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SLIP RATE AND RECENCY OF LARGE PALEOEARTHQUAKE OF SINISTRAL ACTIVE FAULTS IN INDOCHINA REGION

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Abstract

The Indochina region is bounded by two major strike–slip faults; the Red River and Sagaing Faults. The faults in this zone, especially in the northern parts of Thailand and Laos, trend mainly in the NE–SW and E–W directions and show left-lateral strike-slip motion with a minor component of dip–slip. Some of these faults have been regarded as active faults, viz. the Nam Ma Fault (NMF), Mae Chan Fault (MCF), Mae Lao Fault (MLF), and Dien Bien Phu Fault (DBPF), based on seismicity and geomorphological features. The length of these sinistral active faults range from 70 to 330 km. Quaternary slip-rate of these faults is estimated with the hypotheses of fault reactivation since 5 Ma. Here we investigate timing of large paleoearthquakes on the MCF, Uttaradit (UF) and DBPF in Laos, and estimate the slip rates of these faults based on paleoearthquake trenching. The approximately 310 km-long, MCF locates in Chiang Rai and continuing into northern Laos. The approximately 130 km-long, UF, which is a southwestern segment of the DBPF,locates in Uttaradit. The DBPF in Laos has a length of *ca.*330 km. We selected some segments of these faults for paleoearthquake trenching.

Data from trench sites along a segment of the MCF at Ban Pong Pa Kham, Bang Pong Khom were used to analyse the history of fault movement. This study revealed young Quaternary sediments containing evidence for at least eight ground-rupturing earthquakes along the fault. Based on C14 AMS, OSL and TL ages, approximate ages of the paleoearthquake events are: (1) 20,000 yr BP; (2) 10,000 yr BP; (3) 8,000 yr BP; (4) 7,000 yr BP; (5) 4,000 yr BP; (6) 3,000 yr BP; (7) 1,500 yr BP, and (8) 900 yr BP. It is possible that the recurrence interval of seismic events on the MCF is between 1,000 and 3,000 years. Terraces and debris flows offset from a few meters to a kilometer, dated largely by cosmogenic isotopic techniques, and yield a slip rate of ~1.4 mm/yr. For the UF and DBPF, trenching data from Uattradit and Laos revealed young Quaternary sediments containing evidence for at least six ground-rupturing earthquakes along the fault. Based on C14 AMS and TL ages, approximate ages of the paleoearthquake events are: (1) 10,000 yr BP; (2) 7,000 yr BP; (3) 4,000 yr BP; (4) 3,000 yr BP; and (5) 2,000 yr BP; and (6) 1,000 yr BP. It is possible that the recurrence interval of seismic events on the DBPF in Thailand and Laos is 1,000–3,000 years. The largest paleoearthquake event has been identified from trenching at Ban Nong Heo; vertical displacement with 3.3 m suggests that the paleoeartquake event on the UF could have been Mw 7.1, and this is possible to be a minimum slip on the fault. Channel offsets from a few meters to a kilometer, dated by C14 AMS and TL techniques, yield a slip rate of ~0.19–0.21 mm/yr. Thus, we conclude that the MCF, UF and DBPF are still active; these data suggest that the Indochina region will be subject to moderate to large earthquakes in the future.

Keywords: Mae Chan Fault, Uttaradit Fault, Dien Bien Phu Fault, slip rate, active fault, Thailand

1. Introduction

The Indochina region is the continental portion of Southeast Asia, where lies between India and south or southwest of China, and include Thailand, Laos, Cambodia and Vietnam (Fig.1). Since a few decades, this region especially in northern parts of Thailand and Laos has experienced micro-earthquakes, moderate and some strong earthquakes [1]. The reported earthquakes in this region were as follows; in 2007, a strong earthquake of Mw 6.3 [2] occurred along the northeastern part of the Mae Chan Fault (MCF) in Bokeo area, northern Laos; this event caused minor damage in Chiang Rai, northern Thailand. To the north of northern Thailand in easternmost Myanmar, a large-scale earthquake on 24 March 2011 (Mw 6.8) occurred on the Nam Ma Fault (NMF) (Fig.1) [3]. In 2014, a strong earthquake of Mw 6.1 occurred along the northeastern portion of the Mae Lao Fault (MLF) in Mae Lao area, Chiang Rai, northern Thailand [4]; this event caused damages, cracks and sand boils in Chiang Rai, northern Thailand. Unfortunately, one person died during the earthquake [5]. Recently, a Mw 6.2 event on 20 November 2019 (at 23.50 p.m. (UTC), or 21 November 2019, 06.50 a.m. (local time)) causing minor damage in Nan area, northern Thailand has been reported; this earthquake occurred along the southwestern portion of the Dien Bien Phu Fault (DBPF) near the border between Thailand and Laos [6] (Fig. 1). A present-day seismicity in northern parts of Thailand and Laos is, at least to an extent, related to active faults where locate mainly in a zone of strike-slip deformation, between the Red River Fault (RRF) to the east and the compressive Sagaing Fault (SF) to the west [7,8]. According to these earthquake data reported in the region above, it is concluded that the region is possibly located in a seismicity zone.

In order to classify the seismic hazard zone, and benefit for construction designing, active fault data in this region are still necessary for seismic hazard assessment. In northern Thailand, existing data of active faults are available. However, in the northern Laos, there are a few active fault surveys which are insufficient to constrain the paleoearthquake history. Therefore, to get active fault data, better understand and clarify the nature of seismicity in this region, the paleoseismicity of faults along the ENE–WSW trending MCF and NE–SW trending Uttaradit Fault (UF) in northern Thailand, and the NE-SW trending DBPF in Luang Prabang, northern Laos was examined. We also applied C14 AMS and Optically stimulated luminescence (OSL) dating to determine the depositional ages of sediment layers involved in paleoearthquake events.

As explained above, three active faults, including the MCF, UF in northern Thailand and DBPF in Luang Prabang, northern Laos, were selected for a paleoearthquake study. The main objectives of this study 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 faults.

