Micro-Meso and Macro Scale Structures in Syn-tectonic Granite Emplaced in a Ductile Transpressional Shear Zone: A Case Study From the Western Margin of the South Delhi Fold Belt, Rajasthan, India

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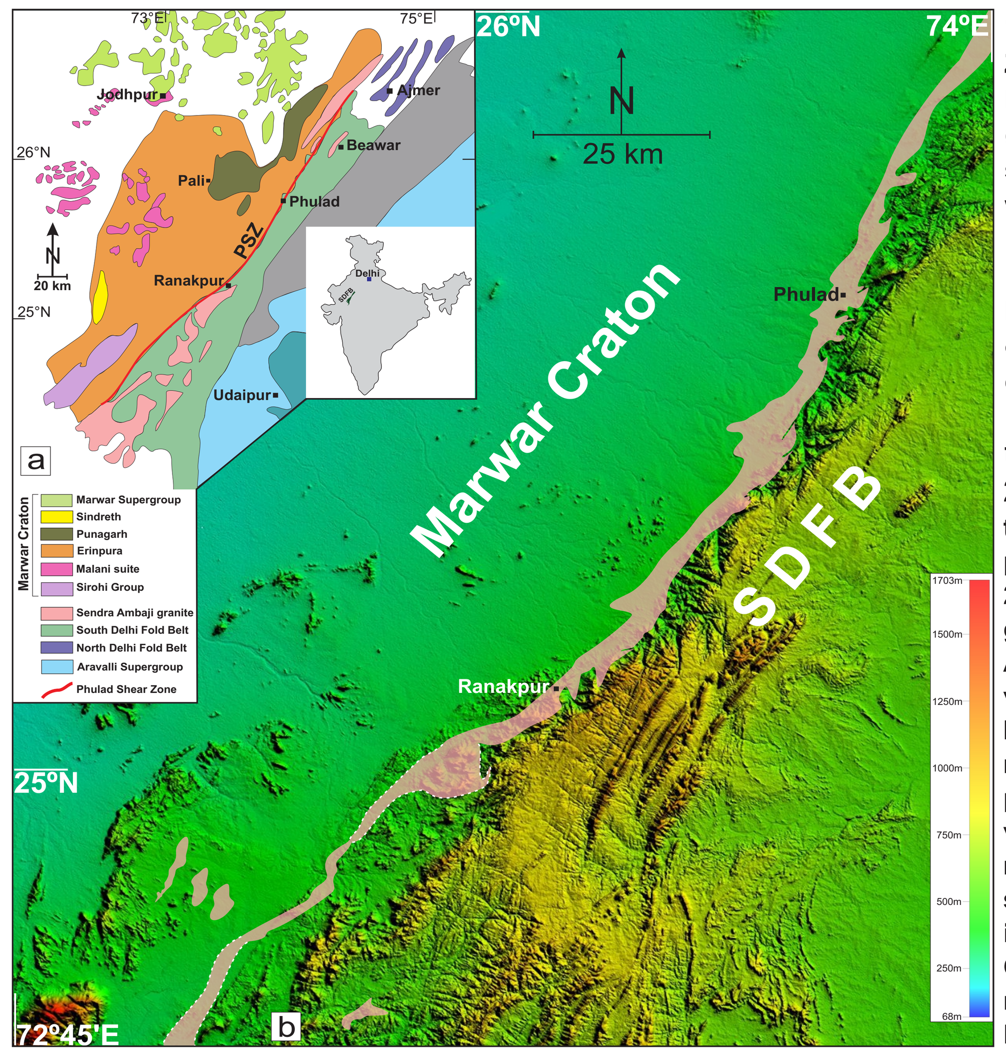
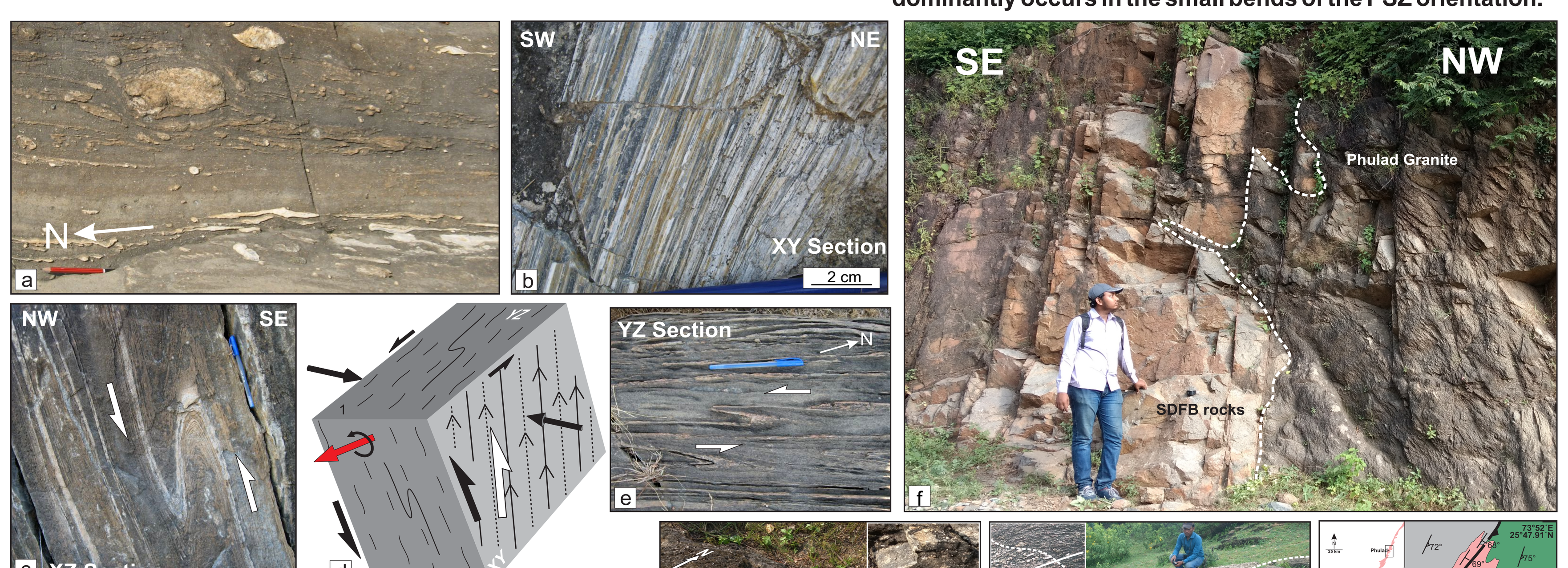
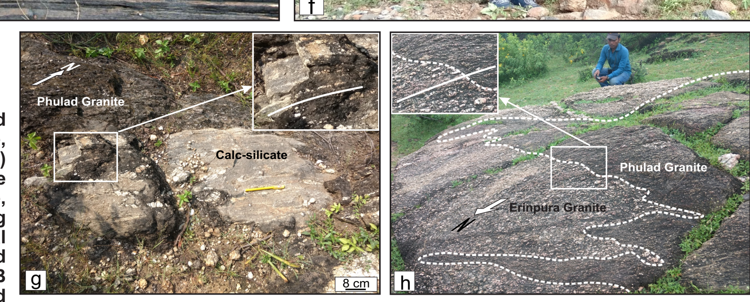


