Abstract

The Gangpur Group has remained an enigma in the Precambrian geology of the Indian sub-continent. In the past this E through W to SW sigmoidal shaped metasedimentary belt comprising of argillaceous, arenaceous, calcareous and carbonaceous rocks has been interpreted as an anticlinorium as well as a synclinorium by different authors. This is why the 'Gangpur Structure and stratigraphy' has been misinterpreted so far. Becuse of very poor exposures in the far western part of the Gangpur Group, earlier workers interpreted the 'Gangpur Fold' on the basis of data from western and eastern parts. Though this work covers the eastern part of the Gangpur Group, an attempt has been made to unravel the structure and stratigraphy of the entire Gangpur Fold and a new model that lucidly explains the structure and stratigraphy has been put forward in this work. This model brings out the structures in the far western part of the Gangpur Group that was hitherto unknown. These structures have been corroborated by modern exploratory tools — satellite imageries and soloid geology data some of which are classified. The integration of these new data along with that of our findings and earlier interpretations brings out an entirely new structure for the Gangpur Group.

Careful investigation of the primary sedimentary structures like the current bedding and graded bedding from several places over the area has helped to decipher the strucrure and stratigraphy of the Gangpur Group. The northerly younging current bedding and graded bedding in the Raghunathpalli conglomerate near Bisra in the southernmost limb of the Gangpur Fold indicates that the Gangpur sediments young towards the core at the outermost stratigraphic level. The south-westerly younging current bedding near Sorda also indicate coreward younging direction at the hinge of the Gangpur Fold. Current beddings in gritty quartzite at Jhirpani near Rourkela proves that the Gangpur sediments young towards north (towards the core of the Gangpur Fold) in the southern limb at the intermediate stratigraphic level. The southerly younging current bedding SW of Purnapani shows coreward younging direction in the northern limb at the intermediate stratigraphic level. The south-westerly younging current bedding near Pandua, SE of Purnapani also indicate core-ward younging sedimentary sequence at the intermediate stratigraphical level. Therefore, the coreward younging sedimentary sequence evident at the outer and intermediate stratigraphical levels, both in the southern and northern limbs belies the fact that the Gangpur Fold is neither an anticlline nor a synclinorium sensu stricto.

The Raghunathpalli conglomerate in the southernmost limb of the Gangpur Foldhas been depicted in the past as an unconformity representing a prolonged period of non-deposition, a disconformity and also as a zone of cataclasis by various authors. Our observation is that the Raghunathpalli conglomerate and the Gangpur sediment as a whole is younger than the rocks that surround it to the south, east and north. The conglomerate does not represent any pronounced unconformity or break in sedimentation; the rocks to the immediate south in the southern limb i.e. the Rajgangpur Formation may

belong to the Gangpur Group in a continuous sequence.

The metasediments of the Gangpur Group bear unequivocal evidence of superposed deformation at the microscopic, mesoscopic and macroscopic scales of observation. The eastern macrodomain to the east of longitude 84° 45′ was divided into 23 statistically homogeneous domains and structural analysis was carried out with a view to finding out the structural relationship among the fold movements. Three generations of fold movement differing in tectonic style and orientation are discernible.

The first fold movement F_1— the earliest tectonic activity in the Gangpur Group, has produced isoclinal reclined folds on the bedding planes (S_0) that plunge easterly. S_1 schistosity is axial planar to the F_1 folds and L_1 lineations are parallel to the F_1 fold axis. The second generation of folds F_2 are upright folds with vertical to sub-vertical axial planes striking E–W. The F_2 folds coaxially fold the limbs and axial planes of the F_1 folds. The β diagrams show nearly identical concentration of the S_0 and S_1 planes which suggests coaxial nature of F_1 and F_2 folds. A perfect coaxiality is observed in a single domain (Domain 15). In some domains a small angle is discernible between the β_1 and β_2 axes which indicates a small deviation from coaxiality.

The superposition of the F_1 and the F_2 folds have resulted in Type 3 interference pattern. The hook-shaped outcrop pattern is evident at the mesoscopic and macroscopic scales. The coaxial relationship between the fold movements is not maintained where the dimensions of the folds vary much. In cases where the F_2 folds are larger in dimension with respect to the first folds then the coaxiality is lost and the smaller F_1 folds are reoriented and rearranged along the limbs and around the hinges of the F_2 folds. The coaxial relationship is maintained where the two generations of folds are of comparable dimension or nearly so.

The third fold movement F_3 are gentle upright folds with N–S trending axial planes. F_3 folds are overprinted on the earlier F_1 and F_2 folds which results in zones of culmination and depression of the axes of earlier folds. The elliptical or eye shaped outcrop patterns of a few centimeters to a few meters dimension characterize outcrop scale doubly plunging folds. The paired girdles of S_0 and S_1 poles around a N–S trending vertical plane of symmetry corroborate the overprinting relationship.

