JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.89, January 2017, pp.5-11

Strain Analysis of the Salem-Attur Shear Zone of Southern Granulite Terrane Around Salem, Tamil Nadu

K. Sundaralingam[1*], T. K. Biswal[1] and V. Thirukumaran[2]

[1]Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai – 400 076, India
[2]Department of Geology, Government Arts College, Salem – 636 007, India
E-mail: *sundarlingam56@gmail.com*; tkbiswal@iitb.ac.in*

ABSTRACT

Salem-Attur shear zone in the Southern Granulite Terrane demarcates the tectonic boundary between Archaean granulites of Dharwar craton and the Palaeoproterozoic granulites of Salem area. The shear zone marks a low angle thrust which has been steepened at places due to late stage folding. Static recrystallisation during late stage folding has removed the strain marker of mylonites to large extent. However, in a few places S-C angle and porphyroclasts are preserved and have been used to compute the strain. The strain shows apparent flattening by simple shear deformation with 35 % volume loss. A minimum displacement along the thrust has been computed to be 2.7 km. The strain k values increases with r suggesting the strain approaching towards prolate field with increase in strain intensity. The above study suggests the Salem-Attur shear zone is a thrust with low to moderate deformation and volume loss.

INTRODUCTION

The E-W running Salem-Attur shear zone marks the tectonic line of juxtaposition between the Archaean Dharwar craton (this includes the granulites and granite greenstone belts) in the north and Neoarchaean-Palaeoproterozoic granulite terrane in the south (Fig. 1 inset). The Palghat-Cauvery shear zone that lies further south probably represents a Cambrian suture between Pan-African mobile nelt in the south and the Archaean-Palaeoproterozoic granulite terrane in the north (Chetty and Bhaskar Rao, 2006; Yellappa et al. 2012 and references therein). However, on the basis of isotopic studies Karur-Kodaikanal-Oddanchatram shear zone has been interpreted to be the terrane boundary between the Archaean-Palaeoproterozoic belts and the Pan-African mobile belt (Bhaskar Rao et al. 1996; Ghosh et al. 1998; 2004). The central Archaean-Palaeoproterozoic granulite terrane which is termed as a marginal terrane shows sporadic Neoproterozoic thermal and magmatic events (Reddy et al. 1995; Bhaskara Rao et al. 2003; Ramakrishnan and Vaidhyanadhan, 2008).

The Salem-Attur shear zone has been interpreted as a dextral strike-slip shear zone based on apparent offset position of structural grains between Billirangan and Nilgiri hill (Drury and Holt, 1980), while Naha and Srinivasan (1996) have described it as a vertical fault on the basis of predominant down dip stretching lineation. Valdiya (1998) also interpreted the shear zone to be a low angle thrust that has been locally steepened. In spite of the down dip lineations and many kinematic indicators suggesting dip-slip character, the shear zone has been interpreted in a number of recent studies to be a transpressional-dextral strike slip shear zone (Chetty and Bhaskar Rao, 1998; Bhadra, 2000; Jain et al. 2003). In this paper, the deformation pattern of the Salem-Attur shear zone around Salem has been studied. Earlier work have shown contrasting shear sense and varied orientation of fabric (Bhadra, 2000; Satheesh Kumar and Prasannakumar, 2009; Biswal et al. 2010).

GEOLOGICAL SETTING

Rock type

The Salem-Attur shear zone is marked by quartzo-feldspathic gneisses and hornblende-biotite gneisses and these occupy the plains of the Kanjamalai-Salem-Sarkar Nattar Mangalam and Attur area and have been eroded in most parts except for Sarkar Nattar Mangalam area where extensive outcrops of porphyroclasts bearing mylonites are exposed in the foothill of the Godumalai. Within the gneissic country, there are a few isolated hillocks of charnockites and basic granulites namely Godumalai and Kanjamalai hills that represent the low strain zone. The charnockites are gneissic rocks comprising of biotite + hypersthene + garnet rich layer alternating with quartz + perthite-antiperthite rich layer. The rocks show equigranular texture. Basic granulites carry opx + cpx + garnet + plagioclase + opaques. Prominently, orthopyroxene is rimmed by garnet at the close proximity of plagioclase. This suggests the following model reaction.

$$\text{Opx} + \text{Pl} = \text{Grt} + \text{Qtz}$$

And the reaction proceeds to the right in response to near isobaric cooling (Harley, 1989). The coexisting mineral phases in the charnockitic rocks indicate the temperature between 602–678ºC and pressure in range of 8.3–9.4 kbar. The zircon geochronology of charnockites gives an age of 2530±39 Ma (Sundaralingam et al. 2012).

