Seismicity of Southern Thailand and Peninsular Malaysia

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ABSTRACT

Prior to the occurrence of the 2004 Sumatra-Andaman earthquake, Southern Thailand and Peninsular Malaysia experienced relatively little earthquake activities and considered as low seismicity regions. However, after the devastating 2004 earthquake, the seismicity in both regions increases with the occurrence of plenty of local intraplate earthquakes. The objectives of this study are: firstly, to analyze the seismicity of Southern Thailand and Peninsular Malaysia focusing on the temporal-spatial distribution and magnitude variation of local earthquakes, and their relationship with local fault zones; secondly, to investigate characteristics of earthquake sequences happened in Phuket Island (Southern Thailand) in 2012 and in Bukit Tinggi (Peninsular Malaysia) in 2007-2009; and thirdly, to evaluate the impacts of several regional earthquakes on the local seismicity and crustal deformation in both regions in terms of geodynamic implications. This study created earthquake catalogs from 227 earthquakes in Southern Thailand covering a period 1970 – 2020 and 58 earthquakes in Peninsular Malaysia during a period 1922 – 2020 which was compiled from observations of local, regional/national, and global networks. Available digital seismograms from both regions were processed and interpreted by using SEISAN software. This study reveals that epicenters of local earthquakes are predominantly distributed in the vicinity of fault zones in Southern Thailand and Peninsular Malaysia, indicating that they are the main contributors to the local seismicity. This study categorizes the 2012 Phuket and 2007-2009 Bukit Tinggi earthquakes as the earthquake swarms and complimented by mini swarms. This study also reveals that several large regional earthquakes in Sumatra region had considerable geodynamic implications on local seismicity and deformation. Therefore, this study is essential for providing considerations on the seismic hazards in both regions.

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CONTENTS

	Page
Title page	i
Approval page	ii
Certification	iii
Abstract	v
Acknowledgements	vi
Contents	viii
List of Tables	x
List of Figures	xii
List of Abbreviations and Symbols	xvi
List of Papers and Proceedings	xviii
1. INTRODUCTION	1
1.1 Background	1
1.1.1 Regional Tectonics and Seismicity	2
1.1.2 Local Tectonics	5
1.2 Data Sources	8
1.2.1 Pre-Instrumental Period	8
1.2.2 Instrumental Period	9
1.3 Earthquake Swarm	14
1.4 Previous Studies	20
1.4.1 Previous Studies on Seismicity in Southern Thailand	20
1.4.2 Previous Studies on Seismicity in Peninsular Malaysia	22
2. OBJECTIVES	24
3. METHODOLOGY	25
3.1 Seismological data compilation	25
3.2 Seismological data processing	25
3.3 Seismological data products	26
3.4 Seismicity analysis	26

