Implication of the 2004 Sumatra-Andaman Earthquake to Seismic Hazards in Southern Thailand

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***Abstract*—Before the Mw 9.2 Sumatra-Andaman Earthquake on 26 December 2004, there was no or little awareness on seismic hazards in Southern Thailand until the region experienced the impacts of the great earthquake. Since then until now, seismic hazards and the potential for the movement or reactivation of existing faults and fault zones in the region, which was around 600 km from the 2004 earthquake epicenter, have been questioned. There are two prominent strike-slip fault zones in the region, i.e. Ranong Fault Zone (RFZ) and Khlong Marui Fault Zone (KMFZ) which cross the Thai Peninsula from Andaman Sea in the west to the Gulf of Thailand in the east. The objective of this study was to evaluate the effect of the 2004 great earthquake to recent seismic hazards in Southern Thailand. Seismogram data were obtained from a temporary seismological network in early 2005. All available digital seismograms were processed and interpreted following standard procedures using freely available SEISAN (Seismic Analysis) software to provide standard earthquake source parameters (origin time, location, depth, and magnitude). This study reveals that all earthquakes recorded here are considered local earthquakes, with epicenters are on land of the Thai Peninsula and off the west and east coasts of the region within an area between 7°.00'N to 10°.45'N and 97°.25'E to 100°.30'E with the focal depth 0–90 km (shallow depth) and local magnitudes ML-0.2–2.0 (microearthquakes). Seismotectonic model reveals that this region can be divided into 5 zones. According to the results, most earthquakes can be associated with the two major faults (RFZ and KMFZ), thus indicating that these faults have to be considered active now and potential to contribute seismic hazards in Southern Thailand. Recent paleoseismological investigations confirmed the KMFZ as active in recent geological times and potential to produce earthquakes with magnitudes much higher than today's records. Such a seismic hazard study is important due to the rapid development of this region and its relations to the issue of buildings' resistance to earthquakes.**

Keywords*—*seismic hazard, Ranong Fault Zone, Khlong Marui Fault Zone, SEISAN, Southern Thailand

I. INTRODUCTION

According to the latest USGS report [1], the Mw 9.2 Sumatra Andaman Earthquake occurred on 26 December 2004 at 00:58:53 UTC (07:58:53 Thai time) at the epicenter of 3.316°N and 95.854°E Off the west coast of northern Sumatra, Indonesia (Fig. 1) with the depth of 30 km. The earthquake occurred when the stress that had accumulated for centuries was released from ongoing subduction of the India Plate beneath the overriding Burma Microplate.

The earthquake triggered a series of the most devastating tsunami in modern times which occurred along the coasts of many countries around the Indian Ocean. It affected more than 18 countries from Southeast Asia to Southern Africa, killing more than 250,000 people in a single day and leaving more than one million people homeless. Other than humanitarian loss, it had also caused economic loss accompanied by environmental and medical threats. Thailand had also been affected by this tsunami with 5,395 people killed and 2,993 people missing [2]. The greatest damage was suffered by Indonesian province of Aceh, the northernmost province of Sumatra Island, claiming 131,000 people confirmed dead, 37,000 people missing, and 500,000 people displaced [3].

Southern Thailand, one of Thailand's regions, is surrounded by the Andaman Sea in the west and the Gulf of Thailand in the east forming the Thai Peninsula which extends south to the border with Malaysia. It is regionally close to the Sumatra–Andaman Subduction Zone which is the regional source of earthquakes. For local origins, there are a series of active fault zones, mainly the Ranong and the Khlong Marui Fault Zones (RFZ and KMFZ), which before the 2004 great earthquake were considered as dormant by the Thailand's Department of Mineral Resources (DMR) [4]. However, after 2004, questions emerged about the impacts of this major earthquake on possible reactivation of these and other fault zones in the region.

Earthquake activities in Southern Thailand, mainly along the major fault zones, RFZ and KMFZ, have been monitored in early 2005 by a temporary network established by the Geophysics Research Center, Prince of Songkla University (GRC–PSU) in collaboration with DMR. This study reprocessed available earthquake data in order to improve the quality of all parameters and to do a reinterpretation of the results. This study aims to evaluate the implication of the 2004 great earthquake to recent seismic hazards in the region.