Structure

The Salem-Attur shear zone is about 100 km long and 2 to 5 km wide and passes through the valley extending from Salem to Attur. The average trend of the shear zone is E-W (Fig. 1). The composition of the mylonites depends on the parent rock; charnockites have been transformed into quartzo-feldspathic gneiss and basic granulites to hornblende- biotite gneiss. The quartzo-feldspathic gneiss near Sarkar Nattar Mangalam carries kinematic indicators to facilitate study the sense of shearing and magnitude of strain. The mylonitic foliations vary in their orientation from very low angle to as steep as 70° to the south and has been marked by down dip stretching lineation. This variation has been due to post-mylonite open upright E-W folding. Intersection lineations are produced showing low plunge towards east.

PETROFABRIC ANALYSIS

Sample Collection

The collection of oriented samples and proper mounting of the thin sections are prerequisite for petrofabric analysis of the shear zones (Biswal et al. 2000). The study is based on the analysis of fifty thin sections made from 25 oriented samples collected by mapping a 2.5 km long strike profile line across the shear zone in Sarkar Nattar Mangalam area, south of Godumalai hill (Fig. 2).

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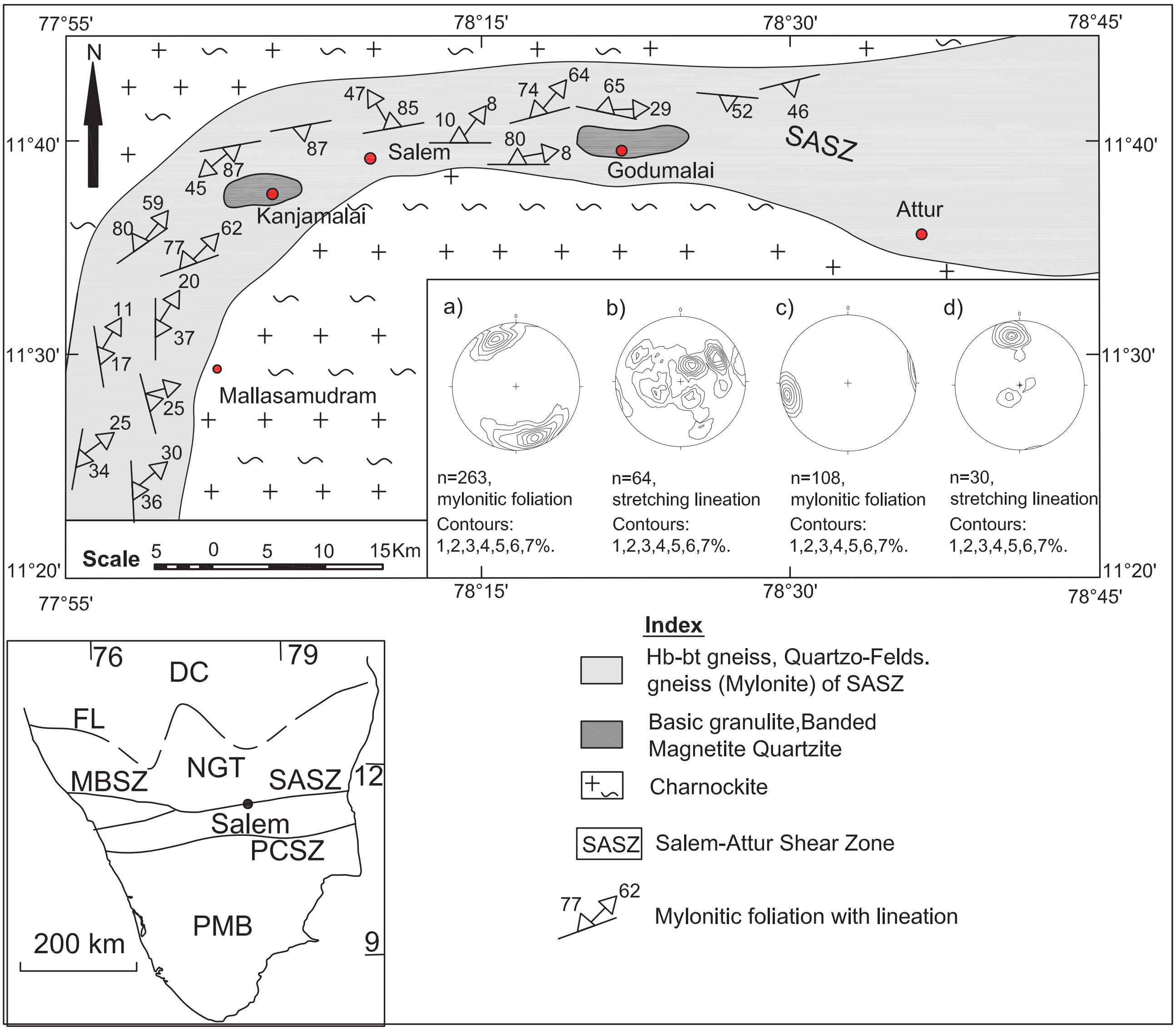

