quatzose and Micaceous Domains in Crenulations Cleavage



Source: Hobbs et al. (1976)

in the northern part of the area is a second generation structure (S_2) which has almost completely transposed the earlier schitosity (S_1). Stages in the development of micaceous and quartzose domains in such transposed foliation are schematically illustrated in (Figure 7).

Linear Structures

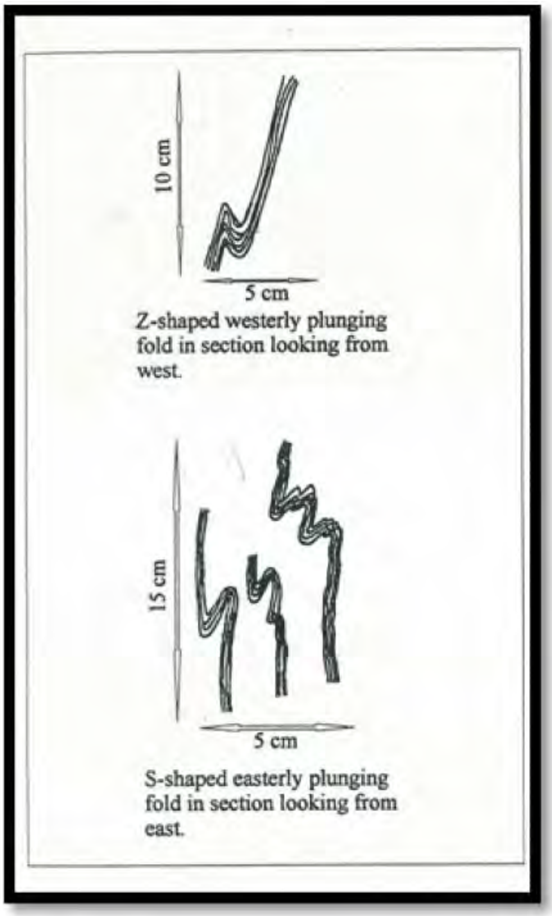
Mineral lineation is best developed in pelitic schist, amphibolites and feldspathic schist. In the schistose rocks this is formed due to linear arrangement of biotite, muscovite and chlorite on the schistosity surface. In some feldspathic schists elongated clots of biotite and chlorite on the mylonitic foliation define mineral lineation. In some deformed granites ribbon shaped quartz grains define a lineation on the foliation surface. Mineral lineation in the rocks of southern part of the area is nearly downdip. These lineations on schitosity are first generation lineation (L_1). Striping lineation is the trace of bedding on the schistosity plane and appears as bands of different colours on the schistosity plane. It is found within quartzite and pelitic schist, mostly in the southern part of the area. In the pelitic schist of the northern part of the area the intersection of crenulation cleavage (S_2) and schistosity (S_1) defines a second-generation lineation (L_2) and is parallel to axes of puckers on schistosity. In amphibolits elongation of amphibole needles defines the mineral lineation which is parallel to the second-generation crenulation axes and S_1/S_2 intersection lineation.

Minor Folds And Puckers

Minor folds of this area belong to different generations. The earliest folds (D_1) are small isoclinals folds with axial plane schistosity found in feldspathic schist, banded semiplite and tourmalinite. Their axes are parallel to the downdip mineral lineation and striping (L_1). Second generation folds (D_2) are crenulations on schistosity and mylonitic foliation. They have a constant sense of asymmetry, being S-shaped in section looking from east or Z-shaped looking from west (Figure 8). Their plunge is generally low but variations are observed. These minor folds bend the early lineation.

At places in Sini Pahar and Charakpathar i.e. in the northern part of the area, the folds on S_1 are overturned and have northerly dipping axial planes. Folds and crenulations with transverse axial planes (D_3) have developed on the different planar fabrics. The strike of axial planes of these transverse minor folds is nearly perpendicular to that of the regional schistosity. Their axes are

Figure 8: Asymmetrical D_2 Folds in Section, Sona Nadi, S-Shaped Looking from East and Z-Shaped Looking from West



nearly downdip on the schistosity surface. In addition to these, very late folds with gently dipping axial planes have bent the S_2 fabric.

