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The tectonic and kinematic evolution of an intra-terrane shear zone – the case of North Purulia Shear Zone and its relation to Rodinia assembly

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Abstract

Intra-terrane shear zones (ITSZs), though widespread across Proterozoic mobile belts, remain underexplored in their structural evolution and tectonic significance. This study explores the anatomy of the North Purulia Shear Zone (NPSZ), a ~E–W trending, steeply dipping ITSZ within the Chotanagpur Granite Gneiss Complex (CGGC), eastern India. Integrated structural, kinematic, anisotropy of magnetic susceptibility (AMS) and microstructural analyses reveal that the NPSZ nucleated within megacrystic granite gneiss during late-Grenvillian tectonism (~0.9–1.1 Ga), contemporaneous with Rodinia assembly. Field and AMS data demonstrate a sub-simple shear regime with a sinistral strike-slip component and magnetic fabrics transition from mixed oblate–prolate in host gneiss to only oblate in mylonitic zones. Recrystallized quartz grain aspect ratios increase significantly toward the core, coupled with elevated strain rates and decreasing flow stress. Deformation temperatures inferred from microstructural observation coupled with quartz dynamic recrystallization mechanisms suggest dominance of dislocation creep, which implies that the shearing took place at deep crustal level. The absence of precursor fractures or dykes and alignment of feldspar megacrysts suggest that the nucleation of the NPSZ was facilitated by anisotropy produced by the magmatic/sub-magmatic gneissic fabric, where interstitial smaller-sized quartz-rich domains in between K-feldspar megacrysts acted as viscous pathways. These findings not only provide first-order insights into ITSZ nucleation mechanisms but also reaffirm the CGGC as a site of late-Grenvillian crustal thickening related to the suturing of North and South Indian cratons during Rodinia amalgamation. The NPSZ thus emerges as a key intra-terrane tectonic structure recording Rodinia-linked crustal reworking within the Indian shield.

1. Introduction

Intra-terrane shear zones (ITSZ) are crustal-scale localized zones of intense shearing that do not coincide with any terrane boundaries. Such zones may represent the sites of crustal thickening due to emplacement of large-scale sheet-like silicic magma (Colliston *et al.* 2017; Mathee and Colliston, 2018) or they might represent the zones of strain partitioning during convergent tectonics (Colliston *et al.* 1991; van der Heyden, 1992; Chardon *et al.* 1999). Several worldwide examples of ITSZs, for example from Bundelkhand Craton of India (Banerjee *et al.* 2022; Maity and Banerjee, 2022), Aggeneys terrane of Bushmanland, South Africa adjacent to Kaapvaal Craton (Colliston and Schoch, 2002), San Juan fault system at the Cascades Orogen, western USA (Bergh, 2002), strike-slip shear zone in central Alaska (Cole *et al.* 1999), and Tabalah/Wadi Ta'al Tectonic Zone in the Asir Terrane of Arabian shield (Stoeser and Camp, 1985), have been documented, but yet their tectonic implications remain debated.

Proterozoic high-grade terranes are characterized by contemporaneous high-grade metamorphism and emplacement of syn-kinematic voluminous granitoid plutons at the lower-to mid-crustal levels (Brown, 1994; Sawyer *et al.* 2011; Brown, 2013). Such plutons are commonly affected by anastomosing networks of ductile shear zones, which neither demarcate the terrane boundaries nor they are the pluton-country rock boundaries (e.g. Vanandois *et al.* 2022; Zhang *et al.* 2022). Multiple studies have already highlighted the connection between magma emplacement and regional deformation, specifically emphasizing the role of shear zone systems on granite emplacement (e.g. Brown, 1994; Vigneresse, 1995; Brown and Solar, 1998; Weinberg *et al.* 2004; Mamtani and Greiling, 2005; Valle Aguado *et al.* 2017; Zibra *et al.* 2018). Most of these studies focused on the architecture of pluton-wall rock boundaries, but the strain pattern within a pluton itself remains comparatively unexplored and poorly understood (de Saint Blanquat *et al.* 2011; Paterson *et al.* 2019; Nahas *et al.* 2023).

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The Chotanagpur Granite Gneiss Complex (CGGC) of the east-central Indian shield represents a Proterozoic mobile belt (e.g. Sanyal and Sengupta, 2012) (Figure 1a). Voluminous granite resulted from the crustal anatexis during the Proterozoic high-grade metamorphism is the most dominant component of the CGGC. Granites in the south-eastern part of the CGGC were deformed by a regional-scale shear zone named as the North Purulia Shear Zone (NPSZ) (Figure 1c). Although petrological and/or geochemical characteristics of the rocks were constrained close to the NPSZ (e.g. Maji *et al.* 2008; Sanyal and Sengupta, 2012; Mukherjee *et al.* 2019 and references therein), no attempts have been made to address its tectonic evolution and significance within the CGGC. In this contribution, we present the structural aspects of the NPSZ and argue that it is an ITSZ, which formed concurrently with the emplacement of the granite. We further suggest that the evolution of NPSZ corresponds to the suturing of the North and South Indian cratonic blocks during the amalgamation of Rodinia supercontinent. In this study, we focus on three aspects: (i) the geometry of the NPSZ, (ii) nucleation of the NPSZ within non-sheared granite/granite gneiss during the Proterozoic active tectonics and (iii) if the Proterozoic crustal accretion drove the intra-terrane shearing. To resolve these issues, mapping, mesoscopic and microscopic analyses with kinematic vorticity and anisotropy of magnetic susceptibility (AMS) analysis were carried out.

2. Geological setting and area of study

Covering an area of ~100 000 km² in the eastern Indian shield, the CGGC constitutes the eastern extension of the composite Satpura orogenic belt. It is bounded by the Monghyr-Saharsa Ridge Fault and South Purulia Shear Zone to the north and south, respectively (Bhattacharyya and Mukherjee, 1987; Acharyya, 2003). Based on the lithological characteristics, metamorphic history and geochronological data, Mukherjee *et al.* (2019) divided the CGGC into three ~E–W trending domains from south to north (Figure 1c). Domain I consists of high-grade metamorphic rocks along with intrusive granite and anorthosite (Bhattacharyya and Mukherjee, 1987; Maji *et al.* 2008); Domain II also known as the Bihar Mica Belt, which includes muscovite-biotite schist interbedded with micaceous quartzite, conglomerates, calc-silicate rocks and hornblende schist (Mahadevan, 2002; Mukherjee *et al.* 2019); and Domain III dominantly comprises of supracrustal rocks such as quartzite and phyllite metamorphosed under low-grade conditions underlain by high-grade migmatitic quartzo-feldspathic gneisses (Chatterjee and Ghose, 2011; Saikia *et al.* 2017; Mukherjee *et al.* 2019). In general, Domain I is envisaged as the deeper and younger crustal section as compared to Domain II and Domain III (Mukherjee *et al.* 2019). Domain I is split by Gondwana-boundary-fault-bounded Damodar Graben, which divides the Domain I into two sub-domains: Domain IA and IB to the south and north, respectively (Figure 1c) (Mukherjee *et al.* 2019). The most striking linear feature of the Domain IA is the NPSZ, which is thought to be the eastern extension of the Tan Shear Zone (Figure 1a) of the CITZ (Mahadevan, 2002; Acharyya, 2003). However, no lithological/geochronological discontinuity is recorded across the NPSZ.

Domain I of the CGGC mostly consists of variably deformed felsic orthogneisses that include porphyritic granite gneiss (commonly referred to as augen gneiss, due to the shape of feldspar phenocrysts/megacrysts), biotite-amphibole gneiss, amphibole-biotite gneiss, charnockitic gneiss and migmatitic gneiss. The felsic

orthogneisses host enclaves of metapelitic gneisses, mafic granulite and calc-silicate gneiss, altogether referred to as enclave suites. In addition, local bodies of anorthosite and alkaline rocks are found as intrusions within the felsic orthogneisses (Sen, 1956; Acharyya, 2003; Chatterjee *et al.* 2008; Goswami and Bhattacharyya, 2008; Maji *et al.* 2008; Chatterjee *et al.* 2010; Chatterjee and Ghose, 2011; Karmakar *et al.* 2011; Sanyal and Sengupta, 2012; Chakrabarty *et al.* 2016; Mukherjee *et al.* 2017; Das *et al.* 2019; Mukherjee *et al.* 2019). The relationships amongst the different lithotypes of the felsic gneisses through Domain I of the CGGC, however, remain elusive. This is directly linked to the fact that the rock exposures are limited compared to the areal extent of Domain I. In the last decade, many attempts have been made to figure out the metamorphic and magmatic history of the CGGC with reference to the supercontinent cycle during the Proterozoic (e.g. Maji *et al.* 2008; Karmakar *et al.* 2011; Goswami and Bhattacharyya, 2014; Mukherjee *et al.* 2018b; Das *et al.* 2020a; Sequeira *et al.* 2022; Basak *et al.* 2025). There is an overall consensus that CGGC is affected by four major metamorphic events and the chronology and metamorphic conditions (pressure-temperature) (Acharyya, 2003; Maji *et al.* 2008; Chatterjee and Ghose, 2011; Sanyal and Sengupta, 2012; Mukherjee *et al.* 2019). The earliest metamorphic event (M_I) occurred at ~1.87 Ga in ultrahigh temperature (>900°C). Vestiges of this event are restricted within the enclave suites. Ultrahigh-temperature metamorphism was followed by intrusion of voluminous felsic magma, which subsequently metamorphosed (M_{II} Stage) to produce migmatitic gneiss during ~1.65–1.55 Ga in a temperature range between 700–800°C at about 0.5–0.7 GPa pressure. In between ~1.20–0.93 Ga, intrusions of anorthosite and porphyritic granite ensued by metamorphism at 650–700°C, and ~0.65 GPa conditions, are designated as the third phase of metamorphism (M_{III} stage). The last phase of metamorphism (M_{IV} stage) occurred during ~0.87–0.78 Ga and is believed to be an infiltration-driven metamorphism under 600–700°C, and ~0.7 GPa conditions preceded by the intrusion of mafic dykes (Maji *et al.* 2008; Karmakar *et al.* 2011; Sanyal and Sengupta, 2012; Mukherjee *et al.* 2019). All the CGGC lithological units are deformed in nature. The number of deformation events was determined considering axial plane orientations of the enclaves contained in the felsic gneisses: while Maji *et al.* (2008) envisaged three phases of deformation, Sanyal and Sengupta (2012) depicted six phases of deformation.

