Re-evaluation of the activity of the Thoen Fault in the Lampang Basin, northern Thailand, based on geomorphology and geochronology

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We applied remote sensing techniques and geomorphic index analysis to a study of the NE-SW-striking Thoen Fault, Lampang Basin, northern Thailand. Morphotectonic landforms, formed by normal faulting in the basin, include fault scarps, triangular facets, wine-glass canyons, and a linear mountain front. Along the Thoen Fault, the stream length gradient index records steeper slopes near the mountain front; the index values are possibly related to a normal fault system. Moreover, we obtained low values of the ratio of the valley floor width to valley height (0.44–2.75), and of mountain-front sinuosity (1.11–1.82) along various segments of the fault. These geomorphic indices suggest tectonic activity involving dip-slip displacement on faults. Although the geomorphology and geomorphic indices in the study area indicate active normal faulting, sedimentary units exposed in a trench at Ban Don Fai show no evidence of recent fault movement. In Ban Don Fai trench No. 2, accelerator mass spectrometry radiocarbon (AMS) ages and optically stimulated luminescence (OSL) ages indicate that deposition of the lowest exposed sedimentary unit occurred between 960 and 910 years ago. Therefore, the most recent movement upon the Ban Don Fai segment of the Thoen Fault occurred more than 960 years ago.

Key words: Thoen Fault, normal faulting, morphotectonic landforms, geomorphic index analysis, OSL dating, AMS radiocarbon dating, Lampang Basin, Northern Thailand.

1. Introduction

Thailand is located to the east of the Andaman-Sumatra earthquake belt, and no large earthquake (i.e., magnitude ≥ 6 on the Richter scale) has recently occurred in this region. Thus, Thailand has not been considered a seismically active country. However, historical earthquakes in Thailand have been reported by Nutalaya *et al.* (1985), based on historical texts, annals, stone inscriptions, and astrological documents in the Thai language. These earthquakes are likely to have originated on the active faults of Myanmar and southern China (Fenton *et al.*, 2003). Although a few moderate earthquakes (i.e., magnitude 3–6 on the Richter scale) have recently been recorded in Thailand, seismicity in Thailand is generally considered to be low, and there is no clear association of seismicity with mapped faults (Bott *et al.*, 1997; Fenton *et al.*, 2003). In addition, geological and geomorphological investigations reveal that Quaternary faults in northern Thailand are characterized by long recurrence intervals of thousands to tens of thousands of years (Bott *et al.*, 1997; Kosuwan *et al.*, 1999; Fenton *et al.*, 2003).

Northern Thailand is located in an active tectonic zone (Natalaya *et al.*, 1985). The Cenozoic Lampang Basin is

bordered on its southeastern side by the Thoen Fault. Based on observations of lineaments using remote sensing, morphotectonic landforms, and micro-earthquakes (i.e., magnitude ≤ 3 on the Richter scale), the Thoen Fault can be classified as active (Hinthong, 1995; DMR, 2006) (Fig. 1). Although no large earthquake has occurred within the Lampang Basin, micro-earthquakes are recorded by seismographs of the Thai Meteorological Department and the Royal Thai Navy Seismic Research Station. Seismogenic faults in this area have not been identified, and it is not certain whether micro-earthquakes in the Lampang Basin are caused by basement tectonics or active faulting. Therefore, to clarify the nature of this seismicity, we examined the paleoseismicity of faults along the border of the Lampang Basin.

In this paper, we document movements along the Thoen Fault (Fig. 1(B)). We used remote sensing techniques and aerial photographs to identify and analyze the characteristic morphotectonic landforms that result from fault movements along the southeastern margin of the Lampang Basin. Based on this analysis, we identified a suitable site for trenching, and compiled the trench-log stratigraphy at this site. Quaternary dating methods, including optically stimulated luminescence (OSL) and accelerator mass spectrometry (AMS) radiocarbon dating, were used to determine the ages of sedimentary layers in the trench. The Thoen Fault can be divided into six segments based on fault geometry: the Ban Don Fai, Ban Mai, Ban Mae Ip, Mae Than, Sop

Fig. 1. Map of Thailand showing active faults (Hinthong, 1995) (A), and location of the Thoen Fault in the Lampang Basin (B).

Prap, and Doi Ton Ngun segments (Fig. 1(B)). Some of these segments were examined as part of a paleoearthquake study; however, paleoearthquake data are insufficient in terms of determining the timing of the most recent event. Trenching studies across the fault segments are necessary to reconstruct the history of displacement. Normal faulting along the Ban Don Fai segment has produced distinct morphotectonic landforms that represent the most important data in terms of site selection for a paleoearthquake study. Thus, our study focuses on the Ban Don Fai segment (segment 1 in Fig. 1(B)).

2. Tectonic Setting

The tectonic framework of SE Asia is dominated by the interaction of three major adjoining lithospheric plates: the continental-oceanic Indian Plate to the west and south, the continental Eurasian Plate in a central location, and the oceanic Philippine Plate to the east (Fenton *et al.*, 2003). Thailand is part of the Eurasian Plate and lies to the east of an active east-dipping subduction zone that extends from north India (Himalaya Frontal Thrust), passes through west Myanmar and west of the Andaman and Nicobar Islands, and then swings eastwards along the Sumatra-Java trench (Reading, 1980) (Fig. 2). Major tectonic events may have occurred in the Indochina region during the late Paleogene (Peltzer and Tapponnier, 1988; Polachan *et al.*, 1991; Charusiri *et al.*, 2002, 2007) and are likely to have been related to the northwards and northeastwards progressive collision of the Indian and Eurasian plates (Peltzer and

Tapponnier, 1988; Charusiri *et al.*, 2007).

