We applied remote sensing and aerial photographic techniques to a study of the Mae Hong Son Fault (MHSF), located in the Mae Hong Son region, northern Thailand. Several fault lines are recognized in the region, trending mainly NE–SW, NW–SE, and N–S. The main morphotectonic landforms associated with the MHSF are fault scarps, offset streams, linear valleys, triangular facets, offset ridge crests, hot springs, and linear mountain fronts. A trench, a quarry, and a road cut in Cenozoic strata were used to analyze fault geometries in the area. We identified eight paleoearthquake events from trenching, quarry, and road-cut data, and from optically stimulated luminescence (OSL) and thermoluminescence (TL) dating. The OSL and TL ages of the events are: (1) 78,000 yr BP; (2) 68,000 yr BP; (3) 58,000 yr BP; (4) 48,000 yr BP; (5) 38,000 yr BP; (6) 28,000 yr BP; (7) 18,000 yr BP; and (8) 8,000 yr BP. The recurrence interval of seismic events on the MHSF appears to be ca. 10,000 years, and the slip rate was estimated as ca. 0.03–0.13 mm/yr. There is a low possibility of a large earthquake on the MHSF in the near future.

Keywords: Mae Hong Son Fault; active fault; quaternary dating; paleoseismology; northern Thailand.

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1. Introduction

Several large earthquakes (Richter magnitude $\geq 6$) have been reported from northern Thailand in a region east of the Sagaing Fault in Myanmar (Fig. 1). Northern Thailand has experienced micro-earthquakes (Richter magnitude $\leq 3$) and moderate earthquakes (Richter magnitude 3–6) since at least 63 BC [Nutalaya et al., 1985; Bott et al., 1997]. Several micro- to moderate earthquakes have been detected along major fault traces in northern Thailand (i.e. the Mae Ping Fault (MPF), Mae Chan Fault (MCF), Thoen Fault (TF), and Mae Hong Son Fault (MHSF); see Fig. 1. Map of Thailand and adjacent areas showing major active and neotectonic faults (modified from Lacassin et al. [1997, 1998], Morley et al. [2011] and DMR [2006]) and the epicentres of large earthquakes; the rectangle shows the location of the study area. MPF, Mae Ping Fault; MCF, Mae Chan Fault; MHSF, Mae Hong Son Fault; RNF, Ranong Fault; TPF, Three Pagoda Fault; UF, Uttaradit Fault; TF, Thoen Fault; PBF, Phetchabun Fault.
Fig. 2. Landsat image showing the location of the study area (Mae Hong Son region) and prominent N–S and NW–SE trending faults (arrows). This image was analyzed to identify lineaments and Quaternary faults. The area covered by this image is shown in Fig. 1.

Fig. 1); morphotectonic landforms have also been observed in this region [Kosuwan et al., 1999; Pailoplee et al., 2009]. The MHSF trends mainly N–S and NW–SE, as inferred from a Landsat image (Fig. 2). Micro-earthquakes were recently recorded in the Mae Hong Son region (for locations, see Fig. 3(c)). The MHSF in the Mae Hong Son region (Figs. 1 and 3) is important because it is the only fault in Thailand with a trend parallel to that of the Sagaing Fault, occurs near the Sagaing Fault and is considered as an active fault zone [Hinthong, 1995, 1997; Department of Mineral Resources (DMR), 2006; Charusiri et al., 2007].

In 1975, a moderate earthquake of Richter magnitude 5.6 and Mercalli intensity VI occurred along the southern part of the MHSF (Fig. 3(c)); this event caused minor damage in the Mae Hong Son region. Seismicity in northern Thailand is, however, generally considered to be low, and there is no clear association between
Fig. 3. The MHSF (see location map, Fig. 1) of northern Thailand and its four major fault segments as interpreted from Landsat 7 images (a) and (c), the principle orientations of faults shown as a rose diagram (b), inset in (a), and the locations of Cenozoic basins showing epicentre distributions (c). The names and locations of individual segments are also displayed. The black stars represent hot spring locations.

seismicity and mapped faults [Bott et al., 1997; Fenton et al., 2003]. Therefore, to better understand and clarify the nature of seismicity in this region, we examined the paleoseismicity of faults along the MHSF.

Earlier work shows that the MHSF trends mainly N–S and NW–SE, and is associated with Cenozoic basin formation [Baum et al., 1970; Charusiri et al., 1993; Hinthong, 1997; DMR, 2006]. The only detailed studies of the stratigraphy and geology of this region are those reported by Hahn et al. [1986] and Srinak et al. [2003, 2007]. Reconnaissance studies on neotectonics and paleoearthquakes were conducted by Takashima and Maneenai [1995], Hinthong [1997], DMR [2007], and Charusiri et al. [2007]. However, no systematic or detailed surveys have so far been
conducted to examine paleoearthquakes in the Mae Hong Son region. Moreover, existing data are insufficient to constrain the paleoseismological history and characteristics of the region. Thus, the main objectives of the current investigation were to (1) identify and characterize morphotectonic landforms resulting from fault movements, (2) determine the numbers of paleoearthquake events, and (3) estimate slip rates and recurrence intervals of the MHSF. In this study, fault segments and their senses of movement along the MHSF were identified using remote sensing techniques. Optically stimulated luminescence (OSL) and thermoluminescence (TL) dating were used to determine the depositional ages of sediment layers involved in paleoearthquake events. Geophysical data from the Electricity Generating Authority of Thailand (EGAT) [2012] were used to locate subsurface structures in some areas. Faults and sediments in trenches and exposures crossing fault segments (Mae La Noi School quarry and Phra That Chom Kitti road cut; Fig. 3(c)) were mapped and their stratigraphy determined to reconstruct displacement histories.

2. Tectonic Setting

Major neotectonic events in the Indochina region are likely related to progressive northward and northeastward movement of the Indian plate and collision with the Eurasian plate [Peltzer and Tapponnier, 1988; Charusiri et al., 2007]. In the Indochina region, collision of the Indian and Eurasian plates since the late Palaeogene has resulted in strike-slip faults that strike mainly NW–SE and NE–SW, and dip-slip faults that strike N–S [Tapponnier et al., 1986; Peltzer and Tapponnier, 1988]. During the late Eocene, collision of the Indian and Eurasian plates resulted in left-lateral displacements along the NW–SE trending Red River Fault, the MPF (Fig. 1), and the Three Pagoda Fault (TPF; Fig. 1) [Lacassin et al., 1997]. Left-lateral displacement along the Red River Fault amounted to hundreds of kilometres during the Eocene–Oligocene, caused by extension within the South China Sea [Morley, 2002]. The Gulf of Thailand was also opening during this time [Srisuwan, 2002]. During the early Oligocene–early Miocene, as the Indian plate collided with the southern margin of the Eurasian plate, the Southeast Asia region was rotated clockwise by ca. 25° and was extruded southeastwards [Peltzer and Tapponnier, 1988; Fenton et al., 2003]. The clockwise rotation of Southeast Asia resulted in a reversal in the sense of movement along the MPF and TPF during the Oligocene–early Miocene, when these faults changed from left-lateral to right-lateral NW–SE trending strike-slip faults, and the Uttaradit Fault (UF; Fig. 1) became a left-lateral NE–SW trending strike-slip fault. At the same time, the Red River Fault remained a left-lateral strike-slip fault [Huchon et al., 1994; Lacassin et al., 1997]. By the middle Miocene, all of the NW–SE trending strike-slip faults in the Indochina region (Red River Fault, MPF, and TPF) had become right-lateral strike-slip faults [Longley, 1997; Srisuwan, 2002]. Taken together, these major faults form a transtensional regime related to the opening of Cenozoic basins in Southeast Asia [Ducrocq et al., 1992; Charusiri et al., 2007].
Thailand lies mainly in a zone of strike-slip deformation, between the Red River Fault to the east and the compressive Sagaing Fault to the west [Morley, 2007; Morley et al., 2011]. In the southwestern part of northern Thailand, the MPF, a NW–SE trending strike-slip fault, connects to the Sagaing Fault. Several seismic profiles show that in the southeastern part of northern Thailand, the NE–SW trending UF has a left-lateral sense of movement [Bal et al., 1992]. The movement on these strike-slip faults during the Cenozoic has resulted in extensional and transtensional stresses in northern Thailand, leading to the formation of a number of basins in this region [Uttamo et al., 1999, 2003]. The Cenozoic basins in northern Thailand are mainly N–S trending grabens and half-grabens, with sediment thicknesses in the range of 1,000–3,000 m [Polachan et al., 1991]. The geometries of the Cenozoic basins and the locations of faults may possibly be controlled by pre-existing fabrics in basement rocks [O’Leary and Hill, 1989; Morley, 2007]. A combination of both dip-slip and lateral strike-slip (i.e. oblique-slip) movement is required to explain the evolution of these basins [Morley et al., 2001, 2004; Morley, 2002, 2007] and the triggering of the faulting observed in this region.

