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Quantitative kinematic analysis within the Khlong Marui shear zone, southern Thailand

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ABSTRACT

The NNE trending Khlong Marui shear zone has a strong geomorphic signal with marked fault-strike parallel topographic ridges. The lithologies within the strike-slip zone mainly consist of vertical layers of mylonitic meta-sedimentary rocks associated with orthogneisses, mylonitic granites, and pegmatitic veins. The pegmatitic veins concordantly intrude the mylonitic foliation but were sheared at the rims indicating syn-kinematic emplacement. Microstructures and mineral assemblages suggest that the rocks in the area have been metamorphosed at amphibolite facies and low to medium greenschist facies by the first deformation. The Khlong Marui shear zone was deformed under dextral simple shear flow with a small finite strain. The ductile-to-brittle deformation involves a period of exhumation of lenses of higher grade rocks together with low grade fault rocks probably associated with positive flower structures. The final stage brittle deformation is reflected by normal faulting and formation of protocataclasites to cataclasites of the original mylonitic meta-sedimentary host rock. Although clear age-constraints are still missing, we use regional relationships to speculate that earlier dextral strike-slip displacement of the Khlong Marui shear zone was related to the West Burma and Shan-Thai collision and subduction along the Sunda Trench in the Late Cretaceous, while the major exhumation period of the ductile lens was tectonically influenced by the early India-Asia collision. The changing stress field has responded by switching from dextral strike-slip to normal faulting in the Khlong Marui shear zone, and is associated with "escape tectonics" arising from the overall India-Asia collision.

1. Introduction

The Khlong Marui and Ranong fault systems are NE–SW striking strike-slip faults in southern Thailand. Models that incorporate these NE–SW striking faults have related their strike slip to the India-Asia collision leading to the southeast extrusion of the Indochina block, whereby these faults are interpreted to form a conjugate system with the NW–SE strike-slip systems of the Ailao Shan-Red River, Mae Ping, and Three Pagodas faults (Lacassin et al., 1997; Tapponnier et al., 1986) (Fig. 1). In this scenario, the NW–SE strike-slip systems started with sinistral movement during the initial collision period and inverted to dextral motion in the Oligocene on the Mae Ping and Three Pagodas faults, and in the late Miocene on the Ailao Shan-Red River Fault (Charusiri et al., 2002; Gilley et al., 2003; Huchon et al., 1994; Lacassin et al., 1997; Leloup et al., 1995, 2001; Tapponnier et al., 1982, 1986, 1990). However, the motion of strike-slip faults induced by extrusion tectonics, and in particular the great Ailao Shan-Red River shear zone has provoked lively discussion on its deformation extent and timing (Briais et al., 1993; England and Houseman, 1986; Gilley et al., 2003; Leloup et al., 1995, 2001; Rangin et al., 1995a,b; Searle, 2006; Wang et al., 1998; Wang et al., 2000; Wang et al., 2006).

The NE–SW striking Ranong and Khlong Marui faults are inferred to have initially displaced with ductile dextral motion and changed to brittle sinistral with their timing of this shear sense inversion implied to be the same as the inversion along the conjugate NW–SE trending faults (Charusiri et al., 2002; Lacassin et al., 1997; Tapponnier et al., 1986). The displacement of the Khlong Marui Fault has been estimated to be at least 200 km sinistral (Garson and Mitchell, 1970; Garson et al., 1975) to 100 km dextral (Kornsawan and Morley, 2002).

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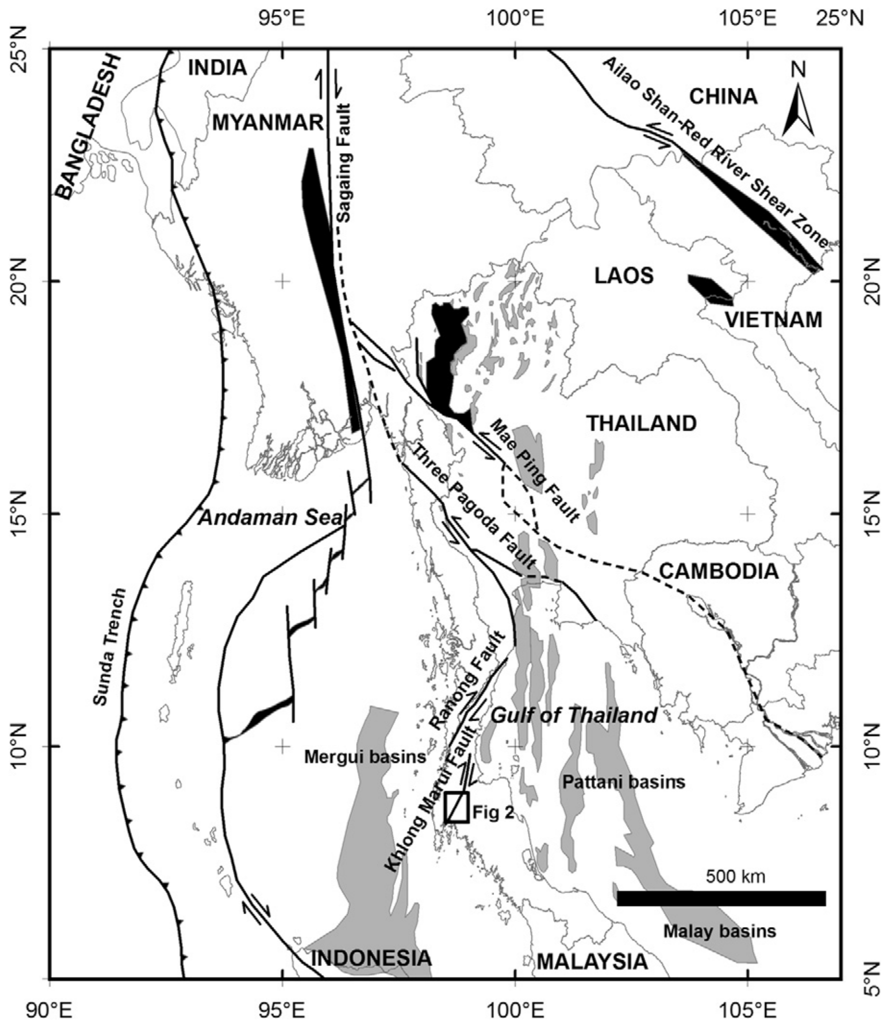

Fig. 1. Regional tectonics framework in Thailand showing major faults and related structures (modified after Morley, 2002; and Polachan and Sattayarak, 1989). Black, metamorphic complex; gray, Cenozoic basins. Box refers to Fig. 2.

