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STRUCTURAL EVOLUTION AND STRAIN PATTERN IN SHEARED GNEISSIC-GRANITICCOMPLEXES AND FELSIC VOLCANICS OF BABINA- PRITHVIPUR AREA, BUNDELKHAND CRATON, CENTRAL INDIA

***Bhatt, S. C. and Khalid Mahmood**

Department of Geology, Institute of Earth Sciences, Bundelkhand University Jhansi, India

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ABSTRACT

The sheared Bundelkhand gneissic complex of Meso to Neoarcheanage (3.4-3.1Ga) and mylonitisedmetasedimentary-felsic volcanics and granitoids of Precambrianto Palaeoproterozoic age are recognizedas important rock units in the study area. The older TTG and streaky gneisses having inclusions of mafic, ultramafic, amphibolites and quartzite were affected by three phases of folding under three regional compressive tectonic episodes (D_1-D_3). An E-W sub-vertical brittle-ductile crustal shear zone(200-500 meter) transecting gneissic, volcanic and granitic terrains, evolved in syntectonicD_4 phase is traced. The linear quartz reefs were emplaced along NE-SW shear zones in last tectonic (D_5) phase and were followed by last magmatic intrusion of doleritic dykes. In the present work the attempts were made to understand the implications of microstructures and strain indicators in evolution of shear zones transecting the older crustal blocks. The shear indicators (mylonitic foliation, lineation, asymmetrical and rotated porphyroclasts) observed on meso and micro scale are found dominant in all mylonites of crustal sheaer zones. The mantled porphyroclasts (σ_a and σ_b) occurring in protomylonite zone exhibit dominant sinistral sense of shear vergence. The presence of undulose extinction, deformation lamellae in quartz and feldspar grains reveal the dominance of crystal plastic and strain softening processes in evolution of crustal shear zones (under low to medium temperature conditions). The overprinting of brittle deformation on ductile phase is evidently supported by presence of micro faults, extensional fractures and pull apart structures in few grains of quartz and feldspar. The higher values of two (Rs=3.4) and three dimensional strain ($\sum$s=0.95) estimated in few specimens are indicative of dominance of high shear strain in central parts of shear zones. Contrary to this, the low values of strain quantified in few specimens are suggestive of presence of low shear strain in marginal parts of shear zones. The affinity of k- values towards flattening field implies that the flattening strain was dominant parallel to Y-axis and is suggestive of volume loss.

INTRODUCTION

The Indian shield constituuting low to high-grade crystalline rocks (3.6–2.6 Ga) of continental crust consists of five major cratons. The Bundelkhand cratona northern segment of Indian peninsula spreading in 26,000 sq.km area mainly constitutes older TTG gneissic complex (Archean to Palaeoproterozoic age) and Precambrian terrains of super acrustalmetasedimentary-metavolcanics of greestone belt and various granitoids of granitic complex (Fig. 1).

****Corresponding author: Bhatt, S. C.***
Department of Geology, Institute of Earth Sciences, Bundelkhand University Jhansi, India

The study area falling in northern and central part of Bundelkhand cratonconsists of complicated geological and structural terrains of older metamorphic (meso to neoarchean), metasedimentary and granitic complexes. Earlier Pascoe (1950), Jhingran (1958), Prakash *et al*. (1970,1975), Sharma (1982), Basu (1986), Roday *et al*. (1995), Prasad *et al*. (1999), Basu (2004) and Basu (2007), Pati *et al*. (2007), Bhatt and Hussain (2008 & 2012), Bhatt and Khalid (2009 and 2012), Bhatt and Gupta (2009), Bhatt and Gupta (2014) Bhatt *et al*. (2014), Singh and Slabunov (2014), Singh and Dwivedi (2015) focused their studies on geological, structural and geochronological aspects of Bundelkhandcraton. The main aim of this work is to explore the significance of shear and strain indicators in tectonic evolution of crustal shear zones in Bundelkhandcraton.