Figure 1: (a) Geological map depicting the different lithotectonic domains in northwestern part of Indian shield, modified after Heron [1953], Gupta et al. [1980], Roy and Sharma [1999] and Roy and Jakhar [2002] PSZ: Phulad Shear Zone, Inset shows the position of Delhi and SDFB (South Delhi Fold Belt) in India. (b) Digital Elevation Model (DEM) map with the outline of Phulad granite along the contact of Marwar craton and SDFB . Granite boundaries marked with white dotted line are inaccessible areas. DEM is prepared from the SRTM data of USGS earth explorer.

1. Introduction: In northwestern India, the Phulad Shear Zone (PSZ) demarcates the boundary between South Delhi Fold Belt (SDFB) to the east and Marwar craton to the west (Figure 1a). The PSZ is described as a terrane boundary shear zone along which the Greater India landmass accreted with the Marwar Craton at ~810 Ma. We have mapped the 200 km long contact between the Marwar cratonic rocks and the rocks of SDFB. The new map shows that the porphyritic Phulad granite occurs parallel to the PSZ and intrudes rocks of the Marwar Craton and SDFB (Figure 1b). In this work we describe the microstructures, new field relations and radiometric age data and discuss the implications of our data for the tectonics of northwestern India.

2. Field relations: The PSZ is characterized by NE-SW trend and steep easterly dipping mylonitic foliation with a prominent set of steep oblique striping lineations (Figures 2a, b). Stretching lineation is defined by stretched quartz grains and occurs parallel to this striping lineation. Asymmetric mesoscopic structures in XZ section (sub-vertical section perpendicular to foliation and parallel to lineation) suggest top-to-the-NNW reverse sense of movement (Figure 2c). This movement direction in PSZ is parallel to the stretching lineation and perpendicular to the vorticity axis (Figure 2d). Because of this oblique reverse slip movement in the shear zone, there is a component of sinistral slip movement on sub-horizontal section. The granite shows interdigited contacts with the host rocks of SDFB and Marwar Craton (Figures 2f-h). The Phulad granite and its country rocks show prominent foliation. The foliation within the Phulad granite is secant to the pluton boundaries and is in continuity with the regional foliation. Detailed mapping of PSZ (Figure 2i) reveals small bends of N-S orientations within the regional NE-SW trend. And the present granite dominantly occurs in the small bends of the PSZ orientation.





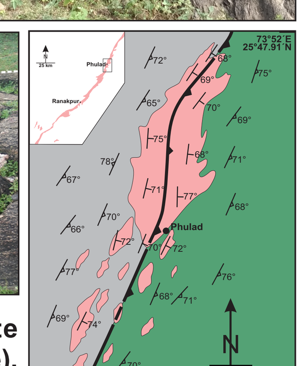


Figure 2: Field photographs showing (a) mylonitic foliation in intercalated calcareous and quartzo-feldspathic layers, (b) striping lineation on foliation plane, (c) asymmetric fold showing top-to-the-NNW reverse sense of movement, (d) Schematic diagram showing the formation of sinistral slip movement on the horizontal section because of the oblique reverse movement on the shear plane, white arrow shows the direction of movement parallel to the stretching and striping lineation, (e) field photograph showing the sinistral slip movement on horizontal section. The length of the pencil in (a) is 10 cm and the pen in (c), (e) is 14 cm. Field photographs showing the contact relationship of the Phulad granite with (f) SDFB rocks, (g) shear zone rocks and (h) Erinpura granite of Marwar craton. Zoomed portions in (g) and (h) show the continuation of Phulad granite foliation with the regional foliation of host rocks.

