Bulletin of Earth Sciences of Thailand

Active fault and seismic zonation in Thailand: An empirical compilation

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Received: 28 Aug 2021
Revised: 7 Feb 2022
Accepted: 14 Feb 2022

Abstract

Thailand has long been recognized as having a low seismicity, even though more than 4,300 small-to-moderate (M_w > 2.0) earthquakes have been detected within and nearby the country. Recent fault activity in Thailand is linked to extrusion tectonics caused by the India-Asia collision during mid-Tertiary time. The fault activity is mainly related to basin flanks in northern Thailand. In order to determine the relative seismic risk of the faults, we apply field, geomorphic, remote-sensing, geochronological, and seismic based evidence. This study concludes five seismically active belts (SABs) in Thailand: the Northern Shan-Thai SAB to the west-northwest, the Central Shan-Thai SAB in northern peninsular Thailand, the Southern Shan-Thai SAB in southern peninsular Thailand, the Lampang-Chiang Rai SAB in the north and the Nakhon Thai SAB in eastern-northeastern Thailand.

Most of the faults in the Central Shan-Thai, Southern Shan-Thai, and Northeastern SABs are inferred as probably and possibly active faults. Many of the faults within the Northern Shan-Thai and Central Shan-Thai SABs are regarded as active faults. Exceptions are the Mae Tha, Nam Pat and Pha Yao faults in northern Thailand. They are ranked as possibly active faults due to their subdued morphology and eroded scarps. We estimate that many of the active faults in Thailand had paleo-earthquakes with magnitudes between 6 and 7 on the Richter scale and have slip rates of between 0.5 and 2.2 mm/yr. Based on the geochronological data, we also estimate that the youngest slip is found in Mae Chan fault with an age of about 1,200 yrs. In this study, we present a new seismic zonation map of Thailand based upon ranking of and present-day seismicity.

Keywords: Thailand, Active Fault, Earthquake, Thermoluminescence Dating, Seismic Zonation

1. Introduction

Recent seismic activity in Thailand, including large, widely felt earthquakes in 1983 (Baoqi and Renfa, 1990) and 2004 (Stein and Okal, 2005), have underscored the lack of attention paid to earthquake hazards in Thailand. Following the installment of the world-wide seismograph network in 1963, more than 1,500 earthquake events with a moment magnitude (Mw) of > 5.0 have been detected in and around Thailand (Figure 1). With the exception of the 2004 Indonesian mega-thrust earthquake (Stein and Okal, 2005) and the 1015 Chiang Saen earthquakes (Penth, 2006), Thailand's earthquakes have been moderate enough to keep earthquake hazards off the public's radar screen. However, strong earthquakes in the neighboring countries (e.g., Myanmar, Laos and southern China) are frequent enough, suggesting that future destructive earthquakes that this map will be used as a basis for future seismic hazard education. could occur in Thailand. For example, the most destructive inland earthquake ever recorded in Southeast Asia occurred in northern Myanmar on 5th May, 1930. With a M_w of 7.3, this tremor almost entirely destroyed Pegu township and more than five hundred people were injured or killed (Brown and Leicester, 1933). The two large submarine earthquakes affecting Thailand took place on 26th June, 1941 and 24th December, 2004 in the Andaman Sea with M_w of 8.1 and 9.3 (Stein and Okal, 2005), respectively.

In this report, we critically review recent geological, geochronological, geomorphic, and seismological data related to the earthquake hazards of Thailand. These data were then applied to classify the status of

Thailand's known faults and to construct a seismic zonation map of Thailand. We hope that this map will be used as a basis for future seismic hazard education.

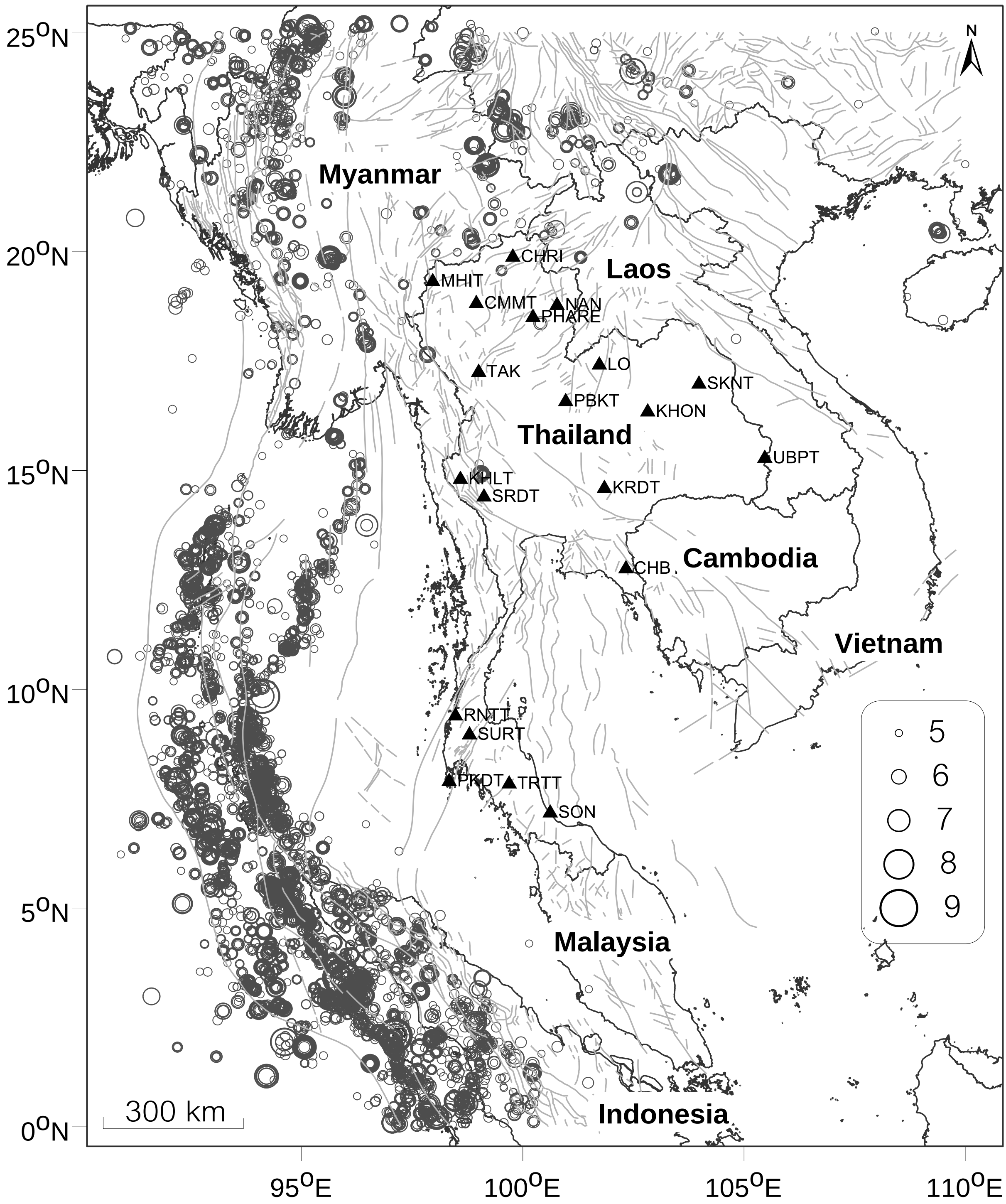

Figure 1. Map of mainland SE Asia showing the distributions of the earthquakes with a M_w of > 5.0 from the IRIS earthquake catalogue. The inland fault traces are interpreted from NOAA-11 satellite image, including fault traces data in the Andaman Sea from Hutchison (1989) and Curray (2005). The triangular symbols represent the location

of the existing seismograph stations, abbreviated as: Chiang Rai (CHRI), Phrae (PHARE), Nan (NAN), Tak (TAK), Loei (LO), Petchabun (PBKT), Sakon Nakorn (SKNT), Khon Kean (KHON), Ubon Ratchathani (UBPT), Nakhon Rachisma (KRDT), Chonburi (CHB), Washiralongkorn Dam (KHLT), Srinakarin Dam (SRDT), Ranong (RNTT), Suratthani (SURT), Phuket (PKDT), Trang (TRTT) and Songkhla (SON).

