Deformation of footwall rock of Phulad Shear Zone, Rajasthan: Evidence of transpressional shear zone

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Phulad Shear Zone (PSZ) of Delhi Fold Belt in Rajasthan is a northeasterly striking ductile shear zone with a well developed mylonitic foliation (035/70E) and a downdip stretching lineation. The deformation in the PSZ has developed in a transpressional regime with thrusting sense of movement. The northeastern unit, i.e., the hanging wall contains a variety of rocks namely calc-silicates, pelites and amphibolites and the southwestern unit, i.e., the footwall unit contains only granitic rocks. Systematic investigation of the granites of the southwestern unit indicate a gradual change in the intensity of deformation from a distance of about 1 km west of the shear zone to the shear zone proper. The granite changes from weakly deformed granite to a mylonite/ultramylonite as we proceed towards the PSZ. The weakly deformed granite shows a crude foliation with the same attitude of mylonitic foliation of the PSZ. Microscopic study reveals the incipient development of C and S fabric with angle between C and S varying from 15° to 24°. The small angle between the C and S fabric in the least deformed granite variety indicates that the deformation has strong pure shear component. At a distance of about 1 m away from the PSZ, there is abrupt change in the intensity of deformation. The granite becomes intensely foliated with a strong downdip lineation and the rock becomes a true mylonite. In mesoscopic scale, the granite shows stretched porphyroclasts in both XZ and YZ sections indicating a flattening type of deformation. The angle between the C and S fabric is further reduced and finally becomes nearly parallel. In most places, S fabric is gradually replaced by C fabric. Calculation of sectional kinematic vorticity number (W_n) from the protomylonitic and mylonite/ultramylonite granites varies from 0.3 ± 0.03 to 0.55 ± 0.04 indicating a strong component of pure shear. The similarity of the geometry of structures in the PSZ and the granites demonstrates that the deformation of the two units is broadly synchronous and the deformation in both the units is transpressional.

1. Introduction

The Phulad Shear Zone (PSZ) (figure 1) of Rajasthan is a long narrow zone of intense deformation, running in a northeasterly direction for several kilometers and demarcates the western margin of the Proterozoic Delhi Fold Belt (Heron 1953; Sychanthavong and Desai 1977; Gupta *et al.* 1980; Sen 1980; Sinha Roy 1988; Sinha Roy *et al.* 1993; Gupta *et al.* 1997; Golani *et al.* 1998; Ghosh

et al. 1999). The PSZ is characterized by extensive mylonitization with a thrusting sense of movement (Sengupta and Ghosh 2004). The average attitude of the mylonitic foliation is 035/70E with subvertical lineation. Detailed structural studies of the PSZ by Sengupta and Ghosh (2004, 2007) indicate that the deformation in the shear zone is transpressional, i.e., in addition to the simple shear there is a component of pure shear across the shear zone. The strain of PSZ mainly concentrates along the

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Figure 1. Simplified geological map of the study area modified after Ghosh *et al.* (1999).

bands of interlayered calcareous and quartzofeldspathic mylonites. The PSZ lies between two different lithounits. The northeastern unit contains a variety of rocks, viz., calc-silicates, pelites and amphibolites and the southwestern unit contains only granitic rocks. The relationship of these southwestern granites with the PSZ is not clear (Heron 1953; Gupta *et al.* 1980, 1997; Sinha-Roy 1988), i.e., whether the granites acted as footwall for the PSZ or emplaced after the deformation of the PSZ. Moreover, there is dearth of information about the deformation pattern of the granites of the southwestern unit. To know whether these granites were really/never part of the PSZ, a systematic study along two transects across the granite was carried out to examine the state of deformation.

2. Mesoscopic structures in granite

The granitic rocks to the southwestern side of the PSZ show prominent development of foliation and lineation that are parallel to the mylonitic foliation

of the PSZ. At a distance of about 1 km away from the PSZ, the granites are coarse grained with some of the feldspar grains varying in size from 3 to 4 cm (figure 2a). The rock shows a crude foliation with barely visible downdip lineation. As we move towards the shear zone the granites gradually become well foliated with strong development of lineation. There is also gradual grain size reduction towards the PSZ. At a distance of about 500 m from the PSZ, the rock becomes finer grained with very well developed foliation and a strong downdip stretching lineation (figure 2b) indicating thereby further increase in the intensity of deformation. Close to the PSZ, there is an abrupt change in the intensity of deformation in the granite (figure 2c). The rock becomes a true mylonite with very strong foliation and downdip lineation. In both XZ section (perpendicular to the foliation and parallel to the downdip lineation) and YZ section (perpendicular to the foliation and downdip lineation), the granite shows stretched grains (figure 3a, b). The aspect ratio of the stretched grains in XZ section varies

Figure 2. (a) Field photograph of weakly deformed coarse grained granite at a distance of 1 km from the proper shear zone. The bold line shows the trace of foliation in the granite. Note the presence of large feldspar clasts. (b) Field photograph of profile section of the granite showing the strong down-dip stretching lineation (marked by broken line). (c) Field photograph of mylonitic granite close to the shear zone. The length of the match stick in (c) is 5 cm.

from 1.5 to 3.8 and in YZ section varies from 1.2 to 2.25 (figure 3c) indicating a flattening type of deformation.