Recently, Watkinson et al. (2008) discussed the kinematic history of the Ranong and Khlong Marui faults in terms of four deformation phases. Two early phases are interpreted as ductile dextral shear starting before Late Cretaceous and ending in the Paleocene to Eocene. These early two ductile phases of movement on the faults preceded the start of the India-Asia collision while a brittle sinistral phase associated with positive flower structures overprinted and exhumed the ductile fault rocks as a response to extrusion tectonics before the last phase of the outcrop scale dextral strike-slip faults (Watkinson et al., 2008).

The NW–SE and NE–SW conjugate strike-slip system is proposed by earlier models to have contributed to Cenozoic basin development in the South China Sea, Andaman Sea and Gulf of Thailand (Briais et al., 1993; Charusiri et al., 2002; Morley, 2002; Packham, 1993; Pigott and Sattayarak, 1993; Polachan et al., 1991; Polachan and Sattayarak, 1989; Tapponnier et al., 1986). The Indian-Asian collision since Eocene probably caused clockwise rotation of Southeast Asia and movements on the strike-slip faults forming Tertiary pull-apart basin development in the Late Oligocene (Pigott and Sattayarak, 1993; Polachan et al., 1991; Polachan and Sattayarak, 1989). Later extension-controlled models are more influenced by changing stress patterns at nearly 90° around the eastern Himalayan syntaxes from east-west to north-south (Huchon et al., 1994). Other models involve subduction rollback-back arc extension combined with strike-slip motion that inverted at about 30 Ma (Morley, 2001, 2002), as well as a lower crustal flow model (Morley and Westaway, 2006).

The Khlong Marui shear zone plays a key role in, and offers critical insight into regional tectonic evolution the NE strike-slip system. In this contribution we present new field evidence, microstructures, quartz textures, and mean vorticity number (W_m) quantitative kinematic analyses to define deformation phases and flow kinematics of the Khlong Marui shear zone.

2. Geological setting

The Khlong Marui shear zone, marked by a large valley and a high topography lozenge-shaped 40 km by 6 km mountain range named Khao Phanom, is the focus of this study. This shear zone affects an area up to 8 km in width from the Khlong Marui Fault eastward to the Bang Kram Fault. The faults cut across the Thai peninsula trending NNE–SSW stretching approximately 150 km from the Gulf of Thailand to the Andaman Sea (Kanjanapayont et al., 2009). The area to the west is bounded by a long, north-south trending mountain range (part of the Western Belt Granite) and Permo-Carboniferous sedimentary rocks (Charusiri et al., 1993; Department of Minearal Resources, 1982). The Permo-Carboniferous Kaeng Krachan Group generally crops out as sequences of mudstone, pebbly mudstone, shale, sandstone, and conglomerate (Ampaiwan et al., 2009; Piyasin, 1975; Raksaskulwong and Wongwanich, 1993; Ridd, 2009; Tantiwanit et al., 1983). The eastern boundary is represented by a valley 2 km in width associated with the Bang Kram Fault, which comprises a long cliff of Permian carbonate and Triassic sedimentary rock (Ampornmaha, 1995; Brown et al., 1951; Department of Mineral Resources, 1982).

The geology within the Khlong Marui shear zone consists of strongly deformed layers of steeply dipping mylonitic meta-sedimentary rocks associated with orthogneisses, mylonitic granites, and pegmatitic veins (Fig. 2). The mylonitic meta-sedimentary rocks belonging to the Permo-Carboniferous Kaeng Krachan Group have been deformed and have developed a mylonitic structure with varying grades of metamorphism. The sequences of clastic sedimentary rocks, mainly mudstones, pebbly mudstones, shales, sandstones, and conglomerates, have been deformed into metapelites, quartzites, and metaconglomerates throughout the shear zone. The metapelites are mainly composed of quartz and biotite with varying grain size and composition throughout the Khlong Marui shear zone. White mica, chlorite, tourmaline, and opaque minerals are the minor components in these rocks. Quartzites in the Khlong Marui shear zone have different grain sizes ranging from fine to coarse grained. Intercalation of coarse and fine grained layers is present in some locations. The metaconglomerates are dominantly greenish color, and composed of quartz, fine grained biotite, chlorite, and pebble clasts of various shapes and sizes. The changing dip of foliations in the western area of meta-sedimentary rocks is interpreted as a local fold.

Orthogneisses and granites are orientated with foliation parallel to the steeply dipping mylonitic meta-sedimentary rocks. The orthogneisses are mainly composed of fine- to coarse-grained quartz, K-feldspar, and biotite. Plagioclase, tourmaline, and white mica are accessory minerals. Tourmalines form large crystals up to 3 × 5 mm, parallel to the foliation. Zircon crystals can be found throughout the rocks. Quartz-feldspar augen structures form parts