3. Microscopic features: The Phulad granite contains quartz, feldspar (k-feldspar and plagioclase), biotite, and muscovite. The granite is characterized by bi-modal grain size population with prominent euhedral phenocrysts of k-feldspar (2–6 cm long) in a fine-grained (<3 mm) mosaic of recrystallized feldspar and quartz aggregates. Microstructural study shows interlocking texture formed by magmatic feldspar, quartz, and biotite (Figure 3a). Alkali feldspar shows simple twin interfaces parallel to the foliation (Figure 3b). Fine grained aggregates of late magmatic minerals (quartz and feldspar) occur between fragmented primary feldspar grains (Figure 3c). Large quartz grains show chessboard twinning (Figure 3d). Recrystallized quartz grains and elongated oblique quartz grains are also present here (Figures 3e and 3f).

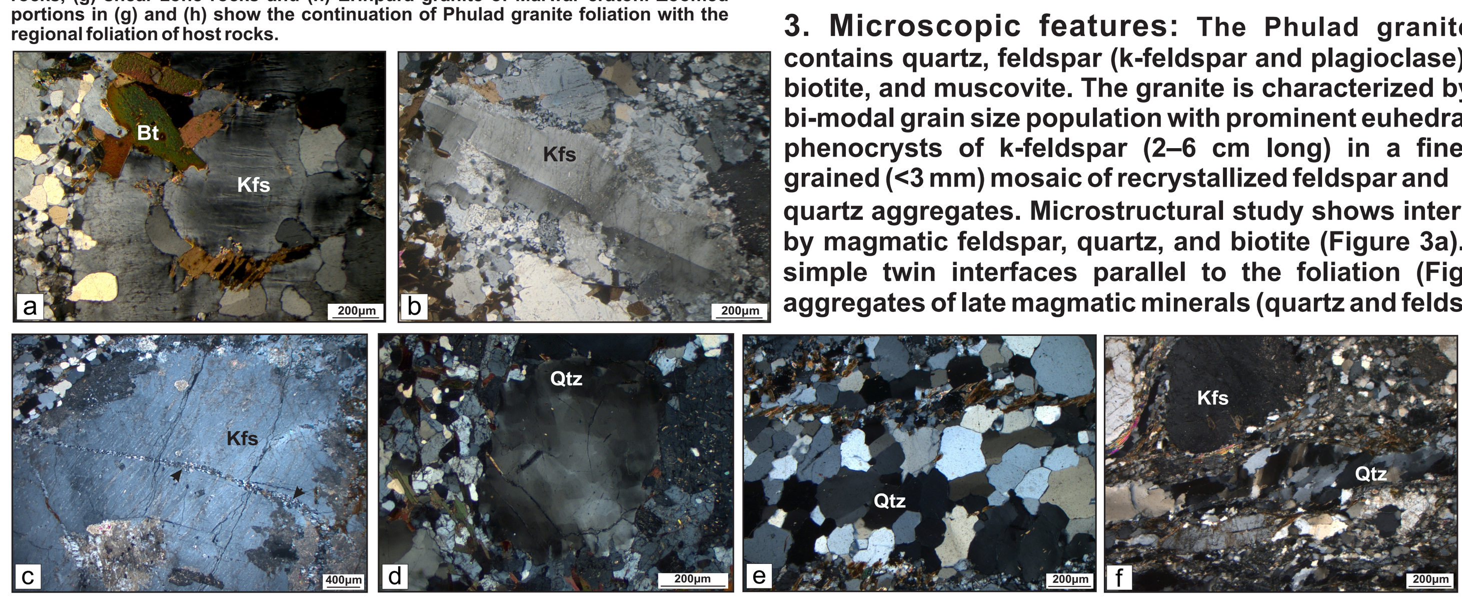


Figure 3: Photomicrographs in cross polarized light showing interlocking texture by primary minerals (a), alignment of simple twin in K-feldspar parallel to the foliation (b), fractured primary K-feldspar grain filled by quartz-feldspar aggregates (shown by black arrow head) (c), chessboard in quartz grain (d), recrystallized quartz grains ribbon (e), and elongated oblique quartz grain (f).