2. Seismic Station

In 1963, the first WWSSN (Worldwide Standardized Seismic Network) station was set up in Chiang Mai (CMMT in Figure 1), northern Thailand, by the Geophysics Subdivision of the Weather Forecasting Division, Meteorological Department of Thailand (TMD), followed by short-period, vertical component and long-period three-component seismographs in Songkhla (SON in Figure 1), southern Thailand in 1965 (Prachaub and Wetchbunthung, 1992).

Following a moderate earthquake in 1975 near Mae Sot in western Thailand, two UNESCO-supported short-period vertical component seismographs were established in Tak and Nakhon Ratchasrima (TAK and KRDT in Figure 1). In order to monitor the seismic activity in the vicinity of new power plants, the Electricity Generating Authority of Thailand (EGAT) and TMD jointly established three additional seismologic stations in western Thailand in 1982. These new stations (i.e., SRDT in Figure 1) were placed in time to capture two m_b 5.9 earthquakes on April 22nd, 1983 near Kanchanaburi, northwestern Thailand (Prachaub, 1996; Klaipongpan et al., 1991). In 1992, the TMD, with the assistance of the US Geological Survey (USGS), installed the computer-linked IRIS II (Incorporated Research Institute for Seismology) seismometer at the bottom of a 100 m deep borehole in Chiang Mai, northern Thailand. In order to extend the ability of the seismic network to monitor earthquakes in northeastern and southern Thailand, two additional stations were installed in Ubonratchathani and Phuket (UBPT and PKDT in Figure 1). At present, there are three broad band and eight short period seismometers authorized by the TMD, and 14 short-period analog stations in Thailand. Additionally, a dozen of strong motion accelerographs (SMA) have been installed at major dam sites.

3. Past Research

The National Earthquake Committee of Thailand (NECT) was established in September 1985 in response to the 1983 Kanchanaburi earthquakes. The major activities of this committee include (1) coordinating with domestic and/or international entities on the exchange of knowledge, information, and opinion, (2) promoting earthquake-related research, (3) proposing measures and strategies for seismic risk mitigation, and (4) distributing knowledge on seismic risk mitigation to the public. The NECT stimulated new research to include the first systematic study on seismicity in Thailand (Natalya et al., 1985). The 1983 earthquakes also stimulated public concern for building safety because no structures in Thailand had ever been designed for seismic safety (Lukkunaprasit, 1994). To comply with the NECT policy, in 1986, Chulalongkorn University and the Department of Public Works set up a network of accelerometers at two buildings in Bangkok to measure accelerations to be used to establish seismically aware building codes (Lukkunaprasit, 1994).

Several studies (e.g., Klaipongpan et al., 1991; Hetrakul et al., 1991; Chang and Chen, 1992; Chung and Liu, 1992; Hinthong, 1995; Charusiri et al., 1996) focusing on the 1983 earthquakes agree that these events were caused by the impoundment of water in the reservoir. Stress from the loading of the reservoir was released along preexisting fault planes. The Kanchanaburi earthquakes stimulated studies of other regions including the Nam Yuam River Basin in the Mae Sariang-Mae Hong Son area in northern

Thailand (Hinthong, 1995).

In 1995, to evaluate seismic hazards in the vicinity of a proposed dam, the Kaeng Sua Ten earthquake project in northern Thailand was granted to the Woodward Clyde Company. That study recognized several active faults throughout northern Thailand (Bott et al., 1997; Fenton et al., 1997, 2003). Recently, the Department of Mineral Resources, Bangkok, Thailand (DMR), in conjunction with Akita University (Japan) and Chulalongkorn University (Thailand), undertook three projects to delineate and characterize active faults using detailed remote-sensing and ground surveys together with trenching and Thermoluminescence (TL) dating methods in the Chiang Rai, Kanchanaburi and Lampang-Phrae provinces (Nuttee et al., 2005, Udchachon et al., 2005; Pailoplee, et al., 2009a).

Siribhakdi (1988) made the first and only attempt to define the seismogenic zones of Thailand. Several years later, Hinthong (1995) compiled an unpublished seismic risk map of Thailand, followed by Warnitchai and Lisantono (1996) who compiled the first seismic risk map for Thailand using probabilistic acceleration analysis. New geologic studies published during the last 10 yrs suggest that the time is ripe for a reevaluation of Thailand's seismic zones. Accordingly, Pailoplee et al. (2009b, 2010b) proposed new seismic hazard maps in Thailand and surrounding regions using seismic source zone (Charusiri et al., 2005) and active fault data for the earthquake source determination.

4. Tectonic Setting and Classification of Active Fault

The assembly of the tectonic framework of Thailand and adjoining regions began with the amalgamation of a diversified set of tectonostratigraphic terranes, including the Shan-Thai or Sibumasu, Lampang-Chiang Rai, Nakhon Thai, and Indochina terranes (Charusiri et al., 2002). These terranes evolved from pre-Mesozoic crustal blocks with some Mesozoic-Cenozoic modifications of the bounding and internal structures. The collision of India with Asia during the mid-Tertiary, and the related escape tectonic structures (Morley, 2004), caused the strike-slip motion of the Indochina block with respect to the Cartesian block. Major faults related to this collision are characterized by large-scale strike-slip movement. Extension related to the escape of the Indochina block result in the opening of Gulf of Thailand (Bunopas, 1992; Morley et al., 2004; Michael et al., 2010), South China Sea (Hutchison, 1989), Andaman Sea (Metcalfe, 2011) and East Vietnam Sea (Michael et al., 2009). Continuing activity related to escape tectonics, perhaps, accounts for the SE Asia's present-day earthquakes, active faulting, magmatism and geothermal activities (Charusiri et al., 1996, 2000, 2002; Morley et al., 2004).

Figure 1 shows the major fault traces of Thailand and nearby regions as interpreted from the NOAA-11 satellite image data and the data for the Gulf of Thailand and the Andaman Sea, which was modified from that of Hutchison (1989) and Curray (2005). It has been suggested that there are several sets of faults of various ages (Charusiri et al., 2002) and slip-directions (Morley, 2004) in Thailand and mainland SE Asia. These faults can be classified as either active or inactive. Debate about the classification of active faults mainly hinges on how far back in time the word "active" indicates, with no current consensus (Lee et al., 2006). Slemmons and de Polo (1986) listed several criteria to use in deciding if a fault is active: the fault is always associated with earthquakes, exhibits geomorphic evidence of recent activity, shows offset during the present seismotectonic regime and the fault has the potential for future slip. Masuda and Kinugasa (1991) suggested that an active fault is one which displays evidence of a repeated movement in recent geologic times. Thus, it seems essential that the age of a fault's last movement is necessary in identifying a fault as active.

The distribution of epicenters

confirms that seismicity in Thailand is diffusely distributed and occurs in an intra-plate setting. Earthquake epicenters are largely associated with known major faults, but others, particularly in northern Thailand, are not located along known fault traces (Fenton et al., 1997; Bott et al., 1997). This may be due to the large uncertainties in locating epicenters of small or moderate-sized earthquakes or may also be the result of deeper hypocenters (15 to 20 km depth) representing background earthquakes that occur on buried faults without any surface expression (De Polo, 1994; Bott et al., 1997).

For Thailand, we identify the active faults based on geologic, geochronological, and seismologic data (Table 1). Since the seismic activity in Thailand is low compared to neighboring countries, such as Myanmar, we have chosen definitions based on what works best for Thailand. Because of the large uncertainties in the ages of slip for many faults, we have chosen to broaden the definition of an active fault by Hart (1977) as one with Holocene slip to include faults with late Pleistocene (<35,000 yrs) slip (Fraser, 2001).

Table 2 summarizes the classification of faults in Thailand, which is primarily based on the age of the last slip. For many faults, the age is inferred from geomorphology or other indirect methods. In this classification, a fault with slip movement during the last 35,000 yrs, or a fault that shows evidence for multiple slip events during the last 100,000 yrs, is classified as active. A fault with slip movement during the last 100,000 yrs is classified as probably active. If the slip movement is younger than 500,000 yrs (but older than 100,000 yrs), the fault is possibly active. Finally, a fault with slip older than 500,000 yrs is herein classified as inactive.