Figure 1: Geological map of Bundelkhandcraton showing location of the study area

Geological Setting

Based on field mapping and petrological data three major rock groups i) Bundelkhad TTG gneissic complex, ii) Greenstone belt and iii) Bundelkhand Granitic complex (Fig.2) were identified in the investigated area. These rock units are discussed in the following paragraphs.

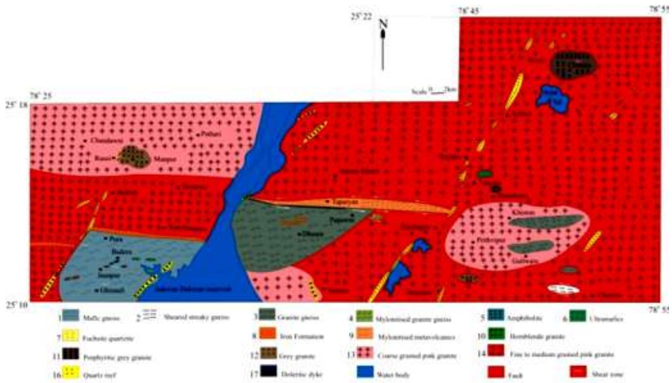


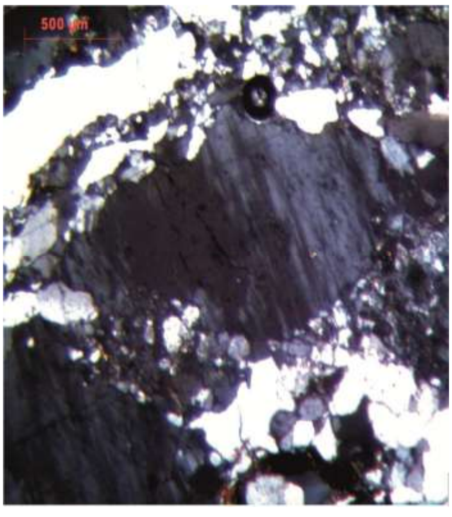
Figure 2: Geological map of Babina-prithipur sector, Bundelkhandcraton, Central India

TTG Bundelkhand Gneissic Complex

The banded gneisses defined by light quartzofeldspathic and dark mafic bands are exposed in the surroundings of Ghisauli, Badera, Jaunpur and Chaurara villages located in the south of Babina (Fig. 2).

a

b



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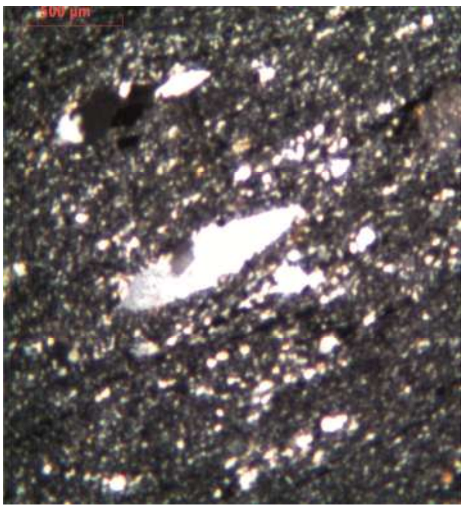

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Figure 3a. Sheared schistose rock associated with Banded Iron Formation (BIF) of Greenstone Complex; Location: NearGhisauli-Purra road; 3b. Open F_2 and F_3 folds in TTG mafic gneisses. Location: left side of Jaunpur-Badera road; 3c. Photomicrograph showing undulose extinction and deformation lamellae in quartz grain in sheared granite gneiss (CPL.2.5x); 3d. Photomicrograph showing elongated quartz grains (strain markers) andrecrystallised quartz matrix in mylonitezone (CPL.4x).