II. GEOLOGICAL SETTING

Southern Thailand, like other regions in Thailand, is located on the intra-plate of Eurasian Plate and about 600-800 km from the plate boundary (closest distance). It is regionally affected by the interaction of the plate boundary between the India Plate and the Burma Microplate (considered part of larger Eurasian Plate), one of the most seismically active plate boundaries, mainly in the Andaman Sea (Fig. 1). For the local tectonic setting, the RFZ and KMFZ which cross the Thai Peninsula from the Andaman

Sea to the Gulf of Thailand in SSW-NNE direction are two prominent fault zones that have long and complex history extending back to Paleozoic Era [5, 6].

Geologically, the southern part of Thailand consists of a succession of Paleozoic and Mesozoic sedimentary and metamorphic rocks, intruded by Late Paleozoic to Mesozoic igneous rocks, and covered by Cenozoic sedimentary rocks or sediments. It has the main chain of granitic mountains which continues north into the Gulf of Thailand where it formed some islands including the famous Koh Samui. It has also a number of scattered and less linear granite bodies (Fig. 2) [5].

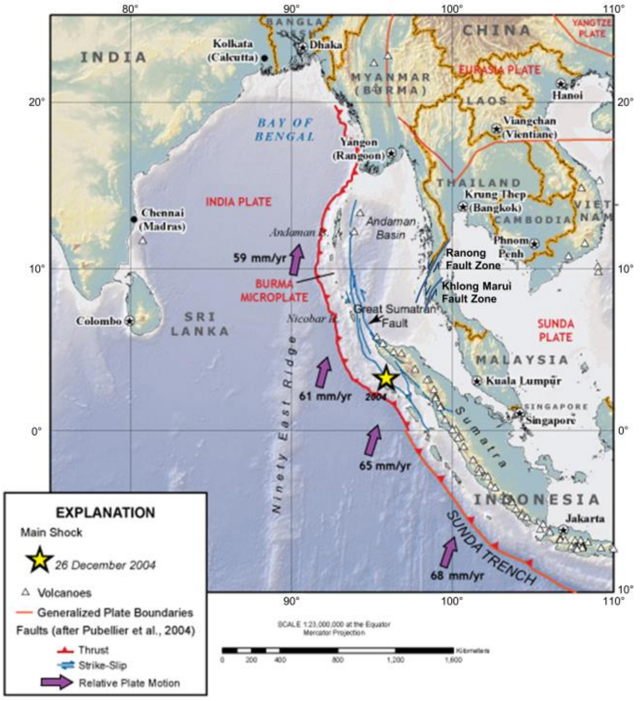

Fig. 1. *Regional tectonic setting of Sumatra–Andaman subduction zone showing relative motion between the India Plate and the Burma Microplate, major fault zones, and location of the 26 December 2004 earthquake (Source: http://walrus.wr.usgs.gov/tsunami/sumatraEQ/tectonic.html)*

Since the occurrence of the 2004 Sumatra–Andaman Earthquake, the two major faults and fault zones have attracted much attention from geologists and seismologists because the potential for the reactivation of these faults is increasing since then[6]. A study conducted by [4] revealed that after the 26 December 2004 earthquake, the existing faults zones in Southern Thailand might be reactivated in a compressional stress regime, increasing the probability of higher magnitude earthquakes. Sutiwanich et al. [7] inferred that Southern Thailand or Thai Peninsula is not tectonically stable anymore as had previously thought. The following sections will explain these two fault zones in more details.

A. *Ranong Fault Zone*

The RFZ is a major NNE-SSW-trending, left-lateral strike slip fault zone which consists of 16 fault segments and most of them have left-lateral motions [8]. The fault zone comprises many faults extending from the Andaman Sea, Ranong province towards the Gulf of Thailand through Prachuab Kirikhan and Chumpon provinces with a total onshore length of about 440 km. Some parts of the fault zone follow the channel of the Kraburi River, and subsidiary faults cut Late Cretaceous and Palaeogene granites and Cenozoic sedimentary rocks (Permian Kaeng Krachan Group). Information from the Landsat images indicates that the fault movement mainly controls the Ranong Bay [6, 9].

B. *Khlong Marui Fault Zone*

The KMFZ is also a major NNE-SSW-trending strike-slip fault zone which coincides with the bend of Thai Peninsula (and separates it into the upper and the lower parts) with the length of 210 km. This fault zone is parallel with the RFZ which together traverses in Southern Thailand. It cuts across Phuket, Phang Nga Bay and Ban Don Bay on the Andaman Sea and partly follows the Khlong Marui channel to the Gulf of Thailand through Surat Thani province, which mainly passes through Late Cenozoic to Palaeogene granites and Paleozoic sedimentary rocks [6,9]. Saetang et al. [10] reported that this fault zone consists of 10 fault segments.