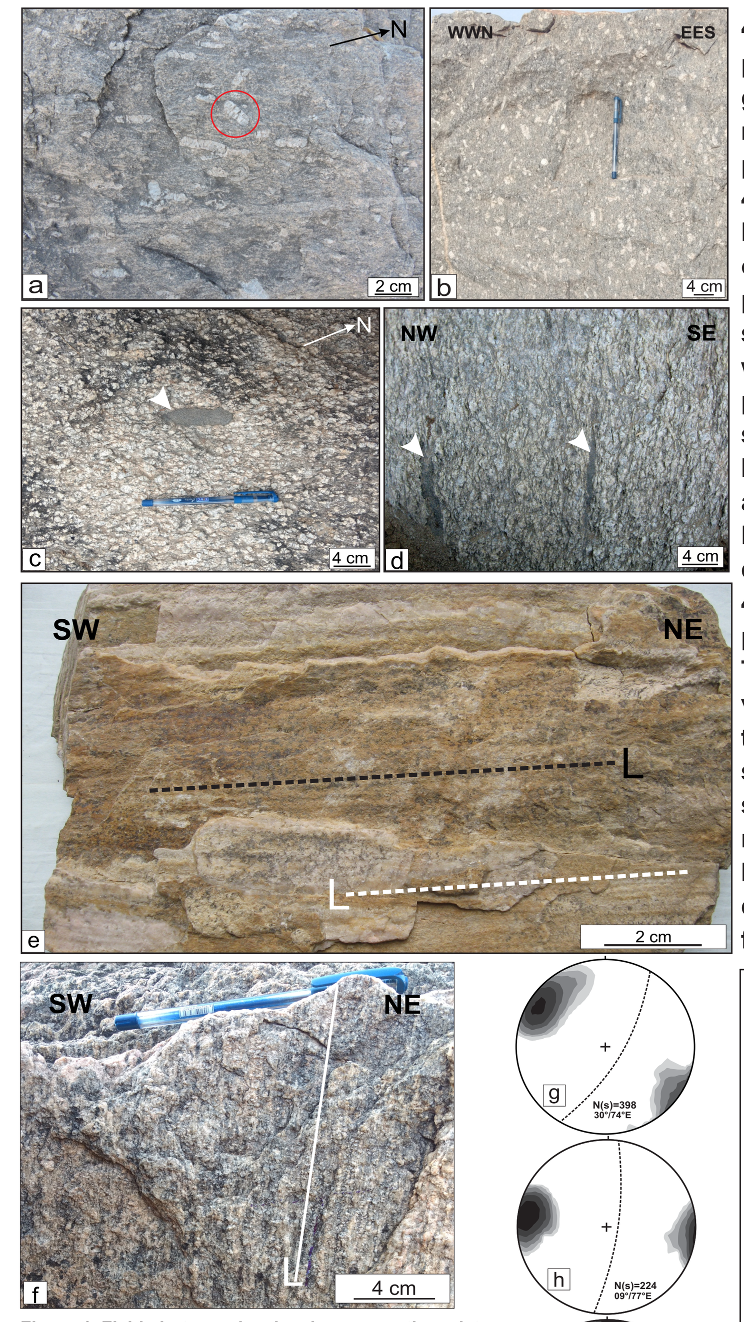
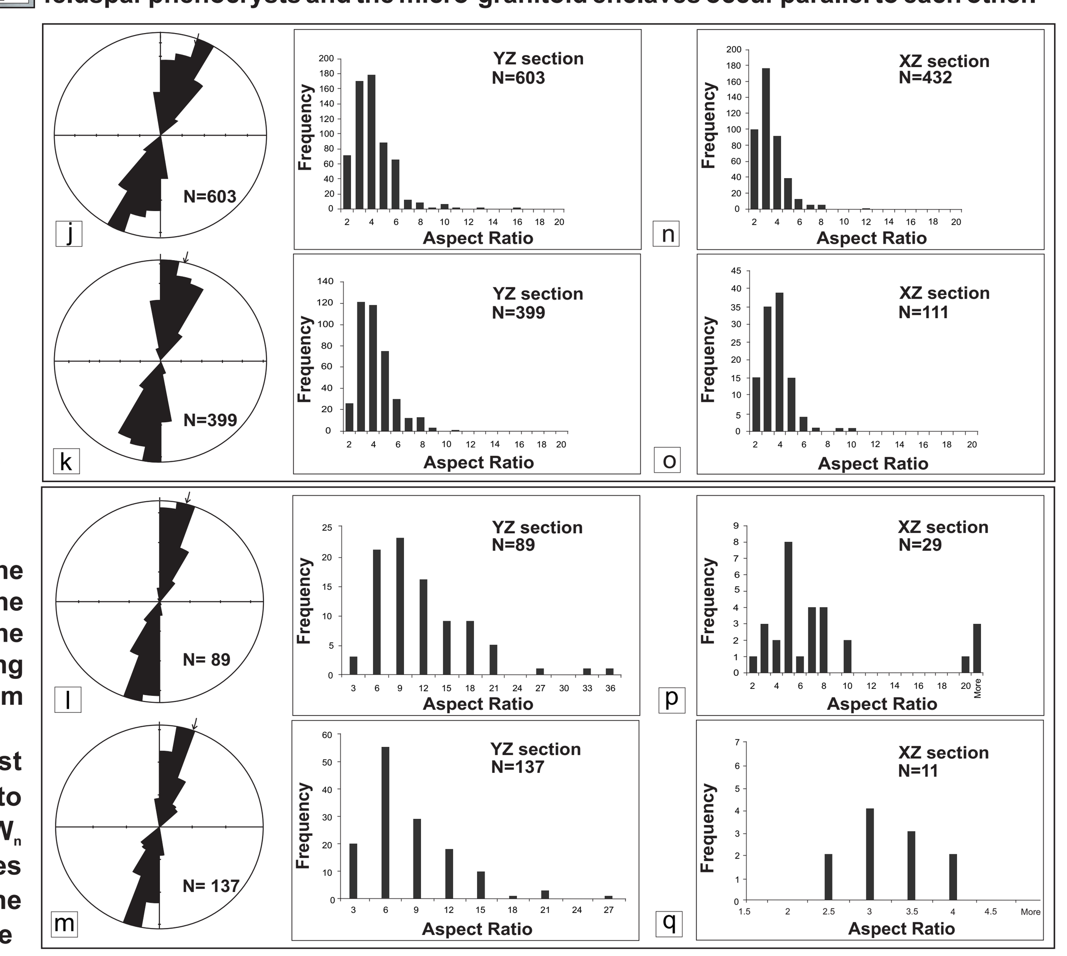