3. Seismicity of the Mae Hong Son Region and Vicinity

The seismotectonic character of northern Thailand is similar to that of the Basin and Range Province of the western United States (i.e. a region of extended crust and basin-and-range topography [MacDonald et al., 1993]), and thus, this region has been called the Northern Basin and Range Province [Fenton et al., 1997]. Approximately 51 earthquake events with Richter magnitudes ($M_L$) of 2–5 have been reported nearby and within the Mae Hong Son region (Fig. 3(c)) [Royal Thai Navy Seismic Research Station (RTNSRS), 2012; Thailand Meteorological Department (TMD), 2012]. Several of these micro-earthquakes occurring near towns have been felt; however, no damage has been reported. The largest known earthquake, with a magnitude of Richter 5.6, occurred on the southern section of the MHSF on 17 February 1975 (Fig. 3(c)). Damage was reported from this event, particularly in the southern part of the Mae Hong Son region. Although no large earthquakes have been recorded within the Mae Hong Son region, farther to the northeast in easternmost Myanmar, a large-scale earthquake on 24 March 2011 (Mw 6.8) occurred on the Nam Ma Fault. Farther to the north, a few intermediate earthquakes causing minor damage have been reported, including a Mw 5.1 event on 1 March 1989. These observations indicate that present-day seismicity is, at least to an extent, related to the MHSF. Present-day hot spring data (stars, Fig. 3(a)) also suggest on-going activity along the fault.

4. Active Fault in Northern Thailand

Paleoearthquake studies aim to determine the occurrence of past earthquakes on active faults. In this paper, we define an active fault as one that has moved at
least once during the late Pleistocene and extending to the present day [Geological Survey of Japan, 1983], and that has the potential to generate another earthquake in the near future [Slemmons, 1982].

In northern Thailand, the ENE–WSW trending MCF (Fig. 1) is a left-lateral strike-slip fault [Fenton et al., 1997]. Strong geomorphological evidence is present for late Quaternary left-lateral displacement along this fault, and recent trench investigations have confirmed late Quaternary faulting [Fenton et al., 1997, 2003; Kosuwan et al., 1999]. Based on remote sensing data, trenching, and geochronological investigations along the MPF, western Thailand, Saithong [2006] identified three paleoearthquake events (at 80,000, 65,000, and 15,000 yr BP) involving dextral movement along the fault. Le Dain et al. [1984] reported a focal plane solution for a 1975 earthquake on the MPF consistent with right-lateral slip. The NE–SW trending TF, a sinistral fault located in the Lampang basin, has been regarded as active [Fenton et al., 1997, 2003; Hinthong, 1997; DMR, 2006]. Several lines of evidence, including geomorphic and stratigraphic, indicate that the TF was an extensional structure during the Holocene [Fenton et al., 2003] and that current displacements involve mainly normal dip-slip and subordinate left-lateral slip movement [Fenton et al., 2003; Morley, 2007]. Based on morphotectonic landform observations in the Lampang basin, Wiwegwin et al. [2011] suggested that the TF was a normal dip-slip fault, without any significant component of strike-slip movement. Fenton et al. [2003] calculated a slip rate on the TF of 0.6 mm/yr. Pailoplee et al. [2009] excavated two trenches along the TF in the Lampang basin, and reported paleoearthquake events at 3,800, 3,500, and 1,800 yr BP. Wiwegwin et al. [2011] also reported that the most recent movement on the Ban Don Fai segment of the TF occurred more than 960 years ago. In the southeastern part of northern Thailand, remote sensing investigations and Quaternary dating have revealed that the UF (Fig. 1) is located within an active tectonic zone [Saithong et al., 2011]. Based on trench investigations, slip rates on the UF have been calculated as between 0.19 and 0.21 mm/yr [Saithong et al., 2011].

Earlier work has demonstrated that the MHSF strikes mainly N–S and NW–SE. Hot springs are present along the fault trace, and may be the result of movement along the fault [Sasada et al., 1987]. Based on field evidence, Charusiri et al. [1993] suggested that the MHSF may have been active during the period of 27.3–1.6 Ma. A fault in the Mae Sariang basin has been interpreted as a splay fault of the active MPF to the south [Morley et al., 2007]. Age dating by TL has revealed that the MHSF was active from 0.89 to 0.32 Ma [Takashima and Maneenai, 1995; Hinthong, 1997]; the fault has been classified as active by Hinthong [1995, 1997], DMR [2007], and Charusiri et al. [2007].

5. Results of Remote Sensing Analysis

Landsat 7 imaging (Fig. 2) has been applied to the interpretation of lineaments and Quaternary faults in the study area. We identified lineaments based
on morphological features, their correlation with tectonic elements, and available geological maps. The orientations of faults at 767 locations along these lineaments are shown in Fig. 3(b).

The MHSF is well defined and is visible as a sharp lineament on aerial photographs and satellite images (Figs. 4(a), 5(a), 6(a), 7(a) and 8(a)). The MHSF strikes mainly N–S, with conjugate faults trending NW–SE and NE–SW. The N–S faults show normal dip-slip movement, and they delineate the margins of elongate N–S basins. The NW–SE faults show right-lateral strike-slip movement. On the other hand, the NE–SW faults show left-lateral strike-slip movement. The MHSF, which has a total length of ca. 202 km, can be divided into four major segments based on fault geometries and the distribution of Caenozoic basins (Fig. 3(c)). Fault traces are visible along the boundaries between Palaeozoic-Mesozoic units and unconsolidated Quaternary sediments; such faults mainly occur within Caenozoic basins. From north to south, the four major segments of the MHSF are the Mae Hong Son, Khun Yuam, Mae La Noi, and Mae Sariang segments (Fig. 3(c)). These segments can be subdivided into 49 smaller segments (all showing clear traces of Quaternary faulting, as interpreted from remote sensing observations); the segments were investigated to determine fault geometries and orientations, associations with morphotectonic landforms, and their seismicity history.

