



Kinematics, strain pattern and geochronology of the Salem-Attur shear zone: Tectonic implications for the multiple sheared Salem-Namakkal blocks of the Southern Granulite terrane, India

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ABSTRACT

Structural mapping, strain analysis, and a variety of geochronological studies were carried out to determine the tectonothermal evolution of the Salem-Attur shear zone in the Southern Granulite terrane of South India. The Salem-Namakkal blocks containing the shear zone consisted of quartzofeldspathic gneiss, charnockite and mafic granulite, and had undergone multiple phases of magmatism spanning over a period of 3.2–0.5 Ga. The rocks were deformed by four phases of deformation D₁–D₄. The D₁ deformation was characterized by isoclinal and recumbent NE-SW trending F₁ fold with a pervasive subhorizontal axial planar granulitic fabric, S₁, and associated quartzofeldspathic leucosomes. Granulite metamorphism was dated at ca. 2.5–2.3 Ga. The F₁ fold and S₁ fabric were coaxially refolded by tight to isoclinal, upright to steeply inclined NE-SW trending F₂ folds during D₂ deformation. The D₂ deformation was associated with F₂ axial planar shear zones, crenulations and leucosomes, S₂ fabric. Large-scale D₂ shear zones characterized by high-temperature ductile shear fabric with a vertical flow host syntectonic syenite pluton which was dated at ca. 2.5–2.4 Ga. A P-T condition of 7 kb/600 °C was inferred for the D₂ deformation. The D₃ deformation was characterized by NW-SE to E-W trending F₃ folds and the Salem-Attur shear zone. The shear zone was a greenschist to amphibolite facies shear zone being characterized by mylonitic foliation and dominantly down-dip stretching lineation defined by quartz, biotite and hornblende minerals and dated at ca. 2.0 Ga. It indicated N-NNE vergence of thrusting with the mean kinematic vorticity number, *W_m*, as 0.7 suggesting general simple shear strain with 50% pure shear component. The D₄ deformation was manifested as NNE-SSW striking strike-slip faults and NW-SE striking extensional normal faults. Pseudotachylite veins having an age of 1.9 Ga injected during strike-slip faulting and granite-pegmatite veins showing age of 0.8–0.5 Ga intruded during normal faulting. The Salem-Namakkal blocks thus recorded a long-lived shearing history. We suggest that the Salem-Attur shear zone and other shear zones such as Palghat-Cauvery, Moyar, Bhavani, Karur-Kambam-Painavu-Trichur and Achankovil shear zones, were Paleoproterozoic intraterrane shear zones which were overprinted by Meso-Neoproterozoic-Cambrian ductile and brittle deformations.

1. Introduction

The structural architecture of an orogen is often defined by shear zones which divide the orogen into a number of domains characterized by distinctive lithology, metamorphic history, structural style and geochronology (e.g., Himalaya orogen- Valdiya, 1984; Limpopo mobile

belt- McCourt and Vearncombe, 1987; Cap de Creus shear zone- Carreras and Druguet, 1994; Sierras Pampeanas shear zone- Sims et al., 1998; Eastern Ghats mobile belt- Biswal et al., 2007; Sierra Ballena shear zone- Oyhantcabal et al., 2010; Southern Granulite terrane, Plavsa et al., 2015). Shear zones undergo principally simple shear deformation, pure shear deformation associates in different proportions.

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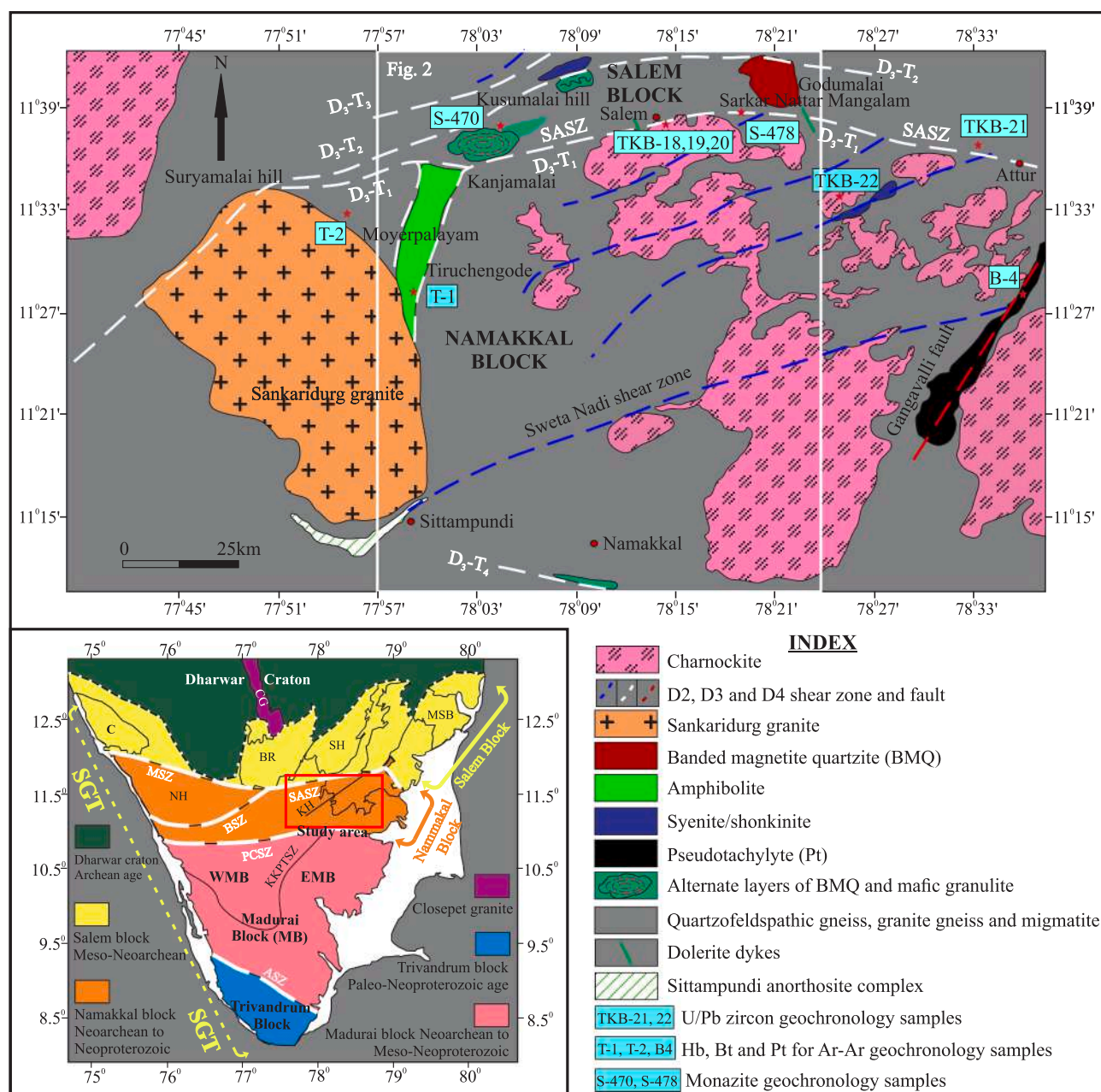


Fig. 1. Regional geological map of the Salem-Namakkal blocks, northern part of the SGT (Sundaralingam et al., 2017). D₂, D₃ and D₄ shear zones/faults are marked in blue, white and red, respectively. Two zircon geochronology samples are plotted in the map, as their locations lie outside the area in Fig. 2. Fig. 2 is marked by white box. *Inset:* Geological map of the SGT (Ramakrishnan and Vaidyanadhan, 2008). ASZ- Achankovil shear zone, BR- Biligirirangan, BSZ- Bhabani shear zone, C- Coorg, CG- Closepet granite, EDC- Eastern Dharwar craton, FL- Fermor's line, KH- Koli hill, KKPTSZ- Karur-Kambam-Painavu-Trichur shear zone, MSB- Madras block, MSZ- Moyar shear zone, PCSZ- Palghat Cauvery shear zone, SASZ- Salem-Attur shear zone, SH- Shevroy hill, WDC- Western Dharwar craton. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Depending on the nature of deformation, shear zones can be characterized by a variety of strain fabrics (Ramsay, 1980; Fossen and Cavalcante, 2017). Mapping out shear zones and structural domains and interpreting the deformation history, shear kinematics, nature of strain and timing of deformation, using different geochronological techniques, help unravel the tectonic history of a mobile belt (Sims et al., 1998; Dumond et al., 2008, 2015; Oyhantcabel et al., 2012; Oriolo et al., 2016).

The Neoproterozoic to Neoproterozoic Southern Granulite terrane (SGT) of South India is transected by several shear zones (Fig. 1 inset) which were considered to be suture between different tectonic blocks (Santosh et al., 2013; Brandt et al., 2014). The Salem-Attur shear zone, the focus of this paper, occurs in the northern part of the SGT. The shear

zone was described as a dextral strike-slip shear zone delineating two contrasting blocks namely Archean Salem block in the North and the Paleoproterozoic Palghat-Cauvery block in the south (also referred to as the Namakkal block) (Chetty, 1996; Chetty and Rao, 1998, 2006; Chetty et al., 2003; Ghosh et al., 2004; Plavsa et al., 2015). Our study focuses on the tectonothermal evolution of the Salem-Attur shear zone based on detailed structural mapping, petrofabric analysis, strain estimation and geochronology. We have constrained the deformation events by zircon U-Pb SHRIMP geochronology on igneous intrusions, monazite U-Th-Pb EPMA dating on metamorphic and sheared rocks and hornblende/biotite ⁴⁰Ar/³⁹Ar dating of pseudotachylite from shear zones and brittle faults. Our study of the Salem-Attur shear zone provides a better understanding of the evolution of SGT in general and

allows regional correlation with other segments of Peninsular India as well as adjoining continents within the Gondwanaland assembly.

2. Geological background

The SGT consists of several tectonic blocks bound by shear zones (Fig. 1 inset). These blocks are characterized by distinct lithological assemblages, grades of metamorphism and isotopic ages. From north to south, these are (i) the Salem block (between the Dharwar craton and the Salem-Attur shear zone), (ii) the Namakkal block (previously referred as the Palghat-Cauvery shear system, bounded by the Salem-Attur and Palghat-Cauvery shear zones), (iii) the Madurai block (between the Palghat-Cauvery shear zone and the Achankovil shear zone), (iv) the Trivandrum block (south of the Achankovil shear zone and (v) the Nagercoil block (Santosh et al., 2009a).

The Salem block consisted of isolated hills of Meso-Neoproterozoic quartzofeldspathic gneiss, charnockite, mafic granulite and BIF. The intrusion of parent magma of mafic granulite was constrained at ca. 2.7 Ga (Sato et al., 2011a), charnockite at 2.6 Ga (Vinogradov et al., 1964; Clark et al., 2009; Saitoh et al., 2011), granite gneiss at ca. 2.5 Ga (Saitoh et al., 2011) and shonkinite and ultramafic rocks at ca. 0.8 Ga (Friend and Janardhan, 1984; Reddy et al., 1995). Several episodes of granulite facies metamorphism affected the block at ca. 2.5 Ga, (Peucat et al., 1993; Sato et al., 2011a; Anderson et al., 2012), ca. 0.7 Ga (Bhaskar Rao et al., 1996) and ca. 0.6 Ga (Ghosh et al., 2004; Bhutani et al., 2007). It was interpreted that the Salem block represented the southern extension of the Dharwar craton, where the greenstone-tonalite-trondhjemite-granodiorite rocks of the craton were metamorphosed to granulite facies (Friend and Nutman, 1992; Bartlett et al., 1998; Bhaskar Rao et al., 2003; Ghosh et al., 2004). The P-T conditions of 8–14 kbar/800–900 °C were estimated for the garnet-orthopyroxene-clinopyroxene-plagioclase assemblage in the Salem block (Mukhopadhyay and Bose, 1994).

The Namakkal block consisted of a similar lithological assemblage and was intruded by ultramafic, ultrabasic and granite rocks of Neoproterozoic to Neoproterozoic ages. The anorthosite pluton at Sittampundi containing mafic granulite enclaves yielded crystallization ages of ca. 2.9 Ga and 2.5 Ga, and a metamorphic ages of 0.7 Ga (Subramanyam, 1956; Rao et al., 1996; Dharma Rao et al., 2013; Mohan et al., 2013). The Sankaridurg granite pluton with several small to large scale roof pendants of marble, pelitic rock and quartzite, was emplaced between 0.6 Ga to 0.4 Ga age (Condie, 1986; Pandey et al., 1993; Ghosh et al., 1994; Nathan et al., 1994; Santosh et al., 2005). Granulite facies metamorphism belonged to two phases at ca. 2.5 Ga (Ghosh et al., 2004; Plavsa et al., 2015) and ca. 0.5 Ga (Collins et al., 2007a; Raith et al., 2010; Santosh et al., 2012). Both high pressure (eclogite facies, Shimpoo et al., 2006; Tsunogae and Santosh, 2006; Sato et al., 2009) and ultrahigh temperature metamorphism (sapphirine and quartz bearing rocks: Kelsey, 2008; Nishimiya et al., 2009) of Neoproterozoic-cambrian phase associated with the Namakkal block. Different interpretations have been proposed for the tectonic setting of this block. One view proposed that it was a part of the reworked Archean Dharwar craton (Harris et al., 1994; Rao et al., 1996; Chetty et al., 2003; Ghosh et al., 2004; Tomson et al., 2006). An alternative model suggested a Cryogenian supra-subduction zone (Santosh et al., 2009a, 2012; Yellappa et al., 2010; Sato et al., 2011b), while another model suggested the Namakkal block represented a collapsed marginal basin (Drury and Holt, 1980). The block was previously known as the Palghat-Cauvery shear system as it contained several ENE-WSW striking shear zones identified by remote sensing. The shear zones were interpreted to constitute a transpressive dextral shear zone system producing a flower structure (Drury and Holt, 1980; Chetty et al., 2003; Chetty and Rao, 2006). The Moyar-Attur-Bhavani shear zone along the northern margin of the shear system was characterized by E-W striking dextral strike-slip (Plavsa et al., 2015). The NW-SE Palghat-Cauvery shear zone along the southern margin of the shear system represented

an extremely shortened zone (Mukhopadhyay et al., 2003), dextral strike-slip shear zone (Drury and Holt, 1980) and a zone of juxtaposition of blocks of different geochronological ages and metamorphism (Harris et al., 1994; John et al., 2005). The Palghat-Cauvery shear zone is further considered to mark the location where the Mozambique ocean was subducted during amalgamation of the Madurai and Salem-Namakkal blocks (e.g., Collins et al., 2014).

The Madurai block was divided into two sub-blocks namely the Neoproterozoic western Madurai and Meso-Neoproterozoic eastern Madurai sub-blocks along the Karur-Kambam-Painavu-Trichur shear zone (Ghosh et al., 2004; Brandt et al., 2014). The Dharwar craton was believed to extend up to the Karur-Kambam-Painavu-Trichur shear zone (Ghosh et al., 2004; Brandt et al., 2014). However, Palaeoproterozoic (2.0–1.6 Ga) crust existed in the Madurai as well as Trivandrum block (Braun et al., 1998; Ghosh et al., 2004). The metamorphism in the Madurai block was constrained at 0.6–0.5 Ga under UHT conditions (Jayananda et al., 1995; Bartlett et al., 1998; Braun, 2006; Santosh et al., 2006a; Braun et al., 2007; Collins et al., 2007b; Brandt et al., 2011).

The Achankovil shear zone juxtaposed the Madurai block with Trivandrum block and interpreted as a magnetic lineament (Rajaram et al., 2003), a dextral or sinistral shear zone (Drury et al., 1984; Rajesh and Chetty, 2006), and coaxial deformation zone (Ghosh et al., 2004). The shear zone experienced high temperature and pressure metamorphism at ca. 0.5 Ga (Santosh et al., 2009b). The Trivandrum block is dominated by khondalites with protolith-sedimentation age was at ca. 1.9 Ga, and recording high-grade metamorphism around 0.5 Ga (Ghosh et al., 2004; Santosh et al., 2006b, c; Collins et al., 2007b). The Nagercoil block was interpreted to have a similar age and evolution as the Trivandrum block (Santosh et al., 2006c) and contained charnockites with a chemistry showing an arc signature (Santosh et al., 2009a).

Kinematics of the shear zones in SGT were interpreted by remote sensing analysis only, leading to contrasting views. Based on remote sensing, the Salem-Attur shear zone has previously been interpreted as a strike-slip (Drury et al., 1984; Satheesh Kumar and Prasannakumar, 2009), a transpressive (Chetty, 1996; Chetty and Rao, 1996; Plavsa et al., 2015) or compressive shear zone (Naha and Srinivasan, 1996; Biswal et al., 2009, 2010; Sundaralingam et al., 2012, 2017), while strike-slip faults hosting pseudotachylites have been interpreted to be produced from N-S compression (Behera et al., 2017).

3. Methodology

3.1. Structural mapping, sampling and petrography

The Salem-Namakkal blocks including the Salem-Attur shear zone were mapped at 1:10,000 scale (Fig. 2). The structural features were photographed on profile section (Figs. 3–5, 7 and 8) and structural data are presented in stereonet (Fig. 2 insets). Samples were collected from different lithounits for petrographic work. Oriented samples were collected at regular interval along a profile across the strike of the shear zones (Fig. 6). The mylonitic foliation and stretching lineations were marked on the sample. The samples were cut into foliation perpendicular thin sections; one section was parallel to lineation (XZ section) and another perpendicular to lineation (YZ section). Photomicrographs of the XZ sections were presented in Fig. 8, which were studied for kinematic and vorticity analysis.

3.2. Mean kinematic vorticity number

The mean kinematic vorticity number (W_m) is an approximate measure of the relative proportion of simple shear and pure shear components (Ghosh and Ramberg, 1976; Passchier, 1987). Several vorticity gauges, including (i) clast-based gauges (Ghosh and Ramberg, 1976; Passchier, 1987; Simpson and De Paor, 1993; Wallis et al., 1993),

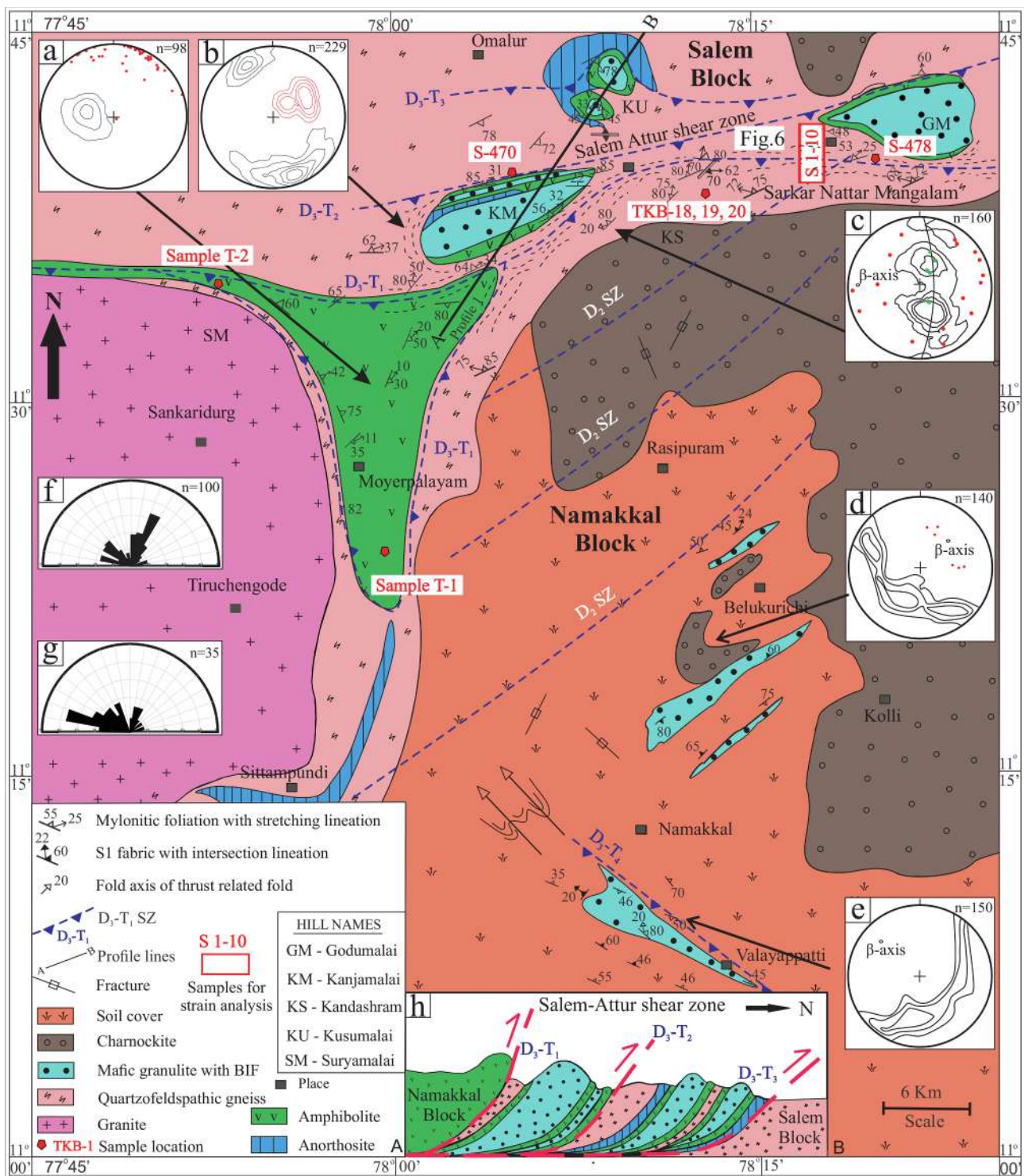
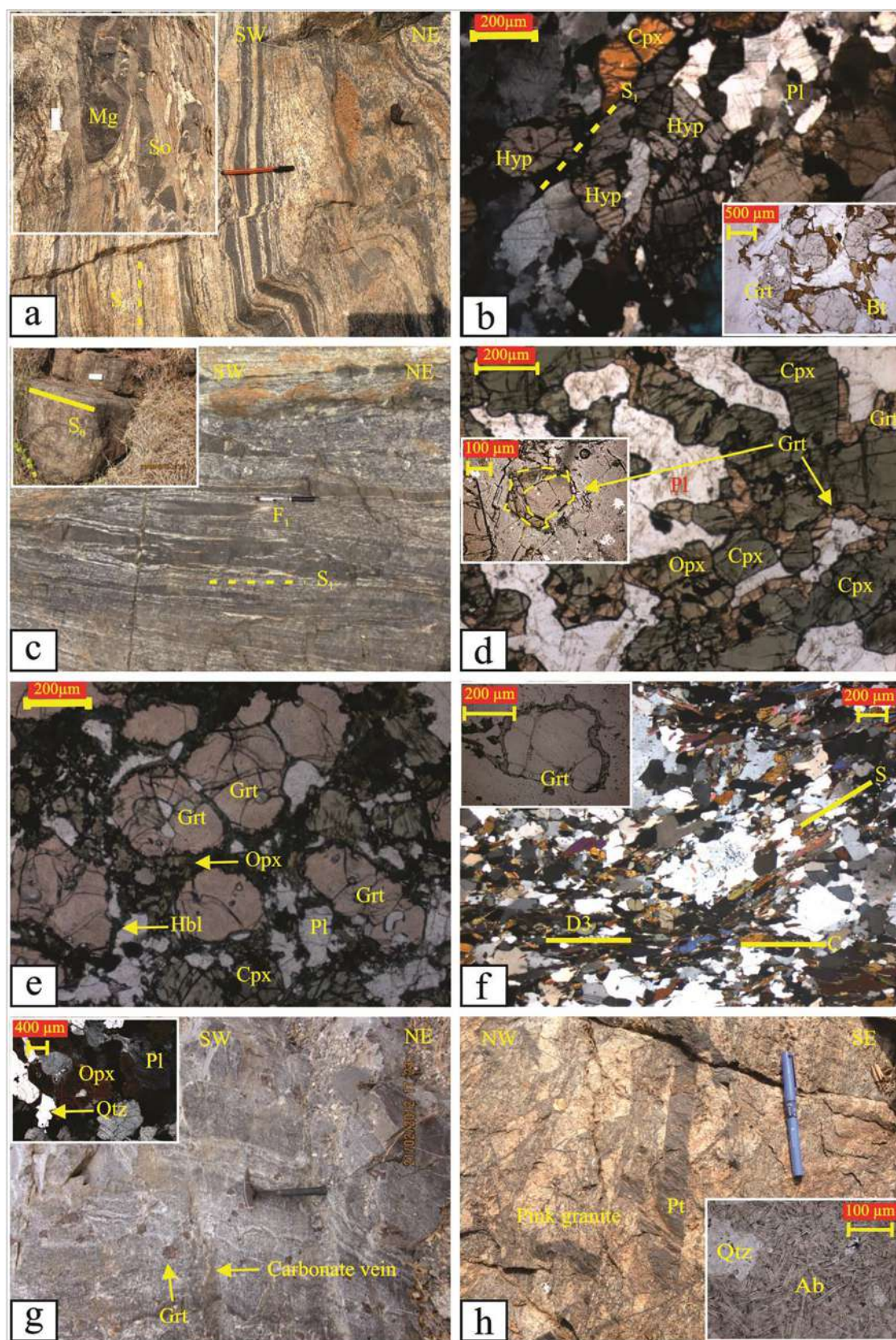