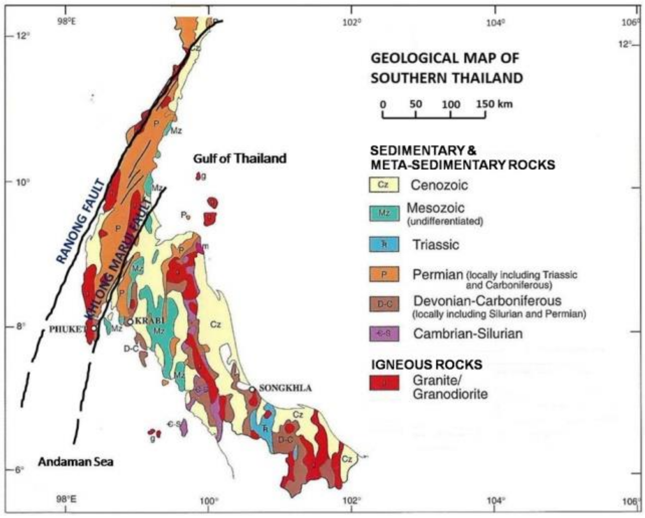

Fig. 2. *Geological map of Southern Thailand (modified from [5])*

III. Data and Methodology

A. *Data source*

This study was carried out in Southern Thailand situated between latitude of 5°30’ and 12°30’N and longitude 97°30’ to 102°30’E. A seismological network comprising four short-period (SP) three-component (Z, N, and E) seismometers was established by GRC-PSU and DMR at the end of December 2004 in Phang Nga (2 stations), Phuket (1 station), and Krabi (1 station) (Table 1, Fig. 3). For this study, digital seismograms from 111 local earthquake events occurred between 14 January and 11 April 2005 and recorded by at least three seismic stations were chosen to be reprocessed.

B. *Methodology*

The first step of seismogram analysis was to identify the seismic phases associated with each earthquake and to determine their arrival times. Seismograms recorded from local earthquakes are dominated by P and S waves. The maximum amplitudes were identified from horizontal components of seismograms (N and E). In this study, seismic phases (mainly P and S waves) and their arrival times as well as maximum amplitudes have been re-measured. Information of earthquake source parameters consists of origin time, location (epicentral coordinates), focal depth, and magnitude; focal depth has not been determined in the earlier study [4]. Seismogram analysis was done by SEISAN software developed by [11]; the software can be downloaded freely at: ftp://ftp.geo.uib.no/-pub/seismo/SOFTWARE/SEISAN/. For this study, SEISAN version 8.2.1 was used.

TABLE 1: *LOCATION OF SP SEISMOMETERS IN EARLY 2005 [4]*

Station/ Code	**Lat. Long.**	**Location**
Station 1/ PSUHY	8°26'3.48"N 98°30'24.48"E	Muang District, Phang Nga Province
Station 2/ PNG2	8°33'27.36"N 98°39'37.44"E	ThapPut District, Phang Nga Province
Station 3/ PSUNM	7°53'28.90"N 98°21'3.96"E	Prince of Songkla University, Phuket Campus, Khatu District, Phuket Province
Station 4/ TBK	8°23'20.28"N 98°44'10.46"E	Tanbokkoranee National Park, AoLuek District, Krabi Province

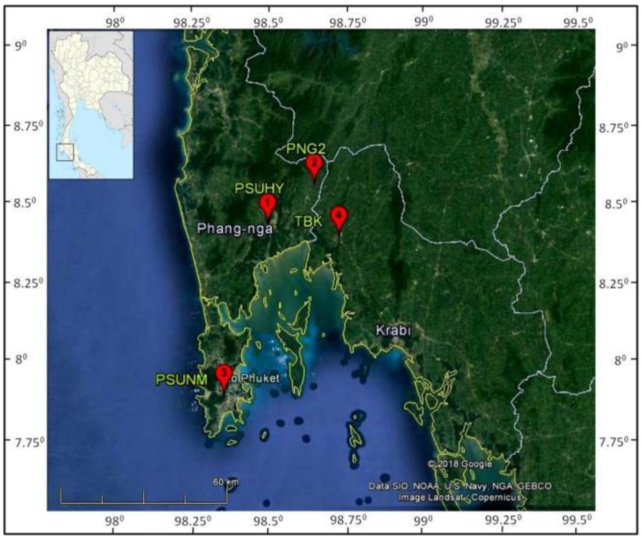

Fig. 3. *Location of 4 seismic stations (PSUHY, PNG2, PSUNM, and TBK) for earthquake monitoring in Southern Thailand in early 2005*

