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Nature of accretion related to Paleo-Tethys subduction recorded in northern Thailand: Constraints from mélange kinematics and illite crystallinity

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ABSTRACT

We reconstructed the accretion process related to Paleo-Tethys subduction recorded in northern Thailand, based on mélange and thrust structures, and metamorphic temperatures derived from illite crystallinity data. Mélange formation was characterized by hydrofracturing and cataclastic deformation, with mud injection under semi-lithified conditions followed by shear deformation and pressure solution. Illite crystallinity data suggest metamorphic temperatures below 250 °C during mélange formation. The combined structural and metamorphic data indicate that during mélange formation, the accretionary complex related to Paleo-Tethys subduction developed at shallow levels within an accretionary prism. Asymmetric shear fabrics in mélange indicate top-to-south shear. After correction for rotation associated with collision between the Indian and Eurasian continents, the trend of the Paleo-Tethys subduction zone is estimated to have been N80 °E. We conclude that the Paleo-Tethys was subducted northward beneath the Indochina Block from the Permian to Triassic.

1. Introduction

The Paleo-Tethys, which opened in response to the Devonian separation of the Indochina Block from Gondwana, occupied a large area around the equator from the Devonian to Triassic, and saw the deposition of carbonates, chert, and basalt in its pelagic domain (e.g., Metcalfe, 1999, 2006; Arias, 2008; Ferrari et al., 2008). These Paleo-Tethyan rocks characterized by Ocean Plate Stratigraphy were subducted beneath the Indochina Block during the Permian to Triassic (Metcalfe, 2002; Wakita and Metcalfe, 2005). However, kinematics and style of the Paleo-Tethys subduction have not been clarified. For reconstructing of subduction tectonics, we focus on component rocks associated with the accretionary complex which remained between the Sibumasu Block (Gondwana domain) and the Indochina Block (Tethyan domain) in northern Thailand.

In northern Thailand, the Nan-Uttaradit Suture has been believed to represent the boundary between the Sibumasu Block and Indochina Block, regarded as a remnant of the main Paleo-Tethys. A new tectonic scheme has recently been proposed for northern Thailand (Kamata et al., 2009; Ueno, 1999, 2002, 2003; Ueno and Hisada, 2001), based on Paleozoic and Mesozoic biostratigraphy and paleobiogeography (e.g., foraminifers and radiolarians), and correlations between northern Thailand and the western Yunnan area of South China. In this scheme, northern Thailand is divided into four geotectonic units (from west to east): the Sibumasu Block, Inthanon Zone, Sukhothai Zone, and Indochina Block (Fig. 1). Based on a new interpretation by Ueno (1999, 2002, 2003), the Inthanon Zone is interpreted to represent nappes of Paleo-Tethyan rocks thrust westward over a marginal part of the Sibumasu Block (Caridroit et al., 1992; Ueno and Hisada, 2001).

The Paleo-Tethyan rocks of the Inthanon Zone have been studied in terms of the paleo-biostratigraphy of chert and limestone (e.g., Sashida et al., 1993; Ueno and Igo, 1997; Sashida and Igo, 1999; Ueno, 1999; Wonganan and Caridroit, 2005; Randon et al., 2006; Ueno et al., 2008; Wonganan et al., 2007) and the geochemistry of basaltic rocks (Barr et al., 1990; Phajuy et al., 2005); however, clastic rocks associated with subduction of the Paleo-Tethys have yet to be investigated.

In the Inthanon Zone, mélanges occur in association with oceanic rocks of the Paleo-Tethys. The mélanges are characteristically chaotic rocks showing block-in-matrix structure, having been deformed during accretion in an ancient subduction zone (e.g., Taira et al., 1988). The fabrics within mélanges provide important information for

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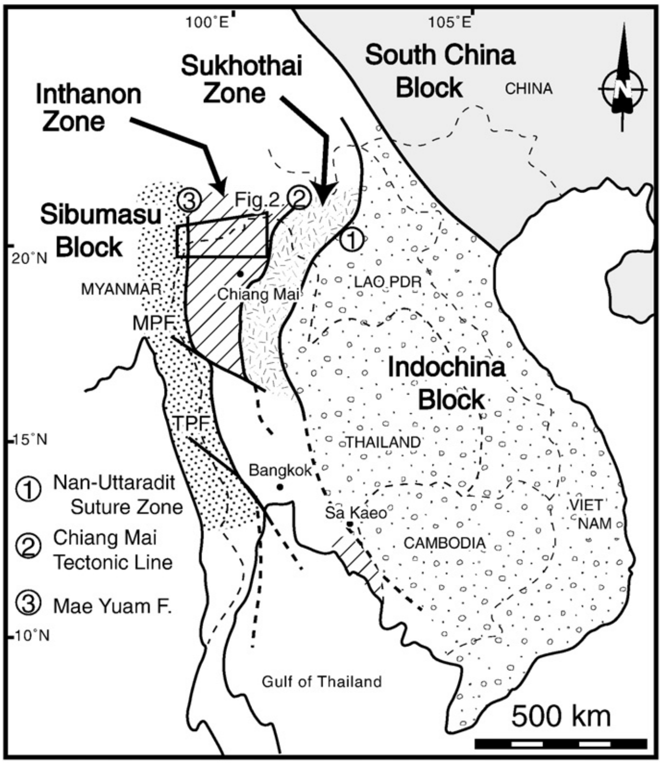

Fig. 1. Tectonic map of Thailand and surrounding region (after Ueno, 1999). Dashed lines are political boundaries. MPF: Mae Ping Fault. TRF: Three Pagodas Fault.

understanding accretionary processes. In particular, asymmetric shear fabrics in mélange can indicate the shear direction along a décollement in the subduction zone, as well as the subduction direction of the oceanic plate (e.g., Fisher and Byrne, 1987; Needham and Mackenzie, 1988; Kano et al., 1991; Onishi and Kimura, 1995; Niwa et al., 2005; Fukui and Kano, 2007).

The aim of this paper is to reconstruct the accretionary process related to subduction of the Paleo-Tethys during the Permian to Triassic, as recorded in northern Thailand. This is achieved based on an analysis of the structure of mélanges and thrusts within the Inthanon Zone. We seek to estimate the process of mélange formation associated with accretion, based on field observations of mélange and analysis of illite crystallinity data, which are commonly employed to clarify the temperature of low-grade metamorphism (Underwood et al., 1993; Awan and Kimura, 1996; Tanabe and Kano, 1996; Hara and Hisada, 2007; Hara and Kimura, 2008). Based on an analysis of asymmetric shear fabrics in the observed mélange, we also discuss the direction of Paleo-Tethys subduction beneath the Indochina Block.

2. Geological outline of Northern Thailand

Ueno (1999, 2002, 2003) proposed four geotectonic units for northern Thailand (from west to east): the Sibumasu Block, Inthanon Zone, Sukhothai Zone, and Indochina Block, separated by the Mae Yuan Fault, Chiang Rai Line, and Nan-Uttaradit Suture, respectively (Fig. 1). Sone and Metcalfe (2008) suggested a similar tectonic scheme.

The Sibumasu Block, also referred to as the Shan-Thai Block (Bunopas, 1981), is characterized by a Gondwanan stratigraphy, including a Lower Carboniferous hiatus, Upper Carboniferous to Lower Permian glaciogenic diamictites with Gondwanan fauna and flora, and Middle–Upper Permian platform carbonates (Ueno, 2003).