Fig. 4. Morphotectonic landforms of the Mae La Noi area. (a) Aerial photograph of the Mae La Noi area, Mae Hong Son region (see Fig. 3(a) for location of the image), and (b) results of remote sensing investigations and the distribution of geological units, showing morphotectonic landforms along Mae La Noi segment nos. 1 and 2 (see Fig. 3(c)).
The morphotectonic landforms observed in the study area include fault scarps, triangular facets, offset streams, hot springs (stars in Fig. 3(a)), linear valleys, and linear mountain fronts. Based on aerial photographic interpretations, the Mae La Noi and Mae Sariang basins are bounded to the east and west by N–S trending
segments and to the north and south by NE–SW and NW–SE trending segments, respectively.

In the Mae La Noi basin, detailed interpretations of aerial photographs reveal small fault scarps, offset streams, and linear valleys along the fault trace (Figs. 4 and 5). To the north of Mae La Noi School, a westward flowing stream channel shows a sinistral offset of ca. 70 m (the stream flows southward along the fault trace before returning to its westward course; Figs. 5(a) and 5(b)); this offset stream indicates left-lateral strike-slip along the Mae La Noi segment no. 2. Small fault scarps are also present on the piedmont behind Mae La Noi School (Figs. 4 and 5).

Morphotectonic landforms observed in the Mae Sariang basin include fault scars, offset streams, triangular facets, offset ridge crests, benches, and linear mountain fronts (Figs. 6–8). The N–S trending faults show normal dip-slip displacement. The NW–SE and NNW–SSE trending faults show right-lateral strike-slip displacement. However, the NE–SW trending fault segments frequently show left-lateral strike-slip displacement. The ridge crest to the northeast of Phra That Chom Kitt temple shows left-lateral offsets across the fault (Fig. 7), indicating left-lateral strike-slip movement on the Phra That Chom Kitt segment. To the north of Phra That Chom Kitt temple (Fig. 7), an eastward flowing stream channel is offset dextrally by ca. 100 m; the stream flows southwards along the fault trace.
Fig. 7. Morphotectonic landforms of the Phra That Chom Kitti area. (a) Aerial photograph showing features along Nong Pa Khaem segment no. 41 and Phra That Chom Kitti segment no. 36 (for locations, see Fig. 3(c)). (b) Topographic map showing fault traces and an offset stream. The displacement of the offset stream is ca. 100 m. Offset ridge crests observed along the Nong Pa Khaem segment indicate right-lateral strike-slip movement, but the offset ridge crest observed along the NE–SW trending Phra That Chom Kitti segment indicates left-lateral strike-slip movement. The location of the figure is shown in Fig. 6(b).

before returning to its eastward course (Fig. 7). The ridge crest to the south of this offset stream also shows right-lateral offset across the fault (Fig. 7). These features indicate right-lateral strike-slip movement on the Nong Pa Khaem segment.

Triangular facets, scarps, and linear mountain fronts can be observed along the eastern margin of the Mae Sariang basin (Fig. 8). These morphotectonic landforms support the interpretation of normal displacement along the fault trace on the basin’s eastern margin. The triangular facets represent a combination of vertical
movements on range-bounding N–S normal faults and stream incision in valleys. Triangular facets are roughly planar surfaces with broad bases and upwards-pointing apices, typically occurring on ridge crests between valleys [Keller and Pinter, 1996]. A time sequence of displacements along a normal fault can produce a vertically stepped series of triangular facets [Hamblin, 1976; Fenton et al., 2003]. A series of triangular facets is present in the Mae Sariang basin along a W-facing escarpment.
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(Fig. 8(c)). We suggest that such features are the result of episodic fault movement, and that the facets formed as a result of fault movement, while the benches formed during intervening periods of tectonic stability. Therefore, it is possible that movement along the MHSF resulted in the development of several sets of triangular facets in the Mae Sariang basin. The locations of triangular facets are also consistent with the locations of surface traces of the MHSF. Series of triangular facets have been reported from other well-studied active fault zones, and they are considered as indicative of mountain fronts bounded by active faults [Hamblin, 1976; Bull and McFadden, 1977; Wallace, 1978; Fenton et al., 2003; Ganas et al., 2005; Picotti et al., 2009; Wiwegwin et al., 2011]. Thus, triangular facets in the N–S trending Mae Sariang basin are considered to be the result of vertical movements of the MHSF.

Fault traces in the southern Mae Sariang basin change orientation from N–S trending to NW–SE trending (Fig. 3). Significant morphotectonic landforms, such as scarps, offset streams, benches, and linear mountain fronts can be observed along the fault trace. Streams are offset dextrally. Thus, we interpret that NW–SE trending fault segments reflect right-lateral strike-slip movement. The NW–SE trending fault segments have the same orientation as that of the MPF to the south, and they may merge with the MPF.

6. Results of Paleoearthquake Investigations

Based on the integration of results from remote sensing interpretations, geophysical investigations, and digital elevation models and geological maps, we selected one quarry and one road-cut exposure for a paleoearthquake study (see Fig. 3(c)). All profiles traversed the NE–SW Mae La Noi segment no. 1 and the Phra That Chom Kitt segment, both of which belong to the MHSF (Figs. 4–7).

6.1. Mae La Noi segment no. 1

Significant morphotectonic landforms, such as offset streams (Figs. 4(b) and 5(b)) and scarps (Fig. 5(c)), are present in the Mae La Noi area. Quaternary faults in the quarry adjacent to the Mae La Noi School cut Cenozoic strata (terrace sediments, Qt, of Chindasut et al. [1990]). Two reverse faults are visible in the quarry wall (F1 and F2; Fig. 9); the faults strike N0°E–N40°E and dip 85°E–70°SE. We observed slickensides on fault planes (Figs. 10(a) and 10(b)) with pitches of 15° (on the F1 fault plane) and 60° (F2) (Fig. 10(c)).

Ten samples were collected for OSL and TL dating (i.e. MLN11–16, MLN2–3, ML1, and ML4 in Fig. 9). The OSL and TL dates are based on the amount of luminescence (paleodose) and the radiation rate (per year) for a radioactive isotope, which yields an annual dose [Vafiadou et al., 2007]. We applied a single-aliquot regenerative (SAR) dose protocol technique to measure the paleodose for OSL samples, and a regeneration technique to measure the paleodose for TL samples.
Fig. 9. Stratigraphy and ages of Quaternary sediments along an E–W transect in the Mae La Noi School quarry (a–d). Close-up photographs of plates (b), (c), and (d) are presented in plates (e), (f), and (g), respectively. The faults identified in the quarry wall are F1 and F2. Black arrows indicate fault traces and half arrows show sense of movement. Samples MLN11–16, MLN2–3, ML1, and ML4 were collected for OSL and TL dating. The location of the quarry is shown in Figs. 4 and 5. Unit A: gravel sand and clay; Unit B: clay and sand; Unit C: gravel, sand, clay, with sand lens; Unit D: sandy clay with gravel; Unit E: clayey sand with gravel; Unit F: gravel, sand, and clay; Unit G: sandy clay with gravel; Unit H: gravel and sand, and Unit I: top soil. The points marked “X” and “X2” indicate the locations of slickensides on fault planes. The point marked “X3” indicates the location where the fault terminates in unit G.
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Fig. 10. Photographs showing slickensides (black arrows) on fault planes at Mae La Noi School quarry. (a) Slickensides resulting from movement on F1 in Fig. 9. (b) Slickensides resulting from movement on F2 in Fig. 9. (c) Stereonet showing the orientations of fault planes and their pitches. Slickensides on the fault plane of F1 can be observed at the point marked “X” in Fig. 9(a), while slickensides on the fault plane of F2 can be observed at the point marked “X2” in Fig. 9(b).
The annual dose was computed using the concentrations of K, U, and Th provided in the standard table in Bell [1979]. The results of paleodoses, annual doses, and OSL and TL dates are summarized in Tables 1 and 2. No carbonaceous materials were observed in the quarry. Based on their sedimentological characteristics and the OSL and TL ages (Tables 1 and 2), the stratigraphy of the quarry wall can be described in terms of nine unconsolidated units; units A to I (Fig. 9).