In the Indochina region, since the late Paleogene, the collision of the Indian and Eurasian plates has resulted in predominantly strike-slip faults that strike NW-SE and NE-SW, and dip-slip faults that strike N-S (Tapponnier *et al.*, 1986; Peltzer and Tapponnier, 1988). Important and well-known fault zones in this region include the Red River Fault Zone in Vietnam (Tapponnier *et al.*, 1986; Morley, 2007), the Sagaing Fault Zone in Myanmar (Tapponnier *et al.*, 1986; Morley, 2007), and the Mae Ping and Three Pagoda fault zones in western Thailand (Morley, 2002; Fenton *et al.*, 2003). During the late Eocene, collision of the Indian and Eurasian plates resulted in left-lateral displacements along the NW-SE striking Red River, Mae Ping, and Three Pagoda faults (Lacassin *et al.*, 1997), but most recently these faults have been characterized by right-lateral displacements (Lacassin *et al.*, 1997; Morley, 2002; Fenton *et al.*, 2003). The left-lateral displacement along the Red River Fault amounted to hundreds of kilometers in the Eocene–Oligocene, related to extension within the South China Sea (Morley, 2002). The clockwise rotation of SE Asia coincided with a reversal in the sense of fault movement along the Mae Ping and Three Pagoda faults in the early Miocene, when these faults changed from left-lateral to right-lateral NW-SE-striking faults. At the same time, the Red River Fault continued as a left-lateral strike-slip fault (Huchon *et al.*, 1994; Lacassin *et al.*, 1997). By the middle Miocene, all of the NW-SE-striking strike-slip faults in the Indochina region (Red River, Mae Ping, and Three Pagoda

Fig. 2. Major tectonic elements in SE Asia and adjacent areas. Arrows show relative directions of plate movement during the late Cenozoic. TPFZ—Three Pagodas Fault Zone; MPFZ—Mae Ping Fault Zone; UFZ—Uttaradit Fault Zone. (Modified from Polachan *et al.*, 1991).

faults) had become right-lateral strike-slip faults (Longley, 1997). The main strike-slip faults (Red River, Mae Ping, and Three Pagoda faults) together form a transtensional regime that is related to the opening of Cenozoic basins in SE Asia (Ducrocq *et al.*, 1992).

Thailand lies mainly in a zone of strike-slip deformation, between the Red River Fault Zone to the east and the compressive Sagaing Fault Zone to the west (Morley, 2007). Cenozoic basins in northern Thailand are mainly N-S-trending graben and half-graben with sediments ranging in thickness from 1,000 to 3,000 m (Polachan *et al.*, 1991). These Cenozoic basins are governed by N-S extensional faults which are inferred to be causally related to right-lateral slip movements on the NW-SE-striking faults, and left-lateral slip on the NE-SW-striking faults (Polachan *et al.*, 1991; Packham, 1993). The geometries of the Cenozoic basins and the locations of faults may possibly be controlled by pre-existing fabrics in the basement rocks (O'Leary and Hill, 1989; Morley, 2007). A combination of both dip-slip and left-lateral strike-slip movement (i.e., oblique sinistral extension) is recognized as being required to explain the evolution of these basins (Morley *et al.*, 2001, 2004, 2007; Morley, 2002, 2007).

3. Active Faults in Thailand

Paleoearthquake studies aim to determine the occurrence of past earthquakes on active faults. An active fault can be defined as one that has moved at least once during the period that includes the late Pleistocene and extends through to the present day (Geological Survey of Japan, 1983). Moreover, an active fault may generate another earthquake in the near future.

Based on seismological and geological evidence, Nutalaya *et al.* (1985) were the first to introduce the concept of seismic source zones in Thailand and neighboring countries. Hinthong (1995, 1997) conducted a project titled "Study of Active Faults in Thailand", and used geological, historical, and seismological data to identify 23 active or suspected active faults in Thailand (Fig. 1(A)). Siribhakdi (1986) studied seismogenic regimes in Thailand, and reported on the earthquakes that had occurred in Thailand throughout the past 1,500 years. Many of these earthquakes were closely related to the Three Pagoda Fault (number 13 in Fig. 1(A)), the Si Sawat Fault (12 in Fig. 1(A)), the Mae Ping Fault (Moei Fault of Hinthong (1995); 11 in Fig. 1(A)), and the Mae Hong Son Fault (Mae Sariang Fault of Hinthong (1995); 3 in Fig. 1(A)). Thiramongkol (1986) provided evidence of Holocene movement on the Bang Pa Kong Fault along the eastern margin of the lower central plain of Thailand (number 23 in Fig. 1(A)). Charusiri *et al.*

(1996) applied several remote sensing techniques to a study of earthquakes in Thailand and neighboring countries. A seismotectonic (or seismic source) map was compiled by Charusiri *et al.* (1996). Rhodes *et al.* (2004) studied the kinematics of the Mae Kuang Fault in northeastern Chiang Mai, northern Thailand, and identified offset contacts and slickenlines on the surface of the fault, indicating a left-lateral slip of 3.5 km and a dip-slip of 600 m. The authors suggested that the fault was initiated between 20 and 5 Ma, simultaneous with a reversal in the movement direction on the Mae Ping and Red River faults, and that it terminates at the northeastern margin of the Chiang Mai Basin. The Mae Kuang Fault does not extend to the western side of the Chiang Mai Basin because it is truncated by the right-lateral Mae Tha Fault.