The Inthanon Zone, originally proposed by Barr and Macdonald (1991), is characterized by Paleo-Tethyan oceanic rocks, pre-Devonian basement rocks, and Late Triassic and Early Jurassic S-type granitoids with gneissose rock. The Paleo-Tethyan rocks consist of pelagic Carboniferous–Permian seamount-type carbonate rocks (the Doi Chiang Dao Limestone) associated with basaltic rocks and Middle Devonian–Middle Triassic radiolarian chert (Ueno, 1999; Ueno and Hisada, 2001; Ueno et al., 2008). The pre-Devonian basement rocks consist of metamorphic rocks of unknown age, Cambrian sandstone, and Ordovician limestone, corresponding to component rocks of the Sibumasu Block. The Cambrian sandstone and Ordovician limestone indicate that marginal sediments of the Sibumasu Block are imbricated with Paleo-Tethyan rocks in the Inthanon Zone.

The Sukhothai Zone, which largely corresponds to the Sukhothai Zone of Barr and Macdonald (1991) and the Sukhothai fold belt of Bunopas (1981), is dominated by deformed Paleozoic to Mesozoic sedimentary rocks, volcanic rocks, and Early Permian to Triassic I-type granitoids. The Sukhothai Zone is considered to represent a volcanic arc developed along the margin of the Indochina Block, related to subduction of the Paleo-Tethys.

The Indochina Block is part of the South China or Indochina Superterrane (Metcalfe, 2000, 2006), and has remained within the paleo-equatorial region since its Early Devonian breakaway from Gondwana. In eastern Thailand, Upper Paleozoic shallow-marine carbonate rocks, containing highly diversified Tethyan faunas, are widely distributed along the margin of the Indochina Block. The Nan-Uttaradit Suture, dividing the Sukhothai Zone and the Indochina Block, is interpreted to represent a remnant of a back-arc basin (Ueno, 1999; Ueno and Hisada, 2001).

3. Reconstruction of ocean plate stratigraphy of the Paleo-Tethys

Ocean plate stratigraphy (OPS) is the original stratigraphy of the ocean floor, before it was incorporated in an accretionary complex, recording the stratigraphic succession from its initiation at a mid-ocean ridge to subduction at an oceanic trench (Matsuda and Isozaki, 1991). The OPS is important for understanding the history of ancient accretionary complexes (e.g., Kawai et al., 2008). Wakita and Metcalfe (2005) reported that an outcrop of OPS of the Paleo-Tethys, exposed in a road cutting south of Chiang Mai, northern Thailand, consists of pillow basalts overlain by chert, pelagic limestone, siliceous shale, and argillaceous rocks. Thus, Paleo-Tethyan rock associations are distributed in the Chiang Dao to Mae Hong Son region of northern Thailand (Fig. 2).

In the Inthanon Zone, the OPS consists of basaltic rocks, chert, carbonates, clastic rocks, and mélange. The basaltic rocks include massive lava, pillow lava, and foliated volcaniclastic rocks (Fig. 3A,B). Barr et al. (1990) suggested that the basaltic rocks were erupted at a subduction margin and within a back-arc basin during the Carboniferous. Phajuy et al. (2005) classified these basaltic rocks as mid-ocean ridge and ocean-island basalts, based on geochemical grounds, and inferred a Permian age of eruption based on the stratigraphic relationship between the basalts and Permian limestone although the Permian age assignment of the relevant basalt needs to be reexamined (Ueno et al., 2008). According to Kamata et al. (2009), pelagic chert of the Paleo-Tethys is characterized by densely packed radiolarians in a microcrystalline quartz matrix, with no terrigenous material. Chert layers are commonly folded (Fig. 3C, D) and range in age from Middle Devonian to Middle Triassic, based on radiolarian and conodont fossils (Sashida and Igo, 1999; Sashida et al., 1993, 2000; Wonganan and Caridroit, 2005; Randon et al., 2006; Wonganan et al., 2007; Kamata et al., 2009).

The Paleo-Tethyan limestone consists of seamount-type carbonate rocks that accumulated under pelagic conditions without any input of terrigenous material (Ueno and Igo, 1997; Ueno, 1999;

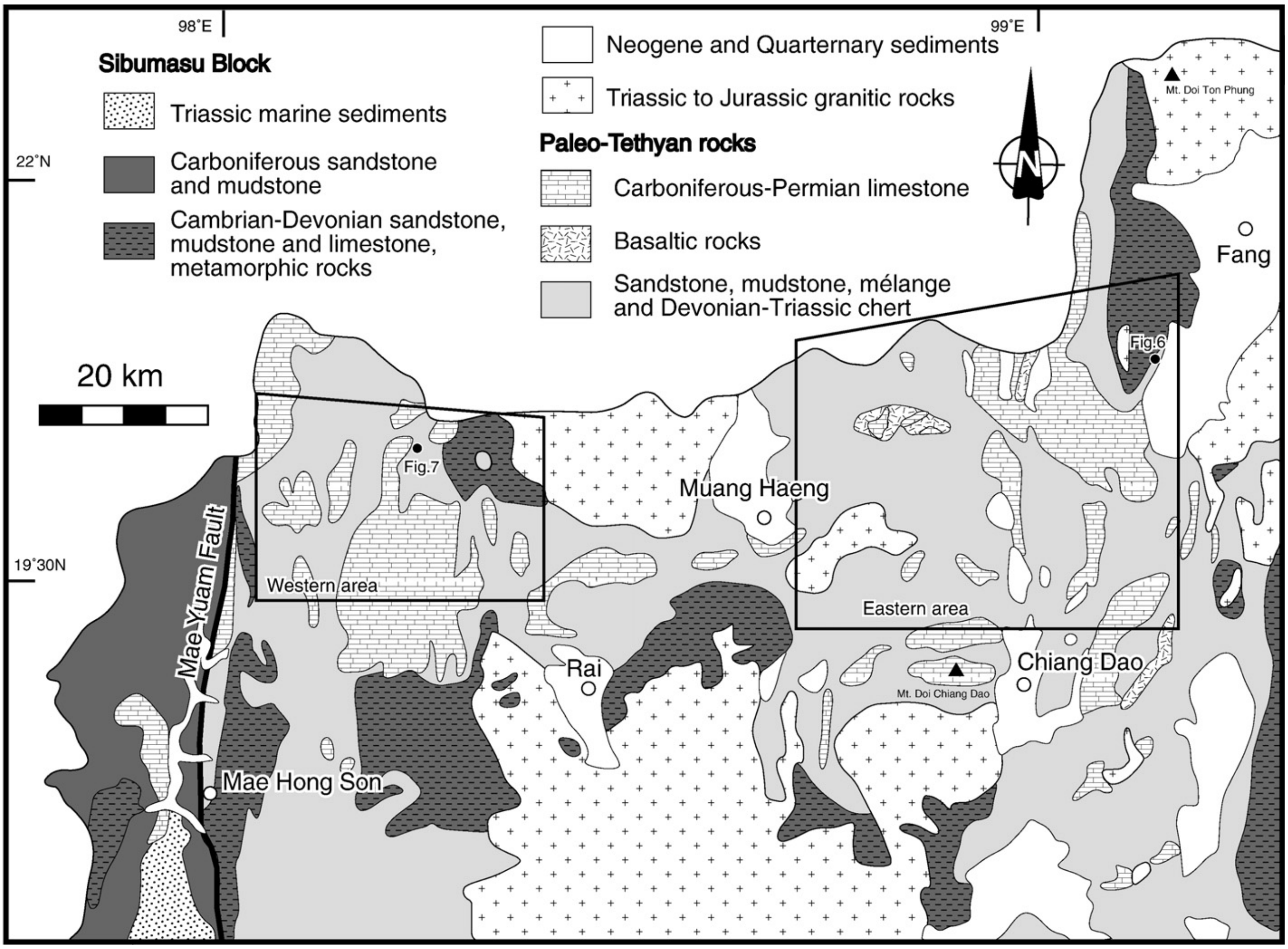

Fig. 2. Simplified geological map of the area between Mae Hong Son in the west and Fang in the east (see Fig. 1 for map location). The two quadrilaterals indicate the western and eastern areas investigated in this study. The map is based on the Geological Map of Thailand (1:1,000,000) published by Department of Mineral Resources (1999).