2. Neotectonics and seismicity in Indochina region

The SE Asia is located in the Eurasian plate to the east of an active east-dipping subduction zone (Sumatra-Andaman trench) and to the west or southwest of South China block [9]. In the SE Asia, neotectonic evolution has been principally caused by the interaction of the Indo-Australian and Eurasian plates since Paleogene. The penetration of Indo-Australian plate into the Eurasian plate has started since 50 Ma [10]. Then, during 35 to 17 Ma (or Mid Oligocene), the Indochina region was extruded southeastward along the RRF [11, 12, 13, 14], based on geochronological data of sinistrally sheared rocks using U/Pb and 39Ar/40Ar ages. After this major tectonic event, the regional compressive stress in this region changed to N-S direction due to the Indo-Australian plate moving to north continuously [13]. This also resulted in a reversal in the sense of movement along the NW–SE trending Mae Ping (MPF) and Three Pagoda (TPF) Faults during the Oligocene–early Miocene (perhaps in 23 Ma) [15], when slip sense of these faults changed to right-lateral, and the NE–SW trending Uttaradit Fault (UF; Fig. 1) became a left-lateral. To the east, the RRF had become right-lateral strike-slip fault in 5 Ma [13, 16]. Taken together, these major faults form a transtensional regime related to the opening of Cenozoic basins in Southeast Asia [17,18]. The present-day, it seems that the fault kinematics of a complex fault system including the NE–SW trending faults in this region may possibly be driven by crustal shearing that relates to indenting of the Indo-Australian into Eurasian plates, southwestward asthenospheric flow around the eastern Himalayan syntaxis, and gravitation or shear-driven indentation from northern part of the Shan Plateau [19].

A complex fault system can trigger a lot of earthquakes in Yunnan, China and Shan plateau, to the southeast of Shan plateau, seismicity in the Indochina region is also considered to be a comparatively high [20,21]. Based on epicenters of earthquake data there is clear association between seismicity and mapped active faults. Approximately 2,583 earthquake events with M_L 2–6.4 have been reported nearby and within the northern regions of Thailand and Laos (data recorded in 2,007-2020) [1]. Several of these micro-earthquakes have been felt; however, no damage has been reported. The largest known earthquake, with a Mw 6.3, occurred along the northeastern part of the MCF in Bokeo area, northern Laos on 16 May 2007 (Fig. 1). Farther to the east in northern Laos, there is an earthquake with the M_L 5.4 in February 2011 (Fig. 1), occurred along the southwestern segment of the DBPF in Xaiyabuli area to the south of Luang Prabang area as reported by Thailand Meteorological Department. Recently, a Mw 6.2 (or M_L 6.4 (Fig. 1) [1]) event on 20 November 2019 has been reported; this earthquake occurred along the southwestern portion of the DBPF near the border between Thailand and Laos [6]. These observations indicate that present-day seismicity is, at least to an extent, related to the MCF, UF and DBPF.

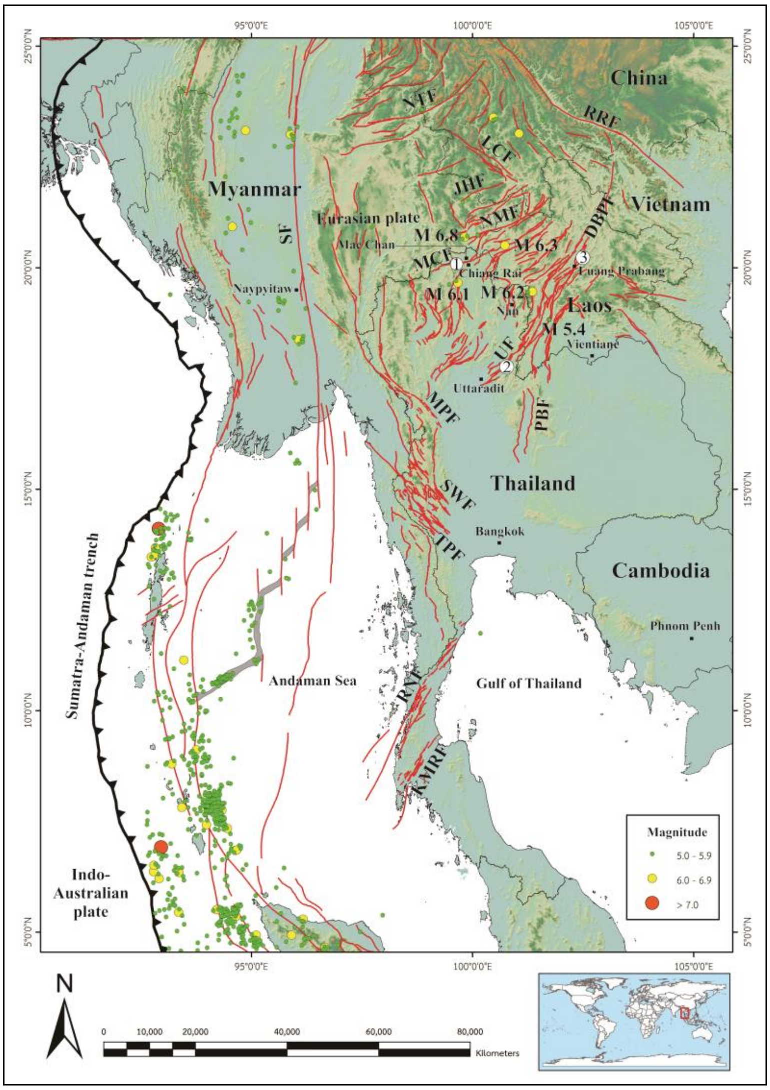

Fig. 1 –Map of Indochina region and adjacent areas showing major active faults (modified from [22,23]) and the epicenters of moderate to strong earthquakes (M>5). Note: 1, Ban Pong Pa Kham trench site; 2, Ban Nong Heo trench site, 3, Ban Had Kang trench site; NTF, Nanting He Fault; LCF, Lancang Fault; JHF, Jinghong Fault; NMF; Namma Fault; MCF, Mae Chan Fault; UF, Uttaradit Fault; DBPF, Dien Bien Phu Fault; SF, Sagaing Fault; MPF, Mae Ping Fault; PBF, Phetchabun Fault; SWF, Srisawat Fault; TPF, Three Pagoda Fault; RNF, Ranong Fault; and KMRF, Klong Marui Fault.

