

Supplementary File

S1. Geological setting of the study areas

We studied ductile shear zones in two regions of the Precambrian craton in Eastern India (Fig. S1 and Fig. 1 of main text): 1) the Singhbhum Shear Zone (SSZ) and 2) Chotanagpur Granite Gneiss Complex (CGGC).

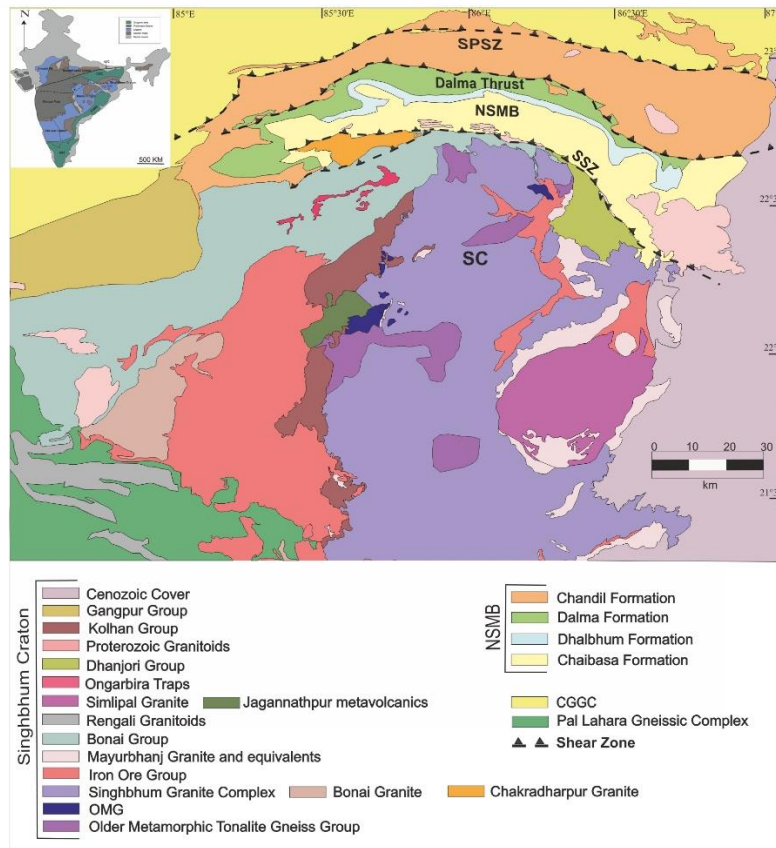


Fig S1. A geological map of the field study area

The Singhbhum Shear Zone (SSZ) is a laterally persistent, arcuate-shaped lineament, with its trend varying from NE-SW in the west flank to NNE-SSW in the eastern part. The SSZ demarcates the interface between the Archean nucleus on south and the North Singhbhum Mobile belt. Structural signatures suggest that it has accommodated large ductile shearing during the north to south crustal shortening (Ghosh and Sengupta, 1987, 1990; Roy and Matin, 2020). In places, the shear zone forms a contact between Chaibasa Formation at the top and the

Dhanjori formation at the bottom. The Chaibasa Formation comprises pelitic schists, intercalated by quartzite beds of varying thickness (less than a meter to tens of meters), whereas

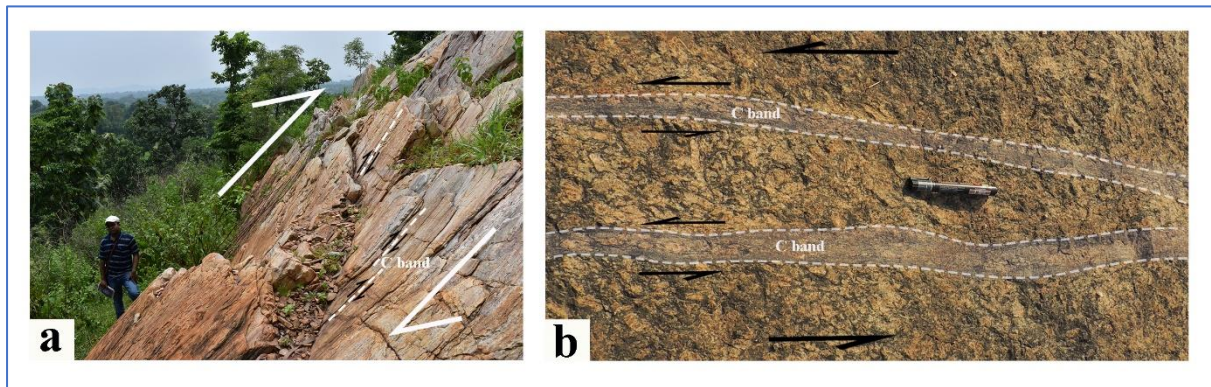


Fig. S2: Shear zones where deformation accommodation mechanism is completely by localised shear accommodation. Note the absence of any S foliation within these shear zones. (a) Shear zones from SSZ having exposed shear surfaces showing slickenlines as an indicator of slip (Fig. 2a). (b) C dominated shear zones from Raghunathpur, Purulia.