5. Dating of Active Fault

The recognition of active faults in Thailand adopted herein requires geologic, historic and/or seismologic criteria similar to those adopted by Slemmons (1982), Masuda and Kinugasa (1991) and McCalpin (1995). Commonly used methods for identifying active faults include geologic, remote-sensing, geophysical and exploratory methods (Slemmons and Depolo, 1986). Several methods for dating fault slips are currently in wide use (Ikeya, 1993; McCalpin, 1995), but among these, C-14 and thermo-/optical-luminescence (TL) methods are the most widely used and accepted approaches (Forman et al., 1991; Hiraka and Nagamoto, 1995; Humphil-Haley et al., 2000; Fattahi et al., 2006). The C-14 method is applicable when the samples contain appropriate amounts of carbonaceous materials, whilst the TL dating technique has been proven to be suitable for dating fault movement using samples from the fault gouge (Forman et al., 1991; Ding and Lai, 1997), fault-related colluvium (Personius and Mahan, 2000; Rhodes et al., 2004) and alluvium (Porat et al., 1996; Bachmanov et al., 2004). However, it is important to note that the issue of zero setting has not been addressed for the TL dating of fault gouge in Thailand. Therefore, great care has to be taken in selecting suitable sample size ranges and the interpretation of the fault movements (Wintle and Murray, 1999; Zander et al., 2000; Sanderson et al., 2001).

Here we use TL dating to estimate the timing of the fault slips throughout northern and western Thailand. We use this method in four situations: (1) rare situations where the fault gouge is exposed and can be directly sampled and dated, (2) sites with offset sediment where the depositions age of the sediment can constrain a maximum age for the slip; (3) sites with scarp-derived colluvium; and (4) sites where uniformed sediment overlies a fault zone resulting in the derivation of the minimum age of the slip. All dates were obtained from >90% purified quartz concentrates extracted from bulk samples, using quartz grains with a size range of 0.074-0.177 mm. We follow the TL dating method of Takashima and Watanabe (1994). Samples were analyzed at the Geochronological Laboratory Center, Akita University (Hinthong, 1995; Takashima et al., 1999; Won-In, 1999; Nuttee et al., 2005) and at the Quaternary Dating Laboratory, Chulalongkorn University (Pailoplee et al., 2009a, 2010a).

The first attempt to date fault movement in Thailand using TL dating (Maneenai and Takashima, 1994) utilized fault-related colluvium and fault-gouge samples from northern and western Thailand. Subsequent TL dating was reported by Takashima and Maneenai (1995) for samples from fault gouge and fault-related colluvium collected from several nearby fault scarps in southern Thailand. Kosuwan et al. (1998), Udchachon et al. (2005) and Pailoplee et al. (2009a) used the C-14 method to date the Mae Chan, Lampang and Phrae faults in northern Thailand.

6. Active Fault Zone

6.1. Seismically Active Belts (SABs)

Seismic source zones or seismotectonic source zones in Thailand were first introduced by Nutalaya et al. (1985), based upon both seismological and geological evidence. Subsequently, Shrestha (1987) identified nine active faults in Thailand on the bases of topographic maps and seismological data. In the last 15 yrs, new historical, seismological and geologic studies (e.g., Hinthong, 1995; Nutalaya et al., 1985; Maneenai and Takashima, 1994; Takashima and Maneenai, 1995), including the new TL dates shown in Figure 2 and summarized in Table 3, have led to a reevaluation of seismic activity and earthquake hazards in Thailand. In addition to this previous work, we also apply our own analyses of fault activity using remotely sensed imagery and field mapping. Our analyses have focused on primary tectonic geomorphology, such as fault scarps, and secondary tectonic geomorphology, such as offset streams, beheaded streams, sag ponds, triangular facets, shutter and pressure ridges. Using these features, we have ranked the activity of faults based on the criteria outlined in Table 1.

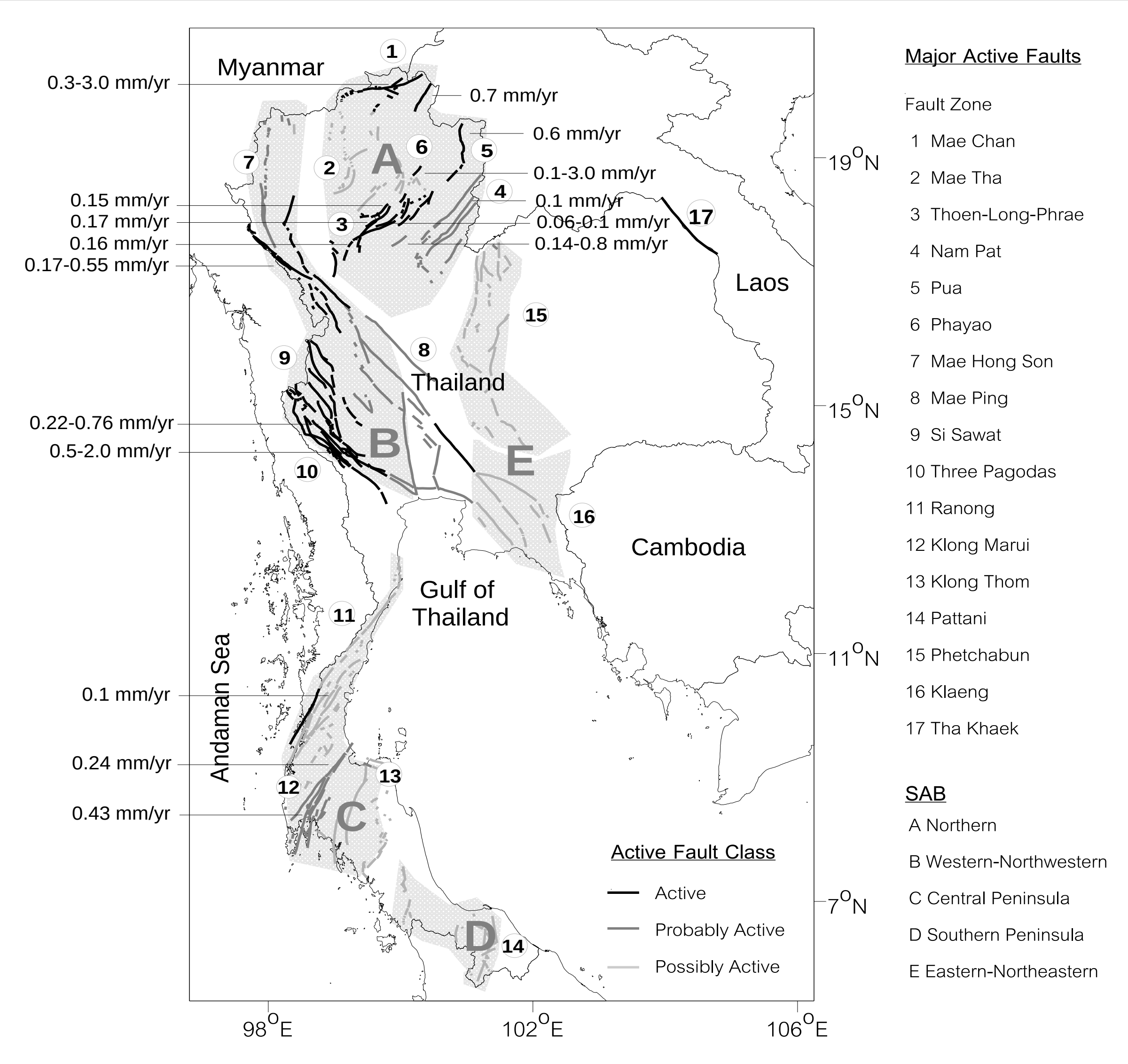

Figure 2. Map of Thailand showing the 17 major active fault zones, active fault class, and the five Seismically Active Belts (SABs), including the slip rate (mm/yr) of each individual fault segment.

Table 1. Active fault rank, criteria and examples in Thailand.

Rank	Historic/Geochronological	Geologic/Geomorphic	Seismologic	Examples
Active	Tectonic fault which displays a history of strong earthquake or surface faulting in the past 35,000 yrs, or a series of quakes during 100,000 yrs, and is expected to occur within a future time span of concern to human society.	Surface faulting, assoc. strong quakes, and geodetic evidence. Young Quaternary deposits cut by fault, distinct youthful geomorphic features.	Epicenters along that fault.	Mae Chan, Phrae, Thoen, Pua
Probably Active	A tectonic fault without historic surface offset, but with a recurrence interval sufficient to human concern, and with an earthquake within 100,000 yrs.	Surface faulting unclear. Subdued and eroded geomorphic features, faults not known to cut young alluviums, but offset older Quaternary deposits.	Alignment of epicenters but with low confidence of assigned locations.	Mae Tha, Mae Hong Son, Srisawat, Three - Pagodas.
Possibly Active	A fault with insufficient data to define its past activity and recurrence interval is relatively very long or poorly defined, or displaying an earthquake within 500,000 yrs.	Data indicate fault evidence, but evidence may not be definitive. Traced clearly by remote-sensing data with some hot springs.	Scarce and low seismicity.	Payao, Nam Pat, Ranong, Klong Marui, Klong Thom, Southern Peninsular.