Fig. 2. Structural map of the Salem-Namakkal blocks. Geochronology sample locations are plotted in red colour. (a–e) Stereoplots of structural features for Moyerpalayam, Kanjamalai, Kandashram, Belukurichi and Namakkal areas. (a) 98 mylonitic foliations, contours in black, 1–5–10%; 53 stretching lineations plotted as red colored dots; (b) 229 S_1 fabric, contours in black, 1–2–3–5–10%, 125 fold axis and lineation, contours in red, 1,2,5,10%; (c) 160 S_1 fabric and mylonitic foliation, contours in black, 1–3–5–10%, girdle with westerly low plunging β axis. There are two sets of lineation, green dots indicate stretching lineations and red dots, fold axis; (d) 140 S_1 fabrics, contours in black, 1–5–10%, girdle distribution with northeasterly plunging β axis. Red dots indicate F_1 – F_2 fold axis; (e) 150 S_1 fabrics show girdle distribution, β axis of F_3 fold plunges to NW, Contours 1–5–10%; (f, g) Rose diagrams for strike-slip and normal faults respectively; (h) Suggestive A–B profile across Salem–Attur shear zone, illustrating D_3 – T_1 , D_3 – T_2 and D_3 – T_3 thrusts that merge at depth, forming a leading imbricate structure. Shear zones are marked in blue color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(ii) the angle between macroscopic foliation and shear zone boundary (R_s/θ or R_{xz}/β , R_{xz}/θ) (Ramsay and Huber, 1987; Tikoff and Fossen, 1995), (iii) oblique dynamically recrystallized grain shape foliation

(Wallis, 1995) and (iv) R_{xz}/δ method (Xypolias 2009, 2010) have been applied to deformed rocks. Here, we followed the clast-based and the R_s/θ techniques. In the clast-based method, the aspect ratio and



(caption on next page)

Fig. 3. (a) Field photograph, quartzofeldspathic gneiss in the Namakkal block, dark layers (S_1) contain hypersthene and biotite, and white layers are quartz and plagioclase bearing. *Inset:* mafic granulite (Mg) band defining S_0 is present within the quartzofeldspathic gneiss; (b) Photomicrograph of quartzofeldspathic gneiss with hypersthene (Hyp) and S_1 foliation. *Inset:* garnet (Grt) porphyroblast surrounded by biotite, indicating retrogression; (c) Mafic granulite consisting of alternate enderbyte layer with plagioclase + quartz and dark garnet + pyroxene-rich layer, the layers define the S_1 foliation. F_1 fold is present in the center. *Inset:* primary cumulate layers (S_0) containing pyroxene and magnetite; (d) Photomicrograph of mafic granulite in the Salem block: garnet corona (Grt) is developed around hypersthene (Opx), clinopyroxene (Cpx) and first stage garnet (Grt-*inset*), in contact with plagioclase; this marks isobaric cooling or loading; (e) Mafic granulite in the Namakkal block: garnet (Grt) is surrounded by hypersthene-corona (Hyp). Hornblende (Hbl) is developed due to retrogression of hypersthene and pyroxene; (f) Amphibolite at Moyerpalayam contains hornblende and biotite defining D_3 -S-C fabric. *Inset:* garnet is retrograded to epidote; (g) Charnockite contains dark and white layers (S_1 foliation), garnet (Grt) porphyroblasts are present randomly in the rock. Carbonate veins (white colour) cross cut the S_1 foliation. *Inset:* Charnockite contains quartz, hypersthene and plagioclase; (h) Pseudotachylite (Pt) veins cross cutting the pink granite. *Inset:* Albite (Ab) microlites and quartz (Qtz) clasts in Pt. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

inclination of porphyroclasts to the shear plane constitute the base data. The 'imageJ' software was used to measure the aspect ratio of the feldspar porphyroclasts. The basic principle underlying the clast based method is that the porphyroclasts rotate in response to shearing. Simple shearing produces forward rotation for any aspect ratio of the clast while pure shearing will tend to rotate clasts in opposite direction if they are oppositely inclined. In general shear, depending on the proportion of pure shear to simple shear, certain aspect ratios of grains will have a forward rotation, even if they are inclined in the opposite direction. Other grains can show a backward rotation while some will show zero rotation rates. Grains with zero rotation rates have critical aspect ratio (R_{crit}) (Ghosh and Ramberg, 1976; Passchier, 1987, 1997; Simpson and De Paor, 1993, 1997; Stahr and Law, 2011, 2014). R_{crit} is a direct measure of the mean kinematic vorticity number, Wm ($Wm = R_{crit}^2 - 1/R_{crit}^2 + 1$) and can be determined geometrically (Rigid Grain Net of Jessup et al., 2007). In the Rs/θ method, the strain ratio (Rs) is calculated using R_f/ϕ method (Ramsay, 1967; Lisle, 1985). The θ angle is obtained by measuring the inclination of the long axis of the quartz grains (S-fabric) with the C-fabric. The $S^\circ C$ angle is a measure of instantaneous strain. If the flow is non-steady, θ values will represent the last instantaneous strain (Wallis, 1995). The Wm is determined from the equation,

$$Wm = \cos[\tan^{-1}\{1 - R_s \tan^2\theta / (1 + R_s) \tan\theta\}]$$

(Xypolias, 2009).

We carried out vorticity analysis of D_3 mylonites of the Salem-Attur shear zone near Sarkar Nattar Mangalam (Figs. 2 and 6). The shear zones lacked P-bands and fissure veins, suggesting that there was minimal volume change (e.g., Ramsay and Lisle, 2000). Feldspar porphyroclasts were devoid of dynamic recrystallization and constituted the major population of rigid grains. They were widely spaced, so they didn't interfere during the rotation. A large variety of aspect ratios grains were included in the analysis. There were few grains with aspect ratios > 5.0 as the samples used for analysis were from mylonite and ultramylonite. The aspect ratio (B^*), vorticity number (Wm) and percentage of pure shear were calculated following Jessup et al. (2007) (for RGN plot, Fig. 9). Further, Rs of the dynamically recrystallized quartz grains was measured on the same petrographic section whose RGN analysis was carried out. The Rs was plotted against θ to get the Wm (Fig. 10a, Ramsay and Huber, 1987; Tikoff and Fossen, 1995). A comparison of Wm obtained by both methods is provided in Fig. 10b and Table 1 (e.g., Tikoff and Fossen, 1995). The values were furthermore, matched with that of Flinn's plot between X/Y and Y/Z ratio of quartz grains (Fig. 10c).

3.3. Zircon U-Pb geochronology

Zircon has a high closure temperature ($> 900^\circ\text{C}$) to the U-Th-Pb system and is therefore ideal to date the crystallization age of intrusive and extrusive rocks (Dahl, 1997; Cherniak and Watson, 2001). We have applied zircon geochronology to date charnockite and granite in the Salem-Namakkal blocks. Zircon U-Pb geochronology was conducted on the SHRIMP ion microprobe at the John de Laeter Centre for Mass Spectrometry at Curtin University in Perth, Australia. Zircon of all shapes and sizes were handpicked and mounted in epoxy resin together

with natural zircon standard BR266 (Stern, 2001), TEMORA-2 (Black et al., 2003, 2004) and CZ3 (Pidgeon, 1994). The samples were loaded in the SHRIMP sample lock 24 h prior to analysis and pumped to $\sim 5 \times 10^{-7}$ Torr to allow degassing. Analytical procedure of the SHRIMP follows methods similar to those described in detail by Claoue-Long (1994). Working conditions for both sessions included a primary beam current of 2–3 nA, slightly elliptical spot size of ~ 25 – $30\ \mu\text{m}$, the sensitivity of > 20 counts per ppm Pb and per nA primary beam current, and a mass resolution of > 4500 . Measurements were conducted on Zr_2O^+ , $^{204}\text{Pb}^+$, background, $^{206}\text{Pb}^+$, $^{207}\text{Pb}^+$, $^{208}\text{Pb}^+$, $^{238}\text{U}^+$, $^{232}\text{ThO}^+$ and $^{238}\text{UO}_2^+$ in sets of six scans, with a total analysis time of about 15 min per sample spot. Analyses of unknown and BR266 standard zircon were interspersed at a ratio 3:1, allowing calibration of $^{238}\text{U}/^{206}\text{Pb}$ ratios and U content using an age of 559 Ma and U content of 909 ppm (Stern, 2001). TEMORA-2 and CZ3 were used as control standards and yielded $^{206}\text{Pb}/^{238}\text{U}$ ages within the error of those reported for them (Pidgeon, 1994; Black et al., 2003, 2004). Common Pb correction is based on measure non-radiogenic ^{204}Pb isotope, and a common Pb composition applied following the Pb-evolution model of Stacey and Kramers (1975). Because analyses that recorded high counts on ^{204}Pb during the first scan were aborted, corrections are small and insensitive to the choice of common Pb composition. Nevertheless, some analyses were characterized by very low contents of U, which combined with the relatively young age, lead to low amounts of radiogenic Pb. In these cases, proportions of common Pb can become relatively high, even though counts on ^{204}Pb were barely above background. Because of the low signal to noise ratio of the ^{204}Pb signal, 204-correction suffers from imprecision particularly in these cases, and we, therefore, report uncorrected ratios in the table (Table 2), and in some cases used these uncorrected values to regress the data to common Pb and constrain an intercept age. Standard calibration errors are reported in the table, but were not included in single spot ages and pooled age calculations. Single spot ages are reported at the 1σ confidence level, while pooled ages are reported at 95% confidence.

3.4. EPMA Th-U-total Pb monazite geochronology

Monazite CHIME geochronology is an effective tool to constrain the tectonic evolution of a geological terrane by correlating ages of monazite in microfabrics with the timing of deformation of the rock. Because it contains a significant amount of Th and U and lacks common Pb, it has been used for Th-U-Pb geochronology by chemical analysis in Electron Probe Microanalyzer (Suzuki and Adachi, 1991; Montel et al., 1996; Williams et al., 2007). Monazite can form as part of metamorphic and hydrothermal events, with closure temperature for Th-U-Pb as high as $> 800^\circ\text{C}$ (Cherniak et al., 2004; Cherniak and Pyle, 2008). At higher temperature, monazite develops dislocation creep (DC) and records fabrics similar to metamorphic minerals. However, monazite can also undergo dissolution and reprecipitation at lower temperatures through dissolution precipitation creep (DPC) (Krohe and Wawrzenitz, 2000; Wawrzenitz et al., 2012). In DPC, newly formed monazite replaces pre-existing grains and forms distinct compositional domains in Backscatter Scanning Electron Microscopy imagery (Zhu and O'Nions, 1999; Williams and Jercinovic, 2002; Pyle and Spear, 2003; Foster et al.,

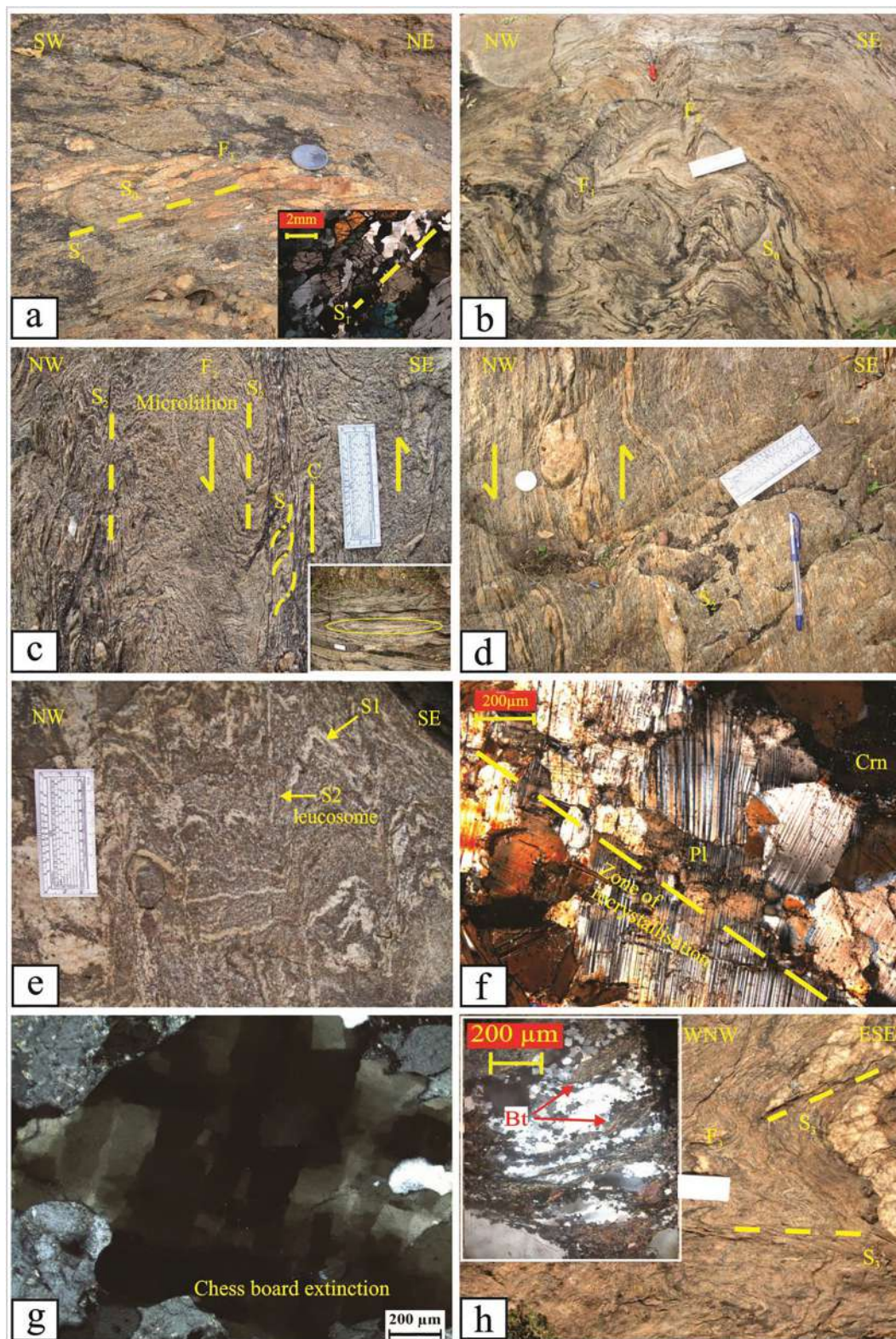


Fig. 4. (a) Horizontal view, metachert/quartzite layers (S_0) in the quartzofeldspathic gneiss are folded by isoclinal F_1 folds. Axial planar gneissosity (S_1) cross cut the S_0 at the hinge zone. *Inset:* S_1 fabric is defined by mineral alignment; (b) Vertical view, F_1 is coaxially refolded by NE-SW trending F_2 fold producing type-3 interference; (c) Vertical section, D_2 shear bands (S_2) and microlithons associated with F_2 fold, S-C fabric is developed along the shear band. *Inset:* F_1 sheath fold on horizontal surface; (d) Vertical section, boudins were rotated in anticlockwise manner along the shear band; (e) S_1 and S_2 leucosomes cross cutting each other. S_1 leucosome is folded by F_2 ; (f) Syenite intruded along D_2 shear zone shows dynamically recrystallization of plagioclase (Pl), suggesting high temperature of deformation (Crn-Corundum); (g) Chessboard extinction in the quartz in the syenite suggesting high temperature of deformation; (h) Horizontal section, NW-SE to E-W striking F_3 folds with axial planar shear, S_3 . *Inset:* Retrogression of minerals to biotite (Bt) along S_3 .

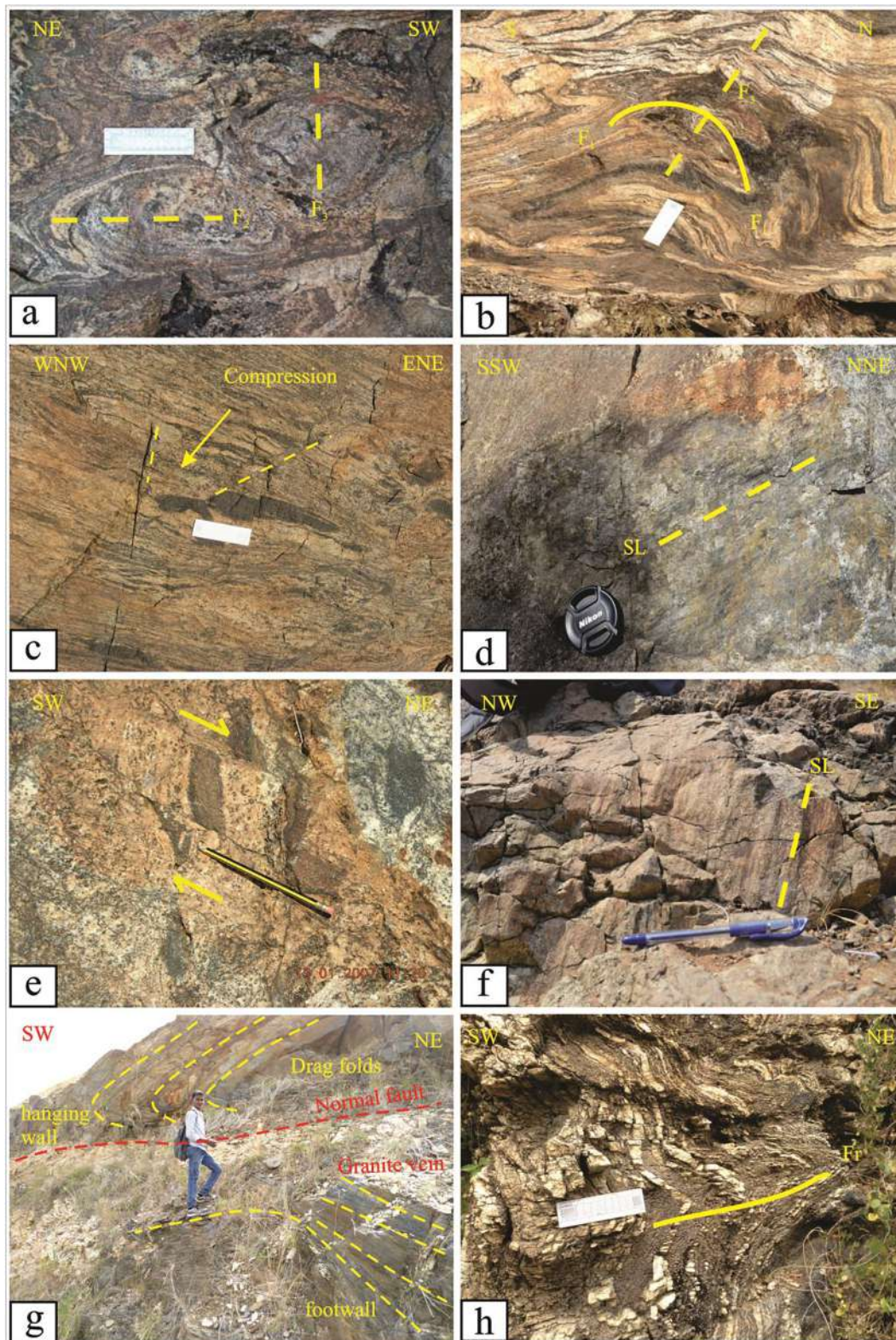


Fig. 5. (a) Horizontal view, type-1 interference pattern due to F_3 superimposed on F_2 ; (b) Vertical view, type-2 interference pattern due to superposition of F_3 on recumbent F_1 ; (c) Horizontal view, conjugate strike-slip faults in quartzofeldspathic gneiss, compression direction marked by arrow; (d) Vertical view, low angle slickenlines (SL) on strike-slip fault; (e) Vertical view, normal faults; (f) Down dip slickenlines (SL) on steep normal fault; (g) Vertical view, drag fold in the hanging wall of low angle normal fault. Granite/pegmatite vein intruded along the fault; (h) Vertical view, disjunctive fracture (Fr) appearing as cleavage in a recumbent fold.