Ueno et al., 2008). Fusulinoidean and foraminiferal faunas are tropical Tethys-type, ranging from Carboniferous to Permian, indicating a long duration of deposition (Ueno and Igo, 1997: Ueno, 1999; Ueno et al., 2008). The Paleo-Tethyan limestone in the Inthanon Zone usually occurs as karst towers (Fig. 3E). Clastic rocks (greywacke sandstone, mudstone, and mélange) occur in association with the Paleo-Tethyan rocks; the sandstone is usually disrupted and broken.

4. Lithology of mélanges

We focus on mélanges in seeking to understand the character of the accretionary complex associated with subduction of the Paleo-Tethyan rocks. In describing the structures of the mélange, we investigated an eastern area and a western area (Fig. 2). In the Paleo-Tethyan region, mélanges are characterized by disrupted and broken sandstone in a weakly foliated argillaceous matrix (Fig. 4). In previous works, these mélanges were described as part of Carboniferous to Permian sedimentary successions (Department of Mineral Resources, 1999) and described as olistostromal (Caridroit et al., 1992; Randon et al., 2006; Wonganan et al., 2007). Mélanges related to subduction of the Paleo-Tethys have also been reported from Peninsular Malaysia (Metcalfe, 2000) and south China (Wang et al., 2000).

In the disrupted sandstone it is possible to reconstruct the original bedding which shows evidence of slumping (Fig. 4A). The broken sandstone is characterized by isolated clasts of sandstone within an argillaceous matrix (Fig. 4B,C). The clasts are angular to subrounded, and lenticular in shape, generally ranging in length from several centimeters to several meters.

We occasionally observed chert-bearing mélange. The chert is also broken, and folded within the mélange. The microscale deformation features of the mélange indicate hydrofracturing under semi-lithified conditions (Fukui and Kano, 2007). The sandstone clasts are angular to subrounded, with both sharp and gradational margins, and range in size from several millimeters to several meters with substantial diversity (Fig. 5A). For sandstone clasts with gradational margins, there exist small, isolated, fractured sandstone grains in the argillaceous matrix surrounding the clast (Fig. 5A). Black pressure solution seams in the matrix wrap around the sandstone clasts, parallel to a scaly foliation. Mud is locally injected into sandstone clasts, which also record fracturing, indicating cataclastic deformation (Lundberg and Moore, 1986; Barber and Brown, 1988). Pinch-and-swell structures with asymmetric tails and boudinage are observed within sandstone clasts (Fig. 5B), having been interpreted as structures indicative of early-stage extension (Byrne, 1984; Fisher and Byrne, 1987). Such features indicate that the mud matrix has flowed in a ductile manner.

Where intensely deformed, the mélanges of the present study are geometrically similar to cataclastic rocks found in brittle fault

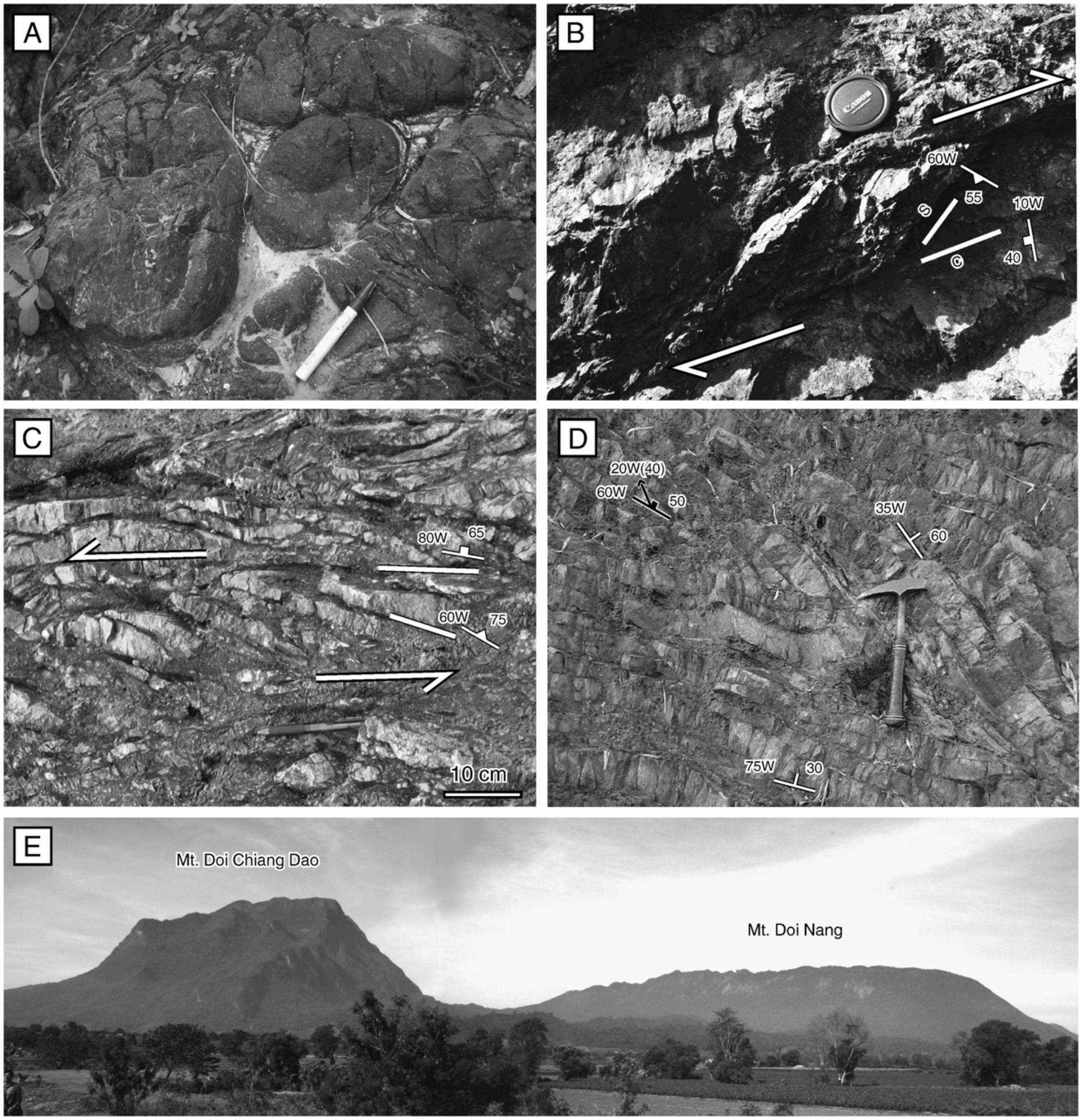

Fig. 3. Outcrop photographs of Paleo-Tethyan rocks. (A) Pillow basalt. (B) Basalt showing structures indicative of dextral shear (see arrows in the figure). (C) Chert beds occurring as a duplex structure indicating sinistral slip (see arrows). (D) Folded chert. (E) Karst tower of limestone. Mt. Doi Chiang Dao is the third-highest mountain in Thailand.