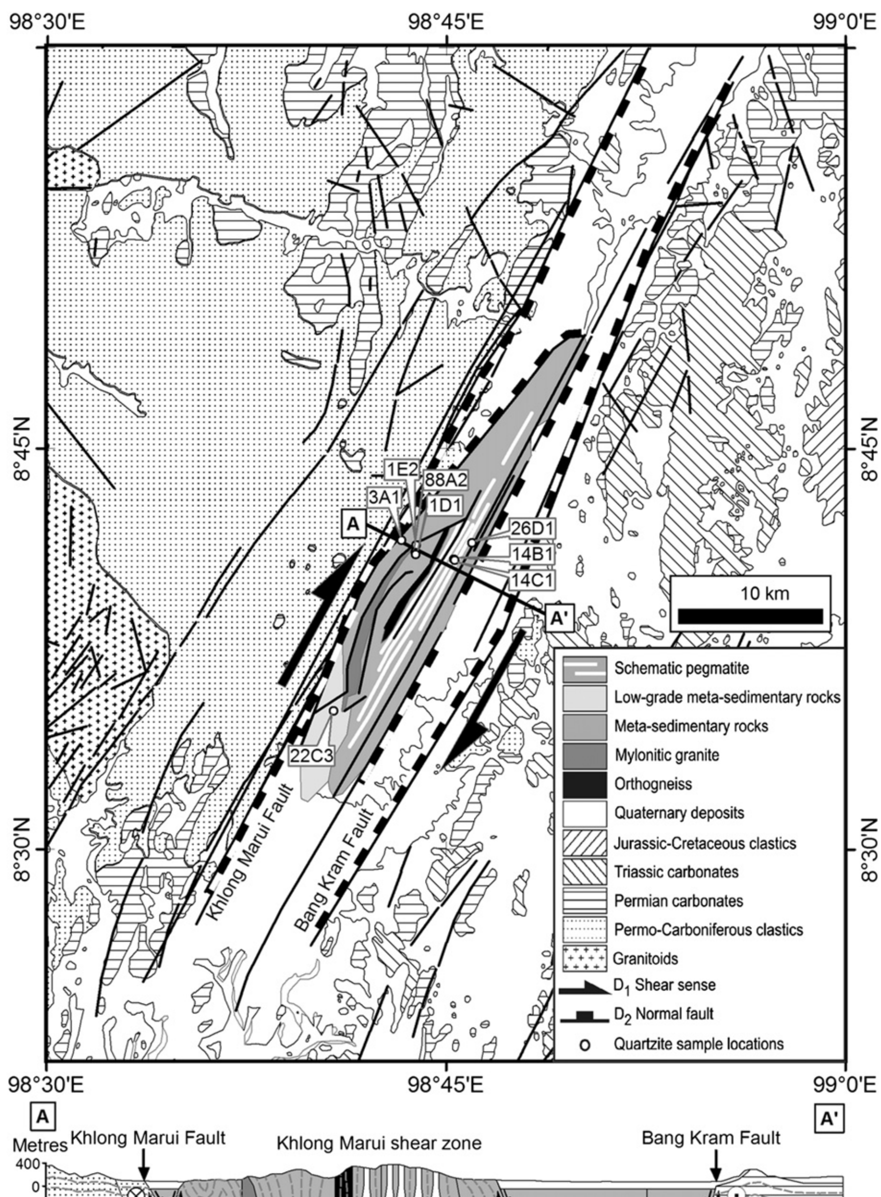

Fig. 2. Geological map of the Khlong Marui shear zone (modified after Department of Mineral Resources, 1982). ENE–WSW cross section is oriented perpendicular to the major structures.

of the gneissic banding. Oscillatory zoning in K-feldspar represents original magmatic crystallization (Fig. 3a). The major mineral assemblage of the mylonitic granite is medium grained quartz, K-feldspar, plagioclase, and biotite with accessory minerals of tourmaline, chlorite and opaque minerals. K-feldspar phenocrysts are characterized by their pinkish gray color in between the black biotite mylonitic layers. Quartz veins 1–1.5 cm in width are typically associated with the mylonitic foliation.

Pegmatitic veins, sized from 1 cm to 3 m, are concordant with the country rocks and are limited to the eastern part of the shear zone. The rocks are mainly pegmatites with rare granitic and aplitic composition. Pegmatite mainly comprises coarse grained quartz, K-feldspar, white mica, plagioclase, and tourmaline. Garnet crystals (1–2 mm) are locally present in the pegmatites. Tourmaline enrichments usually either form black layers at the pegmatite rims or intrude as veins into the metapelite.

The lower elevations in the area are progressively overlain by Quaternary deposits.

3. Deformation history

The Khlong Marui shear zone records a polyphase deformation history both in the ductile lens and the brittle fault structures. The ductile lens defines the mylonitic fault rocks, and it is equivalent to the ductile core of Watkinson et al. (2008). This structural and microstructural study focuses on the characteristics and orientations of foliations, stretching lineations, fault planes and slickenside striations in order to understand the overprinting relationships between these structural elements. Two main deformation phases are identified.

3.1. D_1

3.1.1. D_{1a}

The early first deformation (D_{1a}) is characterized by dextral ductile deformation under moderate metamorphic grades. D_{1a} is commonly preserved in the orthogneiss, mylonitic granite, and isolated blocks of metapelite and quartzite. Quartz crystals of these rocks have been dynamically recrystallized under moderate temperature (>500 °C) conditions as represented by grain boundary migration (GBM) as well as recrsytallized feldspars. Relics of deformed fibrolitic sillimanite and asymmetric myrmekite within the metapelite indicates that the rocks have experienced amphibolite metamorphic conditions (Simpson and Wintsch, 1989) (Fig. 3b, c). Dextral shear is clearly preserved in the gneissic microstructure especially in K-feldspar, which was sheared and developed fractures with antithetic sinistral offset. Further kinematic indicators are asymmetric myrmerkite in K-feldspar porphyrocrysts (Fig. 3b).

3.1.2. D_{1b}

D_{1b} dominates the deformation in the Khlong Marui shear zone and is better preserved than other deformation phases in all rock units. This phase involved dextral ductile and ended with dextral ductile-to-brittle deformation. Microstructures and mineral assemblages suggest that dextral strike-slip deformation occurred under low to medium greenschist facies. This deformation also formed the prevailing foliations and stretching lineations. Foliations are well developed in rocks which are mica-rich, such as metapelites. They form steep-vertical dipping foliations, dominantly striking NNE, parallel with the marked topography. Lineations are clearly observed in all rock types. Stretching lineations are generally defined by elongated quartz grains which are parallel to the orientation of tourmalines in the pegmatite. Poles of the foliations (Fig. 3g) were plotted and contoured on the stereographic net by the Gauss counting method (Robin and Jowett, 1986). The girdle shape of contours shows that the mylonitic foliation strikes 030°, dipping steeply both to the WNW and to the ESE while the subhorizontal stretching lineation has a clearly defined maximum at NNE–SSW. The fabric of these prevailing dextral ductile phases exploits pre-existing anisotropic planes. Aligned tourmalines define lineations in the pegmatites that are oriented in NNE–SSW paralleled to the stretching lineation of the host mylonitic meta-sedimentary rocks.

The minerals such as quartz and mica are orientated parallel to the foliation plane. All kinematic indicators such as σ-shaped clasts, domino-type boudinage, shear band-type foliation, asymmetric folds, and quarter mats in the meta-sedimentary rocks indicate dextral strike-slip deformation (Fig. 3d). Quartz and feldspar porphyroclasts are usually deformed into fish, sigmoids, and σ-type clasts (Fig. 3e). Mica fish are lens-shaped with different aspect ratios and usually form as aggregates. Biotite typically has a subparallel orientation to the schistosity (S) with white mica defining either mylonitic foliations (C) or secondary synthetic foliations (C′). "V"-pull-apart structures (Hippert, 1993) are developed in K-feldspars of the mylonitic granite indicating dextral shear sense (Fig. 3f). Dynamic recrystallized quartz records undulose extinction, basal gliding, bulging (BLG), and subgrain rotation (SGR).

The dextral ductile-to-brittle deformation of D_{1b} is recorded by shear bands and ductile-to-brittle Riedel fractures. The ENE–WSW and NW–SE Riedel shears of major dextral motion are preserved at both mesoscopic and microscopic scales. The ENE–WSW trend reflects dextral movement and usually cuts across the sinistral NW–SE striking sets. A major opening mode I fracture set strikes 110° (Fig. 3h) and is interpreted to represent extension fractures perpendicular to the 030° stretching lineation.