The ESE-WNW to E-W trending gneisses showing steep northly dips (Fig. 3a) and exhibiting three phases of folding (F_1-F_3; Fig.3b) were produced in three tectonic episodes (D_1-D_3). These gneisses were transected by E-W major and minor shear zones (30-40 meters) and can be regarded as equivalent to Kuraicha gneisses (3297±83 Ma; Mondal *et al*. 2002). The streaky gneisses showing wider leucocratic bands and extensive shearing effects strike in ESE-WNW directions and are occurred to the west of Chamon village (Fig. 2). These foliated gneisses characterised by three phases of folding (Fig. 3b) are exposed in the eastern flanks of Babina (2697+3Ma; Mondal *et al*. 2000). The dominant sinistral sense top-to-SWshear movement is exhibited by few porphyroclasts. The E-W to ESE-WNW trending grey and pink banded gneisses are widely exposed in the west of Papawni and Dhauraand south of Khiston and north of Gailwara villages (Fig. 2) and display superimposition of folding.

The thicker leucocratic bands are represented by quartz and K-feldspar with minor biotite, whereas the thinner melanocratic bands are defined by thin layers of mafic minerals (granodiorite to diorite). The extensive shearing effects are noticed in the northwestern part of Papawni village. At some places the inclusions of metabasalt and folded banded iron formation (BIF) occurring as small rafts also reported within these gneisses. A mylonite zone showing intensive shearing effects is recognized in the east of Papawni (Fig. 2). A few isolated fine grained, greyish green to dark green lensoidal bodies of amphibolites (2520 Ma; Mondal *et al*., 2002) associated with the older gneissic complex are found in the south of Badera (Fig. 2) and in the west of Papawni.

Greenstone Complex

a) MAFIC-Ulteramafics

The fine dark green mafic and ultramafic bodies (3249± Ma; Mondal *et al*. 2002) occurring widely in a small hillock located north of Tangara and in eastof Badera (Fig. 2) constitute gabbroic bodies of peridotites, pyroxenites. These gabbroicbodies consist of altered plagioclase pyroxene and amphiboles and at places intruded by conjugate sets of quartz veins. The outcrops of fine grained foliated (ESE-WNW) fuchsite quartzite consisting of white quartz (0.5-1cm) and dark green fuchsite (1.5-3 cm) occurs in the south of Babina near Sukwan Dukwan reservoir (Fig. 2).

b) Metasedimentary and Felsic Volcanics

The reddish brown banded quartz magnetite rocks of Banded Iron Formation (BIF) sandwiched between southern gneissic complex and northern granitic complex are exposed in the southwest of study area (Fig 2). The moderately elevated hillocks of these quartz magnetite rocks exposed in the west of Papawni village exhibit irregular thin (0.1-5cm) quartz and thicker (0.4-1cm) magnetite bands. The crystalline quartz dominant in white bands shows incomplete recrystallisation while the amphiboles (actinolite and cummingtonite) are appeared as accessory minerals. The large outcrops of fine greyish pink and sheared felsic volcanic occurred along E-W mylonitezone are widely exposed near Taparyan and Dhauravillages (Fig. 2) andexhibit mylonitic foliation and stretching lineation (Fig.3a). The mylonitic foliation striking in E-W direction exhibits steep (60-70^0) northerly dips. The ESE-WNW trendingmylonitic lineation represented by the elongated quartz and feldspar grains and streaks of mica lie at 10 to 20^0 to the main mylonitic foliation.

Bundelkhand Granitic Complex

About two km longlensoidal body of fine greyish green hornblende granite is exposed at both sides of Nivari-Prithipur road near Dumduma (Fig. 2) and it contains hornblende and quartz as essential minerals with rare of feldspar. The coarse grained, grey granite consisting of large porphyries (0.3 to 2cm) of quartz and feldspar (mainly orthoclase) are occurred in the eastern flanks of Nivariand southwest of Papawni (Fig 2). At places the shearing effects are evidently documented by the presence of large asymmetrical rotated porphyroclasts of quartz and feldspar and S-C bands. An outermost albite zone completely free form alteration is also examined which shows inclusions of quartz. The secondary recrystallised quartz grains occurred in the margins of host grains and the perthetic growth of microcline is also observed in few well cleaved microcline. The hugeoutcrops of coarse pink granites exposed around Prithipur and its adjoining areas (Fig. 2), are occasionally marked by two sets of tensional fractures and three sets of joints. The two sets of quartz veins trending in NE-SW and E-W directions are also noticed in these rocks.

