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Quantitative finite strain analysis of the quartz mylonites within the Three Pagodas shear zone, western Thailand

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Abstract
The NW–trending Three Pagodas shear zone exposes a high–grade metamorphic complex named Thabsila gneiss in the Kanchanaburi region, western Thailand. The quartz mylonites within this strike–slip zone were selected for strain analysis. 2–dimensional strain analysis indicates that the averaged strain ratio (R_s) for the lower greenschist facies increment of XZ–plane is Rs = 1.60–1.97 by using the Fry's method. Kinematic vorticity analysis of the quartz mylonites in the shear zone showed that the mean kinematic vorticity number of this increment is W_k = 0.75–0.99 with an average at 0.90 ±0.07. The results implied that the quartz mylonites within the Three Pagodas shear zone have a dominant simple shear component of about 72% with a small pure shear component. A sinistral shear sense is indicated by kinematic indicators from macro– to micro–scale. We conclude that the Three Pagodas shear zone deformed in the process of sinstral shear–dominated transpression, which is similar to the Mae Ping shear zone in the north.

1. Introduction
Cenozoic strike–slip systems have played an important role in the tectonic evolution of SE Asia (e.g. Tapponnier et al., 1982, 1986). Their kinematics fit to the continental extrusion model that explains the structural evolution of Tibet and Southeast Asia (Tapponnier et al., 1982, 1986). This continental extrusion model is based on northward drift of the Indian plate and clockwise rotation of the Asian plate around the Eastern Himalayan Syntaxis (e.g. Tapponnier et al., 1982; 1986; Leloup et al., 1995). It presumes that the large thickened continental crusts of Sundaland, Tibet, and South China have been extruded by the Indian subduction through the motion of strike–slip systems to the E and SE direction (Tapponnier et al., 1986). The N–S striking dextral Sagaing fault in Myanmar and the NW–SE striking sinistral Ailao Shan–Red River shear zone in China are the most prominent structures of these strike–slip systems (e.g. Tapponnier et al., 1990; Lacassin et al., 1997; Morley et al., 2007). High–grade metamorphic and plutonic rocks have been exhumed representing the mid–crustal deformation history during continental extrusion within these crustal scale strike–slip shear zones (Lacassin et al., 1997). However, some studies have reported that the ductile strike–slip shearing did not coincide with the India–Asia collision (e.g. Palin et al., 2013), whereas some studies in Tibet and the Ailao Shan–Red River shear zone disagree with the continental extrusion model (e.g. Searle, 2006; Searle et al., 2010, 2011).

In Thailand, the main strike–slip structures are the NW–SE sinistral Mae Ping and Three Pagodas shear zones in the west, and the NE–SW dextral Ranong and Khlong Marui shear zones in the south, respectively (Kanjanapayont et al., 2012a; Kanjanapayont, 2015). The Mae Ping and Three Pagodas shear zone with the generally sinistral strike–slip kinematics possible splays out from the Sagaing fault in Myanmar. However, the area where these strike–slip systems mechanically interact is still poorly documented. Many authors reported that the Mae Ping strike–slip zone is splayed to the Klaeng fault zone in eastern Thailand, and the Three Pagodas strike–slip zone is extended to the Ranong shear zone in the southern Thailand (Lacassin et al., 1993, 1997; Leloup et al., 1995; Gilley et al., 2003; Geard, 2008; Nantasin et al., 2012; Ridd, 2012; Ponmanee et al., 2016). In other geological interpretations (e.g. Morley, 2002; Morley et al., 2007; Smith et al., 2007), the Three Pagodas strike–slip zone is possibly connected to the Klaeng fault zone, which documents ductile sinistral shearing in the Eocene (Kanjanapayont et al., 2013). In southern Thailand, the Ranong and Khlong Marui shear zones extend from the continental margin and Mergui basin to the Gulf of Thailand (Tapponnier et al., 1986; Lacassin et al., 1997; Charusiri et al., 2002). All of the major strike–slip shear zones in Thailand possibly were active during the Eocene (Lacassin et al., 1997; Watkinson et al., 2011; Kanjanapayont, 2015; Kanjanapayont et al., 2012b; Nantasin et al., 2012; Palin et al., 2013).

