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Quantitative finite strain analysis of high-grade metamorphic rocks within the Mae Ping shear zone, western Thailand

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Abstract

The NW trending Mae Ping shear zone exposes high-grade metamorphic rocks, the so called Lansang gneiss in the Tak region, western Thailand. The lithologies within the strike-slip zone mainly consist of orthogneisses and paragneisses. Using Fry's method for 2-dimensional strain analysis we find that the averaged finite strain ratio (R_s) of the XY-plane is R_s = 1.35-1.69. Based on the kinematic vorticity analysis of the mylonitic gneisses in the shear zone, the kinematic vorticity number is W_k = 0.8-1.0 with an average of W_k = 0.95. The results imply that the homogeneously deforming rocks within the Mae Ping shear zone have a strong simple shear component with a minor pure shear contribution of about 15 %. The kinematic indictors from both outcrop and microscopic scales indicate a sinistral strike-slip shear sense. We conclude that the Mae Ping shear zone accommodated crustal scale sinistral transpression.

1. Introduction

The NW-SE striking Mae Ping shear zone in western Thailand has been suggested to be related to the continental extrusion that characterizes the structural evolution of Southeast Asia (Tapponnier et al., 1982, 1986). This model assumes that the large thickened continental crusts of Sundaland, Tibet, and South China have been extruded by the movement of the Indian indenter via the motion of strike-slip systems to the E and SE direction (Tapponnier et al., 1986). Extrusion of Sundaland to the SE is accommodated by dextral shearing along the Sagaing fault in Myanmar, and sinistral shearing along the Ailao Shan-Red River and Mae Ping shear zones in China and Thailand, respectively (e.g. Tapponnier et al., 1990; Lacassin et al., 1997; Morley et al., 2007). Within these crustal scale strike-slip fault zones, high-grade metamorphic and plutonic rocks have been exhumed documenting the mid-crustal deformation history of the continental extrusion (Lacassin et al., 1997). However, recent studies reported that the ductile strike-slip motion was not coincided with the India-Asia collision (e.g. Palin et al., 2013), and some studies in Tibet and the Ailao Shan-Red River shear zone contrast with the continental extrusion model (e.g. Searle, 2006; Searle et al., 2010, 2011).

Furthermore, the exposures of high-grade metamorphic and plutonic rocks 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). In Thailand, syndeformational metamorphic rocks are exposed along the Mae Ping shear, Three Pagodas, Ranong, and Khlong Marui shear zones (Lacassin et al., 1997; Kanjanapayont et al., 2012a; Nantasin et al., 2012; Palin et al., 2013) (Figure 1). In this study we focus on quantitative structural investigations of relatively homogeneously deformed rocks from the Mae Ping shear zone.

2. Geological setting

Mesozoic and Cenozoic strike-slip systems play an important role in the tectonic evolution of SE Asia. These systems have orientations which kinematically fit to the 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). The most prominent structures are the N-S trending dextral Sagaing fault in Myanmar and the NW-SE trending sinistral Ailao Shan-Red River shear zone in China. In Thailand, the major strike-slip structures are the NW-SE sinistral Mae Ping and Three Pagodas shear zones, and the NE-SW dextral Ranong and Khlong Marui shear zones (Kanjanapayont et al., 2012a). The Mae Ping shear zone with the dominantly sinistral strike-slip kinematics probable splays out from the Sagaing fault in Myanmar. However, the region where the two strike-slip systems potentially merge is structurally poorly documented. In many geological interpretations the Mae Ping strike-slip zone is extended to the Klaeng fault zone in eastern Thailand (Lacassin et al., 1993, 1997; Leloup et al., 1995; Gilley et al., 2003; Geard, 2008; Nantasin et al., 2012), which records ductile sinistral shearing during the Eocene (Kanjanapayont et al., 2013). The Ranong and Khlong Marui shear zones in the southern Thailand extend from the continental margin and Mergui basin to the Gulf of Thailand from W to E (Tapponnier et al., 1986; Lacassin et al., 1997; Charusiri et al., 2002). All four major strike-slip shear zones in Thailand were probably active during the Eocene (Lacassin et al., 1997; Watkinson et