The occurrences of mafic enclaves (7 to 15cm) within these granitoids are suggestive the post granitic origin of these rocks. These granites are also occurred near Chandawni, Pathari and Rasoi villages in the north-western parts of the study area (Fig. 2). The northern margins of these massive, compact granitoids are demarcated by the pink granitic gneisses. The large enclaves of granitic gneisses (6 to 12 inches) are found within these granitoids. The phenocrysts of quartz, feldspar (mostly orthoclase), microcline, plagioclase, biotite and inclusions of magnetite with accessories of zircon, epidote and chlorite form the main mineral constituents in these rocks. These rocks are sometimes intruded by conjugate quartz veins and at places these veins are dissected by secondary fractures. The orthoclase, microcline quartz and biotite are examined as chief mineral constituents in these rocks and magnetite, zircon and rutile are appeared as accessories. Two NE-SW trending major quartz reefs (200-300m) offsetting the gneisses and Banded Iron Formation (BIF) are passing from Babina and extended upto the southern part of the area (Fig 2).

These quartz reefs are truncated by oblique faults and at places are characterized by quartz veins and three sets of joints. Another major quartz reef encompassing from north of Nivariand extended in the southwest of Durgapur is markedas a longest quartz reefs in the Bundelkhand massif (Fig 2). The milky white, pinkish white and recrystallisedquartz grains showing undulose extinction are formed main constituents of these rocks. A NW-SE trending doleritic dyke showing a clear intrusive relationship with the pink granites is exposed in the southeast of Arjar Tal (Fig2).These doleriticdykes (1799 Ma; Sarkar *et al*. 1990 and 2150 Ma and 2000Ma byRao *et al*. (2005) constituteaugite, plagioclase (mainly labradorite) hornblende and sericite as the main mineral constituents.