3. Morphotectonic landforms of the MCF, UF and DBPF

We applied Landsat 7, IKONOS satellite images and digital elevation models (DEMs) generated from shuttle radar topography mission (SRTM) and ALOS data, to interpret active faults and their morphotectonic landforms. Fault segments in northern parts of Thailand and Laos are clearly visible on enhanced Landsat 7 images and DEMs, mainly oriented NE–SW, with conjugate faults oriented NW–SE, and some minor N–S faults. The NE–SW-striking faults observed in study area bound the Cenozoic basins, and have been considered to be active faults. There are MCF in the Phang basin, Chiang Mai, the MLF in the Chaing Rai basin, the UF in the Nam Pad basin, Uttaradit, Thailand, and the DBPF in the Piang basin, Xaiyabuli, northern Laos. The length of these NE–SW-striking faults faults range from 70 to 330 km. The NE–SW-striking MCF that bounds the Phang basin is clearly visible along the northwestern side of the basin. The total length of the MCF in Thailand is approximately 150 km, and another 160 km northeast into Laos for a total of 310 km. The fault can be traced along the boundary between Carboniferous Quartzitic sandstone, Triassic granite and unconsolidated Quaternary sediments that are mainly fluvial, colluvial, and alluvial deposits. The main morphotectonic landforms associated with the MCF are fault scarps, offset streams, linear valleys, offset ridge crests, beheaded streams, hot springs, and shutter ridge (Figs. 2A and 2B). To the west of Mae Chan, there are good examples for the offset channels along the fault trace; a northward flowing stream channel shows a sinistral offset of *ca*. 20–25 m (the stream flows westward along the fault trace before returning to its northward course); this offset stream indicates sinistral strike-slip along the MCF. Shutter ridge, a series of offset ridge crests and terrace and debris flows offset from a few meters to a kilometer. A hot spring occurs in the western and central parts of the fault zone. To the east of Mae Chan, the Wiang Nong Lom swamp is bounded by the MCF, and appears the swamp was formed by movement on the MCF, and is inferred to be a sag pond [24,25,26,27]. Moreover, hot springs have been reported within the swamp [28], suggesting the on-going activity along the fault.

In the southern part of northern Thailand, the NE–SW-striking UF bounds the margins of elongate NE–SW Nam Pad basin. The total length of the UF is approximately 130 km. The fault can be traced along the boundary between Paleozoic to Mesozoic sedimentary rocks and unconsolidated Quaternary sediments that are mainly fluvial, colluvial, and alluvial deposits. The main morphotectonic landforms observed along the UF are fault scarps (Fig.2C), offset streams, linear valleys, triangular facets, and linear mountain fronts. To the east of Uttaradit in the Nam Pad basin, a northwestward flowing stream channel shows a sinistral offset of *ca*. 20–180 m (the stream flows southwestward along the fault trace before returning to its northwestward course, then flows into the Nam Pad river); this offset stream indicates sinistral strike-slip along the UF.

To the northeast of Uttaradit area in northern Laos, the NE–SW-striking DBPF can be seen on the satellite images from Dien Bien Phu, northwesten Vietnam, Luang Prabang, and connected with to the UF in Uttaradit, Thailand (Fig. 1). The total length of the DBPF in Laos is approximately 330 km. The fault cuts the upper Paleozoic to Mesozoic sedimentary rocks, and unconsolidated Quaternary sediments that are mainly fluvial, colluvial, and alluvial deposits. Small Cenozoic basins observed along the fault zone are the Phiang, Xaiyabuli and Dien Bien Phu basins. The main morphotectonic landforms observed along the DBPF are fault scarps, offset streams, linear valleys, shutter ridge and triangular facets. Some of the example of offset channel can be found farther to the west of Luang Prabang donwtown, the Mekong river is sinistally offset *ca.* 3 km by the DBPF. Others can be found to the south of downtown, a northwestward flowing stream channel shows a sinistral offset of *ca*. 60–90 m (the stream flows southwestward along the fault trace before returning to its northwestward course, then flows into the Mekong river); this offset stream indicates sinistral movement along the fault in this area. At Ban Had Kang, a linear valley (Fig.2D) and offset channels (*ca.*60–150 m) generated by the movement of the DBPF can be observed.

4. Paleoearthquake investigation of the MCF, UF and DBPF

4.1 Paloearthquake investigations of the MCF

The Ban Pong Pa Kham trench traverses the ENE–WSW Kio Sa Tai segment of the MCF. Significant morphotectonic landforms, such as offset ridge crest (Fig. 2B), offset alluvial fan and scarps, are present in Ban Pong Pa Kham area. The excavated trench was 37 m long, 3.5 m wide, and 3.5 m deep; at the positions 22 to 37 m on the west wall is shown in this paper only, and the stratigraphy of the trench wall can be described in terms of 12

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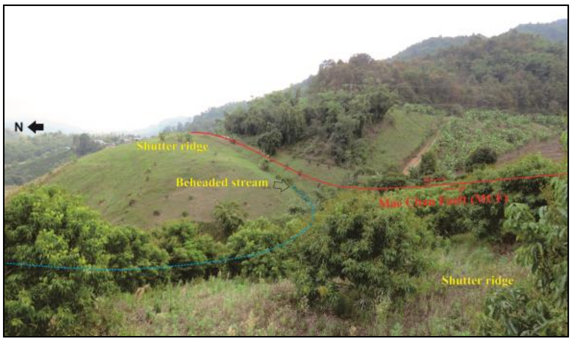
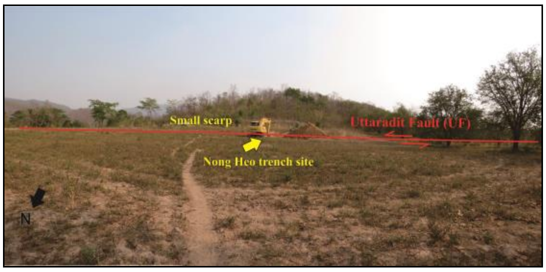


A.

B.



C.

D.

Fig. 2 –Significant morphotectonic landforms of the MCF, UF, and DBPF. A shutter ridge and a beheaded stream in Ban Pong Khom (A), offset ridge crest in Ban Pong Pa Kham, Mae Chan, Chiang Rai (B), a SW-facing small scarp at Ban Nong Heo, Uttaradit (C), and linear valley in Ban Had Kang, Luang Prabang, Laos (D). Yellow arrows point at locations of trench sites, and these locations of trench sites are shown in Fig. 1

unconsolidated units; units A to L, based on their sedimentological characteristics (Fig. 3). Details of the individual units are described below.

Unit A is an alluvial unit composed of pale purple sand, silt and clay, sand size ranges from very fine to very coarse; a lot of charcoal can be observed in the unit. Thickness of this unit is approximately 20 to 50 cm.

Unit B is an alluvial unit composed of greenish grey sand, silt, clay and gravel lens. Charcoal can be found in the unit. The thickness of the unit ranges from 20 to 50 cm.

Unit C is an alluvial unit composed of orangish brown sand, silt and clay with some pebble. Most clasts consist of granite and quartz. The thickness of the unit ranges from 10 to 50 cm. This unit is cut by fault.

Unit D is an alluvial/colluvial unit consisting mostly of gravel, sand, silt, and clay. This unit is clast-supported and consists mainly of subangular to rounded clasts of granite, quartz and feldspar. The thickness of the unit is approximately 1 m. Two sand layers can be observed in the unit as SS-1 and SS-2; SS-1 is mainly fine to very coarse sand (10–15 cm thick), and light grey. SS-2 is mainly fine to coarse sand with clay, and orangish brown with some purple, and has the thickness of about 10–15 cm. In the upper part, the unit shows a clast-supported gravel unit, composed largely of granite and quartz. The unit is poorly to moderately sorted, and loose. This unit is cut by fault.