Moreover, the high–grade metamorphic and plutonic exposures in such crustal scale strike–slip zones represent an important source for investigating the kinematics and the timing of the tectonic evolution of SE Asia (e.g. Lacassin et al., 1997; Palin et al., 2013). Especially in Thailand, syndeformational metamorphic rocks are exposed along the main ductile strike–slip shear zones (Lacassin et al., 1997; Kanjanapayont, 2015; Kanjanapayont et al., 2012a; Nantasin et al., 2012; Palin et al., 2013; Ponmanee et al., 2016) (Fig. 1). In this study, we report quantitative structural investigations of relatively homogeneously deformed rocks from the Three Pagodas shear zone.

2. Geological setting

The mylonites of the NW–SE striking Three Pagodas shear zone is 250 km long and 25 km wide and extends from the Three Pagodas Pass on Thai–Myanmar border towards central Thailand (Kanjanapayont, 2015). This ductile strike–slip shear zone cuts the sedimentary units of the Palaeozoic (Silurian–Permian) and Mesozoic sedimentary units, and subordinate low–metamorphic units of Cambrian–Ordovician (Department of Mineral Resources, 1982). The Three Pagodas shear zone is characterized by a lenticular slice of the high–grade metamorphic rocks named "Thabsila gneiss" or "Thabsila metamorphic complex" in the Kanchanaburi region in western Thailand (Nantasin et al., 2012). It has been inferred as Precambrian basement rock (Bunopas, 1981; Department of Mineral Resources ,1982). The Thabsila gneiss, which shown as mylonites in Fig. 2, is made up of four units based on lithology and structural features: (1) Unit A: marble, mica schist, fine-grained biotite gneiss, and quartzite (Fig. 3), (2) Unit B: mylonitic gneiss and mylonite, (3) Unit C: calc–silicate, and (4) Unit D: biotite gneiss, orthogneiss, and sillimanite gneiss (Nantasin et al., 2012). Augen structures within a very strongly developed foliation can be observed in the mylonitic gneisses of Unit B. Calc–silicates are typically intercalated with the gneisses of Unit B and C as boudins or strongly folded slices, and contain diopside–rich layers alternating with marble layers. The transitional zone of Unit C toward Unit D is characterized by a narrow band of garnet–free amphibolite, which gradually changed into biotite gneiss. Based on petrology and mineral chemistry (Nantasin et al., 2012), the Thabsila gneiss was formed during single metamorphic event at upper amphibolite to lower granulite facies conditions. The rocks experienced constrictional strain and sinistral shearing during exhumation (Nantasin et al., 2012).

In the past, the sharp contact between less metamorphic Paleozoic rocks and the high–grade metamorphic rocks led to the interpretation that these high–grade and partly anatectic metamorphic rocks are Precambrian in age (Department of Mineral Resources, 1982). These high–grade metamorphic rocks were typically intruded by Permo–Triassic and Cretaceous–Tertiary granitic plutons (Lacassin et al., 1997). Previous studies of $^{40}Ar/^{39}Ar$ dating, however, reveal that the deformation of the Mae Ping and the Three Pagodas shear zones terminated around 30.5 Ma (Oligocene), and the lower Mesozoic metamorphic and magmatic belt of northern Thailand experienced rapid cooling in the period of around 23 Ma (Oligocene–Miocene)