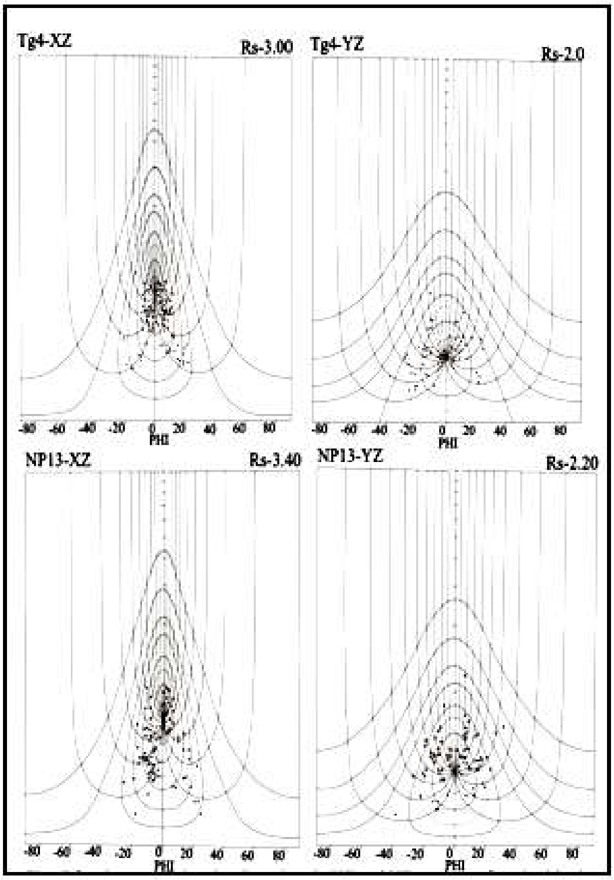

Figure 4a

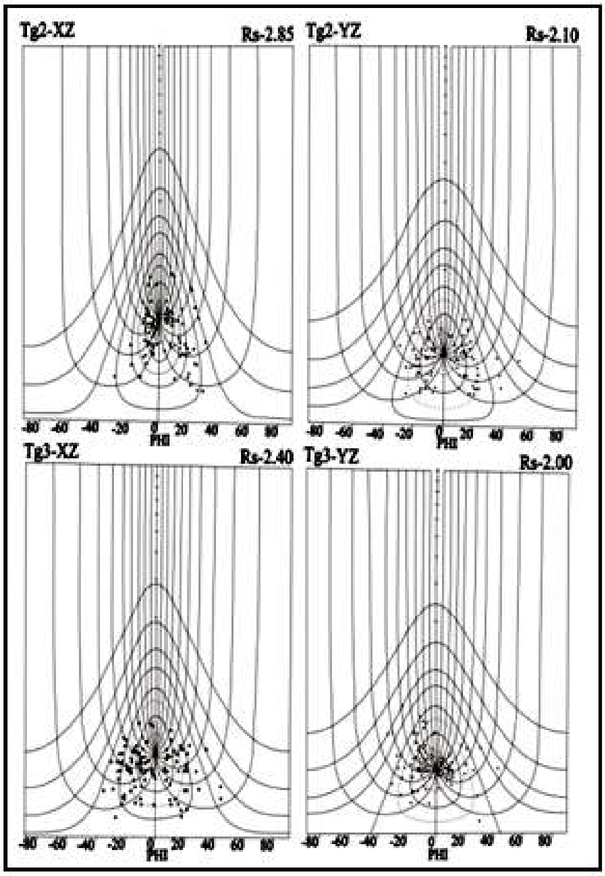

Figure 4b

Figure 4a. Rf and ϕ curves showing Rs values in XZ ad YZ sections (Specimen Tg4 & NP13) of mylonitised felsic plutotonic rocks and sheared grey granite (location: Taparyan village and Nivari)

Figure 4b. Rf and ϕ curves showing Rs values in XZ and YZ sections (Specimen Tg2& Tg3) of mtylonitised felsic plutonic rocks (location: Taparyan village)

Deformation Pattern and Tectonic Evolution of Sheared Gneissic and Greenstone Complexes

The TTG and mafic gneisses were subjected to three phases of folding (F_1-F_3) under regional compressive deformation (D_1-D_3).These folds are commonly observed in gneisses and Banded Iron Formation (BIF) and were earlier studied by Bhatt and Hussain (2008) and Bhatt and Mahmood (2008 and 2012).The F_1 folds showing isoclinal to tight shape with steep (45°) northwest plunging fold axis are represented by S_1 (ESE-WNW to E-W) foliation). The F_2 open and symmetrical folds (coplanar to F_1 folds) andF_3 tight to open folds are commonly noticed in these rocks (Fig. 3b). The S_2axial panes strike in NNE-SSW to N-S direction whileS_3trendin NNW-SSE direction. The tight (isoclinal) to reclined F_1 folds with thick hinges are also reported in quartz magnetite rocks of banded iron formation (BIF).The folds developed in TTG gneissic complex were reoriented and reshaped in the different styles during the progressive shearing stages (D_4 phase).