Table 2. Activity of faults in Thailand based upon age-dating data.

Era	Period	Epoch	Yrs	Fault Activity
Cenozoic	Quaternary	**Holocene**	0	1) Active- if one quake within 35,000 yrs, or several within 100,000 yrs
		Pleistocene	35,000	2) Probably active- if one quake within 100,000 yrs
	Tertiary	**Pliocene**	1,600,000	3) Possibly active - if one quake within 500,000 yrs
		Pre-Pliocene	5,300,000	Inactive fault- if a quake is older than 500,000 yrs
Pre-Cenozoic			> 65,000,000	

Here, we delineate five major "seismically active belts" (SABs) in Thailand (Figure 2). We define an SAB as a linear or an elongate zone of seismicity that is coincident with a major tectonic zone. The five SABs in Thailand are the Lampang-Chiang Rai SAB in the north, Northern Shan-Thai SAB in the west-northwest, Central Shan-Thai SAB in central peninsular Thailand, the Southern Shan-Thai SAB in southern peninsular Thailand and the Nakhon Thai SAB in the east-northeast (Figure 2). Detailed descriptions of the major faults in each SAB and the locations and orientations of the faults with related TL dating data and major instrumental ($M_w \geq 5.0$) earthquakes are illustrated in Figures 1 and 2.

6.2. Lampang-Chiang Rai SAB in Northern Thailand

(i) Mae Chan Fault Zone (MCFZ). The 185 km-long, east-northeast-trending MCFZ (1 in Figure 2) consists of five fault segments ranging from 35 to 55 km in length (Kosuwan et al., 1998, 1999). Field and remote sensing analyses suggest sinistral stream offset of about 550 m in the north of Ban Mae U Sue. Although Shrestha (1987) and Fenton et al. (1997) did not observe any dip-slip, trenching of the fault revealed a significant dip-slip component (Charusiri et al., 2007). TL dating by Takashima et al. (1999) suggests that at least five slip events occurred along this fault between 1.6 and 92 ka. On average, the dip-slip rate obtained from these TL data and measured dip slips recognized in four trenches is about 2.2 mm/yr (Charusiri et al., 2007), lying within the range of 0.3 to 3 mm/yr reported by Fenton et al. (2003) but much higher than the rate in Wood et al. (2001). We also estimated the length of the fault segment using field and Landsat image data. The derived surface rupture length of about 55 km would suggest a paleo-earthquake M_w of about 7, using the method of Wells and Coppersmith (1994). The largest historical earthquake (1 September, 1978) along the Mae Chan fault had a body-wave magnitude (m_b) of 4.0 and a maximum focal depth of about 10 km. Seismological data from the TMD indicate that earthquakes of lower magnitudes also occurred along and in the vicinity of this fault, including at least 10 events greater than m_b 3.0 since 1978, of which three were greater than m_b 4.5. Although Hinthong (1995) categorized this fault as probably active, we agree with Shrestha (1987) that the MCFZ should be classified as active.

(ii) Mae Tha Fault Zone (MTFZ). The 110 km-long MTFZ (2 in Figure 2) forms a distinct S-shaped, roughly north-south-trending lineament east of the Chiang Mai Basin. Takashima and Maneenai (1995) reported TL dates of 0.19 and 0.77 Ma on the fault gouge from this fault. The fault plane has a moderate west to northwest dip and appears to be concave towards the adjacent Chiang Mai basin. Small earthquakes of mostly less than m_b 3.0 have occurred abundantly in the vicinity of the northwestern part of the fault. While its trace is readily apparent on satellite images, closer examination of these images and of topographic maps reveals no compelling geomorphic features, suggesting a youthful slip. Nutalaya et al. (1985) suggested, from analysis of the historical records, that one or more earthquakes up to intensity VII (Rossi Forrel Scale) took place in the MTFZ and this fault was interpreted to be possibly active.

(iii) Mae Kuang Fault (MKF). The MKF (Rhodes et al., 2004) follows the linear Mae Kuang Valley for approximately 30 km through the Mae Tho Range northeast of Chiang Mai, where it cuts Triassic granitic rocks of the Fang-Mae Suai batholith and roof pendants of Paleozoic terranes. Offset contacts and slickenlines on fault surfaces suggest a total sinistral slip of 3.5 km and a dip-slip of 600 m. The fault also offsets three north-flowing tributaries to the Mae Kuang River by 400-700 m. At its southwestern end, the MKF is apparently truncated by the right-lateral MTFZ. Thus, the MKF must have not been younger than the MTFZ.

(iv) Thoen-Long-Phrae Fault Zone (TLPFZ). The arcuate, northeast-trending trace of the TLPFZ (3 in Figure 2) is approximately 120 km long and partly bounds the Phrae and Long basins. This broad fault zone includes several individual fault strands that straddle the Phrae basin. During the past 20 yrs, more than 24 earthquakes with m_b 3.0 to 5.0 occurred in the vicinity of this fault (Bott et al., 1997). On December 22nd and 23rd, 1980, two earthquakes with m_b 4.0 and 3.7 struck the eastern side of the Phrae Basin along the northern end of the TLPFZ. Over the following 3 yrs, several additional m_b 2.5 to 4.0 events occurred in the same general area. Geomorphological evidence, such as linear valleys, offset streams, shutter ridges and triangular facets, suggests fault strands along the western side of the Phrae Basin may be younger than those on the eastern side of the basin and that left-lateral strike-slip predominates. TL dating of the fault-related colluviums suggests Quaternary movement at about 0.16 Ma (Maneenai and Takashima, 1994) and the latest movement at about 2,500 yrs (Udchachon et al., 2005), with a total of four-slip events recorded. Although Hinthong (1995) classified this fault zone as probably active, based on seismic activity and geomorphology, we classify the TLPFZ as active. Using the surface rupture length method of Wells and Coppersmith (1994), Fenton et al. (1997) and Udchachon et al. (2005) suggested that this fault could generate earthquakes up to M_w 7.5. We estimate the short-term slip rate at 0.1 mm/y and the long-term slip rate ranging 0.04 to 0.07 mm/yr.

(v) Nam Pat Fault Zone (NPFZ). Distinct lineaments along the Nan River near Nam Pat District mark the approximately 40 km-long, northeast-trending NPFZ (4 in Figure 2). Satellite images and reconnaissance field work indicate that this fault zone likely extends into northern Laos, where a few earthquakes of M_w 3.0-3.5 have been recorded. Fenton et al. (1997) estimated short-term (Holocene) and long-term (post-Miocene) slip rates to be ca. 0.1 and 0.04 mm/yr, respectively. We calculated a maximum potential earthquake of about M_w 7.0 using the surface rupture length method (Wells and Coppersmith, 1994). However, since the geomorphology suggests pre-Quaternary slip and since the section of this ault zone in Thailand is seismically quiet, we classify the NPFZ as probably active.

(vi) Pua Fault (PF). The approximately 70 km-long, north-trending PF (5 in Figure 2) is a high-angle west-dipping oblique normal fault (Kaovisate, 2007). A very prominent linear escarpment marks its northern segment. Along the central segment of the fault, a well-developed range-front wine-glass canyon marks the mouth of the Nam Khun Valley, near Baan Santisuk village (Fenton et al., 1997). In 1934 and 1935, two m_b 7.0 earthquakes straddled the Laos-Thailand border near the trace of the PF (Bott et al., 1997). Fenton et al. (1997) estimated short- and long-term slip rates of 0.6 and 0.06 mm/yr, with a maximum possible earthquake of M_w 7.3. More recently, Kaovisate (2007) reported TL and electron spin resonance (ESR) derived dates of the sediments offset by the fault. He concluded that the most probable last movement on the PF occurred about 2,800 yrs ago (Table 3). Based on surface-rupture length-analysis, the maximum paleo-earthquake magnitude was M_w 7.0 Kaovisate (2007) also estimated slip rates along the PF of 75 mm/yr, in agreement to Fenton et al. (1997) estimates. Based on geomorphology and the documented late-Pleistocene slip, we classify the PF as active.