Figure 4: Field photographs showing magmatic variety (a)-(d), sub-horizontal lineation (e) and sub-vertical lineation (f). Stereographic plot (g) and (h) show NE-SW and N-S mean orientation respectively, (i) showing two varities of lineations. Rose Diagrams showing NNE-SSW orientation of clasts and enclave of magmatic (j,l), deformed (k,m) variety respectively. Histogram plots showing aspect ratio of magmatic (n,p) and deformed (o,q) variety of clasts and enclaves respectively.

This variation in plunge of lineation varies spatially. The Phulad granite shows steep plunging lineation in the shear zone, in the hanging wall portions and in the domain of footwall that is close to PSZ. The stretching lineation is gently plunging in footwall that is distant from the PSZ.

4. Mesoscopic features: The granitic rock is characterized by bi-modal grain size population with prominent euhedral grains of k-feldspar (2-6 cm long) in a fine-grained (<3 mm) mosaic of recrystallized feldspar and quartz aggregates. At mesoscopic scale the Phulad granite shows alignment of euhedral feldspar phenocrysts with simple twin interfaces parallel to the direction of elongation (Figure 4a). The granite also shows alignment of elongated micro-granitoid enclaves both on horizontal (YZ section) and vertical (XZ section) sections (Figures 4b, c). The orientation and length of long and short axis were measured for feldspar phenocrysts of the granite on sub-horizontal section (YZ). The length of long and short axis was measured for feldspar phenocrysts on sub-vertical section (XZ). Data were taken separately for both magmatic and deformed variety of feldspar phenocrysts (Figures 4a-d). The solid-state foliation varies from N-S to NE-SW. In strongly deformed variety, the granite shows prominent development of stretching lineations, both gentle and steep plunging (Figures 4e, f). Stereogram showing analysis of structural fabrics of Phulad granite collected from (Figure 4g) the regional NE-SW trend (Figure 4h) small bends of N-S trend. Stereographic plots of lineation data show two point maxima with mean orientations 67°→162° and 05°→192° (Figure 4i). The dominant orientation of long axes of magmatic and deformed variety feldspar phenocrysts show strong preferred orientation in NNE- SSW direction (Figures 4j, k). The orientation of the micro-granitoid enclaves of both magmatic and deformed varieties is dominantly in NNE-SSW directions (Figures 4l, m). Histogram plots show the aspect ratio of euhedral feldspar phenocrysts on subhorizontal and subvertical section (4n). Histogram plots show aspect ratio of deformed feldspar phenocrysts on subhorizontal section and subvertical section (4o). Histogram plots showing aspect ratio of microgranitoid enclaves on subhorizontal section, subvertical section in least deformed variety (4p) and subhorizontal section and subvertical section in deformed variety (4q). The aligned euhedral feldspar phenocrysts, deformed feldspar phenocrysts and the micro-granitoid enclaves occur parallel to each other.



5. Kinematic vorticity analysis: Porphyroclast Hyperbolic Distribution (PHD) method was used to calculate the sectional kinematic vorticity number, W_n value for our sample. We have calculated the W_n values of deformed Phulad granite (Figure 5a) from shear zone and hanging wall portions and the respective values are W_n=0.91 and W_n=0.86 (Figures 5b, c). The W_n values of Phulad granite are calculated separately for steep and gentle plunging lineations of footwall unit and the values are W_n=0.82 and W_n=0.47 respectively (Figures 5d, e). The sectional kinematic vorticity numbers are calculated for the country rocks of PSZ and its wall rocks using oblique grain shape foliation. The measured values show W_n = 0.90 to 0.96, W_n = 0.81 to 0.92 for PSZ and hanging wall rocks respectively (Figure 5f). The W_n values of footwall host rocks showing gentle plunging lineation and steep plunging lineations are W_n = 0.32 to 0.51 and W_n = 0.79 to 0.91 respectively (Figure 5f). The present study suggests the ratio of pure and simple shear strain rates mainly control the switching of stretching lineation in Phulad granite and its country rocks.