Since the velocity of different layers within the earth is known, travel times as a function of epicentral distance (distance from station to epicenter) and origin times (time of the event occurrence) can be calculated. In this study, the IASP91 velocity model [12] was used. Origin times and locations (epicenters) were determined by using differences between S and P arrival times from at least three different stations. Time differences between both arrival times, called 'delta time' (Δt), was used to determine the distance between the seismic event and the station. The earthquake hypocenter is expressed by latitude, longitude, and depth while its projection on the surface (expressed only by latitude and longitude) is the epicenter. The local magnitude (ML) was determined by using the IASPEI standard ML [13] with:

$$ML = \log_{10}(A) + 1.11 \log_{10}R + 0.00189 * R - 2.09 \quad (1)$$

where A is the maximum trace amplitude (in nm) that is measured from horizontal components (N and E) of a Wood-Anderson seismogram, and R is the hypocentral distance (in km).

IV. SEISMICITY AFTER 2004

In general, the analysis of seismograms has identified major seismic phases (P and S phases) and their arrival times, including the maximum amplitudes. It was found that many seismograms contain low seismic noise and noticeable P- and S-phase onsets were relatively clear. Fig. 4 and 5 show two examples of seismogram analysis from two different earthquakes (event no.13 and 44) which occurred in Southern Thailand on 18 January 2005 and 3 March 2005 respectively. Station 3 (PSUNM) recorded a slightly higher noise than other stations because of several reasons: firstly, it is located in Phuket Island which is more influenced by ocean waves as one of main sources of seismic noise; and secondly, the island is a major tourism destination and a densely populated area so that anthropogenic activities probably contribute as higher noise levels.

Results of the analysis for the event no. 13 revealed that the origin time of the event is 21:39:13.26 UTC. The location of the earthquake (the epicenter) is 8.142 N and 98.166 E with the focal depth is 0.1 km and the local magnitude (ML) is 0.5. Meanwhile, the analysis results for the event no. 44 gave information on source parameters where the origin time of the event is 11:54:01.92 UTC, the earthquake location is 9.428 N and 98.840 E, the focal depth is 0.0 km (very shallow), and the local magnitude (ML) is 2.0. Table 2 presents a summary of seismogram analysis of event no. 13 and 44 as examples.

From the analysis of selected seismograms, earthquake events occurred in an area between latitude 7°.00'N to 10°.45'N and longitude 97°.25'E to 100°.30'E with focal depths of 0–90 km and local magnitudes (ML) ranging from -0.2 to 2.0. Fig. 6 shows the distribution of earthquakes in relation to the magnitude and depth.

During the monitoring period in early 2005, earthquakes occurred mainly on land in some provinces of Southern Thailand, i.e. Chumpon, Ranong, Surat Thani, Phang Nga, Nakhon Si Thammarat, Krabi, Phuket, and Trang. There is a cluster of epicenters in the Andaman Sea, distributed in offshore of Trang, Krabi, Phang Nga, Phuket, and Ranong. There are also a few earthquake locations in the Gulf of Thailand in Nakhon Si Tammarat and Surat Thani.