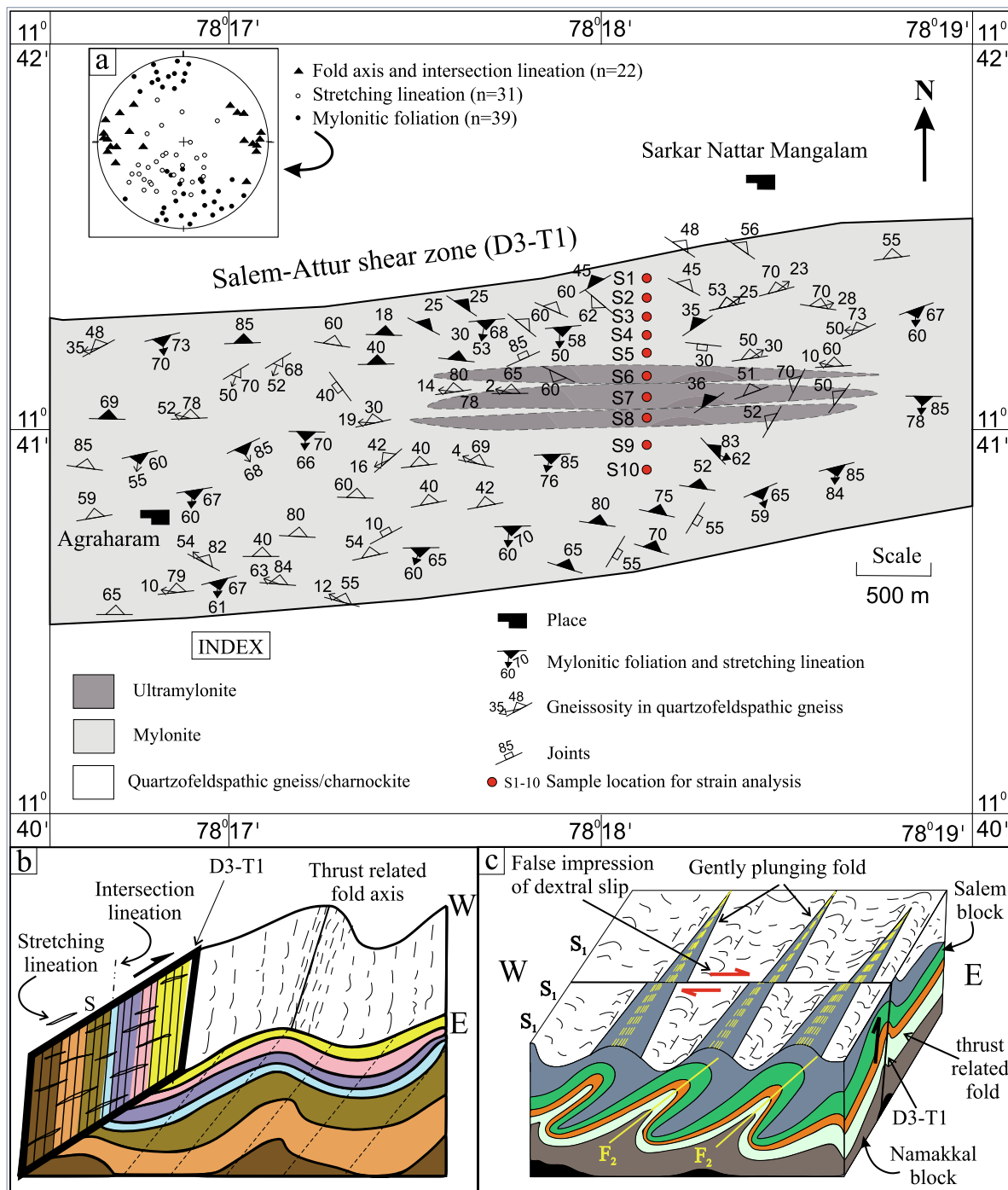


Fig. 6. Geological map of the Salem-Attur shear zone near Sarkar Nattar Mangalam. In the centre, thin bands of ultramylonite was mapped, pseudotachylite vein might be the parent rock for ultramylonite. (a) Stereoplot for mylonitic foliation, fold axis intersection lineation, and stretching lineation. The stretching lineations are at high angle to strike of the mylonitic foliation, fold axis and intersection lineations are at low angle; (b) An illustrative sketch explains, fold axis and intersection lineation remain subhorizontal while the stretching lineation is down-dip (S); (c) A false impression of dextral slip (red arrow) is produced due to intersection between the thrust (black arrow) and S_1 fabric, thrust related fold is produced due to shortening across the thrust. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2004; Mahan et al., 2006; Just et al., 2011). We carried out monazite analysis in the Cameca SX-FIVE Electron Probe Micro-Analyzer (with 5 WDS spectrometers including LLIF and LPET crystals) at the Department of Earth Sciences Indian Institute of Technology Bombay. The single point/average method was used to constrain the dates of the monazites domains (Montel et al., 1996). The age analyses were conducted at an accelerating voltage of 20 keV and a 200 nA prob current with 1 μ m beam diameter (Wawrzenitz et al., 2012). X-ray element

mapping was carried out for Ce, La, Y, Pb, Th, U in monazite was acquired with an accelerating voltage of 20 KeV, beam current of 100 nA and spatial resolution of 1–3 μ m/pixel with dwell times varying between 50 and 80 ms/pixel. Both natural and synthetic glass standards were used to calibrate for major and trace elements. PbMa, ThMa and UMb spectral lines were calibrated with crocoite ($PbCrO_4$), Th glass (ThO_2 - 5 wt%) and U glass (UO_2 - 5 wt%) standards using two spectrometers for 240 s, 160 s and 160 s respectively using sub-counting

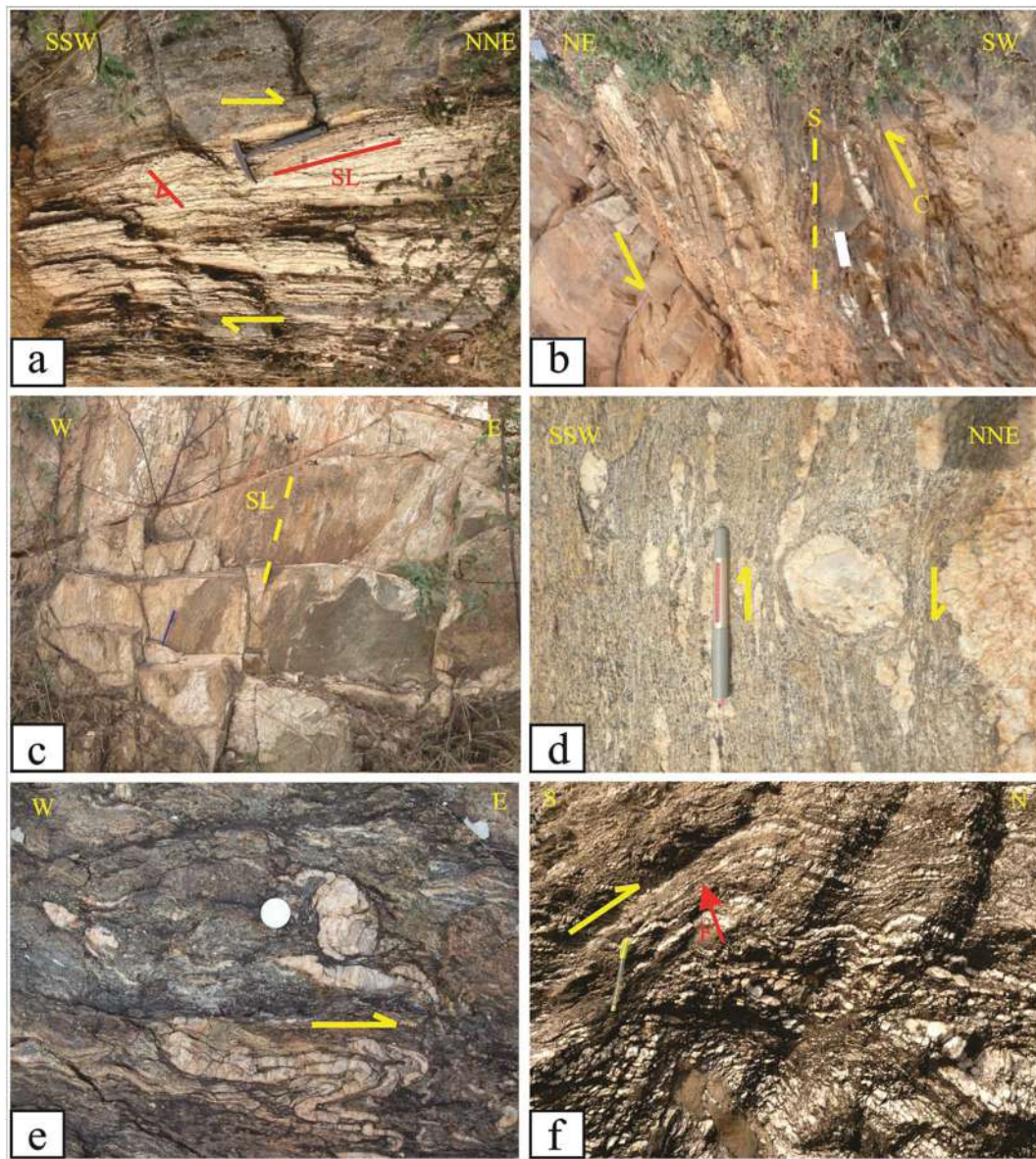


Fig. 7. (a) Vertical view, D₃-T₁, gentle, southerly dipping mylonitic foliation in quartzofeldspathic gneiss, with ductile slickenlines/stretching lineations (SL) indicating NNE vergence; (b) Vertical view D₃-T₁, steeply southerly dipping mylonitic foliation in quartzofeldspathic gneiss, S-C fabric shows top-to-NE vergence; (c) Vertical view, D₃-T₁, steep stretching lineation (SL) plunging to south on S-dipping mylonitic foliation; (d) Vertical view, D₃-T₁, feldspar porphyroclast shows N-NE vergence; (e) Horizontal view, D₃-T₂, F₁ parasitic folds have been reoriented to vertical attitude and give a false impression of dextral shearing; (f) Open upright nonplunging folds, developed in D₃-T₂, indicating that the fold axis (into the photograph) is at right angle to slip direction.

methodology (cf. Spear and Wark, 2009; Prabhakar, 2013). The total counts of PbMa were acquired in the exponential mode to better define the distantly located background positions (Jercinovic and Williams, 2005; Jercinovic et al., 2008; Spear and Wark, 2009; Goncalves et al., 2016). The matrix effects (ZAF) were reduced with X-PHI method (Merlet, 1992). The significant peak interference of ThM2-O4, ThMζ1, ThMζ2, YLC2, YLC3, LaLa on PbMa and ThMc, ThM3-N4 on UMB were corrected during quantification following the values given in Supplementary Table S1. More details on monazite dating protocol and interference corrections were outlined in Pant et al. (2009), Prabhakar (2013), Deshmukh et al. (2017) and Chatterjee et al. (2017). Detection limits were 100 ppm for Th, 110 ppm for U and 80 ppm for Pb. The spot age of individual analysis was computed using the formulae of Montel et al. (1996). If domains and/or mineral grains of a single age with the same amounts of initial Pb but different amounts of Th and U, have remained in a closed system, all analytical data will lie on an isochron with the slope 'm', and from 'm', the age is calculated (Suzuki and Kato,

2008). However, samples (sample –478, –470) in our study, the domains show mixed ages. We therefore used Isoplot (Version 4.14, Ludwig, 2012) to identify distinct age groups as suggested by Sambridge and Compston (1994) and Vlach (2010).

3.5. ⁴⁰Ar–³⁹Ar geochronology

Hornblende and biotite were used for dating shearing events. Both minerals have low closure temperature for the K–Ar system (hornblende 530 ± 40; Harrison, 1981; biotite, 310 ± 40, Harrison et al., 1985). We also used pseudotachylites produced from melting of the parent rock in fault zones (e.g., Kelley et al., 1994; Magloughlin et al., 2001; Warr et al., 2007; Sherlock et al., 2009). The newly-formed melt contains K, which then produces ⁴⁰Ar* on cooling. The Ar-isotopic clock is thus thought to be reset during frictional melting, as all radiogenic ⁴⁰Ar* is lost from the K-bearing minerals. The ⁴⁰Ar–³⁹Ar dating was done at the National Facility at ⁴⁰Ar–³⁹Ar Geo-thermochronology Lab in

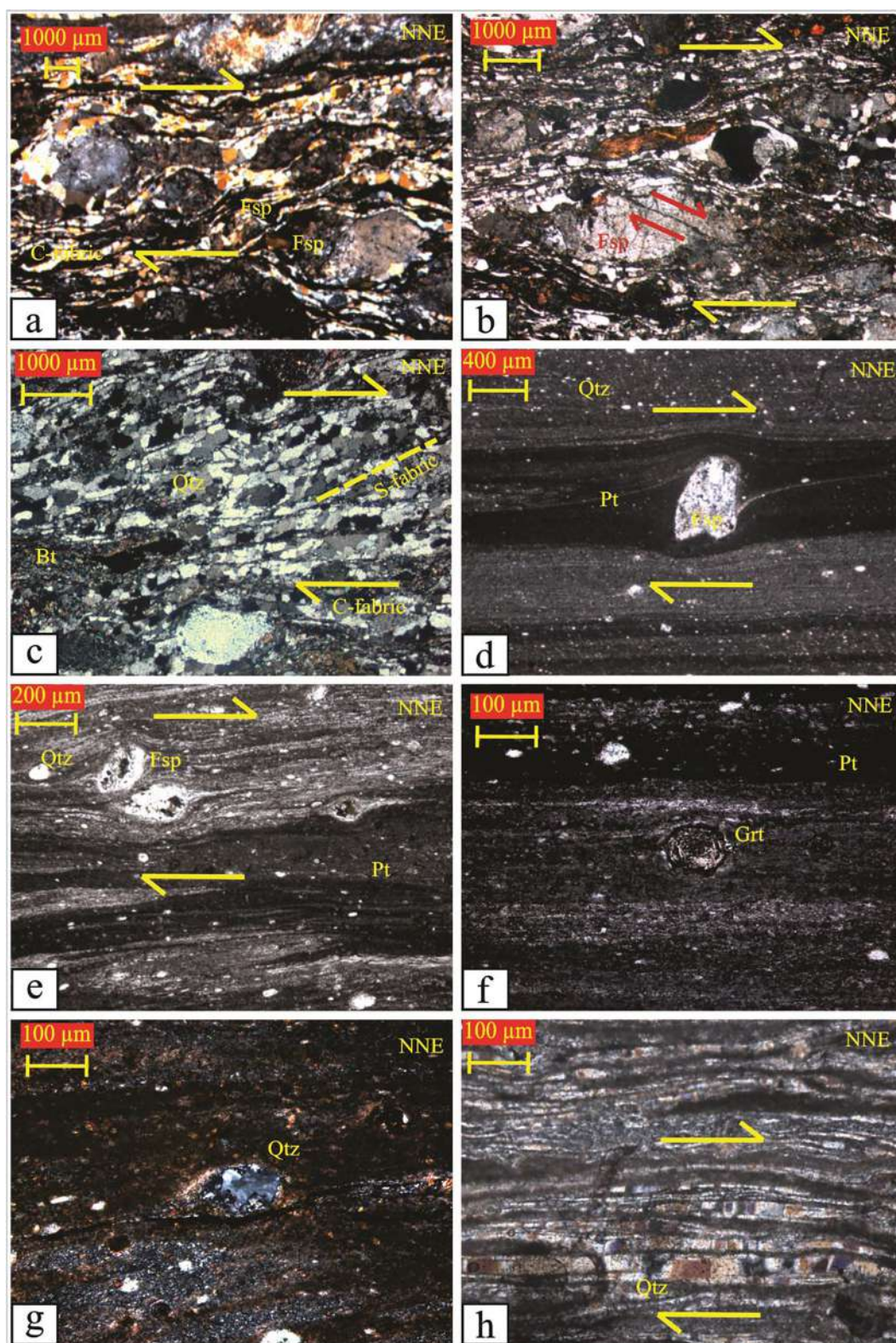


Fig. 8. (a) Quartzofeldspathic mylonites with feldspar (Fsp) porphyroclasts; (b) Low angle intragranular fault, in feldspar (Fsp) porphyroclasts, with synthetic shear; (c) S-C fabric, quartz grains (Qtz) with rotation recrystallization, biotite (Bt) along C-fabric; (d) Delta geometry of feldspar (Fsp) porphyroclasts in ultramylonite; (e-f) Ultramylonite with sigmoidal porphyroclasts; (g) Embayed quartz (Qtz) clasts in ultramylonite; (h) Monomineralic quartz ribbons indicating rotation recrystallization.

RGN Plot of porphyroclasts

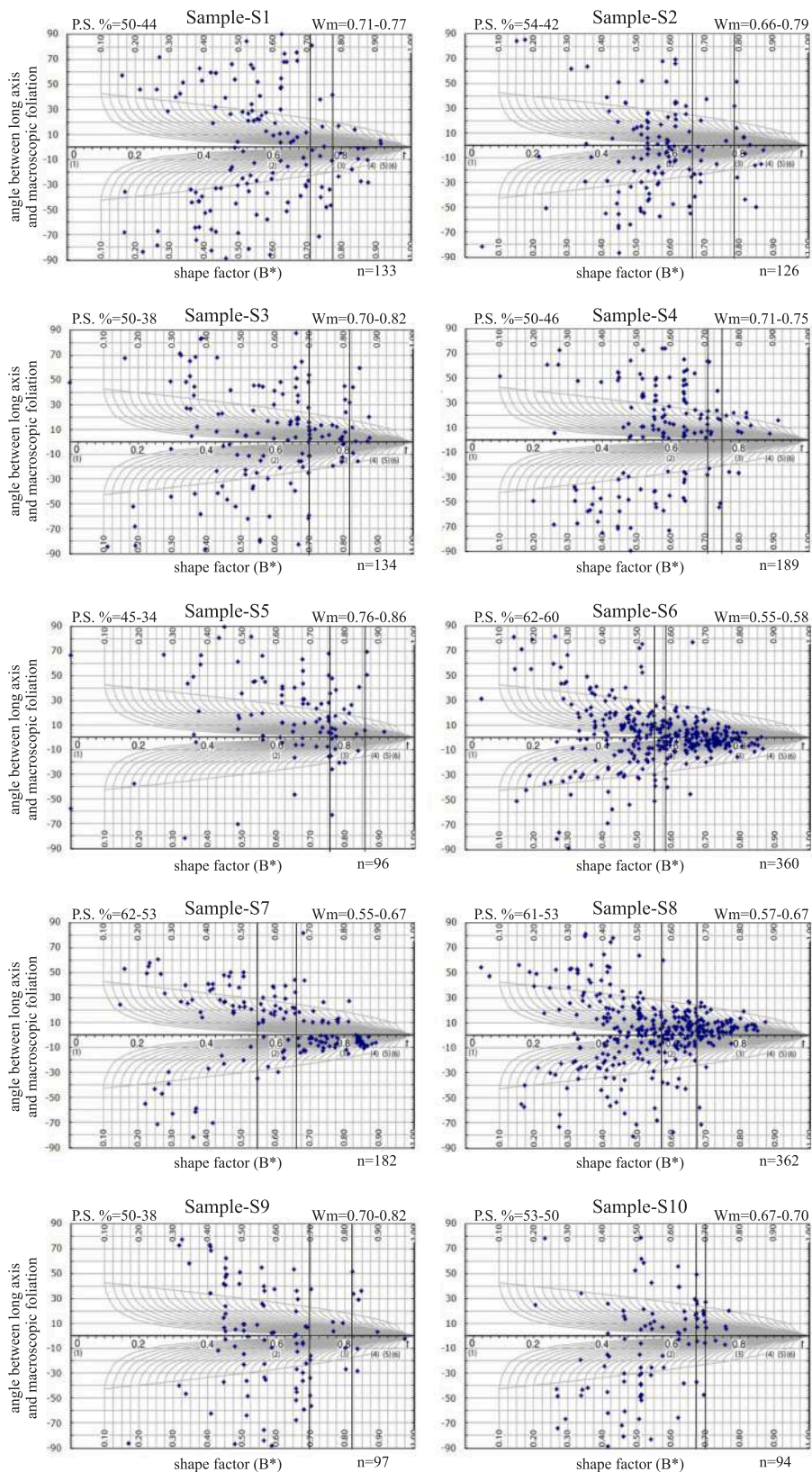


Fig. 9. Rigid grain net plot of rotated porphyroclasts from the mylonite-ultramylonite of the Salem-Attur shear zones, D₃-T₁. Each plot corresponds to one sample and sample locations are shown in Fig. 6. The XZ-sections were used to measure the angle between the long axis of the porphyroclast and C-plane. Sample number, percentage of pure shear (P.S.) and Wm (mean kinematic vorticity number) are mentioned at the top of each figure. (N) Number of grains counted is mentioned at the bottom right corner of the plot. $B^* = (\text{long axis}^2 - \text{short axis}^2) / (\text{long axis}^2 + \text{short axis}^2)$ (Jessup et al., 2007; P.S. after Law et al., 2004). Wm defines the line from where the theta angle sharply rises above the R_c value (for detail see the text).