Major and Minor Shear Zones

Babina- Tapraya -Prithvipur Shear Zone

The imprints of planar and linear structures preserved in the older Archean to Precambrian rocks are considered one of the direct source to reconstruct tectonic history of older crustal rocks (Passchier and Trouw 2005). An E-W Babina-Taparya-Pritipur crustal shear zone (200-500 mwide) passing from south of Babina and Taparyan villages and extend upto (30 km) northwest of Prithipur was evolved in D_4 phase of deformation (Fig. 2). The mylonitisedgneisses and metavolcanics represented by E-W to ESE-WNW trending mylonitic foliation were emplaced along this steep (50-70^0) shear zone. The stretching lineation aligned oblique (10-15^0) to mylonitic foliation is defined by parallel orientation of quartz, feldspar and mica flakes. The small scale shear zones few centimeters to several meters wide and extending up to few hundred meters are also traced in grey granites near Churara village. The large phenocrysts of quartz and feldspar (0.5 to 3cm) are observed in protomylonite zones in the west of Chamon, felsic volcanic suit in the south of Taparyan village and in the north of Churara village (Fig 3c). The identified mesoscopic asymmetrical shear indicators are rotated asymmetrical porphyroclasts, pull-apart structures, strike slip faults and S-C planes. The fine grained ultramylonite (100-150m) containingprotoliths of quartz and feldspar is traced in south of Taparyan village (Figure 6). The rotated pophyroclasts of quartz and feldspar (0.3 to 2cm) in mylonitised gneisses and granitoids exhibit dominant sinistral top-to-SW sense of shear movement.

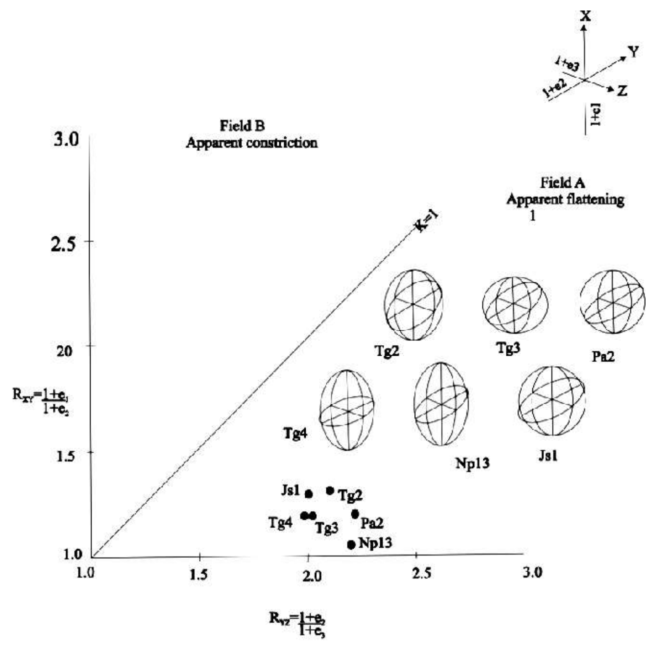

Figure 5. The Flinn graph representing the shape of strain ellipsoids in constriction and Flattening field

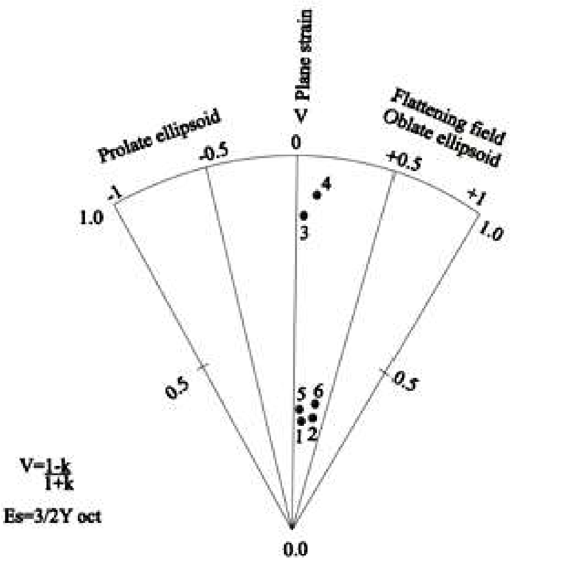

Figure 6. Hossack's plot showing calculated strain states of deformed rocks using Lode's parameters (v) and principal natural logarithmic strain (∑s)