(vii) Phayao Fault (PyF). The more than 35 km-long, north-northwest-trending PyF (6.0 in Figure 2) is clearly visible as a sharp lineament on satellite images. However, in spite of this sharp lineament, analysis of topographic maps and aerial photos suggests a lack of youthful tectonic landforms along the fault's trace (Figure 3). The fault appears to be a range-front, being probably normal-slip fault flanking the west-side of the Payao Basin. Although the 1994 Phan earthquake (m_b 6.0) occurred near the northern extension of the fault, the lack of clear evidence of young slip and the lack of paleo-earthquake data make classification of this fault problematical. Paleo-earthquake data along this fault would aid in determining its age. Until additional data become available, we classify the PyF as possibly active.

Table 3. Summary of the fault age dating adopted in this report.

No.	Fault Name	Fault Segments	SRL	Mw	Age of movements (kyr)	Age of most recent movement (kyr)	Slip Rate (mm/yr)	Recurrence (kyr)	References
1.	Mae Chan	Mae Chan	140	7.5	-	Holocence	0.30-3.00	-	Fenton et.al. (2003)
	Mae Chan	Mae Ai	32	6.8	9, 3, 1.5	1.5	0.7	-	Kosuwan et.al. (2003)
2.	Mae Tha		25	6.7	-	Holocence		-	DMR (2006)
3.	Thoen		120	7.5	-	Holocence	0.6	1.7-2.5	Fenton et.al. (2003)
	Thoen	Ban Mai	32	6.9	-	5	0.15	-	Charusiri et.al. (2004)
	Thoen	Ton Ngun	10	6.2	6.2, 1.9	1.9	0.17	-	Pailoplee et al. (2009a)
	Long		56	7.0	-	Late Pleistocence	0.1	-	Fenton et.al. (2003)
	Phrae		59	7.0	-	Late Pleistocence	0.1	12-15	Fenton et.al. (2003)
	Phrae		20	7.0	1,000, 50-170	-	0.06	90	Udchachon et.al. (2005)
	Mae Yom	Mae Yom	25	6.7	8.5, 7, 5.5	5.5	0.14-0.80	-	Charusiri et.al. (2006)
4.	Nam Pat		38	7.0	-	Late Pleistocence	0.1	8.64	Fenton et.al. (2003)
	Nam Pat		18	6.5	-	Holocence	-	-	Kosuwan et.al. (2004)
5.	Pua		68	7.3	-	Holocence	0.6	-	Fenton et al. (2003)
	Pua	Thung Chang	15	6.5	8, 6, 2.8	2.8	-	-	Charusiri et.al. (2006)
6.	Phayao		28	7.0	-	Late Pleistocence	0.1	-	Fenton et.al. (2003)
	Phayao	Wang Nua	70	7.2	-		0.75-3.0	0.25-0.12	Hongjaisee (1999)
7.	Mae Hong Son		68	7.2	-	Holocence	-	-	DMR (2004)
8.	Mae Ping	Khao Mae Song	25	6.7	108, 60, 17	1.7	0.17-0.55	-	Saithong et.al. (2005)
9.	Sri Sawat	Sri Sawat	44	7.0	-	7	-	-	Kosuwan et.al. (2006)
10.	Three Pagodas		350	7.5		Holocence	0.50-2.00	-	Fenton et.al. (2003)
	Three Pagodas	Chao Nen	62	7.2		5-2.2	0.22-0.50	-	Charusiri et.al. (2004)
	Three Pagodas	Chao Nen	14	6.4	43, 30, 5.8, 1.3	1	0.76	-	Kosuwan et.al. (2006)
11.	Ranong	North Section	200	7.7	5	Pleistocence	0.1	-	Wong et.al. (2005)
	Ranong	South section	130	7.5	-	Pleistocence	0.1	-	Wong et.al. (2005)
12.	Klong Marui	Ban Luk	60	7.1	1.3	1.3	0.43	2	Kaewmuangnoon (2011)
		Bang Sapan	60	7.1	2		0.24		Panyoepas (2011)

Remark: SRL is Surface Rupture Length of the fault (km)

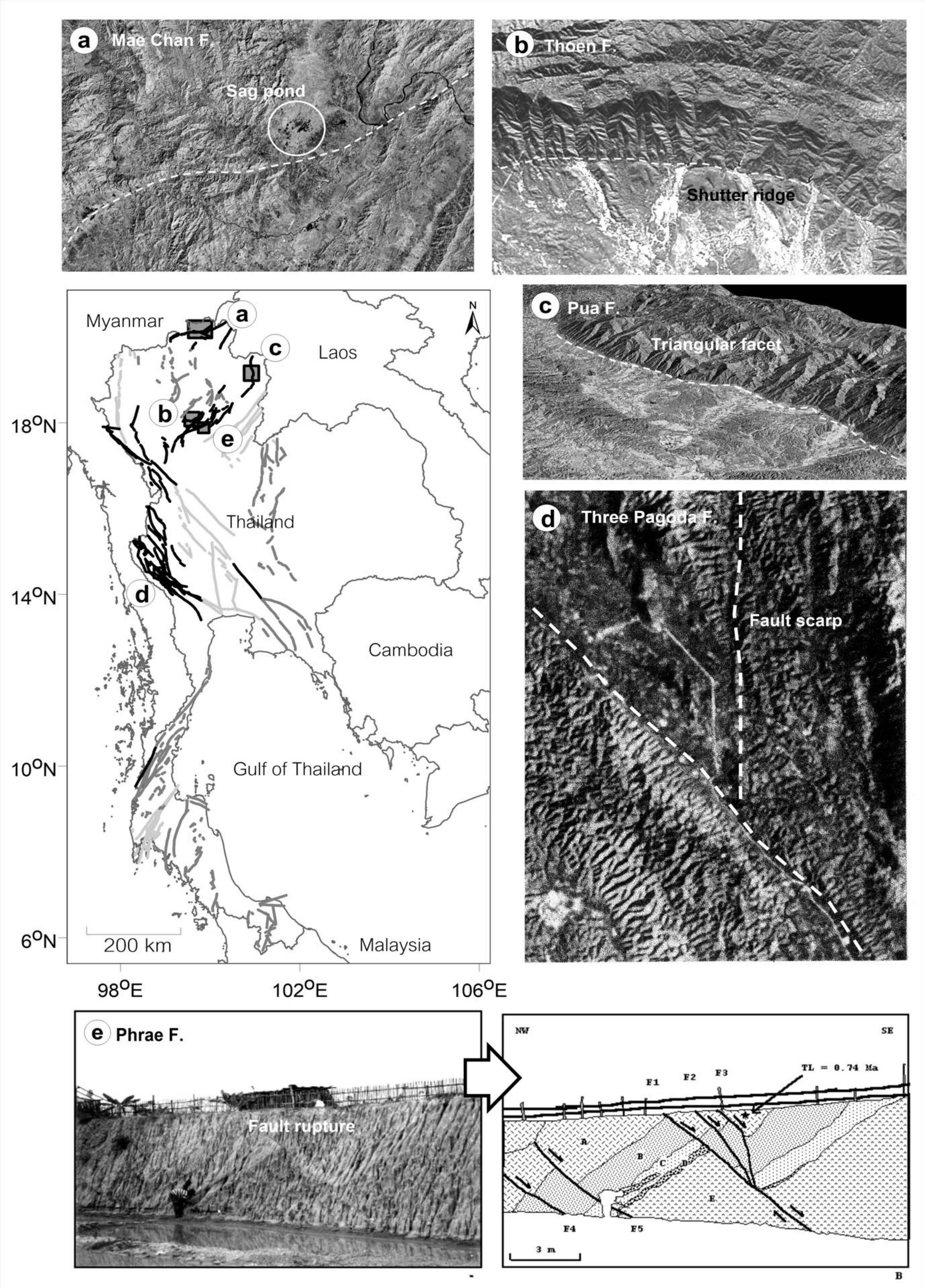

Figure 3. Morphotectonics evidence and sedimentary log profile in various place of Thailand at (a) Mae Chan fault (MCFZ), (b) TLPFZ at Thoen, (c) Pua fault (PF), (d) Three

Pagodas fault zone (TPFZ) and (e) TLPFZ at Phrae showing also the sedimentary profile.