the Department of Earth Sciences, Indian Institute of Technology Bombay. Rock chips of about 20–25 g were cut from the hand specimens to avoid veins and weathered material. The chips were crushed in an agate mortar and sieved and the large grains collected using heavy

liquid separation (sodium polytungstate water solution of specific gravity 2.56). The grains were then cleaned in deionized water in an ultrasonic bath and then heated in an oven to dry. About 0.2 g of each sample was packed in aluminum capsules. The Minnesota hornblende

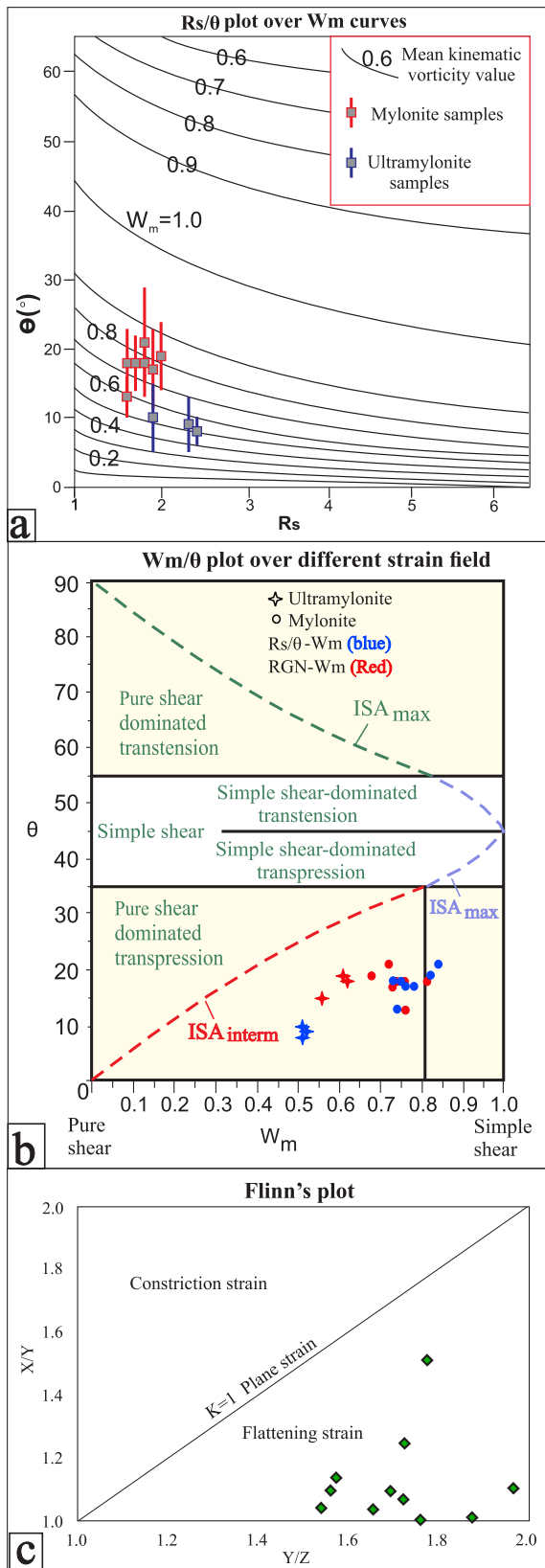


Fig. 10. (a) R_s vs $S^{\circ}C$ angle plot on W_m curves (after Ramsay and Huber, 1983; Fossen and Tikoff, 1993); (b) θ vs. W_m plot (Tikoff and Fossen, 1995). W_m was computed from rigid grain net analysis in Fig. 9. θ is the measure of average $S^{\circ}C$ angle in thin section and W_m is the mean kinematic vorticity number. See Table 1, for the result; (c) Flinn plot, X/Y and Y/Z graph indicates flattening.

reference material (MMhb-1) of age 523.1 ± 2.6 Ma (Renne et al., 1998) and high purity CaF_2 and K_2SO_4 salts were used as monitor samples. High purity nickel wires were placed in both samples to monitor the neutron fluence variation, which was typically $\sim 5\%$. The aluminum capsules were kept in a 0.5 mm-thick cadmium cylinder and irradiated in the light-water moderated CIRUS reactor at the Bhabha Atomic Research Centre (BARC), Mumbai, for ~ 100 h. The irradiated samples were repacked in aluminum foil and loaded on the extraction unit of a Thermo Fisher Scientific noble gas preparation system. Argon was extracted in a series of steps up to $1600^{\circ}C$ in an electrically heated ultra-high vacuum furnace. After purification using Ti-Zr getters, the argon released in each step was measured with a Thermo Fisher ARGUS mass spectrometer. The mass spectrometer is equipped with five Faraday cups fitted with 1011Ω resistors. Interference corrections were made. The irradiation parameter J for each sample was corrected for neutron flux variation using the activity of the irradiated nickel wires (Supplementary Table S2).

4. Result

4.1. Lithology and deformational history of the Salem-Namakal blocks

4.1.1. Lithology

Quartzofeldspathic gneiss, mafic granulite and charnockite were the main lithologies of the Salem-Namakal blocks. The quartzofeldspathic gneiss contained alternate orthopyroxene, hornblende and biotite-rich melanosome, and garnet-quartz-plagioclase-alkali feldspar-rich leucosome (Fig. 3a and b). Garnet in the leucosome was mantled by biotite (Fig. 3b inset, sample from Salem block). These gneisses graded to pyroxene-hornblende-biotite gneiss due to enrichment of melanosome parts. The quartzofeldspathic gneiss enclosed thin layers of chert, BIF and mafic granulite (Mg) which were stretched to form boudins (Fig. 3a inset). The next abundant lithounit was the mafic granulite that contained plagioclase-quartz-rich enderbite layers alternating with pyroxene-garnet-hornblende-biotite-rich layers (Fig. 3c). Garnet corona was developed around clino-orthopyroxenes and garnet (Fig. 3d inset) in the Salem block (Kanjamalai, Kusumalai and Godumalai; Fig. 3d). However, in the Namakal block, garnet was mantled by orthopyroxene corona, (Belukurichi, Valayapatti and Sittampundi areas, Fig. 3e). In a few instance, the primary magmatic layers were preserved in the mafic granulite (east of Kanjamalai hill, Fig. 1), being defined by cumulate layers of magnetite, pyroxene and plagioclase minerals (Fig. 3c inset). The mafic granulite retrograded to amphibolite and a thick amphibolite unit was mapped at Moyerpalayam (Fig. 2 for location, Fig. 3f for microphotograph). In the study area, large-scale charnockite plutons formed high hills at several places (Biligirirangan, Shevroy, Jarugumalai and Kolimalai, Fig. 1). These were characterized by a coarse grained assemblage of quartz, feldspar, hypersthene, garnet porphyroblasts and carbonate minerals (Fig. 3g and inset). Further, several other magmatic intrusives associated with the blocks, e.g., slivers of anorthosite-mafic granulite-eclogitic rocks at Sittampundi, dunite-pyroxenite-shonkinite at Nagarmalai and syenite at Attur (Fig. 1). Dolerite and pink granite dykes intruded along NNW-SSE and NNE-SSW fractures. Pseudotachylite veins injected along faults and fractures, these contained albite microlites and quartz-feldspar clasts within dark glassy matrix. The thickest vein was mapped along Gangavalli fault (Fig. 1 for location, 3 h for outcrop photo, 3 h inset for petrography). The Sankaridurg granite pluton was located to the southwest of the area (Fig. 2) and associated with coeval granite-pegmatite veins that intruded into the pre-existing foliation and fractures in the surrounding rocks.

4.2. Deformational history

4.2.1. D_1 deformation

The Salem-Namakal blocks were characterized by four stages of deformation. The D_1 deformation included NE-SW trending isoclinal

Table 1

Vorticity of freely rotating porphyroclasts (through RGN) and recrystallized grains (Rs/θ) of mylonite and ultramylonite samples from Sarkar Nattar Mangalam area (N11°40'46.71", E78°18'04.95").

Sample No.	Vorticity (W _m)		S-C angle (θ°)	% of pure shear(RGN), Range and avg.	Sample type
	Porphyroclasts (RGN, range, avg.)	Recrystallized grains (Rs/θ)			
S1	(0.71–0.77)0.74	0.75	18	(44–50)47	mylonite
S2	(0.66–0.79)0.72	0.84	21	(42–54)48	mylonite
S3	(0.70–0.82)0.76	0.73	18	(38–50)44	mylonite
S4	(0.71–0.75)0.73	0.76	17	(46–50)48	mylonite
S5	(0.76–0.86)0.81	0.78	17	(34–45)40	mylonite
S6	(0.55–0.58)0.56	0.51	10	(60–62)61	ultramylonite
S7	(0.55–0.67)0.61	0.51	8	(53–62)58	ultramylonite
S8	(0.57–0.67)0.62	0.52	9	(53–61)57	ultramylonite
S9	(0.70–0.82)0.76	0.74	13	(38–50)44	mylonite
S10	(0.67–0.70)0.68	0.82	19	(50–53)52	mylonite

recumbent F_1 folds, which were developed on the lithological layering (S_0) defined by metachert and BIF layers in quartzofeldspathic gneiss and cumulate layers in mafic granulite (Fig. 3c inset, Fig. 4a–b). The folds were extremely flattened to produce intrafolial and boudinaged folds. The F_1 was associated with a penetrative horizontal axial-planar gneissosity (S_1) that cut across the bedding at the hinge zone and remained parallel to the limbs. The granulite facies minerals such as garnet, pyroxene, and plagioclase in mafic granulite and orthopyroxene, plagioclase and garnet in charnockite were developed parallel to the S_1 fabric (Fig. 4a inset) which implied that the granulite facies metamorphism (M_1) was syntectonic with F_1 folding. Further, quartzofeldspathic leucosomes were produced parallel to the S_1 suggesting that the rocks melted during M_1 metamorphism (Fig. 4e). We inferred a PT of 7 kb/800 °C for the M_1 metamorphism from garnet + clinopyroxene + plagioclase assemblage (e.g., Harley, 1989).

4.2.2. D_2 deformation

The D_2 deformation affected the S_0 and S_1 fabrics producing NE-SW trending, open to tight and upright to NW inclined F_2 folds indicating buckling origin (Fig. 4b, c and e). Parasitic folds, cleavage refraction, compositional band boudins, and folded boudins were associated with F_2 folds. Coaxial folding between F_1 and F_2 produced a ubiquitous type-3 fold interference pattern (Ramsay, 1967; Fig. 4b). The recumbent/reclined F_1 folds were reoriented to different attitudes; the hinge zone of the F_2 folds contained the reclined folds and the limb region had inclined/upright folds. The S_2 fabric was developed in form of crenulations and shear bands (C-fabric) parallel to the axial plane of the F_2 fold (Figs. 4c, S1a) and the S_1 fabric was transposed parallel to S_2 . Melting along the shear band produced quartzofeldspathic leucosome (Fig. 4e). Vertical to subvertical flow was indicated by sub vertical stretching lineation (Fig. S1C), deflection of the S_1 fabric (Fig. 4c), rotation of quartzofeldspathic aggregate (Fig. 4d) and oblique S fabric between C-domains (Fig. S1a and d). Microlithons comprising stack of small scale F_2 folds were developed between two consecutive shear bands and had similar kinematics.

The NE-SW trending large-scale F_2 folds were mapped at Belukurichi, and interpreted from stereoplot at Kandashram and Kanjamalai (Fig. 2). Stereoplots of S_1 fabric indicated girdle pattern with gentle to moderately plunging F_2 fold axis (β -axis) in NE, W and ENE trend (Fig. 2c, d). The D_2 shear zones were mapped along the limbs of large-scale F_2 folds. Along the shear zone, F_1 and F_2 fold axes were reoriented to near vertical attitude (Fig. S1b). As a result, the F_1 and F_2 folds were converted to sheath folds producing circular to elliptical outcrops within quartzofeldspathic gneiss (Fig. 4c inset). Several magmatic intrusive rocks, namely basic-ultrabasic-shonkinite at Salem, syenite-gabbro at Attur and anorthosite at Sittampundi were present along the D_2 shear zones. These intrusives were elongated parallel to the S_2 strike and contained coplanar magmatic and solid-state deformation fabric. This suggested that the intrusion was probably

syntectonic with D_2 deformation. Petrographic study of the syenite indicated the dominance of K-feldspar with subordinate amount of plagioclase and quartz. The minerals had undergone crystal plastic deformation and dynamic recrystallization. Plagioclase grains contained kinks, undulose extinction and grain boundary migration recrystallization (Fig. 4f) and quartz grains were marked by chessboard extinction (Fig. 4g). The features suggested a PT of 6 kb/700–800 °C, for D_2 shearing (e.g., Pryer, 1993; Kruhl, 1996; Rosenberg and Stunitz, 2003; Passchier and Trouw, 2005). This might occur in the upper amphibolite to granulite facies.

4.2.3. D_3 deformation

The D_3 deformation developed NW-SE to E-W trending F_3 folds (Fig. 4h), crenulation cleavages and axial planar brittle shear over S_{1-2} fabrics. As the S_1 surfaces had a variable orientation due to F_2 folding, F_3 fold axes acquired variable plunge depending on the attitude of the S_1 surface. Further, type-1 and type-2 fold interference patterns were produced due to superposition of F_3 on F_2 and F_1 folds respectively (Fig. 5a, b). Along F_3 cleavage, hornblende, biotite and muscovites were crystallized due to retrograde metamorphism of granulites (S_3 , Fig. 4h inset, Fig. S1e).

Large-scale F_3 folding in the area was mapped from the variation of orientation of the S_{1-2} fabrics. Variation of S_{1-2} strike from ENE-WSW at Salem to N-S at Moyerpalayam and NW-SE at Valayapatti was due to large-scale F_3 fold (Fig. 2). Several large-scale D_3 -retrograde shear zones were mapped. These included the Salem-Attur shear (D_3 -T₁₋₃) and Valayapatti shear zones (D_3 -T₄, 'T' stands for thrusting). NE-SW striking D_2 shear zones and fabric were at an angle to D_3 shear zones (see near Namakkal and Sarkar Nattar Mangalam, Fig. 2). Mafic granulite overthrust the granite gneiss along the NW-SE striking Valayapatti shear zone (D_3 -T₄, Fig. S1f). The S_1 fabric was folded by large-scale NW plunging folds due to shortening across the thrust (west of Namakkal, Fig. 2e). The thrust was characterized by retrogression of garnet and pyroxene to hornblende. Down-dip stretching lineation defined by hornblende and biotite minerals was produced on southwesterly dipping mylonitic foliation. Rotated porphyroclasts and asymmetric folds indicated top-to-NNE vergence thrust kinematics (Fig. S1g).

4.2.4. D_4 deformation

The D_4 deformation included NE-SW and NW-SE striking strike-slip faults, and WNW-ESE to NW-SE striking normal faults (rose diagrams in Fig. 2f, g). The NE-SW striking Gangavalli sinistral strike-slip fault hosts thick pseudotachylite veins (Fig. 1). In one instance a pink granite pluton that contained large xenoliths of D_3 mylonite was fractured along Gangavalli fault and injected by pseudotachylite veins (Fig. 3h). The relationship suggested that the intrusion of pink granite was between D_3 shearing and strike-slip brittle faulting. Apart from that there were several small-scale strike-slip shears with subhorizontal slickenlines, some of them host pseudotachylite veins (Fig. 5c, d). The

Table 2

Zircon U–Pb SHRIMP data (2σ error of the mean of 0.94%) of sample TKB-18, 19 and 20 (N11°38'04.11", E78°14'25.20"), TKB-21 (N11°36'45.92", E78°33'25.45") and TKB-22 (N11°33'50.29", E78°02'45.02").