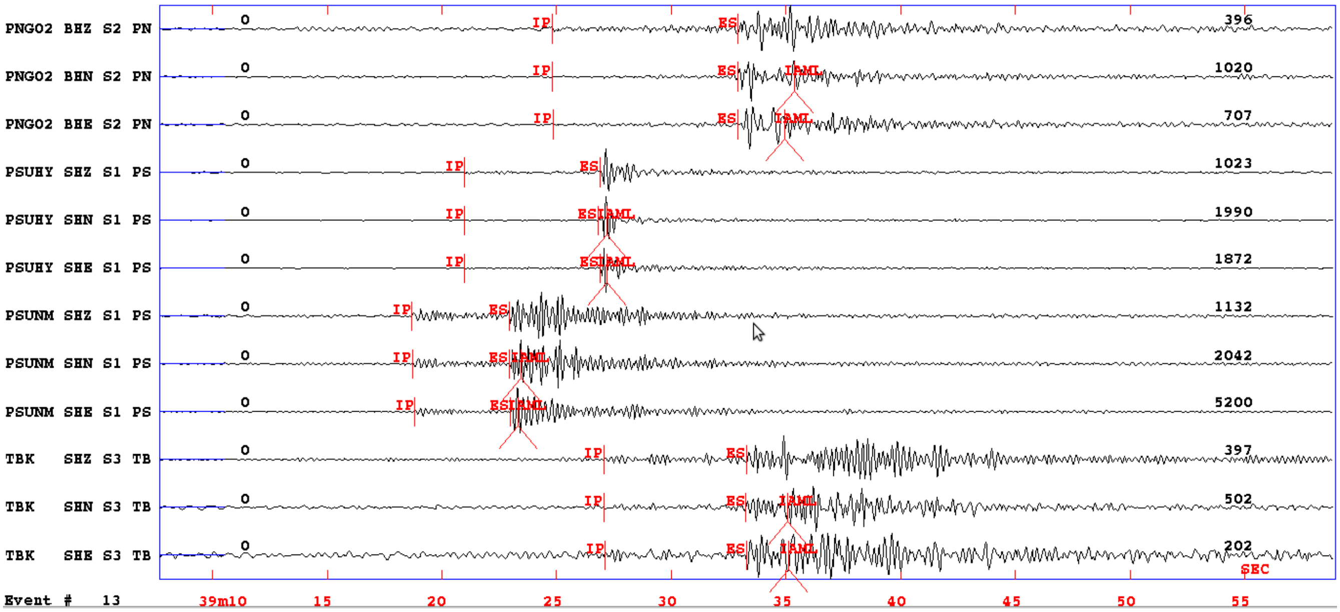

Fig. 4. *Seismogram analysis of event no.13 recorded on 18 January 2005 by 4 seismic stations (Station 1/PSUHY, Station 2/PNG02, Station 3/PSUNM, and Station 4/TBK) with three-component seismographs (Z, N, and E). (IP = P phase; ES = Sphase; IAML = Maximum amplitude)*