6.3. Northern Shan-Thai SAB in Western-Northwest Thailand

(i) Mae Hong Song Fault Zone (MHSFZ). Of the four major fault zones in the west-northwestern SAB, the nearly 200 km-long, linear, north-trending MHSFZ (7 in Figure 2) is located in the northern-most part. Lineaments on the satellite images suggest that the MHSFZ consists of four segments, each one is 25-60 km in length, and suggest a maximum possible earthquake magnitude of about 7. The analysis of remotely sensed imagery confirms the interpretation of Saithong et al. (2005) that the MHSFZ has both thrust and dextral slip components. Although there is no significant seismic activity along this fault in Thailand, its northward extension in Myanmar shows small to moderate earthquakes, including a M_w 5.1 event in March, 1989. Paleo-earthquake studies by Maneenai and Takashima (1994) yielded TL data suggesting slip events at 0.32 and 0.89 Ma. Because of the lack of clear evidence of late-Pleistocene or younger slip in Thailand, we classify the MHSFZ as probably active.

(ii) Mae Ping Fault Zone (MPFZ). The discontinuous, 450 km-long, northwest-trending MPFZ, also called as Wang Chao Fault (Lacassin et al., 1997), Papun Fault in Myanmar (Bunopas, 1992), or the Moei-Uthai Thani Fault Zone (Shrestha, 1987), extends from the Sagaing Fault in central Myanmar to at least the Phitsanulok basin in central Thailand (8 in Figure 2). Our interpretation of remotely sensed images suggests that the MPFZ may extend southeastward into Cambodia and may be related to the formation Ton le Sab Lake in west-central Cambodia. The MPFZ was a major pre-30 Ma structure shown by the left-lateral offset of approximately 160 km during that period affecting major gneissic belts in Western Ranges in Thailand. (Lacassin et al., 1997; Tapponnier et al., 1986). A steeply inclined, 5 km-thick zone of mylonitic gneiss parallels the trace of the faults. Shear-sense indicators within the gneiss indicate uniform left-lateral slip. Lacassin et al. (1997) reported $^{40}Ar/^{39}Ar$ geochronological data indicating that the left-lateral slip most likely occurred between approximately 40 Ma and 30 Ma. Landsat images and topographic maps show a strong structural grain along the trace of the fault zone, some of which reflects erosion of the nearly vertical mylonitic gneisses that mark the fault zone. However, several splays within this zone show sharply defined lineaments on satellite images suggesting a more recent reactivation. A few earthquakes have been recorded along the MPFZ. Shrestha (1987) noted that an earthquake on September 23rd, 1933 (no record of intensity or magnitude) was felt along this fault for about 1 minute. Le Dain et al. (1984) reported a focal plane solution from a 1975 m_b 5.6 earthquake along the MPFZ in Myanmar consistent with right-lateral reactivation. The major west-northwest-trending branch of the MPFZ cuts Holocene sediments in Tak Province (Bhongaraya and Thiramongkol, 1998). Our paleo-earthquake studies and previous TL-dating data both suggest several slip events at about 0.035, 0.042, 0.049 and 0.062 Ma. Based on the recent seismic activity, evidence for late-Pleistocene to Holocene slips, and sharp topographic expression, we classify the TPFZ as active.

(iii) Sri Sawat Fault Zone (SSFZ). The 200 km-long, arcuate north-northeast-to north-northwest-trending SSFZ (9 in Figure 2) consists of four separate fault strands that vary in length from 40 to 65 km. Shrestha (1987) used aerial and topographic data to conclude that the SSFZ is active with a dextral slip. Two moderate earthquakes (m_b 5.3 and 5.9) occurred on April 15th and 22nd, 1983 near the Sri Nakharin Dam, followed by more than 140 aftershocks within a year (Klaipongpan et al., 1991). The location of the epicenter and distribution of the aftershocks suggested that the SSFZ was the source of these events. Nutalaya et al. (1985) reported fissures and landslides along a northwest-southeast trend within the epicentral area. Klaipongpan et al. (1991) concluded that these earthquakes represented reservoir-induced seismicity along the SSFZ. Klaipongpan et al. (1991) studied the long-term seismicity and the focal mechanism for the 1983 earthquakes and concluded that a roughly east-west-trending reverse fault at the southern end of the SSFZ may be active. Trenching and paleo-earthquake analysis, including TL-dating, by Nuttee et al. (2005) revealed that the latest movement on the southern part of the SSFZ occurred at about 5.8 ka. Analysis of the surface rupture length, following the method described by Wells and Coppersmith (1994), on the southern-most fault segment suggests a maximum earthquake magnitude of about M_w 6.3 and an average slip rate of about 0.67 mm/yr (Nuttee et al., 2005). Based on the recent seismicity on at least one of the fault segments, we classify the SSFZ as active.

(iv) Three Pagodas Fault Zone (TPFZ). The TPFZ (10 in Figure 2) is 360 km long and 50 km wide, being defined by numerous anastomosing fault traces and long resistant strike ridges of folded Paleozoic limestone. It extends northwest to the Sagaing fault in central Myanmar, and southeast to pass southwest of Bangkok (Tulyatid and Charusiri, 1999) and then dives beneath the Gulf of Thailand. Recent field studies (Rhodes et al., 2005) suggested three stages of history of the TPFZ that included a long early Tertiary sinistral period (Lacassin et al., 1997), followed by mid-late Tertiary dextral transtension and late-Tertiary to Holocene dextral transpression.

The TPFZ is seismically active, particularly along its northwestern extension in Myanmar. Two large earthquakes of m_b 7.6 and 5.8 were centered within this zone (7 January 1937 and 11 January 1960, respectively), both of which are located close to a nearby reservoir. Focal mechanisms of the Myanmar earthquakes confirmed an active dextral slip (Le Dain et al., 1984). Two other epicenters (m_b 4.5 and 3.0) occurred in 1985 within western Thailand. Hetrakul et al. (1991) interpreted these latter two earthquakes as part of the reservoir-induced seismicity related to the filling of the Khao Laem (now Wachiralongkorn) Reservoir. The spatial and temporal distributions of aftershocks to these earthquakes suggest sinistral motion along a northeast-trending conjugate fault (Hetrakul et al., 1991).

Initial investigation of the TPFZ concluded that the fault was inactive (EBASCO, 1984). However, Won-in (1999) and Fenton et al. (2003) identified numerous geomorphic features indicative of active faulting, including scarps on alluvium, offset streams and shutter ridges. Recent TL-dating data from Quaternary samples collected from fault trenches within the TPFZ on fault-related colluvial and alluvial sediments suggested slips at 2.5 ka, 12 ka, 24 ka, 36 ka, 60 ka and 300 ka (Yunan Seismological Bureau, 1997; Won-in, 1999). Based on the data obtained from trenching, which suggests vertical offsets of about 1-1.25 m (Rhodes et al., 2005), we calculated a slip rate along a single segment of the fault at about 0.1 mm/yr, lower than the 0.19 mm/yr calculated by the Yunan Seismological Bureau (1997).

Increasingly youthful geomorphic expression of fault strands within the TPFZ to the northwest along with an increase in seismic activity and increasingly young TL-dates, suggest that only the northwestern-most segments of this fault are currently active with a reverse-dextral oblique slip (Rhodes et al., 2005). We therefore classify the northwestern part of the TPFZ as active, whereas the southeastern segments as probably active.

6.4. Central Shan-Thai SAB in Northern Peninsular Thailand

(i) Ranong Fault Zone (RFZ). The 290 km-long northwest-trending RFZ (11 in Figure 2) is the northern-most structure of the three major northeast-trending fault zones in Peninsular Thailand. The RFZ follows the V-shaped valley of the Kraburi River and has two major segments (northern and southern segments) with several shorter strands. The RFZ cuts Late Cretaceous granites (Charusiri et al., 2002) and Cenozoic basin-fill sediments.