Spot Name	f206 (%)	U (ppm)	Th	Th/U	(²³⁸ U/ ²⁰⁶ Pb) _{total} (± 1s abs)	(²⁰⁷ Pb/ ²⁰⁶ Pb) _{total}	(²³⁸ U/ ²⁰⁶ Pb) ₂₀₄	(²⁰⁷ Pb/ ²⁰⁶ Pb) ₂₀₄	²⁰⁶ Pb/ ²³⁸ U Age (± 1s Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb Age
TKB-18-C-1	0.03	135	67	0.51	1.97867 ± 0.02943	0.17933 ± 0.00145	1.97924 ± 0.02944	0.17907 ± 0.00146	2636 ± 32	2644 ± 14
TKB-18-C-2	0.06	195	91	0.48	2.09082 ± 0.02906	0.16571 ± 0.00115	2.09204 ± 0.02909	0.16520 ± 0.00117	2519 ± 29	2510 ± 12
TKB-18-C-4	0.04	417	352	0.87	2.06614 ± 0.02524	0.17932 ± 0.00080	2.06693 ± 0.02525	0.17897 ± 0.00081	2606 ± 27	2643 ± 7
TKB-18-C-5	0.11	426	413	1	1.99673 ± 0.02492	0.17979 ± 0.00128	1.99897 ± 0.02495	0.17879 ± 0.00129	2615 ± 27	2642 ± 12
TKB-18-C-6	0.05	152	77	0.52	1.99906 ± 0.02858	0.17929 ± 0.00123	2.00009 ± 0.02860	0.17883 ± 0.00125	2614 ± 31	2642 ± 12
TKB-18-C-7	0.1	359	320	0.92	2.06841 ± 0.02621	0.18035 ± 0.00079	2.07052 ± 0.02624	0.17944 ± 0.00081	2540 ± 27	2648 ± 7
TKB-18-C-8	0.22	287	200	0.72	2.01198 ± 0.02660	0.18190 ± 0.00102	0.18167 ± 0.02667	0.17991 ± 0.00108	2596 ± 28	2652 ± 10
TKB-18-C-9	0.07	247	211	0.88	2.18049 ± 0.02949	0.17034 ± 0.00112	2.18204 ± 0.02952	0.16970 ± 0.00114	2432 ± 27	2555 ± 11
TKB-18-C-10	0.06	212	119	0.58	2.11928 ± 0.02920	0.16862 ± 0.00109	2.12059 ± 0.02922	0.16807 ± 0.00111	2490 ± 28	2539 ± 11
TKB-18-C-11	–	90	326.96	3.75	2.20526 ± 0.03574	0.163922 ± 0.0016328	2.20481 ± 0.035739	0.16411 ± 0.001643	2411 ± 33	2498 ± 17
TKB-18-C-12	0.25	266	149	0.58	2.01321 ± 0.02825	0.17695 ± 0.00133	2.01820 ± 0.02834	0.17475 ± 0.00142	2594 ± 30	2604 ± 14
TKB-18-C-13	2.53	488	396	0.84	3.43140 ± 0.04281	0.19177 ± 0.00210	3.52050 ± 0.04422	0.16920 ± 0.00251	1612 ± 18	2550 ± 25
TKB18-R-1	–	50	64	1.33	2.09132 ± 0.06457	0.16506 ± 0.00203	2.08868 ± 0.06451	0.16619 ± 0.00211	2522 ± 64	2520 ± 21
TKB18-R-2	0.28	64	79	1.28	2.31343 ± 0.06889	0.16679 ± 0.00197	2.31999 ± 0.06911	0.16427 ± 0.00213	2310 ± 58	2500 ± 22
TKB18-R-3	0.07	47	75	1.63	2.37649 ± 0.07220	0.16787 ± 0.00214	2.37814 ± 0.07226	0.16725 ± 0.00218	2263 ± 58	2530 ± 22
TKB18-R-4	2.37	42	8	0.21	2.25903 ± 0.07267	0.17640 ± 0.00292	2.31386 ± 0.07513	0.15532 ± 0.00492	2316 ± 63	2405 ± 54
TKB18-R-5	0.17	38	46	1.25	2.17957 ± 0.06740	0.16762 ± 0.00209	2.18322 ± 0.06753	0.16612 ± 0.00220	2431 ± 63	2519 ± 22
TKB18-R-6	0.07	44	63	1.5	2.49687 ± 0.07554	0.15881 ± 0.00204	2.49857 ± 0.07560	0.15820 ± 0.00209	2170 ± 56	2437 ± 22
TKB18-R-7	0.11	45	63	1.45	2.1387697 ± 0.0647601	0.16771 ± 0.00309	2.14112 ± 0.064842	0.16673 ± 0.00313	2471 ± 62	2525 ± 32
TKB18-R-8	0.04	39	75	1.99	2.19934 ± 0.06914	0.17059 ± 0.00229	2.20021 ± 0.06918	0.17024 ± 0.00232	2415 ± 63	2560 ± 23
TKB18-R-9	0.81	80	90	1.16	1.95114 ± 0.06608	0.17427 ± 0.00195	1.96710 ± 0.06669	0.16703 ± 0.00243	2650 ± 74	2528 ± 24
TKB18-R-10	0.09	18	14	0.79	2.12386 ± 0.07733	0.16804 ± 0.00347	2.12582 ± 0.07743	0.16722 ± 0.00356	2485 ± 75	2530 ± 36
TKB18-R-11	2.65	46	152	3.38	2.08572 ± 0.06493	0.19891 ± 0.00428	2.14245 ± 0.06710	0.17529 ± 0.00535	2469 ± 64	2609 ± 51
TKB18-R-12	0.14	49	182	3.84	2.11565 ± 0.06508	0.16786 ± 0.00210	2.11854 ± 0.06519	0.16665 ± 0.00219	2492 ± 64	2524 ± 22
TKB18-R-13	0.11	59	71	1.26	2.15171 ± 0.06438	0.16312 ± 0.00183	2.15401 ± 0.06446	0.16217 ± 0.00189	2458 ± 61	2478 ± 20
TKB-19-C-1	0.58	844	74	0.09	2.19835 ± 0.02634	0.17048 ± 0.00056	2.21106 ± 0.02651	0.16535 ± 0.00067	2405 ± 24	2511 ± 7
TKB-19-C-2	0.31	998	120	0.12	2.10526 ± 0.02503	0.16926 ± 0.00095	2.11186 ± 0.02514	0.16647 ± 0.00111	2499 ± 25	2522 ± 11
TKB-19-C-3	1.81	202	59	0.3	1.86765 ± 0.02927	0.18686 ± 0.00198	1.90204 ± 0.03014	0.17074 ± 0.00290	2724 ± 35	2565 ± 28
TKB-19-C-4	0.23	273	112	0.43	2.86738 ± 0.06820	0.12853 ± 0.00401	2.87413 ± 0.06837	0.12646 ± 0.00404	1925 ± 40	2049 ± 56
TKB-19-C-5	0.08	71	101	1.47	2.15768 ± 0.03707	0.16638 ± 0.00187	2.15939 ± 0.03712	0.16567 ± 0.00192	2453 ± 35	2514 ± 19
TKB-19-C-6	0.31	165	54	0.34	2.11864 ± 0.02987	0.17018 ± 0.00121	2.12531 ± 0.02999	0.16738 ± 0.00132	2486 ± 29	2532 ± 13
TKB-19-C-7	0.51	876	127	0.15	2.18920 ± 0.02614	0.17274 ± 0.00051	2.20031 ± 0.02629	0.16823 ± 0.00059	2415 ± 24	2540 ± 6
TKB-19-C-8	1.37	121	30	0.26	2.18101 ± 0.03258	0.18756 ± 0.00156	2.21121 ± 0.03378	0.17538 ± 0.00326	2405 ± 31	2610 ± 31
TKB-19-C-9	–	171	90	0.55	3.79163 ± 0.38610	0.11369 ± 0.00787	3.78948 ± 0.38588	0.11419 ± 0.00787	1510 ± 137	1867 ± 124
TKB-19-C-10	0.32	2132	84	0.04	2.11856 ± 0.02583	0.17093 ± 0.00056	2.12544 ± 0.02592	0.16804 ± 0.00059	2486 ± 25	2538 ± 6
TKB-19-C-11	0.09	62	90	1.5	2.17666 ± 0.03888	0.16591 ± 0.00197	2.17857 ± 0.03893	0.16513 ± 0.00202	2435 ± 36	2509 ± 21
TKB-19-C-12	0.62	97	186	1.98	2.14587 ± 0.03387	0.17109 ± 0.00162	2.15932 ± 0.03420	0.16553 ± 0.00200	2453 ± 32	2513 ± 20
TKB-19-C-13	0.27	1275	137	0.11	2.04715 ± 0.02453	0.16864 ± 0.00060	2.05263 ± 0.02461	0.16626 ± 0.00066	2558 ± 25	2520 ± 7
TKB-19-C-14	0.35	1355	75	0.06	2.15037 ± 0.02530	0.16952 ± 0.00041	2.15786 ± 0.02541	0.16643 ± 0.00058	2525 ± 24	2522 ± 6
TKB-19-C-15	0.22	947	120	0.13	2.35753 ± 0.02803	0.16683 ± 0.00049	2.36279 ± 0.02811	0.16485 ± 0.00063	2275 ± 23	2506 ± 6
TKB-19-C-16	0.14	1002	133	0.14	2.14675 ± 0.02553	0.16728 ± 0.00049	2.14976 ± 0.02557	0.16603 ± 0.00051	2462 ± 24	2518 ± 5
TKB-19-C-17	0.2	1037	130	0.13	2.29609 ± 0.02720	0.16455 ± 0.00078	2.30062 ± 0.02726	0.16280 ± 0.00080	2327 ± 23	2485 ± 8
TKB-19-C-18	0.03	881	113	0.13	2.14115 ± 0.02559	0.16752 ± 0.00055	2.14176 ± 0.02560	0.16727 ± 0.00056	2470 ± 25	2530 ± 6
TKB-19-C-19	0.21	1085	125	0.12	2.25372 ± 0.02671	0.16717 ± 0.00048	2.25856 ± 0.02677	0.16526 ± 0.00051	2363 ± 23	2510 ± 5
TKB-19-C-20	0.36	972	129	0.14	2.17729 ± 0.02609	0.17084 ± 0.00055	2.18510 ± 0.02628	0.16766 ± 0.00106	2429 ± 24	2534 ± 11
TKB-19-R-21	0.04	263	186	0.73	2.23876 ± 0.02950	0.16445 ± 0.00194	2.23955 ± 0.02952	0.16413 ± 0.00195	2380 ± 26	2499 ± 20
TKB-19-C-22	0.19	337	414	1.27	1.213657 ± 0.24645	0.05663 ± 0.00116	12.15923 ± 0.24712	0.05512 ± 0.00134	509 ± 10	417 ± 54
TKB-19-C-23	0.08	1418	211	0.15	2.16632 ± 0.02547	0.16652 ± 0.00065	2.16807 ± 0.02549	0.16580 ± 0.00070	2445 ± 24	2516 ± 7
TKB-19-C-24	0.29	93	44	0.49	9.88644 ± 0.24351	0.07117 ± 0.00230	9.91540 ± 0.24480	0.06874 ± 0.00270	619 ± 15	891 ± 81

Spot Name	f206 (%)	U (ppm)	Th	Th/U	$(^{238}\text{U}/^{206}\text{Pb})_{\text{Total}}$ ($\pm 1\text{ s abs}$)	$(^{207}\text{Pb}/^{206}\text{Pb})_{\text{Total}}$	$(^{238}\text{U}/^{206}\text{Pb})_{204}$	$(^{207}\text{Pb}/^{206}\text{Pb})_{204}$	$^{206}\text{Pb}/^{238}\text{U}$ Age ($\pm 1\text{ s Ma}$)	$^{207}\text{Pb}/^{206}\text{Pb}$ Age
TKB-20-H-1	0.06	2871	454	0.16	2.06961 \pm 0.02406	0.16870 \pm 0.00027	2.07092 \pm 0.02408	0.16814 \pm 0.00028	2540 \pm 24	2539 \pm 3
TKB-20-H-2	0.35	1081	253	0.24	2.05476 \pm 0.02441	0.17336 \pm 0.00047	2.06199 \pm 0.02450	0.17023 \pm 0.00052	2549 \pm 25	2560 \pm 5
TKB-20-H-3	0.02	883	277	0.32	2.12838 \pm 0.02547	0.16978 \pm 0.00052	2.12880 \pm 0.02548	0.16960 \pm 0.00052	2482 \pm 25	2554 \pm 5
TKB20-H-4	0.54	349	142	0.42	2.13889 \pm 0.05884	0.16762 \pm 0.00128	2.15057 \pm 0.05918	0.16277 \pm 0.00137	2462 \pm 56	2485 \pm 14
TKB-20-L-1	–	272	121	0.46	4.11342 \pm 0.15362	0.10852 \pm 0.00753	4.11203 \pm 0.15357	0.10882 \pm 0.00753	1403 \pm 47	1780 \pm 126
TKB20-L-3	0.03	402	83	0.21	12.13987 \pm 0.33425	0.05776 \pm 0.00101	12.14351 \pm 0.33437	0.05752 \pm 0.00104	510 \pm 14	511 \pm 40
TKB20-L-4	0.53	373	405	1.12	8.40221 \pm 0.25520	0.06291 \pm 0.00182	8.44737 \pm 0.25725	0.05855 \pm 0.00256	721 \pm 21	551 \pm 95
TKB20-L-5	9.64	625	1271	2.1	10.19910 \pm 0.28823	0.17152 \pm 0.00899	11.28768 \pm 0.35745	0.08909 \pm 0.01575	547 \pm 17	1406 \pm 339
TKB20-L-6	0.15	250	78	0.32	10.89347 \pm 0.30142	0.06325 \pm 0.00121	10.91009 \pm 0.30200	0.06200 \pm 0.00136	565 \pm 15	674 \pm 47
TKB20-L-7	0.02	65	62	0.97	1.83263 \pm 0.05436	0.20761 \pm 0.00185	1.83299 \pm 0.05438	0.20744 \pm 0.00185	2807 \pm 68	2886 \pm 15
TKB20-L-8	0.56	802	140	0.18	10.66350 \pm 0.56369	0.07548 \pm 0.00787	10.72358 \pm 0.56704	0.07081 \pm 0.00799	575 \pm 29	952 \pm 231
TKB20-L-9	0.14	200	107	0.55	2.46262 \pm 0.16359	0.16623 \pm 0.00167	2.46603 \pm 0.16382	0.16500 \pm 0.00172	2194 \pm 124	2508 \pm 18
TKB20-L-10	0.46	179	378	2.18	11.15073 \pm 0.31227	0.06454 \pm 0.00311	11.20199 \pm 0.31423	0.06079 \pm 0.00339	551 \pm 15	632 \pm 120
TKB20-L-11	0.12	56	216	3.99	2.13657 \pm 0.06485	0.16704 \pm 0.00197	2.13913 \pm 0.06495	0.16598 \pm 0.00204	2473 \pm 62	2517 \pm 21
TKB21-1	0.01	344	136	0.41	3.00838 \pm 0.08274	0.11305 \pm 0.00074	3.00860 \pm 0.08275	0.11299 \pm 0.00074	1850 \pm 44	1848 \pm 12
TKB21-2	0.02	273	94	0.36	2.08804 \pm 0.05768	0.16939 \pm 0.00084	2.08848 \pm 0.05770	0.16920 \pm 0.00084	2522 \pm 58	2550 \pm 8
TKB21-3	0.04	146	95	0.67	2.13344 \pm 0.06067	0.16540 \pm 0.00133	2.13432 \pm 0.06070	0.16504 \pm 0.00134	2477 \pm 58	2508 \pm 14
TKB21-4	0.04	453	156	0.36	3.31510 \pm 0.09072	0.11502 \pm 0.00066	3.31645 \pm 0.09076	0.11466 \pm 0.00067	1699 \pm 41	1875 \pm 11
Spot Name	f206 (%)	U (ppm)	Th	Th	$(^{238}\text{U}/^{206}\text{Pb})_{\text{Total}}$ ($\pm 1\text{ s abs}$)	$(^{207}\text{Pb}/^{206}\text{Pb})_{\text{Total}}$	$(^{238}\text{U}/^{206}\text{Pb})_{204}$	$(^{207}\text{Pb}/^{206}\text{Pb})_{204}$	$^{206}\text{Pb}/^{238}\text{U}$ Age ($\pm 1\text{ s Ma}$)	
TKB22-H-1	0	69	10	0.15	2.15866 \pm 0.01729	0.16805 \pm 0.00086	2.15866 \pm 0.01729	0.16805 \pm 0.00086	2454 \pm 16	2538 \pm 9
TKB22-H-1b	0.02	1161	141	0.13	2.09843 \pm 0.01231	0.16503 \pm 0.00038	2.09892 \pm 0.01231	0.16482 \pm 0.00038	2512 \pm 12	2506 \pm 4
TKB22-H-4	0.01	1039	151	0.15	2.10930 \pm 0.01235	0.16645 \pm 0.00039	2.10950 \pm 0.01236	0.16637 \pm 0.00039	2501 \pm 12	2521 \pm 4
TKB22-H-7	0.23	926	86	0.1	2.22363 \pm 0.01807	0.16617 \pm 0.00043	2.22884 \pm 0.01812	0.16408 \pm 0.00046	2389 \pm 16	2498 \pm 5
TKB22-H-8	0.07	779	52	0.07	2.14824 \pm 0.01591	0.16720 \pm 0.00046	2.14985 \pm 0.01592	0.16653 \pm 0.00049	2462 \pm 15	2523 \pm 5
TKB22-H-9	0	1401	186	0.14	2.14216 \pm 0.01453	0.16475 \pm 0.00035	2.14218 \pm 0.01453	0.16474 \pm 0.00035	2470 \pm 14	2505 \pm 4
TKB22-H-12	0.05	2848	175	0.06	2.16803 \pm 0.01996	0.16740 \pm 0.00049	2.16921 \pm 0.01997	0.16692 \pm 0.00049	2444 \pm 19	2527 \pm 5
TKB22-H-13	0.14	721	124	0.18	2.33206 \pm 0.01474	0.16875 \pm 0.00057	2.33533 \pm 0.01477	0.16750 \pm 0.00060	2298 \pm 12	2533 \pm 6
TKB22-H-14	0.2	1097	249	0.23	2.20782 \pm 0.01813	0.16997 \pm 0.00044	2.21217 \pm 0.01817	0.16822 \pm 0.00047	2404 \pm 16	2540 \pm 5
TKB22-H-15	0.15	1748	220	0.13	1.99152 \pm 0.01095	0.16825 \pm 0.00027	1.99444 \pm 0.01097	0.16695 \pm 0.00028	2620 \pm 12	2527 \pm 3
TKB22-H-16	0.04	643	30	0.05	1.56351 \pm 0.00995	0.26081 \pm 0.00101	1.56416 \pm 0.00996	0.26044 \pm 0.00102	3186 \pm 16	3249 \pm 6
TKB22-L-1	0.82	174	51	0.3	2.18203 \pm 0.01932	0.18754 \pm 0.00111	2.19999 \pm 0.01957	0.18026 \pm 0.00136	2415 \pm 18	2655 \pm 13
TKB22-L-2	0.02	184	31	0.18	2.09844 \pm 0.01849	0.17070 \pm 0.00099	2.09891 \pm 0.01850	0.17050 \pm 0.00100	2512 \pm 18	2563 \pm 10
TKB22-L-4	0.18	214	67	0.32	2.05956 \pm 0.01686	0.17296 \pm 0.00089	2.06322 \pm 0.01691	0.17137 \pm 0.00095	2548 \pm 17	2571 \pm 9
TKB22-L-5	0.08	482	168	0.36	2.22414 \pm 0.01475	0.16429 \pm 0.00064	2.22602 \pm 0.01477	0.16353 \pm 0.00066	2392 \pm 13	2493 \pm 7
TKB22-L-6	0.04	346	82	0.24	2.03877 \pm 0.01457	0.17425 \pm 0.00067	2.03965 \pm 0.01458	0.17387 \pm 0.00068	2572 \pm 15	2595 \pm 7
TKB22-L-7	0.17	234	60	0.26	2.11672 \pm 0.01671	0.17176 \pm 0.00084	2.12026 \pm 0.01675	0.17027 \pm 0.00088	2491 \pm 16	2560 \pm 9
TKB22-L-8	0.12	172	84	0.51	1.99136 \pm 0.01754	0.18408 \pm 0.00101	1.99370 \pm 0.01757	0.18304 \pm 0.00104	2621 \pm 19	2681 \pm 9
TKB22-L-9	0.06	899	131	0.15	1.95426 \pm 0.01360	0.17698 \pm 0.00085	1.95539 \pm 0.01361	0.17647 \pm 0.00087	2663 \pm 15	2620 \pm 8
TKB22-L-11	0.06	240	69	0.3	2.14506 \pm 0.01759	0.17143 \pm 0.00097	2.14643 \pm 0.01761	0.17086 \pm 0.00099	2466 \pm 17	2566 \pm 10
TKB22-L-10	0.06	573	46	0.08	2.03468 \pm 0.01338	0.17832 \pm 0.00062	2.03590 \pm 0.01339	0.17779 \pm 0.00063	2576 \pm 14	2632 \pm 6
TKB22-L-12	0	174	58	0.34	2.08694 \pm 0.01873	0.16486 \pm 0.00100	2.08694 \pm 0.01873	0.16486 \pm 0.00100	2524 \pm 19	2506 \pm 10
TKB22-L-13	0.03	269	224	0.86	2.11723 \pm 0.01645	0.16279 \pm 0.00081	2.11779 \pm 0.01645	0.16256 \pm 0.00082	2493 \pm 16	2482 \pm 8
TKB22-L-14	0.09	466	71	0.16	2.10790 \pm 0.01420	0.16700 \pm 0.00063	2.10976 \pm 0.01422	0.16621 \pm 0.00064	2501 \pm 14	2520 \pm 7

Analyses were conducted during three sessions, each with BR266 as standard zircon, with a minimum of 14 standard analyses per session. $^{206}\text{Pb}/^{238}\text{U}$ = proportion of non-radiogenic ^{206}Pb in total ^{206}Pb ; $^{207}\text{Pb}/^{206}\text{Pb}$ denotes uncorrected ratios; ^{204}Pb denotes 204-corrected ratios.

normal faults were vertical to gentle with down dip slickenlines (Fig. 5e, f) and had listric geometry in several places. The hanging wall of the sub-horizontal normal fault developed overturned drag folds (Fig. 5g) and subhorizontal extensional brittle fractures (Fig. 5h). Vertical gneissic layers were deflected by such horizontal fractures developing sinuous/folded structures with open recumbent geometry. The fractures were disjunctive cleavage in such folds, that didn't appear buckle folds (wavelength to thickness relation not followed, Ramsay, 1967). Granite-pegmatite veins intruded along brittle fractures along several orientations from horizontal to inclined and vertical (Fig. 51h).

4.3. D₃- Salem-Attur shear zone

4.3.1. Map pattern and mesoscopic structure

The D₃- Salem-Attur shear zone consisted of three sub-parallel thrusts (Fig. 2, D₃-T₁, D₃-T₂, and D₃-T₃) which were nearly E-W striking and inclined to the south. The Salem and Namakkal blocks lie in the footwall and hanging wall of the thrust system respectively. The NE-SW striking D₁₋₂ fabrics in foot- and hanging walls were aligned parallel to the shear zone close to the thrust (Figs. 1 and 2). The D₃-T₁ developed south of Godumalai and Kanjamalai hills, with a curvilinear trend around an amphibolite outcrop at Moyerpalayam and joined the main shear zone north of Suryamalai hill. The D₃-T₂ developed to the north of Kanjamalai and Godumalai hills, and the D₃-T₃, around Kusumalai hill with a curved geometry in map view. The interpretative cross section AB (Fig. 2h) depicted a trailing imbricate structure with D₃-T₁ considered as main thrust, and the D₃-T₂ and D₃-T₃ are interpreted as trailing thrusts that joined D₃-T₁ at depth. (e.g., Ramsay and Huber, 1987). The shear zones were characterized by biotite-muscovite-quartz-feldspar mylonite developed at Kandashram and Sarkar Nattar Mangalam on a granite gneiss, charnockite and quartzofeldspathic gneiss parent rock. Amphibolite mylonite was developed at Moyerpalayam, Kanjamalai, Kusumalai and Godumalai on mafic granulite. The amphibolite outcrop at Moyerpalayam represented a klippe (Fig. 2). The geological map at Moyerpalayam showed a NW-SE striking mylonitic foliation (D₃) and NNW plunging (D₃) stretching lineation defined by hornblende, biotite and epidote (Fig. 2a, stereonet, Fig. 3f for petrography). The variation in orientation was due to doming up of the Sankaridurg granite pluton. The detailed map of D₃-T₁, near Sarkar Nattar Mangalam (Fig. 2 for location; Fig. 6 for detail map) indicated mylonite and ultramylonite were developed on quartzofeldspathic gneiss. We suggest that, ultramylonite was developed from pseudotachylite veins injected into quartzofeldspathic gneiss.

Mesoscopic structures in the Salem-Attur shear zone included S₃ mylonitic foliations that varied in dip from gentle to steep towards the SSE (Fig. 7a, b). At places dip direction changed to NNE-N-NNW (Fig. 6a) due to progressive shearing. Perfectly down dip (D₃) stretching lineations/ductile slickenlines (e.g., Lin et al., 2007) were developed on gently dipping (D₃) mylonitic foliation (Fig. 7a). Steeply plunging (D₃) stretching lineations (70–80 pitch) were present on the D₃ subvertical mylonitic foliation (Figs. 7c and 6a). The down dip stretching lineation on mylonitic foliation, the S-C fabric (Fig. 7b) and sigmoidal porphyroclasts (Fig. 7d) unequivocally indicated N to NNE vergence thrust kinematics.

There were several structural features that gave a false impression of strike-slip kinematics: (i) The F₁-F₂ folds were reoriented to near vertical attitude due to D₃-thrusting. As a result, asymmetric F₁ parasitic folds were exposed on the horizontal surface producing an impression of sinistral or dextral shearing (e.g., Ramsay and Lisle, 2000; Fig. 7e), however, these folds were pre-kinematic to D₃- shearing. ii) Open folds were developed on S₃ mylonitic foliation as well as on S₁ gneissosity due to progressive shear and shortening across the shear zone. Southerly inclined axial parallel fractures are associated with these folds (Fig. 7f). The folds associated with horizontal fold axes and intersection lineation that gave a false impression of strike-slip. This phenomenon was explained in the structural model, Fig. 6b which indicated north

vergence thrust and close to that the S₁ fabric was compressed to develop E-W trending folds; the fold axes were at right angle to stretching lineations. Therefore, down-dip stretching lineation and horizontal fold axis/intersection lineation coexisted on the same outcrop. We get both lineations in the mylonites of Kandashram and Sarkar Nattar Mangalam area (Fig. 6a). iii) In the structural model, Fig. 6c, the E-W trending thrust produced an apparent dextral strike-slip offset of westerly dipping foliation on horizontal surface near Kandashram. Further, the satellite imagery indicated a dextral deflection of the S₁-S₂ fabrics along the Salem-Attur shear zone.