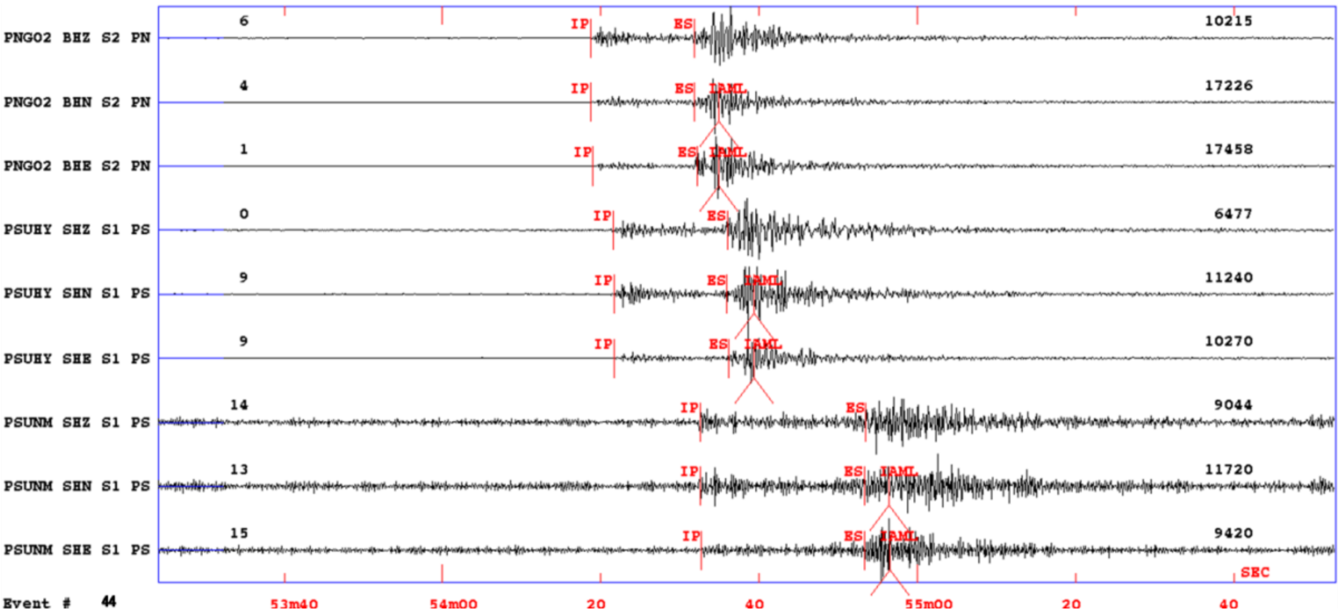

Fig. 5. *Seismogram analysis of event no.44 recorded on 3 March 2005 by three-component seismographs (Z, N, and E) in 3 seismic stations (Station 1/PSUHY, Station 2/PNG02, and Station 3/PSUNM). (IP = P phase; ES = S phase; IAML = Maximum amplitude)*

TABLE 2: *SUMMARY OF DATA FROM THE ANALYSIS OF SEISMOGRAMS FOR EVENT NO. 13 AND 44*

Event No.	Date (dd/ mm/ yy)	Station	P- arrival time (hh:mm: ss.00)	S- arrival time (hh:mm: ss.00)	Δt (s)	Origin time (hh:mm:ss. 00)	Origin time avg(h h:mm: ss.00)	Dist. (km)	D (km)	N Amax (nm)	E Amax (nm)	Amax (sum) (nm)	ML	ML max
13	18/01/ 2005	1 (PSUHY)	21:39:20.98	21:39:26.87	5.89	21:39:12.45	21:39: 13.26	49.5	0.1	2.5	2.5	3.5	0.4	0.5
		2 (PNG02)	21:39:24.80	21:39:32.89	8.09	21:39:12.52		71.2		1.5	1.7	2.3	0.5	
		3 (PSUNM)	21:39:18.75	21:39:22.94	4.19	21:39:12.82		34.4		3.0	6.3	7.0	0.5	
		4 (TBK)	21:39:27.07	21:39:33.25	6.18	21:39:15.26		68.5		0.8	0.6	1.0	0.1	
44	03/03/ 2005	1 (PSUHY)	11:54:21.65	11:54:36.02	14.37	11:54:01.65	11:54: 01.92	116	0.0	13.5	18.1	22.6	1.8	2.0
		2 (PNG02)	11:54:19.17	11:54:31.93	12.76	11:54:02.22		98.3		36.6	32.1	48.7	2.0	
		3 (PSUNM)	11:54:32.58	11:54:53.39	20.81	11:54:01.89		178		4.3	9.0	10.0	1.7	