The present work has been carried out in the eastern extent/segment of the NPSZ in the SE CGGC between Raghunathpur and Saltora towns, 42 km NE and 70 km ENE of Purulia town, respectively (Figure 2a). The study area is characterized by scattered exposures of variably deformed K-feldspar megacryst-bearing granite gneiss (henceforth megacrystic granite gneiss) containing enclaves of amphibolite and migmatitic gneiss. Previous petrological and geochronological studies in and around our study area showed that the lithotypes in the area of study have been achieved by predominated ~1.2–0.9 Ga old M_{III} metamorphic event (e.g. Maji *et al.* 2008; Chatterjee *et al.* 2010; Rekha *et al.* 2011; Chakraborty *et al.* 2019; Basak *et al.* 2025). At least three phases of deformation (D_1 , D_2 and D_3) were documented from our study area (Goswami and Bhattacharyya, 2014). D_1 deformation phase is exclusively preserved within the migmatitic and amphibolite enclaves. It produced migmatitic layering in migmatites and S_1 foliation in amphibolites. S_2 gneissic foliation in granite gneiss, tight to isoclinal folds of D_1 migmatitic layers and S_1 foliation in amphibolite enclaves mark the D_2 deformation phase, while D_3 shear zones affecting the S_2 gneissic foliation within the NPSZ

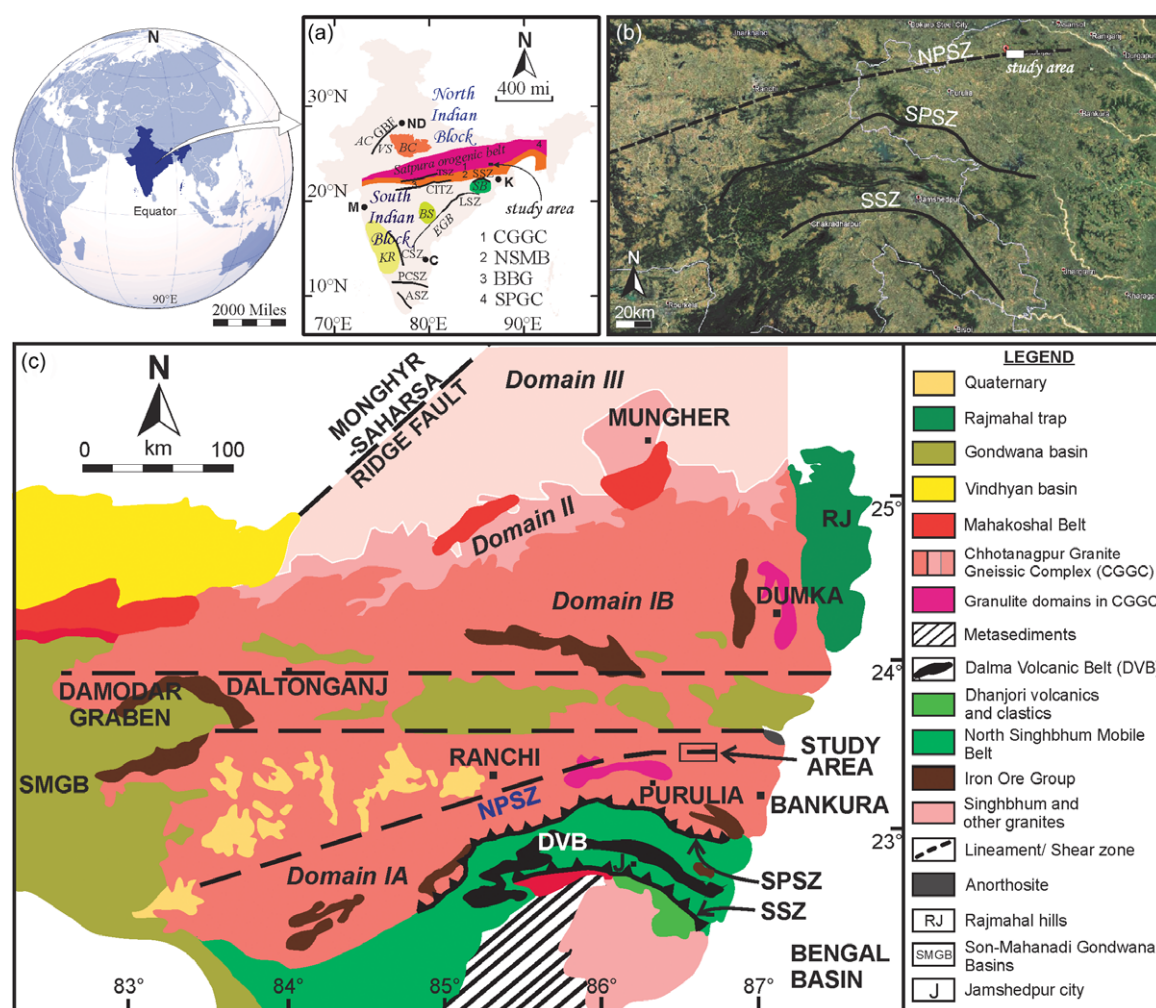


Figure 1. (a) Disposition of the major Archean cratonic blocks and Proterozoic orogenic belts in Peninsular India. BBG: Bhandara-Balaghat granulite; CGGC: Chhotanagpur Granite Gneissic Complex; EGB: Eastern Ghats Belt; NSMB: North Singhbhum Mobile Belt; SSGC: Shillong Plateau Gneissic Complex; VS: Vindhyan Supergroup. Archean cratons: AC: Aravalli Craton; BC: Bundelkhand Craton; BS: Bhandara; KR: Karnataka; SB: Singhbhum; NPSZ: North Purulia Shear Zone; SPSZ: South Purulia Shear Zone; SSZ: Singhbhum Shear Zone; GBF: Great Boundary Fault; ASZ: Achankovil Shear Zone; PCSZ: Palghat-Cauvery Shear Zone; CSZ: Chitradurga Shear Zone; LSZ: Lakhna Shear Zone; TSZ: Tan Shear Zone; CITZ: Central Indian Tectonic Zone (modified after Naganjaneyulu and Santosh, 2010). (b) Google Earth imagery showing the terrane features surrounding the study area. It is important to note the lack of discernible outcrops in and around the eastern part of NPSZ. (c) Simplified regional geological sketch of the CGGC showing spatial distribution of various lithotypes (modified after Archaryya, 2003; Goswami and Bhattacharyya, 2014; Mukherjee *et al.* 2019).

produced S_3 mylonitic fabric (Goswami and Bhattacharyya, 2014). Although the petrological and geochronological evolutions of the amphibolite and migmatite enclaves of the study area are well documented, there is a very little information available about the structural evolution of the host granite gneiss and the NPSZ (Mukherjee *et al.* 2019 and references therein). Moreover, the anatomical features of the NPSZ remain largely unexplored and its relationship with the adjacent non-sheared gneisses (i.e. gneiss non-affected by D_3 deformation event) also remains enigmatic. Therefore, the delineation of structural makeup of the NPSZ not only elaborates on the strain localization in granite but also provides new insights in connection to the granite emplacement and tectonics of the CGGC during the Proterozoic era.

3. Samples and methods

The present study adopts a multi-method approach to characterize the petro-structural features of non-sheared megacrystic granite gneiss and mylonitic granite gneiss samples from 26 outcrops

(Figures 2–8). The orientation data of all identified field fabrics (e.g. non-sheared gneissic fabric, mylonitic fabric and stretching lineation) were measured for further structural analysis and correlation (Figures 2b–f). Oriented samples of megacrystic granite gneiss and mylonitic granite gneiss were collected orthogonal to the trend of the NPSZ for ‘AMS’ studies to identify planar and linear magnetic fabric, which helps in the determination of kinematic reference frame and subsequent preparation of thin sections for petrography and other microscopic investigations. The determination of kinematic reference frame was carried out following established protocol of Mamtani *et al.* (2017) (see Appendix 1 and Supplementary Fig. S1 for details).

A total number of 103 K-feldspar porphyroclasts from six outcrops of the mylonitic gneiss with ubiquitously developed stretching lineations were used for estimation of kinematic vorticity following the porphyroclast hyperbolic distribution (PHD) method (Simpson and De Paor, 1993; Simpson and De Paor, 1997) and the rigid grain net (RGN) method (Jessup *et al.* 2007; Xypolias, 2010). The stretching lineation is rare in the study area, and thus,

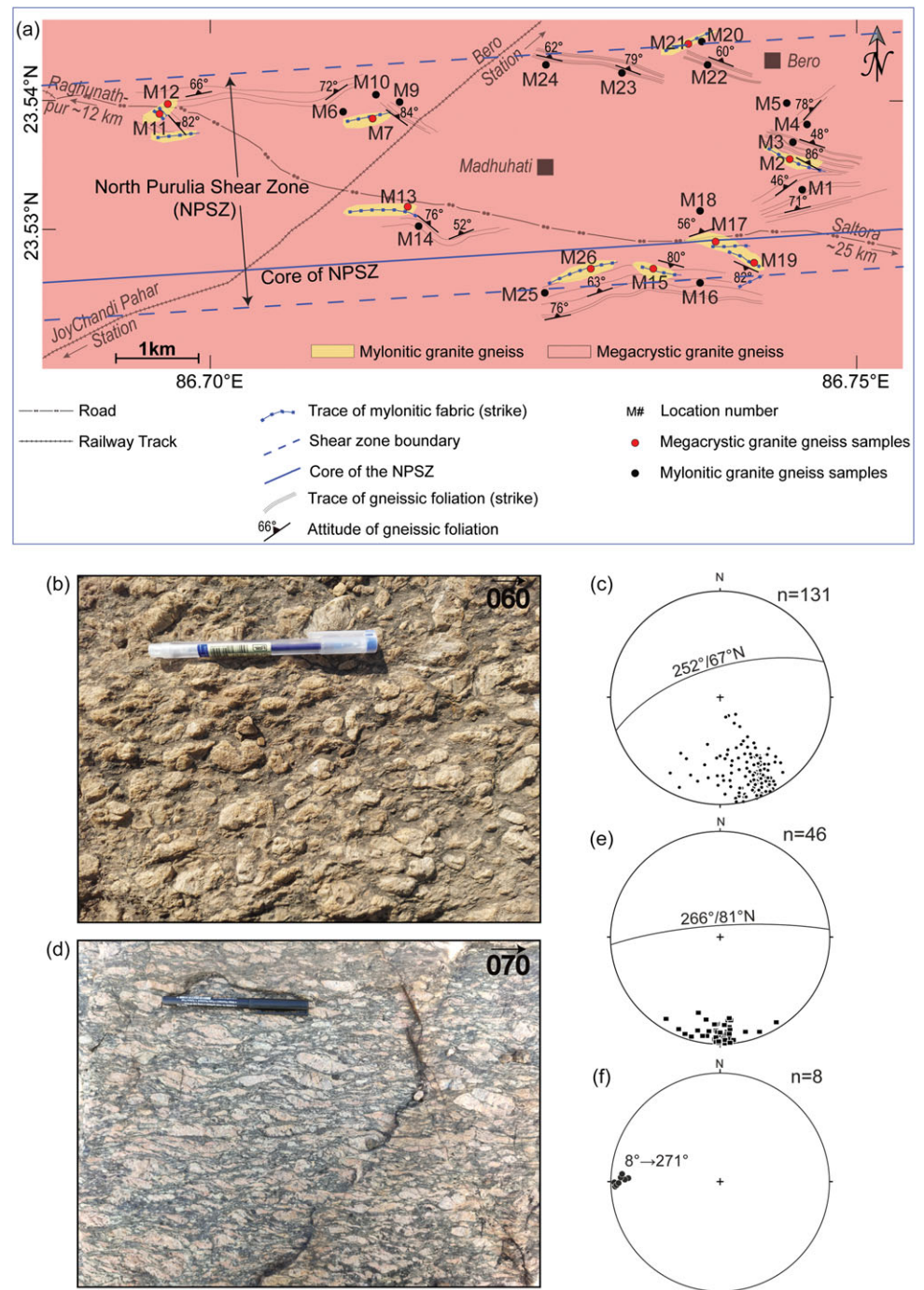


Figure 2. (a) Simplified geological sketch map of the study area. (b) Field photograph of megacrystic granite gneiss exhibiting gneissic foliation as defined by the alignment of feldspar megacrysts. Note that the megacrysts are variable in shape ranging from augen to euhedral shape. (c) Lower hemisphere equal angle projection of pole to the gneissic foliation in megacrystic granite gneiss with mean orientation 252°/67°N. (d) Field photograph of mylonitic granite gneiss with S-C fabric. (e) Lower hemisphere equal angle projection of pole to the mylonitic foliation with mean orientation 266°/81°N. (f) Lower hemisphere equal angle projection of stretching lineation with mean orientation 8°→271°.