4.3.2. Microscopic structure

Both quartzofeldspathic (Fig. 8a–c) and amphibolitic mylonites (Fig. 3f and S1e) were marked by anastomosing C-fabrics (D₃) around the feldspar porphyroclasts that contained intragranular faults and lacked dynamic recrystallization. The C-fabric was marked by biotite, hornblende and muscovite produced from the retrogression of granulite grade minerals. Ultramylonite (Fig. 8d–g) had fewer feldspar and quartz porphyroclasts and was marked by parallel mylonitic bandings with biotite and quartz. Quartz grains in the mylonite were marked by subgrain rotation crystallization and formed an S-C fabric (S₃) with biotite (Fig. 8c). Quartz porphyroclasts in ultramylonite were rounded and contained embayed margins (Fig. 8e and g), and the feldspar porphyroclasts developed sigmoidal tails (Fig. 8e). Further, rectangular quartz grains produced monomineralic quartz ribbons (Fig. 8h). Features like retrogression of minerals, subgrain rotation in quartz grains, development of monomineralic quartz ribbons, brittle behavior of feldspar and lack of leucosome indicated greenschist to lower amphibolite facies conditions (~4kb/500 °C) during D₃ shearing (e.g., Stipp et al., 2002). Abundant shear sense indicators namely S-C fabric (Fig. 8c), sigmoidal feldspar porphyroclasts (Fig. 8b, f and g) and intragranular faults (Fig. 8b) confirmed top- to-NNE thrust kinematics.

4.3.3. Vorticity analysis

The RGN-*Wm* estimates lay between 0.56 and 0.62 for the ultramylonite and between 0.68 and 0.81 for the mylonite (Fig. 9). The percentage of pure shear varied from 57 to 61% for the ultramylonite and from 40 to 52% for the mylonite (Table 1). The *Rs/θ - Wm* estimates were between 0.51 and 0.52 for the ultramylonite and 0.73 and 0.84 for the mylonite (Fig. 10a). The *Wm* vs *θ* plot (Fig. 10b) for both set indicated pure shear dominated transpression and the average *Wm* value was 0.7. Flattening strain in the Flinn's plot supported the pure shear component (Fig. 10c). The ultramylonite experienced more flattening than mylonite (low *Wm*). This could be because of the softer behavior of pseudotachylite from which the ultramylonite was presumably derived. Further, *Rs* vs. *θ* method overestimated *Wm* in ultramylonite compared to RGN-*Wm*. This was due to the fact that the *Rs/θ* method measured the last instantaneous strain while RGN-*Wm* measured the average strain (Wallis, 1995). Hence, the ultramylonite zone experienced more simple shear strain towards the end of deformation. The result indicated that the shear zone had undergone a temporal and spatial strain variation.

4.4. Geochronology

4.4.1. Zircon U-Pb SHRIMP

4.4.1.1. Sample TKB-18. The sample was collected from a charnockite of the Namakkal block (Fig. 2). Zircons ranged in size from 50 to 200 μm (Fig. 11a) and had aspect ratios between 1:1 and 3:1. The zircons were subrounded to round in shape, but many preserve crystal faces indicative of a magmatic character. CL imaging showed that the majority of zircon comprised a zoned inner rim domain with the oscillatory or sector-zoning pattern, overgrown by often extensive bright CL rim domains. Twenty-five analyses were conducted on thirteen grains, including twelve core-rim pairs and one rim. Based on significant common Pb contamination, three analyses were not

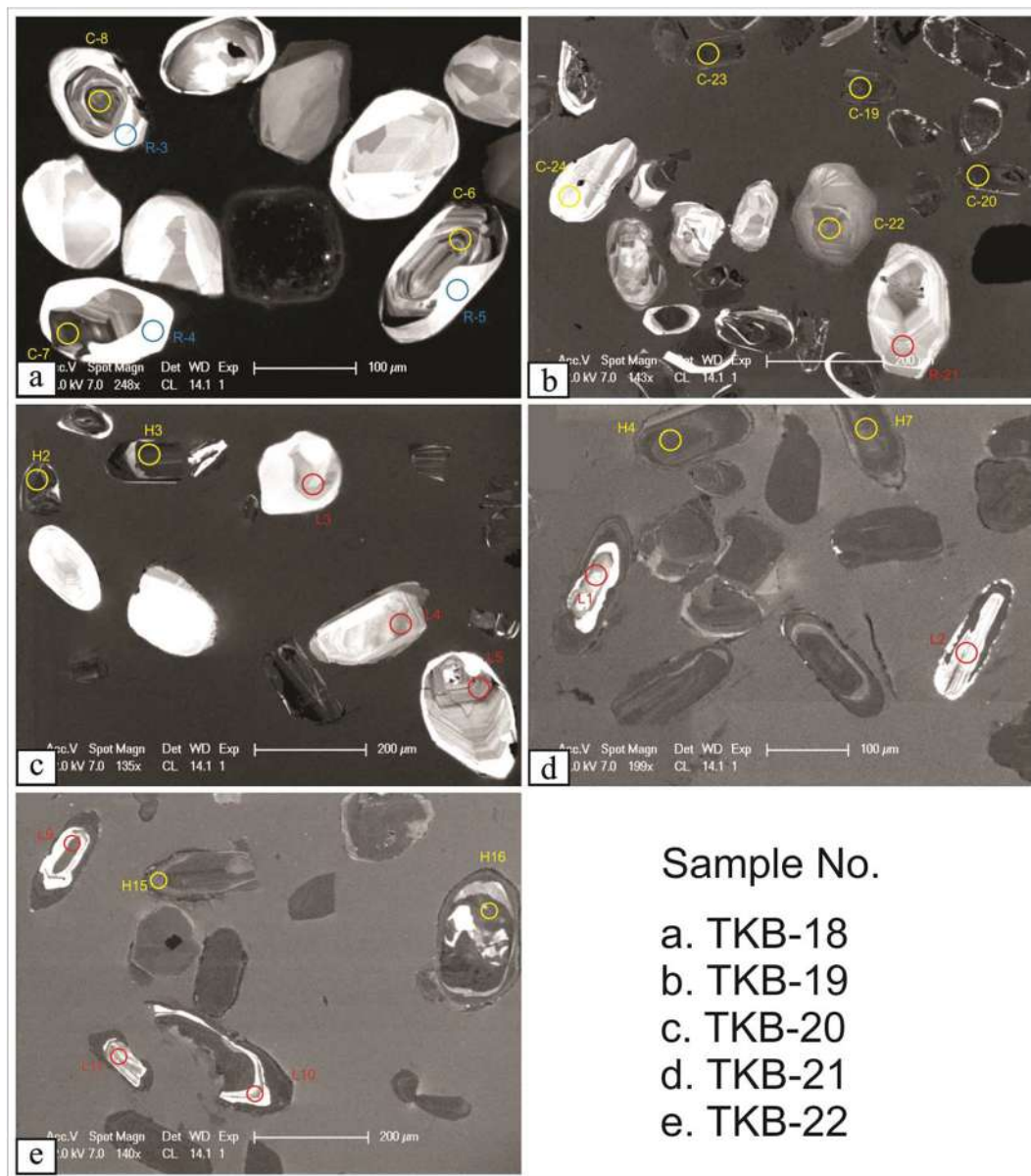


Fig. 11. (a–e) CL images of zircon, sample number TKB-18, 19, 20, 21 and 22.

discussed (see dashed ellipses in Fig. 12a, Table 2). U and Th content on core data were in the ranges 90–488 and 67–413 ppm respectively, with Th/U ratios between 0.5 and 3.8, consistent with magmatic zircon. The rim data were characterized by low U and Th contents, in the ranges 18–80 and 8–182 ppm respectively, with Th/U ratios between 0.2 and 3.8. These values were characteristic of zircon growing from small volumes of partial melt or metasomatic fluids, but not consistent with growth during metamorphism. The data on core appeared to define two separate populations, an older group of six analyses that defined a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2604 ± 28 Ma and a younger group of four analyses giving a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2530 ± 39 Ma. The eleven rim data defined a cluster of analyses that appeared to be aligned along a regression line with the lower intercept at 712^{+780}_{-540} Ma and upper intercept at 2533^{+73}_{-27} Ma. The poor precision of the lower intercept was due to the fact all data were concentrated along the upper part of the regression and using only the six-concordant data points a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2518 ± 21 Ma could be calculated. We interpreted the oldest age group on the core to represent xenocrystic components in the charnockite derived from a uniform source with an age of

2604 ± 28 Ma. The younger core population was interpreted as the emplacement age of the charnockite/granite at 2530 ± 39 Ma. The low U rims were constraining crystallization of the latest-stage fluids during cooling of the granite at 2518 ± 21 Ma.

4.4.1.2. Sample TKB-19. The sample was collected from charnockite/granite in the Namakkal block. Zircons range in size from smaller than $50 \mu\text{m}$ to over $200 \mu\text{m}$ and have aspect ratios from 1:1 to 4:1. The grains were either subrounded to rounded or elongate with clearly defined crystal faces. CL imaging indicated two types of zircon in the sample (Fig. 11b, Table 2). The largest population were elongated and had very low luminescence. Some of these grains had narrow bright CL rim overgrowths, one of which was analyzed (TKB-19-R-8). A smaller second population comprised larger, often equant grains that displayed very high CL response. Some of these larger grains also had core and rim domains, and one rim was large enough for analysis (TKB-19-R-21, Fig. 11b). Twenty-four analyses were conducted on 24 zircons, including 22 single analyses on zircon and one core-rim pair (TKB-19-C-7, TKB-19-R-8, Table 2). Common Pb was relatively high in four points which were not further discussed (see dashed ellipses in Fig. 12b,

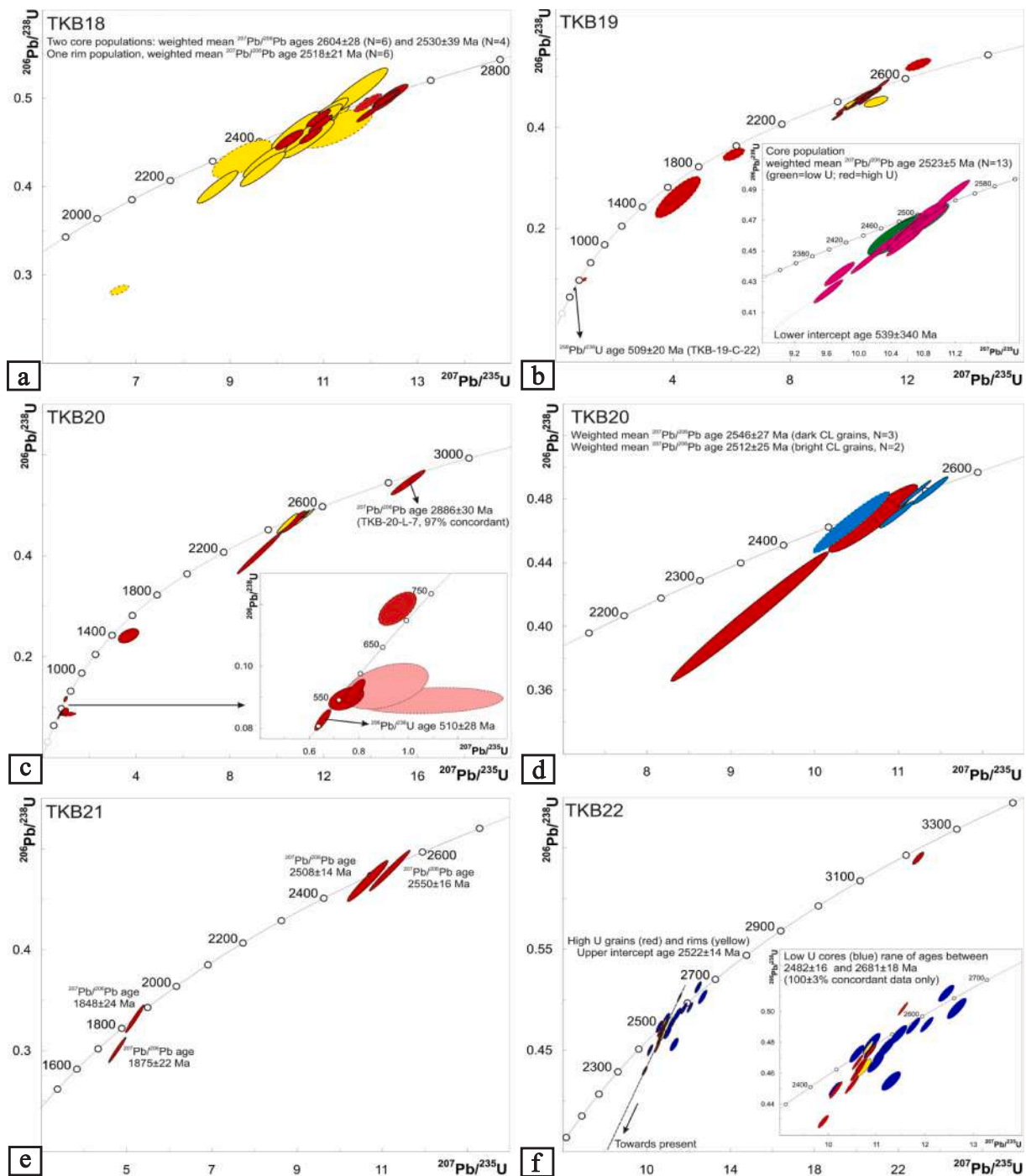


Fig. 12. Zircon U-Pb data for samples TKB-18, 19, 20, 21 and 22 sample locations are in Figs. 1 and 2. Errors are at 1 σ confidence level.

Table 2). One data point (TKB-19-C-22, Figs. 11 and 12) plots on concordia and defines a $^{206}\text{Pb}/^{238}\text{U}$ age of 509 ± 20 Ma. This point records a U and Th values of 337 and 414 ppm respectively and has a Th/U ratio of 1.3, consistent with magmatic zircon (Fig. 12). The remaining data, including both high CL (low U) and low CL (high U) grains, clearly plot along a discordia line for which a lower intercept of 539 ± 340 Ma and upper intercept of 2531 ± 11 Ma could be calculated. Considering only the more precise high U analyses, corresponding to the population of dark CL grains, the upper intercept was 2534 ± 17 Ma. A weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2523 ± 5 Ma could be calculated from the 13 concordant data points that was interpreted to be the best estimate for the emplacement age of the charnockite/granite. The lower intercept, although very imprecise,

suggested that the rock was affected by a Pb-loss event at around 540 Ma, further supported the youngest concordant grain, dated at 509 ± 20 Ma.

4.4.1.3. *Sample TKB-20.* The sample was collected from charnockite/granite to the east of Salem. Zircons ranged in size from $< 50 \mu\text{m}$ to over $250 \mu\text{m}$ and had aspect ratios between 1:1 and 4:1. The zircon was subrounded, but many preserved crystal faces. CL imagery indicated two populations (Figs. 11 and 12; Table 2); one of smaller grains with a very low response, one of larger grains with very luminescent character. Many analyses on dark-CL grains were discarded due to significant counts on ^{204}Pb . Two analyses, which also recorded relatively high amounts of common Pb, were completed, but need to be excluded as

they had large errors and were significantly discordant (TKB-20-L-5, Fig. 12c and d; TKB-20-L-8). The bright-CL grains defined a wide range of apparent ages between 510 and 2807 Ma, while the dark-CL grains defined a more narrow range of $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 2560 and 2485 Ma. The oldest analysis was on a bright CL round zircon which recorded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2886 ± 30 Ma (TKB-20-L-7). Three dark-CL grains gave a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2546 ± 27 Ma, while two less precise bright-CL grains gave the weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2512 ± 26 Ma. One dark CL zircon gave yet a slightly younger $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2485 ± 28 Ma. Together these analyses were taken to indicate crystallization of primary zircon from various melt batches that generated the charnockite/granite. We, therefore, considered the granite to have been emplaced sometime between 2550 and 2480 Ma. A number of analyses on bright-CL zircon yielded $^{206}\text{Pb}/^{238}\text{U}$ ages of between 575 and 510 Ma (excluding one strongly inversely discordant point, TKB-20-L-4, Fig. 12c). The most concordant and youngest data point provided a $^{206}\text{Pb}/^{238}\text{U}$ age of 510 ± 28 Ma and was taken to provide an estimate for crystallization of these zircons (Figs. 11 and 12; Table 2). This corresponded to the intrusion of granite veins during brittle fracturing.

4.4.1.4. Sample TKB-21. The sample belongs to pink granite mixed with pseudotachylite, it was collected from the Gangavalli shear zone (Fig. 3h). The granite was a small circular plutonic body with dimension of 20 m across, having been traversed by several fractures and pseudotachylite veins. Therefore, the granite intrusion was pre-tectonic to strike-slip fracturing (D_4). As it contained xenoliths of D_3 -mylonites, it was post-tectonic to ductile shearing (D_3). It is therefore aimed that the age of the granite would constrain the upper age limit of ductile shearing and the lower age limit of brittle fracturing. Only very few zircons were recovered from the sample. The zircons were broken but had euhedral shapes with well-developed crystal faces. In CL, the zircon produced medium to high response, with prominent oscillatory zoning pattern indicating a magmatic character (Figs. 11-H-4, H-7, L-1, L2 and 12; Table 2). Four analyses were conducted on four zircons. The data defined two age groups: the oldest analyses gave $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 2550 ± 16 and 2508 ± 14 Ma, while two younger analyses gave $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1848 ± 24 and 1875 ± 22 Ma (Figs. 11d and 12e; Table 2). We interpreted that these zircon grains were all magmatic, so they were most likely magmatic components, unrelated to the pseudotachylite formation. This suggested protolith would have been perhaps between 1848 ± 24 and 1875 ± 22 Ma, with xenocrysts of 2550 ± 16 and 2508 ± 14 Ma.

4.4.1.5. Sample TKB-22. The sample was collected from syenite intruded along D_2 shear zone west of Attur. Zircons were between 50 and 300 μm in size and had aspect ratios between 2:1 and 5:1. The grains were sub- to euhedral and had well-preserved crystal faces and bipyramidal terminations, all indicative of a magmatic character. CL imagery revealed a dark population of zircon in which there was sometimes a small lighter CL core domain. A minority of zircon were bright CL, similar in character to the preserved cores (Figs. 11e and 12; Table 2). Twenty-four analyses were conducted, eleven on bright CL core domains, nine on dark CL grains, two on dark CL rim domains overgrowing small bright CL cores, one on a non-complex bright CL zircon (TKB-22-L-13) and one on an anomalous dark-CL core of a large zircon (TKB-22-H-16). The data on dark CL-zircon had a higher U content and lower Th/U ratios than data from bright CL zircon. Ten analyses of the dark-CL zircon, including the two analyses on rim domains, defined a linear array with lower intercept indicating recent Pb-loss, and the upper intercept age was 2522 ± 14 Ma. The bright-CL core data defined a scattered population with the concordant data providing apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 2482 ± 16 and 2681 ± 18 Ma. The anomalous dark-CL core analyzed gave a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3249 ± 12 Ma (Fig. 12f). We interpreted the dark and bright CL cores to indicate various inherited

zircon component, while the dark CL zircon and rims gave an emplacement age of 2522 ± 14 Ma for the syenite.

Zircon geochronological data suggested that intrusion of charnockite/granite gneiss in the Salem-Namakkal blocks was constrained over a broad age range between ca. 3250 and ca. 2500 Ma. There were several phases of charnockitic magma intrusion comparable to many granulite terranes (e.g., Oyhantcabal et al., 2012; Oriolo et al., 2016). This was consistent with the result obtained by Clark et al. (2009), about the age of the charnockite from the Salem block. Hence, charnockitic intrusion in both Salem and Namakkal blocks was of same age. The D_3 thrusting along the Salem-Attur shear zone was a younger than ca. 2500 Ma event. The lower age of the thrusting was constrained by the intrusion of the pink granite at ca. 1900 Ma.

4.4.2. Monazite geochronology

4.4.2.1. Sample S-478. Monazite grains were present within the quartz-biotite-rich mylonite that was characterized by distinct D_3 mylonitic foliation with sigmoidal feldspar porphyroclasts (Fig. 13a–e). The monazite grains were round to subrounded with a distinct mantle structure. Mantle consisted of newly crystallized monazites marked by DPC produced during shearing. The mantle was converted to asymmetric wings producing sigma-type monazite porphyroclasts, aligned parallel to the D_3 -mylonitic foliation (Fig. 13a and c). The structure was exactly similar to the winged feldspar porphyroclasts produced during D_3 shearing (Fig. 8a, b). Hence, the core part represented the D_{1-2} monazite and the mantle grains represented the D_3 monazite. Elemental analysis of core and mantle indicated that the core was rich in Y, HREE and depleted in Th while the opposite was the case for the mantle (Table 3). This was also indicated by the X-ray images of some of the grains (Fig. 13d, e). Other elements like Pb and U had low concentration and Ce a higher concentration in the mantle compared to the core. Depletion in Y probably happened due to the mobilization of Y into biotite and garnet that developed during shearing. Further, the monazites were fractured subsequent to ductile deformation (Fig. 13b). Sixty-seven analyses were completed, and the isopleth was constructed (Fig. 13f) which had three clusters of ages as ca. 2435 Ma, ca. 2010 Ma, and ca. 860 Ma (Fig. 13f). The oldest ages were derived from cores and indicated the age of granulite facies metamorphism ($\text{syn-}D_{1-2}$); the second ca. 2.0 Ga age was derived from the mantles and indicated the age of ductile shearing (D_3) while the youngest ages ca. 0.8 Ga probably indicate hydrothermal alteration during brittle shearing (D_4).