Unit E is a clast-supported colluvial unit characterized by gravel (pebble to boulder) sand, silt and clay. Most clasts in the unit are subangular to rounded (maximum diameter, *ca*. 30 cm) and, consist of granite, quartz and feldspar. The unit is approximately 50 cm to 1.5 m thick. The unit is poorly to moderately sorted. This unit is cut by fault.

Unit F is a clast-supported colluvial unit consisting mostly of gravel, sand, silt and clay (matrix: clay and silt). Gravel size ranges from pebble to boulder. Most clasts consist of granite and quartz, poorly to moderately sorted.

Unit G is an alluvial unit characterized by orangish brown sand, silt and clay with gravel. Most clasts are granite and quart. Gravel size ranges from pebble to cobble. This unit is cut by fault in the middle part of unit.

Unit H is an alluvial unit composed of orangish brown sand, silt and clay with weathered granite clasts.

Unit I is an alluvial/colluvial unit characterized by dark brown sand, silt, clay and gravel.

Unit J is a clast-supported colluvial unit characterized by boulder, cobble, pebble and sand. Most clasts consist of granite, quartz and feldspar.

Unit K is an alluvial unit composed predominantly of light brown to grey sand, silt and clay.

Unit L is the topmost soil layer; it is approximately 10-30 cm thick and consists mainly of organic rich silt/clay and sand.

At least two faulting events have been identified (Fig. 3); the faults strike 090° and dip 75°–80° to south. The fault traces cut units A–G, and terminate in the upper part of unit G. The first movement of the fault caused displacements of units A, B, C, D and E, and created the sharp contact among these five units. After deposition of unit G, the second faulting event may deform this unit. It is possible to constrain the timing of faulting if the depositional ages of sedimentary layers, seen to be associated with faults in trench exposures, can be determined. Thus, we sampled sands from units A, B, C and G for the Optically Stimulated Luminescence (OSL) dating with application of Single Aliquot Regeneration techniques (SAR). Equivalent dose (ED) measurements of OSL dating were made using an OSL instrument (Model Lexsygsmart-Automated TL/OSL Reader, Germany) at the Thailand Institute of Nuclear Technology (TINT), Thailand. The instrument was equipped with a $^{90}Sr/^{90}Y$ beta source delivering 0.136 Gy/sec to the sample. For the annual dose (AD), the concentrations of U, Th, K and Rb were analyzed using HPGe Gamma Spectrometer at TINT. We also sampled charcoals from units A and B for C14 AMS dating. The OSL and C14 AMS ages are summarized in Tables 1 and 2. Based on OSL and C14 AMS ages, the first paleoearthquake event in this trench might have occurred at *ca.* 20,000 yr BP. The second event occurred at *ca.* 8,000 yr BP.

4.2 Paloearthquake investigations of the UF

The Ban Nong Heo trench traverses the NE–SW Nong Heo segment of the UF. Small scarp and offset stream are present in Ban Nong Heo area (Fig. 2C). The excavated trench was 18 m long, 3.5 m wide, and 3.5 m deep, and the stratigraphy of the trench wall can be described in terms of 3 unconsolidated units; units A to C (excluding sandstone of the basement rock unit), based on their sedimentological characteristics (Fig. 4). Details of the individual units are described below.

Unit A is an alluvial unit consisting mostly of gravel, sand, silt, and clay. This unit is clast-supported and consists of subangular to rounded clasts of quartz, sandstone, and shale. The thickness of the unit ranges from 20–1 m. This unit is cut by the fault.

Unit B is an alluvial unit with a thickness of 2–2.5 m; it consists mainly of light yellowish brown sandy clay, sand, silt, and minor amounts of gravel. Most of the clasts are subangular to rounded, and consist of sandstone, shale and quartz. This unit is cut by the fault.

Unit C is a top soil consisting of sand, silt, and clay (20–50 cm thick), and is disturbed by human activity.

Thrust faults are visible in the middle part of trench wall (Fig. 4); the faults strike 050° and dip 10°–15° to southeast. The fault traces cut units A and B, and terminate in the middle part of unit B. Vertical displacement genreated by the fault is approximately 3.3 m, and suggests that the paleoeartquake event on the UF could have been Mw 7.1 using the Eq. (1) of Wells and Coppersmith [29].

$$M = 6.69 + 0.74 \log (MD) \quad (1)$$

where MD is the maximum displacement in trench site.

We sampled charcoals from unit B for C14 AMS dating. The C14 AMS ages are summarized in Table 2. Based on C14 AMS ages, the large paleoearthquake event in this trench might have occurred at *ca.* 4,000 yr BP.

4.3 Paloearthquake investigations of the DBPF

The Ban Had Kang trench traverses the NE–SW DBPF. Linear valley and offset channel are present in Ban Had Kang area (Fig. 2D). The excavated trench was 16 m long, 3.5 m wide, and 3.5 m deep, and the stratigraphy of the trench wall can be described in terms of 4 unconsolidated units; units A to D (excluding faulted shale of the basement rock unit), based on their sedimentological characteristics (Fig. 5). Details of the individual units are described below.

Unit A is an alluvial/colluvial unit consisting mostly of gravel, clay, sand, and silt. Most of the clasts are subangular, and consist of shale and quartz. Gravel size ranges from pebble to cobble. This unit is cut by fault, and the lower part of unit are dragged into the basement rocks. The thickness of the unit ranges from 10–80 cm.

Unit B is an alluvial unit with a thickness of 15 cm–1 m; it consists mainly of light yellowish brown sandy clay and minor amounts of gravel. Most of the clasts are subangular to rounded, and consist of shale and quartz.

Unit C is an alluvial unit comprising yellowish brown sandy clay with small amounts of gravel; its thickness is 50 cm to 1 m. Most of the gravel clasts are of pebble size and consist of shale and quartz.

Unit D is a top soil consisting of dark clay, sand and silt, and is disturbed by human activity, i.e., farming. The unit is *ca.* 20–50 cm thick.

The reverse fault can be observed in the basement rock unit (reddish brown, brown and black shale), and unit A (F in Fig. 5; strike 040°–080° and dip 40° to southeast). The unit B is not cut by fault. Vertical displacement genreated by the fault is approximately 1.7 m, and suggests that the paleoeartquake event on the UF could have been Mw 6.9 using the Eq. (1) of Wells and Coppersmith [29]. We sampled charcoals from units A–D for C14 AMS dating to constrain the depositional ages of those units, and the timing of faulting. The C14 AMS ages are summarized in Table 2. Based on C14 AMS ages, the last large paleoearthquake event in this trench might have occurred at *ca.* 3,000 yr BP.