the Dhanjori Group is made up of conglomerate-arkose phyllite assemblage in association with mafic to ultramafic volcanics, are metamorphosed to greenschist facies (Mukhopadhyay and Deb, 1995). The boundary between the shear zone and associated Dhanjori Group and Chaibasa Formation is not sharp. The mica schists, quartzites, granites and amphibolites are strongly sheared to produce mylonites and phyllonites within the SSZ (Sengupta and Ghosh, 1997). Mylonitised granite within the shear zone is interpreted to have intruded the host rock at an early stage of deformation. It has been interpreted that the degree of mylonitisation in the shear zone varied spatially, leaving unsheared or weakly deformed lenses (Sengupta and Ghosh, 1997). Our fieldwork concentrated in the southeastern flank of the SSZ at Patheragora ($22^{\circ}32'37.911''\text{N}$, $86^{\circ}26'31.223''\text{E}$) near the old Surda copper mines and Musabani ($22^{\circ}30'59.3''\text{N}$ $86^{\circ}26'26.5''\text{E}$) region in Purbi Singhbhum District, Jharkhand (Fig. 1b). These locations show excellent exposures of sheared quartzites (Fig. S2a), containing a prominent set of northward dipping foliations with down-dip lineations. We studied their internal structures, such as macroscopic foliations and shear bands on the XZ sections of the shear zones.

Our fieldwork in the CGGC localized in the northern region of Purulia District, where the host rocks are primarily granite gneisses, interspersed with metasedimentary and metabasic rocks. They have been metamorphosed into lower amphibolite to higher granulite grades (Roy et al., 2021). The study areas show an assemblage of various lithological types, including porphyritic and non-porphyritic granite gneisses, quartzo-feldspathic pegmatites and mafic

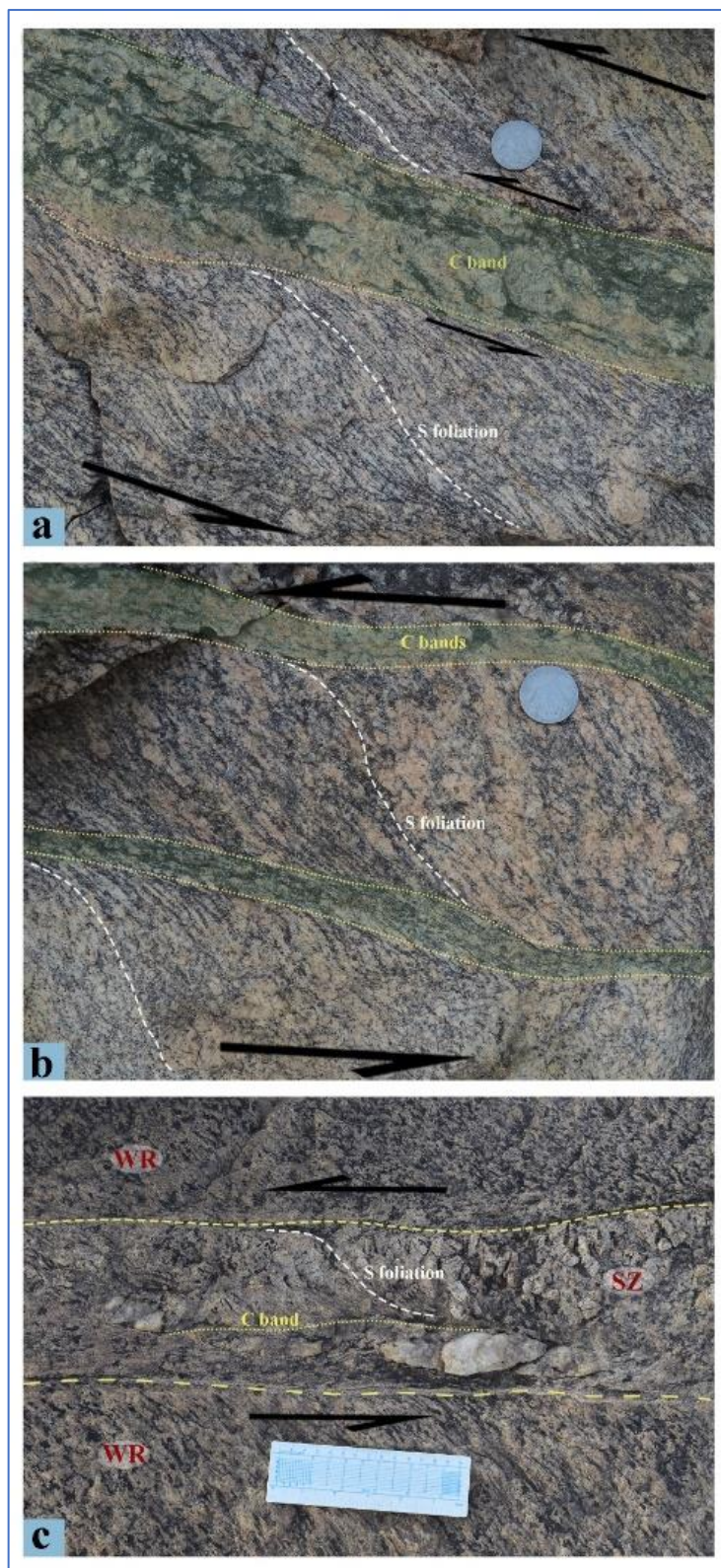


Fig. S3: Field photographs exhibiting ductile shear zones accommodating shear both by homogeneous deformation and by strain localisation and formation of shear zone parallel C bands. (a-b) shear zones from Bero, Purulia. (b) Shear zones from Anandanagar. SZ: Shear Zone, WR: Wall Rock.