4.4.2.2. Sample S-470. The sample was collected from the granite gneiss intruded within mafic granulite in the Kanjamalai Hill of the Salem block. The granite gneiss was marked by D_1 gneissic fabric. The monazites were present as inclusions inside quartz and underwent DC. These were smaller in size, equant to irregular in shape and had compositional domains (Fig. 14a–c). No DPC fabrics were recorded as the sample lie away from the Salem-Attur shear zone. The compositional domains do vary in chemistry with the younger domains recording lower Y, Th, HREE, Pb, U and high in LREE (Table 3). The Y and HREE were mobilized to garnet developed during high grade metamorphism. The histogram had three clusters of ages at ca. 2580 Ma, 2460 Ma and 2250 Ma (Fig. 14d). First one corresponded to the age of granitic intrusion and later two to the timing of granulite metamorphism syntectonic with D_{1-2} deformation.

4.4.3. ^{40}Ar - ^{39}Ar analysis

4.4.3.1. Sample T-1. Large D_3 hornblende crystals, from amphibolites, near Tiruchengode (Fig. 2) were used for ^{40}Ar - ^{39}Ar dating. The data defined a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 2049.4 ± 4.7 Ma (MSWD = 0.27, probability = 0.95) (Fig. 15a and Table 4). We interpret this age to reflect the age of hornblende growth and D_3 - ductile shearing.

4.4.3.2. Sample B-4. A fresh and unaltered sample of pseudotachylite

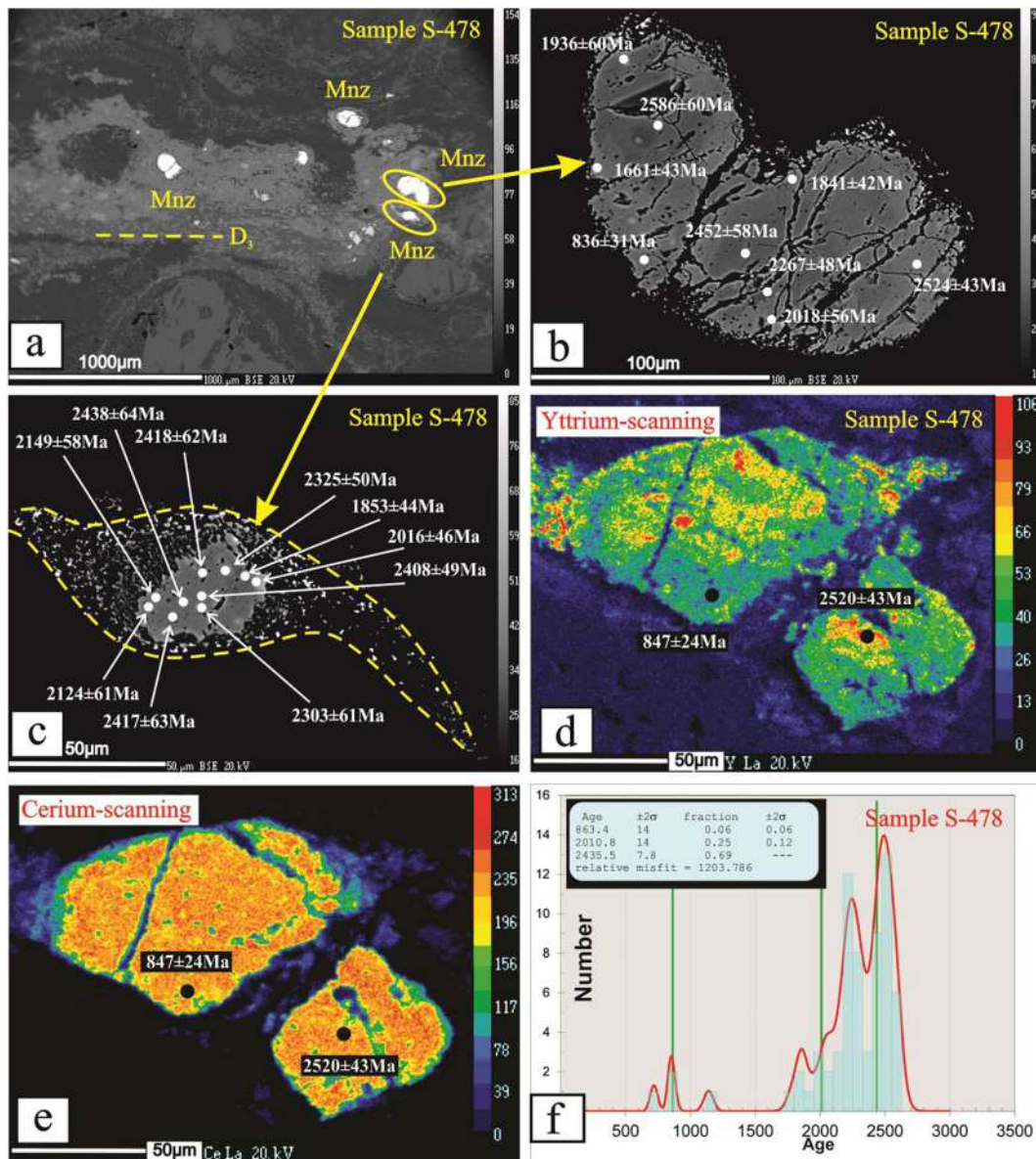


Fig. 13. (a) EPMA back scatter electron (BSE) Image taken in EPMA, Sample S-478, D₃- mylonite containing monazite (Mnz) grains within the quartz-biotite matrix; (b) One of the monazite grains has micro monazite grains precipitated around the larger grain. The original grain is broken by fractures, older ages are seen in the core of the grain, while younger ages in the periphery; (c) Monazite porphyroblast with asymmetric wings. The peripheral grains have ca. 2.0 Ga and the core has ca. 2.4 Ga; (d-e) X-ray images of D₃- monazites with Y and Ce variation from core to the periphery; (f) The histogram has ca. 2.4, 2.0 and 0.8 Ga ages corresponding to metamorphism (D₁-D₂), ductile shearing (D₃) and brittle shearing (D₄ normal faulting).

from the Gangavalli strike-slip fault was chosen for ^{40}Ar - ^{39}Ar dating through step heating (Fig. 1 for sample location). A plateau age of 1852 ± 9 Ma can be calculated (MSWD = 0.02, probability = 1) (Fig. 15b and Table 4). This age marked the timing of strike-slip brittle shearing.

4.4.3.3. Sample T-2. This was a biotite sample from a granite/pegmatite vein intruded along the normal faults. The biotite produced a well-defined ^{40}Ar / ^{39}Ar plateau age of 563 ± 2 Ma (MSWD = 0.89, probability = 0.50) suggesting its cooling/crystallization age (Fig. 15c and Table 4). This age may reflect the minimum age of normal faulting and granite/pegmatite intrusion.

5. Discussion

5.1. Deformation in the Salem-Attur shear zone

The Salem-Namakal blocks had recorded multiple stages of shearing that included D₂- high temperature shearing, D₃- low temperature shearing and D₄- brittle shearing. The Salem-Attur shear zone represented a D₃ shear zone which formed at quartz ductile- feldspar brittle zone. It was a retrograde shear zone characterized by retrogression of granulite minerals to hornblende, biotite and muscovite. From outcrop to microscopic scale, the mylonites recorded a top to N-NNE thrust slip kinematics. The RGN and Rs/θ analyses suggested that the shear zone underwent a general simple shear with an average 50% pure shear component. The average Wm value derived from both methods was about 0.7. The presence of the pure shear component led to variation in finite strain and the orientation of stretching lineation. The D₃- stretching lineation was down dip in gently dipping D₃-

Table 3
Monazite compositions and U-Th-Pb (total) monazite ages obtained from mylonite (Sample S-478; N11°40'05.09", E78°19'02.11") and granitic gneissic (Sample S-470; N11°38'05.26", E78°04'28.52") using electronprobe micro analysis (EPMA).

Sample S-470																		
DataSet/Point	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	Y ₂ O ₃	La ₂ O ₃	Ce ₂ O ₃	Pr ₂ O ₃	Nd ₂ O ₃	Sm ₂ O ₃	Gd ₂ O ₃	Dy ₂ O ₃	PbO	ThO ₂	UO ₂	Total	Age (Ma)	± Age (Ma)
2/1	0	2.185	26.366	0.141	4.846	8.622	23.554	3.409	15.203	3.19	2.81	1.333	0.564	4.784	0.259	97.268	2198	54
3/1	0.029	2.157	25.943	0.065	2.006	11.093	26.469	3.441	13.774	2.637	2.08	0.742	0.664	6.029	0.16	97.292	2247	50
4/1	0	1.557	26.76	0.163	4.348	10.701	25.056	3.177	13.178	2.702	2.333	1.169	0.589	4.741	0.168	96.642	2438	58
5/1	0	1.679	27.193	0.204	3.766	11.642	25.302	3.14	12.728	2.553	2.183	1.039	0.624	4.941	0.172	97.168	2480	57
6/1	0	1.716	27.116	0.235	3.555	11.888	25.342	3.134	12.786	2.602	2.196	0.99	0.608	4.887	0.19	97.245	2416	57
7/1	0	1.333	28.044	0.134	5.417	8.424	23.335	3.379	15.41	3.253	2.937	1.435	0.452	3.426	0.235	97.214	2331	66
8/1	0	1.86	26.875	0.181	5.143	7.876	22.246	3.325	15.318	3.297	3.001	1.381	0.736	5.487	0.311	97.039	2449	52
9/1	0	1.056	28.4	0.136	5.213	9.105	24.832	3.527	15.154	3.027	2.565	1.327	0.295	2.235	0.182	97.055	2251	86
10/1	0.006	0.995	28.143	0.114	4.831	9.826	25.94	3.545	14.502	2.698	2.216	1.207	0.27	2.034	0.156	96.483	2292	94
11/1	0.037	1.543	27.323	0.187	4.044	11.131	25.271	3.169	13.158	2.658	2.235	1.088	0.571	4.469	0.149	97.033	2518	62
12/1	0.023	3.388	24.45	0.246	3.718	7.437	20.882	3.157	14.278	3.012	2.633	1.114	1.349	11.163	0.298	97.148	2446	37
13/1	0.282	1.537	27.849	0.139	5.201	9.303	24.823	3.355	14.314	2.775	2.432	1.284	0.404	3.358	0.176	97.232	2247	68
14/1	0.054	0.92	27.974	0.124	3.916	10.72	26.902	3.524	14.536	2.606	2.102	1.014	0.218	1.723	0.146	96.478	2157	103
17/1	0.028	1.909	26.963	0.179	4.29	9.888	24.199	3.235	13.216	2.7	2.415	1.152	0.72	5.702	0.177	96.773	2508	53
18/1	0	1.059	29.398	0.084	2.443	11.618	26.627	3.549	14.635	2.481	1.824	0.877	0.256	2.275	0.095	97.221	2181	93
19/1	0.014	1.526	28.912	0.185	3.45	12.32	26.396	3.192	12.991	2.72	2.26	0.909	0.484	3.735	0.104	99.199	2595	71
20/1	0.002	1.909	27.754	0.186	3.983	10.857	24.692	3.176	13.19	2.637	2.358	1.065	0.61	5.402	0.174	97.995	2259	52
21/1	0.044	1.868	27.905	0.216	4.273	9.173	23.381	3.304	14.285	3	2.649	1.134	0.702	5.656	0.129	97.72	2539	54
22/1	0.027	1.324	28.675	0.08	2.826	11.477	27.579	3.498	14.159	2.531	1.923	0.795	0.316	2.505	0.142	97.858	2319	87
25/1	0.009	1.136	28.904	0.145	5.895	9.404	24.507	3.33	14.088	2.744	2.481	1.357	0.333	2.604	0.165	97.103	2304	80
26/1	0.004	1.489	28.5	0.15	5.118	8.603	23.394	3.391	15.307	3.182	2.902	1.355	0.482	3.864	0.231	97.971	2276	62
27/1	0.009	2.627	26.608	0.222	3.383	8.882	23.252	3.234	14.252	2.854	2.352	0.91	0.961	8.381	0.082	98.008	2470	42
28/1	0.006	2.275	27.036	0.159	4.532	8.702	22.89	3.304	14.751	3.12	2.818	1.234	0.704	5.946	0.293	97.772	2238	48
29/1	0.088	1.129	28.979	0.118	5.136	9.564	25.069	3.485	14.525	2.74	2.32	1.236	0.329	2.499	0.15	97.367	2384	85
30/1	0.079	1.255	30.184	0.122	4.426	10.158	25.769	3.499	14.619	2.697	2.35	1.098	0.212	1.898	0.157	98.521	1931	92
31/1	0.006	2.517	26.874	0.196	4.848	7.62	21.364	3.188	14.665	3.247	2.908	1.294	0.99	7.702	0.347	97.765	2439	43
32/1	0	1.647	28.009	0.232	3.664	9.478	24.127	3.388	14.621	3.054	2.635	1.038	0.595	5.04	0.061	97.588	2515	57
33/1	0	1.732	28.008	0.217	5.609	10.156	23.789	3.098	12.716	2.639	2.515	1.306	0.596	4.704	0.178	97.262	2461	58
34/1	0.319	4.047	24.217	0.266	3.582	6.908	19.613	3.047	13.796	2.974	2.561	1.038	1.715	13.891	0.206	98.181	2598	35
Sample S-478																		
DataSet/Point	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	Y ₂ O ₃	La ₂ O ₃	Ce ₂ O ₃	Pr ₂ O ₃	Nd ₂ O ₃	Sm ₂ O ₃	Gd ₂ O ₃	Dy ₂ O ₃	PbO	ThO ₂	UO ₂	Total	Age (Ma)	± Age (Ma)
1/1	0	0.915	29.02	2.166	0.895	13.001	27.205	3.138	12.14	2.217	1.494	0.361	0.395	4.297	0.089	97.333	1936	60
2/1	0.014	0.972	29.34	0.653	1.227	14.169	28.204	3.027	11.831	2.127	1.469	0.419	0.648	5.151	0.107	99.358	2586	60
3/1	0	1.257	29.102	0.595	1	14.226	28.127	3.013	11.438	2.084	1.357	0.38	0.486	6.497	0.052	99.615	1661	43
4/1	0	1.102	29.262	0.545	1.23	14.371	28.358	3.039	11.65	2.061	1.32	0.391	0.644	5.258	0.157	99.389	2452	58
5/1	0.004	1.064	29.448	0.541	1.1	14.403	28.46	3.058	11.907	2.08	1.365	0.408	0.527	4.973	0.134	99.472	2166	57
6/1	0.142	2.273	28.567	0.653	0.622	13.62	26.979	3.068	11.857	2.083	1.265	0.22	0.623	6.238	0	98.209	2248	48
7/1	0.665	1.08	28.287	0.524	1.492	13.605	27.623	3.092	12.205	2.249	1.59	0.469	0.47	4.709	0.149	98.209	2018	56
8/1	0.076	1.654	28.513	0.739	0.656	13.679	27.585	3.072	11.849	2.09	1.262	0.284	0.716	6.838	0.07	99.083	2267	48
9/1	0	1.788	27.938	0.856	0.304	13.156	27.507	3.11	11.938	2.092	1.193	0.166	0.849	7.914	0	98.811	2407	44
10/1	0.006	1.779	28.229	0.798	0.182	13.184	27.416	3.063	11.853	2.091	1.202	0.164	0.966	8.556	0	99.492	2524	43
11/1	0	1.017	29.444	0.758	1.206	14.398	28.042	3.055	11.562	2.081	1.397	0.379	0.575	5.546	0.113	99.574	2168	53
12/1	0.022	1.724	28.172	0.585	0.227	13.517	28.044	3.155	12.037	2.133	1.211	0.191	0.547	8.168	0	99.732	1535	35
17/1	0.275	1.79	28.774	3.989	0.421	13.226	25.457	3.003	11.311	1.904	1.191	0.213	0.574	7.098	0	99.226	1841	42
21/1	0.002	0.939	29.149	0.519	1.084	14.304	28.581	3.119	12.058	2.164	1.439	0.346	0.542	4.482	0.126	98.853	2438	64
22/1	0.006	1.245	28.696	0.722	0.839	13.475	27.609	3.088	11.864	2.206	1.452	0.361	0.688	6.45	0.05	98.753	2325	50
27/1	0.004	1.5	28.517	0.65	0.632	13.651	27.777	3.14	12.289	2.183	1.382	0.283	0.523	6.419	0	98.95	1853	44
28/1	0.006	1.001	29.633	0.585	1.251	14.488	28.086	3.099	11.845	2.084	1.424	0.381	0.557	4.697	0.118	99.255	2418	62
29/1	0.035	0.923	30.407	0.729	1.214	14.584	28.555	3.045	11.812	2.148	1.423	0.415	0.544	4.62	0.106	100.561	2417	63
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Table 3 (continued)

Sample S-470																		
DataSet/Point	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	Y ₂ O ₃	La ₂ O ₃	Ce ₂ O ₃	Pr ₂ O ₃	Nd ₂ O ₃	Sm ₂ O ₃	Gd ₂ O ₃	Dy ₂ O ₃	PbO	ThO ₂	UO ₂	Total	Age (Ma)	± Age (Ma)
30/1	0.02	0.984	29.693	0.608	1.673	13.362	27.753	3.179	12.628	2.406	1.665	0.517	0.547	4.342	0.194	99.569	2398	63
31/1	0.038	1.827	27.83	0.886	0.5	13.353	26.607	3.092	12.047	2.105	1.181	0.199	0.833	7.499	0	97.997	2485	46
33/1	0.007	1.415	28.571	0.597	0.647	13.834	28.027	3.099	12.227	2.198	1.392	0.275	0.671	6.244	0	99.204	2408	49
34/1	0.016	0.881	29.755	0.63	1.125	14.711	28.476	3.051	11.699	2.107	1.388	0.394	0.492	4.807	0.094	99.626	2149	58
35/1	0.017	0.878	30.023	0.596	1.224	14.269	28.423	3.069	12.045	2.258	1.483	0.438	0.463	4.542	0.099	99.826	2124	61
36/1	0	0.994	29.325	0.532	1.082	14.369	28.487	3.081	12.154	2.2	1.447	0.373	0.534	4.706	0.129	99.412	2303	61
37/1	0.015	1.491	28.202	1.083	0.631	13.784	28.109	3.122	12.346	2.196	1.398	0.265	0.565	6.348	0	99.554	2016	46
38/1	0.013	1.551	27.919	0.306	0.147	15.172	28.897	3.047	11.572	1.761	0.883	0.096	0.275	7.466	0.06	99.165	836	31
1/2	0	0.915	29.02	2.166	0.895	13.001	27.205	3.138	12.14	2.217	1.494	0.361	0.398	4.29	0.089	97.329	1950	61
2/2	0.014	0.972	29.339	0.653	1.227	14.169	28.204	3.027	11.831	2.127	1.469	0.419	0.653	5.151	0.107	99.363	2605	61
3/2	0	1.257	29.102	0.595	1	14.226	28.127	3.013	11.438	2.084	1.357	0.381	0.486	6.497	0.049	99.612	1664	43
4/2	0	1.102	29.262	0.545	1.23	14.371	28.358	3.039	11.65	2.061	1.32	0.391	0.649	5.258	0.157	99.393	2467	59
5/2	0.004	1.064	29.448	0.541	1.1	14.403	28.46	3.058	11.907	2.08	1.365	0.408	0.527	4.973	0.134	99.472	2166	57
6/2	0.142	2.273	28.567	0.653	0.622	13.62	26.979	3.068	11.857	2.083	1.265	0.22	0.623	6.238	0	98.209	2248	48
7/2	0.665	1.08	28.287	0.524	1.492	13.605	27.623	3.092	12.205	2.249	1.59	0.469	0.47	4.709	0.149	98.209	2016	57
8/2	0.076	1.654	28.514	0.739	0.656	13.679	27.585	3.072	11.849	2.09	1.262	0.284	0.716	6.838	0.064	99.077	2274	48
9/2	0	1.788	27.938	0.856	0.304	13.156	27.507	3.11	11.938	2.092	1.193	0.166	0.849	7.914	0	98.811	2407	44
10/2	0.006	1.779	28.228	0.798	0.182	13.184	27.416	3.063	11.853	2.091	1.202	0.164	0.972	8.557	0	99.497	2540	44
11/2	0	1.017	29.444	0.758	1.206	14.398	28.042	3.055	11.562	2.081	1.397	0.379	0.58	5.547	0.113	99.578	2185	54
12/2	0.022	1.724	28.172	0.585	0.227	13.517	28.044	3.155	12.037	2.133	1.211	0.191	0.547	8.168	0	99.732	1535	35
17/2	0.275	1.79	28.771	3.989	0.421	13.226	25.457	3.003	11.31	1.904	1.191	0.213	0.595	7.099	0	99.243	1903	45
21/2	0.002	0.939	29.149	0.519	1.084	14.304	28.58	3.119	12.058	2.164	1.439	0.346	0.542	4.476	0.126	98.847	2440	64
22/2	0.006	1.245	28.696	0.722	0.839	13.475	27.609	3.088	11.864	2.206	1.452	0.361	0.692	6.45	0.05	98.756	2338	50
27/2	0.004	1.5	28.516	0.65	0.632	13.651	27.777	3.14	12.289	2.183	1.382	0.283	0.535	6.419	0	98.96	1892	46
28/2	0.006	1.001	29.631	0.585	1.251	14.488	28.086	3.099	11.845	2.084	1.424	0.381	0.564	4.708	0.117	99.271	2441	65
29/2	0.035	0.923	30.407	0.729	1.214	14.584	28.555	3.045	11.812	2.148	1.423	0.415	0.544	4.62	0.106	100.561	2417	63
30/2	0.02	0.984	29.692	0.608	1.673	13.362	27.753	3.179	12.628	2.406	1.665	0.517	0.549	4.35	0.193	99.578	2405	64
31/2	0.038	1.827	27.829	0.886	0.5	13.354	26.607	3.092	12.047	2.104	1.181	0.199	0.842	7.499	0	98.005	2511	47
33/2	0.007	1.415	28.571	0.597	0.647	13.834	28.027	3.099	12.227	2.198	1.392	0.275	0.671	6.244	0	99.204	2408	49
34/2	0.016	0.881	29.755	0.63	1.125	14.711	28.476	3.051	11.699	2.107	1.388	0.394	0.497	4.807	0.094	99.631	2169	59
35/2	0.017	0.878	30.023	0.596	1.224	14.269	28.423	3.069	12.045	2.258	1.483	0.438	0.461	4.542	0.099	99.825	2117	64
36/2	0	0.994	29.325	0.532	1.082	14.369	28.487	3.081	12.154	2.2	1.447	0.373	0.537	4.706	0.129	99.415	2316	62
37/2	0.015	1.491	28.202	1.083	0.631	13.784	28.109	3.122	12.346	2.196	1.398	0.265	0.565	6.348	0	99.554	2016	46
38/2	0.013	1.551	27.918	0.306	0.147	15.172	28.897	3.047	11.572	1.761	0.883	0.096	0.277	7.466	0.06	99.167	843	31