3. Microstructural variation of the granite

The granitic rock, southwestern unit of the PSZ, is mainly consists of quartz, feldspar (plagioclase and K-feldspar) and biotite. On the basis of their intensity of deformation, i.e., fabric development, grain size reduction and degree of recrystallization the granite is divided into three longitudinal divisions, e.g., (1) weakly deformed granite, (2) protomylonites, and (3) mylonites and ultramylonites.

3.1 Weakly deformed granite

At a distance of about 1 km away from the shear zone the granitic rocks are categorized as weakly deformed granite. These weakly deformed granites show a crude foliation defined by broad parallelism of biotite flakes and weak shape preferred orientation of quartz-feldspar aggregates. These granites contain large porphyroclasts of feldspar within a matrix (10–20%) of fine-to-medium grained assemblage of quartz, feldspar and biotite. Feldspar grains show strong undulose extinction with curved grain boundaries, kink and bent twin lamellae. Bulging grain boundaries, subgrains and grain refinement indicate dynamic recrystallization (figure 4a–c). Feldspar grains with brittle fractures are also common. At places small recrystallized grains of quartz are present along fractures of the feldspar porphyroclasts (figure 4a). Polygonized quartz grains with development of triple junction mainly occur in the matrix (figure 4d). Few isolated flattened quartz with strong undulose extinction are also present mainly wrapping large feldspar grain.

3.2 Protomylonites

As we move towards the PSZ, the rock becomes more strained with decreasing number of porphyroclasts. The percentage of recrystallized matrix varies between 20 and 50%. Feldspar megacrysts show irregular grain boundaries with strong undulose extinction. Polygonized quartz grains with triple junction at grain boundaries are preserved only in the lensoidal aggregates (figure 5a). However, quartz grains are mainly stretched to form polycrystalline ribbon structure. Quartz grains within the ribbon structure show irregular grain boundaries with undulose extinction. Quartz ribbon also warps around large feldspar grains (figure 5b). Matrix quartz grains show irregular grain boundaries. Isolated quartz megacrysts with strong undulose extinction are stretched parallel to the foliation. Protomylonites show incipient development of C–S fabric where C denotes the shear plane and S denotes the plane containing the

Figure 3. (a) Block diagram showing the XZ (perpendicular to the foliation and parallel to the lineation), YZ (perpendicular to the foliation and lineation) and XY (parallel to the foliation and lineation) sections. (b) Hand specimen photograph showing the stretched porphyroclasts in both XZ and YZ sections. (c) Histogram showing the distribution of aspect ratio of stretched porphyroclasts in XZ and YZ sections. Note the aspect ratio in XZ is greater than YZ section. 'n' denotes the number of data.

Figure 4. (a) The photomicrograph shows the presence of quartz grains along the fracture of the feldspar grain (marked by arrow head). (b) Feldspar grain showing bent twin lamellae. (c) Feldspar grain showing kink. (d) Recrystallized quartz in the matrix shows dominant grain refinement. Quartz grain triple junction is shown by arrow head. Photomicrographs (a–d) are in cross polarized light.

Figure 5. (a) Aggregates of polygonized quartz grains with triple junction are preserved in lensoidal forms. (b) Incipient development of polycrystalline quartz ribbon with curved boundary wrapping around the feldspar porphyroblast. (c) Photomicrograph showing C-S fabric. Angle between C (Black line) and S (Black broken line) is 12° . (d) Photomicrograph showing the stretched feldspar grain aligned parallel to the mylonitic foliation. (e) Feldspar porphyroblast (centre) showing irregular grain boundary and undulose extinction. (f) Mylonite showing well developed polycrystalline quartz ribbon with quartz subgrain formation. Photomicrographs (a-f) are in cross polarized light. White arrows with black border in photomicrographs (b-f) indicate the general sense of shearing.

maximum and intermediate axes of strain. The C-fabric is demarcated by biotite and recrystallized subgrains of quartz, whereas the S-fabric is mainly

defined by quartz subgrains with few biotite. The angle between C and S ($C \wedge S$) varies between 20° and 24° . This angle between C and S further

reduces gradually as we move towards the PSZ (figures 5c, 6).