kinematic vorticity was estimated only from those mylonitic outcrops where it is ubiquitously developed and the XZ section can be defined unambiguously. Therefore, the reported Wk values represent the lineated, high-strain mylonitic exposures (six outcrops) and not all mapped outcrops. Since Xypolias and Kokkalas (2006) have argued that the PHD method overestimates the pure-shear component in absence of porphyroclasts with large aspect ratio, the kinematic vorticity number is also determined using the RGN method and compared with the results of the PHD method.

The petro-structural analyses of the samples were carried out from X–Z sections of the samples. The X–Z sections were identified with the aid of field foliation and stretching lineation. In case where

stretching lineation is absent, we used the results of AMS analysis. Grain-scale features from 8 thin sections (2 of granite gneiss and 6 of mylonitized granite gneiss) were used to estimate flow stress and deformation temperature that prevailed during the nucleation of the NPSZ. Analyses of recrystallized quartz grain size, dominant dynamic recrystallization mechanism and the density of the microfractures across the NPSZ were utilized as proxies to estimate the approximate width of the dislocation zone representing the core of the NPSZ.

To estimate the relative strain rate variations across the shear zone and linking it with the associated estimated temperatures, fractal analyses were carried out from 8 thin sections (as mentioned

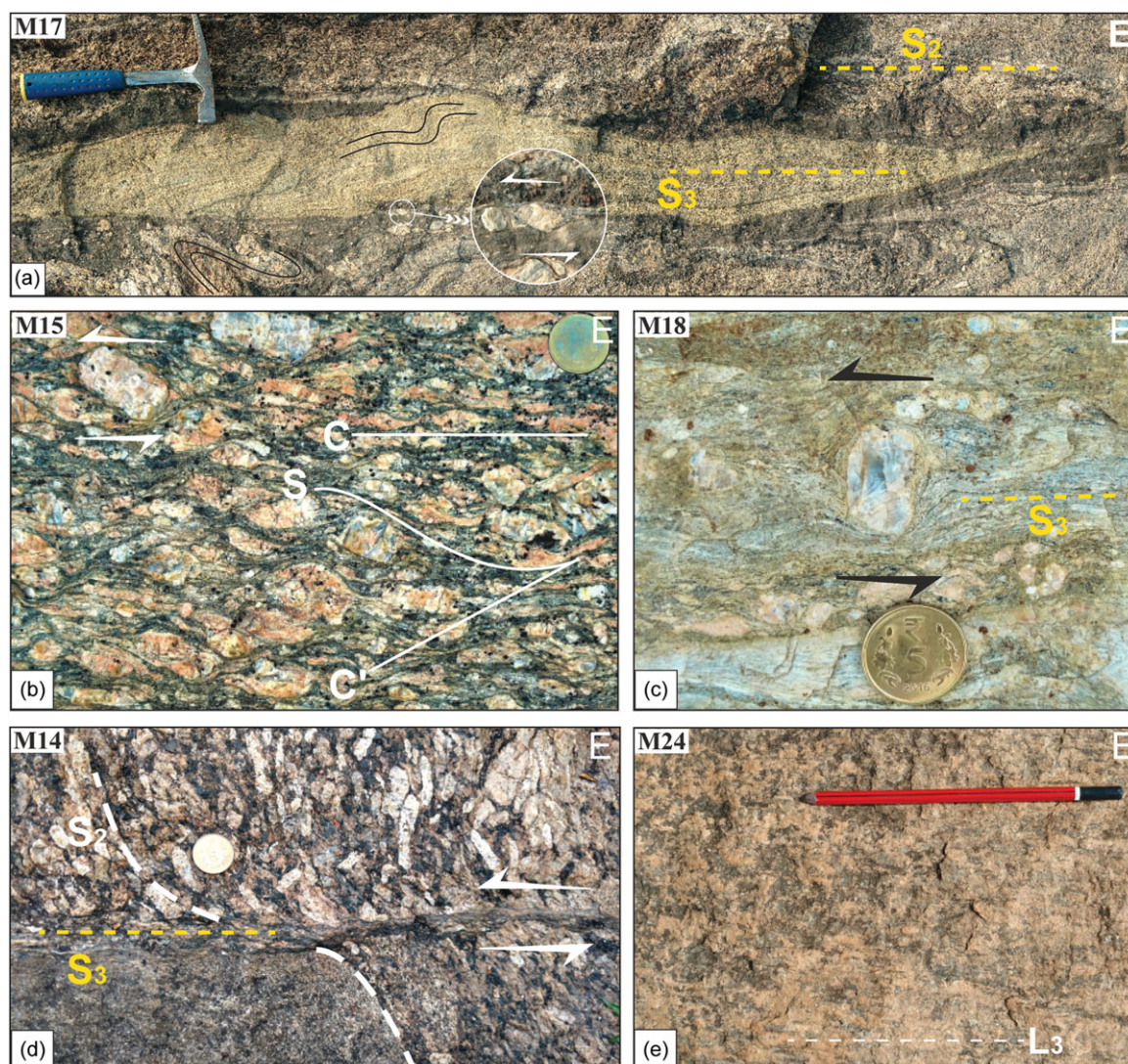


Figure 3. Field photographs of mylonitic granite gneiss. Location numbers are indicated on the top left corners of the photographs (see Figure 2a). (a) Panoramic view of mylonitized granite with S_3 mylonitic foliation within granite gneiss with S_2 foliation. Presence of asymmetric feldspar porphyroclast along with the occurrence of asymmetric folds in the host granite gneiss depicts a sinistral shear sense; (b) S-C' fabric and σ -type porphyroclast depicting sinistral sense of shear in mylonitic granite gneiss; (c) δ -type porphyroclast showing sinistral sense of shear; (d) sigmoidal S_2 foliation deflected by S_3 mylonitic foliation. Note that the shear plane has a high angle with the gneissic foliation; (e) sub-horizontal L_3 mineral stretching lineation defined by elongated quartz crystals in mylonitic granite gneiss.

above). The area-perimeter fractal dimensions (D) of the samples were carried out from recrystallized quartz grains. Areas (A) and perimeters (P) of >200 recrystallized quartz grains from each thin section were measured by using ImageJ software (Java-based image processing program). The grain diameter (d) of a circle having the equivalent area (A) as that of a quartz grain was calculated. Takahashi *et al.* (1998) demonstrated that d and P of quartz have a relation $P \propto d^D$. P and d values of the quartz grains from a particular sample (thin section) were plotted and a least-square linear fit was obtained. The slope of the latter is the D for that sample, which follows the relationship of $1 \leq D \leq 2$ since measurements were made from 2-dimensional images (Takahashi *et al.* 1998). It is, however, important to note that the procedure of strain rate calculation in natural rocks following Takahashi *et al.* (1998) possibly overestimates the absolute value of strain rate (Mamtani and Greiling, 2010). Therefore, in this study we gave weightage to the relative strain rate variations rather than the absolute strain rates.

4. Results

4.a. Mesoscale structures

The study area is predominantly occupied by megacrystic granite gneiss (Figure 2a), characterized by non-sheared to negligibly-sheared gneissic S_2 foliation as defined by the parallel alignment of euhedral to augen-shaped K-feldspar megacrysts (Figure 2b). The gneissic foliation is commonly oriented along ENE–WSW direction with a mean orientation of $252^\circ/67^\circ N$ (Figure 2c).

The megacrystic gneiss is sheared along a ~E–W trending D_3 linear zone, which consists of multiple steeply dipping, sub-parallel to anastomosing discrete ductile shear zones (Figures 2a and 3a). Each shear zone is characterized by a S_3 mylonitic foliation highlighted by S–C fabric and S–C' fabric (Figures 2d and 3b), in which K-feldspar megacrysts are commonly sheared and turned into asymmetric σ -type sigmoidal porphyroclasts (Figure 3b). Locally, δ -type porphyroclasts are also developed (Figure 3c). The S_3 mylonitic foliation is nearly sub-parallel to the S_2 gneissic

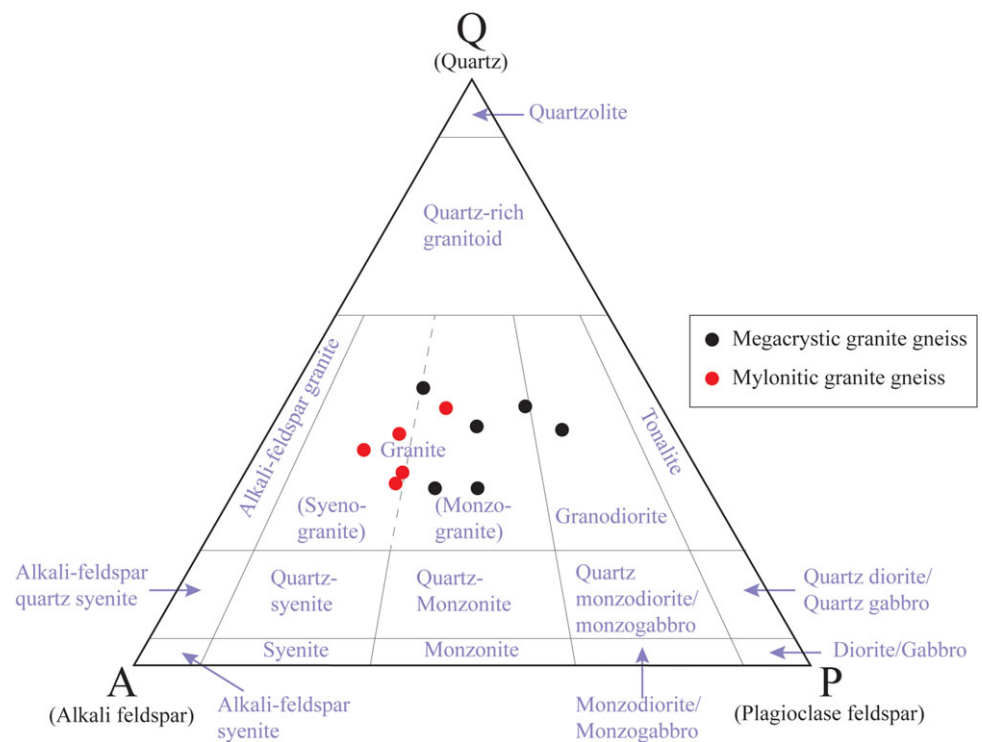


Figure 4. Q-A-P diagram of collected megacrystic granite gneiss and mylonitic granite gneiss samples. Modal percentage data are provided in Supplementary Table 1.

foliation with a mean orientation of $266^{\circ}/81^{\circ}\text{N}$ (Figure 2e). Locally, it is developed at a high angle to the gneissic foliation (Figure 3d). L_3 stretching lineation associated with S_3 mylonitic foliation is rare. It has an E-W trend and a sub-horizontal to shallow plunge mainly toward W (Figures 2f and 3e).