5. Paleoearthquake events and slip rate of sinistral active faults in northern parts of Thailand and Laos

5.1 Paleoearthquake events and slip rate of the MCF

Based on the results of this study (see details in paleoearthquake investigation) and previous trenching studies [30,31,32,33,34], eight paleoearthquake events have been identified along the MCF. Approximate ages of the paleoearthquake events are: (1) 20,000 yr BP; (2) 10,000 yr BP; (3) 8,000 yr BP; (4) 7,000 yr BP; (5) 4,000 yr BP; (6) 3,000 yr BP; (7) 1,500 yr BP, and (8) 900 yr BP. We inferred that the recurrence interval (RI) of seismic events on the MCF is between 1,000 and 3,000 years, based on the 2nd–7th events (see discussion). For slip rate estimate, a set of stream incised into 20–30 Ka alluvial sediments are offset at least 25 m at Ban Pong Pa Kham site, however, the best displacement on this fault can be observed at Ban Pang Sa to the east of Ban Pong Pa Kham trench, 17,500 years ago with 24.5 m displacement of terraces and debris flows, dated largely by cosmogenic isotopic techniques, and yield a slip rate of ~1.4 mm/yr.

5.2 Paleoearthquake events and slip rate of the UF and DBPF

Based on the results of this study (see details in paleoearthquake investigation) and previous trenching studies [35], at least six ground-rupturing earthquakes along the DBPF including the UF have been identified, preliminary approximate ages of the paleoearthquake events are: (1) 10,000 yr BP; (2) 7,000 yr BP; (3) 4,000 yr BP; (4) 3,000 yr BP; and (5) 2,000 yr BP; and (6) 1,000 yr BP. It is possible that the RI of seismic events on the DBPF in Thailand and Laos is 1,000–3,000 years. The vertical displacement with 3.3 m in Ban Nong Heo trench wall suggests that this is possible to be a minimum slip on the UF. Thus, we estimate a slip rate of the UF and DBPF based on lateral offset of channel, yield ~0.19–0.21 mm/yr.

6. Discussion and conclusions

Based on the timing of earthquake events of the MCF, it seems likely that the RI of seismic events on the MCF ranges from 600 to 3,000 years; this RI has been considered since Holocene. Unfortunately, we lack C14 ages at the upper part of faulted sediment unit in the Ban Pa Tueang trench; this age is useful to constrain the eight faulting event, it is possible that the latest movement of MCF might have occurred younger than 900 years (it might possibly have occurred *ca.* 500 yr BP). Thus, we inferred that the RI of seismic events on the MCF is between 1,000 and 3,000 years. To the east of the MCF, it seems that some evidences of large earthquake occurred as shown in the historical record, the ancient city named Wiang Yonok Nakhon established in the legendary 4th century, an early Lanna (Thai) Kingdom in Chiang Rai, possibly located in Wiang Nong Lom swampy area. During the AD 460, there was great flood, then, the Wiang Yonok Nakhon was submerged. All resident, except one old widow passed away. The submergence of this city is thought to be caused by the great earthquake. According to the 7th large earthquake from this study (1,500 yr BP), it is inferred that this event is possibly cause a submergence of the Wiang Yonok Nakhon.

Maximum slip rates of sinistral active faults are inferred from sinistral offsets with hypothese of reactivation on the faults since 5 Ma. Slip rate of NMF is 2.4–2.6 mm/yr, and that of MCF is 0.3–1.0 mm/yr [19, 36, 37]. To farther south, slip rate of UF in Uttaradit and DBPF in southwest of Luang Prabang, Laos ranges between 0.2–0.8 mm/yr [35,38,39], however, this value changes to 2.4–2.5 mm/yr when the DBPF locates in Vietnam [19,40], implying the fault segments in northeastern portion of the DBPF is more active than those in southwestern portion in Luang Prabang and Uttaradit. In 2003, slip rate of the MCF was estimated again by total offset of youngest geomorphic feature or stratigraphic unit divided by its relative age, and range between 0.3 and 3.0 mm/yr [41]; the author noted that the uncertainties on these slip rates are at least ± 50%. In term of Global Positioning System (GPS) velocity fields, slip rate of the DBPF observed from Luang Prabang, northwest Vietnam and south China is about 2 to 3 mm/yr [19, 40]. Unfortunately, no GPS velocity data cross the NMF, MCF and UF. It seems that the geological slip rates of sinistral active faults in Shan Plateau are declined southeastwards to Indochina region; however, the author noted that the slip rate of DBPF in Lung Prabang, northwest Vietnam and south China is increased [19]. It is possible that slip rate of the MCF should be less than those of NMF and DBPF in Vietnam, and more than those of UF and DBPF in southwest of Luang Prabang. We estimated slip rate of the MCF that is to be 1.4 mm/yr, and also slip rate of the UF is about 0.19–0.21 mm/yr that these slip rate values are reasonable and consistent with slip rate estimated from recent studies [30,31,35,42].

Our study revealed young Quaternary sediments showing evidence of at least eight ground-rupturing earthquakes along the MCF, based on C14 AMS, OSL, and TL ages. Approximate ages of the paleoearthquake events are: (1) 20,000 yr BP; (2) 10,000 yr BP; (3) 8,000 yr BP; (4) 7,000 yr BP; (5) 4,000 yr BP; (6) 3,000 yr BP; (7) 1,500 yr BP, and (8) 900 yr BP. This RI has been considered since Holocene. Unfortunately, we lack C14 ages at the upper part of faulted sediment unit in the Ban Pa Tueang trench; this age is useful to constrain the eight faulting event, it is possible that the latest movement of MCF might have occurred younger than 900 years (it might possibly have occurred *ca.* 500 yr BP). Thus, we infer that the RI of seismic events on the MCF is between 1,000 and 3,000 years. Terraces and debris flows offset from a few meters to a kilometer, dated largely by cosmogenic isotopic techniques, and yield a slip rate of ~1.4 mm/yr. For the UF and DBPF, trenching data from Uattradit and Laos revealed young Quaternary sediments containing evidence for at least six ground-rupturing earthquakes along the fault. Based on C14 AMS and TL ages, approximate ages of the paleoearthquake events are: (1) 10,000 yr BP; (2) 7,000 yr BP; (3) 4,000 yr BP; (4) 3,000 yr BP; and (5) 2,000 yr BP; and (6) 1,000 yr BP. It is, therefore, considered that the RI of seismic events on the DBPF in Thailand and Laos is 1,000–3,000 years. The largest paleoearthquake event has been identified from trenching at Ban Nong Heo; with a vertical displacement of 3.3 m indicating the paleoeartquake event occurred by the movement on the UF that could have been Mw 7.1. We estimated slip rate the UF is ~0.19–0.21 mm/yr. Thus, we strongly believe that the MCF, UF and DBPF are still active; these data suggest that the Indochina region will be subject to moderate to large earthquakes in the near future.