4. RESULTS AND DISCUSSION 27

4.1 Seismicity in Southern Thailand 27

4.1.1 Brief History on Pre-Instrumental Seismicity in Southern Thailand 27

4.1.2 Instrumental Seismicity in Southern Thailand 29

4.1.3 Earthquake Swarm in Phuket (2012) 45

4.1.4 Relations between Seismicity and Local Tectonics in Southern Thailand 52

4.2 Seismicity in Peninsular Malaysia 54

4.2.1 Brief History on Pre-Instrumental Seismicity in Peninsular Malaysia 54

4.2.2 Instrumental Seismicity in Peninsular Malaysia 56

4.2.3 Earthquake Swarm in Bukit Tinggi (2007-2009) 65

4.2.4 Relations between Seismicity and Local Tectonics in Peninsular Malaysia 70

4.3 Implications of Regional Geodynamics 72

4.4 Comparisons of Seismicity between Southern Thailand and Peninsular Malaysia 79

5. CONCLUSION 81

5.1 Conclusion 81

5.2 Novelty 82

5.3 Recommendation 83

References 84

Appendices 104

Letter of permission to use published article from CMJS

Paper 1

Letter of permission to use published article from SN Applied Sciences

Paper 2

Proceeding 1

Proceeding 2

Vitae

LIST OF TABLES

Table		Page
1.1	Information on seismological stations for the monitoring of earthquake activities in Southern Thailand and West Malaysia (for this study) (Duerrast et al., 2007; MMD, personal communication; RID, personal communication; Vanichnukhroh, 2013).	10
1.2	Information on datasets of local earthquakes used in this study.	14
1.3	Main types of earthquake sequences and their relations to structures of medium and applied stress (adapted from Mogi, 1963, 1967).	16
4.1	Earthquake data of instrumental period in Southern Thailand from various local, regional/national, and international seismological networks and previous studies.	31
4.2	Focal mechanism determination with the strikes, dips, and rakes for the two fault plane solutions (FP1 and FP2) for three local earthquakes in Southern Thailand (http://www.globalcmt.org/CMTsearch.html; Pornsopin et al., 2012).	44
4.3	Numbers of local earthquakes in Southern Thailand during the instrumental period (1970 – 2020) based on their focal depth distribution and moment magnitude variation.	45
4.4	Chronology of the 2012 Phuket earthquake swarm activity.	46
4.5	Calculation of skewness (S) and kurtosis (K) of the 2012 Phuket earthquake swarm.	49
4.6	Earthquake data in West Malaysia compiled from various catalogues of national and international seismological networks and previous studies.	57
4.7	Focal mechanism determination with the strikes, dips, and rakes for the two fault plane solutions (FP1 and FP2) for four local earthquakes in West Malaysia (Mat Said and Hara, 2012).	64
4.8	Numbers of local earthquakes in West Malaysia during the period 1922 – 2020 based on their focal depth distribution and moment magnitude variation.	64

4.9	Chronology of the 2007-2009 Bukit Tinggi swarm activity per month.	66
4.10	Calculation of skewness (S) and kurtosis (K) of the 2007-2009 Bukit Tinggi earthquake swarm.	68
4.11	Comparisons between Southern Thailand and Peninsular Malaysia in terms of their seismicity	79

LIST OF FIGURES

Figure		Page
1.1	Regional tectonic setting surrounding Southern Thailand and West Malaysia where the Indian and Australian Plates subduct under the Burma Microplate and the larger Eurasian Plate forming the Sunda Subduction Zone (SSZ) or Sunda Trench, and other major tectonic features such as Sumatra Fault Zone (SFZ), West Andaman Fault (WAF), Seuliman Fault (SEU) and Sagaing Fault (SF) (Adapted from Curray, 2005).	3
1.2	Location map of Southern Thailand and West Malaysia including their provinces or states.	5
1.3	Geological map of Southern Thailand region (modified from Ridd et al., 2011).	6
1.4	Geological map of West Malaysia region (Metcalfe, 2012) with the local faults (adapted from Tjia, 1978, 1999) (1 = Bok Bak Fault; 2 = Kelau-Karak Fault; 3 = Lebir Fault; 4 = Bukit Tinggi Fault; 5 = Kuala Lumpur Fault; 6 = Mersing Fault; 7 = Ma Okil Fault; 8 = Lepar Fault).	7
1.5	Location map of seismological stations in Southern Thailand.	13
1.6	Location map of seismological stations in West Malaysia.	13
3.1	Summary of methodology used in this study.	27
4.1	Temporal distribution of local earthquakes in the instrumental period in Southern Thailand (1970-2020).	37
4.2	Epicenter map of Southern Thailand showing the earthquake distribution during the period 1970 – 2020 with different magnitude and focal depth values. Focal mechanisms of two largest events happened offshore Prachuap Khiri Khan (source: http://www.globalcmt.org/ CMTsearch.html) were added. Red lines (A-A’, B-B’, and C-C’) indicate the lines of cross section. Depth profiles of these lines can be seen in Figure 4.4 (a-c).	40

4.3 Epicenter map of Phuket Island showing the 2012 earthquake swarm and other earthquake events. A focal mechanism of the swarm's largest event occurred onshore the island (Pornsopin et al., 2012) was added. The red line (D-D') indicates the lines of cross section. Depth profiles can be seen in Figure 4.4 (d). 41

4.4 Vertical sections (depth profiles) of seismicity in Southern Thailand during the instrumental period from several lines: (a) Along the KMFZ, (b) Semi-parallel to and in between the KMFZ and RFZ, (c) Perpendicular to the RFZ and KMFZ, and (d) Across Phuket Island. The map showing cross section lines can be seen in Figures 4.2 and 4.3. The depth of Moho in this region was obtained from Naisagool et al. (2014), Tadapansawut et al. (2012), and Wongwai (2011). 42