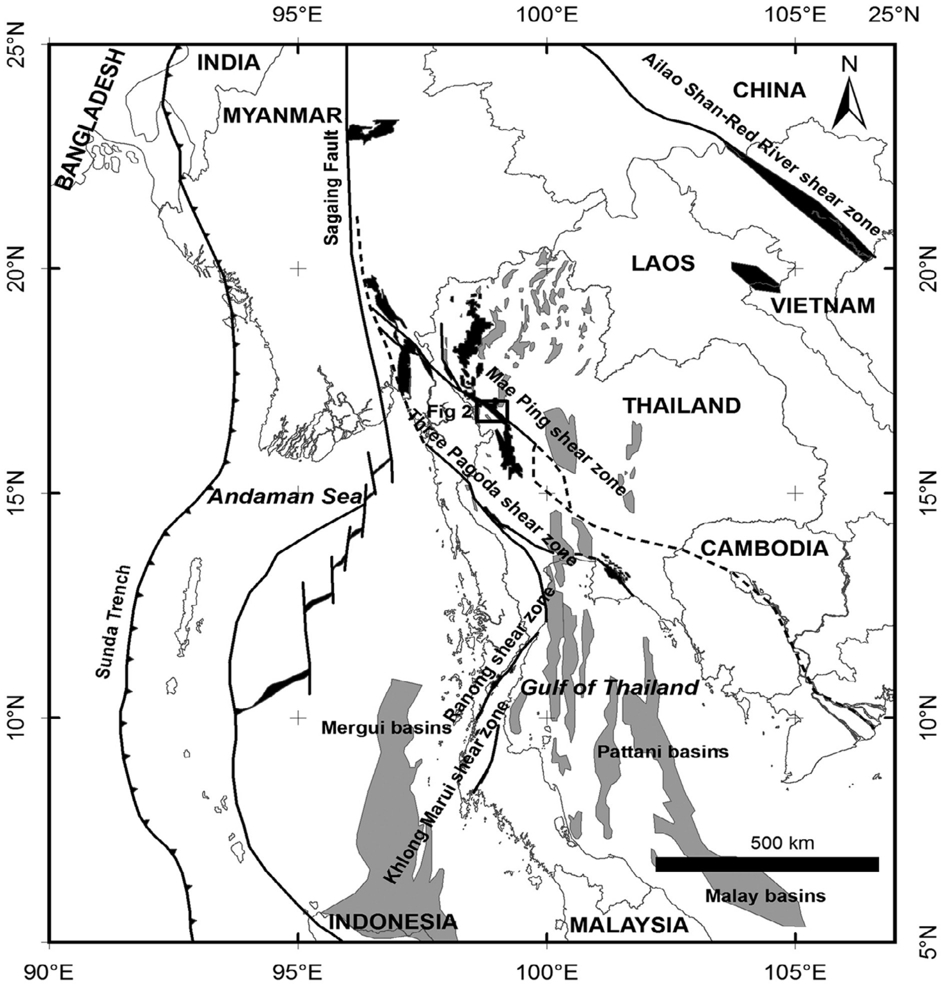

Figure 1: Simplified regional tectonics map of Thailand showing the major shear zones and related structures (modified after Macdonald et al., 2010; Mitchell et al., 2012; Morley, 2002; Polachan and Sattayarak, 1989). Black, metamorphic complex; grey, Cenozoic basins; arrows, ductile shear sense. Box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

al., 2011; Kanjanapayont et al., 2012b; Nantasin et al., 2012; Palin et al., 2013).

The Mae Ping shear zone cross cuts a major metamorphic and magmatic belt, the "Chiang Mai-Lincang belt" (CM-LB) (e.g. Lacassin et al., 1993; Palin et al., 2013). This N-S trending belt is the most important structural feature in NW Thailand. The CM-LB is about 70 km wide and offset by numerous strike-slip shear zones such as the Mae Ping and Three Pagodas shear zones. High-grade metamorphic rocks of various composition and origin occur within the CM-LB and some of them are exposed within the Mae Ping shear zone (Lacassin et al., 1997; Palin et al., 2013). In the past, the juxtaposition of less metamorphic Paleozoic rocks led to the interpretation that these high-grade, partly anatectic metamorphic rocks are of Precambrian age (Department of Mineral Resources, 1982), which were intruded by mainly Permo-Triassic and Cretaceous-Cenozoic granitic plutons (Lacassin et al., 1997).