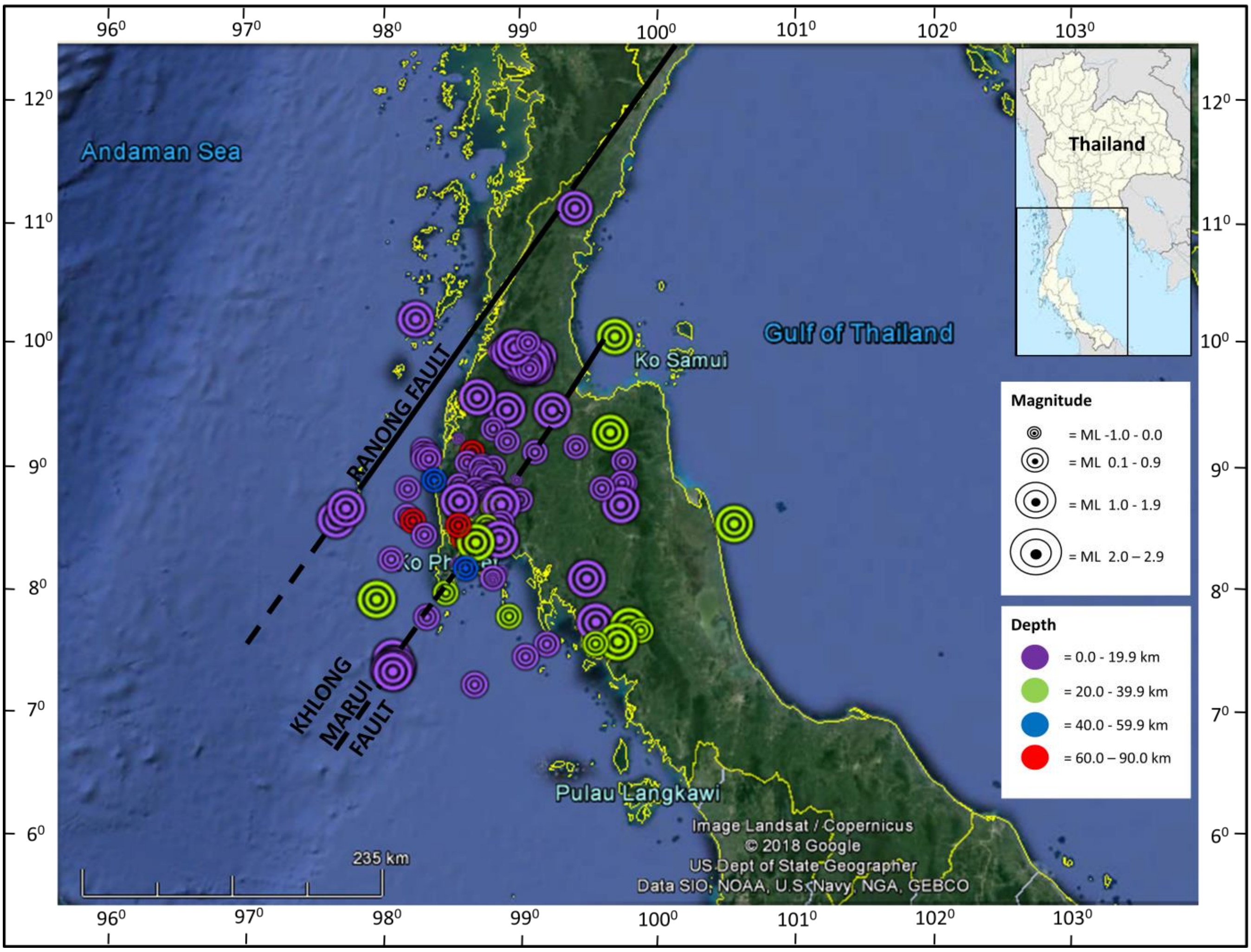

Fig. 6. *Map of earthquake locations (epicenters) in Southern Thailand from January 14th to April 11th, 2005*

Generally, those earthquake locations are distributed in a NNE-SSW trend following the direction of the two major faults in Southern Thailand, the Khlong Marui and Ranong Faults. Many epicenters are located in or parallel to these fault lines and many others are within the areas of the fault zones (KMFZ and RFZ). There is also a cluster of N-S-trending epicenters in Nakhon Si Thammarat and Trang provinces which, according to the detailed map of the Thai Peninsula showing those fault zones [14], can be interpreted due to the existences of some minor faults in granitic bodies in the areas.

In terms of their focal depths, most of the recorded earthquakes have very shallow depths (depth = 0.0 – 19.9 km, symbolized by purple circles in the map above) scattered in and around the fault zones. The category of deepest earthquakes (depth = 60.0–90.0 km, symbolized by red circles in the map above) are all located in Phang Nga province.

In relation to the magnitude, most of local earthquakes occurred during the monitoring period have their local magnitude (ML) between 0.1 to 0.9 which are concentrated in the fault lines of the Khlong Marui and Ranong Faults and within the areas of the fault zones. Earthquakes with minimum magnitudes (ML -0.2 to 0.0) are concentrated in some areas in Krabi, Phang Nga, and Phuket. The maximum magnitude is ML 2.0 located near Surat Thani–Ranong border.

V. Seismotectonic Model

A seismotectonic model represents zones with a distribution of earthquake activities and associated tectonic setting. These zones were delineated based on the observed spatial density of earthquake activities (seismicity) in this region and corresponding tectonic setting [15]. In this study, seismotectonic model of Southern Thailand has been identified as shallow crustal source zone where the sources were from active faults and fault zones as well as areal sources with the shallow depth (between 0–90 km).

The map of seismotectonic zones of Southern Thailand are shown in Fig. 7 and the summary of the zones is presented as follows:

Zone 1: Relatively high seismicity on the land between two fault zones (RFZ and KMFZ) and related to the activity of these fault zones. This zone includes some provinces in this region: Chumpon, Ranong, Surat Thani, Phang Nga, Phuket, and Krabi.

Zone 2: Relatively intermediate seismicity located offshore in the west and east of Thai Peninsula (Andaman Sea and Gulf of Thailand) and related to the activity of the fault zones (RFZ and KMFZ).

Zone 3: Relatively intermediate seismicity on the land related to the activity of some smaller faults (or fault zones). This zone includes some provinces: Nakhon Si Thammarat, Krabi, Trang, and Phattalung.