A four stage evolution model of the Gangpur Group is presented to explain the structure and stratigraphy of the entire Gangpur Group. The interference patterns that are discernible at the mesoscopic scale are believed to have shaped the macroscopic scale Gangpur Fold.

It is thought that the first fold movement brings out two macroscopic isoclinal reclined antiforms in association with two isoclinal reclined synforms (total five isoclinal limbs) over the area. The axial planes and limbs strike N-S and fold plunges gently towards east down the dip of their axial plane. The stratigraphy maintains its normal position during this stage.

During the next stage the F_2 folds are coaxially superposed on the F_1 folds resulting in large scale axial plane folding. The axial planes and limbs of the F_1 folds are folded by the open upright F_2 folds. Accordingly the N-S oriented F_1 anticlinal and synclinal hinges are reoriented towards west and the F_2 hinges are oriented towards east. During this stage the stratigraphic inversion and reinversion is believed to have taken place. The N–S trending upright F_3 folds in the next stage cause culminations and depressions in the axes of F_1 and F_2 folds.

In this model there is a E-W trending inversion axis that runs through the hinges of easterly closures. North of this inversion axis, former F_1 reclined anticlines are reoriented to synformal anticlines and former F_1 synclinal reclined folds are reoriented to synformal synclines at the far west of the Gangpur Group. Along this inversion axis the inversion is more frequent — from the outermost to the innermost F_2 fold closures the folds are antiformal syncline $\rightarrow$ antiformal anticline $\rightarrow$ antiformal syncline $\rightarrow$ antiformal anticline $\rightarrow$ antiformal syncline.

The Gangpur Fold thus represents a kilometer scale Type 3 interference pattern. The resulting pattern depicts a compound fold where the compressed F_1 fold hinges are stacked up one above the other in the western end and the F_2 hinges show a concentric disposition where the successively inner stratigraphic levels are encased one inside another. The shape typically resembles a "nested hook" pattern. Thus the Gangpur Fold may be aptly described as a "Nested Hook fold".

Earlier workers have described more than one Carbonaceous Phyllitic Quartzite (CPQ) bands belonging to several stratigraphic horizons. One CPQ band belongs to the Laingar Formation (the oldest of the CPQ bands), the second one at the intermediate stratigraphic level belonging to the Kumarmunda Formation and/or a third CPQ band (the youngest of the CPQ bands) describing the core of the Gangpur Fold at Dublabera. This implies that these three CPQ bands are chronologically and geologically different.

In our opinion, however, one and only one CPQ band exists in the Gangpur stratigraphy. The repetition of the CPQ band is attributed to the special geometry of the folds by which the early folds have been refolded by the second fold movement. The special geometry of the superposed folds has caused the repetition of a single band several times over at several stratigrahic levels and also has caused the frequent inversion of the structure along an E–W axis.

We have documented a small scale shear zone exposed in two half-kilometer stretches in the impure marble rocks around Purnapani and named it "Rourkela Shear Zone". This shear zone post-dates the F_1 and F_2 fold movements. The hinges and limbs of the F_1 and F_2 folds are disrupted and displaced by discrete oblique shears of few centimeters to few meters in length. The hinges and limbs of small mesoscopic F_1 folds occurring on the flanks of big F_2 folds have been accentuated and greatly compressed. The F_3 folds may postdate the shear zone as indicated by: doubly plunging folds, elliptical outcrop patterns, zones of culmination and depression inside the shear zone. The occurrence of rootless early folds in the shear zone is significant. The rootless early folds are due to extreme flattening along the shear plane that have caused transposition of mylonitic schistosity on earlier structures leading to flow from the limb towards the hinges. This has led to thinning of limbs and in extreme cases detachment of limbs giving rise to rootless folds. The strong flattening along the shear plane is indicative of sub-simple shear deformation. The occurrence of discrete oblique shears and discrete oblique fractures are strong indicators of sub-simple shear at the mesoscopic scale. Thus shear zone deformation strongly deviated from the often assumed simple shear deformation.

Shear planes and mylonitic schistosity S_m accompanied with it are parallel to the regional foliation defined by white gray colour layering. Mesoscopic shear sense indicators such as shear zone restricted asymmetric folds show that zones of reverse shear coexist with that showing dextral sense of shear. Though majority of the folds reflect dextral shear sense which is consistent with the bulk shear sense, some of them reflect sinistral sense of shear.