Shear Zone Structures

The feldspathic schists are ultramylonites derived from granite. The occurrence of these and of the phyllonites in the southern part of the present area marks the Singbhum Shear Zone. The nearly downdip lineation indicates the movement direction during the main mylonitization phase. There is no distinct structural or metamorphic break across the shear zone. The structural features of the Singhbhum Shear Zone are well documented in the region east of the present area (Ghosh and Sengupta, 1990; and Mukhopadhyay and Deb, 1995). The mylonitic foliation is parallel to the schistosity in the surrounding schists and phyllites (Figure 9). Hence, the mylonitisation is regarded to have started during the first deformation. Shear sense is indicated by consistent asymmetry of minor folds of the mylonitic foliation, c-c' relation, asymmetric deflection of foliation against porphyroblasts, stair-stepping of tails (Passchier and Trouw, 1998) against lenticular aggregates of porphyroblasts and elongation of dynamically recrystallized quartz (Figure 10). Axes of the asymmetrical folds mylonites and phyllonites have variable plunge, from being nearly downdip to gentle westerly plunge. The folds also show varying degrees of tightness. While in cross section the folds always show the same sense of vergence (S-shaped viewed from east), on the horizontal surface both S and Z shapes are found depending on the direction of the plunge. Similar phenomena have been described by Mukhopadhyay and Deb (1995) east of the present area. Following them, we interpret this as being due to rotation in

Figure 9: Mylonitic Foliation in Feldspathic Schist Folded on Transverse Axial Planes, Sona Nadi, Southern Part of the Area

Figure 10: Asymmetrical Deflection on Foliation Against Garnet Porphyroblast

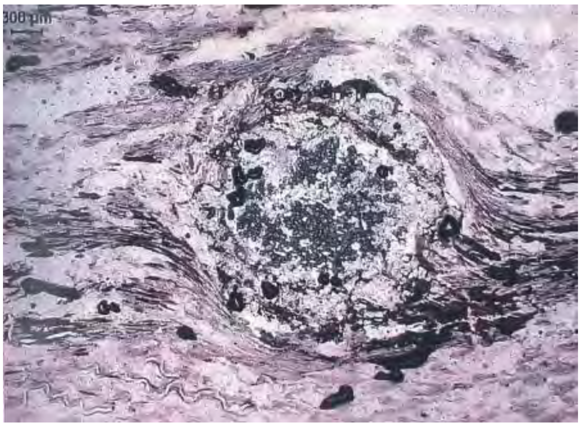
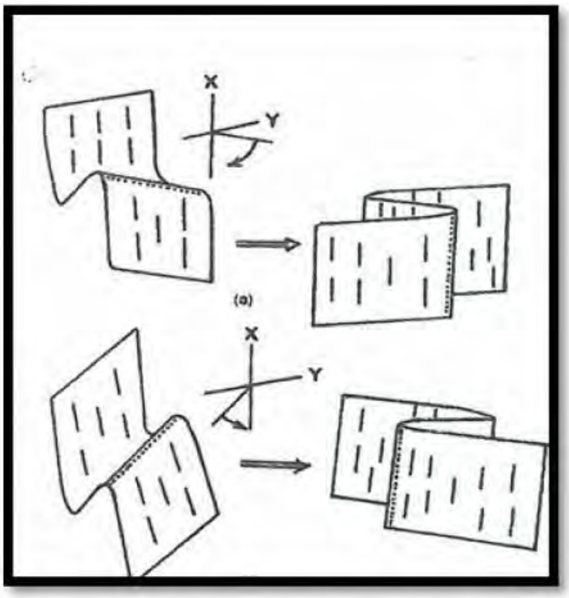


Figure 11: S Shape and Z Shape in Plan of D_2 Minor Folds Caused by Rotation in Opposite Sense of Axis of Asymmetrical Folds