The Thoen Fault in the Cenozoic Lampang Basin strikes NE-SW, and has been regarded as an active fault (Hinthong, 1995, 1997; Fenton *et al.*, 1997, 2003). Based on morphotectonic landforms and geochronological data, the Department of Mineral Resources in Thailand (DMR, 2006) also classified the Thoen Fault as active. Quartz-rich samples from fault-related colluviums, and charcoal samples, provide displacement ages of 4,000, 3,000, and 2,000 years BP using thermoluminescence (TL) dating and the ^{14}C method, respectively (DMR, 2006). Moreover, from 1990 to the present day, more than two dozen earthquakes with magnitudes of M_b 3.0–5.0 have been detected near this fault. Danphaiboonphon (2005) studied the characteristics of the Thoen Fault, using remote sensing, petrographic analysis, and geophysical investigation, and suggested that it is an oblique strike-slip fault. Several lines of evidence, using geomorphology and stratigraphy, indicate that the Thoen Fault was an extensional structure during the Holocene (Fenton *et al.*, 1997, 2003), and that the displacements are mainly normal dip-slip and subordinate left-lateral slip. The slip rate of the fault is about 0.6 mm/yr (Fenton *et al.*, 2003). Pailoplee *et al.* (2009) excavated two trenches on the Ban Mai (number 2 in Fig. 1(B)) and Doi Ton Ngun (6 in Fig. 1(B)) segments of the Thoen Fault in the Lampang Basin. Based on trench-log interpretations, the Ban Mai segment records a single main paleoearthquake, at 3,800 years ago; the slip rate is approximately 0.06 mm/yr. The Doi Ton Ngun segment records evidence for two paleoearthquake events at 3,500 and 1,800 years ago; the average slip rate since the last fault movement is 0.18 mm/yr, and the recurrence interval for earthquakes is 1,700 years. Based on the current study of seismicity (i.e., the b value of the Gutenberg-Richter (G-R) relationship, where a low value indicates high earthquake activity) upon the Thoen Fault (Lampang Basin) and upon the Phrae Fault (Phrae Basin), the b value for the Thoen Fault is lower than that for the Phrae Fault (Pailoplee *et al.*, 2009). Pailoplee *et al.* (2009) also suggested that the Thoen Fault in the Lampang Basin is capable of generating more earthquake activity than the Phrae Fault.

4. Interpretation of Remote Sensing Data

Lineaments and faults in the Lampang Basin and adjacent areas are visible on enhanced Landsat 7 images, mainly oriented NE-SW, with conjugate structures oriented NW-SE, along with some minor N-S structures (Fig. 3). The NE-

SW-striking fault that bounds the Lampang Basin is clearly visible along the southeastern side of the basin (Fig. 4). The total length of the Thoen Fault in the Lampang Basin is approximately 75 km. The fault can be traced along the boundary between Triassic marine sandstone and unconsolidated Quaternary sediments that are mainly fluvial, colluvial, and alluvial deposits.

The Thoen Fault is well defined, visible as a sharp lineament on aerial photographs and satellite images (Fig. 4). Detailed interpretations of aerial photographs reveal fault scarps at Ban Mai, Ban Don Fai, and Ban Samai Nuea ((A) and (C) in Fig. 4), and reveal the following six geometrical fault segments along the southeastern margin of the Lampang Basin: Ban Don Fai, Ban Mai, Ban Mae Ip, Doi Ton Ngun, Mae Than, and Sop Prap (Fig. 1(B)).

The morphotectonic landforms observed in the Lampang Basin include fault scarps, triangular facets, wine-glass canyons, and linear mountain fronts. A combination of vertical movement on range-bounding normal faults and stream incision in the valleys results in the formation of triangular facets. Triangular facets are roughly planar surfaces with broad bases and upwards-pointing apexes that occur between valleys (Keller and Pinter, 1996) (Fig. 5(B)). The occurrence of a sequence of displacements along a normal fault would produce a series of triangular facets (Hamblin, 1976; Fenton *et al.*, 2003) (Fig. 5(D)). A series of triangular facets is found in the Lampang Basin along the NW-facing escarpment (Figs. 5(A) and 5(C)). Hamblin (1976) proposed that such features could result from episodic fault movement, and that the facets would form during fault movement while the benches form during the intervening periods of tectonic stability. According to this model, triangular facets first form by stream-cutting across the fault scarp (I–II in Fig. 6), producing a first set of triangular facets develop (II in Fig. 6). During a succeeding period of tectonic quiet, a narrow pediment develops (III in Fig. 6). Then, renewed displacement on the normal fault results in a new fault scarp (IV in Fig. 6), and streams develop on this new scarp. Thereafter, a second set of triangular facets develops (V in Fig. 6). A succession of similar events would result in several sets of triangular facets (VI–VIII in Fig. 6). Based on this model, the triangular facets in the Lampang Basin might correspond to stage VIII. Triangular facets may be caused by lateral erosion or by differential erosion acting on a lithologic boundary between resistant and non-resistant rocks; however, several streams that cross the Ban Don Fai, Sop Prap, and Ban Mai segments pass through wine-glass canyons (Fig. 7) and V-shaped valleys. The presence of wine-glass canyons indicates steepening of the faceted spurs at the base of the escarpment, suggesting in turn that the Ban Don Fai and Ban Mai segments, and possibly other segments, are currently undergoing renewed or increasing vertical displacement. Rapid down-cutting results in the formation of a narrow slot in a wine-glass canyon. A line of small, triangular facets at the base of the range front coincides with the locations of a narrow slot in a wine-glass canyon, and with the surface trace of the Thoen Fault. A NW-facing escarpment of triangular facets is developed in Triassic marine sandstone, with slope angles (50° – 60°) steeper than the dip of bedding (45° – 50°).