Fig.1. Geological Map of the SASZ, near Salem, Tamil Nadu. **(a)** Mylonitic foliation data; contours 1,2,3,4,5,6,7 % near SASZ. **(b)** Lineations data; contours 1,2,3,4,5,6,7 % near SASZ. **(c)** Mylonitic foliation data; contours 1,2,3,4,5,6,7 % S. of Kanjamalai. **(d)** Lineations data; contours 1,2,3,4,5,6,7 % S. of Kanjamalai. Inset: Shear zone of Southern Granulite Terrane after Ramakrishnan and Vaidyanathan (2008).

Kinematic Indicators

The following field and microscopic features have been used to interpret the sense of shear. These are (i) mylonitc foliation and stretching lineations, (ii) S-C fabric, (iii) asymmetric feldspar porphyroclasts and (iv) intragranular fault. In ductile shear zone mylonites are the most important constituent which resulted from the crystal-plastic deformation of the rocks whereby new minerals grow through dynamic recrystallisation showing preferred shape as well as optic orientation. Depending on the amount of strain, the relative proportion of residual grains (porphyroclasts) to newly recrystallised grains (matrix) varies, thus giving rise to protomylonite (clast > 50%), mylonite (clasts, 50-10%) and ultramylonite (clast < 10%) zones from periphery to centre of the shear zone (Ramsay and Huber, 1987). Mylonites and ultramylonite zones are well developed compared to protomylonites. The mylonitic foliation in the charnockitic mylonites is marked by long stretched quartz ribbons which carries square to rectangular grains indicating static recrystallisation following mylonitisation (Fig. 3a). The quartz ribbons have been folded and static recrystallisation is probably synkinematic with such folding (Fig. 3b). However, in quite a few instances oblique quartz grains have been preserved which are used to measure S-C angle and strain calculation. Feldspar porphyroclasts are in general elliptical and rounded except in few cases where due to shearing along the intragranular faults elliptical geometry is distorted (Fig. 3c and d). The quartz ribbons are warped around the feldspar porphyroclasts. In the mylonites made up of hornblende biotite gneiss, biotite fishes and hornblende sigmoidal clasts are observed (Fig. 3e, f). All these kinematic indicators point towards a north to NE sense of vergence.

STRAIN ANALYSIS

In recent years, strain analysis is developed as an integral tool in understanding the mode and intensity of deformation in an area to interpret the nature and regime of tectonic condition. Various methods have been adopted for calculating strain taking into account the grain shape and size, shape preferred orientation and S-C angle.

Flinn Plot

Two dimensional strain for deformed quartz grains have been measured on X/Y and Y/Z sections (Table 1) and plotted in Flinn plot to know three dimensional strain (Flinn, 1962). The samples lie in the field of apparent flattening indicating simple shear with volume