The NW-SE trending Mae Ping shear zone extends for more than 600 km across Thailand. It forms a number of strike-slip duplex complexes and exposes a granite-gneiss complexes along 120-150 km (Lacassin et al., 1997). The rocks within the Mae Ping shear zone are dominated by mylonitic orthogneisses and paragneisses, the "Lansang gneiss" in the Tak region in western Thailand (Figure 2). The Lansang gneiss is made up of orthogneisses (Figure 3a), strongly deformed metasediments (quartz-feldspar-biotite paragneisses, micaschists, calcsilicate rocks and marbles) (Figure 3b), pegmatite, quartz and micro-granite (Lacassin et al., 1993, 1997). Quartz-feldspar-biotite gneisses, calcsilicate rocks and marbles are the most frequent lithologies. They occurred as bands of layered mylonites, which either trend parallel to the main foliation and alternate with paragneisses, micaschists, deformed pegmatite veins and orthogneisses. The calcsilicate rocks consist of alternating green and brown bands of quartz, plagioclase, pyroxene, hornblende, calcite, muscovite and garnet. The layered dark marbles contain abundant boudin structures of calcsilicate rocks and leucocratic granites.

Previous geochronological studies reveal $^{40}Ar/^{39}Ar$ deformation ages of the Lansang gneiss around 30.5 Ma (Oligocene) and suggest that the early Mesozoic metamorphic and magmatic belt of northern Thailand records a rapid cooling in the period of around 23 Ma (Lacassin et al., 1997). Sinistral shearing occurred after the indentation of India into the Asia, which later rotated and pushed large slices of Indochina southeastward leading the formation of the South China Sea (Lacassin et al., 1993; 1997). Based on these results, the extrusion of this part of Indochina occurred during the late Eocene to early Oligocene along ductile sinistral shear zones.

Monazite U-Pb ages from a sheared biotite-K-feldspar orthogneiss implied two events of monazite recrystallization (Palin et al., 2013). Core ages are between 114-123 Ma, while the rims show ages around 37-45 Ma. Based on these results, the ductile shearing along the Mae Ping fault occurred either during or after the metamorphic events, the last of which occurred during the Eocene. Besides, monazite ages from a undeformed garnet-bearing two-mica granite dyke, which intruded the metamorphic rock at Bhumibol Lake, are 66.2 ±1.6

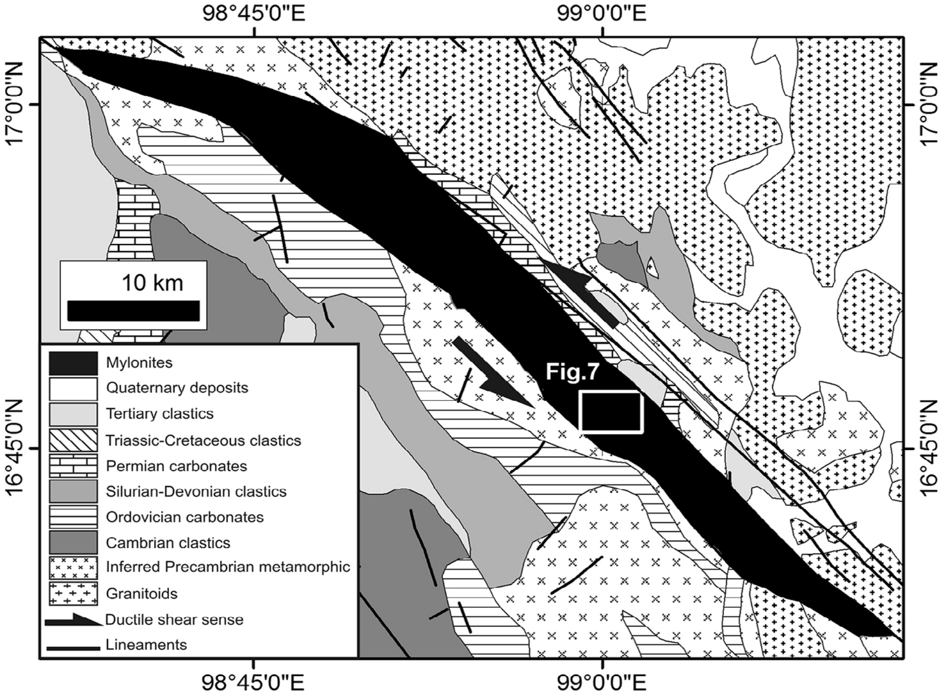

Figure 2: Geological map of the Mae Ping Shear zone and adjacent area (modified after Department of Mineral Resources, 1982). Box refers to Figure 7.