3.2. D_2

The last deformation phase, D_2, involves brittle normal faulting dominantly striking between 000° and 030°. The faults in the area are geomorphically expressed by fault scarps, triangular facets (Fig. 4a), and a linear valley. The steeply dipping faults are associated with proto-cataclasites to cataclasites along both sides of the main fault zone ductile lens. The brittle rocks have the same lithology as the meta-sedimentary sequences. The fragments of cataclasite form highly angular shapes. Steeply-dipping fault planes and striations of cataclasites show a dominant NNE–SSW orientation of the normal faults on stereographic plot (Fig. 4b). Non-cohesive cataclasites can be found together with cohesive cataclasites. A normal fault component is suggested by slickenside striations, and associated shear sense indicators such as lunar structures and chatter marks. Polished surfaces can be observed along this damage zone. The hanging wall is overlain by Quaternary sediments and thick soil development.

4. D_1 quartz textures

Kinematics of flow can be determined by well-developed *c*-axis fabrics in naturally deformed quartzites (Fritz et al., 1996; Grasemann et al., 1999; Lister and Hobbs, 1980; Schmid and Casey, 1986; Wallis, 1992, 1995; Xypolias, 2009). Eight samples of quartzite from a WNW to ESE transect across the Khlong Marui shear zone were analyzed for quartz textures in order to understand the flow parameters.

Fig. 5 a and b show the orientation of kinematic directions in a transpressional and transtensional setting; a_1 and a_2 are the two eigenvectors of the deformation tensor, i.e. the directions where material lines do not rotate. Under transpression, the stretching eigenvector, and under transtension, the shortening eigenvector are parallel to the shear zone boundary. The Cosine of the angle between the eigenvectors gives the mean kinematic vorticity number. The ISA_1 and ISA_2 represent the instantaneous stretching

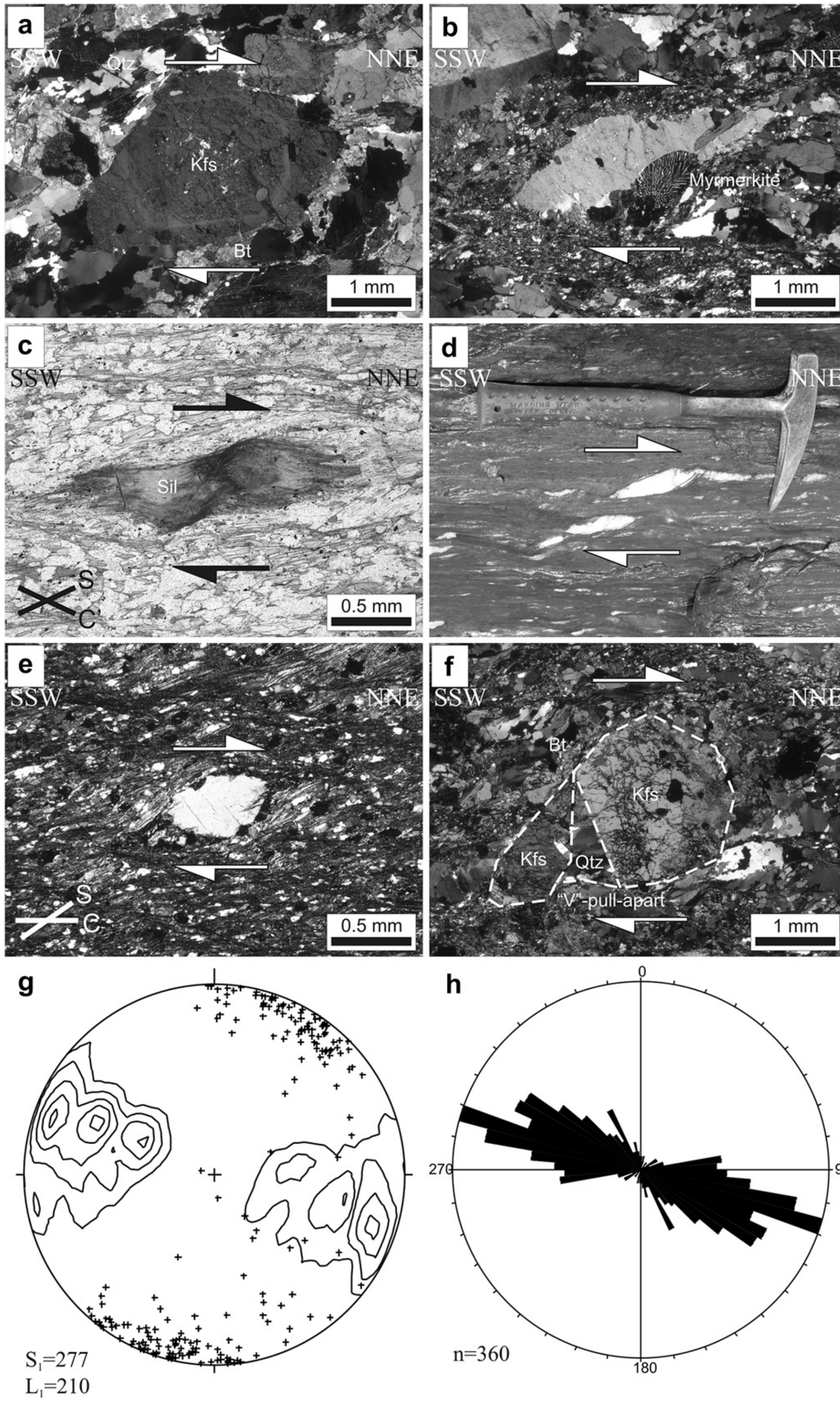

Fig. 3. The first deformations (D_1); (a) feldspar in the orthogneiss show oscillatory zoning, typical for magmatic recrystallization, (b) asymmetric myrmekite of D_1, (c) fibrolitic sillimatie along the S–C′ fabric in metapelite, (d) σ-clast in the metaconglomerate, (e) σ-clast of K-feldspar in the S–C fabric, (f) "V"-pull-apart structures of the mylonitic granite, (g) stereographic plot of the foliations (S_1) and stretching lineations (L_1) (contours of the plotting are 1%, 2%, 3%, 4%, and 5% per 1% area), (h) ESE–WNW trending of mode I fractures.