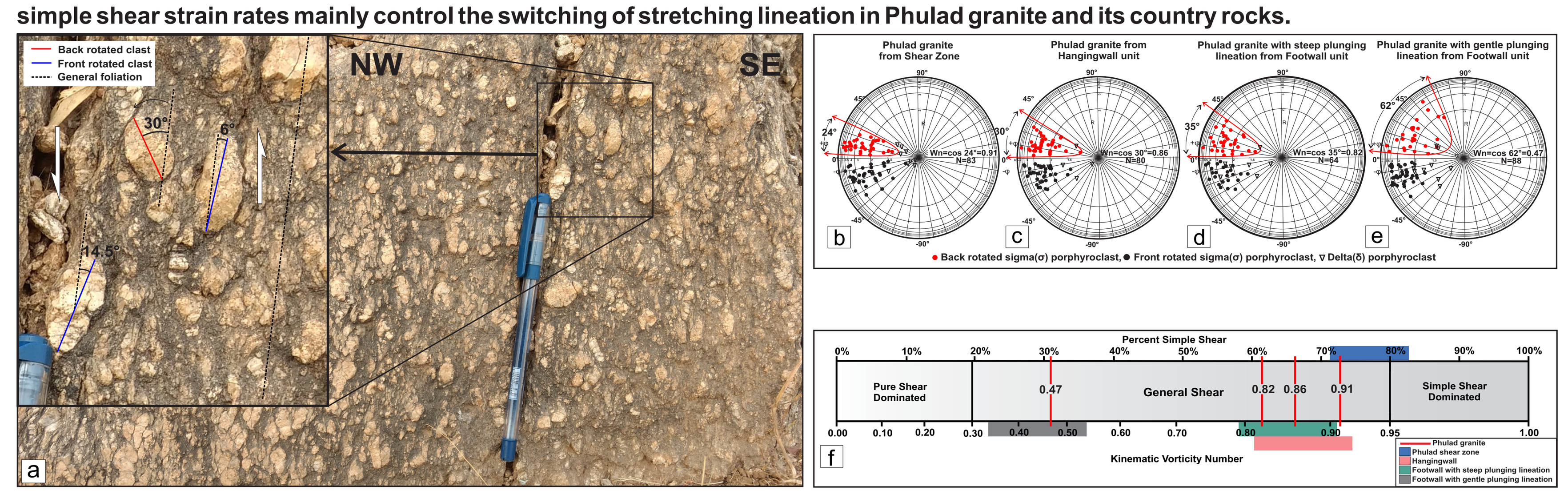


Figure 5: (a) Field photograph showing back rotated and front rotated clasts along with general foliation in Phulad granite. (b), (c), (d) and (e) hyperbolic stereonet plots of both front and back rotated porphyroclasts of Phulad granites from the shear zone, hanging wall portions, footwall with steep plunging and footwall with low plunging respectively. (f) Range of measured W_n values of Phulad granite and the country rocks from shear zone, hanging wall and footwall portions are shown in kinematic vorticity number and percent simple shear relation diagram (after Forte et al., 2007). The length of the pen in (a) is 14 cm. N = number of data.