Our interpretation of Landsat and Aster satellite images suggests that the wedge-shaped valley of Ranong Bay is largely controlled by the movement along the RFZ. In addition, data from 3D seismic stratigraphy of the off-shore Andaman coast indicates a well-defined RFZ cross-cutting nearly the entire section of Cenozoic sediments (Thitipawaret et al., 2006). Garson et al. (1975) interpreted 20 km of sinistral slip along the RFZ and Shrestha (1987) reported a m_b 5.6 earthquake along the RFZ on 30 September 1978. Otherwise, seismic activity is limited to a few diffuse, very small (2.0 to 3.0 M_w) earthquakes. Preliminary TL dating data of sediments cut from two trenches at a fault across the northern segment revealed that there were at least two fault movements in the trench with the latest slip having occurred about 30 ka. A stream nearby the trenches was sinistrally offset by 200 m, suggesting an average slip rate of 0.7 mm/yr. Based on the youthful morphology of this fault, evidence of late Pleistocene slip, and historic seismicity, we classify the RFZ as probably active.

(ii) Klong Marui Fault Zone (KMFZ). The 150 km-long KMFZ (12 in Figure 2) extends across peninsular Thailand from Phang Nga Bay on the west coast to Ban Don Bay on the east coast. Traces of faults within the KMFZ follow the Klong Marui River where they cut Early Tertiary granitic rocks (Charusiri et al., 2002) and Cenozoic sedimentary rocks. Garson et al. (1975) suggested a total of 150 km of Middle Tertiary sinistral displacement along this zone. Although no significant seismic activity occurring along the KMFZ, preliminary TL geochronological data from trenches across fault segments within this zone suggested a long and complex history of slip with events at 0.18, 0.29, 0.40, 0.44, 0.70, 0.85 and 1.01 Ma (Maneenai and Takashima, 1994). Our preliminary analysis of offset streams using Landsat and Aster imageries plus ground surveys suggests that the Klong Marui Fault Zone shows left lateral displacement. The length of individual fault segments within the fault zone suggests a maximum potential earthquake of M_w 6.6-6.8 by the method of Wells and Coppersmith (1994). Present-day stress directions (Zoback, 1992) are consistent with the KMFZ having an active left-lateral slip. Therefore, we classify the KMFZ as probably active.

(iii) Klong Thom Fault Zone (KTFZ). The 150 km-long, northeast-southwest striking KTFZ (13 in Figure 2) cuts across peninsular Thailand parallel to and south of the KMFZ. Two distinct segments have approximately equal lengths (Figure 2). The KTFZ is marked by a series of west-dipping, poorly defined scarps visible on topographic maps and Landsat images. Apparent offset streams along the fault suggest young, sinistral slip. Maneenai and Takashima (1994) reported TL dates from trenches across the western segment of the fault that indicate slip events at 0.76, > 0.86, and 1.24 Ma. Based on its indistinct geomorphic expression, we classify the KTFZ as possibly active.

6.5. Southern Shan-Thai SAB in Southern Peninsular Thailand

The Southern Peninsular SAB includes of a set of discontinuous, relatively short (10-30 km long) faults with strikes that vary from northwest to northeast (Hinthong, 1995). Most of these faults can be grouped into a single zone as the north-northeast-trending Pattani Fault Zone (PaFZ) (14 in Figure 2), as proposed by Hinthong (1995). The PaFZ corresponds fairly well with the Mesozoic Pattani suture (Charusiri et al., 2002) and extends southwards to northern Malaysia, following the Bentong-Raub Suture (Hutchison, 1989). Based on only poorly defined scarps along a crudely linear valley with some apparent triangular facets, and possibly offset streams along these faults, we classify the faults within the PaFZ as possibly active.

6.6. Nakhon Thai SAB in Eastern-Northeastern Thailand

(i) Petchabun Fault Zone (PeFZ). The PeFZ (15 in Figure 2) consists of a 50-75 km wide, 300 km long set of approximately north-south-trending fault segments that extend from northeast of Bangkok to the Laos border in Loei Province. The longest of these segments borders the eastern side of the Petchabun Basin. Its northward extension into Laos follows the trace of the Mesozoic Loei suture (Charusiri et al., 2002). Only a few small to moderate earthquakes (up to m_b 3.0) have been recorded along this zone. Based on the sparse seismic activity and subtle geomorphic expression, we classify the faults of the PeFZ as possibly active.

(ii) Klaeng Fault Zone (KFZ). The 50 km-wide, 100 km-long, northwest-trending KFZ (16 in Figure 2) may be a southeastern extension of the MPFZ. Many of the fault segments within this zone lie in pre-Cenozoic rocks. The KFZ is marked by sparsely distributed hot springs and a few small Cenozoic basins. Only sparse and small (m_b < 3.0) earthquakes have affected this area. The geomorphic expression of the fault segments in this zone is subdued, therefore, we classify this zone as possibly active.

7. Seismic Zonation Map

Chandragsu (1986), as part of Thailand's first set of building codes, made the first attempt at compiling a seismic zonation map (Figure 4). This early edition built on the seismic intensity map compiled by Nutalaya et al. (1985) a year earlier which was based on archeological, historical and seismological data. Chandragsu's seismic zonation map, with modifications by Prachaub and Wechbunthung (1992), consists of four main seismic zones: zone 0 (aseismic areas) and zones 1 to 3 corresponding to mild, intermediate and strong seismic intensities. Subsequently, improvements to these maps have been based on seismic coefficient (Lukkunaprasit, 1994) and probabilistic seismic hazard analyses using peak ground acceleration of historical seismicity (Warnitchai and Lisantono, 1996).

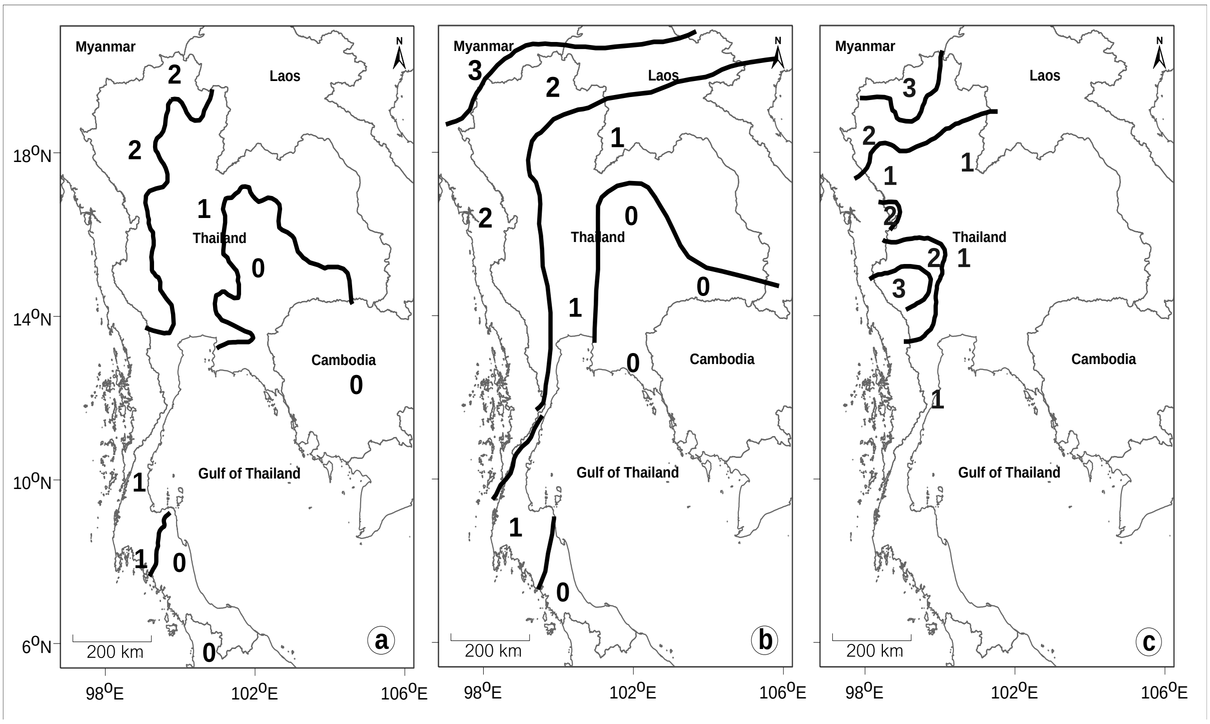

Figure 4. Map of Thailand showing earlier seismic zoning data from (a) Chandrarangsu (1986), (b) Prachaub and Wechbunthung (1992) and (c) Lukkunaprasit (1994). Seismic zones are shown in terms of seismic intensities as (0) aseismic, (1) mild, (2) intermediate and (3) strong.