4.b. Mineralogy and microstructure

Both the megacrystic granite gneiss and mylonitic granite gneiss have a mineral association of K-feldspar + plagioclase feldspar + quartz + amphibole + biotite along with accessories such as allanite, apatite, titanite, zircon and opaque minerals. Despite a few samples of granodiorite gneiss, most of the megacrystic gneiss and mylonitic gneiss samples have granitic composition (Figure 4 and Supplementary Table 1). The amphibolite enclaves have a mineral association of amphibole + plagioclase feldspar + quartz + biotite $\pm$ titanite $\pm$ apatite, diagnostic of mid-to higher-amphibolite facies metamorphism.

The megacrystic granite gneiss exhibits pervasive S_2 gneissic foliation as defined by the preferentially aligned framework of moderately deformed to partially recrystallized K-feldspar megacrysts and ribbon-shaped quartz (Figure 5a). The K-feldspar megacrysts typically exhibit simple twinning. Generally, the twin planes are aligned parallel to the S_2 gneissic foliation (Figure 5b). Interstitial spaces between K-feldspar megacrysts and quartz ribbons are commonly filled up with amphibole, biotite and smaller-sized recrystallized plagioclase and quartz grains (Figures 5a–b).

Contrary to the megacrystic granite gneiss, the S_3 mylonitic granite gneiss samples are strongly deformed and characterized by partially to completely recrystallized K-feldspar megacrysts (Figure 5c) wrapped by recrystallized asymmetric quartz ribbons (Figure 5d). Additionally, chessboard-patterned sub-grains in quartz (Figure 5e) and sigmoidal feldspar megacrysts with partial to complete recrystallization (Figures 5f and c) are also common.

S_3 foliation in the mylonitized granite gneiss locally wraps feldspar porphyroclasts (Figure 5g). It is also important to note that the mylonitic granite gneiss samples have more recrystallized quartz and K-feldspar as compared to the megacrystic granite gneiss (See Figure 5a vs. 5c). The kinematic indicators such as asymmetric feldspar porphyroclasts indicate a sinistral kinematics (e.g. Figures 5f–g), which confirms the observation made at the meso-scale (see Figure 2c).

The mafic amphibolite enclaves are characterized by S_1 foliation defined by the strongly aligned grains of hornblende, biotite and variably deformed plagioclase crystals (Figure 5h).

4.c. Kinematic vorticity number

The angles between the long axes of the porphyroclasts to the C-planes of the mylonitic fabric (Φ) were measured on XZ planes at the outcrops, where positive and negative Φ values indicate forward-rotated and back-rotated grains, respectively (Figure 6a). For the PHD method, the front-and back-rotated porphyroclasts were plotted on a hyperbolic net (cf., De Paor, 1988) (Figure 6b). The cosine of this angle (Φ) yields the kinematic vorticity number (Bobyarchick, 1986):

$$W_k = \cos(\Phi) \quad (1)$$

Here, the calculated Φ value is 38° resulting in a W_k value of 0.788 (Figure 6b). In case of the RGN method (Jessup *et al.* 2007), the orientation of the rotated grains' long axes with respect to the trace of the foliation or shear plane was plotted against the shape factor B of the grains. The shape factor was determined by the following equations (Passchier, 1987):

$$B = [(Mx)^2 - (Mn)^2] / [(Mx)^2 + (Mn)^2] \quad (2)$$

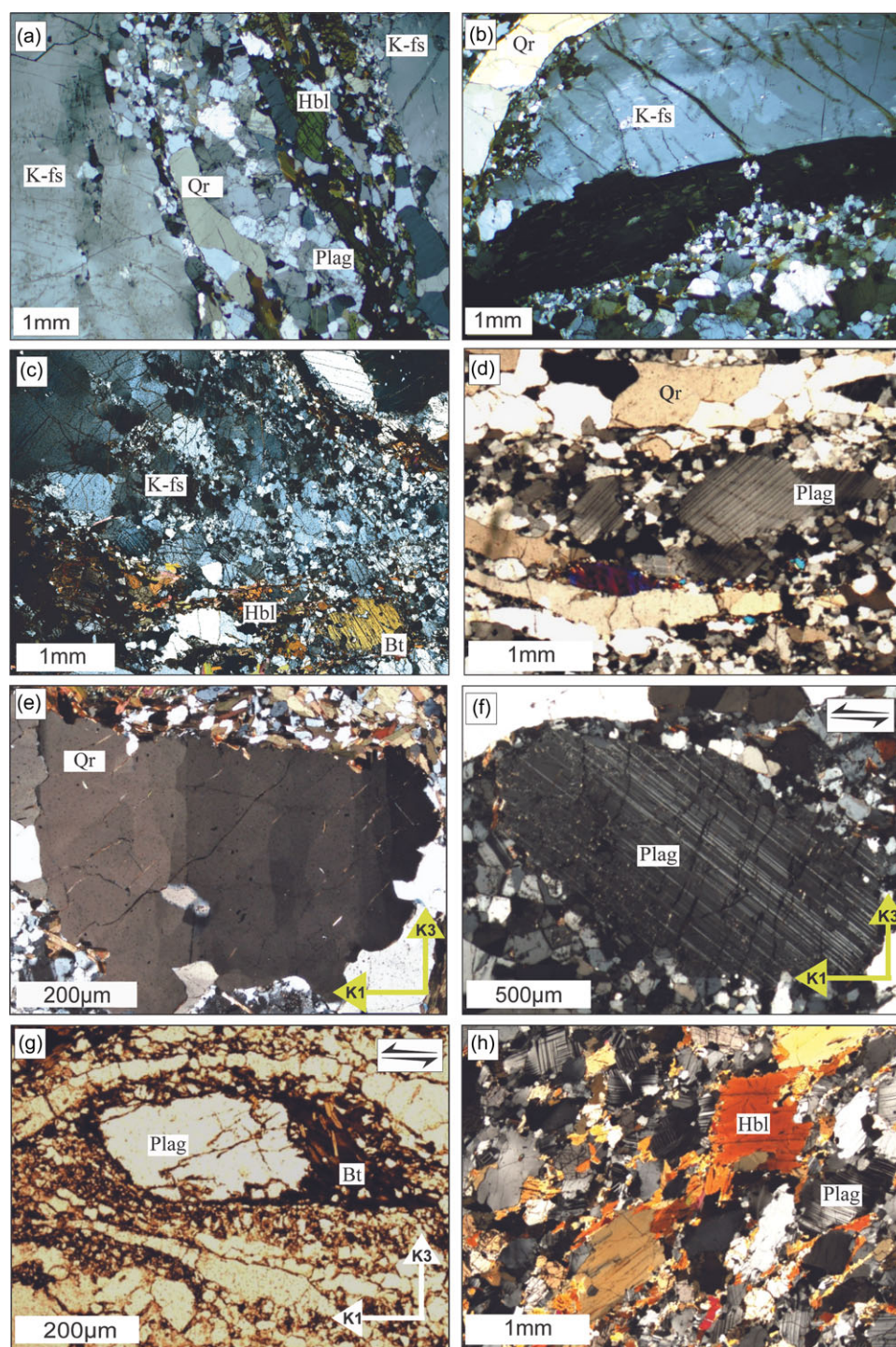


Figure 5. Photomicrographs showing (a) megacrystic granite gneiss (K-fs: K-feldspar; Qr: quartz; Hbl: hornblende; Plag: plagioclase); (b) weakly deformed, simple twinned K-feldspar megacryst (K-fs) and ribbon-shaped quartz (Qr) embedded within a partially recrystallized matrix highlight the S_2 gneissic foliation; (c) mylonitic granite gneiss, where K-feldspar megacryst shows complete recrystallization (K-fs: K-feldspar; Hbl: hornblende; Bt: biotite); (d) S_3 mylonitic foliation in mylonitic granite gneiss, where the elongated quartz ribbons (Qr) show recrystallization. Note that deformed partly recrystallized plagioclase feldspar (Plag) porphyroclasts are present within the recrystallized matrix in between quartz ribbons; (e) chessboard-patterned sub-grain formation in quartz (Qr) in mylonitic granite gneiss (K1 & K3: Long and short axis of AMS ellipsoid); (f) recrystallization mantled porphyroclast of plagioclase feldspar (Plag) in mylonitic granite gneiss (K1 & K3: Long and short axis of AMS ellipsoid); (g) asymmetric porphyroclast of plagioclase feldspar (Plag) mantled by recrystallized biotite (Bt) matrix (K1 & K3: Long and short axis of AMS ellipsoid); (h) amphibolite enclave, where preferential alignment of hornblende (Hbl) grains and elongated plagioclase grains (Plag) define the S_1 foliation.

where Mx represents the long axis of the grain and Mn represents the short axis of the grain.

The plots of the back-and front-rotated porphyroclasts are shown in Figure 6c. The vertical lines corresponding to the positive and the negative hyperbolas delineate the critical value for the shape factor B (e.g. Xypolias, 2010). This value is essentially equivalent to the kinematic vorticity number W_m . The estimated value of the kinematic vorticity number from the RGN for the back-rotated clasts is 0.85 and for the front-rotated clasts is 0.78 (Figure 6c).

Both the RGN and PHD methods yield a comparable result, with kinematic vorticity numbers ranging from 0.78–0.85 and 0.79, respectively, signifying a sub-simple nature of progressive deformation in the NPSZ. It is, however, interesting to note that the low to moderate vorticity values obtained from 2-dimensional surfaces are commonly biased, and, therefore, a consideration of minimum systematic error of 0.2 is recommended (Iacopini *et al.* 2011). Considering the error of 0.2, it could be asserted that the vorticity values could possibly lie in the range of 0.58–0.65.