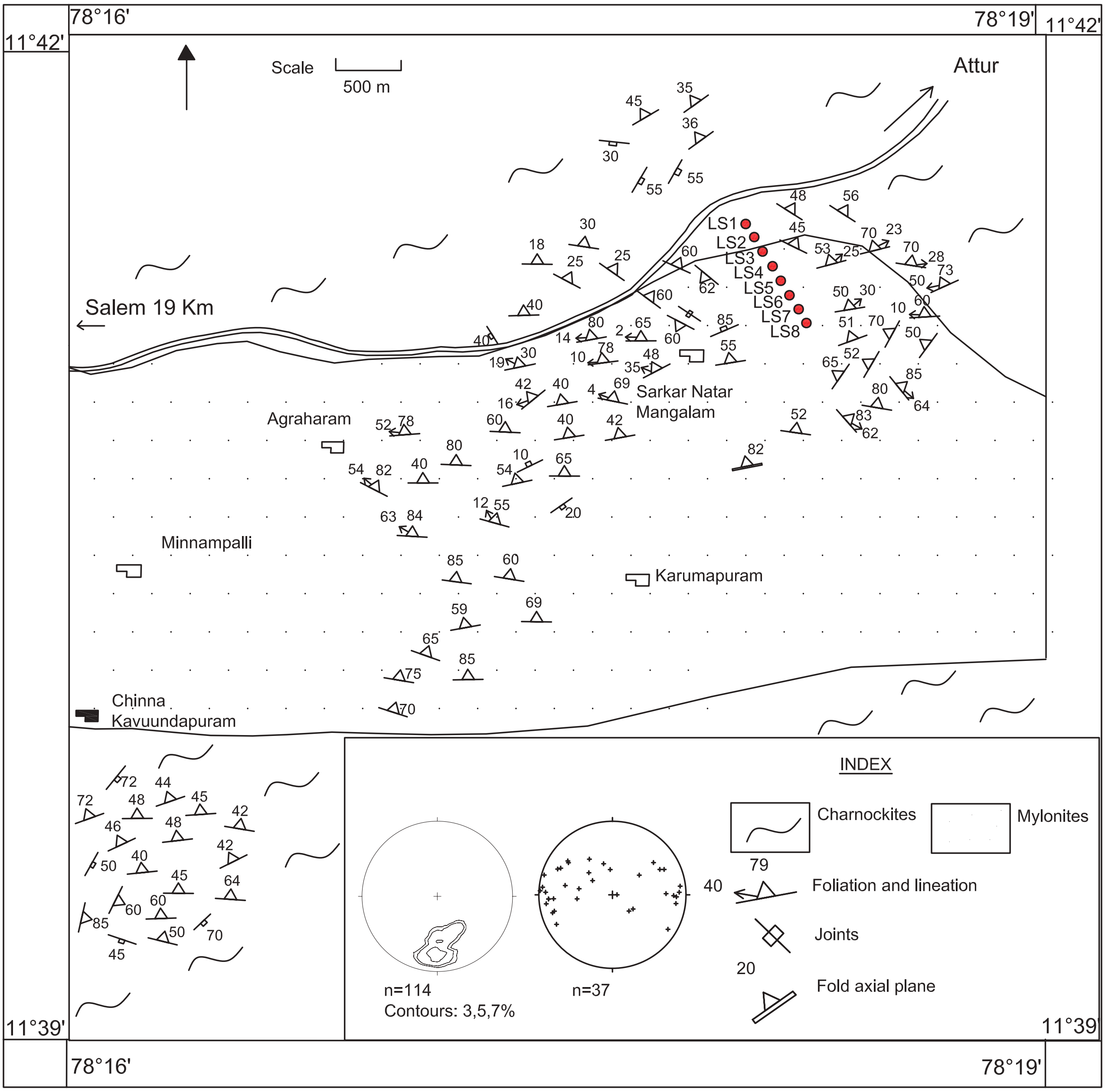

Fig.2. Geological map of the Sarkar Nattar Mangalam area near Salem showing the sample location for strain analysis.

loss (Fig. 4a, b, c and d) (Ramsay and Wood, 1973). The values of parameter k =, [((x/y)-1) / ((y/z) -1)], (Mawer, 1983) describing the shape of strain ellipsoid is less than 1, varying from 0.008 to 0.662 (Table 1). Further, the log Flinn plot shows approximately 35 % of volume loss (Fig. 4d). The parameter r = [(x/y) + (y/z) – 1], (Watterson, 1968 and Mawer, 1983) the measure of the strain intensity suggests a low to moderate state of strain, with the values ranging between 1.58 and 2.28, (Table 1). As the strain intensity increases, a general trend towards prolate field has been observed in k and r plot. (Fig. 4b).

Modified Normalized Fry Method

In 1979, Fry developed a technique called Fry method for quantifying strain from the aggregates of grains based on distribution of object centres. In 1988, Erslev modified the method to overcome the problem of scatter distribution in the Fry plot, the effect of variability of two dimensional grain size by normalizing the distance between two dimensional grain centres. Erslev and Ge (1990) developed the program INSTRAIN 3.0 where they approximated each grain as an ellipse by calculating the least square best fit ellipse to equally spaced points along grain boundaries. Mc Naught (1994) developed ANGGRAIN 1.1 program attempting to approximate grain boundaries by constructing polygons. Modified Normalized Fry method (McNaught, 1994) is well advanced by defining the grain boundaries in polygonal approximation method which is more accurate than to approximate non elliptical grain boundaries by best fit ellipses.

Photomicrographs have been used to trace the grain boundaries of XZ and YZ sections with the aid of SIGMA SCAN PRO, digital image processing software for precisely estimating the area and centroid coordinates of individual grain. ANGGRAIN 1.1 is used to construct a normalized Fry plot from the values obtained. The procedure is repeated several times for accurate results by calculating the plane strain irrotational inverse deformation; this results in a circle which approaches the axial ratio of 1.00. The axial ratio (R_f) and long axis orientation (θ) of strain ellipse have been recorded in Table 2.