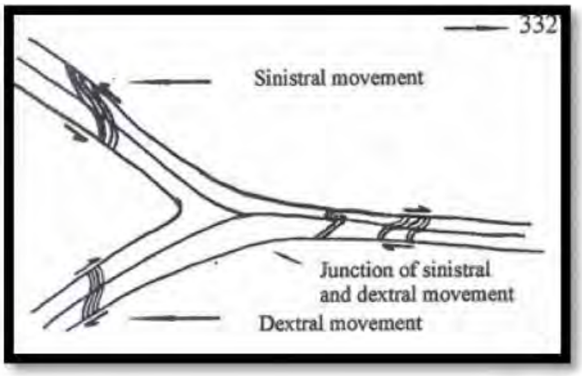


Source: Mukhopadhyay and Deb (1995)

opposite sense of axes of asymmetric minor folds during progressive shearing (Figure 11).

Though the effects of shearing are more common in the southern part of the area, even in the higher grade rocks of the north shear planes are discernible.

Figure 12: Conjugate Shear Zones in Granite, Sona Nadi (S-C Angles are Only Schematically Shown), Southern Part of the Area



The presence of ultramylonitic granites indicates a phase of pre-mylonitisation granite emplacement. On the other hand, the younger coarse-grained granite and granophyres are post-mylonitization. However, later discrete shear zones, tens of centimetres wide, are present in them and the granite is converted to quartzo-feldspathic schist within these discrete shear zones. The shear zones sometimes show anastomosing pattern and at places conjugate shear zones (Figure 12) are present.The internal mylonitic foliation in these shear zones is at acute angle to the shear zone walls and often displays a sigmoidal curvature. The sense of movement can be inferred from the sigmoidal shape of the foliation. In the central part of the shear zone where the deformation is more intense the foliation is almost parallel to the shear zone walls. Majority of those discrete shear zones in granite show dextral sense of movement on horizontal surface. The presence of the shear zones within granite indicates that shearing movement continued to the late stages in the history of evolution of the belt.

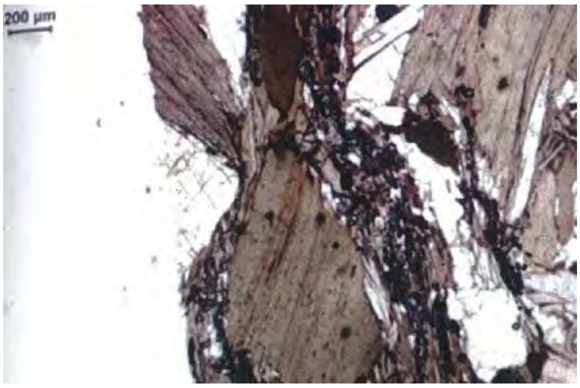
Deformation Sequence

The first phase of deformation (D_1) produced the schistosity (S_1) which is axial planar to the minor isoclinal folds. Early folds are found in feldspathic schist near Ukri in the southern part of the area and in banded tourmalinite and pelitic schist near Kukudungri in the eastern part. In the semi-pelitic schist a secondary compositional banding is at places produced by the deformation. The stretching lineation (L_1) associated with this deformation is nearly downdip on the schistosity surface.

The second phase of deformation (D_2) produced asymmetric folds and bent the first lineation. Axial plane crenulation cleavage (S_2) is observed in the southern part of the area and in the northern Part S_2 has completely transposed S_1 to become the main planar fabric in the rocks. Both S_1 and S_2 are northerly dipping but S_2 dips more steeply than S_1.In the northern part of the area near Bikanipur and Rangamatiya, the main foliation, which is a transposition structure (S_2), is again folded at a few places on steep northerly dipping axial planes. Unlike in S_2 no segregation banding is produced parallel to these axial planes. These folds have the same sense of asymmetry as the D_2 folds and probably represent continuation of the D_2 deformation episode. These are labelled as D_{2A} folds. Mylonitization involved slip on the D_1 schistosity surface and the mylonitic foliation is parallel to S_1. However shearing continued in the late stages also though its intensity was less. This is indicated by the presence of isolated shear zones within the younger granophyre and of S_2–parallel shear planes in the staurolite-kyanite-sillimanite bearing mica schists (Figures 13).