3.3 Mylonites and ultramylonites

At the contact of PSZ, there is a sharp increase in the degree of recrystallization and the rock

becomes a mylonite and with further reduction of porphyroclasts, transformed to an ultramylonite. Most of the feldspar grains are stretched parallel to the mylonitic foliation (figure 5d). Few feldspar grains show strong undulose extinction with irregular grain boundaries (figure 5e) depicting grain boundary migration recrystallization (Vernon 2004; Passchier and Trouw 2005). Quartz mainly occurs as bands forming ribbon structure with curved grain boundaries (figure 5f). Formation of quartz subgrain within the ribbon structure is also common. The angle between C and S fabric is further reduced and S is gradually replaced by C. Figure 6 shows the variation of $C^{\wedge}S$ with increasing distance from the PSZ.

Figure 6. Graphical representation of the change of angle between C and S with increasing distance from the PSZ.

4. Kinematic vorticity analysis

The measure of the degree of instantaneous non-coaxiality of a flow is represented by the kinematic vorticity number, W_k . There are several methods to obtain the kinematic vorticity number. For the convenience of our work we chose Oblique grain-shape foliations of recrystallized quartz aggregate to calculate the sectional kinematic vorticity number,

Figure 7. (a) Summary diagram showing the systematic change of granite grain size as we move towards the PSZ. (b) Schematic representation showing the angle between C–S decreases towards the PSZ. (c) Schematic profile section showing distribution of weakly deformed granite, protomylonite, mylonite and ultramylonite and the orientation of respective mesoscopic fabrics are shown in insets. Sketch not to scale.

W_n (as it is a monoclinic flow) value. According to Wallis (1995), the orientation of the long axes of quartz neoblasts within an oblique foliation delineates the direction of the extensional ISA_2 (Instantaneous Stretching Axes). Experimental studies (Dell'Angelo and Tullis 1989; Ree 1991; Herwegh and Handy 1998) also support this assumption, which showed that during progressive deformation oblique grain-shape fabrics nucleate with their long axes in a fixed orientation with respect to the imposed kinematic reference frame. We can obtain the sectional kinematic vorticity number, W_n by using the equation $W_n = \sin 2\xi$ (Weijermars 1991) where ξ is the greatest angle between the oblique foliation (ISA_2) and the flow apophysis A_2 (Xypolias 2010). In our study area we calculated this W_n value for the granitic rocks on XZ section, i.e., the plane perpendicular to the foliation (XY) and parallel to the lineation (X). In the protomylonitic variety of granites, the angle ξ varies from 7° to 10° with W_n value varying from 0.24 to 0.34 with an average of 0.3 ± 0.03 . For mylonite and ultramylonite variety, the ξ angle varies from 15° to 18° and the W_n value varies from 0.5 to 0.59 with an average of 0.55 ± 0.04 . W_n value for weakly deformed granite could not be measured using this method as the quartz aggregate of this granite does not show any distinct oblique grain shape. The calculated W_n values for the granitic rocks falls in the pure shear dominated transpression regime (Fossen and Tikoff 1993).

5. Discussion and conclusion

During ductile deformation of any shear zones, the rocks of the footwall side may remain rigid or may suffer deformation along with the shear zone with similar geometry of structures (Ramsay and Huber 1983; Daniel *et al.* 1996; Gutierrez-Alonso 1996; Singh and Thakur 2001; Tripathy *et al.* 2009; Fossen 2010). The wall rocks generally remain undeformed where the deformation in the shear zone is by simple shear only. However, if the strain deviates from simple shear, the wall rocks may get deformed (Simpson and De Paor 1997, p. 171).

The present investigation indicates a gradual change in the intensity of deformation in the granites that lies southwestern part of the PSZ from a distance of about 1 km west to the shear zone proper (figure 7). The granite changes from weakly deformed to a mylonite as we proceed towards the PSZ with attitude of foliation parallel to the mylonitic foliation of the shear zone. The weakly deformed granite also shows a crude foliation with the same attitude of mylonitic foliation. There is incipient development of C and S fabric with $C \wedge S$ varying from 24° to 15° . The small angle between

the C and S fabric in the least deformed variety indicates that the bulk deformation is transpressional. As we move towards the shear zone, the rock becomes more deformed with further decrease in the angle between C and S. At a distance of about a meter from the proper shear zone, the granite becomes mylonite to ultramylonite. The angle between C and S is greatly reduced and S is replaced by C. Presence of stretched grains in both XZ and YZ sections in granites also indicate a three dimensional strain with a component of flattening across the shear zone. Kinematic vorticity analysis from the different parts of granites revealed that the deformation has occurred in pure shear dominated transpression regime. Presence of deformed wall rocks also indicates that the bulk strain in the PSZ is not by simple shear alone (Simpson and De Paor 1997). The similarity of the geometry of structures in the PSZ and the granites indicates that the deformation of the two units is broadly synchronous and the bulk strain in both the units is transpressional.

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