zones (e.g., Kano et al., 1991; Tanaka, 1992). S- and C-planes of shear fabrics are developed within the argillaceous matrix, which contains a scaly foliation (Fig. 4D). The C-planes are a spaced scaly foliation; the slip surface is parallel to the shear direction, showing slickenlines and slickensides. The S-planes are a scaly foliation oriented at 10–30° from the C-planes, converging to parallelism. Sandstone and chert lenses are observed along the S-planes, occasionally with sigma-type asymmetric tails (Fig. 4E). Black pressure solution seams occur parallel to the S- and C-planes, and anastomose around sandstone clasts. The seams indicate shear deformation and pressure solution (Groshong, 1988).

5. Thrusts within the Inthanon zone

In the Inthanon Zone, thrusts are observed within the Paleo-Tethyan rocks. We studied in detail two representative outcrops in the Inthanon Zone that contain thrusts (one in the eastern area, and one in the western; Fig. 2).

At the first outcrop (19°48′54″N, 99°06′21″E), a thrust is developed beneath a sandstone layer within mélange that consists of broken sandstone layers within argillaceous rocks (Fig. 6A). The thrust surface corresponds to C-planes developed in the mélange. The mélange beneath the thrust records intense shear deformation (Fig. 6B). The S- and C-planes observed in the outcrop indicate dextral shear slip, with sandstone lenses showing sigma-type asymmetric tails.

At the second outcrop (19°38′51″N, 99°13′42″E), the hanging wall consists of mélange containing chert and sandstone, while the footwall consists of coherent bedded sandstone and mud (Fig. 7A). Chert within the hanging wall is folded and broken (Fig. 7B; Kamata et al., 2009). Sandstone layers in the footwall are slightly sheared, and contain well-rounded quartz grains. Bivalve and gastropod fossils are found in the quartz-rich sandstone within the footwall.

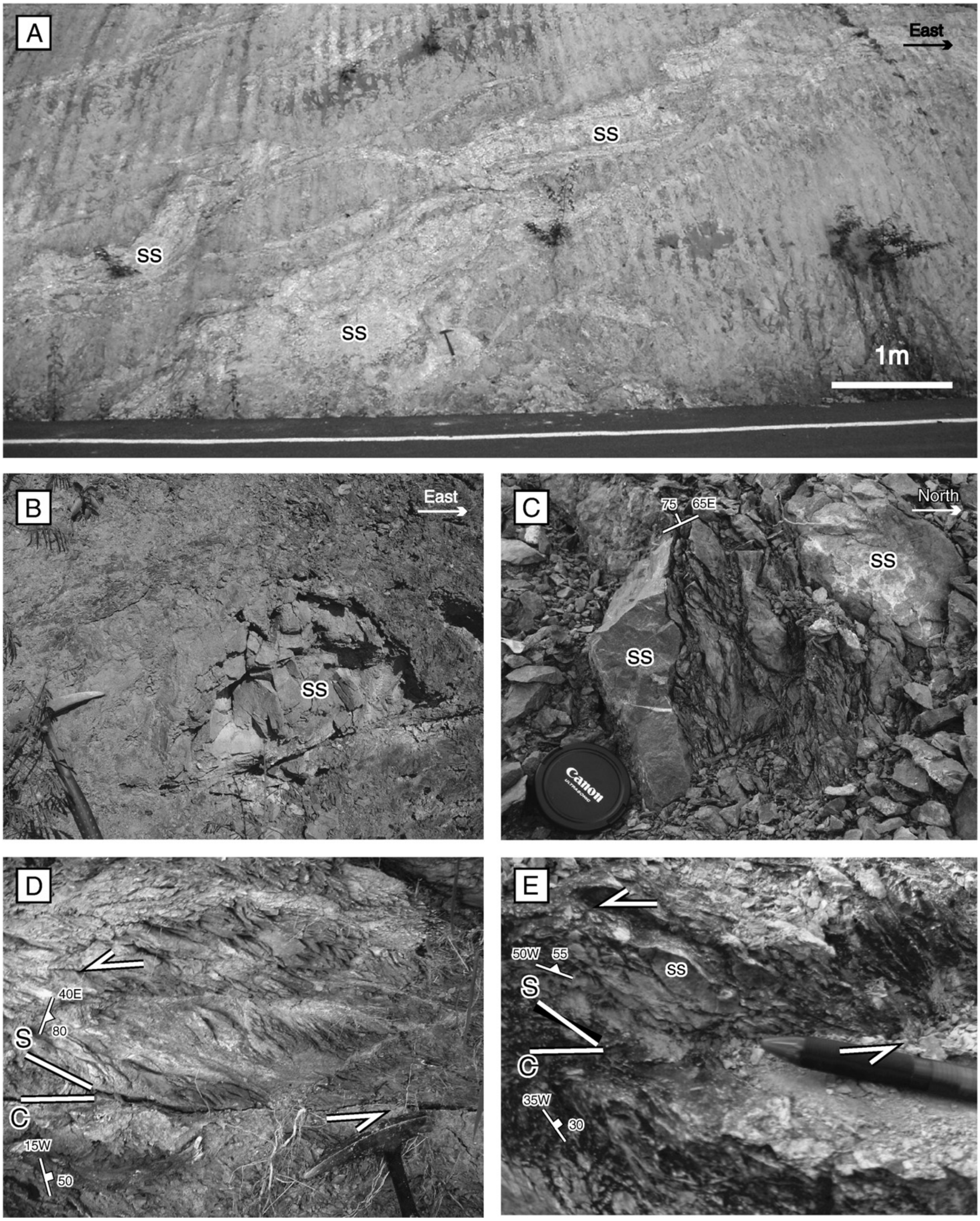

Fig. 4. Outcrop photographs of mélange. (A) Disrupted sandstone beds (ss) within mud stone. (B) Isolated sandstone block (ss) within an argillaceous matrix. (C) Lenticular sandstone blocks (ss) showing evidence of shear deformation. (D) S- and C-planes developed in mudstone, showing sinistral slip (see arrows). (E) Sheared mélange. A sandstone clast (ss) with sigma-type asymmetry and S- and C-planes indicate sinistral slip (see arrows). S: S-plane, C: C-plane.

The character of sandstone bearing fossils of the footwall seems to be component rock of the Sibumasu Block. The thrust plane is marked by a layer of weathered gouge up to several centimeters thick, and S- and C-planes developed in adjacent rocks due to shear deformation (Fig. 7C). The geometry of the shear fabric suggests that the hanging wall was thrust over the footwall after mélange formation.