Table 1. Results of OSL dating of quartz concentrates from sediment samples collected in the Mae La Noi (ML and MLN) and Phra That Chom Kitt (PCT) areas, Mae Hong Son region, northern Thailand.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>W (%)</th>
<th>AD (Gy/ka)</th>
<th>ED (Gy)</th>
<th>Age (yr)</th>
<th>Error (yr)</th>
</tr>
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<td>MLN11</td>
<td>3.33</td>
<td>39.02</td>
<td>6.06</td>
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<td>9.58</td>
<td>82.21</td>
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<td>620</td>
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<td>MLN12</td>
<td>4.54</td>
<td>38.45</td>
<td>5.97</td>
<td>17.84</td>
<td>9.70</td>
<td>93.21</td>
<td>9,600</td>
<td>720</td>
</tr>
<tr>
<td>MLN13</td>
<td>3.26</td>
<td>26.68</td>
<td>4.21</td>
<td>18.96</td>
<td>6.85</td>
<td>81.18</td>
<td>11,840</td>
<td>1,150</td>
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<tr>
<td>MLN14</td>
<td>5.21</td>
<td>65.26</td>
<td>7.10</td>
<td>14.65</td>
<td>12.90</td>
<td>106.49</td>
<td>8,300</td>
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</tbody>
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Note: Locations of samples are shown in Figs. 9 and 11. Measurements were performed using a Model OSL/TL-DA-15 analyzer (Riso National Laboratory, Denmark). The single-aliquot regenerative (SAR) dose protocol technique was applied to measure the paleodose (ED) for each sample. The annual dose (AD) was computed using the concentrations of K, U, and Th provided in the standard table of Bell [1979].
consist of sandstone and quartz. The OSL and TL ages (Tables 1 and 2) show that of gravel; its thickness is 30 cm. Most of the gravel clasts are of pebble size and in the middle part of the unit.

graded beds of 30–50 cm thickness are sand, and clay. The gravel clasts are mainly subangular to rounded in shape (maximum diameter, greater than 6 m; the unit is a clast-supported gravel consisting mainly of gravel, subangular to rounded in shape (maximum diameter, thick and consists of a clast-supported river gravel unit. The gravel clasts are mainly found in the unit. The OSL and TL dates from quartz grains indicate that the unit was deposited at 24,260–18,500 yr BP (Tables 1 and 2).

are found in the unit. The OSL and TL dates from quartz grains indicate that the unit was deposited at 24,260–18,500 yr BP (Tables 1 and 2).

Table 2. Results of TL dating for quartz concentrates from sediment samples collected in the Mae La Noi (ML and MLN) and Phra That Chom Kitti (PCT) areas, Mae Hong Son region, northern Thailand.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>W (%)</th>
<th>AD (Gy/ka)</th>
<th>ED (Gy)</th>
<th>Age (yr)</th>
<th>Error (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLN1</td>
<td>3.33</td>
<td>39.02</td>
<td>6.06</td>
<td>17.03</td>
<td>9.58</td>
<td>82.80</td>
<td>8,640</td>
<td>880</td>
</tr>
<tr>
<td>MLN2</td>
<td>4.54</td>
<td>38.45</td>
<td>5.97</td>
<td>17.84</td>
<td>9.70</td>
<td>105.00</td>
<td>10,850</td>
<td>1,110</td>
</tr>
<tr>
<td>MLN3</td>
<td>3.26</td>
<td>26.68</td>
<td>4.21</td>
<td>18.96</td>
<td>6.85</td>
<td>100.00</td>
<td>14,600</td>
<td>1,490</td>
</tr>
<tr>
<td>MLN4</td>
<td>5.21</td>
<td>65.26</td>
<td>7.10</td>
<td>14.65</td>
<td>12.90</td>
<td>107.00</td>
<td>8,300</td>
<td>850</td>
</tr>
<tr>
<td>MLN5</td>
<td>4.56</td>
<td>55.29</td>
<td>6.99</td>
<td>13.94</td>
<td>12.00</td>
<td>125.40</td>
<td>10,460</td>
<td>1,080</td>
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<td>3.07</td>
<td>35.60</td>
<td>5.71</td>
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<td>9.02</td>
<td>126.00</td>
<td>13,980</td>
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<td>43.84</td>
<td>4.18</td>
<td>23.92</td>
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<td>165.00</td>
<td>20,610</td>
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<td>MLN8</td>
<td>3.77</td>
<td>34.30</td>
<td>4.13</td>
<td>22.15</td>
<td>7.31</td>
<td>135.00</td>
<td>18,500</td>
<td>2,010</td>
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<tr>
<td>ML1</td>
<td>4.20</td>
<td>45.83</td>
<td>4.46</td>
<td>17.14</td>
<td>8.63</td>
<td>65.00</td>
<td>7,550</td>
<td>650</td>
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<tr>
<td>ML4</td>
<td>4.71</td>
<td>47.47</td>
<td>4.12</td>
<td>20.39</td>
<td>8.41</td>
<td>55.00</td>
<td>6,540</td>
<td>710</td>
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<tr>
<td>PCT21</td>
<td>1.02</td>
<td>38.66</td>
<td>4.11</td>
<td>15.00</td>
<td>7.14</td>
<td>705.00</td>
<td>90,030</td>
<td>7,890</td>
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<tr>
<td>PCT22</td>
<td>13.58</td>
<td>27.42</td>
<td>4.76</td>
<td>13.20</td>
<td>9.94</td>
<td>530.00</td>
<td>53,300</td>
<td>4,760</td>
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<tr>
<td>PCT23</td>
<td>11.70</td>
<td>35.41</td>
<td>5.63</td>
<td>8.88</td>
<td>11.11</td>
<td>400.00</td>
<td>35,990</td>
<td>3,440</td>
</tr>
<tr>
<td>PCT24</td>
<td>21.57</td>
<td>55.86</td>
<td>4.39</td>
<td>11.58</td>
<td>13.43</td>
<td>554.00</td>
<td>41,240</td>
<td>3,460</td>
</tr>
<tr>
<td>PCT25</td>
<td>24.75</td>
<td>37.70</td>
<td>3.50</td>
<td>18.08</td>
<td>11.71</td>
<td>460.00</td>
<td>39,300</td>
<td>3,410</td>
</tr>
<tr>
<td>PCT26</td>
<td>23.88</td>
<td>35.68</td>
<td>3.89</td>
<td>13.26</td>
<td>11.88</td>
<td>360.00</td>
<td>30,040</td>
<td>3,290</td>
</tr>
</tbody>
</table>

Note: Locations of samples are shown in Figs. 9 and 11. Measurements were performed using a TL analyzer (C123 photon counter; Hamamatsu Photonics) and an SU-11 temperature controller (Chino Co. Ltd.) with a heating rate of 120°C per minute in a well-designed nitrogen purge condition. The regeneration technique was applied to measure the paleodose (ED) for each sample. The annual dose (AD) was computed using the concentrations of K, U, and Th provided in the standard table of Bell [1979].

Unit A, which is the oldest in the quarry, is an alluvial unit with a thickness of greater than 6 m; the unit is a clast-supported gravel consisting mainly of gravel, sand, and clay. The gravel clasts are mainly subangular to rounded in shape (maximum diameter, ca. 15 cm), and consist mostly of quartz, sandstone, granite, and shale.