dikes. The porphyritic granite gneisses, characterized by their distinct large K-feldspar crystals, form elongated structures oriented east-west, often exhibiting discernible gneissic foliations and occasional augen structures. Notably, the degree of metamorphism within these formations increases from the western flank near Jhalda-Kotshila to the eastern extremity near Raghunathpur, as suggested from petrological studies providing pressure-temperature (P-T) estimates of around 820°C and 7 kilobars (7 ± 0.5 Kb) (Das et al., 2020). In addition to the porphyritic varieties, non-porphyritic granite gneisses constitute a significant portion of the CGGC terrain. These gneisses host enclaves of various rocks, such as mica-schists, amphibolites, khondalites, quartzites, and migmatites. Pegmatite veins, cutting across these gneisses and migmatites,

are a common occurrence. Notably, we observed outcrop-scale shear zones within pegmatite veins (Fig. S3c and S4c), which are particularly prominent in the Anandanagar area of the Purulia district. These shear zones occur sporadically in porphyritic granite gneisses and other mafic and metasedimentary rocks. They provide spectacular structural manifestations of shear deformations. Outcrops in Raghunathpur (Fig. S3a, b and S2b) and Bero (Fig. S4a and b) were also investigated where the porphyritic granite hosted shear zones show a range of internal structures.

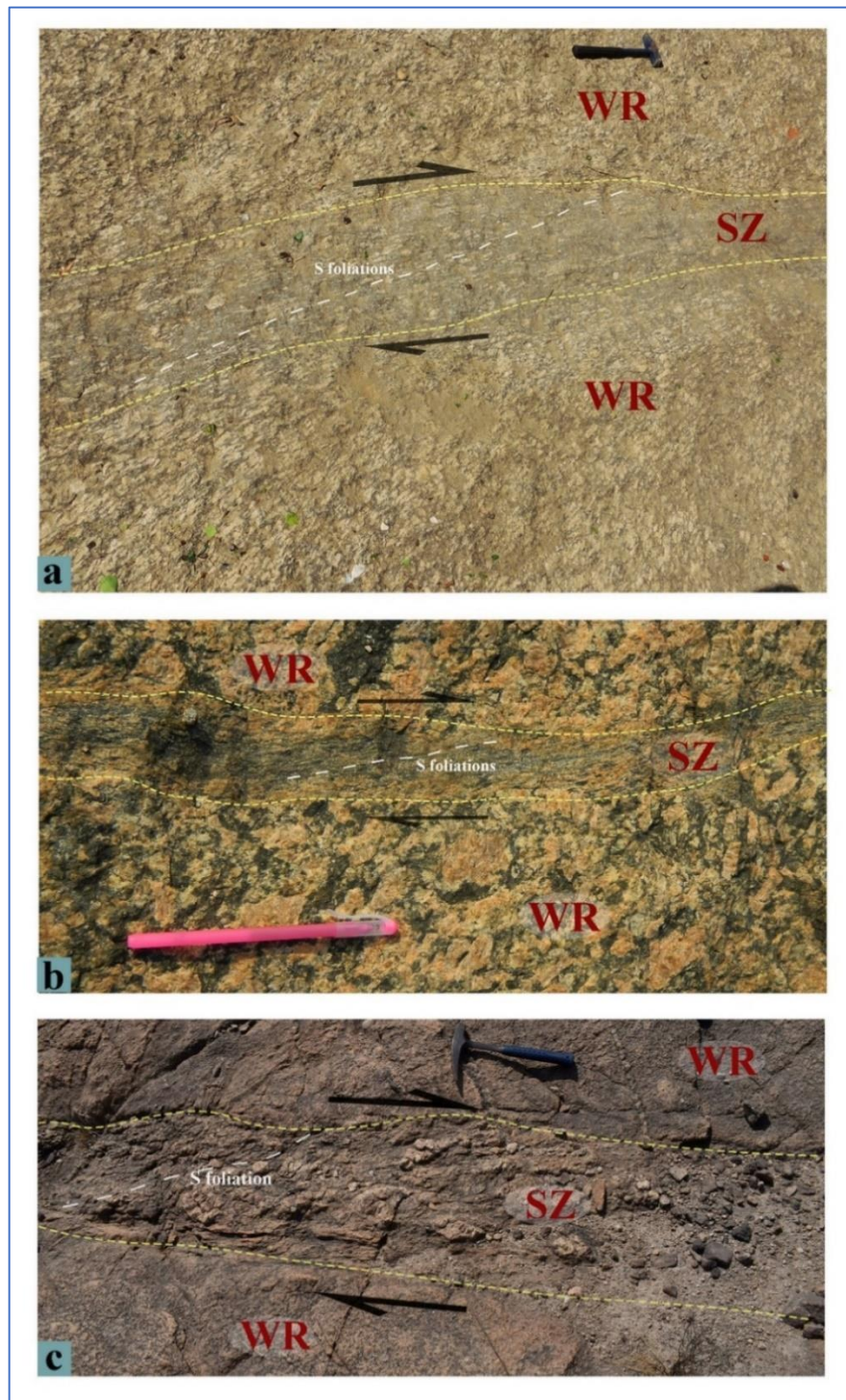


Fig. S4: Outcrop scale ductile shear zones where shear accommodation is mostly by homogeneous viscous strain (S-foliation development). (a-b) Shear zones in Raghunathpur, Purulia, (b) Shear zones in Anandanagar. WR- Wall Rock, SZ- Shear Zone.