The progressive shearing effects represented by of S and C planes are corresponding with type I S-C mylonites of Lister and Snoke (1984). The C- planes showing obliquity (30° to 40˚) to main mylonitic foliation are resembling with CC' bands of Berthe *et al.* (1979) and containing identical mineralogical composition were produced in the same shearing event (Passchier and Trouw, 2005). The microstructural observations show distinct gradation from protomylonite to ultramylonite. The microstructural observations show distinct gradation from protomylonite to ultramylonite. The protomylonite constituting large porphyroclasts of quartz and feldspar (50-90%) and smaller amount of matrix are showing two generations of quartz (porphyroclasts) characterized byundulose extinction and deformation lamellae (Fig 3c).

The undulose extinction (Fig 3c) and low temperature grain boundary migration displayed by quartz were formed between 300-400^{0}C (Stipp *et al*., 2002) whereas the bending undulose extinction and subgrain formation exhibited by feldspar were evolved under low to moderate temperature conditions (400-500^{0}C; Pryer 1993). Two types of mantled σ porphyroclasts (σ_a and σ_b) are recognised in protomylonite. The σ_a mantled porphyroclasts exhibit sinistral sense top –to- SW shear movement (Figure3c).The elongated and ribbon shaped quartz and feldspar grains (aspect ratio; 1:5 to 1:7) characterised by preferrely oriented mylonitic foliation and mylonitic lineation (Figs. 3d) were produced under medium to high shear strain conditions. The microslip faults and microcracks examined in a few feldspar grains are indicative of later brittle deformation operated in cataclastic regime. The microfaulting occurred due to brittle deformation is commonly associated to cataclastic failure (Tullis and Yund 1987; Altenberg and Wilhelm 2000). Due to intensive granulation effects and dynamic recrystallisation, the percentage of relicts of quartz and feldspar (<10) is consistently reduced and as result the transition zone switches to superplastic ultramylonite zone (Fig. 3d).

Strain in Two and Three Dimensions

The strain in deformed rocks plays an important role in reconstruction of tectonic history of a geological terrain. Therefore, in present work the elongated quartz grains were selected as strain markers to estimate tectonic strain. In order to estimate the tectonic strain about 100-150 oriented specimens belonging to low to high shear strain domains were collected and thin sections parallel to XZ, YZ and XY planes were prepared. One hundred to one hundred twenty elongated quartz grains were measured in XZ and YZ plane of each section. The Rf/Ø, Flinn (1962) Nadai (1963) and Hossack's (1968) plots were used for strain analysis and resulted curves were matched with best fit reference curves of Lisle (1985). The two dimensional strain data (Table-1) for each specimen reveals that the mylonite (NP 13) belonging to high shear strain domains exhibits higher values of two dimensional strain (Rs=3.4; Fig.4a).Contrary to this the lowest Rs values (Rs=2.4) is shown by the specimen (Tg3) located in the low shear domains (Fig.4b). The values of two dimensional strains (Rs) were plotted on Flinn graph representing field of apparent constriction and apparent flattening (Fig. 5).

Most of the k-values (0.04 t0 0.35) falling in flattening field show oblate ellipsoids. The specimen (NP13) belonging to protomylonite zone, located near Churara village exhibits more affinity towards more oblateness (Fig. 5). The three dimensional finite strain ∑s is calculated for all specimens by applying methods proposed by Nadai (1963) and Ramsay and Huber (1983). An octahedral shear strain (Yoct) represents the major amount of distortion in a strain ellipsoid is calculated (Table-1). The all values plotted on Hossack plot (Fig. 6) indicates that most of the specimen exhibit oblate shapes (Fig. 6). This analysis reveals that the most of the specimens close to high shear domains are showing higher values of finite strain ($\sum^{-}$s =0.95) with lower values of k=0.04.This increasing trend of three dimensional strain ratio and octahedral strain is indicative of predominance of intensive deformation in central parts of shear zones. In contrast to this, the lower values of finite strain ($\sum\bar{s}$ =0.316), octahedral strain (Yoct=0.365 and higher values of k (0.35) are suggestive of low intensity of deformation in marginal are of low shear strain.