6. Analysis of the shear direction recorded within mélange and upon thrusts

Shear sense indicators, such as S- and C-planes and sigma-type asymmetric tails, form by layer-parallel shear with a component of extension, thereby recording the shear direction in ancient accretionary complexes (e.g., Fisher and Byrne, 1987; Byrne and Fisher,

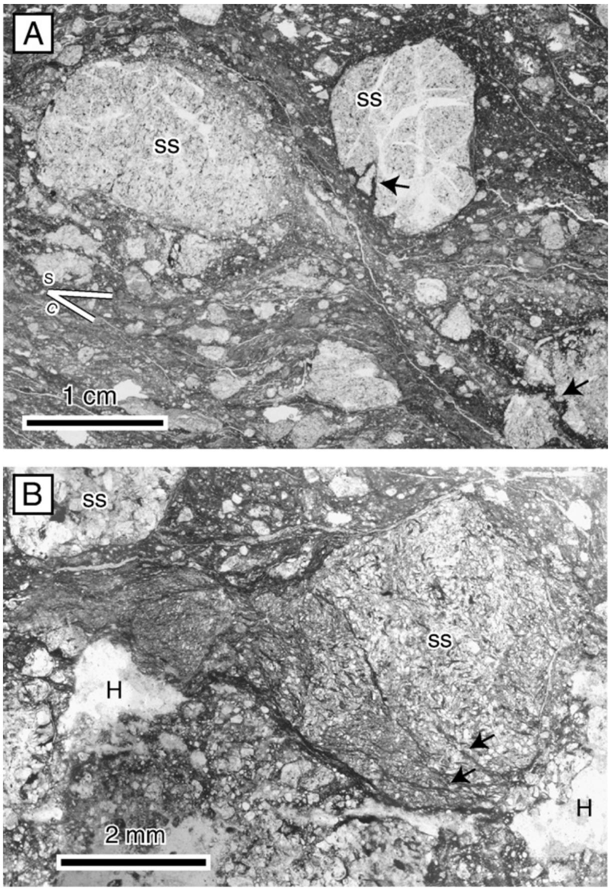

Fig. 5. Photomicrographs of mélange. (A) Hydrofracturing of sandstone clasts (ss) with mud injections (black arrows) and cataclastic deformation. S- and C-planes are observed within that part of the rock subjected to cataclastic deformation. S: S-plane, C: C-plane. (B) Pinch-and-swell structure sandstone clast (ss) with mud injections (black arrows). H: hole in thin section.

1990; Kano et al., 1991; Kusky and Bradley, 1999; Onishi and Kimura, 1995; Onishi et al., 2001; Niwa et al., 2005; Niwa, 2006; Fukui and Kano, 2007).

In the present study, we estimated the shear direction from shear fabrics observed in mélange and along thrust planes, based on a rotation of the intersection of S- and C-planes by 90°, as described by Kano et al. (1991). The strike of bedding is different between the western and eastern areas (N80°E and N5°W, respectively; Fig. 8), reflecting large-scale folding or bending; however, these structures are not yet understood. We adopt the strike of N5°W for analyses of shear direction, as most of the structural data considered in this study are derived from the eastern area. This orientation is also similar to the strike of the Chiang Mai Tectonic Line and the trend of the volcanic arc within the Sukhothai Zone.

To enable correlations between the western and eastern regions, C-planes in the western area were rotated clockwise by 95° about a vertical axis. Assuming that the mélange fabrics formed during the early stages of deformation related to subduction, the sedimentary layers would have been gently dipping (Fukui and Kano, 2007); consequently, we performed a tilt correction for the C-planes in the mélange. The C-planes along the thrusts were not corrected for tilting. The restored slip directions within hanging walls vary between top-to-the-south and top-to-the-southwest, except for two examples in the mélange (Fig. 9). The mean slip direction indicates top-to-the-south motion, toward 190°. Of the five slip directions determined for thrusts, two are top-to-the-north, two are top-to-the-south, and one top-to-the-west (Fig. 9). The trends of the slip directions are similar (i.e., north–south) in the mélange and along the thrusts.

7. Illite crystallinity analysis

To estimate the temperature of low-grade metamorphism during mélange formation, we measured illite crystallinity (IC) values for nine samples of black pelitic rocks collected from the Inthanon Zone. For comparison, IC values were also determined for four samples from the Sibumasu Block.

IC is determined from the Kübler index, which is the peak width at half maximum height of the 10 Å illite peak, as expressed in $\Delta°2\theta$ (Frey, 1987; Kübler, 1968). The intensity of the preferred orientation of clay minerals generally increases with decreasing IC values.

The samples were washed, crushed in a swing mill for 10 s, and passed through a 72-mesh sieve. Ten grams of the resulting powder was then suspended in a test tube. The ≤2 μm clay fraction was separated by gravity settling and concentrated by centrifuge before being pipetted onto two glass slides to make sedimented slides. The average thickness of clay on the slides was maintained between 5 and 10 mg/cm^2, as clay thickness is known to affect the intensity of crystallinity (Kisch, 1991). Analyses were performed using a JEOL 8030 X-ray diffractometer housed at the Geological Survey of Japan, Tsukuba, Japan, using the following measurement conditions: CuKα radiation at 40 kV and 40 mA, step scan speed of 0.01 °2θ/s, divergence and scatter slits of 1°, receiving slit of 0.2 mm, and scan range of 6.5–10.5 °2θ. Two slides of each sample were scanned to check for errors. Samples were then treated with ethylene glycol to remove the smectite peak that overlaps with the illite peak. For inter-laboratory calibration, Warr and Rice (1994) proposed the CIS (Crystallinity-Index Standard), which comprises standard samples used for calibration in studies of illite crystallinity. Based on measured

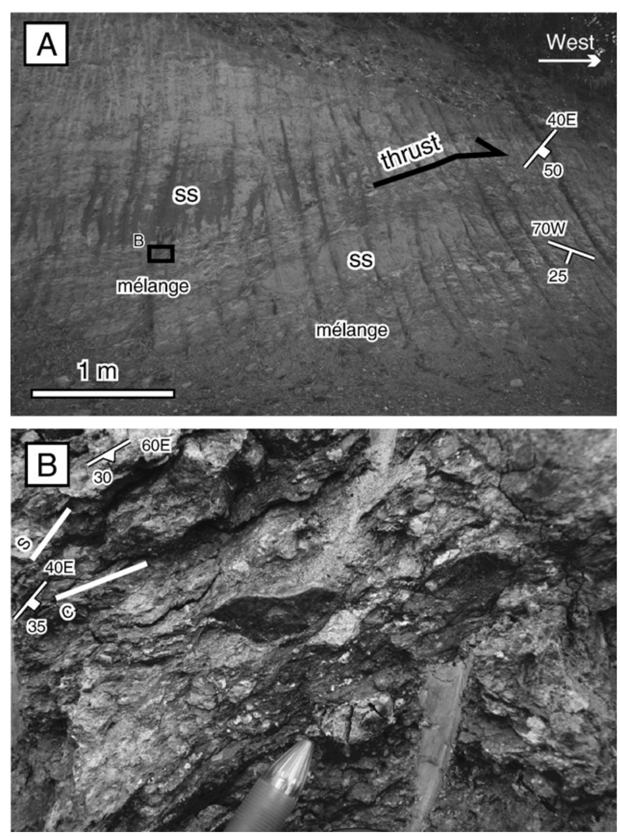

Fig. 6. (A) Outcrop photograph of a thrust developed in mélange and sandstone layers (ss). The black rectangle indicates the area shown in (B). See Fig. 2 for the location of this outcrop. (B) Shear fabrics observed just beneath the thrust shown in (A), indicating dextral slip based on sigma-type asymmetric tails to sandstone clasts. S: S-plane, C: C-plane.