4.5 (a) Number of earthquakes per day (grey bars; lower left-hand side scale) and local magnitude variation (circles; right-hand side scale) during the 2012 Phuket swarm; (b) Cumulative number of earthquakes (black dots) for the first seven days (first phase) of the swarm. 48

4.6 Seismotectonic map of Southern Thailand showing the relation between the seismicity with local tectonics. Faults and fault zones were mapped by Charusiri (1999). Focal mechanisms for several events (http://globalcmt.org/CMTsearch.html; Pornsopin et al., 2012) and hot spring manifestations (Ngansom and Duerrast, 2019) were added. RFZ=Ranong Fault Zone, KMFZ=Khlong Marui Fault Zone, KTFZ=Khlong Thom Fault Zone. 54

4.7 Temporal distribution of local earthquakes in the pre-instrumental period (recorded in 1922 and 1927) and in the instrumental period (recorded during 1978 to 2020) in Peninsular Malaysia. 59

4.8	(a) Epicenter map of West Malaysia (1922 – 2020); (b) Epicenter map of Bukit Tinggi earthquakes (2007 – 2009) with focal mechanisms of four events (Mat Said and Hara, 2012). Red lines (A-A', B-B', and C-C') indicate the lines of cross section. Depth profiles can be seen in Figure 4.9. Note: BBFZ = Bok Bak Fault Zone; BRS = Bentong – Raub Suture (Kelau-Karak Fault Zone); LbFZ = Lebir Fault Zone; BTFZ = Bukit Tinggi Fault Zone; KLFZ = Kuala Lumpur Fault Zone; MFZ = Mersing Fault Zone; MOFZ = Ma Okil Fault Zone; LpFZ = Lepar Fault Zone).	62
4.9	Vertical sections of seismicity in West Malaysia during 1922 - 2020 from several lines (A-A', B-B', and C-C'): (a) Depth profile A-A' with the trend NW-SE in the west of the region; (b) Depth profile B-B' with N-S-SE direction in the central part; and (c) Depth profile C-C' with W-E direction. The map showing cross section lines can be seen in Figures 4.8 (a).	63
4.10	(a) Number of earthquakes per month (grey bars; lower left-hand side scale) and local magnitude variation (circles; right-hand side scale) during the Bukit Tinggi swarm (2007-2009); (b) Cumulative number of earthquakes (black dots) for the first phase of the swarm (2007-2008).	67
4.11	Seismotectonic map of Peninsular Malaysia showing the relation between the seismicity and local tectonics. Faults and fault zones were mapped by Tjia (1978; 1999) and Department of Mineral and Geoscience Malaysia (2014). Focal mechanisms for several events in Bukit Tinggi area (Mat Said and Hara, 2012) and hot spring manifestations (Samsudin et al., 1997; Shuib, 2009) were added. BBFZ=Bok Bak Fault Zone; BRS=Bentong-Raub Suture (Kelau-Karak Fault Zone); LbFZ=Lebir Fault Zone; TFZ=Terengganu Fault Zone; LpFZ=Lepar Fault Zone; BTFZ=Bukit Tinggi Fault Zone; KLFZ=Kuala Lumpur Fault Zone; MFZ=Mersing Fault Zone; MOFZ=Ma Okil Fault Zone.	71

4.12 Graphs of time series of horizontal displacements in Phuket, Southern Thailand (1994-2018; Simons et al., 2019) and their relations with several large regional earthquakes near Sumatra and the cumulative number of local earthquakes. Numbers on top indicate the regional earthquakes: 1 = 2004 Sumatra-Andaman earthquake, 2 = 2005 Nias earthquake, 3 = 2007 Bengkulu earthquake, 4 = 2009 West Sumatra earthquake, and 5 = 2012 East Indian Ocean earthquakes. 77

4.13 Graphs of time series of horizontal displacements in Langkawi, Peninsular Malaysia (December 2004-January 2014; Gill et al., 2015) and their relations with several large regional earthquakes near Sumatra and the cumulative number of local earthquakes. Numbers on top indicate the regional earthquakes: 1 = 2004 Sumatra-Andaman earthquake, 2 = 2005 Nias earthquake, 3 = 2007 Bengkulu earthquake, 4 = 2009 West Sumatra earthquake, and 5 = 2012 East Indian Ocean earthquakes. 78