S2. Microstructural description of Shear Zone rocks and their rheological implications

To understand the deformation characters of the Sheared Quartzites in the SSZ, thin sections were made from rock slabs cut perpendicular to the mylonitic foliation and parallel to the stretching lineation. The rock is dominantly quartz, showing a bimodal grain size distribution, with very little amount of biotite, chlorite and some oxides. The quartz grains show different kinds of microstructures such as undulose extinction and subgrain formation. The grains vary in size; length and width of the quartz grains varies from 660 μm to 200 μm and 150 μm to 85 μm respectively. The long axis of some of the quartz grains are oriented at an angle to the shear direction though no dominant S fabric was observed in the rock samples. The fine-grained recrystallized quartz form in linear zones parallel to the bulk shear direction which indicates that this localized reduction in grain size is the resultant of strain rate enhancement. The small amounts of biotite and chlorite present in the rock samples are also found parallel to the shear direction within the fine-grained quartz or at the boundary of coarse and fine quartz grains (Fig. S5 b,c). They are most probably a consequence of small scale yielding along localized regions and later fluid influx resulting in their crystallization.

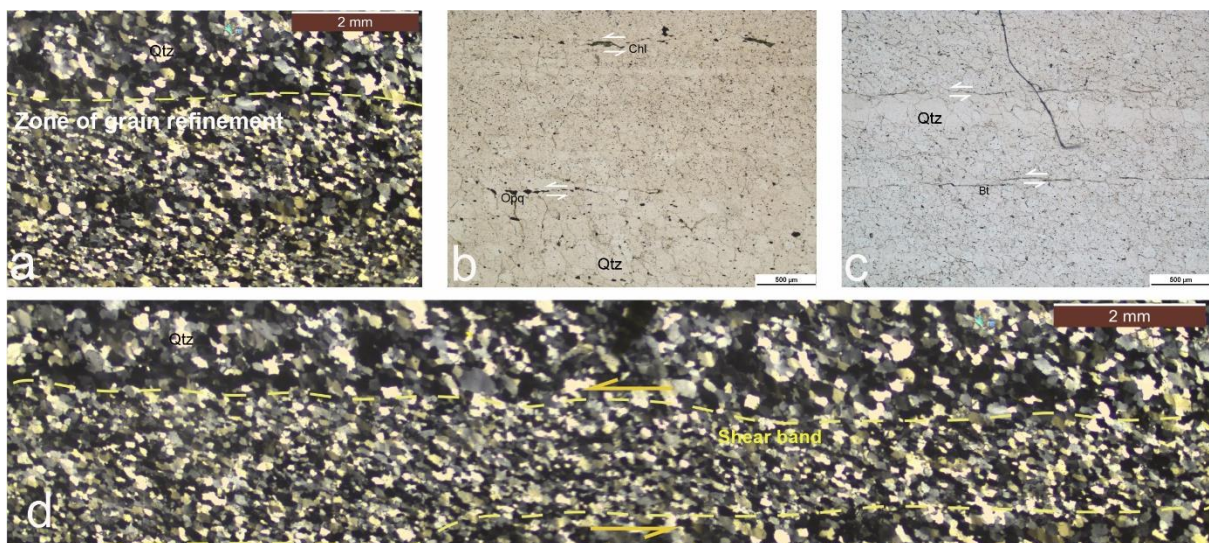


Fig. S5: Microphotographs of Sheared Quartzites showing dominant C band formation from Musabani area. (a) Shear zones showing the boundary between fine grained and coarse grained quartzites in cross polars. (b-c) Micro-scale slip surfaces filled up by chlorite, biotite and oxides. (d) Localized high-strain zones showing grain size reduction and dynamic recrystallization bounded by regions of coarser quartz grains. Sense of Shear: Sinistral. Qtz: Quartz; Bt: Biotite; Ch: Chlorite; Opq: Opaque Oxides.

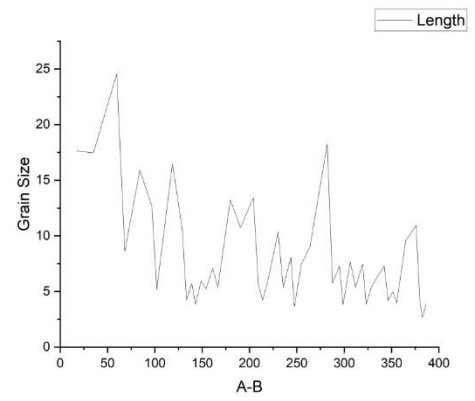
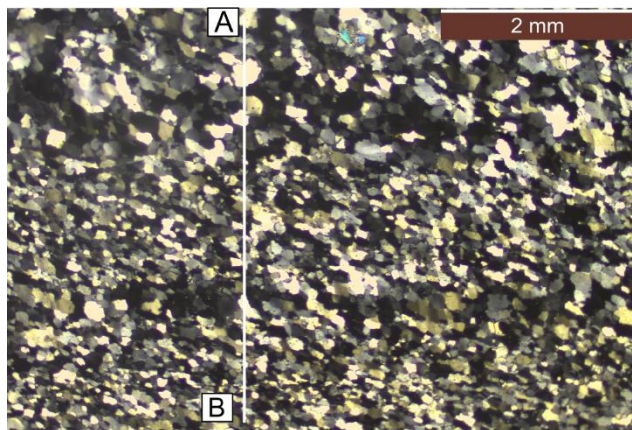


Fig. S6: Grain size variation across a C band.