In this poorly exposed shear zone, a detailed investigation of the mylonitic microstructure has helped to decipher important information about deformation in natural shear zones. Microstructure reveals a sequence of transition indicating contributions from several deformation mechanisms at low temperature greenschist facies conditions. A range of microstructures representing all stages of mylonitization from protomylonite to ultramylonite is observed.

The protomylonite, much like the protolith is very coarse grained and has undergone very little grain refinement. Twinning is the dominant deformation mechanism at this stage. As twinning alone is incapable of accommodating total strain some amount of intracrystalline slip mechanisms accompany in order to accommodate bulk strain and to maintain strain compatibility.

The porphyroclastic mylonite is identifiable by the presence of few calcite porphyroclasts along with advanced stages of grain refinement. Few porphyroclasts that survive in the aggregate show intense intracrystalline deformation. The undulatory extinction, deformation bands, initiation of polygonization into subgrains, core and mantle microstructure are prevalent in this stage.

The coarse mylonites appear next in the mylonitization process. Disloaction creep mechanisms dominate where recovery processes apparently counteract the earlier work hardening created by dislocation tangles. The polygonization of subgrains give rise to smaller grains enclosed by high angle grain boundaries due to dynamic recrystallization by grain boundary migration or by sub-grain rotation recrystallization.

The S-C mylonite is finer grained than the coarse mylonites and display good shape fabric. The intracrystalline slip mechanism completely dominate during this stage accompanied by little recrystallization. Grain boundaries are relatively straight and grains exhibit sharp extinction.

The ultramylonite is very fine grained equant grain aggregate. The grain boundaries are straight or slightly curved but equilibrated. They lack the shape preferred orientation (SPO) that was evident during earlier stages of mylonitization. Grain boundary sliding mechanisms are dominant during this stage.

There is no demonstrable evidence to show that higher stages of mylonites have passed through all the previous stages of mylonitization though preservation of some microstructural characteristics across microstructural transitions are highly suggestive of a progressive mylonitization. Small areas of high temperature deformation regime were recorded where thermally activated dislocation creep mechanisms were locally active. In these areas, dynamic recrystallization by grain boundary migration have given rise to significant grain growth to produce mega-grains.

We have attempted to quantify deformation microstructures statistically in order to infer deformation mechanisms and processes. ANalysis Of VAriance (ANOVA) test on grain size variations at the scale of a domain and at the scale of a sample was found to be statistically significant. It is demonstrated that there is much variation of the mean grain size between the specimens than the variation within a single specimen. Therefore, it is inferred that the deformation mechanisms which is strongly grain size sensitive should have varied between specimens. Frequency histograms of comparative roundness ratio show a clear modal value of more than unity (very often 1.2 or more), which indicate that the grains have sutured or rugged grain boundaries in general — thus some amount of grain boundary migration might have been active at all stages of mylonitization during grain shape evolution.

Finite strain was determined for each microdomain. It was recorded that the magnitude of finite strain varies from one microdomain to another in a single specimen. The maximum finite extension (MFE) direction X_f also vary from one microdomain to another. All these observations corroborate that the flow lines and flow mechanisms may have varied over very short distances of the magnitude of adjacent microdomains and adjacent layers. These observations are in agreement with the theoretical and experimental studies in published literature.

Microstructures indicating sense of shear are abundant in the aggregate. The δ-porphyroclasts mainly indicate dextral shear sense, though a few sinistral indicators are also recorded. Admittedly some porphyroclasts could not be classified or their sense of shear could not be ascertained. The globular porphyroclasts indicating local pure shear were also observed. Few porphyroclasts showing very small appendages on one or both lateral sides that do not stair step are also recorded. Such porphyroclasts are known to occur in sub-simple shear regime and represent initial stages of porphyroclast development. Abundance of δ-porphyroclasts, δ-porphyroclasts with single lateral appendage, occurrence of θ-porphyroclasts lacking appendage and porphyroclasts with minute appendages indicate low normalized recrystallization rate or prevalence of locally high strain rate.

The pressure fringes of face controlled deformable fibre type showing both dextral and sinistral type are recorded. Some typical face controlled type of pressure fringes display symmetrical, constant and uncurved orientation. They lack the segmented character of the individual fibres and suture marks typical to the pressure fringes of non-coaxial deformation. Such small and unbent fibred pressure fringes may have evolved under sub-simple shear regime with very small W_k ($W_k \to 0$) and very small magnitude of strain to be nearly pure shear. Alternatively, such pressure fringes may have been frozen during the initial stages of their evolution prior to the rotation of the pyrite inclusion or the fibre fringes. These microstructures thus reflect local pure to sub-simple to simple shear.