Calculation of Shear Strain using S^C Angle

In general, most of the shear zones have two planar fabrics,

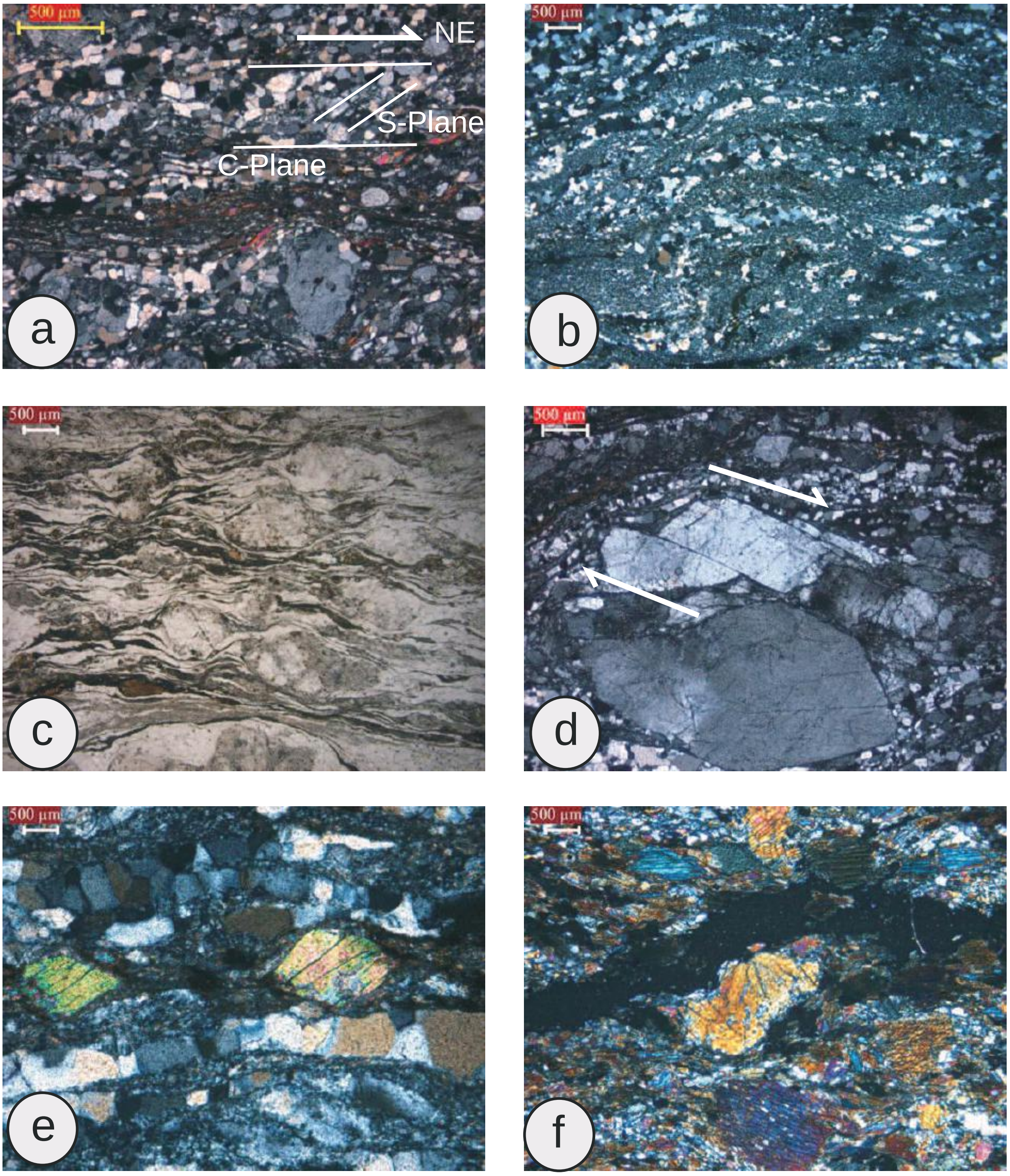

Fig.3. Photomicrographs of the Salem-Attur shear zone **(a)** Quartz-feldspathic gneiss shows S-C fabric with NE vergence shear sense **(b)** Quartz ribbon has been folded in quartz-feldspathic gneiss **(c)** Photomicrograph of asymmetric porphyroclast **(d)** Intragranular fault shows dextral sense of shear **(e)** Photomicrograph of hornblende fish **(f)** Mylonitised basic granulite shows fish structures.