4.14 Maps of regional geodynamic situation in Southern Thailand and West Malaysia associated with several large earthquakes near Sumatra region: (a) Prior to the 2004 Sumatra-Andaman earthquake (inter-seismic); (b) Co- and post-seismic of the 2004 earthquake; (c) Co- and post-seismic of the 2005 Nias earthquake; (d) Co- and post-seismic of the 2007 Bengkulu earthquake; (e) Co- and post-seismic of the 2009 West Sumatra earthquake; and (f) Co- and post-seismic of the 2011 earthquakes. Red arrows indicate the directions of plate movements. Red areas indicate the rupture zones of regional earthquakes: 2004 (Ammon et al, 2005), 2005 (Walker et al., 2005), 2007 (Tsang et al., 2016), 2009 (Wiseman et al., 2012), and 2012 (Pollitz, 2012). 80

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation

AS	Aftershock
BTFZ	Bukit Tinggi Fault Zone
DMG	Department of Mineral and Geoscience, Malaysia
DMR	Department of Mineral Resources, Thailand
EMSC	European-Mediterranean Seismological Centre
ES	Earthquake swarm
FDSN	International Federation of Digital Seismograph Networks
FMS	Focal Mechanism Solution
FP1	Fault Plane 1
FP2	Fault Plane 2
FS	Foreshock
GCMT	Global Centroid Moment Tensor
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRC-PSU	Geophysics Research Center – Prince of Songkla University
IFSAR	Interferometric Synthetic Aperture Radar
ISC	International Seismological Center
KLFZ	Kuala Lumpur Fault Zone
KMFZ	Khlong Marui Fault Zone
KTFZ	Khlong Tom Fault Zone
MMD	Malaysian Meteorological Department (MetMalaysia)
MMI	Modified Mercalli Intensity
MS	Mainshock
OSL	Optically Stimulated Luminescence
PGA	Peak Ground Acceleration
RFZ	Ranong Fault Zone
RID	Royal Irrigation Department
SEISAN	Seismic Analysis Software

SEU	Seuliman Fault
SF	Sagang Fault
SFZ	Sumatra Fault Zone
SRTM-DEM	Shuttle Radar Topography Mission – Digital Elevation Model
SSZ	Sunda Subduction Zone
TL	Thermoluminescence
TMD	Thai Meteorological Department
USGS-NEIC	United States Geological Survey – National Earthquake Information Center
UTC	Universal Time Coordinated
WAF	West Andaman Fault

Symbol

K	Kurtosis
M	Magnitude
M_I	Intensity Magnitude
ML	Local Magnitude
M_o	Moment of earthquake
Mw	Moment Magnitude
mb	Body wave Magnitude
m_o	Normalized moment
Nm	Maximum daily number of earthquakes
S	Skewness/skew value
T	Duration of the earthquake sequence
t	Weighted mean time
μ_3	Third central moment of the sequence
μ_4	Forth central moment of the sequence
σ	standard deviation

LIST OF PAPERS AND PROCEEDINGS

Papers

1 Nazaruddin, D.A. and Duerrast, H. (2021). 2012 earthquake swarm in Phuket, Southern Thailand. *Chiang Mai Journal of Science*, 48 (2), 648-663.

2 Nazaruddin, D.A. and Duerrast, H. (2021). Intraplate earthquake occurrence and distribution in Peninsular Malaysia over the past 100 years. *SN Applied Sciences*, 3, 693. DOI: 10.1007/s42452-021-04686-2.

Proceedings

1 Nazaruddin, D.A. and Duerrast, H. (2018). Spatial distribution of shallow and intermediate earthquake in Southern Thailand after the 26 December 2004 Sumatra-Andaman earthquake. *Proceedings of the 8th International Conference on Applied Geophysics (Geophysics Songkhla 2018)*, 8-10 November 2018, Songkhla, Thailand.

2 Nazaruddin, D.A. and Duerrast, H. (2018). Implication of the 2004 Sumatra-Andaman earthquake to seismic hazards in Southern Thailand. *Proceedings of the 7th Asia Conference on Earthquake Engineering (ACEE)*, 22-25 November 2018, Bangkok, Thailand.