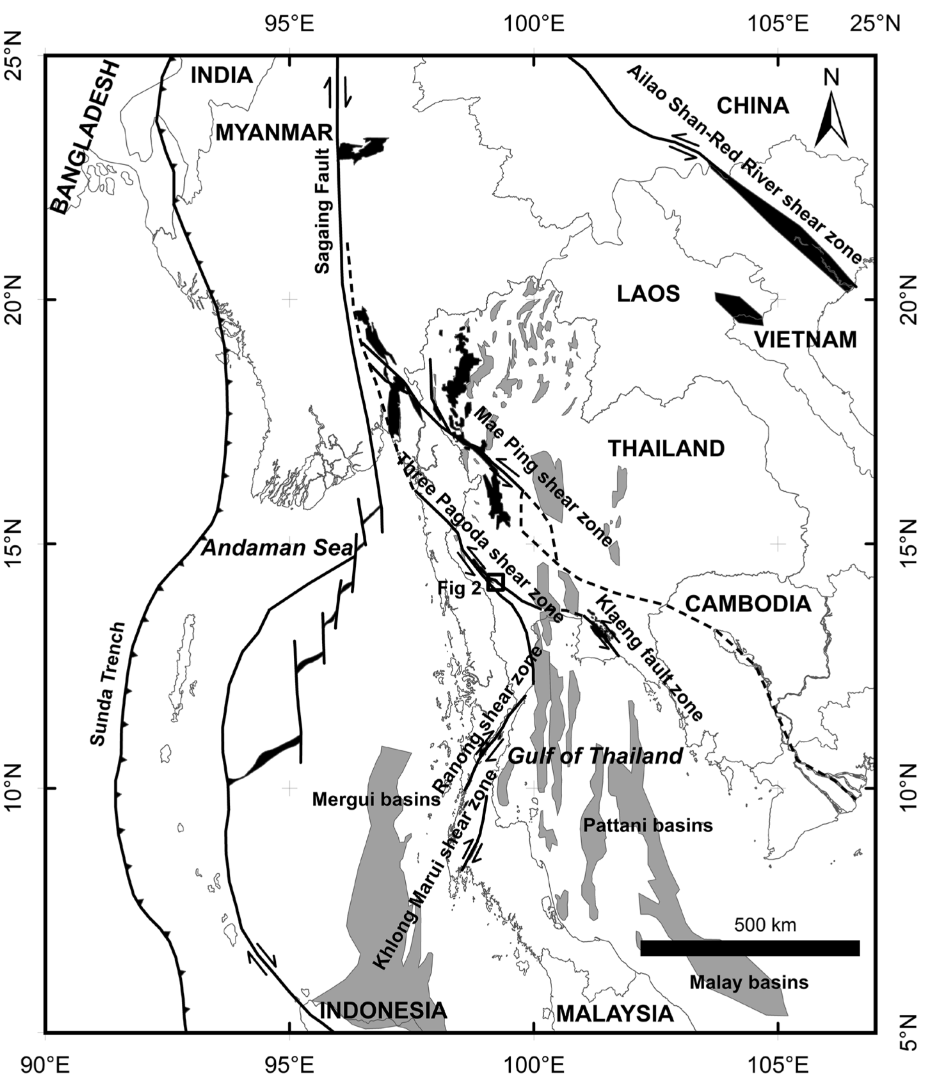

Figure 1: Simplified regional tectonic map of Thailand and adjacent areas showing the major shear zones and related structures (modified after Macdonald et al., 2010; Mitchell et al., 2012; Morley, 2002; Polachan and Sattayarak, 1989). Black, metamorphic complex; grey, Cenozoic basins; arrows, ductile shear sense. Box refers to Fig.2.

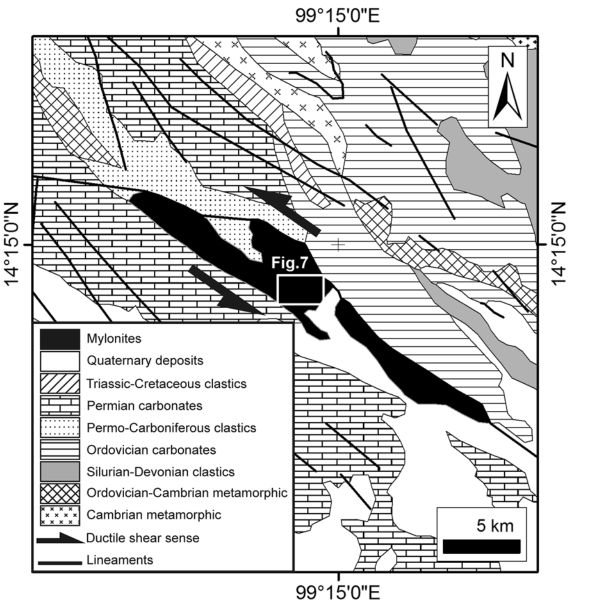

Figure 2: Geological map of the Three Pagodas Shear zone and neighboring area (modified after Department of Mineral Resources, 1982). Box refers to Fig.7.