Zone 4: Relatively low seismicity in other areas, not related to the activity of major or minor fault zones.

Zone 5: No to relatively very low seismic activity (no earthquakes here from this study). This zone includes Nakhon Si Tammarat, Patthalung, Satun, Songkhla, Pattani, Yala, and Narathiwat provinces.

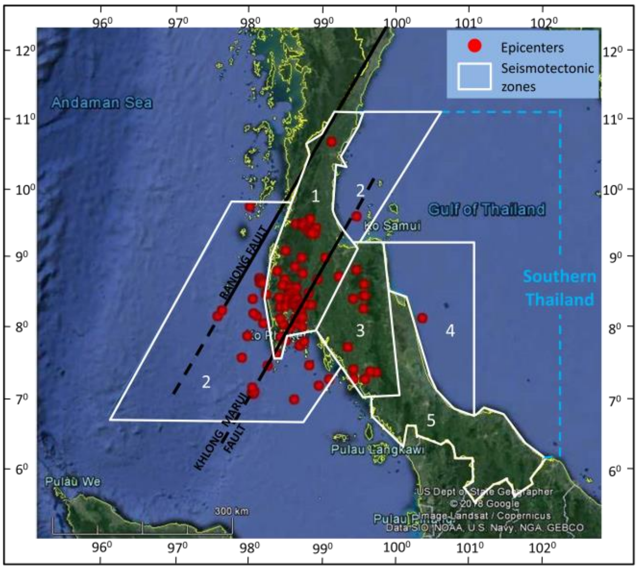

Fig. 7. *Seismotectonic zones of Southern Thailand based on earthquake activities recorded from 14 January to 11 April 2005*

VI. Recent Paleoseismological Investigation

A fault movement is evidence for an earthquake occurrence. The geological environment of a fault or a fault zone, where earthquakes occurred, provides information about the past movements. For ancient earthquakes (paleoearthquakes), where no seismograms are available, geological evidences are essential to be used.

Paleoseismological investigations conducted in the eastern part of the KMFZ have managed to identify several locations with paleoearthquake evidences. From thermoluminescence and optically-stimulated luminescence methods it can be concluded that there has been at least three periods of paleoearthquakes occurred in this area, i.e. at 33–112 ka, 2.5–10 ka, and younger than 2.5 ka. The investigations have also shown that the KMFZ has generated earthquakes with Mw 6.6 to 7.8, higher magnitudes than any seismogram has ever recorded for this region [16]. These evidences have proven that the fault zone has been active since the ancient time and it is probable to generate earthquakes in the future with much higher magnitudes than today's records. This is important for the seismic hazard analysis of this region.

VII. Conclusion

Results of this study show that after the December 26th, 2004, Mw9.2 Sumatra-Andaman Earthquake, many earthquakes occurred in Southern Thailand. Based on the distribution of epicenters, these events are mostly distributed along and in between the Ranong and Khlong Marui Fault Zones, so that it can be interpreted that most of the recorded earthquakes are related to the movement or reactivation of these existing fault zones. Most recorded earthquakes have sources of shallow depth (less than 20 km) and are categorized as microearthquakes (ML≤2.0).This study indicates that other than Sumatra-Andaman Subduction Zone, the active fault zones (mainly RFZ and KMFZ) contribute significantly to the seismic hazards in this region.

Seismological data contribute to the identification of the fault extension and the seismotectonic zones. From this study, the relative orientation of the faults has been defined by the distribution of earthquake locations (epicenters) where the RFZ and KMFZ follow the NNE-SSW direction in line with the main trend of epicenters. This region has been divided into five seismotectonic zones based on the distribution of epicenters and associated tectonic setting.

Although all these recorded events are small in term of the magnitude, not felt earthquakes as well as not destructive, paleoseismological studies have reported that this region is still probable to generate stronger earthquakes with magnitude about 6-8, higher than what have been recorded until today.

This study monitored earthquakes over a short period of time, so it might be not adequate to represent the recent seismic hazards in Southern Thailand. Therefore, it is suggested to monitor and analyze the earthquake data from time to time to obtain more accurate seismic hazard analysis. The study of seismic hazards should be taken into consideration before the development of areas in the southern part of Thailand with newly planned infrastructures and facilities, e.g. new airport in Phuket and a new train system in Phuket and Phang Nga, and its relations to the buildings' resistance to earthquakes (building codes).

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