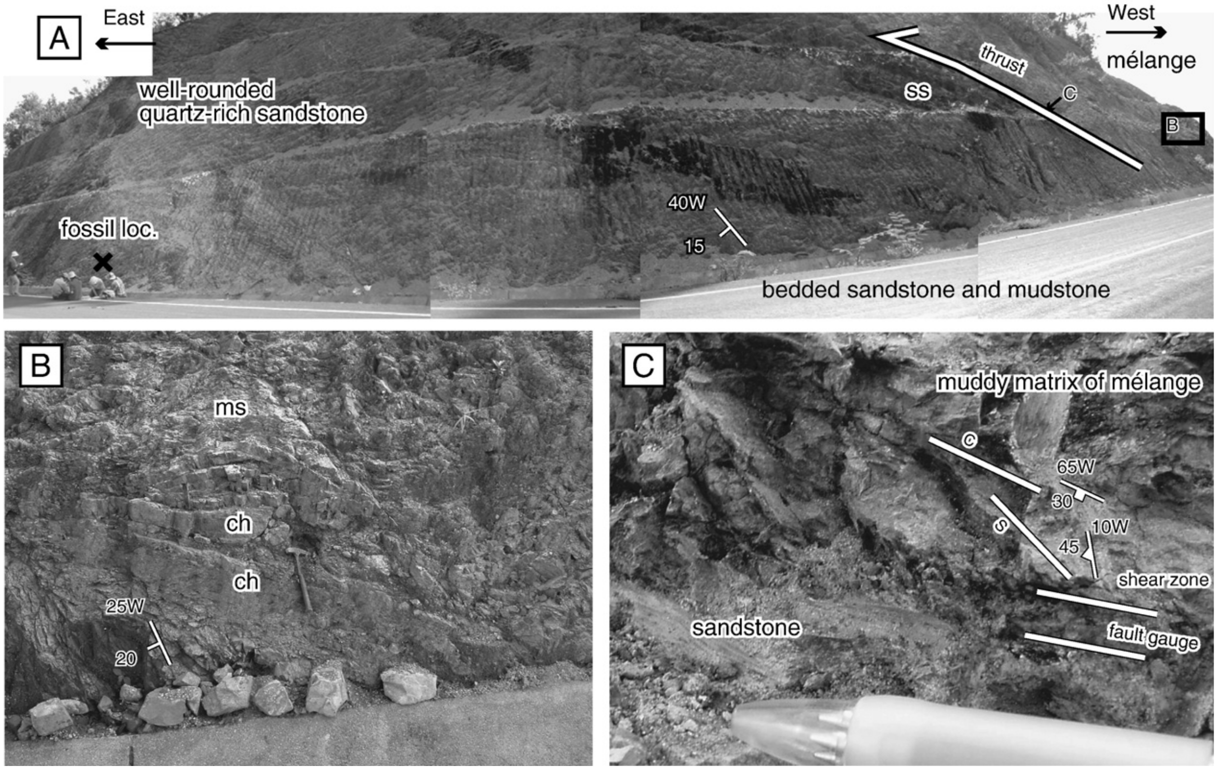

Fig. 7. (A) Outcrop photograph showing a thrust developed between mélange in the hanging wall and well-bedded sandstone (ss) in the footwall. The black rectangle and small arrow indicate the locations of (B) and (C), respectively. See Fig. 2 for the location of the outcrop. (B) Chert-bearing mélange in the hanging wall. ch: chert; ms: mudstone. (C) Shear fabric observed just above thrust, indicating sinistral slip. The thrust plane consists of weathered clay gouge. S: S-plane, C: C-plane.

values of CIS compiled by the Geological Survey of Japan, Hara and Kimura (2003) reported the following correlation equation: IC (CIS) = 1.55 IC (GSJ) − 0.07, with a correlation coefficient of 0.99.

Fig. 10 shows the obtained IC values plotted on a geological map of the study area. Most of the IC values determined for the Paleo-Tethyan rocks in the Inthanon Zone fall within the range 0.42 to 0.59 $\Delta°2\theta$ (mean = 0.52 $\Delta°2\theta$, $1\sigma = 0.024$), while the samples from the Sibumasu Block yield values between 0.22 and 0.35 (mean = 0.28 $\Delta°2\theta$, $1\sigma = 0.074$). The difference in IC values between the Paleo-Tethyan rocks and samples from the Sibumasu Block is estimated to be approximately 0.2–0.3 $\Delta°2\theta$.

8. Low-grade metamorphism and mélange formation related to Paleo-Tethyan subduction

The maximum temperatures indicated by illite crystallinity data can be quantitatively estimated based on the relationship between IC values and vitrinite reflectance data (Guthrie et al., 1986; Kosakowski et al., 1999; Underwood et al., 1993). Mukoyoshi et al. (2007) described a relationship between illite crystallinity and mean random vitrinite reflectance (Rm%) estimated for the Shimanto accretionary complex, Kyushu, Southwest Japan. Their analyses of illite crystallinity were performed at the Geological Survey of Japan using the same sample preparation and measurement conditions as those employed in the present study. The correlation between Rm and IC values in this earlier study indicates a linear regression equation of Rm (%) = 6.9 − 8.2 IC ($\Delta°2\theta$), with a correlation coefficient of 0.91.

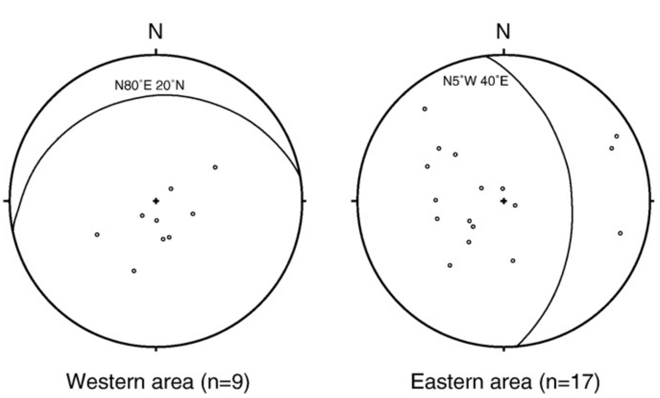

Fig. 8. Stereonets showing poles to bedding planes and best-fit girdle to the poles for the western and eastern areas (see Fig. 2). Lower hemisphere, equal-angle projections.

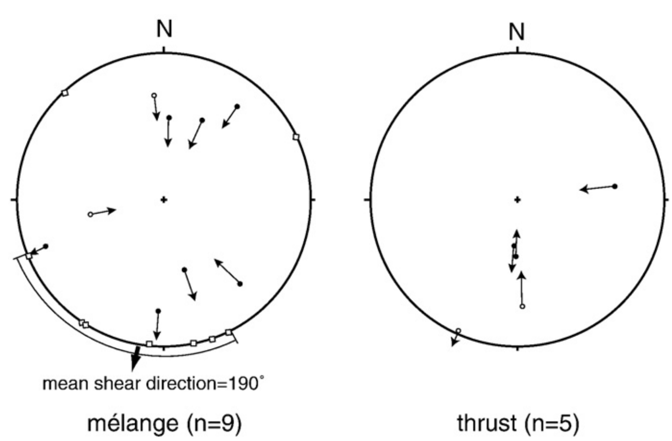

Fig. 9. Stereonets showing shear directions recorded in mélange and along thrust planes. Data collected from the western area (see Fig. 2) were subjected to a clockwise rotation of 95° to enable comparison with data from the eastern area. See the text for a detailed explanation for restoration of the shear directions. Lower hemisphere, equal-angle projections. Open circles are data from western area after correction for whole-block rotation relative to the eastern area. Black circles are data from eastern area. Black arrows are shear direction. Open rectangles indicate shear direction recorded within the mélange after the removal of tilting.