Shear zones hosted in porphyritic granite gneiss comprises mainly quartz, K-feldspar (microcline), plagioclase, garnet, biotite, hornblende and other accessory opaque minerals. A

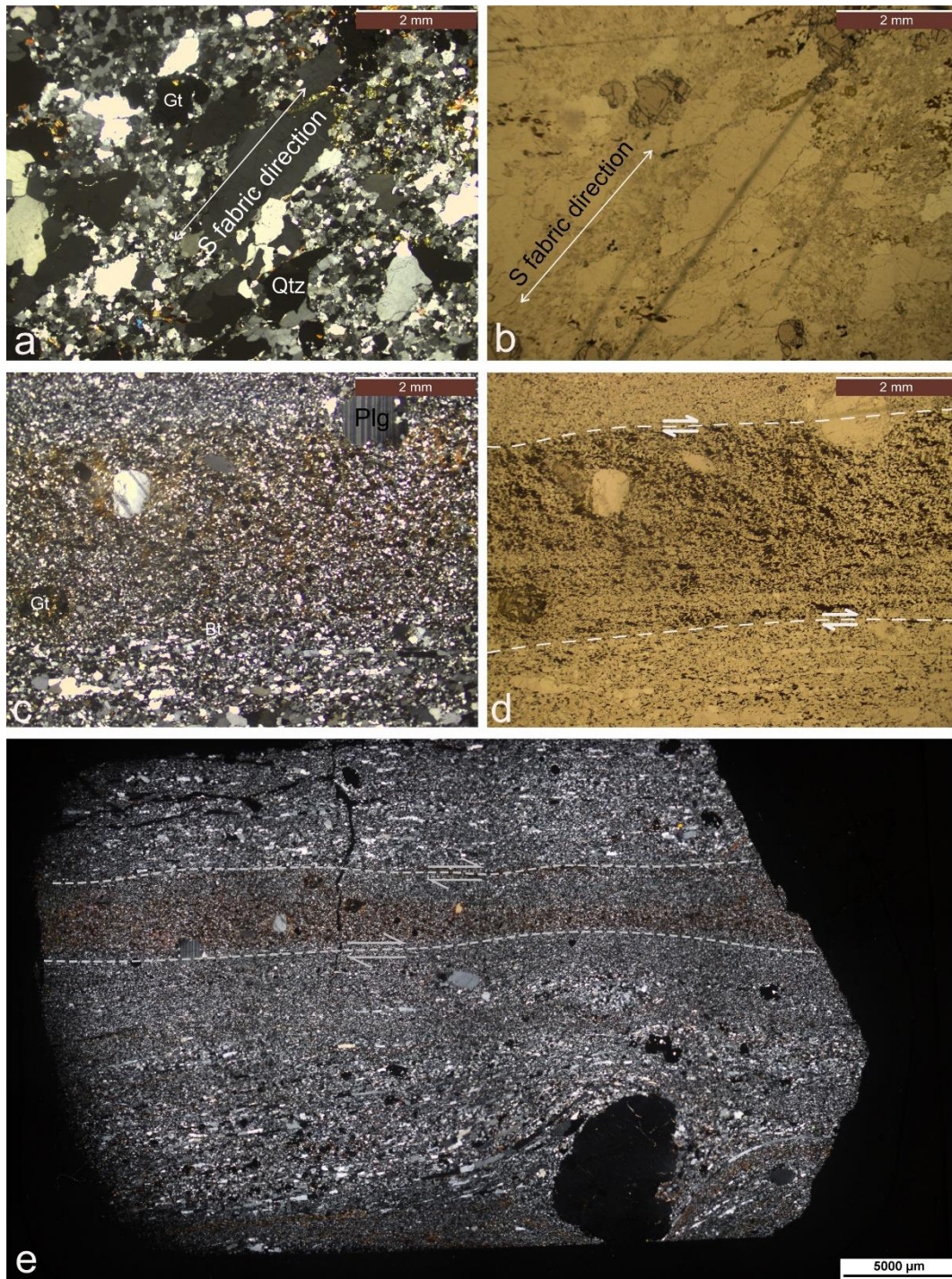


Fig. S7: Microphotographs of shear zones of Bero Hills where the rocks accommodate shear both by distributed strain and localized band formation. (a) Regions of the shear zone where S foliations form in the macroscopic scale. (b) Corresponding plane polarized photograph of (a). (c) Regions of shear zone where C bands localize. Note the finer grain size compared to the reegions of distributed deformation. (d) Plane polarized photograph of (c). There is secondary mineralization of biotote parallel to the bulk shear direction. (e) Microphotograph of shear zone where localized deformation takes place. The shape fabrics and assymetric drag structures indicate that the sense of shear is dextral. Qtz: Quartz; Plg: Plagioclase; Bt: Biotite; Gt: Garnet.

fraction of the quartz grain population occurs as lenticular, anhedral, elongate grains (ribbon), often warping feldspar megacrysts (Fig. S7e). The rest is represented by much finer, recrystallized quartz grains. K-feldspar varies in grain size, ranging from large megacrysts (0.8-1cm) to medium as well as fine-grained recrystallized matrix (200 – 400 μm). Plagioclase occurs mainly as medium to small grains, forming aggregates with the groundmass minerals, mainly quartz and biotite. Observing regions of the shear zone showing homogeneous deformation from Bero area under microscope reveal undulose extinction and grain elongation of quartz (2mm in length and 1mm in width) along with recrystallization of feldspar grains at an angle($\sim 40^\circ$) to the shear direction in accord to the macroscopic S foliation(Fig. S7a,b). On the other hand, thin sections from locales of localized strain and shear band formation show characteristic grain refinement by dynamic recrystallization(Fig. S7c,d). The grain size in these regions are extremely small(less than 0.5mm) with some relict feldspar and garnet of much larger grain-size. Biotite grains are shown to form linear zones parallel to the bulk shear direction but the individual grains are oriented at very low angles($\sim 5^\circ$) to the shear zone. Asymmetric drag structures are observed around some large feldspar porphyroclasts whose rotation conforms to the general shear direction.