Hence it is concluded that mylotinization started during D_1. The shear sense criteria indicate top-to-the-south sense of movement (thrust sense). The asymmetry of D_2 folds is consistent with this sense of movement and it is likely that D_2 folds is consistent with this sense of movement and it is likely that D_1, and D_2/D_{2A} represent early and late stages of a continuous episode of deformation in which south directed shear was an important component. Extensional crenulations cleavage with gentle northerly dip has caused sigmoidal curvature of S_1 and S_2 foliation. These are c' planes formed at late stage of shearing deformation.

Figure 13: S_2 Parallel Shear Surfaces Marked by Granules of Staurolite and Small Parallel Flakes of Biotite Truncating Earlier Biotite Porphyroblasts, Direction Sense of Movement is Indicated by Dragging of Basal Cleavage of One Biotite Porphyroblast, Near Sini Pahar, Northern Part of the Area



A third phase of deformation (D_3) has given rise to broad warps on the schistosity with transverse axial planes and nearly downdip axes. An excellent example of Type 2 interference pattern (boomerang form) resulting from D_2 and D_3 folds is observed at Kukudungri (Figure 14). The early mineral lineation is bent by tight asymmetric D_2 folds with steep dipping axial planes. The D_2 axial planes are refolded sinistrally by D_3 folds. The D_2 fold axes are also bent by the later deformation producing Type 2 interference pattern. The D_{2A} folds have NNE-SSW trending subvertical axial planes and the axes have

Figure 14: Interference Pattern Produced by D_1 and D_{2A} Folds, Mineral Lineation is Bent by D_2 Folds

different orientation on the two limbs of the D_2 folds. In addition, gentle folds on S_2 with sub-horizontal to low dipping axial planes are sporadically found. These have resulted from vertical compression on the steep dipping foliation and probably formed at a very late stage due to superecumbent load.

Structural Synthesis

Regional schistosity is northerly dipping throughout the study area. Isoclinal minor folds on compositional banding, with axial planar schistosity, are observed at places.

In the south within the granite mylonite and the phyllonitic rock the mylonitic foliation is parallel to the first schistosity. This would suggest that the mylonitization started during the first phase of deformation (D_1). The nearly downdip mineral lineation represents the stretching direction and indicates the direction of movement during shearing. Shear sense indicators point to thrust type movement (top-to-the-south). The high easterly rake of the lineation maximum (i.e., in the southern part of the area) indicates that the thrust movement was combined with horizontal sinistral component. This mylonitic zone is the western continuation of the Singhbhum Shear Zone.

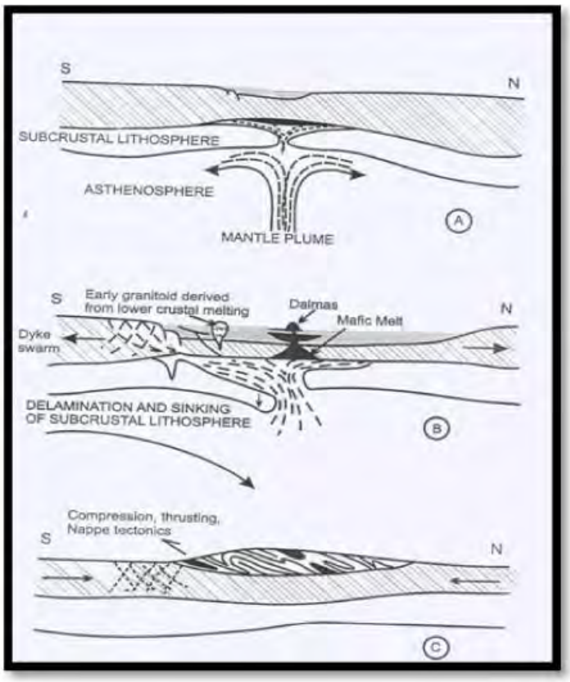
The schistosity and mylonitic foliation are folded into asymmetrical folds (D_2) with axial planes dipping more steeply than the schistosity. The folds had gentle plunges in the initial stages and with increasing deformation the axes rotated towards the direction of elongation. They have a constant sense of vergence (S-shaped in section looking from east), consistent with the top-to-the-south shear sense.