Fig. 3. Map showing lineaments in the Lampang Basin, northern Thailand (A), and a rose diagram of lineament orientations (B).

These morphotectonic landforms (i.e., triangular facets, V-shaped valleys, and wine-glass canyons) have been reported from other well-studied active fault zones and are considered to indicate mountain fronts bounded by active faults (e.g., Hamblin, 1976; Bull and McFadden, 1977; Wallace, 1978; Fenton *et al.*, 2003; Ganas *et al.*, 2005; Picotti *et al.*, 2009). Our explanation of the origin of triangular facets is consistent with the findings of previous studies that linked facet formation to periods of active faulting.

5. Analyses Based on Geomorphic Indices

Geomorphic indices are useful for the level of tectonic activity, and zones of active tectonism (Keller and Pinter, 1996; Bull, 2008). Geomorphic indices represent preliminary tools for identifying areas that are experiencing rapid tectonic deformation (Keller and Pinter, 1996; Bull, 2008).

Geomorphic indices, including the stream length gradient index (SL), the ratio of valley floor width to valley height (Vf), and mountain-front sinuosity (Smf), were used in the present study to identify tectonic activity within the Lampang Basin. All the parameters for the geomorphic index analysis are taken from the Mae Tha (map sheet 4945 III) and Sop Prap (map sheet 4844 I) 1:50,000 topographic maps.

5.1 Stream length gradient index (SL)

The SL index is correlated with stream power (Hack, 1973; Keller and Pinter, 1996). The total stream power available at any particular reach of a channel is an important hydrologic variable because it relates to the ability of a stream to transport sediments and erode its bed. The available stream power is proportional to the slope of the water surface and the discharge. The gradient of the water sur-

Fig. 4. Panchromatic Landsat image of the Thoen Fault in the Lampang Basin, showing a sharp lineament near Ban Mai, Ban Don Fai, and Ban Samai Nuea (B), and aerial photographs of the Thoen Fault showing the fault scarps at Ban Mai, Ban Don Fai, and Ban Samai Nuea ((A) and (C)). The location of this image is shown in Fig. 3.

face correlates with the channel slope (Keller and Pinter, 1996). The SL index is a useful tool for evaluating changes in channel slope: high values are most simply related to resistant rock units, but they may also be related to the presence of an active tectonic zone (Keller and Pinter, 1996). The SL index is calculated from the gradient of the reach and the total channel length, as follows:

$$SL = (\Delta H / \Delta L) * L \quad (1)$$

where SL is the stream length gradient index, ΔH is the change in elevation of the reach, ΔL is the length of the reach, and L is the total length of the channel from the point of interest to the highest point of the channel.

In the small river basins of an active tectonic area, the SL index is a valid tool for detecting the incipient local processes of tectonic activity (Troiani and Della Seta, 2008). For our study, we measured the SL index for streams around the southeastern margin of the Lampang Basin. SL indices for the Ban Mai, Ban Don Fai, and Sop Prap segments ((A)

and (B) in Fig. 8) indicate steeper slopes near the mountain front (360–400 m and 280–420 m in elevation) along the southeastern margin of the basin (Figs. 9 and 10). These steeper slopes may have developed from resistant bedrock located near the mountain front or as a consequence of active tectonics with a large component of vertical displacement. Based on a 1:250,000 geological map of the Mae Tha and Sop Prap areas, the Thoen Fault is located along the steeper slopes near the mountain front (DMR, 1994). Thus, these steeper slopes are possibly caused by normal dip-slip movement on the Thoen Fault.

5.2 Ratio of valley floor width to valley height (Vf)

The Vf index is the ratio between the width of the valley floor and the mean height of the valley. The index is sensitive to tectonic base-level falls, because a narrowing of a valley floor is caused by downcutting of the stream (Bull, 2008). High values of Vf are commonly associated with low uplift rates (where streams cut broad valley floors), whereas low values correspond to deep valleys

Fig. 5. Panoramic view of the NW-facing escarpment with three lateral series of triangular facets at Doi Mae Tom in the Sop Prap area (A); an idealized model showing triangular facets of the Lampang Basin (B); a three-dimensional model of the Ikonos image of the Sop Prap area, showing a series of triangular facets (C); and a NW-SE cross-section across Doi Mae Tom (D).

Fig. 6. Development of a series of triangular facets produced by vertical tectonic movement (modified from Hamblin, 1976).

(V-shaped valleys) that result from vertical incision of the stream (Keller and Pinter, 1996). The index is calculated as

$$Vf = 2Vfw / ((Eld - Esc) + (Erd - Esc)) \quad (2)$$

where Vf is the ratio of the valley floor width to valley height, Vfw is the width of the valley floor, and Eld and Erd are the elevations of the left and right valley divides, respectively. Esc is the elevation of the valley floor.