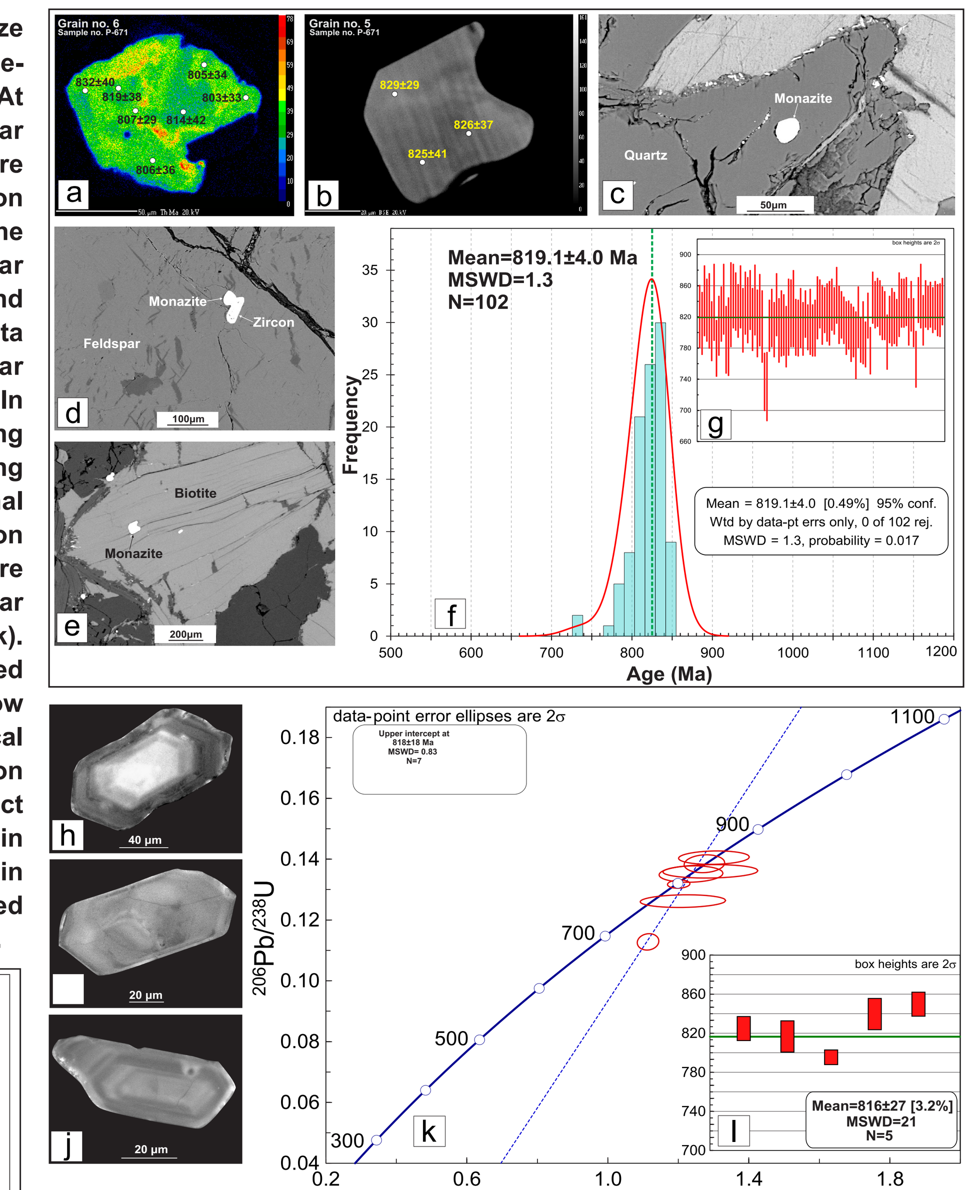
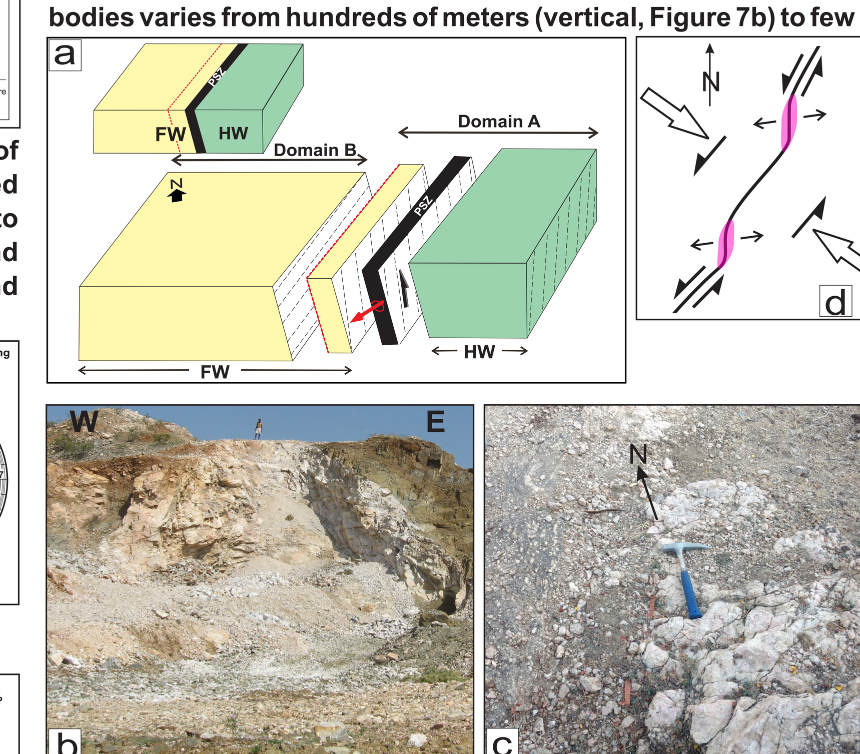


Figure 6: Photomicrographs in Th X-ray map (a) and BSE image (b) showing the euhedral monazite grains, BSE images (c-e) showing monazite grain included in quartz, feldspar and biotite grains in Phulad granite respectively, (f) plot of relative probability and frequency of spot ages in monazite grains of Phulad granite, (g) weighted average age of the Phulad granite monazite =819.1 ± 4 Ma with MSWD =1.3. Photomicrographs in Cathodoluminescence image (h-j) of zircon grains of Phulad granite. Concordia diagram (k) shows the upper intercept age of 818± 18Ma (MSWD=0.83) and the weighted average age (l) near concordia age is 816± 27Ma (MSWD=21).

6. Monazite and Zircon age determination: The monazites within Phulad granites are 50 to 100 µm in diameter (Figures 6a, b) with dominantly euhedral faces. They are mainly included in primary minerals most notably in quartz, feldspar and biotite grains (Figures 6c-e). These monazites do not occur in clusters. The morphology, internal structure and high Th value of these monazite grains suggest magmatic origin and therefore the ages obtained are taken to represent the timing of granite crystallization. All the monazite spot ages in Phulad granite correspond to a single age group (Figure 6f). The weighted average age is 819.1 ± 4 Ma with MSWD (mean square weighted deviation) = 1.3 (Figure 6g).