Shear zones of Anandanagar observed under the microscope mimics the macro-scale observations(Fig. S8). The grains of quartz show undulose extinction while the feldspar grains

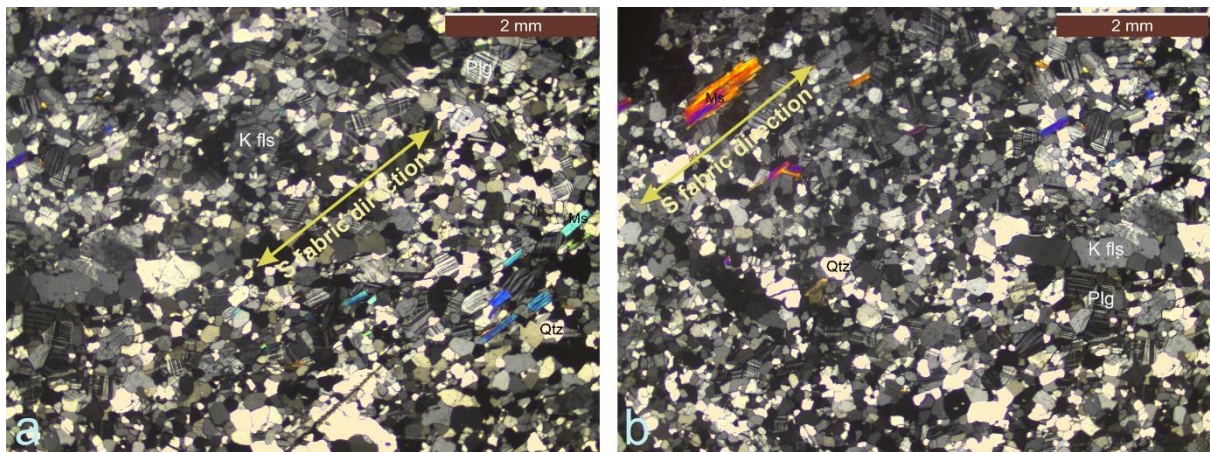


Fig. S8: Shear Zones of Anandanagar, where S foliations dominate. (a-b) Microphotographs of shear zones showing the development of shape fabrics defined by muscovite grains and feldspar recrystallization. Sense of Shear: Dextral. Qtz: Quartz; K Fls: Potash Feldspar; Plg: Plagioclase; Ms: Muscovite.

show extensive recrystallization. The elongated muscovite grains are oriented at an angle($\sim 30^\circ$) to the bulk shear direction which, along with the recrystallized grains gives a fabric like

appearance to these rocks. Similar to the rocks observed in the field, we do not observe any zones of high strain localization within these shear zone rocks.

S3. Rheological Implications from Microstructural Analyses

The microscale features observed from all of our field areas show crystal plastic deformation and dynamic recrystallization indicating that the shear zones underwent viscous deformation. Observing the regions of C band formation shows a significant reduction in grain size compared to the inter-band region with signatures of recrystallization. Also, there are some fabrics in these C bands forming oblique to the shear direction but at much lower angles compared to the inter-band region. The locales of mineralization of biotite, chlorite and various oxides in the C bands are regions parallel to the general direction of shear. The regions of C band formation are thus regions of yielding, secondary mineralization, and localized zones of high shear strain accommodation as evident from the dynamic grain-size reduction and shape fabrics oriented almost parallel to the shear direction. These observations lead us to consider a visco-plastic rheology to simulate the shear zones where the viscous component signifies homogeneous continuous deformation while the plastic part introduces a pressure sensitive yield behaviour associated with mechanical weakening to localize the shear bands.

S4. Shear accommodation mechanisms

The differing patterns of distributed S foliation and localized C bands within the shear zones of our study areas (SSZ and CGGC) indicate three contrasting mechanisms for accommodating shear (Fig. S9). In the Anandanagar region of CGGC, shear is accommodated through homogeneously distributed viscous deformation, with minimal macro-scale shear band formation. This leads to the formation of S-foliations within the sheared rocks of this area. Conversely, in the SSZ, regional shear is primarily accommodated through the formation of localized C bands in initially undeformed rocks. Within the CGGC (Bero Hills region), most of the shear zones exhibit a hybrid mode of evolution, where both distributed viscous strain and localized C band formation operate with comparable significance.