Unit B is an alluvial unit consisting of light brown clay and sand layers, and with a thickness ranging from 1 to 3 m. Clasts of iron concretions, quartz, and shale are found in the unit. The OSL and TL dates from quartz grains indicate that the unit was deposited at 24,260–18,500 yr BP (Tables 1 and 2).

Unit C is an alluvial/colluvial unit containing gravel and sand lenses; it is 2 m thick and consists of a clast-supported river gravel unit. The gravel clasts are mainly subangular to rounded in shape (maximum diameter, ca. 10 cm) and consist mostly of quartz, sandstone, granite, and shale. Graded beds of 30–50 cm thickness are intercalated in the unit, and coarse to very coarse grained sand lenses are present in the middle part of the unit.

Unit D is an alluvial unit comprising light brown sandy clay with small amounts of gravel; its thickness is 30 cm. Most of the gravel clasts are of pebble size and consist of sandstone and quartz. The OSL and TL ages (Tables 1 and 2) show that the unit was deposited at ca. 14,600–11,810 yr BP.
Unit E is an alluvial unit consisting of reddish-brown clayey sand and gravel. The unit is ca. 50–70 cm thick. Most clasts are subrounded and consist of sandstone, shale, and quartz. The OSL and TL ages (Tables 1 and 2) show that the unit was deposited at ca. 10,830–9,400 yr BP.

Unit F is an alluvial/colluvial unit consisting mostly of sand, silt, clay, and gravel. This unit is clast-supported and consists of subangular to rounded clasts of quartz, sandstone, and shale (maximum diameter, ca. 5 cm). The thickness of the unit ranges from 50 cm to 2 m.

Unit G is an alluvial/colluvial complex with a thickness of 2–2.5 m; it consists mainly of reddish-brown sandy clay and minor amounts of gravel. Most of the clasts are subangular to subrounded, and consist of sandstone, shale, and quartz (maximum diameter, ca. 3 cm). The upper part of unit G is not cut by faulting (X3 in Figs. 9(a) and 9(c)). The OSL and TL ages (Tables 1 and 2) show that the unit was deposited at ca. 8,640–7,150 yr BP.

Unit H is a clast-supported colluvial unit characterized by gravel and sand. Most clasts in the unit are subangular to subrounded (maximum diameter, ca. 5 cm) and the sediments consist of quartz, sandstone, and shale. The unit is approximately 50 cm to 1 m thick.

Unit I is a top soil consisting of sand and silt with a few gravel beds. Plant roots and debris with organic matter are common in the unit, and are somewhat disturbed by human activity. The unit is ca. 20 cm to 1 m thick.

Overall, the grain sizes of sediments in the quarry range from clay to cobble. The sediments in the clast-supported gravel units (units A, C, F, and H) are moderately to poorly sorted. Clasts in the gravel layers are subangular to rounded; they are randomly oriented, with some elongate gravel clasts oriented with their long axes at a high angle to bedding. The sedimentary structures suggest that the gravel units were deposited by clast-rich debris flows. Sediments of clast-rich debris flow origin are typically very poorly sorted, and with clast-supported gravels within a fine-grained matrix [Larsen and Steel, 1978; Steel and Gloppen, 1980]. Matrix-supported (i.e. matrix-rich) gravels deposited by debris flows have been reported in India by Shukha [2009] and in northern Thailand by Rhodes et al. [2005]. The sediments in the matrix-supported gravel units (units B, D, E, and G) are poorly sorted and consist of mixed sand, silt, clay, and gravel. The sedimentary structures suggest that these units were deposited by matrix-rich debris flows.

6.2. Phra That Chom Kitt segment
Quaternary faults cutting Cenozoic terrace deposits (Qt of Bunkapai [2005]) have been observed at the road cut on the road to the pagoda of Phra That Chom Kitt temple (Figs. 6 and 7). The mapped faults (F1–F4 in Fig. 11) strike N50°E–N72°E and dip 70°NW–80°SE. The results of OSL and TL dating on six samples (PCT21, PCT23, PCT25, PCT27, PCT28, and PCT29; Fig. 11) are summarized in Tables 1 and 2. The Quaternary stratigraphy and structural geology of the road-cut wall are
Fig. 11. Quaternary sediments (a), stratigraphy and ages of Quaternary sediments along the SE–NW transect in the Phra That Chom Kitti road-cut exposure (b). Faults identified in the road-cut wall are F1–F4. Black arrows indicate fault traces and half arrows show the sense of movement. Samples PCT21, PCT23, PCT25, PCT27, PCT28, and PCT29 were collected for OSL and TL dating. The location of the wall is shown in Figs. 6 and 7. Unit A: brown to yellowish sand; Unit B: clay with clasts of feldspar and quartz; Unit C: brown to yellowish sand with gravel; Unit D: light brown to yellowish sand; Unit E: clay, sand and with some gravels; Unit F: gravel, sand, and clay; Unit G: gravel with sand; Unit H: top soil.

depicted in Fig. 11(b); the identification of units and structures was based on field data and sedimentological characteristics of the strata.

Unit A, the oldest unit in the road cut, is an alluvial unit consisting mainly of moderately sorted, brown to yellowish very fine to coarse sand. The minimum thickness of the unit is 1.5 m.
Unit B is an alluvial unit consisting of silty clay and clasts of feldspar and quartz. The thickness of the unit ranges from 50 cm to 1 m. The OSL and TL ages (Tables 1 and 2) show that the unit was deposited at ca. 90,030–89,720 yr BP.

Unit C is an alluvial/colluvial unit containing brown to yellowish sand with gravel. Grain sizes range from very coarse to fine sand. Most clasts are angular to subrounded, pebble sized, and comprised of sandstone and quartz. Thin layer of Fe oxide serves as a marker for the contact between unit C and the overlying unit D. The thickness of the unit ranges from 50 cm to 1.20 m. The OSL and TL dates of unit C (Tables 1 and 2) indicate that the unit was deposited at 53,300–49,980 yr BP.

Unit D, with an average thickness of 80 cm, is an alluvial unit comprised of light brown to yellowish sand. Grain sizes vary from coarse to fine sand; pebbles of quartz and sandstone are sparsely distributed in the unit. The OSL and TL ages (Tables 1 and 2) indicate that the unit was deposited at ca. 44,910–41,240 yr BP.

Unit E, with an average thickness of 2 m, is an alluvial unit comprised of clayey sand and sandy clay with minor gravel. The lower part consists principally of clay and sand; gravels are sparsely distributed in the upper part. The OSL and TL ages (Tables 1 and 2) for the lower part of the unit show that the unit was deposited at ca. 39,700–35,990 yr BP.

Unit F, with an average thickness of 2.5 m, is an alluvial unit comprised of gravel, sand, and clay. The gravel beds in unit F are clast-supported. The gravel clasts are mainly subrounded to rounded and consist mostly of quartz, sandstone, and shale; their maximum diameter is ca. 6 cm. Sand layers are prominent in the unit. The unit consists of intercalated graded beds with thicknesses of 30–50 cm. The OSL and TL ages (Tables 1 and 2) of quartz grains in the sand layers show that the unit was deposited at ca. 39,300–36,540 yr BP.

Unit G is a 30 cm thick colluvial/alluvial complex consisting of poorly sorted gravels and sands. Most clasts are subangular to rounded (maximum diameter, ca. 4 mm), and are comprised of quartz, sandstone, and shale. The OSL and TL ages (Tables 1 and 2) indicate that the unit was deposited at ca. 30,040–27,580 yr BP.

Unit H, the youngest units, is the topmost soil layer; it is approximately 10 cm thick and consists of organic rich silt/clay with some gravel and sand.