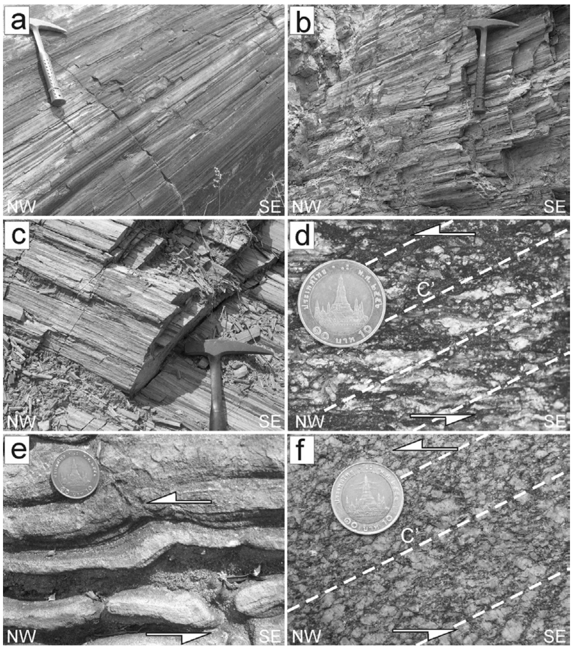

Figure 3: Macro– and microstructures the Three Pagodas shear zone; (a) subhorizontal stretching lineations, (b) subvertical dipping foliation, (c) quartz mylonites with foliations and stretching lineations, (d) C'–type shear band in the biotite gneiss, (e) asymmetric folds in calc–silicates, and (f) C'–type shear band in the orthogneiss.

(Lacassin et al., 1997). Sinistral shearing occurred after the collision of India and Asia, which later rotated and pushed a large portion of Indochina southeastward leading the formation the South China Sea (Lacassin et al., 1993, 1997). These results imply that extrusion of this part of Indochina occurred during the Upper Eocene to Lower Oligocene along ductile sinistral shear zones.

Recent geochronology data from the Thabsila gneiss reveal both events in the Three Pagodas shear zone

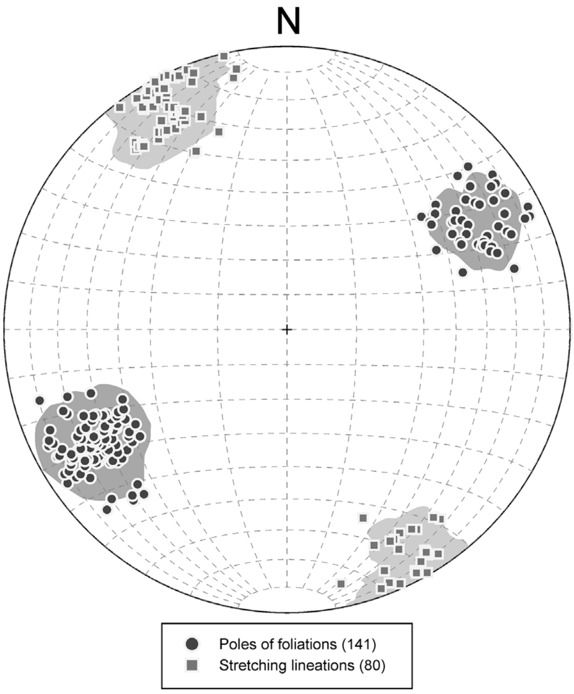

Figure 4: Stereographic plots of the mylonitic foliation with 5% contours indicated and the stretching lineations. The software InnStereo Beta 5 (http://innstereo.github.io/) was applied for preparing stereoplots.

(Nantasin et al., 2012). Zircon rims U–Pb ages at 51–57 Ma suggest that the peak upper amphibolite facies metamorphism occurred during the early collision between India and Asia in the Paleocene–Eocene (Nantasin et al., 2012). The biotite Rb–Sr ages of 32–36 Ma, are in accord with biotite K–Ar ages of 33–36 Ma (Bunopas, 1981) and biotite $^{40}Ar/^{39}Ar$ age of 33 Ma. (Lacassin et al., 1997), and reveal cooling of the basement rocks during the Eocene–Oligocene (Nantasin et al., 2012).

3. Structural geology

3.1 Foliation and lineation

The outcrops of all rock types within the Three Pagodas shear zones generally present a well–developed steep to subvertical dipping foliation with NW–SE strike direction and a subhorizontal stretching lineation (Fig. 3a–c). The dip angles of the foliation show more variation in the calc–silicates, which are associated with asymmetric NW–vergent folds (Fig. 3e). Isoclinal folds, which have fold axis parallel to the stretching lineation, can be found in some layers of the calc–silicates. The stereoplots of our structural data representative for the ductile deformation in this shear zone present a steeply NE–SW dipping mylonitic foliation with a subhorizontal NW–SE trending stretching lineation (Fig. 4).

3.2 Kinematic indicators

Various types of kinematic indicators (for terminology and classification see Passchier and Trouw, 2005) are preserved in all rock units of the Three Pagodas shear zone. All kinematic indicators indicate a sinistral sense of ductile shearing. C– and C′–type shear band with monoclinic symmetry (Fig. 3d, f) are observed in the biotite gneisses. Isolated σ–type clasts of K-feldspar with a clear stair stepping geometry are frequently observed in the orthogneisses (Kanjanapayont, 2015). In some layers of the calc–silicates, the sinistral shear sense is recorded by asymmetric folds (Fig. 3e) and by asymmetric shear band boudinage.