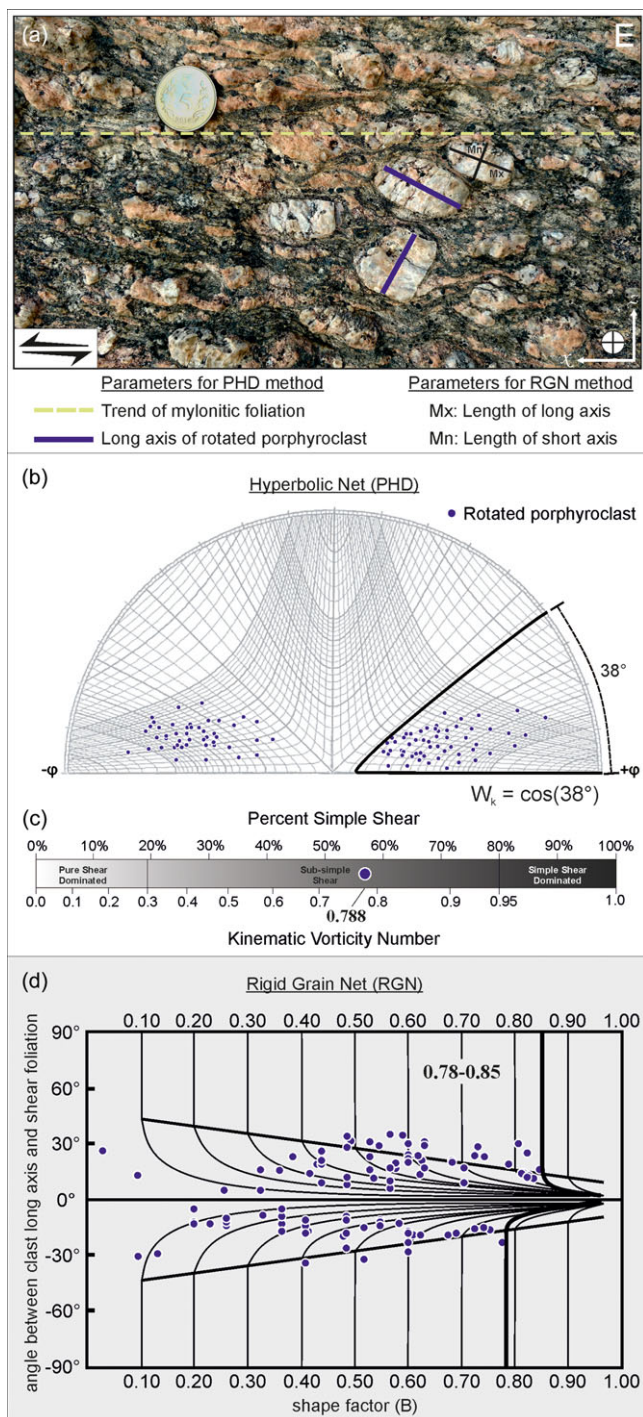


Figure 6. (a) Field photograph depicting the angular relationship between the mylonitic foliation and long axis of front-/back-rotated porphyroclasts; (b) hyperbolic net (Simpson and De Paor, 1993; 1997) plots of porphyroclasts of mylonitic granite gneiss; (c) calculated W_k value is shown in kinematic vorticity number and percent simple shear relation diagram (after Forte and Bailey, 2007). (d) Rigid grain net (after Jessup et al. 2007; Xypolias et al. 2010) plots of porphyroclasts of mylonitic granite gneiss.

4.d. AMS analysis

AMS of both granite gneiss and mylonitic gneiss across the NPSZ was measured from oriented samples to determine the mean susceptibility (K_m), degree of magnetic anisotropy (P_j) and shape parameter (T_j). The mean susceptibility (K_m) values of both megacrystic granite gneiss and mylonitic granite gneiss samples are

strongly variable. In mylonitic gneiss, the K_m values range from 167 to 22 200 μSI , whereas for megacrystic granite gneiss these range from 211 to 32 500 μSI (Table 1). The P_j values for granite gneiss and mylonitic gneiss vary from 1.03 to 1.54 and 1.02 to 1.83, respectively (Table 1). The AMS analysis revealed that the samples of both megacrystic granite gneiss and mylonitic granite gneiss have a scattered distribution of both magnetic foliation and lineation (Figures 7a, b). The calculated mean orientations with 95% confidence ellipses illustrating the uncertainties of the magnetic fabrics are also shown in Figures 7a and b. The large uncertainty bounds of the confidence ellipses indicate that both types of gneisses lack a consistent magnetic fabric and vary from sample to sample. The K_m and P_j values for both granite gneiss and mylonitic granite gneiss show a strong positive correlation. However, the P_j values in relation to the K_m values are notably higher in case of the mylonitic gneiss samples as compared to the granite gneiss samples (Figure 7c). It is also interesting to note that all the analysed samples of mylonitic gneiss here have a positive T_j value ranging from 0.02 to 0.68, while the granite gneiss samples record both positive and negative T_j values ranging from 0.72 to -0.45 (Table 1). The variation in the T_j values signifies a change in the shape of the AMS ellipsoid from only oblate in case of mylonitic gneiss samples to prolate & oblate in case of the megacrystic granite gneiss samples (Figure 7d).

4.e. Petro-structural analyses

4.e.1. Recrystallization mechanisms and aspect ratio of recrystallized quartz grains

Long and short axes of the recrystallized quartz grains were measured from the eight samples. Two samples are megacrystic granite gneiss (sample nos. M24 and M25), and six are mylonitic granite gneiss (sample nos. M2, M7, M12, M13, M17 and M26). The mean ratios of length to width of the recrystallized quartz grains vary from ~ 1.1 to ~ 1.8 and from ~ 1.3 to ~ 1.8 in mylonitic granite gneiss and granite gneiss, respectively, indicating that the shapes vary from equidimensional to elongated (Supplementary Table 2). The mean aspect ratios of both granite gneiss and mylonitic gneiss samples were plotted as a function of distance from the central part of the NPSZ. In both types of gneisses, the plot depicts a significant rise in the aspect ratios towards the central part of the shear zone (Figure 8a). The relative abundances of the recrystallization mechanisms in quartz were determined from the same eight samples and presented in Figure 8b. In both megacrystic granite gneiss and mylonitic granite gneiss, high-temperature grain boundary migration (GBM) recrystallization mechanism dominates towards the central part of the shear zone, while sub-grain rotation recrystallization (SGR) mechanism becomes prominent away from the shear zone (see Figure 8a for location of the sample and Figure 8b for mechanism of recrystallization).

4.e.2. Flow stress calculation from recrystallized quartz grains

The basis for a palaeo-piezometer, using the variation of dynamically recrystallized grain size of a wide variety of minerals with stress at steady state creep, was suggested by Twiss (1977). Based on the theoretical assumptions and experimental results (Appendix 1), Twiss (1977) proposed the following global piezometer:

$$\sigma = Bd^{-0.68} \quad (3)$$

where σ is in MPa, d is in mm, and B is 5.5 (for quartz). Here, the flow stress for each sample was determined using Equation (3).

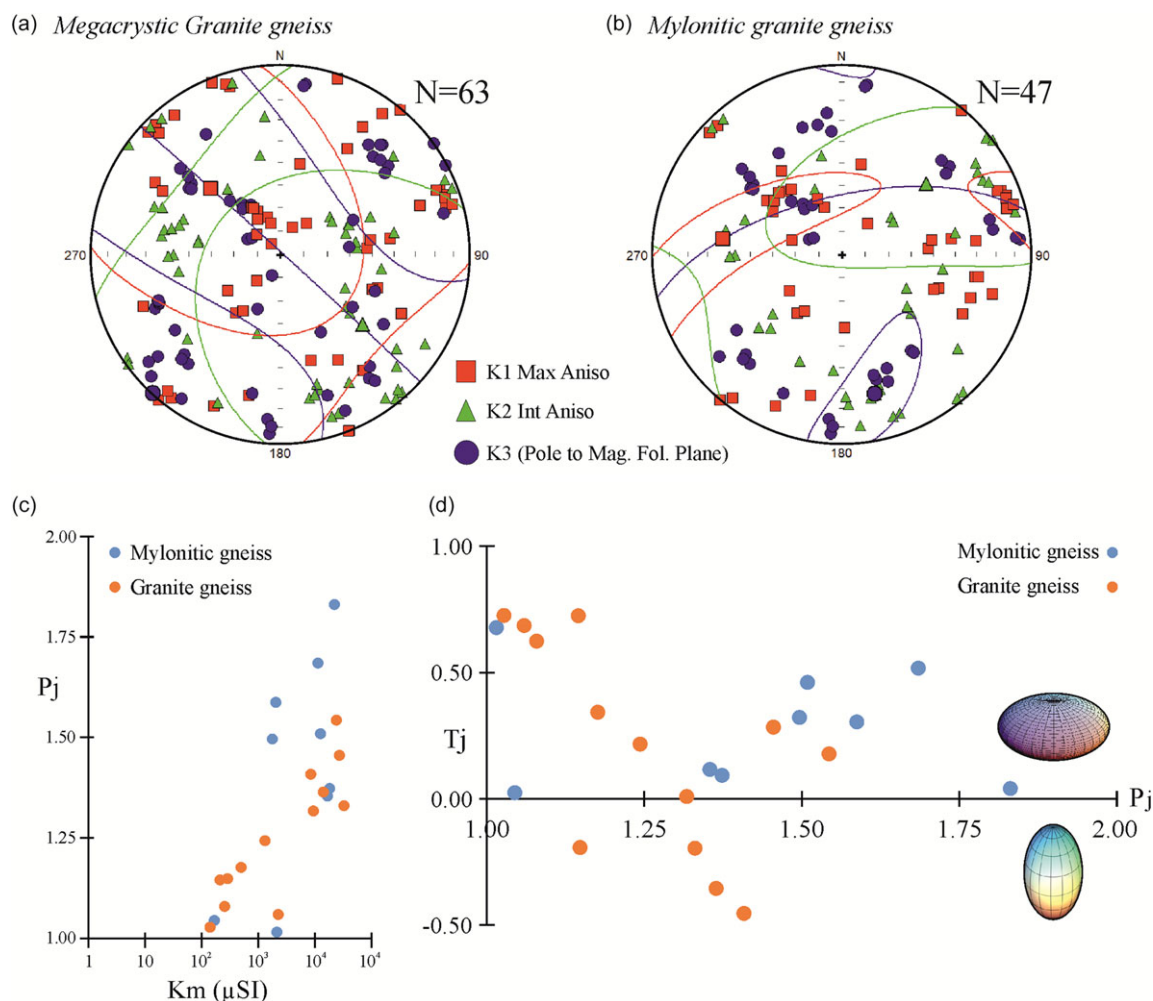


Figure 7. Results of AMS analysis. (a & b) Lower hemisphere equal area projections of eigen vectors K1, K2 and K3 orientations of the AMS ellipsoid for analysed megacrystic granite gneiss and mylonitic granite gneiss across the NPSZ; (c) K_m vs P_j plots of all analysed samples; (d) P_j vs T_j plots of all analysed samples. Data presented in Table 1.