The sediments of units B and E are chiefly clay and silt with minor sand; they are considered to represent fluviolacustrine environments. The sediments of units A, C, D, and G are poorly sorted and subangular, and are characterized by mixtures of sand, silt, clay, and gravel. The geometries of the sedimentary packages and structures indicate that these units were possibly deposited by matrix-rich debris flow, similar to those reported by Shukha [2009] and Rhodes et al. [2005]. The clast-supported gravel of unit F, however, contains mostly subrounded clasts, and the sediments are poorly to moderately sorted; graded beds have been encountered in this unit. We interpret that the sediments of unit F were possibly deposited by clast-rich debris flows similar to those reported by Larsen and Steel [1978], Steel and Gloppen [1980], and Rhodes et al. [2005], as well as by occasional channel flood deposits.
7. Paleoearthquake Events

Based on field and geochronological data, we have identified eight paleoearthquake events occurring along the MHSF, as shown in Fig. 12. The evidence for these paleoearthquake events consists of offsets of stratigraphic units in the quarry and trench walls, as well as geophysical data from EGAT [2012].

The first paleoearthquake event (F1; Fig. 11) may be related to movement of the Phra That Chom Kitt segment (no. 36 in Fig. 3(c)). The fault cuts units A and B, and terminates in the upper part of unit B. Unit A is offset vertically by ca. 30 cm. We interpret that the sense of movement was mainly vertical, and that this is a normal fault. The fault cuts through a sedimentary unit (unit B) that was deposited at ca. 89,720 yr BP, and hence must be younger than the unit. However, no geochronological ages are available to constrain the depositional age of the lower part of unit C. Thus, based on OSL and TL ages of unit B (Fig. 11), we suggest that this fault was active at ca. 78,000 yr BP.

The second paleoearthquake event may be related to movement on the Ban Pae segment (no. 31 in Fig. 3(c)), as reported by DMR [2007] (although we here reinterpret the age of fault movement based on data from the trench). The fault cuts through a sedimentary unit that was deposited at ca. 69,740 yr BP (for the depositional ages, see Fig. 12), and hence must be younger than the unit. However, no geochronological dates are available to constrain the timing of the cessation of fault movement. Thus, based on the OSL age from DMR [2007], we roughly constrain the timing of the event as having occurred at ca. 68,000 yr BP.

![Fig. 12](image-url)
Data for the third paleoearthquake event, which is identified from radon and resistivity investigations (Fig. 13) and OSL ages from the Mok Chum Pae trench (see Fig. 3(c)), indicate that faulting occurred on the Mok Chum Pae segment (no. 3 in Fig. 3(c)); the fault cuts through weathered rock and overlying sediments in the trench [EGAT, 2012]. The fault cuts sediment layers deposited during the period
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of 58,670–57,670 yr BP, which we interpret as representing a third paleoearthquake event, which might have occurred at ca. 58,000 yr BP.

The fourth paleoearthquake event (F2; Fig. 11) is possibly related to movement on the Phra That Chom Kittī segment. Units B and C and the lower (but not upper) part of unit D are cut by fault F2. The fault cuts sediment layers deposited during the period 53,300–41,240 yr BP, and we interpret this as a fourth paleoearthquake event (Fig. 11) that might have occurred at ca. 48,000 yr BP.

The fifth paleoearthquake event (F3; Fig. 11) may be related to movement on the Phra That Chom Kittī segment. The fault cuts units A–F, and, except for the youngest unit, all units to the right of the fault (Fig. 11) are offset vertically by ca. 30 cm, whereas all units to the left side of the fault are offset vertically by ca. 50 cm. We interpret that this fault is mainly a normal fault, as the fault cuts the lower part of unit E and terminates in the upper part of unit F. The fault cuts sediment layers that were deposited during the period 39,300–36,540 yr BP, and we interpret this as a fifth paleoearthquake event (Fig. 11) that might have occurred at ca. 38,000 yr BP.

The sixth paleoearthquake event occurred at ca. 28,000 yr BP. Evidence for this event was encountered on the Phra That Chom Kittī segment. The fault is observed in the centre of the quarry wall (F4 in Fig. 11); the fault trace cuts units A–F and terminates in the lower part of unit G. Movement of the fault caused displacements of units E and F, and created the sharp contact between these two units. We interpret that movement during the sixth event was principally lateral (strike-slip). An offset defined by the shift of a ridge crest suggests a left-lateral strike-slip sense of movement.

Evidence for the seventh paleoearthquake event consists of a fault on the western side of the quarry at Mae La Noi School (F1 in Fig. 9). The fault cuts units A and B, and the latter unit yields an OSL and TL ages of 24,260–18,500 yr BP. A well-defined slickenside on the foot wall of the fault, located on the western side of the quarry wall, has a pitch of 15° (Figs. 10(a) and 10(c)). The low pitch (15°) suggests that movement was nearly horizontal. In contrast to the other movements, the vertical offset of units A and B on the western side of the quarry wall is ca. 1.0 m; it seems unlikely that a single movement on this fault (F1 in Fig. 9) would generate this amount of offset on the western side of the quarry. Thus, we interpret that repeated movements may have occurred along this fault. Because offset is observed in unit F, we interpret that fault movement may post-date the deposition of unit B, and that faulting may have occurred at ca. 18,000 yr BP.

The latest recognized paleoearthquake event occurred on the Mae La Noi segment no. 1 (labeled no. 25 in Fig. 3(c)). Evidence of movement is visible on a fault on the eastern side of the quarry wall (F2 in Fig. 9). Units A–F and the lower part of unit G are displaced along a dipping fault plane. The gravel bed in the upper part of unit G is not cut by the fault (X3 in Figs. 9(a) and 9(c)), which indicates that faulting must have terminated before deposition of the gravel bed. No offsets are observed in younger units (i.e. units H and I). A slickenside on the hanging wall
of the fault, on the eastern side of the quarry, has a pitch of 60° (Figs. 10(b) and 10(c)). The pitch angle indicates that fault movement was oblique (i.e. a combination of reverse and sinistral strike-slip movement). Based on the OSL and TL dates of unit G (Fig. 9(c)), the most recent movement on the fault occurred between 8,300 yr BP and 7,150 yr BP. We infer that this paleoearthquake occurred at ca. 8,000 yr BP. The orientation and location of the Mok Chum Pae segment are based on the results of radon and resistivity surveys conducted on Quaternary sedimentary strata. However, evidence for this youngest faulting event is not apparent in the trench. However, high radon emissions in the trench may be related to the most recent paleoearthquake on the Mok Chom Pae segment. It is possible that this faulting was contemporaneous with the most recent paleoearthquake in the Mae La Noi basin.

8. Discussion

8.1. Timing of MHSF movement

A preliminary study of the timing of movement on the MHSF revealed that the most recent detected movement of the fault occurred during the period of 890,000–320,000 yr BP, as determined from TL ages on sediments [Takashima and Maneenai, 1995; Hinthong, 1997]; we suggest that this timing is more recent than that proposed by previous researchers. In previous studies, the samples for TL dating may have been collected from fault gouge, in which partial bleaching of the luminescence signal may have occurred; in this case, the TL ages would overestimate the actual age of fault movement. In our study, the quartz grains for OSL and TL dating were collected from young sedimentary strata that are cut by faulting, although the samples themselves are not disturbed by the faulting (Fig. 9). Thus, we believe that our OSL and TL ages represent the most recent movement of the MHSF. We propose a new age of several thousand years for the most recent movement of the MHSF. On the other hand, if the most recent movement of the MHSF proposed by Takashima and Maneenai [1995] and Hinthong [1997] is correct, the timing of MHSF movement as determined in previous studies might represent an early stage of fault activity, which would suggest that the MHSF has been active since at least the late Pleistocene, as proposed by Takashima and Maneenai [1995] and Hinthong [1997], and that the fault is still active today.