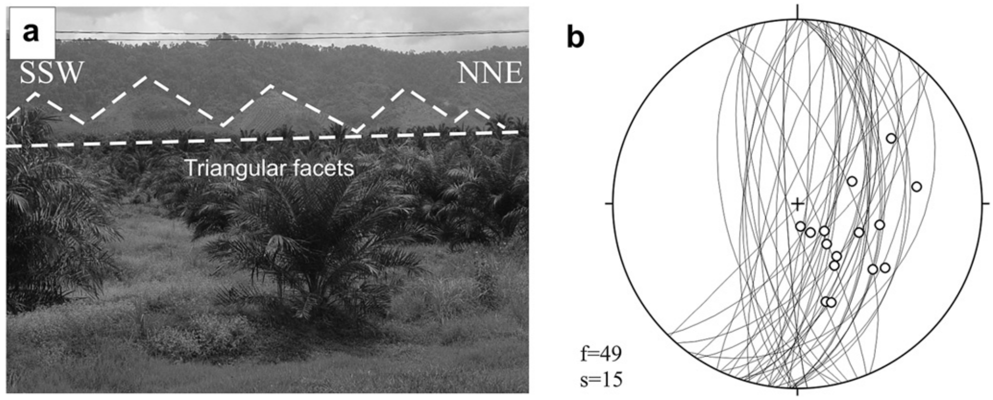

Fig. 4. Brittle deformation (D_2) in the field; (a) triangular facets along the east of the Khlong Marui shear zone, (b) stereographic plot of the fault planes (*f*) and their striations (*s*).

axes. These are orientations where material lines experience maximum and minimum values of instantaneous length change. These directions are always perpendicular to each other and correspond to the principal stress directions. The angle between the instantaneous stretching axis (ISA_1) and the foliation is represented by the $\delta + \beta$ (Xypolias, 2009) The δ and β angles are defined by two assumptions as follows:

4.1. δ angle

The long axis of dynamically recrystallized quartz grains has been suggested to be parallel to the instantaneous stretching axis (ISA_1) (Wallis, 1995). The oblique foliation (S_B) has a fixed orientation with respect to the external kinematic frame (A_1) during progressive non-coaxial shearing (Herwegh and Handy, 1998; Herwegh et al., 1997; Ree, 1991). Therefore, the angle, δ, between the oblique grain shape fabric (S_B) and the main foliation (S_A) is equal to the angle between the ISA_1 and the largest principal axis of the finite strain (Fig. 5c).

4.2. β angle

The central girdle segment of quartz *c*-axis fabrics develops orthogonally to the flow plane under progressive simple, pure, and general shear (Law et al., 1990; Lister and Hobbs, 1980; Platt and Behrmann, 1986; Vissers, 1989; Wallis, 1992). From this assumption, the angle (β) between the perpendicular to the central girdle segment of quartz c-axis fabric (S_A) and the main foliation is equal to the angle between the flow plane (A_1) and the flattening plane of finite strain (Fig. 5d).

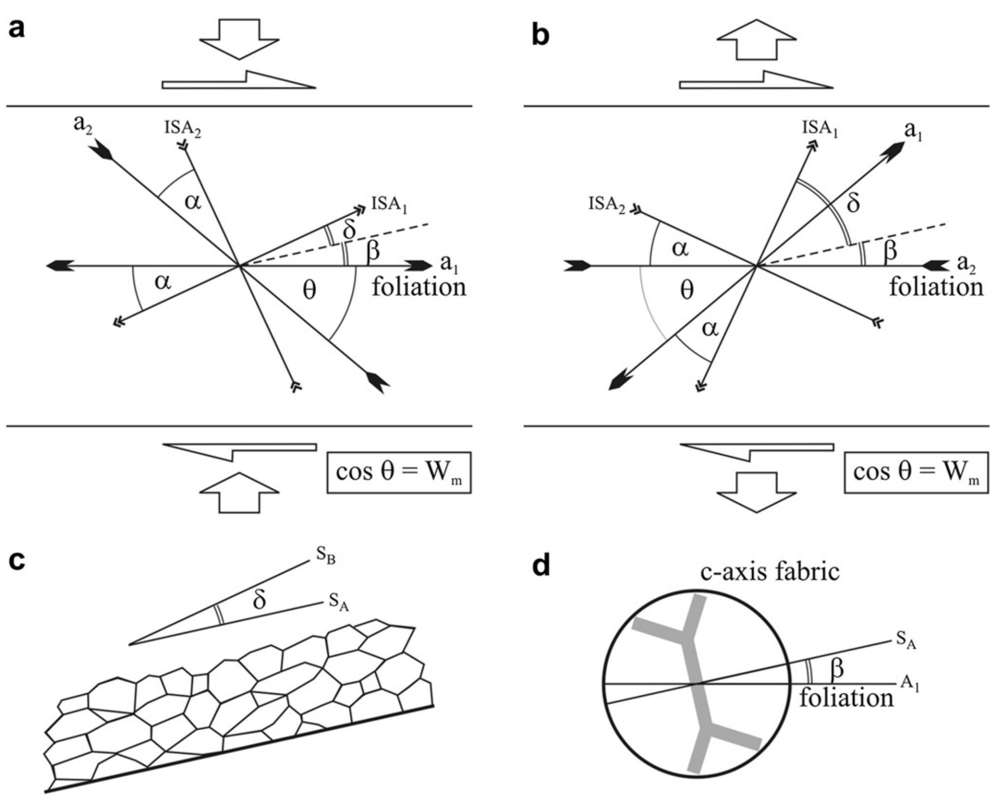

Fig. 5. Sketch showing the relative orientation of eigenvector (a_1 and a_2), instantaneous flow elements (ISA_1 and ISA_2), and their angular relationship in (a) transpression physical space and (b) transtension physical space. (c) The angle, δ, between the oblique grain shape fabric and the main foliation. (d) The angle, β, lies between the perpendicular to the central girdle segment of quartz *c*-axis fabric and the main foliation.

The Cosine of $\theta = \delta + \beta$ between the two eigenvectors gives the mean kinematic vorticity number (W_m) in two-dimensional flow (Bobyarchick, 1986; Passchier, 1986; Wallis, 1995). If both angles are known then an estimate of vorticity number (W_m) can be obtained using the equation:

$$\cos\theta = W_m \quad (1)$$

Dynamic recrystallization of quartz forms well developed grain shape preferred orientation (GSPO) and optic axis lattice preferred orientation (LPO) patterns. The thin-sections of quartzite were measured under the microscope for the angle between the oblique grain shape fabric and the main foliation (δ) (Fig. 6). The δ angles of quartzite in the Khlong Marui shear zone are between 19° and 57°.

The specimens were cut to a rock chip size of between 10 × 6 × 2 mm and 20 × 10 × 7 mm and polished for optic axis measurement. They were measured by an x-ray texture goniometer in reflection mode (wavelength CuKα = 1.5418, beam current = 40 kV and 30 mA). Lattice planes of <100>, <110>, <102>, <200>, <201>, <112>, <211>, <113> have been measured at angle between 0° (center) and 80° (periphery). Fourier analyses were applied for correction of defocusing effects. Lattice planes <001>, <100> and <110> were calculated by the harmonic method of Roe (1965) and Bunge (1969). A detailed description of the technical procedure can be seen in Wenk (1985).