The flow stress calculated from the recrystallized quartz grains in mylonitic granite ranges from ~46 to 12 MPa, whereas in granite gneisses it ranges from ~8 to 68 MPa (Table 2). The calculations of the flow stresses from the diameters of the recrystallized quartz grains are presented in *Supplementary Fig. S2*.

4.e.3. Micro-fracture density as a function of distance from shear zone

The measured mean values for micro-fracture density (Supplementary Table 3) have been plotted as a function of distance (plotted on semi-log scale) from the central part of the shear zone (Figure 8c). The plot portrays an exponential decrease in the density of micro-fractures as we move away from the anticipated core of shear localization (Figure 8c).

4.f. Fractal analysis

4.f.1 Estimation of strain rate across the shear zone using fractal analysis

The results of the fractal analysis are given in Table 3 and *Supplementary Fig. S3*. Strain rate calculations from the fractal dimension analysis show that, in case of mylonitic granite gneiss, the estimated strain rate ranges from $\sim 10^{-9.45}$ (sample M7) to $\sim 10^{-14.14}$ (sample M26), whereas in granite gneiss it ranges from $\sim 10^{-11.19}$ (sample M25) to $\sim 10^{-14.12}$ (sample M24).

4.e.2. Strain rate vs. temperature map

A deformation mechanism map (e.g. Frost and Ashby, 1982) is an effective way of representing the dominant mechanism responsible for deforming a material under a given set of conditions, which include field of stress, temperature, strain rate, etc. In the present work, the strain rate of samples as estimated from fractal analysis (Table 3) and their corresponding deformation temperatures ascertained from microstructures (Figures 5 and 8b) are plotted on the deformation mechanism map of Stipp *et al.* (2002). Two calculated parameters, strain rate and temperature, have been used for the plot (Figure 8d). The plot exhibits a comparable trend of megacrystic granite gneiss and mylonitic granite samples (coloured circles) with respect to the natural examples as shown in cf. Figure 8 of Stipp *et al.* (2002). From Figure 8d, it is ascertained that the deformation mechanisms responsible for the dynamic recrystallization of quartz in both types of gneisses occurred at a higher strain rate and a temperature range of ~420–630°C under stress condition $\cong 100$ MPa.

5. Discussion

5.a. Geometry and evolution of the NPSZ

The NPSZ represents an E–W trending, steeply dipping zone within megacrystic granite gneiss (Figure 2). It consists of multiple

Table 1. Anisotropy of magnetic susceptibility (AMS) data of Granite gneiss and Mylonitic Granite gneiss Granite. Km = Mean susceptibility; Pj = corrected degree of magnetic anisotropy; L= magnitude of lineation; F= magnitude of foliation; Tj = shape parameter. D and I are declination and inclination (in degrees), respectively, of the maximum (K₁) and minimum (K₃) principal axes of the AMS ellipsoid. Data for each site are the mean values obtained from analysis of multiple cores

Sample number	Km(× 10 ^{−6} SI units)	Pj	L	F	Tj	K ₁		K ₃	
						D	I	D	I
Megacrystic granite gneiss									
M1	211	1.15	1.02	1.11	0.72	93	42	185	3
M3	140	1.03	1.00	1.02	0.72	327	23	226	26
M4	252	1.08	1.01	1.06	0.62	212	7	308	39
M5	286	1.15	1.09	1.06	−0.19	70	10	317	66
M18	494	1.18	1.05	1.11	0.34	222	60	50	29
M24	2240	1.06	1.13	1.08	0.69	356	36	124	12
M25	1310	1.24	1.14	1.15	0.22	298	37	157	16
M9	32 500	1.33	1.19	1.12	−0.20	41	8	145	60
M10	27 200	1.46	1.14	1.27	0.28	153	36	44	24
M14	9380	1.32	1.15	1.14	0.01	340	2	248	31
M16	14 100	1.36	1.23	1.11	−0.36	302	23	109	67
M22	24 000	1.54	1.19	1.29	0.18	341	74	231	6
M23	8450	1.41	1.27	1.10	−0.45	315	74	145	15
Mylonitic granite gneiss									
M2	167.00	1.04	1.02	1.02	0.02	98	26	350	32
M17	2040.00	1.59	1.17	1.34	0.30	312	53	156	35
M21	2130.00	1.02	1.00	1.01	0.68	321	61	82	14
M26	1770.00	1.50	1.16	1.26	0.32	325	51	146	43
M7	16 600.00	1.35	1.15	1.18	0.12	122	39	21	13
M11	11 300.00	1.69	1.12	1.46	0.52	280	36	44	38
M12	12 600.00	1.51	1.11	1.34	0.46	287	10	27	44
M13	18 200.00	1.37	1.14	1.20	0.09	335	10	211	72
M19	22 200.00	1.83	1.34	1.37	0.04	174	44	336	45

Table 2. Results of calculated flow stress responsible for dynamic recrystallization of quartz grains in megacrystic granite gneiss and mylonitic granite gneiss samples across the NPSZ following Twiss (1977)

	Sample no.	No. of quartz grains measured	Flow stress (MPa)
Mylonitic granite gneiss	M2	272	38.55–13.86
	M7	203	46.48–14.88
	M12	272	39.93–13.56
	M13	271	42.86–11.97
	M17	218	38.91–13.03
	M26	270	39.76–9.0
Megacrystic granite gneiss	M24	271	68.34–9.69
	M25	270	53.84–7.72

steeply dipping, sub-parallel to anastomosing discrete ductile shear zones with sinistral kinematics. Each of the shear zones is characterized by mylonitic S₃ fabric, which developed over the S₂ fabric of the megacrystic granite gneiss. The S₃ mylonitic fabric is

subsequently overprinted by a later set of extensional fractures (Figure 2a, d). The entire zone evolved in a sub-simple shear condition (Figure 6). Analyses of microstructural features indicate that the core of the NPSZ represents a high-strain zone compared to its distal part (Figure 8)

Microstructural observation shows that the mineralogical compositions of the granite gneiss and mylonitic granite gneiss are similar (Figure 4), but the shapes and sizes of the K-feldspar crystals are the prime attributes that differentiate the megacrystic granite gneiss from its mylonitized counterpart. Both S₂ gneissic fabric and S₃ mylonitic fabric are characterized by consistent shape preferred orientation (Figures 2b–e). In contrast, the magnetic foliations in both megacrystic granite gneiss and mylonitic granite gneiss show variable orientation (Figures 7a, b), which depicts a strong decoupling between the shape preferred fabric and AMS fabric. The decoupling suggests that the shape preferred fabric is controlled by the feldspar megacrysts, while the AMS fabric is controlled by the paramagnetic minerals such as amphibole, biotite, ilmenite in the interstitial spaces between the megacrysts. Although the magnetic foliation is variable in both types of gneisses, the mylonitic granite gneiss samples have higher Pj values as compared to the host megacrystic granite gneiss samples (Figure 7c). Anatomy of

Table 3. Results of fractal analysis from recrystallized quartz grains following the method of Takahashi *et al.* (1998) along with minimum temperature estimates from microstructures

	Sample no.	No. of quartz grains measured	<i>d</i> range (μm)	Calculated <i>D</i> value	Strain rate (s ⁻¹) along with <i>T</i> (°C) estimated from microstructure
<i>Mylonitic granite gneiss</i>	M2	275	57.05632–277.7046	1.2711	10 ^{-12.03} (~490°)
	M7	203	43.33342–231.392	1.3360	10 ^{-13.68} (~420°)
	M12	272	54.18626–265.3795	1.2489	10 ^{-12.26} (~490°)
	M13	271	48.83121–317.6442	1.3135	10 ^{-11.57} (~490°)
	M17	217	56.29406–281.3378	1.3456	10 ^{-9.45} (~560°)
	M26	270	54.53954–484.70424	1.4209	10 ^{-14.14} (~600°)
<i>Megacrystic granite gneiss</i>	M24	271	24.59–434.837	1.2949	10 ^{-14.12} (~420°)
	M25	270	34.91866–607.1652	1.3492	10 ^{-11.19} (~490°)

magnetic fabric in a rock is known to be controlled by combination of multiple factors such as mineral-physics properties, symmetry crystal, mineral abundances, crystal orientation-distribution, stress or strain, kinematic history and certain tectono-metamorphic processes like dynamic recrystallization, crystal plasticity, diffusion and neo-mineralization (Borradaile and Jackson, 2004). In the present case, both host gneiss and mylonitic gneiss have common mineralogical composition (Figure 4 and Supplementary Table 1) and lack any evidence of metamorphic transformations, and, therefore, it could be regarded that strain-induced processes such as dynamic recrystallization was the chief controlling factor that enhanced the degree of magnetic anisotropy within the mylonitic granite gneiss compared to its surrounding granite gneiss. Microstructurally, the mylonitic gneiss has more recrystallized mass (e.g. Figures 5c and d) compared to its host counterpart, which indeed endorses the inevitable role of strain on the evolution of magnetic fabric. Furthermore, a strong contrast has been noted between the shape parameter (*T_j*) values of the mylonitic gneiss samples, which are restricted within a narrow range on the oblate field, and the host gneiss samples, which are dispersed over both oblate and prolate field (Figure 7d). Less oblateness and restricted range of the *T_j* values in the mylonitic gneiss samples suggests a strong strain-induced reorganization of the magnetic fabric.

Occurrence of elongated recrystallized quartz grains (mean aspect ratio > 1.5) and nearly equidimensional recrystallized quartz grains (mean aspect ratio < 1.5) in and off to the shear zone, respectively, advocate the high-strain localization along the NPSZ (Figure 8a). The elongation of the recrystallized quartz grains suggests dynamic recrystallization (Passchier and Trouw, 2005), and the grains with higher aspect ratio indicate their involvement in the ongoing process of deformation after its formation (Banerjee and Matin, 2013). The variable aspect ratio of the recrystallized quartz grains also suffices for the protracted period of recrystallization during deformation. It is also interesting to note that the flow stress values inferred from the recrystallized quartz grains are lower in the mylonitic gneiss than the megacrystic gneiss

indicating a plastic strain-induced stress relaxation in the mylonitic gneiss within the NPSZ (Poirier, 1985).