8.2. Average recurrence interval of MHSF activity

The average recurrence interval of movement on the MHSF may be on the order of 10,000 years (Fig. 12). Other active faults in northern Thailand are characterized by relatively long recurrence intervals of thousands to tens of thousands of years (Table 3) [Bott et al., 1997; Kosuwan et al., 1999; Fenton et al., 2003]. Based on our study, the recurrence interval of the MHSF is consistent with the results of previous studies on active faults in Thailand.
Table 3. Summary of the characteristics of active faults in northern Thailand, northwestern Laos, and eastern Myanmar.

<table>
<thead>
<tr>
<th>Fault (length, km)</th>
<th>Segment</th>
<th>Orientation</th>
<th>Sense of movement</th>
<th>Relative age of last movement (Kyr)</th>
<th>Geomorphic Maximum development and pedologic slip rate (mm/yr)</th>
<th>Recurrence (Kyr)</th>
<th>Maximum credible earthquake (MCE), (Mw)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoen (120 km)</td>
<td>Ban Mai</td>
<td>NE-SW</td>
<td>Normal fault and subordinate left-lateral strike-slip fault</td>
<td>3.80 Quaternary</td>
<td>0.06</td>
<td>–</td>
<td>–</td>
<td>Pailoplee et al. [2009]</td>
</tr>
<tr>
<td>Doi Ton Ngun</td>
<td>NE-SW</td>
<td>Normal fault and subordinate left-lateral strike-slip fault</td>
<td>1.80 Quaternary</td>
<td>0.18 1.70</td>
<td>–</td>
<td>–</td>
<td>Pailoplee et al. [2009]</td>
<td></td>
</tr>
<tr>
<td>Ban Don Fai</td>
<td>NE-SW</td>
<td>≥ 0.96 Holocene</td>
<td>–</td>
<td>0.60 1.70-2.50 7.5</td>
<td>–</td>
<td>–</td>
<td>Wiwegwin et al. [2011]; Fenton et al. [2003]</td>
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</tr>
<tr>
<td>Uttaradit (160 km)</td>
<td>Khun Non</td>
<td>NE-SW</td>
<td>Oblique-slip fault (a combination of normal and left-lateral strike-slip fault)</td>
<td>2.50 Quaternary</td>
<td>0.19-0.21</td>
<td>–</td>
<td>6.51 Saithong et al. [2011]</td>
<td></td>
</tr>
<tr>
<td>Mae Chan (140 km)</td>
<td>Mae Ai</td>
<td>ENE-WSW</td>
<td>Left-lateral strike-slip fault</td>
<td>17.00 Holocene</td>
<td>0.7</td>
<td>–</td>
<td>–</td>
<td>Kosuman et al. [1999, 2003]; Lacassin et al. [1998]; Fenton et al. [2003]</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>ENE-WSW</td>
<td>Left-lateral strike-slip fault</td>
<td>–</td>
<td>Holocene 0.3-3.0</td>
<td>–</td>
<td>7.5</td>
<td>(Continued)</td>
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</table>

Note: MCE is estimated using the equation from Wells and Coppersmith [1994].
### Table 3. (Continued)

<table>
<thead>
<tr>
<th>Fault (length, km)</th>
<th>Segment</th>
<th>Orientation</th>
<th>Sense of movement</th>
<th>Trench investigations (Kyr)</th>
<th>Geomorphic relationships and pedologic development</th>
<th>slip rate (mm/yr)</th>
<th>Recurrence (Kyr)</th>
<th>Maximum credible earthquake (MCE), (Mw)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mae Ping (230 km)</td>
<td>Khao Mae Song</td>
<td>NW–SE</td>
<td>Right-lateral strike-slip fault</td>
<td>15.00</td>
<td>Pleistocene</td>
<td>0.17–0.73</td>
<td>–</td>
<td>6.7</td>
<td>Saithong [2006]; Saithong et al. [2005]</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>NW–SE</td>
<td>Right-lateral strike-slip fault</td>
<td>–</td>
<td>Quaternary</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Le Dain et al. [1984]</td>
</tr>
<tr>
<td>Three Pagoda (350 km)</td>
<td>–</td>
<td>NW–SE</td>
<td>Right-lateral strike-slip fault</td>
<td>–</td>
<td>Holocene</td>
<td>0.5–2.0</td>
<td>–</td>
<td>7.5</td>
<td>Fenton et al. [2003]</td>
</tr>
<tr>
<td>Mengxian (75 km)</td>
<td>–</td>
<td>ENE–WSW</td>
<td>Left-lateral strike-slip fault</td>
<td>–</td>
<td>Quaternary</td>
<td>4.8 ± 0.2</td>
<td>–</td>
<td>–</td>
<td>Lacassin et al. [1998]</td>
</tr>
<tr>
<td>Nam Ma (177 km)</td>
<td>–</td>
<td>ENE–WSW</td>
<td>Left-lateral strike-slip fault</td>
<td>–</td>
<td>Quaternary</td>
<td>2.4 ± 0.4</td>
<td>–</td>
<td>–</td>
<td>Lacassin et al. [1998]</td>
</tr>
<tr>
<td>Sagoon Fault (1000 km)</td>
<td>–</td>
<td>N–S</td>
<td>Right-lateral strike-slip fault</td>
<td>M 7.3 1930 Pegu (Bago) earthquake</td>
<td>Holocene</td>
<td>18.00</td>
<td>≥ 0.16</td>
<td>–</td>
<td>Tsutsumi and Sato [2009]</td>
</tr>
<tr>
<td>Mae Hong Son (202 km)</td>
<td>Mae La Noi no. 1</td>
<td>NE–SW</td>
<td>Oblique-slip fault (a combination of reverse and left-lateral strike-slip fault)</td>
<td>8.00</td>
<td>Holocene</td>
<td>0.05–0.13</td>
<td>10.00</td>
<td>5.2</td>
<td>this study</td>
</tr>
<tr>
<td>Phra That Chom Kitti</td>
<td>NE–SW</td>
<td>Oblique-slip fault (a combination of normal and left-lateral strike-slip fault)</td>
<td>28.00</td>
<td>Pleistocene</td>
<td>0.03–0.05</td>
<td>10.00</td>
<td>5.1</td>
<td>this study</td>
<td></td>
</tr>
</tbody>
</table>
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Wells and Coppersmith [1994] proposed an estimate of paleomagnitude based on surface rupture length,

\[ M = 5.08 + 1.16 \log(SRL), \]  

(1)

where SRL is the surface rupture length determined as the straight-line distance between the rupture endpoints. Using Eq. (1), the paleomagnitude of the latest paleoearthquake event (possibly occurring at ca. 8,000 yr BP) on the 1.4 km Mae La Noi segment no. 1 was Richter 5.2.

Our estimated recurrence interval suggests that Mae La Noi segment no. 1 may have ruptured approximately every 10,000 years. This segment has not ruptured during the last 8,000 years; we consider that the next earthquake event generated by this fault segment may be of Richter magnitude 5.2. For the Phra That Chom Kitt segment, the magnitude of past earthquake events was approximately Richter 5.1, as derived from Eq. (1). If our estimate of the recurrence interval is correct, the last earthquake event on this segment possibly occurred several thousand years ago. However, the last movement on this segment observed in the road-cut wall was at about 28,000 yr BP. It is possible that a younger fault has not yet been detected, and will be recorded in other areas along the fault trace. These unresolved questions suggest a need to study trenches in young sedimentary deposits in other areas along the fault trace so as to constrain the timing of fault movements on this segment. By contrast, the Phra That Chom Kitt segment has not ruptured in the last 28,000 years.