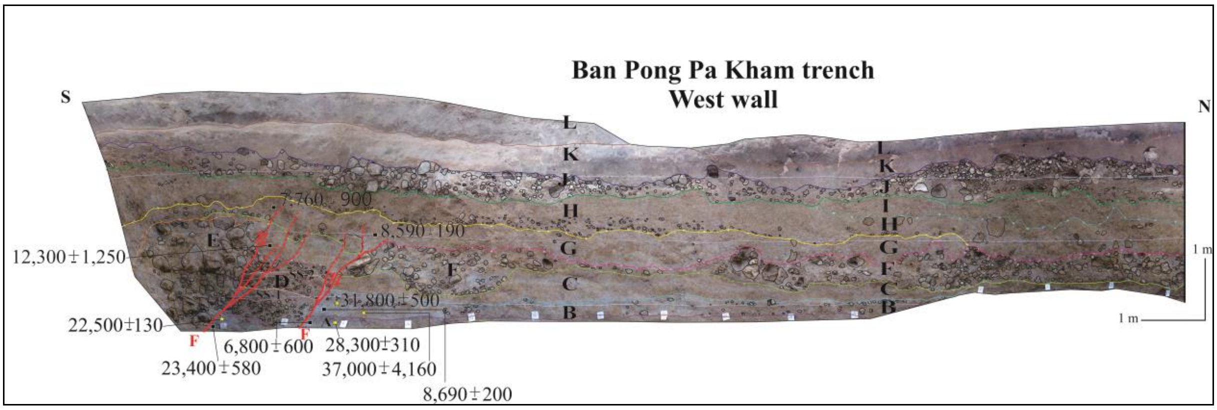


Fig. 3–Stratigraphic units and ages of the Quaternary sediments along the west wall of the Pong Pa Kham trench. Fault identified in the trench wall is F. The location of the trench wall is shown in Fig.1. Unit A: alluvial unit; Unit B: alluvial unit; Unit C: alluvial unit; Unit D: alluvial/colluvial unit; Unit E: colluvial unit; Unit F: colluvial unit; Unit G: alluvial unit; Unit H: alluviall unit; Unit I: alluvial/colluvial unit; Unit J: colluvial unit; Unit K: alluvial unit; and Unit L: top soil. Yellow star represents C14 ages and black square represents OSL ages.

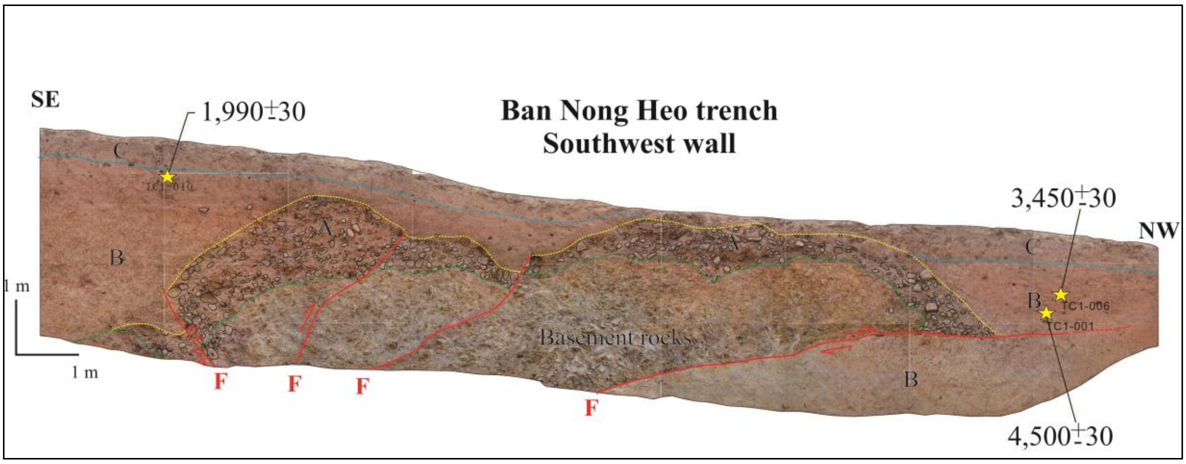


Fig. 4–Stratigraphic units and ages of the Quaternary sediments along the southwest wall of the Nong Heo trench. Fault identified in the trench wall is F. The location of the trench wall is shown in Fig.1. Unit A: alluvial unit; Unit B: alluvial unit; and Unit C: top soil. Yellow star represents C14 ages.

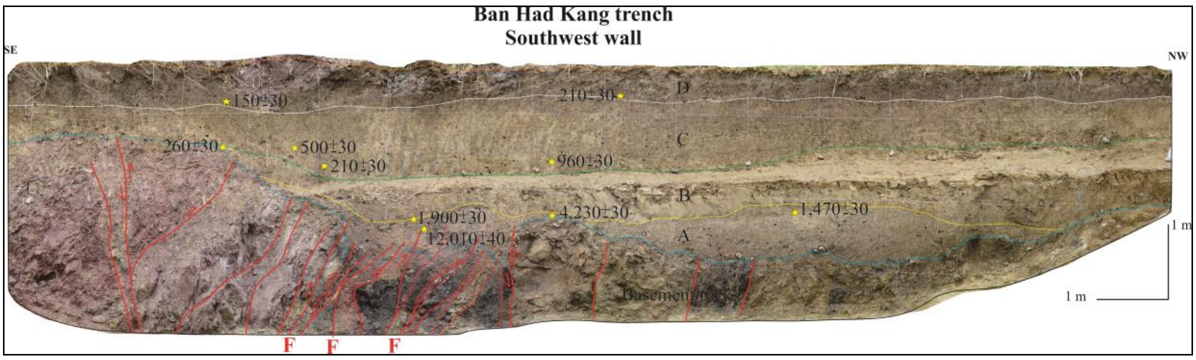


Fig. 5–Stratigraphic units and ages of the Quaternary sediments along the southwestwest wall of the Ban Had Kang trench. Fault identified in the trench wall is F. The location of the trench wall is shown in Fig.1. Unit A: alluvial/colluvial unit; Unit B: alluvial unit; Unit C: alluvial unit; and Unit D: top soil. Yellow star represents C14 ages.