Bull and McFadden (1977) showed that Vf values in the active tectonic zones of arid areas are characterized by Vf

values from 0.05 to 0.9, whereas Vf values in less active and inactive tectonic areas tend to fall in the ranges 0.5–3.6 and 2–47, respectively. The Vf index has seldom been applied to active tectonic areas in the tropics. A Vf analysis along the Lo River Fault in northern Vietnam produced low values (0.06 to 0.61), indicating recent uplift upon the fault (Cuong and Zuchiewicz, 2001).

In the present study, Vf values were determined for streams near the southeastern margin of the Lampang Basin. The values obtained for the Ban Mai, Ban Don Fai,

Fig. 7. Panoramic view of Doi Chang mountain, looking towards the SE, showing a wineglass canyon along the Sop Prap segment of the Thoen Fault.

Fig. 8. Map showing the locations of streams used for calculating SL and Vf indices, and trenching site. The numbers in circles indicate the locations of streams used for calculation of the Vf index.

Fig. 9. Stream length-gradient index (SL) analysis in the Ban Mai and Ban Don Fai segments. The figure shows steeper slopes near the mountain front, along the margin of the basin, at elevations of 360–400 m above m.s.l. Locations of streams are shown in Fig. 8.

Fig. 10. Stream length-gradient index (SL) analysis in the Sop Prap segment. The figure shows steeper slopes near the mountain front, along the margin of the basin, at elevations of 280–420 m above m.s.l. Locations of streams are shown in Fig. 8.

Table 1. Parameters for calculating the ratio of Valley floor width to Valley height (Vf) in the southeastern Lampang Basin.

Sop prap area/Stream name and location (No.)	Vfw (m)	Eld (m)	Erd (m)	Esc (m)	Vf
Huai Mae So (1)	104	480	460	360	0.95
Huai Sammai (2)	100	380	360	300	1.40
Huai Som (3)	160	360	380	260	1.45
Huai Pa Phai (4)	76	340	360	300	1.52
Huai Mae Wa (5)	110	340	340	300	2.75
Huai Kom Ko (6)	81	360	380	300	1.16
Huai Mae Thok Noi (7)	76	380	360	300	1.09
Ban Mai Area/Stream name and location (No.)	Vfw (m)	Eld (m)	Erd (m)	Esc (m)	Vf
Huai Sam Kha1 (8)	45	420	400	380	1.50
Huai Sam Kha2 (9)	87	560	600	380	0.44
Huai Mae Sapao (10)	119	580	560	380	0.63
Huai Mae Iak (11)	105	520	580	360	0.55
Huai Mae Mai (12)	67	350	460	340	1.03
Huai Mae Tap (13)	66	480	460	360	0.60

Remarks

Vfw = Width of the valley floor (m). Esc = Elevation of valley floor (m). Eld = Elevation of left valley divide (m). Vf = Ratio of valley floor width to valley height. Erd = Elevation of right valley divide (m). Smf = Mountain-front sinuosity. Locations of streams are shown in Fig. 8.

and Sop Prap segments vary from 0.44 to 2.75 (Table 1). Figure 8 shows the locations where Vf was determined. All of these sites are located within V-shaped valleys; however, smaller streams possess relatively little downcutting

power. As a result, smaller streams tend to have lower Vf values than larger streams within the same tectonic regime (Wiltshko *et al.*, 2010). Thus, the Vf values obtained in the present study are highly variable.

Table 2. Parameters for calculating values of mountain-front sinuosity (Smf) in the southeastern Lampang Basin.

Ban Mai area/Location	Lmf (m)	Ls (m)	Smf
1	17525	14289	1.23
2	1772	1154	1.54
3	1325	1182	1.12
4	1861	1678	1.11
5	2040	1472	1.39
6	1593	1040	1.53
7	1764	1549	1.14
8	2559	1874	1.37
9	5842	4561	1.28
10	6430	4949	1.30
11	8166	4491	1.82
12	9447	6744	1.40
13	7545	5560	1.36
14	2408	1707	1.41

Remarks

Lmf = length of mountain front along the foot of the mountain chain.
 Ls = straight-line length of the mountain front. Smf = mountain-front sinuosity. Locations are shown in Fig. 11.

5.3 Mountain-front sinuosity (Smf)

Mountain-front sinuosity (Smf) is calculated from the ratio of the length of the mountain front along the foot of the mountain chain (Lmf), to the mountain-front length as the crow flies (Ls). The Smf index reflects the balance between erosional power, which tends to embay frontal slopes, and tectonic power, which tends to produce a straight mountain front. The index is calculated as

$$Smf = Lmf/Ls \quad (3)$$

The Smf values for active tectonic zones in arid areas are relatively low (Bull and McFadden, 1977), typically between 1.2 and 1.6, while values for slightly active or inactive tectonic areas tend to fall in the ranges 1.8–3.4 or 2–7, respectively (Bull and McFadden, 1977). Smf analysis was previously applied to the Lo River Fault in northern Vietnam, yielding low values (1.11–1.59) that indicate recent uplift of the footwall (Cuong and Zuchiewicz, 2001).

In the present study, we measured the Smf index for streams around the southeastern margin of the Lampang Basin. The Smf values in the Ban Mai and Sop Prap areas vary from 1.11 to 1.82 (Table 2). The locations where Smf was determined are shown in Fig. 11.