8.3. Slip rate of the MHSF

In this study, the slip rate was determined from the vertical offset of stratigraphic units and the ages of sedimentary deposits displaced by the fault. For example, an average slip rate on Mae La Noi segment no. 1 can be estimated using the average or mean offset of the bases of units B–G and a properly estimated age of the base of unit B (Fig. 9). The average vertical offset of units B–G is ca. 1.0 m. Using 20,000 yr BP as the age of the base of unit B, we calculated an average slip rate of ca. 0.05 mm/yr.

The slip rate can also be estimated from the amount of displacement during the most recent fault movement, and the age of the movement (8,000 years), which yields a slip rate of ca. 0.13 mm/yr. This slip rate is useful in seismological research required to produce seismic hazard maps.

The average slip rate on the MHSF can also be estimated from

\[ \text{Slip rate} = \frac{D}{R}, \]  

(2)

where \( D \) is the slip per event and \( R \) is the recurrence interval. Based on our data, \( D \) is in the range of 30 cm to 1 m (determined from the vertical offsets on faults in the quarry and road-cut walls) and \( R \) is ca. 10,000 years; therefore, the average slip rate is ca. 0.03–0.10 mm/yr. These estimates suggest that movements on the
MHSF, particularly on Mae La Noi segment no. 1 and the Phra That Chom Kitt segment, are in the range of ca. 0.03–0.13 mm/yr, which is consistent with the slip rate of active faults in northern Thailand (Table 3). On the other hand, DMR [2007] reported that the slip rate on Ban Pae segment no. 31 (Fig. 3(c)) is ca. 0.0028 mm/yr; however, this estimate, which is considerably less than ours, was based on data from the second paleoearthquake event (68,000 yr BP), possibly suggesting that the late Quaternary was a period of increased faulting activity in this region, or that recently renewed activity followed a prolonged period of quiescence. In either case, the slip rate of the MHSF is quite low (0.03–0.13 mm/yr).

8.4. Neotectonics of the MHSF

The Eocene–Oligocene collision of the Indian and Eurasian plates resulted in N–S compressive stresses in the Indochina region. It is likely that the N–S compressive stresses caused dextral motion on major NW–SE trending faults in northern Thailand. The movement on faults accompanying regional E–W extension during the late Oligocene–Miocene initiated the formation of Neogene basins. We suggest that the onset of Cainozoic basin formation in the Mae Hong Son region occurred during this time. We propose that strike-slip tectonics in the Neogene played a critical role in the generation of neotectonic patterns and active faulting. On this basis, we have proposed the following model for basin development associated with faulting in the Mae Hong Son region (illustrated in Fig. 14).

The N–S trending MHSF (the Mae Yuam Fault), is interpreted as the boundary between the Sibumasu block and the Inthanon zone [Ueno, 1999; Hisada et al., 2004], represents a splay fault of the NW–SE trending MPF to the south [Morley et al., 2007]. Based on remote sensing data, the NW–SE trending MHSF in the south possibly merges into the MPF. It is possible that dextral movement on the MPF during the Oligocene caused reactivation of MHSF strike-slip movement. This movement may have initiated E–W extension and grabens that developed into sedimentary basins in the Mae Sariang area, as suggested by Uttamo et al. [2003]. A series of triangular facets observed along the Nong Mae La and Kon Phung segments may be evidence that vertical dip-slip movement resulted in E–W extension.

During the Miocene, the N–S Sagaing Fault was an active right-lateral strike-slip fault system [Morley, 2002]. The MHSF shows the same sense of movement as that of the Sagaing Fault. Within the MHSF zone, two fault strands (zones A and B; Figs. 3(c) and 14) contemporaneously generated the N–S Quaternary Mae Sariang basin during the late Pleistocene. Some faults strands (e.g. zone C) located within zones A and B may also have been generated (Fig. 14). Morphotectonic landforms indicative of active faults also developed at this time, as indicated by features such as offset streams and linear valleys, and the development of scarps related to active faulting. From the late Pleistocene until the present, the region has been influenced by the development of an alluvial plain. However, present-day tectonic processes are going-on.
8.5. Fault activity in northern Thailand

In northern Thailand, earthquake events caused by active faults have been reported on the basis of trench investigations (Table 3). However, the level of activity on the MHSF seems low by comparison with the timing of the latest fault movement and slip rates on other active faults in northern Thailand. The NW–SE trending MPF and TPF are the principal right-lateral strike-slip faults in the area; however, the NE–SW trending MCF and UF are left-lateral strike-faults which are truncated by the NW–SE trending right-lateral strike-slip faults [Polachan et al., 1991]. To the west of northern Thailand in Myanmar, the N–S Sagaing Fault, which is the most active fault in the region, exhibits dextral displacement [Morley et al., 2011]. The MPF extends into Myanmar (Fig. 1), where it either merges with or is cut by the N–S trending Sagaing Fault. Movement on the Sagaing Fault was continuous during collision of the Indian and Eurasian plates [Morley, 2002]. Displacement may also have occurred on the NW–SE trending MPF. Because the MHSF is probably a splay fault of the MPF [Morley et al., 2007], it may also have moved during this time. However, the NE–SW trending faults on the MHSF, which are conjugate faults, may have moved slightly as well. Moreover, the numbers and magnitudes of recorded earthquakes decrease southwards toward Thailand [Morley, 2007; Morley et al., 2011], and stress magnitudes in the Yunnan region also progressively diminish to very low levels in northern Thailand [Morley, 2007; Morley et al., 2011]. However,
micro-earthquake events recorded from the TMD and RTNSRS have been observed in the Mae Hong Son region (Fig. 3(c)). These micro-earthquakes, which are quite scattered in their distribution, indicate that this region may be in a low seismicity zone. As explained above, the micro-earthquakes may represent low-level activity on the MHSF.

9. Conclusions

The MHSF in the Mae Hong Son region, northern Thailand, trends mainly N–S, and shows conjugate fault sets trending NW–SE and NE–SW. The N–S trending faults show a normal dip-slip sense of motion, and bound the margins of N–S trending elongate basins. The NW–SE and NE–SW trending faults show right-lateral strike-slip and left-lateral strike-slip movements, respectively. Morphotectonic landforms associated with the MHSF are fault scarps, offset streams, linear valleys, offset ridge crests, triangular facets, hot springs, and linear mountain fronts.

In this study, a trench, a quarry, and a road cut in Cenozoic strata have been used for fault geometry analysis. We were able to identify eight paleoearthquake events in the Mae Hong Son region based on trenching data, including offset stratigraphic units in the quarry wall and the road-cut exposure, and OSL and TL ages (first event: 78,000 yr BP; second event: 68,000 yr BP; third event: 58,000 yr BP; fourth event: 48,000 yr BP; fifth event: 38,000 yr BP; sixth event: 28,000 yr BP; seventh event: 18,000 yr BP, and the most recent event: 8,000 yr BP). The recurrence interval on the MHSF may be on the order of 10,000 years and the slip rate is estimated as ca. 0.03–0.13 mm/yr. We conclude that the MHSF is currently active, and that Mae La Noi segment no. 1 and the Phra That Chom Kitti segment are active oblique-slip faults (Mae La Noi segment no. 1 represents combined reverse and left-lateral strike-slip motions, while the Phra That Chom Kitti segment represents combined normal and left-lateral strike-slip motions). However, we infer that activity on the MHSF is low.

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