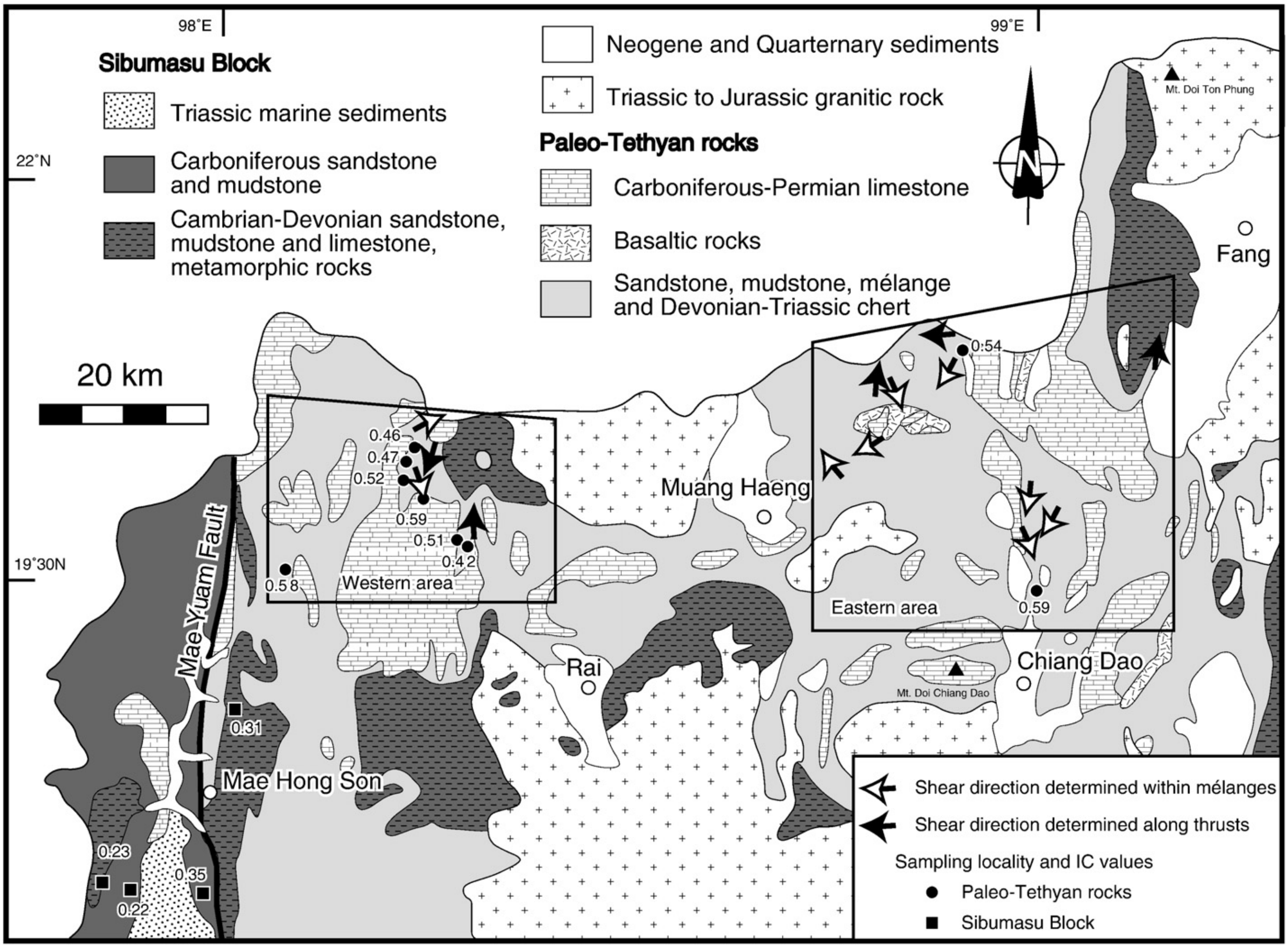

Fig. 10. Illite crystallinity values plotted on a simplified geological map of the Inthanon Zone. Black circles indicate sample localities within the Inthanon Zone; black squares indicate sample localities within the Sibumasu Block; the accompanying numbers are IC values (Δ°2θ). The shear directions presented in Fig. 9 are plotted on this map.

Using the equation of Sweeney and Burnham (1990) to convert vitrinite reflectance into temperature over a heating duration of 10 Ma, the temperature conditions represented by the illite crystallinity data are calculated using the following equation: T (°C) = 353 − 206 IC (Δ°2θ), with a correlation coefficient of 0.92 (Mukoyoshi et al., 2007). Most of the IC values determined in the present study for the Inthanon Zone range from 0.47 to 0.59 Δ°2θ (diagenetic zone; Kübler, 1968), yielding temperatures between approximately 230 and 256 °C (mean = 246 °C) when calculated using the equation proposed by Mukoyoshi et al. (2007). In contrast, the temperature calculated for the Sibumasu Block is 295 °C (mean IC value = 0.28 Δ°2θ).

The temperature estimates calculated from IC values are interpreted to represent the maximum temperature within the accretionary complex, indicating the conditions after mélange formation (e.g., Hara and Hisada, 2007). The obtained IC values of 0.47–0.59 Δ°2θ indicate temperatures below 250 °C during mélange formation, corresponding to diagenesis or low-grade metamorphism.

At the microscale, the mélanges associated with Paleo-Tethys subduction are characterized by hydrofracturing under semi-lithified conditions, with no evidence of recrystallization or the plastic deformation of quartz grains. Sandstone clasts are also subjected to cataclastic deformation and fracturing. The argillaceous matrix was ductile, and was injected into fractures within sandstone clasts. Subsequent to hydrofracturing and cataclastic deformation, sandstone clasts were reoriented along S- and C-planes by shear deformation. Based on these microscopic features of the mélange and the estimated temperatures, accretion of the Paleo-Tethyan rocks is interpreted to have occurred at shallow levels within the accretionary prism, as described by Byrne (1984) and Fukui and Kano (2007).

9. Direction of Paleo-Tethys subduction

Many workers have reconstructed the direction of oceanic plate subduction based on asymmetric shear fabrics recorded in ancient accretionary complexes (e.g., Fisher and Byrne, 1987; Needham and Mackenzie, 1988; Kano et al., 1991; Onishi and Kimura, 1995; Fukui and Kano, 2007). Such fabrics are produced by shear along a décollement in the subduction zone. Using this method, we estimated the subduction direction of the Paleo-Tethys based on asymmetric shear fabrics observed in mélange. We obtained a mean slip direction indicating top-to-the-south motion (190°). Assuming orthogonal subduction, the trend of the subduction zone must have been N80°W (Fig. 11A).