3.3 Microstructure

A variety of microscale shear sense indicators such as stair stepping along σ–type clasts, strain shadows with monoclinic symmetry, mica fish, SC/SCC′ fabrics and oblique foliation and shape preferred orientations furthermore confirmed the sinistral shear sense in the Three Pagodas shear zone. The orthogneisses and quartzites display elongate deformed quartz crystals with a strong preferred orientation oblique to the main mylonitic foliation (Fig. 5a). K–feldspars in the orthogneisses are typically deformed into σ–type clasts (Fig. 5b), while micas in the biotite gneisses are generally deformed into mica fishes (Fig. 5c). The sinistral shear sense interpretation of domino type boudinage in fractured K–feldspars is supported by differential rotation of grain fragments (Fig. 5d). Some feldspar grains of the orthogneisses show deformed twins (Fig. 5e). Strain shadows with monoclinic symmetry consisting of both fine recrystallized quartz and feldspar are typically presented around K-feldspar (Fig. 5f). Patchy extinction, dislocation glide, bulging, and subgrain rotation indicate dynamic recrystallization of quartz under greenschist metamorphic conditions in this shear zone.

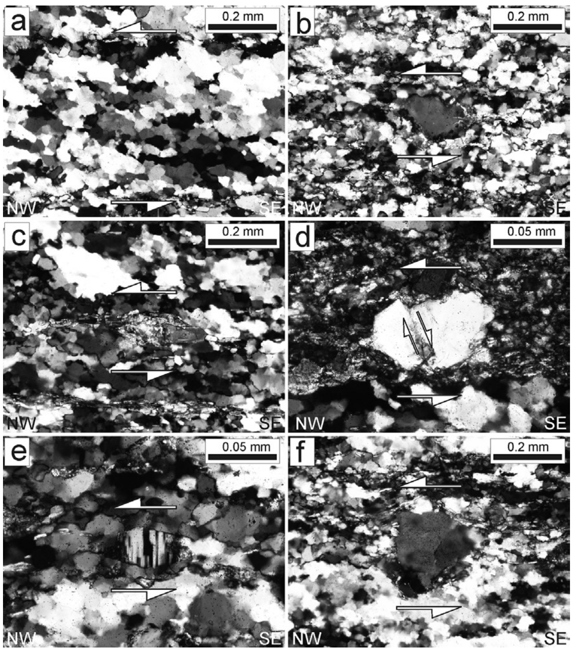

Figure 5: Microstructures of mylonites within the Three Pagodas shear zone; (a) sharp preferred orientation of recrystallized quartz oblique to the main mylonitic foliation, (b) σ–type clasts of K-feldspar, (c) sinistral mica fish, (d) domino-type porphyroclast of feldspar, (e) sinistral deformed twin in feldspar clast, and (f) strain shadow of fine recrystallized quartz and feldspar associated with K–feldspars.

4. Sampling and finite strain analysis

The quartz mylonites or quartzites in the Unit A of Nantasin et al. (2012) were collected from the outcrops in the Kanchanaburi region, western Thailand. The sampling line was perpendicular to the mean foliation strike in order to obtain data across the shear zone. The oriented samples were cut perpendicular to the foliation and parallel to the lineation for the thin sections. Multiple thin sections of each samples were investigated by polarized microscope in order to select strain markers for the strain analysis using the Fry method (Fry, 1979). The Fry method is based on the nearest–neighbor centre–to–centre technique, which uses the relative distance between the centers of each particles or minerals. In two–dimensions, the particles had a roughly random anticlustered orientation in undeformed state. When homogeneous deformation affects these particles, the distance between the center points of the particle are modified. Then the modified particle centers can be used to quantity strain ellipsoid (for details about the method see Lacassin and Van Den Driessche, 1983; Genier and Epard, 2007). We are aware of the problems applying the Fry method to rocks where the finite deformation is accommodated by various deformation mechanisms (see Ramsay and Huber, 1983; Xypolias et al., 2007). Our samples show a strong shape preferred orientation, which formed by dislocation glide and bulging with minor subgrain rotation (not considered in our Fry analysis) and therefore only this increment of strain can be quantified with the Fry method.