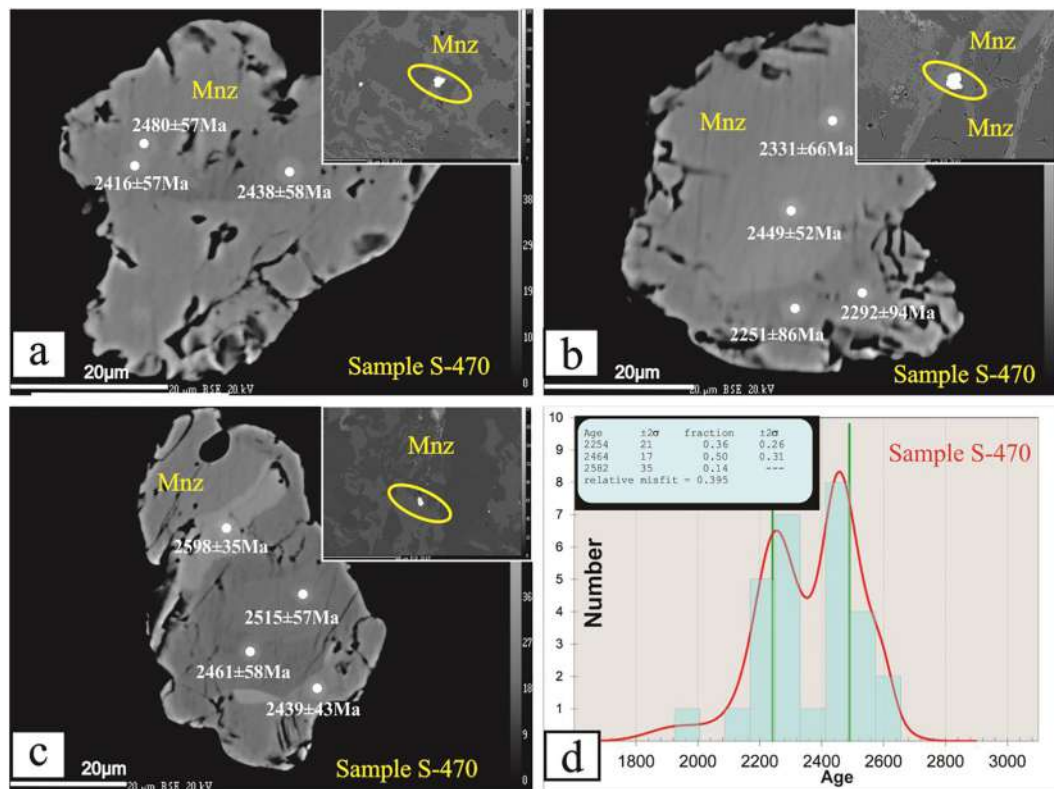


Fig. 14. (a–c) Sample S-470: granite gneisses from Kanjamalai hill, *Inset*: monazite grains are present within quartz without any feature related to DPC strain during D₃- ductile shearing; (d) The histogram has two prominent peaks at ca. 2.4 and 2.3 Ma indicating age of metamorphism (M₁), ca. 2.6 Ma peak reflects age of intrusion of granite gneiss.

mylonites because the pure shear strain axes was close to the simple shear strain axes. In steeply dipping D₃- mylonitic foliation, the D₃-stretching lineation had a pitch of 70–80° since the strain axes of pure and simple shear deviated similar to in an inclined transpression (Jones et al., 2004). Additionally, the Salem-Attur shear zone was developed on heterogeneous protolith with heterogeneity was produced due to D_{1–2} deformation, metamorphism and melting. As a result orientation of D₃ strain fabric varied depending upon the attitude of preexisting heterogeneity and rheological properties of the rocks (Ramsay and Lisle, 2000; Jones et al., 2004). This was evident in lesser *Wm* estimates of ultramylonite where the interpreted protolith was weak (probably pseudotachylite). The weak protolith accommodated more compression than the mylonite.

5.2. Tectonothermal evolution of the Salem-Attur shear zone

The Salem Namakkal blocks underwent common magmatic history spanning over ca. 3.2–0.5 Ga as suggested by several phases of charnockitic and mafic granulite magma intrusion. The D_{1–2} fabrics were related to granulite facies metamorphism. Pressure and temperature estimates of M₁ metamorphism (D₁ fabric) were inferred to be ca. 7 kb/800 °C. The D₂ deformation recorded a PT of 6 kb/700 °C indicated by dynamic recrystallization of plagioclase and chessboard twinning in quartz. The D_{1–2} deformations were constrained at 2.5–2.3 Ga by both zircon and monazite geochronology (Table 5). As per the published work, the granulite facies metamorphism was correlated with Neo-archean-Paleoproterozoic subduction (Santosh et al., 2013; Brandt et al., 2014).

The D₃ fabric developed in greenschist to amphibolite facies condition and was defined by hornblende, biotite and muscovite. During D₃ deformation, the feldspar behaved as a brittle phase and quartz underwent sub grain rotation recrystallization. These criteria constrained the PT conditions at ca. 4 kb/500 °C, corresponding to the upper crust

(15 km). The D₃- shearing was constrained at 2.0 Ga by monazite and hornblende geochronology (Table 5). The lower age limit of shearing was at ca. 1.9 Ga indicated by the age of a post D₃ and pre-D₄ pink granitic pluton. We, therefore infer that the Namakkal block was exhumed from lower to middle upper crust between ca. 2.5 Ga to 2.0 Ga. Orthopyroxene corona around garnet-clinopyroxene in the Namakkal block (Fig. 3d) suggested isothermal decompression (Harley, 1989; Thost et al., 1991; Kumar and Chacko, 1994; Biswal et al., 2007) related to thrust tectonics. The Salem block recorded a loading (Spear et al., 2002; Abati et al., 2003) or isobaric cooling (Harley, 1989; Thost et al., 1991) indicated by growth of garnet corona around M₁-garnet-clinopyroxene-orthopyroxene (Fig. 3c inset).

Subsequently, the Salem-Attur shear zone was affected by brittle deformation (D₄). The strike-slip faults were produced through N-S compression and injected by pseudotachylite veins as in the Gangavalli fault (Behera et al., 2017). High strain slip along the fault resulted in frictional melting of the rocks (above 1000 °C) to produce pseudotachylite. ⁴⁰Ar–³⁹Ar geochronology of pseudotachylite constrained the shearing event at ca. 1.9 Ga (Table 5). Normal faults constituted a younger stage of brittle shearing when the rocks had undergone fluid activity alteration (e.g., Teufel and Heinrich, 1997). The age of shearing was broadly constrained between 0.8 and 0.5 Ga by the monazite and zircon ages (Sample S-478 and TKB-19, 20). Biotite obtained from the granite vein produced ⁴⁰Ar–³⁹Ar cooling age at ca. 0.5 Ga (sample T-2, Table 5). Similar ages were obtained from different parts of the SGT. The Sankaridurg granite pluton, which was considered to be the source of granite-pegmatite veins, was reported to be Neo-proterozoic-Cambrian age (ca. 0.4–0.7 Ga. Pandey et al., 1993; Ghosh et al., 1994; Santosh et al., 2005). Alkaline granite and carbonatite intrusions were at ca. 0.8 Ga (Schleicher et al., 1997) and thermal resetting of isotopic ages along the Moyar-Bhavani shear zone was at ca. 0.5 Ga (Deters-Umlauf et al., 1997; Meibner et al., 2002; Ghosh et al., 2004).

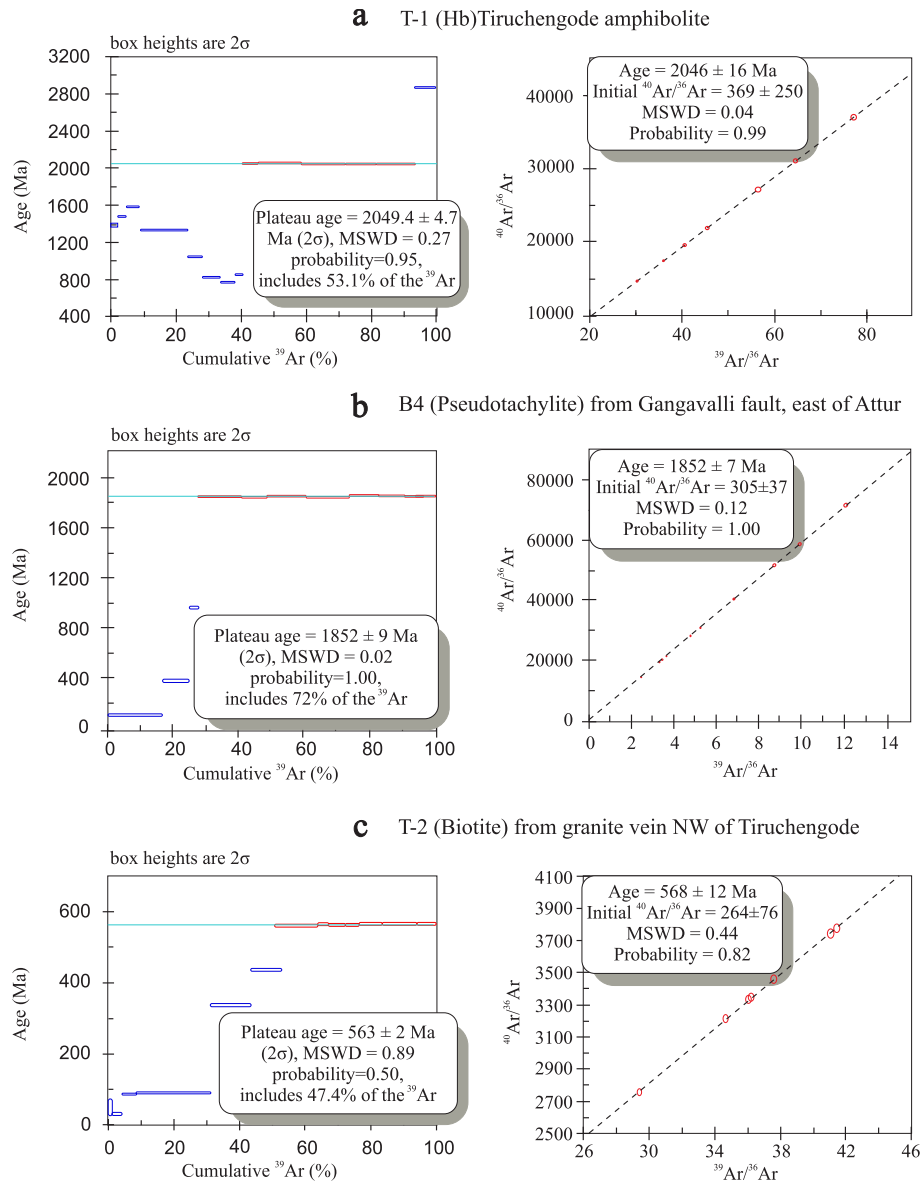


Fig. 15. (a) T-1 sample, hornblende from amphibolite from Tiruchengode, Fig. 1, $^{40}\text{Ar}/^{39}\text{Ar}$ plateau spectra (left panels) and isochron plots (right panels); (b) Pseudotachylite from Gangavalli fault, close to Attur, Fig. 1; (c) Granite veins from NW of Tiruchengode Fig. 1. In the plateau spectra, the plateau is drawn with red outlines and the nonplateau with dark blue outlines. The value of mean square weighted deviate (MSWD) for each analysis is mentioned. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.3. Tectonic implication

The Salem-Namakkal blocks consisted of similar lithologies and a common magmatic and deformational history (D_{1-2}). Charnokite magmatism was at ca 3.2–2.6 Ga and M_1 metamorphism took place at 2.5–2.3 Ga (Clark et al., 2009; Plavsa et al., 2015, present study

Table 5). Hence, the blocks were contiguous before the D_3 -Salem-Attur shear zone affected them at ca. 2.0 Ga. The Namakkal block overthrust the Salem block to the N-NNE. The regional map of the SGT depicted the Salem-Attur shear zone merging with Moyar-Bhavani shear zone to the west (Fig. 1 inset). The Moyar-Bhavani shear zones were not studied with respect to shear kinematics, strain pattern and

Table 4

Summary of ^{40}Ar - ^{39}Ar dating results for sample T-1 ($N11^\circ28'14.86''$, $E77^\circ59'15.25''$) from amphibolite rock, sample B-4 ($N11^\circ28'10.09''$, $E78^\circ36'02.07''$) from pseudotachylite vein and sample T-2 ($N11^\circ32'52.15''$, $E78^\circ55'17.28''$) from granite vein.

Sample	Plateau					Isochron				Inverse isochron			
	Steps	% ^{39}Ar	Age(Ma)	MSWD	p	Age(Ma)	Trap	MSWD	p	Age(Ma)	Trap	MSWD	p
T-1 (Hornblende from Tiruchengode)	16	53.1	2049.4 ± 4.7	0.27	0.95	2046 ± 16	369 ± 250	0.04	0.99	2046 ± 11	359 ± 150	0.12	0.99
B4 (Pseudotachylite from Gangavalli)	17	72	1852 ± 9	0.02	1.00	1852 ± 7	305 ± 37	0.12	1.00	1852 ± 7	295 ± 10	0.02	1.00
T-2 (Biotite from granite veins, NW of Tiruchengode)	13	47.4	563 ± 2	0.89	0.50	568 ± 12	264 ± 76	0.44	0.82	568.7 ± 9.7	262 ± 59	0.74	0.60

Table 5

Comparison of tectonothermal age in Salem-Namakkal blocks.

Events	Salem block	Namakkal block
Intrusion of charnockites, granite gneiss	Ca.2.5 Ga Clark et al. (2009) , Sato et al. (2011a)	Ca 2.5 Ga Ghosh et al. (2004)
Anorthosite intrusion		Ca.2.5 Ga (<i>Present study, TKB-18, 19, 20</i>)
Syenite intrusion		Ca. 2.5 Ga Mohan et al. (2013)
		Ca.2.5 Ga (<i>Present study TKB –22</i>)
Age of metamorphism	Ca. 2.4–2.5 Ga Clark et al. (2009)	Ca.2.4–2.5 Ga Mohan et al. (2013)
D ₁ and D ₂	Ca. 2.4–2.5 Ga Sato et al. (2011a)	Ca. 2.5 Ga Plavsa et al. (2015)
D ₂ shearing	Ca. 2.4–2.5 Ga, <i>M₂</i> , ca. 2.3 Ga (<i>Present study, S-470, monazite geochronology</i>)	Ca. 2.5 Ga Brandt et al. (2014)
		Ca. 2.2 Ga Brandt et al. (2014)
Age of ductile shearing D ₃ shearing	Ca. 2.0 Ga (<i>present study, S-478, monazite geochronology</i>), ca 2.0 Ga ages are reported from Trivandrum block Ghosh et al. (2004) , Second metamorphism in Moyar-Bhavani, Brandt et al. (2014)	
Age of strike-slip shearing and pseudotachylite emplacement D ₄ shearing	Ca.1.9 Ga (<i>Present study, TKB-21</i>), ca.1.8 Ga granitic magmatism Ghosh et al. (2004) , Brandt et al. (2014)	
Age of normal faulting and granite-pegmatite vein intrusion D ₄ shearing	Ca 0.8–0.5 Ga. (<i>Present study, TKB-19,20, S-478</i>), ca. 0.5 Ga Brandt et al. (2014) , Plavsa et al. (2015)	

timing of shearing. The available age data suggested a reset ages at ca. 0.5 Ga ([Deters-Umlauf et al., 1997](#)). Recent geochemical and geochronological studies of rocks near the Bhavani shear zone suggested it to be a Neoproterozoic suture zone ([Santosh et al., 2013](#); [Brandt et al., 2014](#); [Table 5](#)). Similarly, the Palghat-Cauvery shear zone was once described to trace a late Neoproterozoic-Cambrian suture representing the closure of the Neo-proterozoic Mozambique Ocean during Gondwana amalgamation ([Collins et al., 2007a](#); [Santosh et al., 2009a,b, 2012](#); [Sato et al., 2011a](#)). In an alternative model the Palghat-Cauvery shear zone was considered a Neoproterozoic suture as ca. 2.5 Ga rocks existed on either side ([Brandt et al., 2014](#)). [Brandt et al. \(2014\)](#) suggested that the Karur-Kambam-Painavu-Trichur shear zone was a Late-Palaeoproterozoic to early-Mesoproterozoic collision zone. Our study on the Salem-Attur shear zone led to the interpretation that the shear zones between different blocks might not be suture zones, but they represented intra-terrane shear zones within a single Archean-Paleoproterozoic SGT. Even Palaeoproterozoic (2.0–1.6 Ga) crust existed in the Madurai as well as Trivandrum block ([Braun et al., 1998](#); [Ghosh et al., 2004](#); [Table 5](#)). The SGT has been reactivated during different period. There was stronger Pan-African overprint in the Madurai and Trivandrum blocks as these were closer to the Pan-African Betsimisaraka suture in Madagascar ([Collins et al., 2007a](#)). As the Salem-Namakkal block was far away from this proposed suture, the Pan-African orogeny was only expressed as brittle normal faults.

The SGT was considered to be a reworked part of the Dharwar craton. The Antongil (ca. 3.32–3.18 Ga; [Tucker et al., 1999, 2011a](#); [Schofield et al., 2010](#); [Key et al., 2011](#); [De Waele et al., 2011](#)) and Antananarivo cratons (granulite facies metamorphism 2.5 Ga; [Kroner et al., 2000](#)) were considered part of the greater Dharwar craton (e.g., [Tucker et al., 2011a, b](#)). In this model, the Salem-Namakkal blocks could have been contiguous with Antananarivo block. The eastward extension of the Salem-Namakkal block to the Bastar craton and into Sri Lanka is unknown. The Madurai and Achankovil blocks were correlated with the Wani complex of Sri Lanka ([Braun and Kriegsman, 2003](#); [Cenki et al., 2004](#); [Kooijman et al., 2011](#); [Kroner et al., 2012](#); [Plavsa et al., 2012](#)). The Madurai block has been extended eastward into the Ongole domain of the Eastern Ghats mobile belt ([Kovach et al., 2001](#); [Bose et al., 2011](#); [Sarkar and Schenk, 2012](#)). It is thus plausible to suggest that fragments of the Dharwar craton, which underwent reworking during the Neoproterozoic-Paleoproterozoic period, now occur in several continental fragments of Gondwanaland. Most of these fragments later underwent Mesoproterozoic and Neoproterozoic-reworking, resulting in reactivation of shear zones.

6. Conclusions

Detailed structural mapping of the Salem-Namakkal blocks;

including kinematic study and vorticity analysis of the shear zone and multi-thermo-chronometric study of the magmatic rocks and mylonites were integrated to establish the tectonothermal evolution of the Salem-Attur shear zone of the SGT in South India. The lithological assemblage in the Salem-Namakkal blocks formed between 3.2 and 2.6 Ga, and were deformed (D_{1–2}) and metamorphosed to granulite facies at 2.5 Ga and 2.3 Ga. The D₁ deformation produced F₁ isoclinal recumbent folds and S₁ subhorizontal fabric, while D₂ deformation produced tight upright to inclined F₂ folds. Several D₂ ductile shear zones were developed characterized by high temperature vertical shearing. The syenites (ca. 2.5 Ga) intruded syntectonically during D₂ shearing. Dynamic recrystallization of plagioclase and chessboard twinning in quartz of syenite suggested P-T conditions of 7 kb/600 °C. The Salem-Attur blocks formed a single block before the development of the Salem-Attur shear zone deformed it. The Salem-Attur shear zone formed during D₃ in feldspar brittle-quartz ductile zone. Charnockite, granite gneiss and quartzofeldspathic gneiss retrograded to quartz-biotite-muscovite mylonite, and mafic granulite to hornblende-albite mylonite. P-T conditions of around 4 kb/500 °C was interpreted for D₂ shearing based on retrogression of minerals, rotation recrystallization of quartz and brittle nature of feldspar. The Salem-Attur shear zone consisted of three southerly dipping imbricate thrusts with dips varying from near horizontal to subvertical. On low dipping mylonitic foliation, the stretching lineations were perfectly down dip; while in steeper foliation the pitch of the lineations was 70–80° which was attributed to pure shear component. Abundant shear sense criteria suggested an N-NNE verging thrust slip, suggesting that the Namakkal block was thrust over the Salem block. The kinematic vorticity number derived from RGN and Rs/θ analysis suggested general simple shear with 50% pure shear component. Th-U-total Pb monazite and hornblende ⁴⁰Ar-³⁹Ar geochronology constrained the age of shearing to 2.0 Ga. Latter brittle deformation affected the Salem-Namakkal blocks including strike-slip shearing at 1.9 Ga and normal faulting at 0.5 Ga. The strike-slip faults were produced through N-S compression, with the high slip rates generated pseudotachylites along the Gangavalli fault. Normal faults were developed through extension during the Pan-African orogeny. We suggested that the Salem-Namakkal blocks experienced a long lived shearing history from ca. 2.5 Ga to 0.5 Ga and that shear zones were reactivated during different period of global orogeny. This polyphase tectonic evolution may be applicable for the entire SGT.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.precamres.2019.01.022>.

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