The lattice preferred orientation pattern is displayed in pole figures of c-axis (Fig. 7). The maximum extension direction is oriented NNE–SSW parallel to the main foliation in the fabric diagrams. Most samples developed oblique girdle segments with respect to the foliation plane. The optic axis lattice preferred orientation patterns show dextral shear sense across the range of moderate to high temperature (Stipp et al., 2002). The maxima at the center of quartz texture sample 1E2 and 88A2 gives the highest temperature deformation. Quartz texture of samples 14C1 and 14B1 suggests a higher contribution of basal <a> glide probably suggesting lower temperature during deformation. The angle between the perpendicular to the central girdle segment of quartz axis fabric and the main foliation (β) is determined for all the quartzite samples (Fig. 7).

5. Kinematic vorticity number (Wk) derived from the D_1 quartz textures

The angles from the sample measurement and the mean vorticity number (W_m) are summarized in Table 1. The summation of δ and β angles and kinematic indicators indicate that the shear zone mainly deformed in the transpressional environment. Transtensional deformation is represented by the samples 1E2, 88A2, 14C1, and 14B1 which have summation of δ and β of more than 45° (Law, 2010).

$W_m = 0$ applies to pure shear and simple shear gives $W_m = 1$ for the mean degree of non-coaxiality (Bobyarchick, 1986; Passchier, 1986). Measured W_m values indicate that the flow type for the deformation period in the Khlong Marui shear zone is simple shear (except sample 14C1 showing a general shear).

The angle between the normal to the central girdle and the foliation (β) and the mean vorticity number (W_m) are plotted on a diagram for finite strain (Fig. 8) (see Grasemann et al., 1999). The plot shows two groups of ellipticity of the finite strain ellipsoid (R_f) which have values of about 7 and 1. The major ellipticity of about 7 represents the strain in the shear zone and the elliptictiy of about 1 is limited to the area of strain partitioning between rheologically stronger and weaker layers.

6. Discussion

6.1. Kinematic history of deformation events

Microstructures together with the quartz textures and field evidence clearly indicate that the rocks were deformed at moderate temperature conditions during dextral shear in the first stage

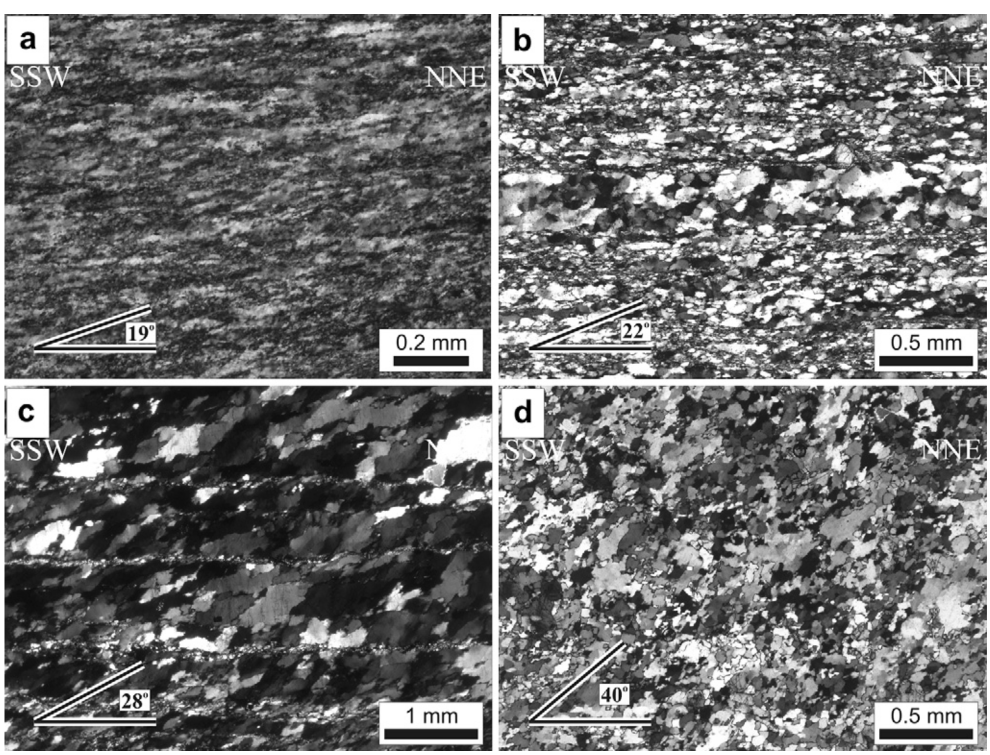

Fig. 6. Angle between the oblique grain shape fabric and the main foliation under crossed polarized light of the sample 3A1 (a), 22C3 (b), 88A2 (c), and 14B1 (d).

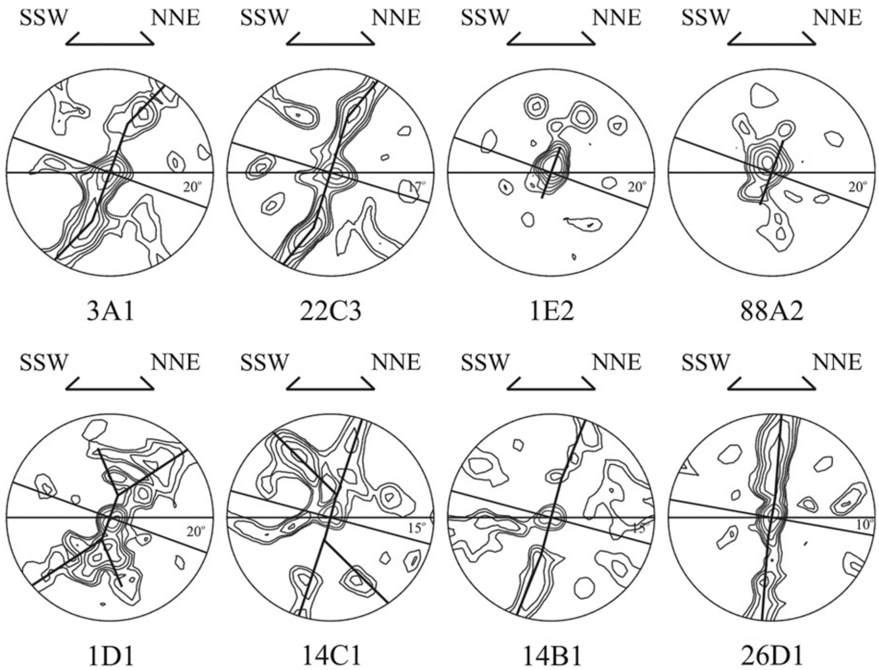

Fig. 7. Stereographic plots of quartz c-axis fabrics through the Khlong Marui shear zone with the angle between the perpendicular to the central girdle segment of quartz axis fabric and main foliation. The location of the quartzite samples is displayed in Fig. 2.