In the Three Pagodas shear zone, the result of the Fry method is represented by an elliptical vacancy field around the origin of reference point (Fig. 6). The axial ratio (R_s) is measured for the strain of the last strain increment recorded in the greenschist facies quartz mylonites,

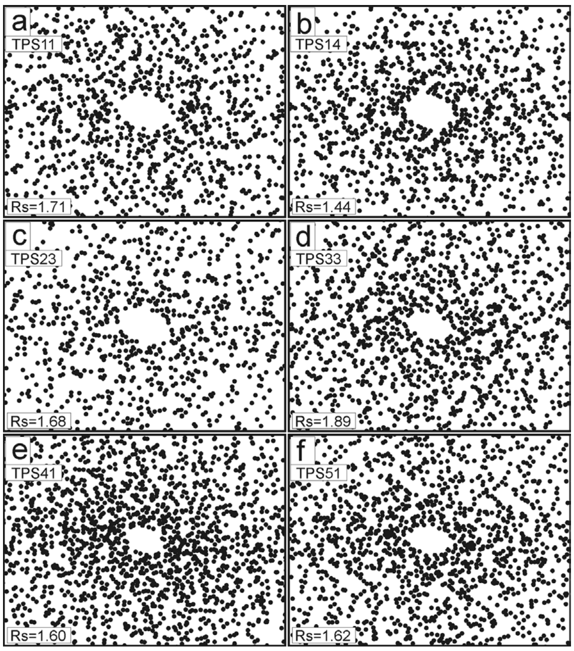

Figure 6: The finite strain ellipses derived from XZ–sections using the nearest neighbour center–to–center Fry method (Fry, 1979). The high–resolution finite strain ellipses of XZ–plane of the samples along the Three Pagodas shear zone; (a) TPS11, (b) TPS14, (c) TPS23, (d) TPS33, (e) TPS41, and (f) TPS51. They commonly present uniform and homogeneous deformation.

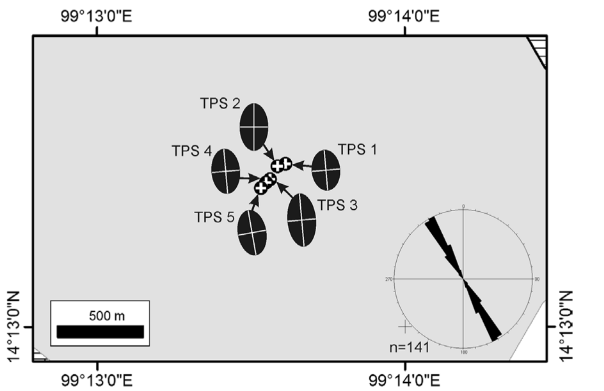

Figure 7: Ellipticities represented the finite strain along the Three Pagodas shear zone profile. Rose diagram presents the major foliation trend in the direction of 150°.

and the distribution of the measured finite strain is plotted in the map of the Three Pagodas shear zone as finite strain ellipse (Fig. 7).

5. Kinematic vorticity number

In ductile shear zones, the mean kinematic vorticity number is a significant quantity characterizing the nonlinear ratio of simple shear to pure shear deformation. The kinematic vorticity number is calculated from the magnitude of the vorticity vector and the principal stretching rates (Truesdell, 1954; Means et al., 1980). In this study, we use the mylonitic quartz fabric, which records a strong shape preferred orientation. The flattened grains clearly develop under low-greenschist facies conditions and we are aware that any earlier deformation history recorded by dynamic recrystallization, in particular subgrain rotation, is not considered by this method. We applied two different methods (for a review and details of methods deriving the vorticity number from natural shear rocks see Xypolias, 2010).

(i) The strain-ratio/quartz c-axis-fabric method assumes that the long axis of flattened grains approximates the orientation of the long axis of the finite strain ellipsoid of a given strain increment (R_s). The angle (θ) between the oblique-grain-shape fabric and the flow plane combined with the strain-ratio (R_s) in the xz-plane of the investigated strain increment can be used to derive the mean kinematic vorticiy number (W_k) of the increment.
The kinematic vorticity number (W_k) is calculated by the following equation (Wallis, 1992; Wallis et al., 1993; Sarkarinejad, 2007):

$$W_k = \sin\left\{\tan^{-1}\left[\frac{\sin(2\theta)}{(R_s+1/(R_s-1)-\cos(2\theta))}\right]\right\} \times \frac{(R_s+1)}{(R_s-1)} \quad (1)$$

The averaged finite strain ratios (R_s) range from 1.60 to 1.97 (Tab. 1), and the angle (θ) is from 18° to 33°.