S-fabric defining the XY plane of the strain ellipsoid and the C-fabric representing the slip plane. The angle between these two foliations depends on the finite strain existing or developed at that point. Several theories for the origin and evolution of planar fabrics in shear zones have already been proposed (Ramsay, 1967; 1980; Berthe et al. 1979; Lister and Snoke, 1984 and Platt, 1984). In the present study, the S fabric is considered to represent the local XY plane. So, the longest axis of recrystallised (synkinematic to shearing) quartz grain is parallel to X-axis of local finite strain ellipsoid on "XZ" sections (Blenkinsop and Treloar, 1995). In the present approach, the strain is calculated assuming a simple shear deformation, for the sake of simplicity in the calculation. The strain is calculated by using S^C angles, measured from the samples collected at regular interval across the shear zone, following the equation:

$$\gamma = 2 \cot 2\theta \text{............} (1) \quad \text{(Ramsay and Huber, 1983; 1987)}$$

where, γ is the shear strain and θ is the angle between the foliation (S plane) and shear zone boundary (C plane). The systematic variation of S-C angle is observed from wall to the centre (Table 3). Figure 5 shows the cross sections along the traverse on which sample locations have been plotted. The average dip of the shear zone varies along the strike length. The true width line for traverse is drawn by connecting a perpendicular line to the shear zone wall. Then, the sample location points are projected onto the true width line. The measured true width

Table 1. Calculated data of X/Z, Y/Z and X/Y aspect ratio and k and r values at different location along a profile line of Salem-Attur shear zone

Sample No.	X/Z	Y/Z	X/Y	r	k
S1	1.7186	1.6546	1.0387	1.6933	0.0592
S2	1.9012	1.8741	1.0145	1.8886	0.0165
S3	1.7670	1.7562	1.0061	1.7732	0.0080
S4	2.1718	1.9649	1.1053	2.0702	0.1091
S5	2.1528	1.7229	1.2496	1.9724	0.3452
S6	2.6791	1.7725	1.5115	2.2840	0.6621
S7	1.8418	1.7207	1.0704	1.7911	0.0977
S13	1.7149	1.5614	1.0984	1.6597	0.1752
S23	1.8571	1.6922	1.0974	1.7897	0.1407
S24	1.6062	1.5381	1.0442	1.5824	0.0822
S25	1.7958	1.5742	1.1408	1.7150	0.2452

Table 2. Calculated data of R_f and Theta values at different location along a profile line of Salem-Attur shear zone using ANGGRAIN 1.1 program

Sample No.	Axial Ratio	Orientation	Average Error in %	Rf	Theta
S1	1.06	33	0.92	1.07	142
S2	1.03	-21	1.09	1.52	64
S3	1.01	119	0.10	2.12	134
S4	1.04	22	1.25	2.12	103
S5	1.00	114	2.97	2.33	73
S6	1.03	-40	1.59	1.24	106
S7	1.01	1	1.73	1.57	68
S13	1.00	79	0.44	1.40	138
S23	1.01	118	0.12	1.40	29
S24	1.04	-15	1.65	2.03	53
S25	1.02	28	3.46	2.03	53

of the traverse is 705 m. From the figures, the average true width is estimated. The values are plotted on graph for shear strain against sample locations on true width line as shown in Fig.5a and b. The plot shows gradual increase in shear strain from the wall towards the centre. The maximum shear strain is found to be 3.4. From the above shear strain value, the angular displacement is calculated using the equation,

$$\psi = \tan^{-1}\gamma \;.......\; (2) \quad \text{(Ramsay and Huber, 1983, 1987)}$$

where, ψ is the angular displacement. The angular displacements at each sampling site are graphically integrated over the entire width of the zone to calculate the total displacement for profile (Fig. 5c). The total displacement for profile is estimated by integrating the angular displacements at each sampling site graphically over the entire width of the zone. The displacement is about 1300 m. As mentioned earlier, the above calculation is done assuming a simple strain condition. Hence, the result gives minimum displacement value along the thrust plane. If 35% volume loss has taken into calculation then the displacement would be 2.7 km. Further, it is observed that the shear