In the northern part of the study area near Sini Pahar and Charakpathar the main foliation is more steeply dipping compared to the southern part of the area. This is because this is the later foliation (S_2) which has almost completely transposed the earlier schistosity (S_1). Continued deformation (D_{2A}) has at a few places folded the S_2 fabric on steep northerly dipping axial planes.

Consistency of the asymmetry of the D_2/D_{2A} folds with the other shear sense criteria associated with mylonitization suggest that D_1, D_2 and D_{2A} represent the early and late stages of a continuous period of deformation. This deformation was caused by N-S compression combined with simple shear that gave rise to ductile shear zone with thrust sense of movement (top-to-the-south) combined with a sinistral horizontal component.

Mylonitic fabric and downdip lineation are absent in the northern part of the area where the rocks are more metamorphosed in comparison to the southern part. This metamorphism was post-mylonitization and it has obliterated any shear related fabric that might have been present in the northern part. It is also to be noted that in the northern part the D_2 folds are mostly gently plunging and hence their axes have not rotated much from their initial orientation.

Figure 15: Tectonic Model of North Singhbhum Fold Belt



Source: Ghosh et al. (2006)

A third set of minor folds has steep dipping axial planes, which are transverse to the strike of the main planar fabric and the axes are nearly downdip on main foliation plane. These belong to the last stage of deformation and are present throughout the study area.

CONCLUSION

Conclusion from the deformation history initial asthenospheric upwelling and rifting followed by intracontinental subduction and compressional deformation leading to loading and heating is envisaged. Sedimentation was going on along the continental margin of the southern Singhbhum Archaen nucleus when the subduction process started. The metasedimentary sequence has been intruded by granitic rocks in two phases. Weakly deformed younger granite ('Arkasani Granophyre' of Dunn, 1929) intruded during the waning stage of deformation. Signatures of polyphase deformation are clearly recognisable in the rocks. First phase deformation (D_1) produced schistosity (S_1) with downdip lineation and the rarely observed isoclinals minor folds. Second phase deformation (D_2) produced asymmetric folds on S_1 and axial planar crenulations cleavage (S_2). In the northern part S_2 has completely obliterated S_1 and the regional schistosity is here combined S_1/S_2. The down dip mineral lineation is absent in northern schistose rocks having transposed S_1/S_2 schistosity. A continuation of the second phase of deformation (D_{2A}) folded the transposed schistosity (S_1/S_2) on steep northerly dipping axial planes. The last deformation episode D_3 gently folded S_1 and S_2 on transverse axial planes. Mylonitic foliation is parallel to S_1. Mylonites and ultramylonites are confined to the southern part of the area, which represents the western extension of the Singhbhum Shear Zone. Sporadic small scale shear zones are found even in the schistose rocks to the north and within the late phase granite. Mylonitisation started during D_1, but formation of late stage shear zones and the asymmetry of D_2 and D_{2A} minor folds indicate existence of simple shear regime throughout the deformation history. Shearing had consistent thrust sense (top-to-the-south) movement. D_1, D_2, D_{2A} and ductile shearing parts of the same deformation cycle with N-S compression combined with simple shear with top-to-the-south sense of shear.

Deformation history of the present area is consistent with the tectonic model presented by Ghosh *et al.* (2006) (Figure 15). Their model envisages initial asthenospheric upwelling and rifting followed by compressional deformation leading to loading and heating. New information from sediment geochemistry suggests active continental margin setting. Hence a subduction zone (intracontinental subduction) process started when sedimentation was going on along the continental margin of the southern Singhbhum Archean Nucleus. More information about the sedimentation history, geochronology and timing of deformation and metamorphic events is needed to tightly constrain the tectonic model.

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