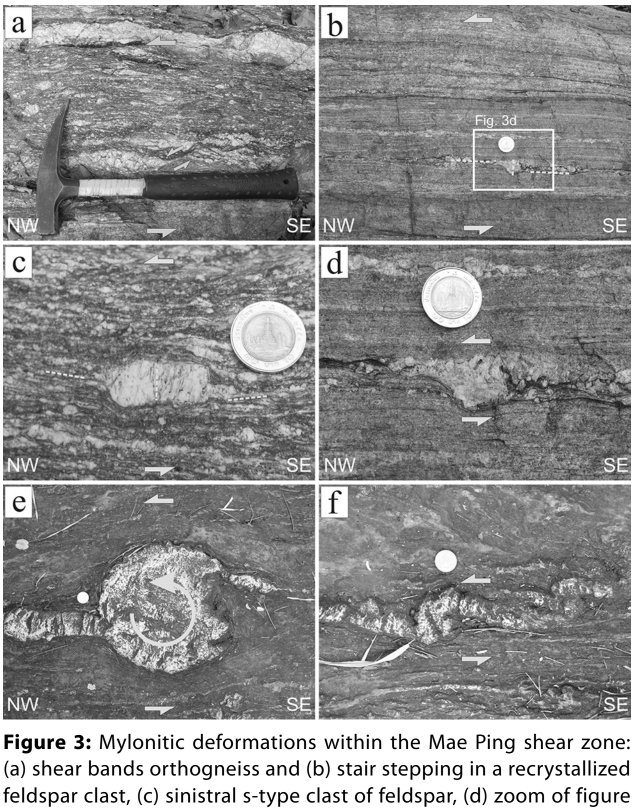

Figure 3: Mylonitic deformations within the Mae Ping shear zone: (a) shear bands orthogneiss and (b) stair stepping in a recrystallized feldspar clast, (c) sinistral s-type clast of feldspar, (d) zoom of figure b), (e) sinistral winged inclusion and (f) asymmetric drag fold in the calc-silicate layer.

Ma. This age implies that the Mae Ping fault crosscuts earlier formed magmatic and high-grade metamorphic rocks. Most importantly, the study concludes that both metamorphism and regional cooling was not related to the strike-slip movement, and the early Cenozoic deformation along the Mae Ping shear zone was not related to the escape tectonics (Palin et al., 2013).

3. Structural geology

3.1 Foliation and lineation

The general characteristics of ductile deformation in all rock types within the Mae Ping shear zone are a) a subvertical foliation and nearly horizontal lineation (Figure 3a-b). The foliation and layering of the orthogneisses are nearly vertical, while the paragneisses dip steeply toward to the NE and SW with more variation. The shear planes present various obliquities to the foliation planes. Poles of the foliations were plotted and contoured using the software InnStereo Beta 5 (http://innstereo.github.io). The simple data distribution record a steeply NE and SW dipping mylonitic foliation with a subhorizontal NW-SE trending stretching lineation (Figure 4).

3.2 Kinematic indicators

The strike-slip sinistral ductile deformation of the Mae Ping shear zone is recorded in numerous kinematic indicators (for classification see Passchier and Trouw, 2005). Shear bands, SC, SCC' fabrics (Figure 3a), and σ-type clasts with a clear stair stepping geometry (Figure 3b-d) have been identified in the orthogneisses. Winged inclusions (Grasemann and Dabrowski, 2015) (Figure 3e) and asymmetric drag folds (Figure 3f) are recorded in the paragneisses.

3.3 Boudinage structure

The boudinage structures within the Mae Ping shear zone are developed in leucocratic veins parallel to the mylonitic foliation suggesting a non-coaxial component during deformation. Based on boudinaged veins, a simple shear strain of $\gamma = 7 \pm 4$ to 9, and a minimum strike-slip displacement along the sinistral shear zone in the range of 35 ±20 km has been estimated (Lacassin et al., 1993).