RESULTS

Based on the above analysis, the following research findings are found:

- The oldest crust consisting of TTG gneissic complex (3.1-3.3Ga) and Banded Iron Formation (BIF) of Greenstone Complex (Palaeoproterozoic age) were influenced by three phases of folding (F_1-F_3) under three compressive tectonic episodes (D_1-D_3).The major crustal shears were evolved in D_4phase which were followed by emplacement of quartz reefs along NE-SW shears (D_5) and intrusion of doleritic dykes along NW-SE strike slip faults.
- Thus it is concluded that the Babina-Prithipur crustal shear zone is a major strike slip shears and exhibit sinistral top- to- SW shear movement and evolved at intermediate to shallow depth. These shears were formed in brittle ductile regime under the influence of non-coaxial strain.
- The microstructural analysis envisages that asymmetrical structures and rotation of quartz and feldspar took place in crystal plastic and strains softening processes under low to moderate temperature conditions at intermediate to shallow depth.
- The small scale to major crustal shear zones were produced in intracratonic areas of Bundelkhandcraton mostly due to reactivation of major Son Narmada Lineament in Archean to Palaeoproterozoic period. The Son Narmada Lineament was probably considered key source for all thermo tectonic activities occurred in this region.

DISCUSSION AND CONCLUSIONS

The microstructural and strain analysis of deformed rocks imply that the sheared TTG gneissic, Greenstone and granitic complexes were syntectonically deformed during progressive shearing (D_4). The presence of mylonitic foliation, mylonitic lineation, S-C fabrics, rotated asymmetrical porphyroclasts, microslip faults and displaced axial planes of folds evidently proved that the major crustal shear zones were developed under brittle-ductile conditions. The undulose extinction, deformation lamellae, pressure shadows, grain boundary migration and dynamic recrystallisation observed in strained quartz and kink bands and alteration effects in feldspar indicate that these grains were deformed by plastic strain softening processes in ductile regime under low to medium temperature condition. The angularity between S and C bands reveals that the S-C bands were evolved in the initial stage of evolution of S-C fabrics. The occurrence of microcracks, microfaults and extensional cracks in asymmetrical phenocrysts of K-feldspar and kinking in plagioclase are suggestive of overprinting of brittle deformation on ductile deformation in low temperature conditions. This process was progressed in strain hardening andcataclastic regime. The geometry and attitude of σ_a mantled porphyroclasts of quartz and feldspar and other rotated asymmetrical fabrics is dominantly exhibiting sinistral-top- SW shear movement. The occurrence of σ_a and σ_b mantled porphyroclasts also infer that such asymmetrical fabrics were possibly formed under high differential stresses in crystal plastic deformation mechanism. The interplay of all the above studies infer that the three types of mylonites were progressively evolved in different domains shear zones in D_4phase of deformation under non coaxial and extensional regime. The higher values of two (Rs=3.6) and three dimensional strain ($\sum$s=0.40) measured in specimen no.NP13 located on Nivari-Prithipur highway with k-value 0.52 infers that the fabrics belonging to central part of shear zone are represented by flattening type of strain with oblate ellipsoid and constant volume loss. The lower values of two (Rs=2.4) and three dimensional strain ($\sum$s=0.316) recorded in specimen number Tg2 located to the south of Taparyan village shows maximum oblateness (k=0.20). The predominance of flattening type of strain and oblate type of ellipsoids infer that the elongation was initially parallel to Y -axis which subsequently aligned parallel to X-axis with the consistent ratio of X, Y and Z axis. The consistent reduction in k-value in these specimen also imply that the flattening strain was dominant due to maximum extension parallel Y-axis and the shortening of strain quartz grains measured parallel to Y, which is suggestive of volume loss.

Acknowledgements

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