(i.e. D_{1a}). Grain boundary migration (GBM), recrystallized feldspar, fibrolitic silimanite, asymmetric myrmekite, and the maxima at the center of stereographic plots of quartz texture all correspond to the amphibolite metamorphic conditions during D_{1a}. This is followed by D_{1b}, the dominant deformation phase in the Khlong Marui shear zone, which is better preserved than other deformation phases in all rock units. Low-grade ductile conditions during D_{1b} are recorded by dynamically recrystallized quartz, particularly by undulose extinction, basal gliding, bulging, and subgrain rotation. Abundant kinematic indicators both at outcrop and microscopic scales indicate that the D_{1b} ductile deformation had a dextral shear sense. Mean vorticity numbers (W_m) of quartz textures and kinematic indicators suggest transpressional simple shear during D_{1b}. During ductile deformation at mid-crustal levels, pegmatite bodies intruded into the shear zone. The pegmatites cross-cut an early mylonitic dextral foliation but were still affected by ductile dextral shear thereby indicating the protracted nature of the Khlong Marui shear zone's dextral displacement. Dextral deformation continued further during cooling and exhumation of the shear zone at upper-crustal levels, forming positive flower structures (c.f. Watkinson et al., 2008). This interpretation is further supported by the striking contrast between the intense deformation conditions of the shear zone rocks and the un-deformed sedimentary host rock units. This ductile-to-brittle stage is associated with Riedel shears and extension joints, and probably with the early development and formation of the cataclasite zone.

Table 1
Summarized data from quartzite samples in the Khlong Marui shear zone.

Sample	δ	β	$\delta + \beta$	θ	W_m
3A1	19	20	39	12	0.98
22C3	22	17	39	12	0.98
1E2	45	20	65	40	0.77
88A2	28	20	48	6	0.98
1D1	20	20	40	10	0.99
14C1	57	15	72	54	0.59
14B1	40	15	55	20	0.94
26D1	20	10	30	30	0.87

The NNE striking dextral shearing, the ENE–WSW, NW–SE Riedel shear and the dilational joints show that the shortening orientated E–W, and extension was oriented N–S during D_1 (Fig. 9a).

D_2 normal faults overprint both sides of the ductile lens in the final deformation period. Our mapping and field studies surveyed all accessible side valleys and identifiable outcrops of the Khlong Marui shear zone and found no clear evidence of sinistral movement of the fault during D_2 phase through the shear zone. The implications of this are discussed under "tectonic implications", below. The normal faults of D_2 indicate that shortening was oriented N–S and extension was oriented E–W in a horizontal plane strain (Fig. 9b).

6.2. Tectonic implications

This section discusses the tectonic significance of the structural results within the regional tectonic framework. The Khlong Marui Fault displacement history has been previously interpreted to start

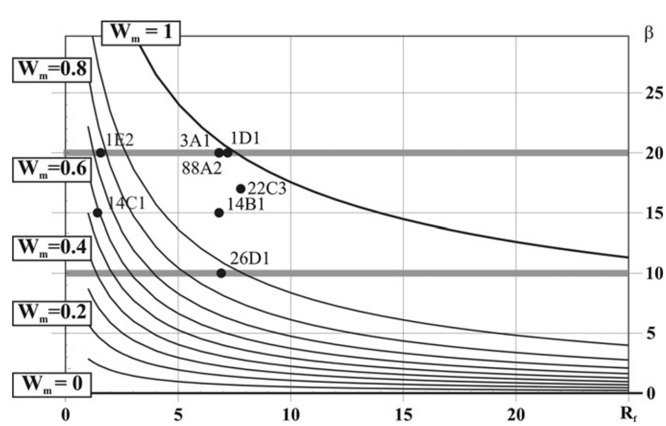

Fig. 8. Diagram plots of the angle between the normal to the central girdle and the foliation (β) and the mean kinematic vorticity number (W_m) showing the ellipticity of the finite strain ellipsoid (R_f).

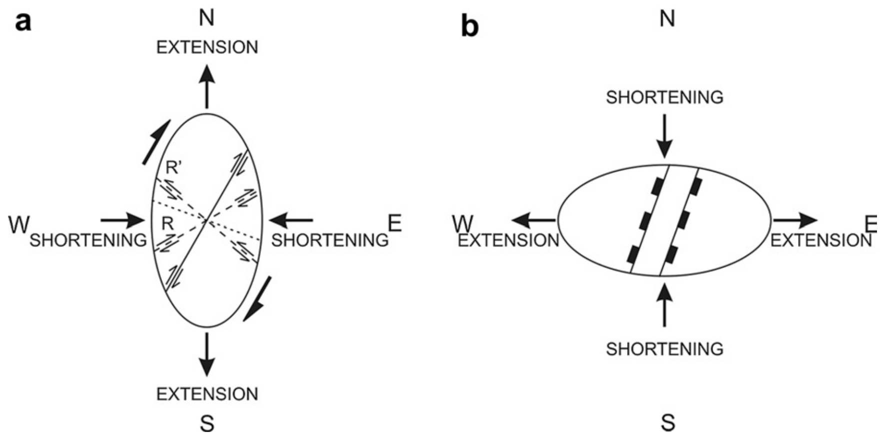

Fig. 9. Integrated kinematic analyses indicate an E–W shortening with N–S extension of D_1 (a) before changing strain pattern to N–S shortening of D_2 (b).

with dextral movement during the initial India-Asia collision period, i.e. early Cenozoic (Charusiri et al., 2002; Lacassin et al., 1997; Tapponnier et al., 1986). However, many paleogeographic reconstructions suggest a collision of West Burma with the Shan-Thai microcontinents in the Late Cretaceous resulting in dextral shear along NE–SW striking faults (Bunopas, 1981; Charusiri, 1989; Charusiri et al., 2002; Hutchison, 1996; Mitchell, 1981, 1993), and the Sn-W-REE rich S- and I-type Western Granite Belt is also proposed to be associated with this West Burma – Shan-Thai collision (Charusiri et al., 1993, 2002; Hutchison, 1996). Watkinson et al. (2008) consider that the Western Granite intrusion and the northern Thailand orogenic events coincide with at least some of the period of dextral shearing on the Khlong Marui Fault. The mechanism of the West Burma – Shan-Thai collision produces an E–W shortening which fits with our plane strain for the dextral strike-slip system of the Khlong Marui shear zone. Therefore, we suggest that the first dextral ductile phases of the Khlong Marui shear zone and the Western Granite magmatism were probably influenced by the West Burma and Shan-Thai collision in the Late Cretaceous.