Paleomagnetic studies of Jurassic and Cretaceous sedimentary basins have revealed that northern Thailand underwent 20° or more of clockwise rotation during the Middle Miocene in response to collision between the Indian and Eurasian continents (Charusiri et al., 2006; Aihara et al., 2007). To take this rotation into account in our analysis, we rotated the original slip directions anticlockwise by 20° (Fig. 11A). The trend of the Paleo-Tethys subduction zone is then estimated to be N80°E, indicating that the Paleo-Tethys was subducted to the north, beneath the Indochina Block.

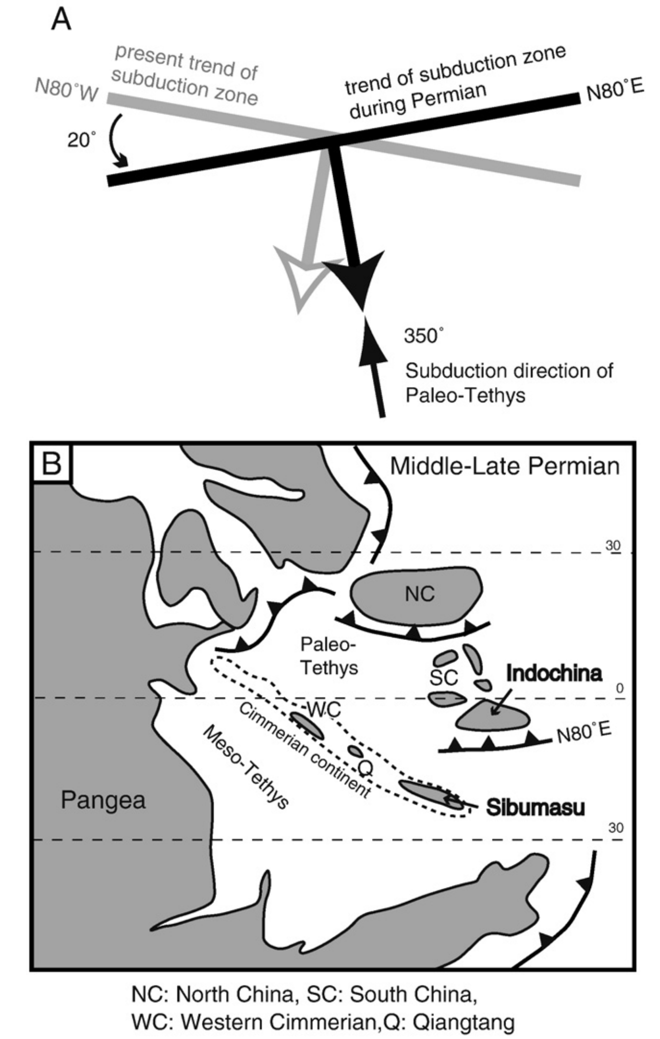

Fig. 11. (A) Restored mean shear direction of the hanging wall in the mélange. Open arrow indicates the present-day position of shear direction, and the black arrow is the paleo-position before collision between the Indian and Eurasian continents. See the text for a detailed explanation. (B) Paleogeographic reconstruction of subduction zone between Indochina and Sibumasu Blocks during Middle to Late Permian, modified from Metcalfe (2002) with our own interpretations.

Metcalfe (1999, 2002, 2006) proposed a paleogeographic reconstruction of the Paleo-Tethys region from the Permian to Triassic, involving an E–W-trending subduction zone along the southern margin of the Indochina Block. Our results, based on an analysis of asymmetric shear fabrics in mélange (Fig. 11B), support Metcalfe's model for the Paleo-Tethys subduction zone. We also propose that the present-day internal structure of the accretionary complex (e.g., imbricated structure) is oriented oblique to the volcanic arc within the Sukhothai Zone. This re-orientation appears to have resulted from displacement along the Chiang Mai Tectonic Line and the Mae Yuam Fault, and strike-slip fault developed during Tertiary (Morley et al., 2001; Morley, 2002).

In the Inthanon Zone, thrusting was synchronous with and post-dated mélange formation. Thrusts are divided into in-sequence thrusts, out-of-sequence thrusts, and back thrusts (Fabbri et al., 1990; Kimura and Hori, 1993; Ohmori et al., 1997; Kimura, 1998). To discriminate among these types of thrusts, information is required regarding not only the geometry and kinematics of the thrust, but also the geological ages of the hanging wall and footwall, the timing of thrusting, and the relationship of the paleogeothermal structure (Kimura, 1998). This information is lacking in the present study; consequently, we were unable to identify the types of thrusts; however, the trends of the slip directions along the thrusts are similar to those recorded in the mélange. Various types of thrusts (e.g., in-sequence thrusts, out-of-sequence thrusts, and back thrusts) appear to have developed during Paleo-Tethys subduction and subsequent collision tectonics between the Indochina and Sibumasu Blocks.

10. Accretionary complex within the Paleo-Tethys subduction zone

Accretionary complexes related to subduction of the Paleo-Tethys occur along the margin of the Indochina Block. Within the Inthanon Zone in northern Thailand, Paleo-Tethyan rocks associated with a large extent of oceanic plate indicate a long duration of deposition (e.g., Middle Devonian to Middle Triassic cherts and Carboniferous to Permian limestones). In addition, the accretionary complex preserved in the Inthanon Zone is characterized by accretion within the shallow levels of an accretionary prism. An accretionary complex is also found in the Sa Kaeo–Chanthaburi area of western Thailand (Chutakositkanon et al., 2004; Hada et al., 1999; Hara et al., 2006), consisting of a chert–clastic sequence and mélange units (Hada et al., 1999), and characterized by southwest-verging imbricated structure (Chutakositkanon et al., 2004). The cherts are indicative of pelagic depositional conditions from the Early Permian to Middle Triassic (Hada et al., 1999; Metcalfe, 1999; Kamata et al., 2009). Most of the illite crystallinity values obtained from the Sa Kaeo–Chanthaburi area indicate conditions of the diagenetic zone (210–270 °C), suggesting accretion, low-grade metamorphism, and uplift as an accretionary complex (Hara et al., 2006).

The absence of fossils within clastic rocks of accretionary complexes associated with subduction of the Paleo-Tethys means that their ages of accretion are poorly constrained. Hada et al. (1999) proposed that the Paleo-Tethys closed during the latest Triassic, based on the widespread deposition of the non-marine Khorat Group after the latest Triassic, which covered the Indochina Block and Sibumasu Block in northern Thailand (Department of Mineral Resource, 1999). It is possible that Paleo-Tethyan rocks were subducted and accreted along the margin of the Indochina Block from the Permian to Triassic. Subsequent to closure of the Paleo-Tethys, collision tectonics occurred between the Sibumasu and Indochina blocks, and the Paleo-Tethyan rocks were thrust over the Sibumasu Block.

11. Conclusions

Based on an analysis of mélange structures and metamorphic temperatures derived from illite crystallinity data, we reconstructed the accretionary process related to subduction of the Paleo-Tethys, as recorded in northern Thailand. Our field observations indicate that the accretionary complex formed at shallow levels within the accretionary prism, being characterized by hydrofracturing and cataclastic deformation with mud injections, with local shear deformation and pressure solution. Illite crystallinity data indicate that mélange formation occurred below 250 °C. We also reconstructed the direction of Paleo-Tethys subduction based on asymmetric shear fabrics in mélange. After correction for rotation associated with collision between the Indian and Eurasian continents, the trend of the Paleo-Tethys subduction zone is estimated to have been N80°E. The Paleo-Tethys was subducted northward beneath the Indochina Block from the Permian to Triassic.

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