3.4 Microstructure

The microstructures in the Mae Ping shear zone show that the sinistral shear sense clearly documented by the oblique foliation, stair stepping along σ-type clasts, mica fish, SC and SCC' fabrics. In thin sections the orthogneisses record a mylonitic fabric with elongate deformed quartz deformed by dis-

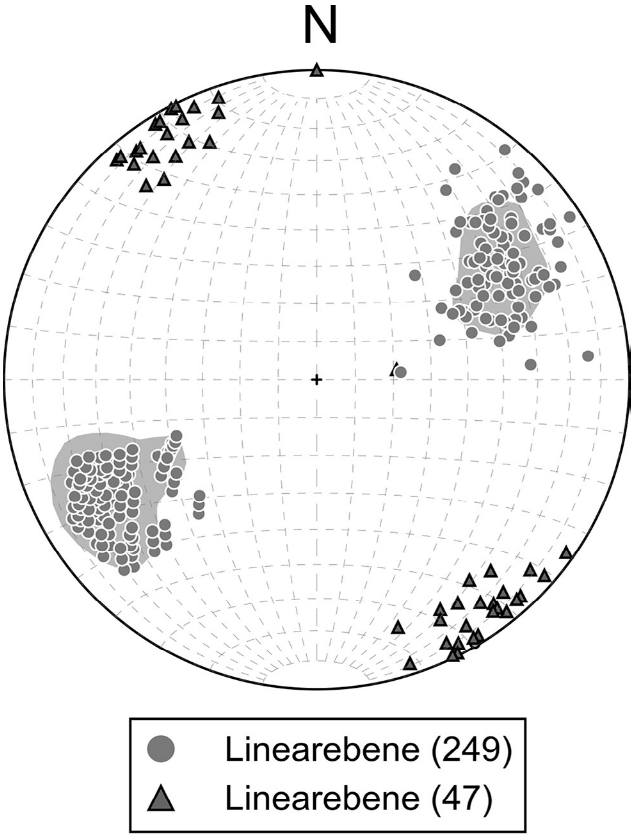

Figure 4: Stereographic plots of the mylonitic foliations (5 % contours indicated), and the stretching lineations.

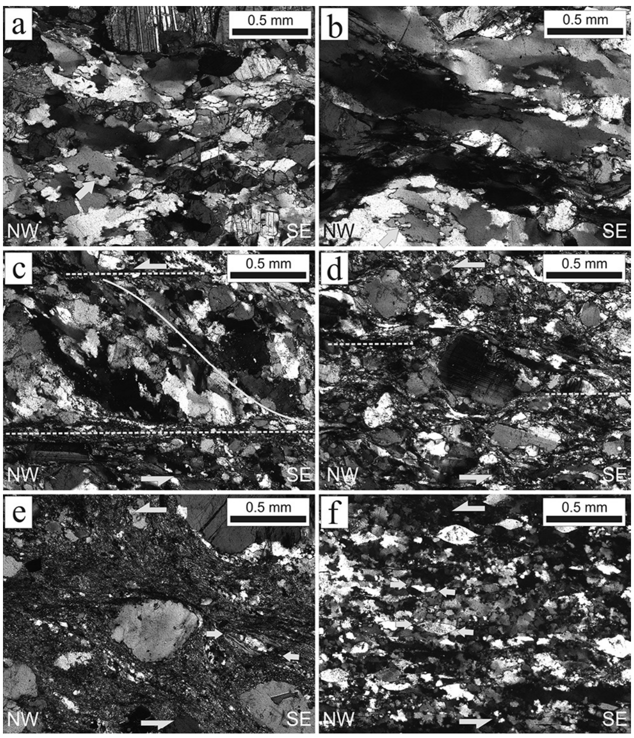

Figure 5: The photomicrographs of the high-grade metamorphic rocks within the Mae Ping shear zone; (a) undulatory extinction and grain low-temperature bulging in quartz, (b) elongate ductile deformed quartz grains and biotite, (c) shaped preferred orientation of quartz (SC fabric), (d) s-type clast of feldspar with stair stepping, (e) feldspar clast and sigmoidal shape of a recrystallized quartz lense, and (f) mica fish.

location glide/low-temperature bulging and biotite which, displays a medium to strong shaped preferred orientation (Figure 5a-c). Quartz grains from both ortho- and paragneisses deform into elongated crystal with a shap preferred orientation oblique to the main mylonitic foliation. Feldspars are typically deformed into σ-type clasts with strain shadows of fine recrystallized quartz and feldspar (Figure 5d-e). Both white mica and biotite deform into mica fish geometries (Figure 5f). Patchy undulose extinction, basal gliding, bulging, subgrain rotation and grain boundary migration indicated dynamic recrystallization of quartz under decreasing temperature conditions.