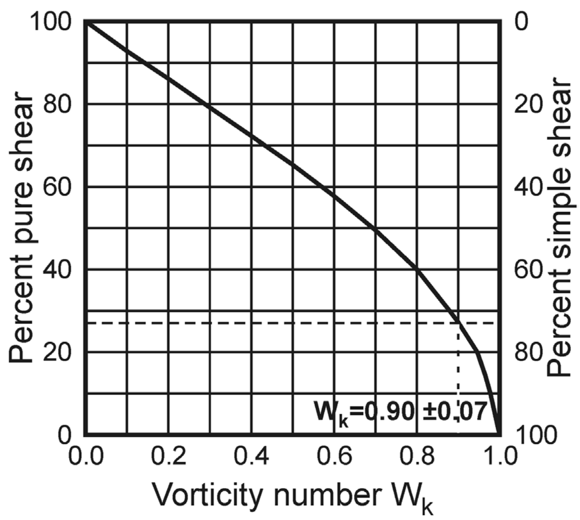

Figure 8: Diagram presenting the relationship between kinematic vorticity number (W_k) of pure shear and simple shear component (Law et al., 2004). Pure shear and simple shear components for instantaneous 2D flow contribute to the instantaneous flow at W_k = 0.90 ±0.07.

Thus, the kinematic vorticity number (W_k) is between 0.75 to 0.99 with the average of 0.90 ±0.07 (Fig. 8); data of the Three Pagodas shear zone are presented in Tab. 1.

(ii) Based on observation in natural mylonites and results from experiments (e.g. Ree, 1991; Herwegh and Handy, 1998), it has been suggested that the long axes of quartz neo-blasts within a shape preferred orientation initially align almost parallel to the extensional instantaneous stretching axis (ISA_1). Measuring the maximum observation angle (θ_{max}) between the oblique-grain-shape fabric and the flow plane might be used to estimate the kinematic vorticity number (W_k) is estimated by the following equation (Xypolias, 2009, 2010):

$$W_k = \sin 2\theta_{max} \quad (2)$$

The maximum angle (θ_{max}) of 33° of the rocks within Three Pagodas shear zone will give the mean kinematic vorticity number (W_k) of 0.91 for the low-greenschist facies increment of deformation.

6. Discussion

We estimated the finite strain ellipsoid and the mean kinematic vorticity number (W_k) in order to quantify the flow within the Three Pagodas shear zone. Although our approach is based on a number of assumptions in deformation history such as steady–state deformation or isochoric plane strain flow, our derivation of W_k and the finite strain can be used as a first estimation for the flow within the Three Pagodas shear zone. In nature, the deformation in strike–slip shear zones may occur in a simple shear and pure shear combination, which can be described in terms of transpressional to transtensional deformation. Sanderson and Marchini (1984) reported that the W_k value can be used to discriminate between pure–shear dominated

Named of sample sites	Strain ratio		Angles			Kinematic vorticity number	
	(R_s) min.–max.	(R_s) avg.	(θ) min.–max.	(2θ) min.–max.	(radian) min.–max.	(W_k) min.–max.	(W_k) avg.
TPS 1	1.44–1.71	1.60	20–25	40–50	0.70–0.87	0.79–0.88	0.90±0.07
TPS 2	1.69–1.90	1.82	27–33	54–66	0.94–1.15	0.94–0.99	
TPS 3	1.88–1.91	1.89	23–30	46–60	0.80–1.05	0.88–0.98	
TPS 4	1.60–2.21	1.97	25–27	50–54	0.87–0.94	0.88–0.96	
TPS 5	1.62–1.82	1.75	18–24	36–48	0.63–0.84	0.75–0.89	

Table 1: Summarized data from the mylonitic rocks within the Three Pagodas shear zone.

and simple shear–dominated transpressional deformation. W_k ranging between 0 and 0.81 suggest the characteristics of a pure shear–dominated transpression zone, and W_k range from 0.81 to 1 is typical for simple shear–dominated transpression (Fossen and Tikoff, 1993). Note, that any deviation from ideal simple requires decoupling at the shear zone boundaries (Means, 1989), volume change (Ramsay and Huber, 1983) and /or non-plane strain conditions (Fossen and Tikoff, 1993). Although the investigated outcrops in the present day do not allow to discriminate between these different processes, it is interesting to note, that within the Three Pagodas shear zone, the W_k value of all investigated samples from two different methods give the similar kinematic vorticity numbers (W_k). It ranges between 0.75 and 0.99 clearly indicating simple shear–dominated transpression. The average kinematic vorticity numbers (W_k) of 0.90 ±0.07 of the deformation in the Three Pagodas shear zone indicate that 71.5% simple shear and 28.5% pure shear controlled the flow (Fig. 8).