U-Pb LA-ICP-MS zircon geochronology from one representative Phulad granite sample (P-647) was carried out using a Resonetics Resolution M-50 series 193 nm excimer laser ablation system equipped with a Laurin Technic Pty S-155 ablation cell at Activation Laboratories, Ancaster, Ontario, Canada. The data were standardized against FC1 zircon (1099 ± 2 Ma), which was analyzed at least 16 times per run and distributed evenly throughout the sequence. Each ablation lasted for 30 s and was preceded by 30 s of background collection. The data were reduced offline using VizualAge (Petrus & Kamber, 2012) and Iolite v2.5 (Paton et al., 2011) running as plugins in Wavemetrics Igor Pro 6.23. Concentration data were calculated relative to NIST610 (distributed throughout the sequence) and using the Iolite trace elements "internal standardization" data reduction scheme. All diagrams were produced using the Isoplot V3.0 program of Ludwig [4.1]. Zircon grains in Phulad granite (P-647) are mostly euhedral, 70–200 µm in length with aspect ratio varies between 2 and 4 (Figures 6h–j). Zircon grains are optically clear, colorless, and inclusion free. CL images clearly show the magmatic oscillatory zoning and do not show any overgrowth textures. The morphology and their internal structure suggest that they are magmatic in origin, and therefore, the ages obtained are taken to represent the timing of granite crystallization. Both the core and rim were analyzed from these magmatic zircon grains to confirm the crystallization age. The data plot of 206Pb/238U and 207Pb/235U ratios in the Concordia diagram gives an upper intercept age of 818 ± 18 Ma with MSWD = 0.83 (Figure 6k). The weighted average of 206Pb/238U of near Concordia data is 816 ± 27 Ma with MSWD = 21 (Figure 6l). Though the numbers of ablated zircon grains are statistically low (N = 7) nevertheless their morphology, internal structure, and concordant data confirms their magmatic age.

7. Discussion and conclusion: The PSZ is characterized by prominent development of mylonites with regional NE-SW trend and small bends of N-S orientations. Structural analysis indicates that PSZ has developed in ductile transpressive regime with top-to-the-NNW reverse sense of movement associated with sinistral-slip movement on the horizontal section. The 200 km by 6 km porphyritic Phulad granite occurs along and across the PSZ and it is variably deformed. The Phulad granite shows evidence of magmatic foliation with preservation of parallel alignment of euhedral feldspars phenocryts and micro-granitoid enclaves. The feldspar phenocrysts show simple twin interfaces parallel to the direction of elongation. This granite also shows development of solid-state foliation parallel to this magmatic foliation. A detailed study of structural elements suggests that the Phulad granite has formed during the regional deformation in the country-rock shear zone prior to its complete crystallization. The Phulad granite and the associated host rocks show both gentle (domain B) and steep plunging (domain A) stretching lineations in the footwall and hanging wall side (Figure 7a). Since N-S bends occur as fractal in nature so the size of these pegmatite bodies varies from hundreds of meters (vertical, Figure 7b) to few meters depending on the size of the N-S bend (horizontal, Figure 7c).



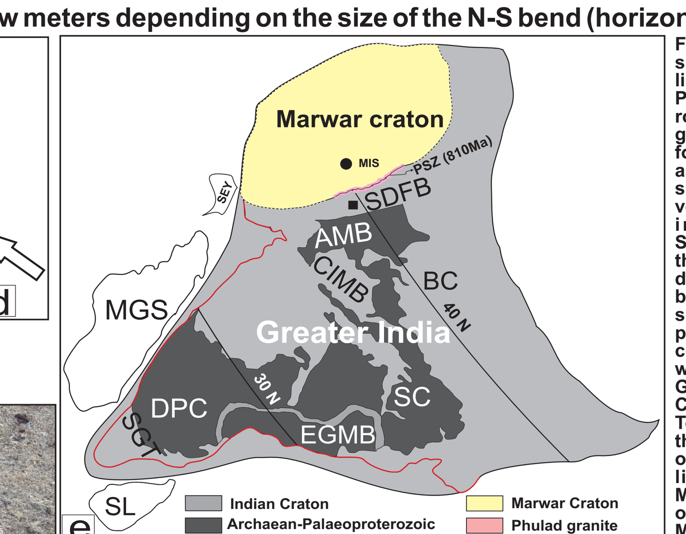


Figure 7: Schematic diagram (a) showing the steep plunging lineation in the footwall close to PSZ, at PSZ and in hanging wall rocks (marked as Domain A) and gentle plunging lineation in the footwall distant from PSZ (marked as Domain B). Field photograph showing pegmatite body on (b) vertical and (c) horizontal section in the N-S trends of PSZ. Schematic diagram (d) showing the sinistral sense along NE-SW direction with dilation at the small bends. Geological map (e) showing the position of stitching pluton (Phulad granite) at the contact (PSZ) of Marwar craton with the remaining part of the Greater India (modified after Collins and Pisarevsky 2005; Torsvik et al., 2001). The width of the Phulad granite is exaggerated on the map. The palaeolatitude lines are superimposed from Meert 2003. The red line shows the outline of India. AMB: Aravalli Mobile Belt, BC: Bundelkhand Craton, CIMB: Central India Mobile Belt, DPC: Dharwar Protocontinent, EGMB: Eastern Ghats Mobile Belt, MGS: Madagascar, MIS: Malani Igneous suit, SDFB: South Delhi Fold Belt, PSZ: Phulad Shear Zone, SC: Singhbhum Craton, SEY: Seychelles, SGT: Southern Granulite Terrane, SL: Sri Lanka.

Our data indicate that the releasing bends of N-S orientation within the PSZ (Figure 7d) have provided the space required for the emplacement of the Phulad granite in a transpressional regime. EPMA U-Pb-Th monazite and U-Pb LA-ICP-MS zircon ages in the Phulad granite indicate a magmatic age of 819.1± 4 Ma and 818 ± 18 Ma . The present study suggests that the Phulad granite acted as a stitching pluton during the suturing of the Marwar craton with the remaining India (Figure 7e) to form the Greater India along PSZ at 810-820 Ma.

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