4. Sampling and finite strain analysis

Samples of Lansang gneiss were collected along the Lansang waterfall in the Tak region, western Thailand. The rock samples were cut perpendicular to the foliation and parallel to the lineation. Multiple thin sections of each sample was examined by polarizing microscopy in order to select strain markers for the strain quantitative analysis followed by Fry's method (Fry, 1979).

Fry's method focuses on two- dimensions. The theory of Fry (1979) is derived from the technique of nearest- neighbor centre-to-centre using the relative distance between the center point of each rigid particles or minerals, which had a roughly random anticlustered orientation before deformation. Thus when homogeneous deformation affects these particles, the distance between particle centers are modified and can be used to quantity the strain ellipsoid (for details about the method see Ramsay and Huber, 1983; Genier and Epard, 2007; Lacassin and Van Den Driessche, 1983).

The result of the Fry's method is represented by an elliptical vacancy field around the origin of reference point (Figure 6). The finite strain can be measured by the axial ratio R_s. The distribution of the measured finite strain is plotted in the map of the Mae Ping shear zone as finite strain ellipse (Figure 7).

5. Kinematic vorticity number

The mean kinematic vorticity number is an important quantity characterizing the nonlinear ratio of simple shear to pure shear deformation in ductile shear zones. The number is calculated from the magnitude of the vorticity vector and the principal stretching rates (Truesdell, 1954; Means et al., 1980), which equals the cosine of the angles between the eigenvectors of the flow.

To calculate the kinematic vorticity number (W_k), the following equation (Wallis, 1992; Wallis et al., 1993; Sarkarinejad, 2007) has been used:

$$W_k = sin\left\{ tan^{-1}\left[\frac{sin(2\theta)}{(R_s+1/(R_s-1)-cos(2\theta))}\right]\right\} x \frac{(R_s+1)}{(R_s-1)} \quad (5)$$

The averaged finite strain ratios (R_s) are between 1.35 and 1.69, and the angle (θ) is from 22° to 41°. The kinematic vorticity number (W_k) thus ranges from 0.79 to 1.00, and the

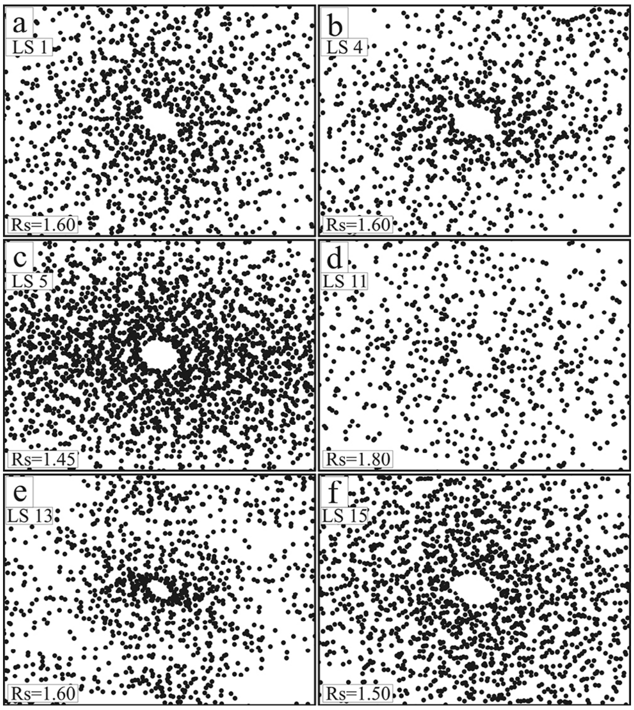

Figure 6: The finite strain ellipses derived from XY section using the nearest neighbor center to center Fry method. The finite strain ellipses of XY-plane typically present homogeneous deformation.