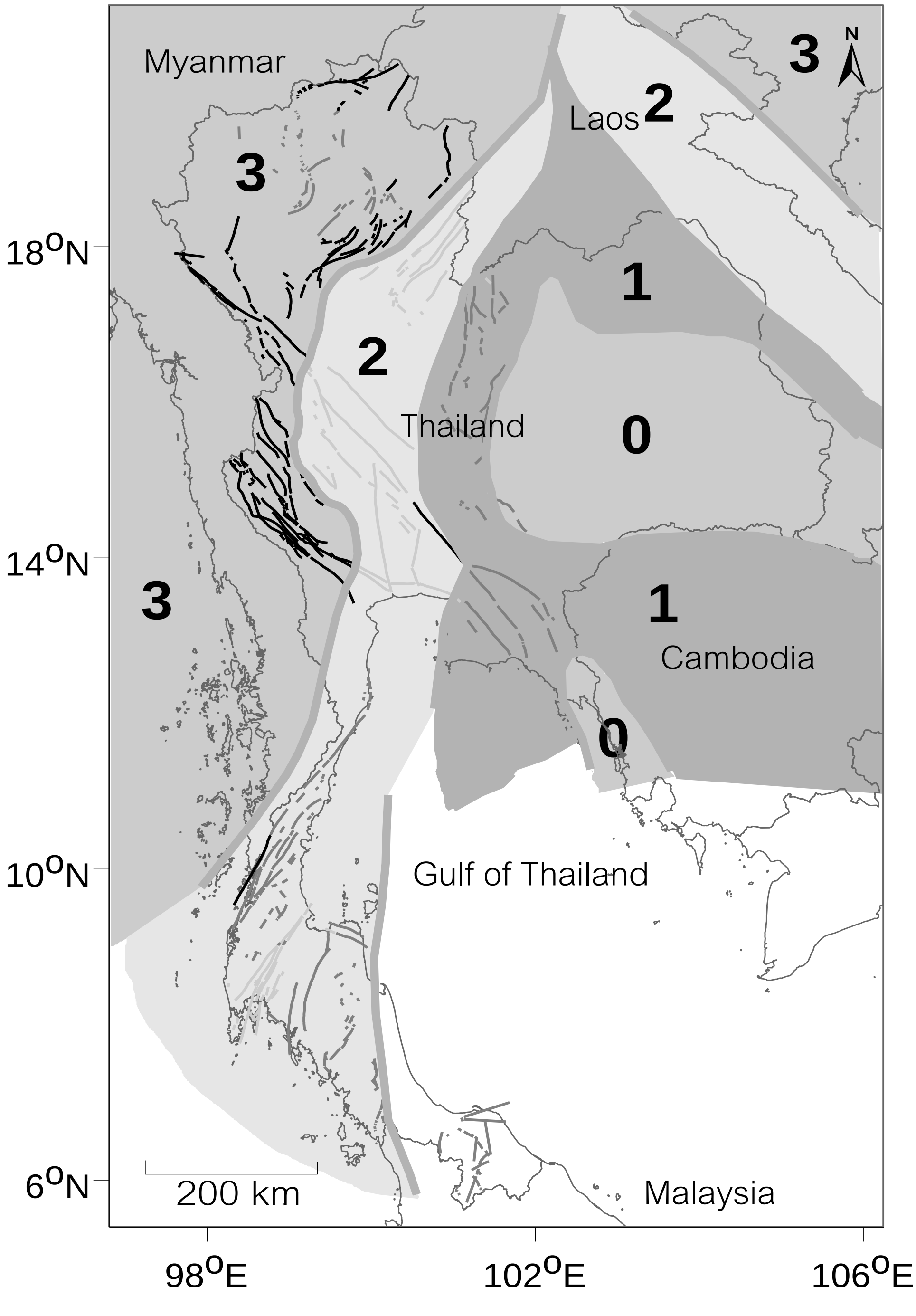

Figure 5. A seismic zonation map of Thailand showing the four zonal subdivision based upon the currently available data (see text in detail)., where: (Zone 0) earthquakes rarely occur; most faults are inactive; earthquake magnitude is normally less than 2 in Richter or II in Mercalli intensity scale; (Zone 1) very slightly earthquake prone; most faults are possibly active; earthquake magnitude is between 2 to 3 in Richter or II to III in Mercalli intensity scale; (Zone 2) prone to earthquakes and with possibly and probably active faults; earthquake magnitude is about 4 to 5 in Richter or about IV to VI in Mercalli intensity scale.; and (Zone 3) very prone to earthquakes with active and probably active faults; earthquake magnitude is at least equal to 5 in the Richter scale or to VI in the Mercalli intensity scale.

Based on new data compiled over the last decade, we compiled three new maps, a seismotectonic map of Thailand and adjoining regions (Figure 4), and a new seismic zonation map (Figure 5). The seismotectonic map was built from the geologic and tectonic features from Charusiri et al. (2000, 2002), and took into account new seismological data, geothermal activity, paleo-earthquake and TL geochronological data, historical records, and geomorphic evidence. Our new seismic zonation map builds on the seismotectonic data and includes our own observations regarding the major fault zones in Thailand, and our rankings of fault activity. Our map differs significantly from earlier seismic zonation maps since the seismic zone boundaries are fit to the distribution of major fault boundaries on our map and do not rely only on seismic activity. Our map is an improvement on the seismic risk map developed by the DMR (2004) which fails in our view to indicate clear-cut criteria for determining seismic zone boundaries.

8. Conclusion and Recommendation

Based on our compilation of remote-sensing, tectonic geomorphologic, geochronological and seismic data, derived from the many studies that followed the establishment of the National Earthquake Committee in 1984, we conclude that seismic activity in Thailand can be tied to the active zones of faulting. Furthermore, we subdivide Thailand, based upon available geological historical and seismological data, into five SABs, namely the northern, western-northwestern, central peninsular, southern peninsular and eastern-northeastern SABs (Figure 2). Not all SABs are considered to be active “sensu stricto”, especially those associated with extrusion tectonics (such as the NPFZ and MTFZ). However, some SABs were generated as a result of the India-Asia continental collision during Middle Tertiary and the reactivation of the older fault zones (such as the TPFZ and the MPFZ). Generally, the faults belonging to the southern, central peninsular and eastern-northeastern SABs are regarded as less dangerous, those in the central and northern peninsular Thailand are inferred to be mostly active or probably active and the northern and west-northwestern SABs are the most likely to be active.

Thailand has recently gained new expertise in paleo-earthquake research, so the time is now apt for beginning new, more detailed studies, particularly those relevant to seismic potential, earthquake recurrence intervals, seismic hazards planning and geochronology. Our new seismic zoning map is preliminary but provides an important first step towards understanding Thailand’s future seismic risk.

Acknowledgements

This research work was mainly supported by the Thailand Research Fund. The authors wish to express their very sincere gratitude to C. Hinthong, former Director of Geological Survey Division, Department of Mineral Resources, Bangkok, for providing us with valuable advice. C. Fenton, I. Wong, T. Supajanya and A. Lumjuan are thanked for their fruitful discussion on seismological and tectonic geomorphologic interpretation. M. Udchachon, K. Khaowisate, R. Nuttee, K. Kaovisate and R. Songmuang are thanked for field assistance and artwork. Akita University is acknowledged for providing TL-dating facilities. Special thanks are extended to B. Wechbunthoen for providing seismological data. J. Hoomhuek and V. Lamul are thanked for manuscript preparation, drafting and drawing arrangements. Special thanks are extended to Chulalongkorn University and the DMR for providing facilities, data and materials. This paper was written while P. Charusiri was a visiting professor at the Akita University under the Akita University research scholarship. B. Rhodes acknowledges the donors of the American Chemical Society Petroleum Research Fund, for partial support of his participation in this research. The faculty of science, Chulalongkorn University provided the financial support to SP and PC through the Ratchadapiseksomphot Endowment Fund 2020 of Chulalongkorn University (CU_GR_63_158_23_24) and the Thai Government Stimulus Package 2 (TKK2555: PERFECTA). We thank the Publication Counseling Unit (PCU), the faculty of science, Chulalongkorn University for a critical review and improved the English. We acknowledged thoughtful comments and suggestions by the Editor-In-Chief and anonymous reviewers which enhanced the quality of this manuscript significantly.

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