The fractal analysis of recrystallized quartz grains reflects relatively high-strain rate at the core of the NPSZ relative to its distal part. It is important to note that the procedure of strain rate calculation in natural rocks following Takahashi *et al.* (1998) possibly overestimates the absolute value of strain rate (Mamtani and Greiling, 2010). Although some calculated strain rate values in the present study definitely exceed the reported natural strain rate of 10⁻¹⁴ to 10⁻¹² s⁻¹ (Passchier and Trouw, 2005), recent accounts show that the maximum strain rate within viscous high-strain zones is in the range of 10⁻¹³ to 10⁻⁸ s⁻¹ (Gueydan *et al.* 2005; Boutonnet *et al.* 2013; Viegas *et al.* 2016). It is also estimated that if slip rates are 1–10 mm/yr for shear zones of width ranging from 1–1000m exhibited by mid-to lower-crustal mylonites, the strain rates may vary from 10⁻¹⁴ to 10⁻¹⁰ s⁻¹ (Harris, 2017; Fagereng and Biggs, 2019).

The microstructural investigations of both megacrystic gneiss and mylonitic granite gneiss suggest that both types experienced quasi-plastic deformation at high temperature where both quartz and feldspars deformed by dislocation creep-assisted recrystallization. However, the mylonitic gneiss in the NPSZ records much more intense intracrystalline deformation relative to the megacrystic gneiss (see Figure 5a vs. 5c). The quartz grains are recrystallized by either SGR or high-temperature GBM (Figure 8b), suggesting a minimum deformation temperature 400–500°C or even higher (Stipp *et al.* 2002). Such thermal conditions are supported by the presence of strain-free monomineralic quartz ribbons (e.g. Figure 5d) and chessboard extinctions in quartz grains (Figure 5f) (Wallis *et al.* 2019). Like quartz, feldspar crystals are also affected by intracrystalline deformation. Recovery structures such as sub-grain formation, recrystallization of both K-feldspar and plagioclase along with the formation of asymmetric 'fish'-like structures (e.g. Figures 5d, g and h) in feldspar suggest a high-temperature deformation condition most likely above >500°C (Pryer, 1993; Passchier and Trouw, 2005). All constituent minerals except biotite are fractured, which indicates that the

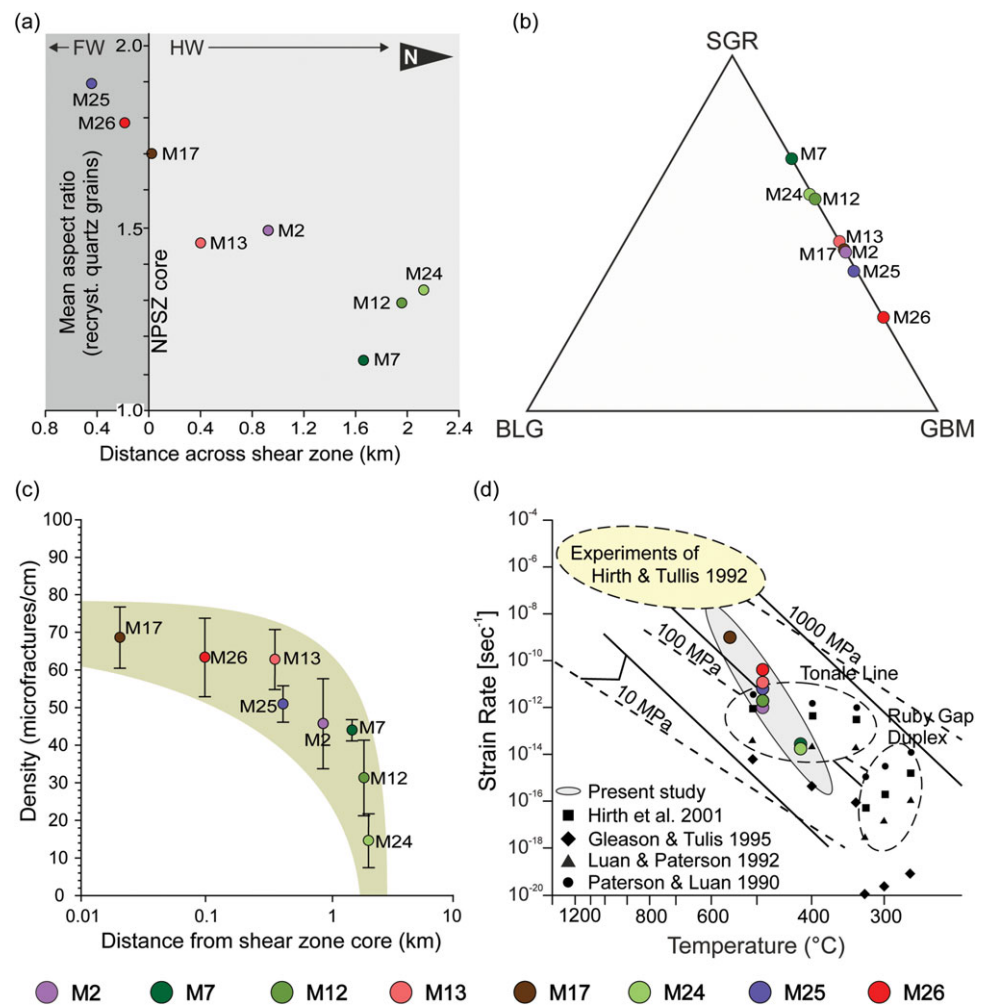


Figure 8. (a) Plot of mean aspect ratio of recrystallized quartz grains vs. distance from shear zone core; HW: hanging wall, FW: footwall; (b) triangular diagram showing relative dominance of mode of recrystallization estimated from recrystallized quartz grains; BLG: Bulging recrystallization, SGR: Sub-grain rotation recrystallization, GBM: grain boundary migration. (c) Micro-fracture density of megacrystic granite gneiss and mylonitic granite gneiss samples plotted as a function of distance from shear zone core. The plot shows an exponential rise in the micro-fracture density towards the core of the shear zone. (d) Megacrystic granite gneiss and mylonitic granite gneiss samples are plotted on a strain rate vs. temperature map; calculations are provided in Table 3.

brittle deformation took place in the waning stage of deformation at a temperature $\sim 300^\circ\text{C}$ since quartz behaves in brittle manner below this temperature (Stipp *et al.* 2002).

5.b. Nucleation of the NPSZ

Nucleation of shear zones, particularly in isotropic rocks, like granite, is a long-lasting debate for the last few decades. One of the most effective models suggests that nucleation of ductile shear zone in granite requires precursor structures like fractures or dykes. Such precursor structures are the primary site for shear zone nucleation (Christiansen and Pollard, 1997; Mancktelow and Pennacchioni, 2005; Pennacchioni and Mancktelow, 2007; Goncalves *et al.* 2016; Sarkar *et al.* 2020).

In the study area, the megacrystic granite gneiss lacks any evidence of precursor fractures or dykes and, hence, precludes the possibility of nucleation along precursor brittle structures. However, the host gneiss contains a strong structural anisotropy in the form of gneissic foliation. The apparent parallelism of the gneissic foliation and the mylonitic foliation in the outcrops strongly suggests that both foliations developed under the same stress field.

In the granite gneiss parallelly aligned feldspar megacrysts containing simple twin (Figures 2b and 5a), which indicates crystallization from a magmatic environment (Vernon, 2000;

Vernon and Paterson, 2008). Although solid-state deformation significantly modified the grain boundaries of the megacrysts, the twin planes of the megacrysts remain parallel to the shape preferred orientation, which defines the gneissic foliation. Hence, it is reasonable to infer that the gneissic foliation resulted or at least initiated at the magmatic stage where the megacrysts aligned themselves along the magmatic flow direction (e.g. Vernon, 2000). We propose that the quartz and other smaller-sized crystal-rich domains in between the interstices of the megacrysts in the granite gneiss acted as the precursor to the shear zone nucleation. Mechanical behaviour of a polymineralic rock depends upon the relative strengths of the constituent minerals (Handy, 1990). At any given temperature, quartz is much weaker compared to feldspar (Passchier and Trouw, 2005), and hence, the quartz-rich domains between the megacrysts are the primary site of strain localization. The crystal plastic deformation followed the grain size reduction by dynamic recrystallization of the quartz-rich domains, aiding the incipient shear zone development (Montési and Hirth, 2003; Foley, 2018). The system could be visualized as a non-slipping viscous matrix surrounding a monoclinic rigid clast (Mancktelow *et al.* 2002). Continuous deformation of the quartz-rich domains in anastomosing pattern is dictated by the initial disposition of the megacrysts (e.g. Figure 2b). The decoupling of deformation between the megacrysts and crystals of the interstitial spaces can be supported by the fact that the shape preferred fabric