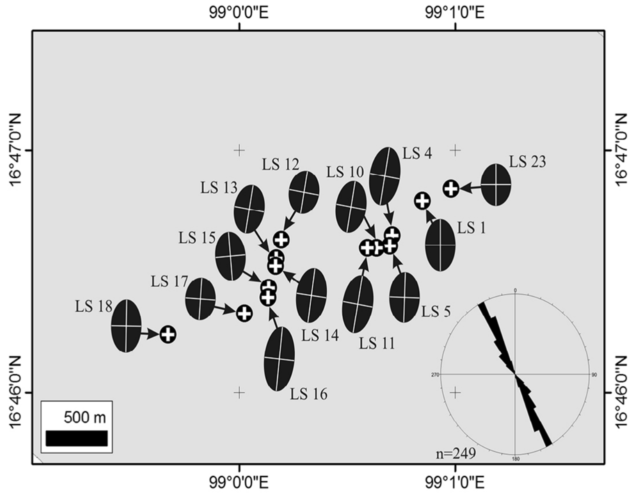

Figure 7: Ellipticities represented the finite strain along the profile of the Mae Ping shear zone. Rose diagram illustrates the major foliation trend in the direction of 150°.

average W_k is 0.96 ±0.05. The data of the kinematic vorticity number (W_k) are summarized in Table 1.

6. Discussion

In order to quantify the flow within the Mae Ping shear zone we estimated the finite strain ellipsoid and the mean kinematic vorticity number. Although our approach is based on a number of assumptions about the deformation history (e.g. steady-state deformation, isochoric plane strain flow), our derivation of W_k and the finite strain can be used as a first order estimation for the flow within the Mae Ping shear zone. The plane strain deformation in nature always occurs in the combination of a simple shear and pure shear, which can be described in terms of transpressional to transtensional deformation. In the Sanderson and Marchini model (1984), the transpressional deformation can be divided into pure-shear dominated and simple shear-dominated by the W_k value. W_k range from 0 to 0.81 imply the characteristics of a pure shear-dominated transpression zone. W_k ranging between 0.81 and 1 is typical for simple shear-dominated transpression (Fossen and Tikoff, 1993). The W_k value of all investigated samples ranges between 0.79 and 1.00 clearly indicating the dominance of simple shear-dominated transpression within the Mea Ping shear zone. The average kinematic vorticity numbers (W_k) of 0.96 ±0.05 of the deformation in the Mae Ping shear zone suggest that 84 % simple shear and 16 % pure shear controlled the flow (Figure 8).

Both the macroscopic and microscopic kinematic indicators (σ-clast, δ-clast, winged inclusions, shear bands, SC and SCC' fabrics, asymmetric drag folds) clearly suggest sinistral non-coaxial flow in accordance with previous studies (Lacassin et al., 1993, 1997; Palin et al., 2013). Furthermore, the deformation mechanisms recorded in the quartz, which comprise subgrain rotation, bulging, dislocation glide and undulatory extinction suggest that the rocks were mylonitized under decreasing temperature conditions. We conclude that the major deformation in the Mae Ping shear zone is sinistral strike-slip transpression, which exhumed during deformation under greenschist metamorphic conditions (Figure 9).

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.
LS 1	1.45-1.60	1.54	30-40	60-80	1.05-1.40	0.94-1.00	0.96 ±0.05
LS 4	1.38-1.80	1.59	33-40	66-80	1.15-1.40	0.97-1.00	
LS 5	1.45-1.56	1.49	32-33	64-66	1.12-1.15	0.96-0.98	
LS 10	1.38-1.64	1.56	22-40	44-80	0.77-1.40	0.82-1.00	
LS 11	1.45-1.80	1.68	30-40	60-80	1.05-1.40	0.97-1.00	
LS 12	1.33-1.40	1.37	30-40	60-80	1.05-1.40	0.93-1.00	
LS 13	1.38-1.60	1.49	29-40	58-80	1.01-1.40	0.92-1.00	
LS 14	1.50-1.70	1.57	36-39	72-78	1.26-1.36	0.99-1.00	
LS 15	1.46-1.64	1.53	22-35	44-70	0.77-1.22	0.79-0.99	
LS 16	1.50-2.00	1.69	27-40	54-80	0.94-1.40	0.93-1.00	
LS 17	1.31-1.91	1.58	23-40	46-80	0.80-1.40	0.85-1.00	
LS 18	1.42-1.67	1.53	26-35	52-70	0.91-1.22	0.91-0.98	
LS 23	1.29-1.45	1.35	25-41	50-82	0.87-1.43	0.84-1.00	

Table 1: Summarized data from the high-grade metamorphic rocks within the Mae Ping shear zone.