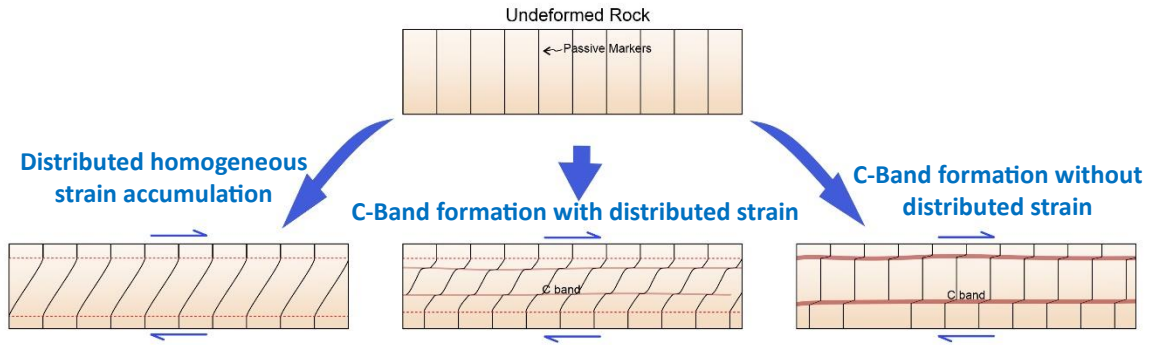


Fig. S9: A schematic diagram showcasing the three modes of shear accommodation observed in ductile shear zones in the Singhbhum Shear Zone and the Chotonagpur Granite Gneissic Complex.

S5. Weakening in Model Shear Zones

The nonlinear relationship between viscosity and strain rate after weakening in model shear zones is explained in the figure below.

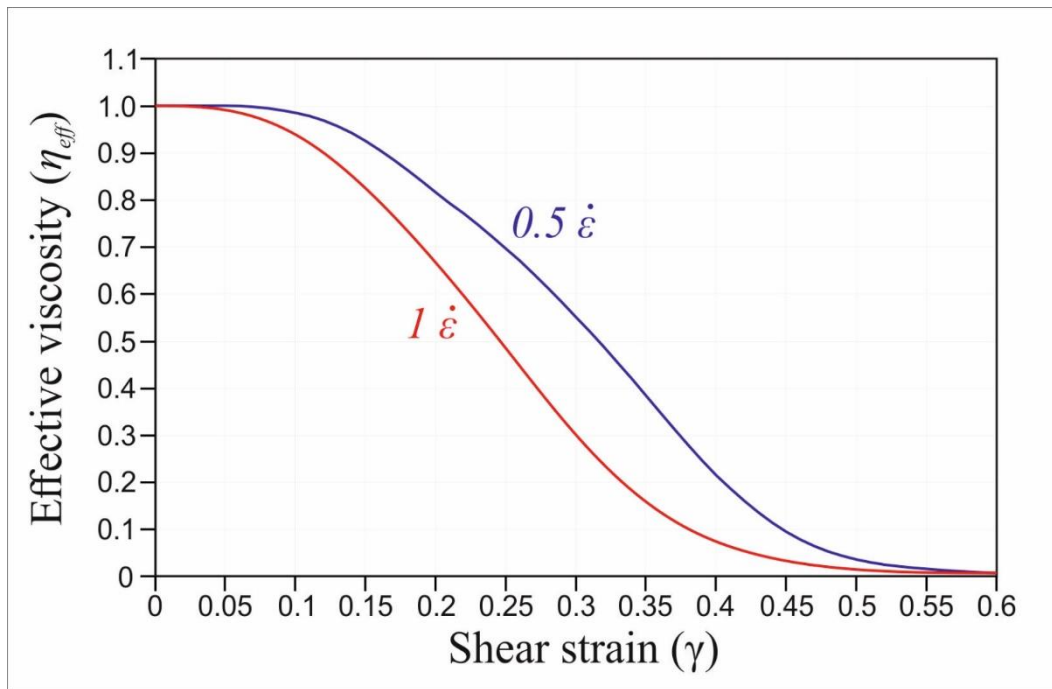


Fig. S10: Viscous weakening of the material, introduced by plastic yielding where the modified viscosity decreases nonlinearly with increasing strain. This implies a strain softening rheology for our shear zone models.

S6. Modelling of ductile shear zones

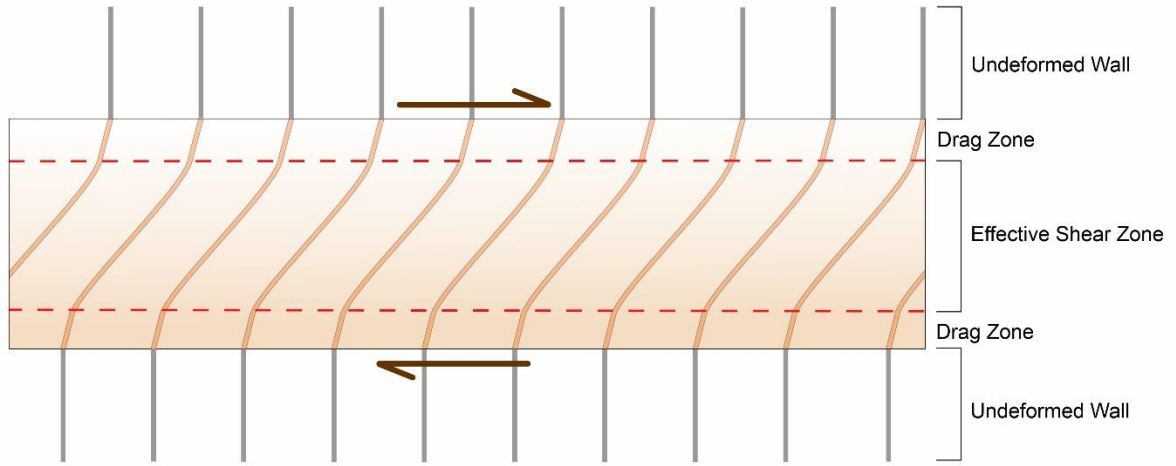


Fig. S11: The three layered structure of natural shear zones observed in the field study. The coloured portion represents the numerical model definition.