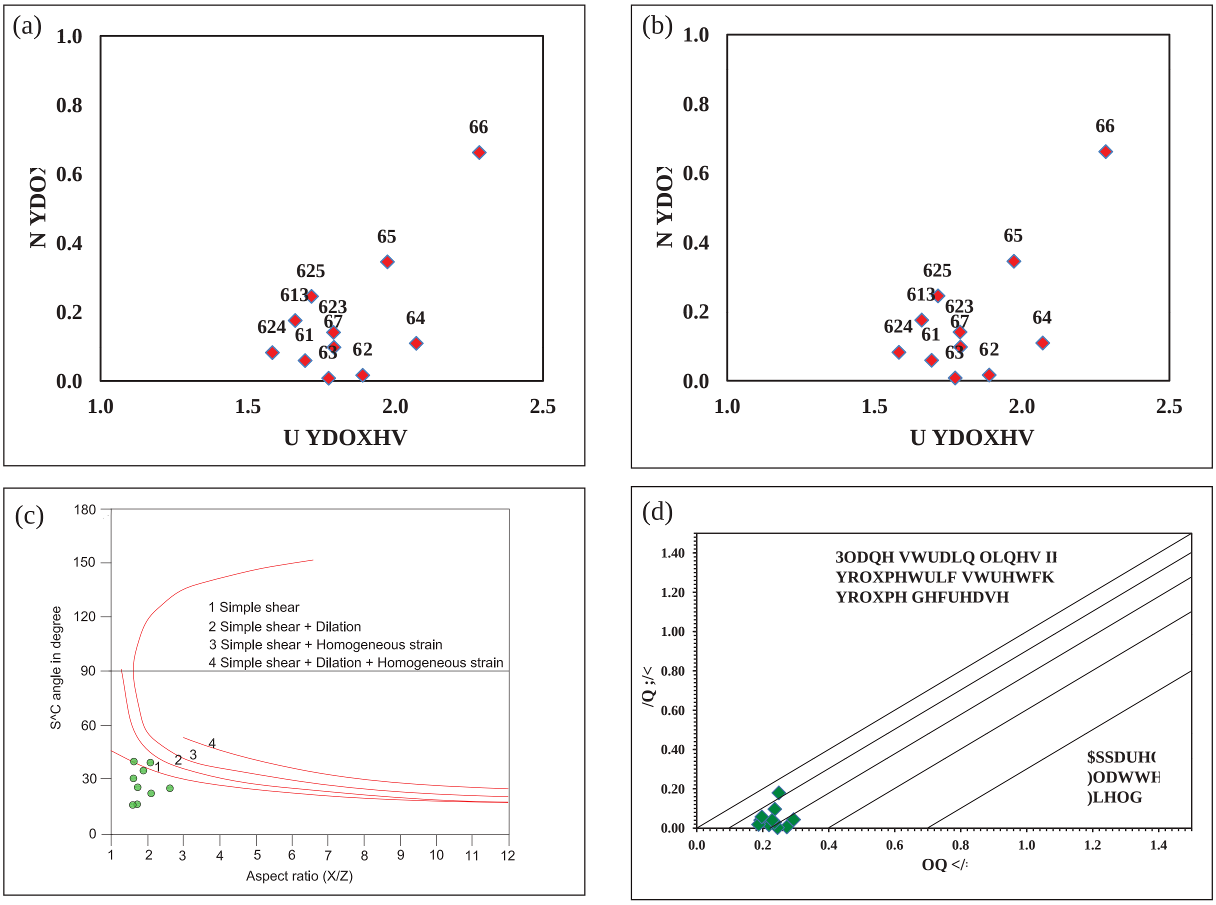

Fig.4. (a) Flinn plot (Y/Z vs X/Y) for nearly foo dynamically recrystallised quartz grains from 22 thin sections (L and T sections) of mylonites. While L section gives X/Z ratio, the T sections give Y/Z ratio. X/Y was calculated by dividing the average value of X/Z by average of Y/Z value. Though the aspect ratio varies within the slide due to jostling of the porphyroclasts (Hudleston, 1999), the bulk strain lies in the field of flattening zone indicating dominant simple shear strain in the Salem-Attur shear zone. **(b)** Graph of k vs r shows the strain ellipsoid changes from oblate to more prolate structure. **(c)** Aspect ratio (X/Z) vs S^C angle graph for ductile shear zones undergoing various types of strain (after Ramsay and Huber, 1987). The curve for simple shear touches the X axis at 45Ú position. The samples of the Salem-Attur shear zone almost coincide with simple shear curve with little volume loss. **(d)** Logarithmic Flinn plot (Y/Z vs X/Y) for deformed quartz grain shows approximately 35% of volume loss.