5.4 Summary of analyses based on geomorphic indices

SL indices for the Thoen Fault, along the southeastern margin of the Lampang Basin, indicate a steeper slope near the mountain front, possibly the result of normal faulting. Moreover, most of the Vf and Smf values obtained for the Ban Mai, Ban Don Fai, and Sop Prap segments are low (0.44–2.75 for Vf and 1.11–1.82 for Smf ; Tables 1 and 2), which may indicate an area of weakly active tectonism characterized by normal dip-slip fault movement.

6. Trench Investigations

Based on morphotectonic landforms, detailed topographical and geological maps, ground penetrating radar data, and geomorphic indices developed for the Ban Dan Fai

area in the Lampang Basin (Fig. 12), we selected a site for trenching at Ban Don Fai, along the northern segment of the fault (Ban Don Fai trench No. 2; 18°6′19.042″N, 99°41′14.875″E; number 1 in Fig. 12). We excavated a trench of 19 m long, 2 m wide, and 3.5 m deep. The sediments exposed in the trench can be divided into six unconsolidated units (excluding the top soil) that are exposed in both sidewalls. A detailed trench log is shown in Fig. 13. Details of the individual units, in descending stratigraphic order, are described below.

Top soil: reddish-brown clayey sand. This is a soil used for agriculture, and organic matter is commonly found. The unit is approximately 30 cm thick.

Unit A: sand and gravel. The gravels consist mainly of sub-angular to angular clasts of sandstone and shale, and clast size varies from pebble to cobble. The thickness of this unit ranges from 10 cm to 1 m.

Unit B: brown clayey sand with gravel. Most of the clasts in the gravel are subangular and consist of sandstone, shale, and quartz. The unit is exposed on the southeastern side of the trench, but was not found on the northwestern side. The thickness of the unit ranges from 10 cm to 50 cm.

Unit C: brown sandy clay, with a little gravel. Most of the gravel clasts are sandstone. The unit is exposed only on the southeastern side of the trench, where its thickness ranges from 10 to 50 cm.

Unit D: sand with gravel. Most of the gravel clasts (of pebble size) are of sandstone and shale. The unit is exposed on the southeastern side of the trench, but it is absent at the point marked ‘x’ in Fig. 13. The thickness of the unit ranges from 10 to 30 cm.

Unit E: reddish-brown clayey sand, with sparsely distributed pebbles. This unit is limited to the southeastern part of the trench, where it is approximately 30 cm thick.

Unit F: gravel, sand, and silt with carbonaceous clay. The gravel clasts are mainly subangular to rounded, and most consist of quartz, sandstone, and shale. The unit contains graded beds of 10–50 cm in thickness. A lenticular layer of sand (20 cm thick) occurs between layers of gravel. The total thickness of this unit exceeds 1.5 m.

The grain size of sediment in this trench ranges from clay to coarse gravel. The stratigraphic relationships between unit F and overlying units indicate that the top of unit F is an erosional surface (Fig. 13). The sediments in unit F are poorly sorted. Clasts in gravel layers are subangular to rounded, and the unit contains a lenticular layer of sand and graded beds. The clasts are randomly oriented, with some elongate gravel clasts oriented with their long axes at a high angle to bedding. The sedimentary structures indicate that unit F was deposited by a gravity flow (e.g., Steel and Gloppen, 1980). The sediments of units A–E are poorly sorted, and the mixed sand, silt, and gravel of these units was possibly deposited from a sandy gravity flow. The sediments in this trench are laterally continuous, and no faults are observed.

Fig. 11. Map showing the locations used for calculation of the Smf index near the Sop Prap and Ban Mai areas. Lmf is the length of the mountain front, as measured along the foot of the mountain chain (taking into account its sinuosity), and Ls is the mountain-front length as the crow flies.

7. Geochronological Investigations

The trench-log stratigraphy in Ban Don Fai trench No. 2 shows no evidence for recent fault movement, but to put this finding in context it is necessary to determine the age of the sediments exposed in the trench. Having established the stratigraphy of the Ban Don Fai trench No. 2, we then proceeded to collect samples for OSL and AMS radiocarbon dating.

7.1 AMS radiocarbon dating

The ^{14}C method of dating is often applied in archaeology and geology, but the method is only accurate for samples younger than 45,000 years (Roberts *et al.*, 1994). For paleoearthquakes investigations in Thailand, AMS radiocarbon dating is commonly used for determining the age of sediments in a trench. For example, Pailoplee *et al.* (2009) and DMR (2006) succeeded in dating carbonaceous and charcoal samples, and these ages were then used for estimating the timing of fault movements. In the present study, three carbonaceous clay samples were collected from unit F in the Ban Don Fai trench No. 2 (Fig. 13), and the samples were processed for AMS radiocarbon dating at Beta Analytic Inc. (USA). The dating results are shown in Table 3.

7.2 Optically Stimulated Luminescence (OSL)

OSL dating is based on detecting the amount of luminescence and the radiation rate (per year) for the radioactive

isotope (Vafiadou *et al.*, 2007). The method is widely used in dating geological sediments such as aeolian quartz-rich sediments, marine sands, and colluvial materials (Murray and Olley, 2002). Six samples from units C, E, and F in Ban Don Fai trench No. 2 were prepared for OSL dating (Fig. 13). Samples were dried, and the water content analyzed. Each sample was sieved using a 0.84 mm mesh filter for annual dose analysis (300 g). Grains between 0.25 and 0.075 mm in size were extracted by re-sieving the remaining sample. Thereafter, these samples were treated with 35% hydrochloric acid (HCl) for at least 30 minutes to remove carbonates and organic material. Ferromagnetic fragments in the samples were separated from quartz using an isodynamic magnetic separator. Feldspar was removed by treatment with 24% hydrofluoric acid (HF). X-ray diffraction analysis (XRD) was used to ensure no feldspar remained in the samples; if feldspar was detected, we treated the samples again with hydrofluoric acid until all feldspar had been removed.