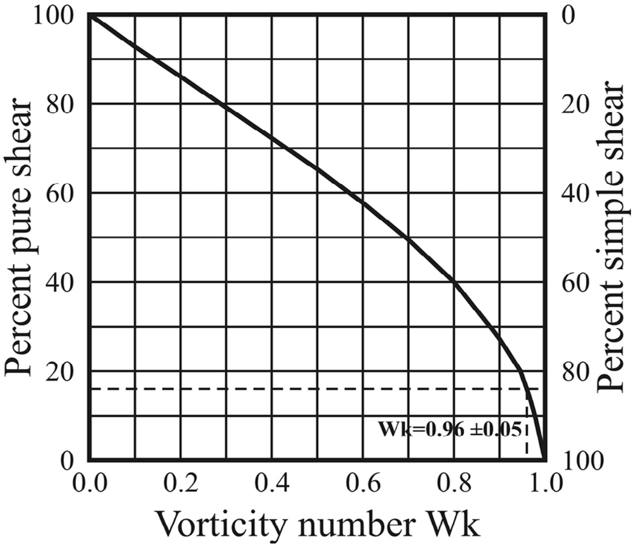

Figure 8: Diagram showing the relationship between kinematic vorticity number (Wk) of pure shear and simple shear component for instantaneous 2D flow (Law et al., 2004).. Pure shear and simple shear components contribute to the instantaneous flow at Wk = 0.96 ±0.05.

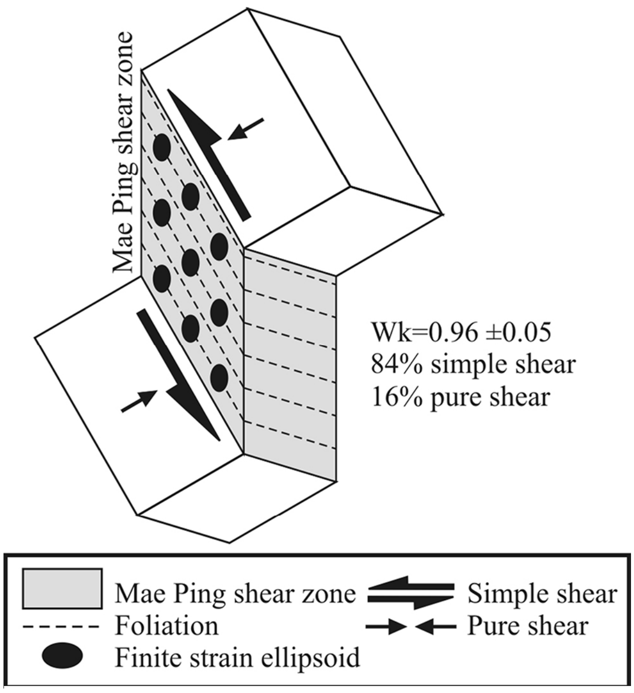

Figure 9: Schematic block diagram illustrating the deformation of the Mae Ping shear zone. It is characterized by sinistral ductile shear. The estimated mean Wk values show that simple component were dominantly involved in the strike-slip ductile deformation.

7. Conclusions

We used two-dimensional quantitative strain analysis of orthogneisses and paragneisses from the Lansang gneiss in Tak region, western Thailand in order to determine the kinematics of the Mae Ping shear zone. We found that the averaged finite strain ratio (R_s) and the angle (θ) range between 1.35-1.69 and 22°-41°, respectively. Based on the relation between the two values, the kinematic vorticity number (W_k) is between 0.79-1.00 and clearly describes the characteristics of a sinistral simple shear-dominated transpression. All kinematic indicators of the high-grade metamorphic rocks within the Mae Ping shear zone record clear sense of the sinistral shear. The dynamic recrystallization of quartz in this area preserves undulatory extinction, basal gliding, bulging, and subgrain rotation suggesting deformation under greenschist metamorphic condition and decreasing temperatures.

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