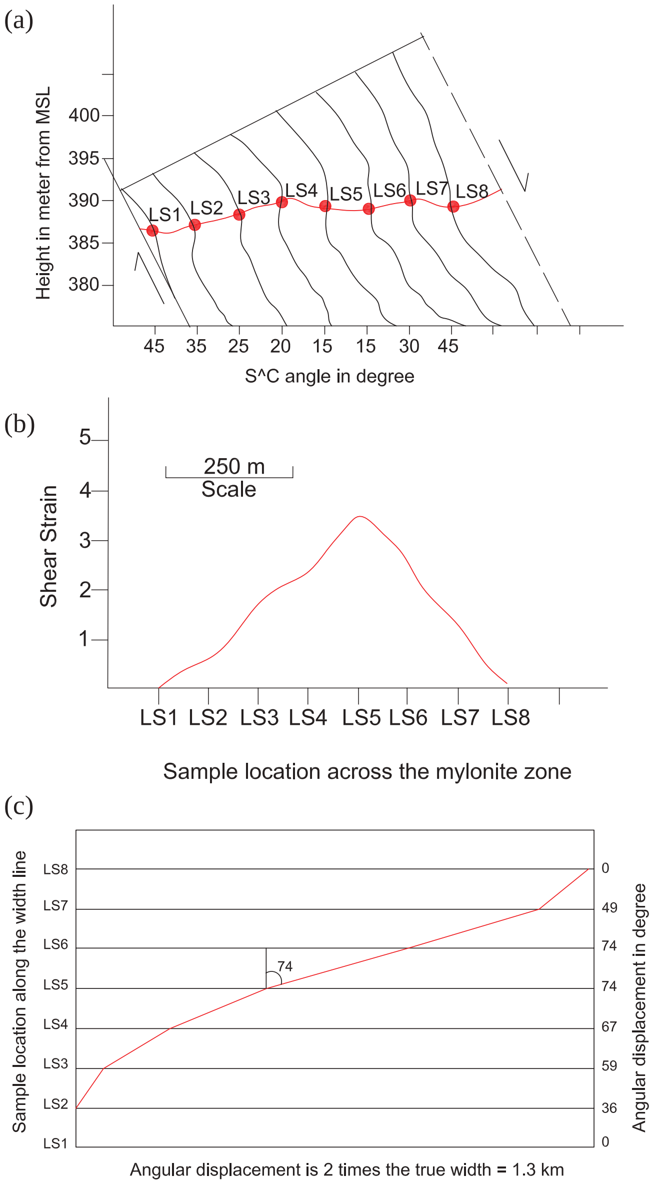

Fig.5. (a) Shear strain evaluation along profile of Salem-Attur shear zone shows the profile plane and true width line of the shear zone. The samples (1-8) are located on the profile line. S-fabric is drawn using the S^C angle measured in the samples collected from that location. S-fabric meets the shear zone wall at 45° angle since γ value is zero at the wall. **(b)** Shows strain variation along the true width line. The shear strains are not similar. **(c)** Shows graphical integration of angular displacements recorded at each sampling site. The values of shear strain and angular displacement have been listed in Table 3 (Ramsay and Huber 1983 and 1987).

strain varies among profiles and shows a gradient towards the centre of the shear zone.

DISCUSSION AND CONCLUSION

Salem-Attur shear zone demarcates the boundary between Archaean granulites from the Palaeoproterozoic granulites. The shear zone is marked by mylonites represented by quartzo-feldspathic gneiss and hornblende-biotite gneiss. The Sarkar Nattar Mangalam area shows development of mylonites having excellent kinematic indicators like S-C fabric, sigmoidal porphyroclasts, mica fishes and intragranular faults. The study of these indicators reveals that the shear zone is dominated by N to NE verging thrust. As thrusting is followed by folding and low grade metamorphism, the dynamically recrystallised quartz grains show static recrystallisation. There is a volume loss associated with thrusting. This is manifested in form of development of micas out of opx, cpx and garnet in the charnockites and basic granulites. The volume loss is about 35%. And the displacement may be around 2.7 km.

The Southern Granulite Terrane consists of many shear zones like the present one. If all these shear zones are visualized to be part of thrust system, then it is likely that the belt forms a Palaeoproterozoic fold thrust belt that has been over thrusted onto the Dharwar craton. The Salem-Attur shear zone may be the frontal thrust of the thrust belt. The time of emplacement of such thrust belt is not certain. The zircon geochronology of charnockite mylonite provided an age of 2.5 Ga. The belt is intruded by Neoproterozoic rocks like shonkinite, dunite, pyroxenite, peridotite and granites. The age of such intrusives is broadly Neoproterozoic. It is proposed that the thrusting age may be as young as Neoproterozoic.

Table 3. Calculated data of θ, γ and ψ at different locations along a profile line of the Salem-Attur shear zone.

Sample No.	S^C angle θ in degree	Shear strain γ	Angular displacement ψ in degree
S1	45	0	0
S2	35	0.73	36.12
S3	25	1.68	59.24
S4	45	0	0
S5	20	2.3	66.5
S6	25	1.68	59.24
S7	15	3.4	73.97
S13	15	3.4	73.97
S25	30	1.15	48.99

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(Received: 29 September 2015; Revised form accepted: 14 January 2016)