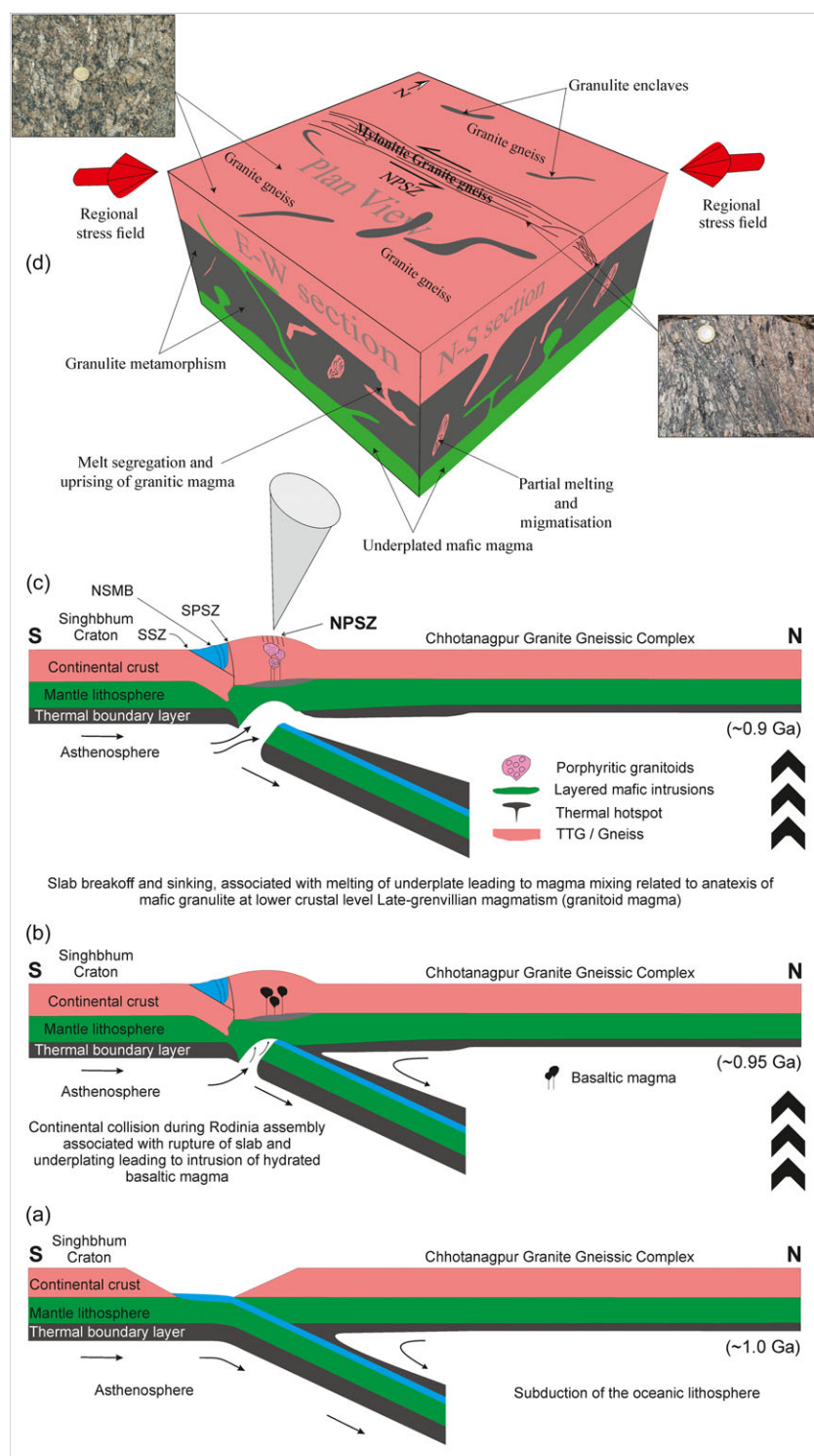


Figure 9. (a–c) Evolutionary model of the NPSZ in relation to the emplacement mechanism of the granite gneiss, now transformed into the mylonitic granite gneiss in the vicinity of the NPSZ during the amalgamation of North and South Indian Cratonic blocks (the sequence of events is adopted from Atherton and Ghani, 2002). (d) 3-D structural model of the study area illustrating the structural relationships in the different crustal domains. The ~NNE–SSW compressional event during ~1000–950 Ma led to the nucleation of the NPSZ and modified the magmatic event associated with it. The ~E–W trending mylonitic foliation in mylonitic granite gneiss along NPSZ and conspicuous development of shear planes on cross-sectional view in mylonitic granite gneiss is also depicted in the model.

of the megacrysts and the AMS fabric hardly comply each other (see Figures 2c and e with Figures 7a and b). Continuous dynamic recrystallization along the interstitial spaces eventually caused strain hardening within the anastomosing shear zone networks. The strain hardening within the incipient shear zones ultimately transmitted the stress into the surrounding feldspar megacrysts and engulfed the megacrysts into the shear zone, which eventually widened the shear zone (Hobbs *et al.* 1990).

5.c. Implication of NPSZ: late-Grenvillian magmatism and linkage to Rodinia supercontinent

The tectono-thermal events of the CGGC suggest that it evolved in a continent–continent collisional zone and represents a zone of amalgamation of north and south Indian cratonic blocks during the Neoproterozoic. The southern block is represented by the Singhbhum craton and North Singhbhum Mobile belt, while the northern block remains enigmatic since the northern side of

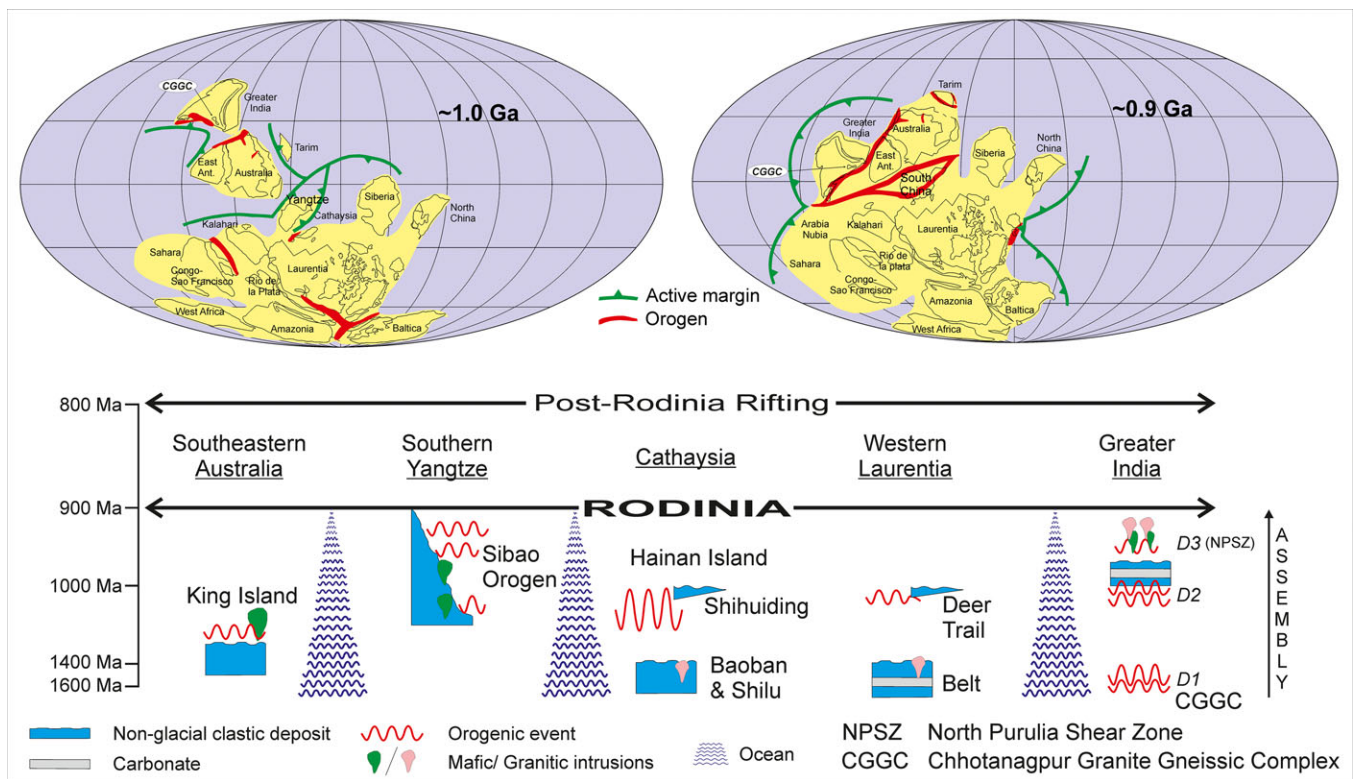


Figure 10. Temporal stages of Rodinia supercontinent assembly at ~1.0 Ga and ~0.9 Ga (Li *et al.* 2008). Tectonostratigraphic correlations between Australia, Yangtze Craton, Cathaysia and Laurentia (Li *et al.* 2008). The Greater India is included in the existing framework from the present study with approximate timing of deformation events (as discussed in text).

the CGGC is hidden beneath recent alluvium. It is generally believed that the CGGC is thrust over the NSMB with a southward vergence (Mahadevan, 2002; Mukherjee *et al.* 2019).

Recently, a two-phase model of continent–continent collision with intermittent rifting has been suggested for the tectonic evolution of the mafic intrusive rocks in the Domain I of CGGC (Figure 1c), which witnessed two major orogenesis (D₂ before 950 Ma and D₃ after 920 Ma) separated by a period of lithospheric extension (Mukherjee *et al.* 2018a). More recently, from field relation of coronae-bearing mafic rocks in the Domain I of CGGC, Adak and Dutta (2021) opined that the mafic intrusion was prior to D₃ but after D₂ and is related to rifting, comparable to the 950–920 Ma event of Mukherjee *et al.* (2019). A tectono-thermal event is also suggested at ~1.0 Ga in CGGC related to continent–continent collision between the North and the South Indian blocks (Goswami and Bhattacharyya, 2008; Maji *et al.* 2008). Therefore, it is opined that the accretion of the continental blocks initiated at ~1.0 Ga (Figures 9a–c), due to the gradual subduction of oceanic crust and closure of the basin between the Singhbhum Craton and the CGGC (e.g. Rekha *et al.* 2011). The mafic magma was generated in a post-collisional extension possibly because of delamination of subducting slab (e.g. Sylvester, 1998). The underplating of such basic magma under the lower crust might have triggered partial melting of the mafic lower crust, forming a crustal-scale silicic magma (Figure 9d). Mingling between the basic magma and the silicic magma, followed by crystal fractionation of mafic minerals (hornblende) and accessory minerals like apatite and allanite, may have led to the formation of the megacryst-bearing granitoids of the present area. The mixing of mantle-generated basic magma and crustal magma and later fractional crystallization

at lower crust produced the parental magma of granitoids representing the late-Grenvillian magmatic episode and is contemporaneous with the assembly of Rodinia (Figure 10). This interpretation agrees with general idea proposed very recently by several authors of considering the CGGC as part of a late-Grenvillian orogenic belt along which the North and South Indian Cratonic blocks amalgamated between 1.1 and 0.9 Ga (Duchesne *et al.* 1998; Atherton and Ghani, 2002; Jiang *et al.* 2002; Naganjaneyulu and Santosh, 2010; Das *et al.* 2020b) leading to crustal thickening. The megacryst-bearing granite gneiss of the CGGC thus represents batholith emplaced along suture zones after the collisional assembly, similar to those in many other collisional orogenic sutures (Santosh *et al.* 2009). It is also envisaged that these events are plausibly related to the India–Antarctica amalgamation during the formation of Rodinia at ~0.9 Ga as depicted in Figure 10 (Li *et al.* 2008). In the absence of geochronological data, the exact age of the intrusion and its subsequent metamorphism could not be established in the present study but considering the shoshonitic variety of granites in the vicinity of the study area, Goswami and Bhattacharyya (2014) also suggested the emplacement of the porphyritic granites in a collisional setting.

6. Conclusions

The present study shows that intra-cratonic or ITSZs can be identified within cratonic regions by an integration of field observation, AMS studies and petro-structural analyses methods, and corroborated with the analysis of kinematic vorticity. The most significant conclusions are:

- a. The NPSZ is a shear zone where deformation is partitioned into several steeply dipping discrete ductile sinistral shear zones characterized by a sub-simple shear component of deformation developed under flattening regime.
- b. The discrete shear zones nucleated within the quartz-rich domains located between K-feldspar megacrysts in non-sheared granite gneiss.
- c. The emplacement of the megacryst granite gneiss resulted from magmatic underplating related to the anatexis of mafic granulite at lower-crustal levels during the amalgamation of CGGC and Singhbhum Craton.
- d. The NPSZ is an ITSZ in the CGGC concomitant to the granite emplacement and crustal thickening during the amalgamation of the North and South Indian blocks during 0.9–1.1 Ga and Late-Grenvillian magmatism at ~0.9 Ga during the assembly of Rodinia supercontinent.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/S0016756826100612>

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Author contribution. Sayandeep Banerjee: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft and revisions, Fund acquisition, Goutam Sarkar: Conceptualization, Investigation, Methodology, Writing – original draft and revisions, Visualization, Validation, Manish Mamtani: Methodology, Visualization, Validation, Writing – editing.

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