Measurements were made using an OSL instrument (Model OSL/TL-DA-15, Risø National Laboratory, Denmark) at Chulalongkorn University, Thailand. The instrument was equipped with a $^{90}\text{Sr}/^{90}\text{Y}$ beta source delivering 0.14 Gy/sec to the sample. In such a system, the OSL signals from the samples are produced by using Blue-LED ar-

Fig. 12. Shows topographical and geological maps, the survey line (in the Ban Dan Fai area) investigated by ground penetrating radar, and the sites of trenches excavated in this study and in a previous study.

Fig. 13. Trench-log stratigraphy and Holocene age data for Ban Don Fai trench No. 2. The location of the trench is shown in Fig. 12 (number 1). Top soil: clayey sand; A: sand and gravel; B: clayey sand with gravel; C: sandy clay with minor gravel; D: sand with gravel; E: clayey sand; F: gravel, sand, and silt with carbonaceous clay. The point marked 'x' indicates the location where unit D is absent.

Table 3. Result of AMS radiocarbon dating (C-14) of carbonaceous sediments from Ban Don Fai trench No. 2.

Sample No.	^{14}C measured radiocarbon age (yr BP)	$^{13}\text{C}/^{12}\text{C}$ (per mil)	^{14}C conventional radiocarbon age (yr BP)
C001	940 $\pm$ 40	-25.1	940 $\pm$ 40
C002	940 $\pm$ 40	-23.9	960 $\pm$ 40
C003	910 $\pm$ 40	-24.6	920 $\pm$ 40

Remarks

Method: AMS-Standard ^{14}C . Sample: Organic sediment. Locations of sample sites are shown in Fig. 13.

Table 4. OSL dating results for quartz concentrates from sediment samples collected in the Lampang Basin, northern Thailand.

Sample	U (ppm)	Th (ppm)	K (%)	W (%)	AD (Gy/ka)	ED (Gy)	Age (Yr)	Error (Yr)
DF1	3.14	15.07	2.52	1.50	4.66	2.92	630	60
DF2	3.00	15.64	2.87	2.56	5.01	3.67	730	80
DF3	2.59	10.52	1.88	4.06	3.49	1.77	510	40
DF4	2.94	12.21	2.03	7.46	3.80	2.19	580	80
DF5	3.17	15.50	2.35	5.99	4.44	2.73	610	60
DF6	3.51	16.20	2.25	7.79	4.44	4.04	910	40

Remarks

Locations of samples are shown in Fig. 13.

rays (470 ± 30 nm) as stimulation light sources. We applied a single-aliquot regenerative dose (SAR) protocol in order to measure a paleodose for all samples. The paleodoses are summarized in Table 4.

For the annual dose, the concentrations of U, Th, and K were analyzed using gamma spectrometry at Chulalongkorn University. The annual dose was computed using the concentration of K, U, and Th in the standard table described by Bell (1979). The results of annual doses and OSL dating are summarized in Table 4.

Figure 13 shows the stratigraphic units, and the measured OSL and AMS radiocarbon dates for sediments from Ban Don Fai trench No. 2. The OSL ages indicate that the sediments were deposited during the past 910 years. Three AMS radiocarbon dates indicate that the sediments in the lowest unit were deposited from about 960 to 920 years BP, and these dates are consistent with the OSL ages for sediments in unit F. Thus, the OSL method is useful for estimating the age of deposition of the quartz-rich sample. This result is encouraging in terms of the future use of OSL dating.

8. Discussion

8.1 Sense of fault movement

The Thoen Fault, along the southeastern margin of the Lampang Basin, has been regarded as an active fault (Fenton *et al.*, 1997, 2003; DMR, 2006). Morley *et al.* (2007) and Fenton *et al.* (2003) suggested that the fault is characterized mainly by normal dip-slip and subordinate left-lateral slip.

Measurements of geomorphic indices (SL , Vf , and Smf indices) in the Lampang Basin are consistent with dip-slip movement on the Thoen Fault. The SL indices from the southeastern margin of the basin indicate steeper slopes near the mountain front, and most of the Vf and Smf values from the Ban Mai, Ban Don Fai, and Sop Prap segments are quite low (0.44 – 2.75 for Vf and 1.11 – 1.82 for Smf). The geomorphic characteristics of the Thoen Fault are simi-

lar to those of the Lo River Fault in northern Vietnam, where values of Vf (0.06 – 0.61) and Smf (1.04 – 1.16) are low because of recent tectonic uplift (Cuong and Zuchiewicz, 2001).

The Thoen Fault is well defined by geomorphology, and is evident as sharp lineaments on aerial photographs and satellite images (Fig. 4), associated with morphotectonic landforms such as fault scarps, triangular facets, wine-glass canyons, and a linear mountain front. Detailed interpretations of aerial photographs clearly reveal fault scarps at Ban Mai, Ban Don Fai, and Ban Samai Nuea ((A) and (C) in Fig. 4). A series of triangular facets on the NW-facing escarpment (Fig. 5) might represent stage VIII of Hamblin's model (Fig. 6). A series of streams crossing the Ban Don Fai, Sop Prap, and Ban Mai segments of the fault pass through wine-glass canyons (Fig. 7) and V-shaped valleys, suggesting multiple episodes of tectonic uplift.