Table 1- OSL dating results for quartz concentrates from sediment samples collected from Ban Pong Pa Kham, Mae Chan, Chiang Rai, northern Thailand.

Sample	W (%)	Cosmic ray dose (Gy)	Rb (ppm)	U (ppm)	Th (ppm)	K (%)	AD (Gy/ka)	ED (Gy)	Age (ka)	Error (Yr)
PPK-02	1.11	0.18	441	18.49	60.66	4.76	10.50	81.49	7.76	900
PPK-03	1.59	0.18	450	5.13	31.11	4.01	5.02	61.93	12.300	1,250
PPK-04	0.54	0.18	462	14.38	46.20	5.94	8.93	209.25	23.40	580
PPK-05	1.87	0.18	467	17.79	53.61	4.77	9.75	83.83	8.59	190
PPK-08	2.24	0.18	433	18.41	58.44	5.05	10.22	88.84	8.69	200
PKK-09	1.28	0.18	460	19.99	71.70	5.53	11.88	80.97	6.80	600

Remarks Age (ka) = Equivalent dose or ED (Gy)/Annual dose or AD (Gy/ka); the ED is the radiation dose, measured in the laboratory, which has been received by the sediment since some resetting event. The AD is the radiation rate of the radioactive isotope per year. Gray (Gy) is the SI unit of the absorbed radiation.

Table 2- Result of AMS radiocarbon dating (C-14) of charcoal from Ban Pong Pa Kham, Mae Chan, Bang Nong Heo, Uttaradit, Thailand, and Had Kang, Luang Prabang, Laos.

No.	Sample	$d^{13}C$	C14 age (Yr)	Error(Yr)
1	PPK-C6	-25	22,500	130
2	PPK-C11	-	28,300	310
3	PPK-C12	-25	37,000	4160
4	PPK-C13	-26.03	31,800	500
5	TC1-001	-25.2	4,500	30
6	TC1-006	-27.5	3,450	30
7	TC1-010	-26.2	1,990	30
8	TC1-C05	-20.4	4,230	30
9	TC1-C06	-20.6	12,010	40
10	TC1-C07	-25.7	1,470	30
11	TC1-C08	-12.7	260	30
12	TC1-C10	-26.6	150	30
13	TC1-C11	-25.8	1,900	30
14	TC1-C12	-23.9	210	30
15	TC1-C13	-28.0	500	30
16	TC1-C14	-27.7	960	30
17	TC1-C15	-26.9	210	30

7. References

[1] Thailand Meteorological Department (2019): Earthquake statistics of Thailand, available at http://www.seismology.tmd.go.th (in Thai).

[2] United States Geological Survey (2007): Earthquake Data Base, available at https://earthquake.usgs.gov/eqcenter/recenteqsww /Quakes/us2007ckan.php

[3] United States Geological Survey (2011): Earthquake Data Base, available at https://web.archive.org/web/20110630101620 /http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/usc0002aes.php#details.

[4] United States Geological Survey (2014): Earthquake Data Base, available at https://earthquake.usgs.gov/earthquakes/eventpage /usb000qack/executive.

[5] Department of Disaster Prevention and Mitigation (Chiang Rai province office) (2014): The report of the damage from the M 6.3 Chiang Rai earthquake, available at http://www.dmpccr.wordpress.com (in Thai).

[6] United States Geological Survey (2019): Earthquake Data Base, available at https://earthquake.usgs.gov/earthquakes /eventpage /us70006ara/executive.

[7] Morley CK (2007): Variations in Late Cenozoic-Recent strike slip and oblique- extensional geometries, within Indochina: The influence of pre-existing fabrics. *Journal of Structural Geology*, **29**, 36–58.

[8] Morley CK, Charusiri, P, Watkinson IK (2011) Structural geology of Thailand during the Cenozoic. I*n The Geology of Thailand*, eds. Ridd MF, Barber AJ, Crow MJ (The Geological Society, London), 273–334.

[9] Reading HG (1980): Characteristics and recognition of strike-slip fault system. *Special* Publications *of the* International Association *of Sedimentologists*, **4**, 7–26.

[10] Packham G 1996: Cenozoic SE Asia: reconstructing, its aggregation and reorganization. In: Hall R &Blundell DJ (eds) Tectonic Evolution of Southeast Asia. *Geological Society, London, Special Publication*, 106, 123-152.

[11] Tapponnier P, Lacassin R, Leloup PH, Schärer U, Zhong Dalai, Liu Xiaohan, Ji Shaocheng, Zhang Lianshang, and Zhong Jiayou (1990): The Ailao Shan/Red River metamorphic belt: Tertiary leftlateral shear between Indochina and South China. *Nature*, **343**, 431–437.

[12] Schärer U, Zhang Lian-Sheng, Tapponnier, P (1994): Duration of strike-slip movements in large shear zones: The Red River belt, China. *Earth and Planetary Science Letters*, **126**, 379–397.

[13] Leloup PH, Lacassin R, Tapponnier P, Zhong Dalai, Liu Xiaohan, Zhang Lianshang, Ji Shaocheng, Phan Trong Trinh (1995): The Ailao Shan–Red River shear zone (Yunnan, China), Tertiary transform boundary of Indochina. *Tectonophysics*, **251**, 3–84.

[14] Hall R, (1996): Reconstructing Cenozoic SE Asia. In: Hall R & Blundell OJ (eds) Tectonic Evolution of Southeast Asia. *Geological Society, London, Special Publication*, **106**, 153-184.

[15] Lacassin R, Hinthong C, Siribhakdi K, Chauviroj S, Charoenravat A, Maluski H, Leloup PH, Tapponnier P (1997): Tertiary diachronic extrusion and deformation of western Indochina: Structure and $^{40}Ar/^{39}Ar$ evidence from NW Thailand. *Journal of Geophysical Research*, **102** (5), 10013–10037.

[16] Srisuwan P (2002): Structural and sedimentological evolution of the Phrae basin, northern Thailand. *Ph.D. thesis, Department of Geology, Royal Holloway, University of London.*

[17] Ducrocq S, Buffetaut E, Buffetaut-Tong H, Chimanee Y, Jaeger JJ, Lacassin R, Suteethorn V (1992): Tertiary continental basins of Thailand as a result of strike-slip motions induced by the India-Asia collision. *Journal* of *Southeast Asian Earth Sciences*, **7**, 260.