Another model concerning the NE–SW dextral shear is the subduction along the Sunda Trench. The model involves the northwards subduction of Ceno-Tethys oceanic lithosphere as India separated from Gondwana (Ramana et al., 1994; Metcalfe, 1996). The Ceno-Tethys was subducted into the Sunda Trench west of 95°E from Late Cretaceous time (Hall et al., 2008). Dextral shear between the rapidly subducting oceanic crust and the inactive trench segment east of 95°E may have been transferred into the overriding plate, close to the position of the Khlong Marui Fault (Watkinson et al., 2008).

The E–W contraction may have caused the exhumation of the Khlong Marui ductile shear zone core by forming a positive flower structure during the D_{1b} transpressional phase (Fig. 10). This regional E–W compression was widespread in the SE Asia region, and was tectonically influenced by the early India-Asia collision during Late Cretaceous to Early Tertiary (Aitchison et al., 2007; Klootwijk et al., 1992; Molnar and Tapponnier, 1975; Searle et al., 1997). We therefore suggest that the Khlong Marui shear zone core was exhumed at the same time as the early India-Asia collision.

The exhumed faults related to the positive flower structure (this study; Watkinson et al., 2008) are inferred to represent the anisotropic fabric that was subsequently affected by the rotated stress field, producing D_2 NNE-SSW normal faults in the study area. This changing of the regional stress field involves a clockwise rotation of the maximum horizontal stress from roughly E–W to roughly N–S caused, or primarily influenced by the India-Asia collision (Huchon et al., 1994; Richter and Fuller, 1996). The India-Asia collision engendered extrusion tectonics persisted at least as far southeast as the major strike-slip faults in Thailand including the Khlong Marui Fault (Charusiri et al., 2002; Morley, 2002). The E–W extension attendant to this model would be a result of a generally N–S directed maximum horizontal stress, wherein the preferentially localized deformation on the above noted anisotropic fabric precludes any greater accuracy in this model. We note that this E–W extension fits well with the Cenozoic basin development in

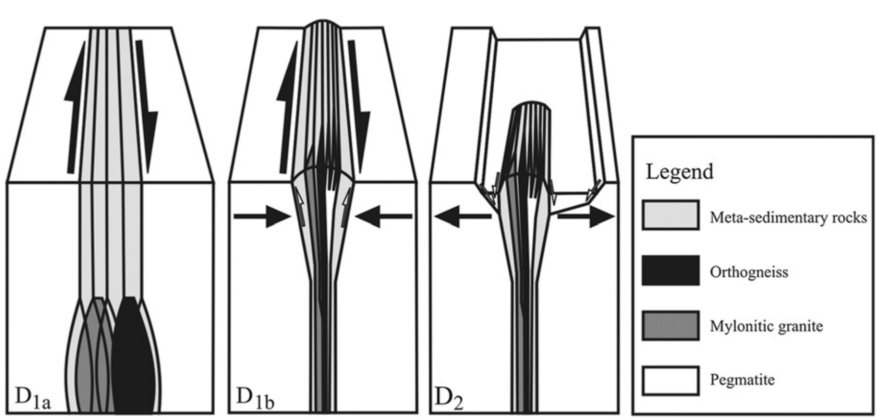

Fig. 10. Schematic block diagram illustrating three major deformations of the Khlong Marui shear zone. D_{1a} is characterized by dextral ductile deformation under high metamorphic grades. The positive flower structure of D_{1b} is formed by dextral transpressional deformation at mid-to-upper crustal levels causing the exhumation of the shear zone. The E–W extension model of D_2 is represented by the normal faults.

Thailand, both onshore and offshore (Briais et al., 1993; Charusiri et al., 2002; Morley, 2001, 2002; Packham, 1993; Pigott and Sattayarak, 1993; Polachan et al., 1991; Polachan and Sattayarak, 1989; Tapponnier et al., 1986). However, we suggest that when the regionally changing stress field manifested itself at the Khlong Marui Fault, the significantly far-field position of the Khlong Marui Fault with respect to mainland SE Asia resulted in local kinematics that switched from dextral strike-slip to the normal faulting. Further speculation on the broader tectonic history and on alternative competing/additional scenarios is outside the scope of this contribution.

7. Conclusions

The results from our data deliver new detailed data on the kinematics of the Khlong Marui shear zone with the following providing important constraints on the shear zone's structural style and evolution:

- Two deformation phases D_1 and D_2 are recorded in the Khlong Marui shear zone. D_1 are characterized by dextral ductile deformation with mylonitic foliation striking 030° and NNE-SSW subhorizontal stretching lineation. It was separated into D_{1a} and D_{2b} by the different metamorphic conditions. D_{1a} occurred during amphibolite facies metamorphic conditions, and D_{1b} occurred under low to medium greenschist facies metamorphic conditions. The ductile-to-brittle deformation during D_{1b} involved a period of ductile lens exhumation associated with positive flower structures. D_2 is brittle normal faulting dominantly striking between 000° and 030°.
- Quartz dynamically recrystallized during D_{1a} generally records grain boundary migration (GBM) while undulose extinction, basal gliding, bulging (BLG), and subgrain rotation (SGR) occurred during D_{1b}. All kinematic indicators support dextral strike-slip motion.
- The mean kinematic vorticity number (W_m) of D_1 quartz textures indicate simple shear flow with a small finite strain ellipsoid (R_f) in a transpression zone.
- During D_2, the stress field was rotated, and pre-existing faults that had been involved in the exhumation of the positive flower structures were reactivated as normal faults. These normal faults are associated with proto-cataclasites to cataclasites, and geomorphically expressed by fault scarps, triangular facets, and the principal linear valley.
- Based on the plane strain and the regional tectonic framework, the D_{1a} dextral ductile phase of the Khlong Marui shear zone and the Western Granite magmatism were caused by the West Burma and Shan-Thai collision and subduction along the Sunda Trench in the Late Cretaceous. The major exhumation period of the ductile lens, $D_{1b,}$ was Late Cretaceous to Early Tertiary and therefore was tectonically influenced by the early India-Asia collision. The changing stress field caused by the India-Asia collision caused the Khlong Marui shear zone's switch from dextral strike-slip to normal faulting.

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