From macroscopic and microscopic investigations, all kinematic indicators (σ–type clasts, strain shadow, mica fish, SC and SCC′ fabrics, oblique foliation, stair stepping, asymmetric folds, asymmetric boudins) clearly suggest sinistral non–coaxial flow. The deformation mechanisms recorded in the quartz, which comprise undulose extinction, dislocation glide, bulging, and subgrain rotation suggest that the rocks were mylonitized under greenschist metamorphism. Both kinematic indicators and deformation mechanism confirmed the previous studies (Lacassin et al., 1997; Nantasin et al., 2012). We conclude that the major deformation in the Three Pagodas shear zone is sinistral strike–slip transpression, and the shear zone exhumed during deformation (Fig. 9). These results fit well with the extrusion model in the SE Asia region (Lacassin et al., 1993, 1997). The Three Pagodas shear zone is characterized by flow geometry similar to that recorded in the parallel northward Mae Ping shear zone (Ponmanee et al, 2016) with a smaller kinematic vorticity numbers (W_k) (Fig. 10).

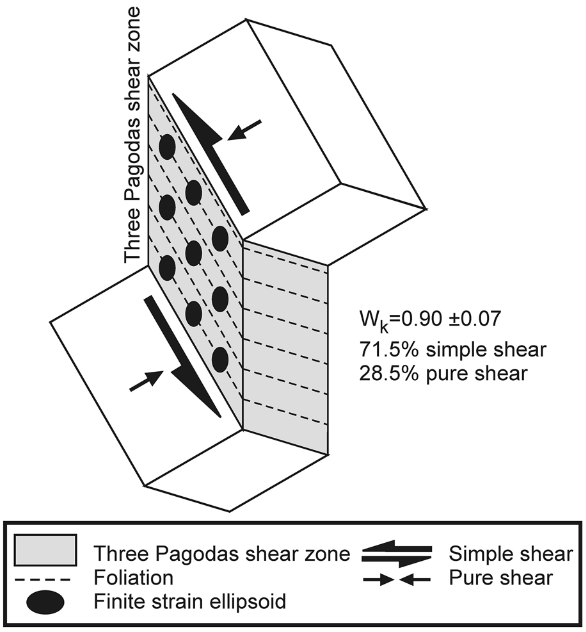

Figure 9: Schematic block diagram illustrating the sinistral ductile deformation within the Three Pagodas shear zone. The values of estimated mean W_k suggest that simple component was predominantly associated with the strike–slip ductile deformation.

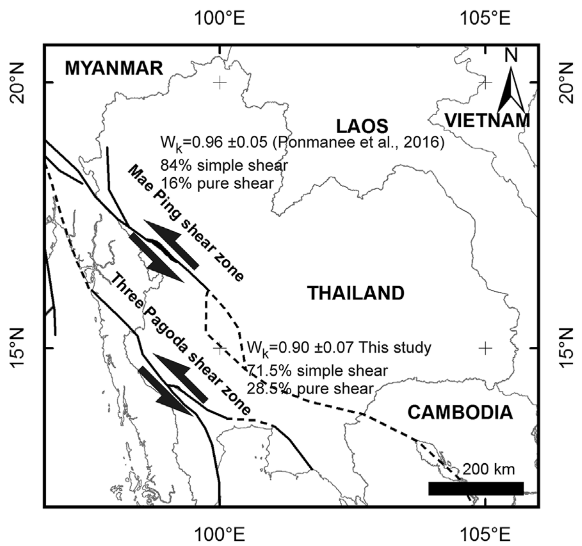

Figure 10: Map showing the kinematic vorticity number (W_k) with simple shear and pure shear components of the sinistral Mae Ping and Three Pagodas shear zones in western Thailand.

7. Conclusions

We used two–dimensional quantitative strain analysis of quartz mylonites from the Thabsila gneiss in Kanchanaburi region, western Thailand in order to determine the kinematics of the Three Pagodas shear zone. We found that the averaged finite strain ratio (R_s) and the angle (θ) range between 1.60–1.97 and 18°–33°, respectively. Based on the relation between the two values, the kinematic vorticity number (W_k) is between 0.75–0.99, which clearly described the characteristic of a sinistral simple shear–dominated transpression in this strike–slip ductile shear zone. All kinematic indicators of the high–grade metamorphic rocks clearly indicate the sinistral shear sense within the Three Pagodas shear zone.

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