[18] Charusiri P, Rhodes BP, Saithong P, Kosuwan S, Pailoplee S, Wiwegwin W, Daorerk V, Hinthong C, Klaipongpan S (2007): Regional tectonic setting and seismicity of Thailand with reference to reservoir construction," *Int. Conf. Geology of Thailand: Towards Sustainable Development and Sufficiency Economy (GEOTHAI'07)*, Bangkok, Thailand, pp. 274–287.

[19] Shi X, Wang Y, Sieh K, Weldon R, Feng L, Chan CH, Liu-Zeng J (2018): Fault slip and GPS velocities across the Shan Plateau define a curved southwestward crustal motion around the eastern Himalayan syntaxis. *Journal of Geophysical Research: Solid Earth*, **123**, 2502–2518. https://doi.org/10.1002/ 2017JB015206.

[20] Pailoplee S, Channarong P, Chutakositkanon V (2013): Earthquake Activities in the Thailand-Laos-Myanmar Border Region: A Statistical Approach. *Terrestrial, Atmospheric and Oceanic Sciences*, **24**, 721–730. doi:10.3319/TAO.2013.04.26.01(T).

[21] Ornthammarath T, Warnitchai P, Worakanchana K, Zaman S, Sigbjörnsson R, Lai CG, (2011): Probabilistic seismic hazard assessment for Thailand. *Bulletin of Earthquake Engineering*, **9**, 367–394.

[22] Earth Observatory of Singapore and Department of Mineral Resources, Thailand (2016): Active fault data of SE Asia.

[23] Department of Mineral Resources, Thailand (2019): Active fault map of Thailand.

[24] Nutalaya P, Sodsri S, Arnold EP (1985): Series on seismology Vol. II – Thailand. *Technical report*, Southeast Asia Association of Seismology and Earthquake Engineering Project, USGS.

[25] Pailoplee S (2012): *Soft Quake*. Chulalongkorn University Printing House, 206.

[26] Fenton CH, Charusiri P, Wood S H (2003): Recent paleoseismic investigations in northern and western Thailand. *Annual of Geophysic*, **46** (5), 957–981.

[27] Wiwegwin W, Junpangngern J, Hinsaeng P, Weldon R, Weldon E, Kosuwan S, Xuhua S, Phumsonklin R (2018): Did the movement on the Mae Chan Fault generate the legendary AD 460 earthquake and cause the submergence of the ancient city of Wiang Yonok Nakhon, Chiang Rai, northern Thailand?, *15th Regional congress on geology, mineral and geology resources of Southeast Asia*, Hanoi, Vietnam.

[28] Wood SH, Singharajwarapan FS, Bundarnsin T, Rothwell E (2004): Mae Sai basin and Wiang Nong Lom: Radiocarbon dating and relation to active strike-slip Mae Chan Fault, northern Thailand. *International conference on applied geophysics*, Chiang Mai, Thailand.

[29] Wells DL, Coppersmith KJ (1994): New empirical relationships among magnitude, rupture length, rupture area, and surface rupture displacement. *Bulletin of the Seismological Society of America*, **84**, 974–1002.

[30] Weldon E, Weldon R, Xuhua Sh, Wiwegwin W, Lewis O, Kosuwan S, Muangnoicharoen N, Kanjanapayont P, Rymer M, Punyawai W, Prentice C, Treerotchananon A, Min, S, Khaing SN, Wood S (2016): The left-lateral Mae Chan Fault, southern Shan plateau, northern Thailand; new constraints on slip rate and recency of large earthquakes. *13th Annual meeting Asia Oceania Geosciences Society*, 31 July-5August 2016, Beijing, China

[31] Wiwegwin W, Weldon R, Weldon EM, Junpangngern J, Kosuwan S, Phumsonklin R, Hinsaeng P, Xuhua S (2019): Evidence of large paleoearthquakes generated by the Mae Chan Fault, Chiang Rai, Northern Thailand. *Advances in Seismic Hazard Assessment through Paleoseismic and Tectonic Geomorphic Fault Studies: In Honor of Ray J. Weldon II, for His Career and Contributions to the Field (Posters), Geological Society of America*, **51**, No. 4, ISSN 0016-7592, doi: 10.1130/abs/2019CD-328972

[32] Department of Mineral Resources (2009): Investigation on recurrence interval in areas showing trace of movement along the faults in the Chiang Rai, Chiang Mai and Phayao provinces (Mae Chan and Phayao Faults). *Technical Report*, Environmental Geology Division, Department of Mineral Resources, Thailand (in Thai).

[33] Kosuwan S. Saithong P, Lumjuan, A (2003): Paleoearthquake on the Mae Ai segment of the Mae Chan Fault Zone, Chiang Mai, northern Thailand. *Technical Report*, Geological Survey Division, Department of Mineral Resources (in Thai with English abstract).

[34] Kosuwan S, Saithong P, Lumjuan A, Takashima I, Charusiri P (1999): Preliminary results of studies on the Mae Ai segment of the Mae Chan Fault Zone, Chiang Mai, northern Thailand. *The CCOP Meeting on Exodynamic Geohazards in East and Southeast Asia*, Pattaya, Thailand, pp. 1–8.

[35] Department of Mineral Resources (2011): Investigation on recurrence interval in areas showing trace of movement along the faults in the Uttaradit, Nan, Phitsanulok and Sukhothai provinces (Uttaradit and Phua Faults). *Technical Report*, Environmental Geology Division, Department of Mineral Resources, Thailand (in Thai).

[36] Lacassin R, Replumaz A, Leloup PH (1998) Hairpin river loops and slip-sense inversion on Southeast Asia strike-slip faults. *Geology*, **26**, 703–706.

[37] Wang Y (2013): Earthquake geology of Myanmar. *Ph.D. thesis*, California Institute of Technology, USA

[38] Nualkhao P, Charusiri P, Sutiwanich C, Pailoplee S (2016): Paleoearthquakes along Xaignabouli Fault Zone in Western Lao PDR. *Bulletin of Earth science of Thailand*, **7** (1),25-32.

[39] Gianguo Z (2019). Personal communication.

[40] Kuang-Yin L, Yue-Gau C, Doãn Đinh Lâm (2010): Insight of the reactivated Dien Bien Phu fault, northwest Vietnam: Implication of the kinematics in north Indochina. *Geophysical Research Abstracts*, **12**, EGU 2010-7519,

[41] Fenton CH, Charusiri P, Wood SH (2003): Recent paleoseismic investigations in northern and western Thailand. *Annals of Geophysics*, **46** (5), 957–981.

[42] Elizabeth RC, Weldon R, Wiwegwin W, Weldon E (2017): Paleoseismology of Sinistral-Slip Fault System, Focusing on the Mae Chan Fault, on the Shan Plateau, SE Asia. *AGU fall meeting 2017*, New Orleans, USA, 11-15 December 2017.