A geological survey performed at the Mae Than mine (Morley *et al.*, 2001) in the northern Sop Prap area confirmed the presence of NE-SW-striking normal faults. These normal faults form a right-stepping relay ramp in the eastern part of the mine area (Fig. 14), where a syncline and anticline occur, with axial planes that strike at right angles to the NE-SW-striking fault. The syncline and anticline have been interpreted to represent shortening associated with a left-lateral component of oblique slip on the boundary fault at a restraining right-stepping transfer zone (Morley *et al.*, 2001). Our remote-sensing data, however, suggest that the morphotectonic landforms in the Lampang Basin were caused only by dip-slip normal fault movements, as explained above and as indicated by seismological analysis. For example, Bott *et al.* (1997) examined the focal mechanisms of three earthquakes in northern Thailand, indicating E-W to NW-SE extension.

A sequence of alluvial gravels and lacustrine clays is cut by a NE-SW-striking normal fault along Highway 11 (from Lampang to Phrae) at 28 km from Lampang. This offset is exposed on the western side of the main escarpment along

Fig. 14. Geological map of the Mae Than mine, showing a syncline and anticline near the fault tip of the Mae Than fault segment (modified from Morley *et al.*, 2001). The location of the Mae Than fault segment is shown in Fig. 8.

the Ban Mai segment. The total vertical displacement is 1.3–1.6 m (Charusiri *et al.*, 1997; Fenton *et al.*, 2003). The timing of the faulting is interpreted to be Late Quaternary (Fenton *et al.*, 2003). The relationship between this fault and the Thoen Fault remains unknown, although its location and orientation suggest that it is a synthetic fault (i.e., it has the same dip and sense of movement as the main fault) (Fenton *et al.*, 2003).

8.2 Age of fault movement

Geomorphological features and geomorphic indices in the study area indicate active normal faulting. However, the sediments in the trench at Ban Don Fai show no clear-cut evidence of recent fault movement. At Ban Don Fai trench No. 2, AMS radiocarbon and OSL dates show that the sediments of the lowest unit (Unit F in Fig. 13) were deposited between 960 and 910 years ago. The lack of evidence in the trench for recent fault movement indicates that the fault is located below the depth of the trench; i.e., the most recent movement upon the fault pre-dates the deposition of the oldest sediments in the trench. In the case that the trench did not intercept the fault trace, the most recent movement on the fault may be younger than the oldest sediments in the trench; however, the location of the trench was decided based on a careful analysis of aerial photographs, and based on the distribution of morphotectonic landforms observed in the field. Thus, it is possible that the most recent movement on the Ban Don Fai fault segment occurred more than 960 years ago. Based on TL dating of sediments at trench sites (Pailoplee *et al.*, 2009), the most recent movement on the Ban Mai segment of the fault took place about 3,800 years ago (2 in Fig. 12), while the last movement on the Doi Ton Ngun segment was about 1,800 years ago. However, the TL method of dating involves uncertainties. The apparent TL ages calculated for fluvial sediments are often

3–8 times higher than TL or AMS radiocarbon dates for adjacent buried soils (McCalpin *et al.*, 1994). Fluvial sediments are usually deposited episodically by water flowing in the river channel. They probably receive limited exposure to light, and as a consequence, they are likely to retain a large inherited TL signal (McCalpin *et al.*, 1994). Alluvial sediments are rapidly deposited by gravity flows, which may also result in a large inherited TL signal. Thus, TL dates for fluvial and alluvial sediments may systematically result in overestimating the ages of deposition (Forman, 1989; McCalpin *et al.*, 1994). For this reason, the TL dating method is unsuitable for determining the deposition ages of fluvial and alluvial sediments in the Lampang Basin.

9. Conclusions

The Thoen Fault in the Lampang Basin, northern Thailand, strikes NE-SW. Morphotectonic landforms caused by normal faulting in the Lampang Basin are well represented by fault scarps, triangular facets, wine-glass canyons, and linear mountain fronts. On the other hand, morphotectonic landforms that would indicate strike-slip faulting are not found.

Along the fault at the southeastern margin of the Lampang Basin, the stream length gradient index (SL index), as measured near the mountain front, records steeper slopes which possibly relate to normal faulting. Moreover, along the Ban Mai, Ban Don Fai, and Sop Prap segments of the fault, the ratio of valley floor width to valley height (Vf) is generally low (0.44–2.75), as are values of mountain-front sinuosity (Smf) (1.11–1.82). Low Vf values reflect deep V-shaped valleys, and low Smf values are associated with active tectonic zones. Together, these geomorphic indices suggest an area of weakly active tectonism characterized by dip-slip normal fault movement.

Although the geomorphological features and geomorphic indices in the study area are consistent with active normal faulting, the sediments exposed in the trench at Ban Don Fai provide no clear-cut evidence of recent fault movement. In Ban Don Fai trench No. 2, AMS radiocarbon and OSL dating indicate that the sediments of the lowest exposed unit were deposited between 960 and 910 years ago. Accordingly, we conclude that the most recent fault movement along the Ban Don Fai segment of the Thoen Fault occurred more than 960 years ago.

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