SPO of grains is used to infer the sense of shear in the microdomains. It was observed that, though a great majority of microdomains indicate a shear sense consistent with the bulk shear sense, reverse sense of shear may coexist in adjacent microdomains. This inconsistency is also observed at the mesoscopic and microscopic scales as shown by other familiar shear sense indicators. Thus sense of shear may vary spatially as well as temporally. Strain partitioning as well as heterogeneity of natural deformation were invoked to explain the reversal of shear sense among the microdomains and layers.

It is argued that the shape preferred orientation and the crystal preferred orientations are an exclusive reflection of the crystal plastic deformation mechanism. In order to accommodate the strain, the intracrystalline slip planes of the constituent grains attempt to align themselves parallel to shear planes that give rise to crystal preferred orientations (CPO) and the slip directions align themselves with shear direction which give rise to SPO (and/or CPO). In concert with observations in single crystal deformation, polycrystalline deformation and computer simulations we infer that the external change of shape of grains are consistent with the active slip systems.

The natural rocks being heterogeneous materially, rheologically, as well as geometrically, the bulk vorticity (W_k) is unequally distributed among the different rheological domains — the competent and incompetent domains or layers. The distributed vorticity (W_k') is further partitioned into shear induced vorticity and spin. The bulk deformation does not dictate the local deformation.

The discontinuities in the shear zone (such as layerings and schistosity) may induce vorticity partitioning between adjacent domains and subsequently effects the deviation of local flow. The proportion of competent and incompetent layers (heterogeneity factor, H) plays a crucial role in the deformation of a domain. The reversal in the sense of shear may occur depending on the instantaneous orientation of the layer and the heterogeneity factor. Reversal in the sense of shear can occur in a single layer with time; or even in the adjacent layers simultaneously. Rheological variation and/or time-dependent flow may induce non-zero spin and drastically change the geometric and kinematic relationship between the fabric and the host shear zone. Therefore, unequal distribution of bulk vorticity and their subsequent partitioning over different rheological domains and microdomains may result in heterogeneous deformation.

In a polycrystalline aggregate where grains with all kinds of orientation are present, the constituent grains deform by partitioning of bulk deformation. According to their spatial orientation with respect to the deformation environment, the grains can be 'soft' grains — grains with easy glide orientation, and hard grains — grains whose active slip planes are at high angles to the shear plane. The distributed strain is further partitioned at the time of deformation — a component is utilised in the intragranular deformation — lattice plane reorientation, and another component is used up in the rigid body rotation of the grain depending upon the orientation of the grain. The soft grains start deforming early during the deformation history and accommodate major part of the strain during that stage. A soft grain may show visible signs of deformation in the form of change of shape or differential lattice orientation. The hard grains undergo rigid body rotation in order that their active slip planes can be aligned in the direction of shear. Strain heterogeneity in the polycrystalline aggregate can arise due to the contrasting deformability of the constituent grains. The deviation of local deformation from the ideal simple shear as well as spatial variation of vorticity may give rise to reversal of shear sense and deformation heterogeneity.

In addition to the heterogeneity that accompany the polycrystalline deformation, twins in calcite may impart heterogeneity in the aggregate from many angles — the spatial incompatibility, geometrical as well as strain incompatibility. Similarly a grain with two or three sets of twins is a much intricately twisted entity and the application of heterogeneous deformation on such entity is certainly to give rise to considerable heterogeneity. Moreover, it is argued that once heterogeneity is introduced in the aggregate it is never possible to restore homogeneity practically. Therefore, natural rocks that are heterogeneous inherently can only accumulate heterogeneity in deformation.

Several grain scale mechanisms — rotation of slip planes due to glide-induced vorticity, rigid body rotation of grains, sub-grain rotation recrystallization, nucleation of subgrains and grain boundary migration recrystallization – are at work at different proportion to shape the microstructure of an aggregate. The combination of these grain scale mechanisms at different proportions accommodate the bulk strain.

Strain heterogeneity is obvious at several scales of observation — intragranular, intergranular, supragranular and at the specimen scales besides the mesoscopic and macroscopic scales. While the strain heterogeneity at these scales give rise to strain incompatibility, the intragranular strain heterogeneity helps achieve the strain compatibility and stress equilibrium in the polycrystalline aggregate.

Correlation of shear sense at several scales of observation is a common practice. Geologists often make observations at several order of magnitude smaller or larger than those at which they seek to apply their deductions. There are numerous instances in the published literature where the shear sense inferred at the microscopic scale has been equated to the bulk shear sense and thus the bulk boundary displacements. Such blissful deductions thus presume a single homogeneous movement picture for the shear zone. These inferences are clearly erroneous and unjustified in the light of this discussion. Thus kinematic analysis is recommended only within a homogeneous domain over a steady period of deformation. In order to get a bulk scale movement picture, integration and comparison of spatial and temporal kinematic history of different microdomains is strongly recommended.