To model the strain variation in the core-wall transition in a ductile shear zone (Fig. S10), we choose a hyperbolic tangent function,

$$\mathcal{F}(y) = [\tanh((S_w - y)H_F) + \tanh(H_F(y)) - \tanh(H_F)]^{2p}$$

where y stands for the normal distance of a given point from the shear zone boundary, S_w is the distance between the shear zone boundaries, H_F is a non-dimensional constant, and p stands as an exponent factor. The above function is multiplied with the plastic strain value at every point of the shear zone in each iteration. The value of the function is 0 at the model boundary and 1 at the shear zone core (Fig. S11). Therefore, the plastic strain value, inside the shear zone core remains unaltered in every step. Also, the plastic strain value at the model boundary remains 0 at every step. Inside the drag zone, the plastic strain is dampened considerably which hinders the process of plastic strain accumulation. The above hyperbolic tangent function is chosen as it satisfies a two- fold objective. Not only does the function stops the localized strain to reach the shear zone boundary but it also helps in defining the property (diffused or sharp) and thickness of the drag zone. Figure S10 shows the change in shape of the function when the

constants are varied. The drag zones are diffused for lower values of H_F and sharp for higher values of H_F .

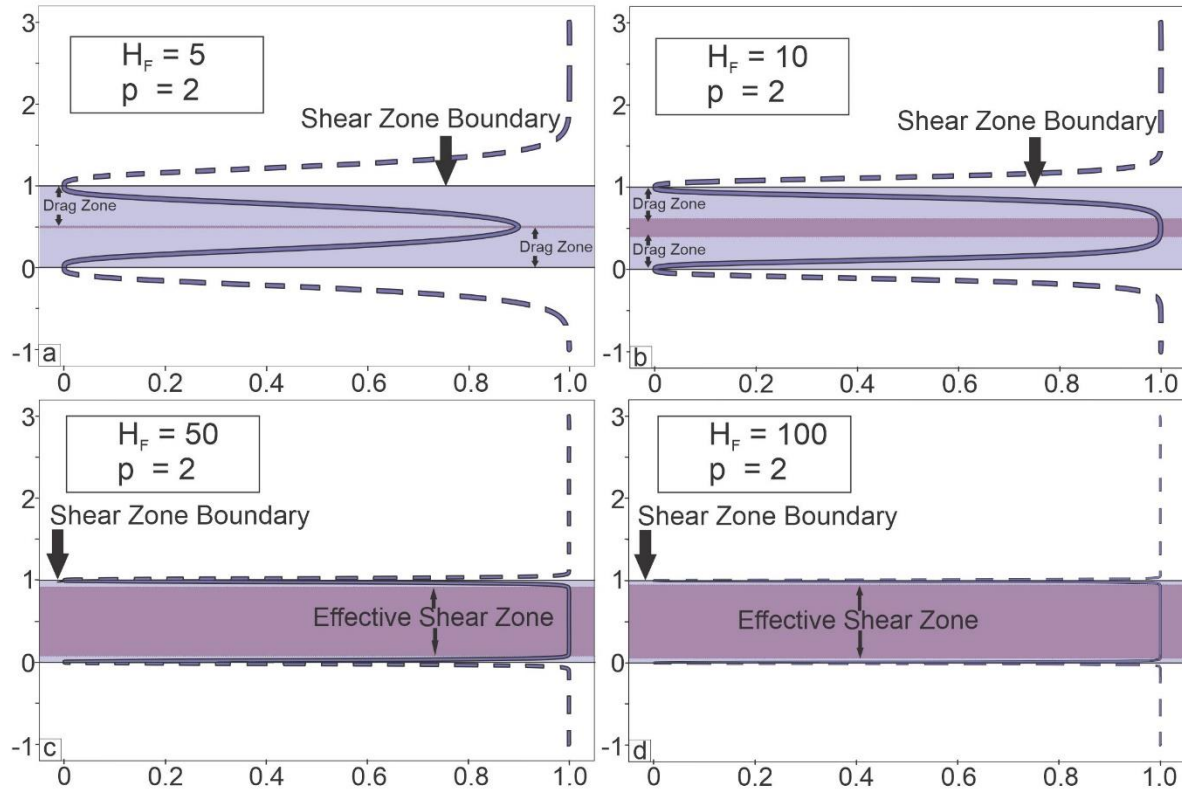


Fig S12: Graphical presentation of the hyperbolic tangent function for varying parameter H_F . The function is applicable in the range $0 < y < 1$ for the present shear zone models. ($S_w = 1$ for all cases).

S7. Reference Model Videos

Supplementary Video 1:

Evolution of a model ductile shear zone assisted by the mechanism of homogeneously distributed strain accumulation.

Supplementary Video 2:

Complete evolution of a model ductile shear zone, accommodating shear by a combination of homogeneously distributed strain accumulation and shear band formation.

Supplementary Video 3:

Complete evolution of ductile shear zone model showing strain localization in the form of narrow linear shear bands.

References

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