1. INTRODUCTION

This part contains the background information of the study with the emphasis on the regional tectonics and seismicity as well as local tectonics; data sources during pre-instrumental and instrumental periods; and the earthquake swarm as a special seismological behavior. Previous studies of earthquakes in Southern Thailand and Peninsular Malaysia were added in this part.

1.1 Background

According to the glossary of the seismological terms (https://earthquakescanada.nrcan.gc.ca/info-gen/glossa-en.php), the term of ‘earthquake’ is defined as the sudden release of the stored elastic energy due to the sudden fracture or movement of rocks along a fault. Some of this energy released as seismic waves which cause the ground shaking. The scientific study of earthquake and all related to it (e.g. seismic sources and the propagation of seismic waves through the Earth) is called ‘seismology’ and the scientist who studies earthquakes is called a ‘seismologist’. Meanwhile, ‘seismicity’ is defined as the earthquake occurrence in terms of space and time. Satake et al. (2017) defined ‘seismicity’ as the rate of earthquake occurrence or activity (in a region).

Earthquake is one of the natural hazards which can happen everywhere on the Earth. Most earthquakes (around 90%) are generated at plate margins (areas nearby plate boundaries) which are called ‘*interplate earthquakes*’. This type of earthquakes can delineate plate boundaries and show plate motions occurring there. Meanwhile, ‘*intraplate earthquakes*’ which take place in the interiors of tectonic plates and far from plate boundaries are less numerous and much rarer. However, intraplate earthquakes are now more studied to provide data and information when the plate tectonic theory does not fully explain tectonic processes (Stein and Wysession, 2003). Intraplate regions are generally vulnerable to smaller magnitude earthquakes which, among others, are caused by the reactivation of preexisting faults due to the long wavelength tectonic stress which comes from plate boundary forces (Gosh, 2019).

In the South East Asia region, the country like Indonesia, which is located in the plate margin, experiences a lot of tremors (high seismicity) and some of them are large quakes (M>8). Meanwhile, Thailand and Malaysia are situated in the plate interior (intraplate) of Sundaland (the SE Asian part of the Eurasian Plate) experiencing little seismic activity (low seismicity) and not so vulnerable to large earthquakes. However, intraplate earthquakes must also be taken into account for seismic hazard assessment, especially if they happen in a populated area equipped with critical facilities and other man-made structures. According to Lay and Wallace (1995), the distribution of this kind of seismicity has attracted the attention of seismologists in order to obtain precise earthquake locations and to study the faulting motions in the region.

1.1.1 Regional Tectonics and Seismicity

Southern Thailand and Peninsular Malaysia (also called West Malaysia), which become the study areas of this research, are occasionally affected by tremors originating from both regional and local tectonics. The regional sources primarily come from the Sunda Subduction Zone (SSZ) which is about 500-600 km to the nearest coast lines in both areas. Several large quakes took place along this subduction zone, such as the 26 December 2004 Sumatra-Andaman earthquake (M 9.1), the 28 March 2005 Nias earthquake (M 8.6), the 12 September 2007 Bengkulu earthquake (M 8.4), the 30 September 2009 Southern Sumatra earthquake (M 7.6), and the two subsequent 11 April 2012 East Indian Ocean earthquakes (M 8.6 and M 8.2) (Hayes et al., 2017). The SSZ is the contact between two plate combinations where one plate combination (the Indian and Australian Plates in this case) subducts beneath another plate combination (the Burma Microplate and Eurasian Plate) in NNE direction (approximately N010E) forming the Sunda Trench or Sunda Megathrust. This trench extends continuously from the south of Bangladesh and Burma in the north to the south along Andaman-Nicobar Islands and the west of Sumatra, and turn to the east along south of Java and Sumba Island with the total length of 5,500 km. Forces generated by the interactions of these plate margins have also yielded volcanic arcs and several compressional and oblique structures including of the Sumatra Fault Zone (SFZ). This major fault zone is a 1,900 km long dextral strike-slip fault running in NW-SE direction along the Sumatra Island and located to the east around 200 km away and parallel to the SSZ. In addition, there are several other regional oblique structures, such as the West Andaman Fault (WAF), the Seuliman Fault (SEU) and the Sagang Fault (SF) (Curray, 2005; Hutchison, 2007; Pulonggono, 2000; Sieh; 2007). Figure 1.1 illustrates the regional tectonic setting of Southern Thailand and West Malaysia.

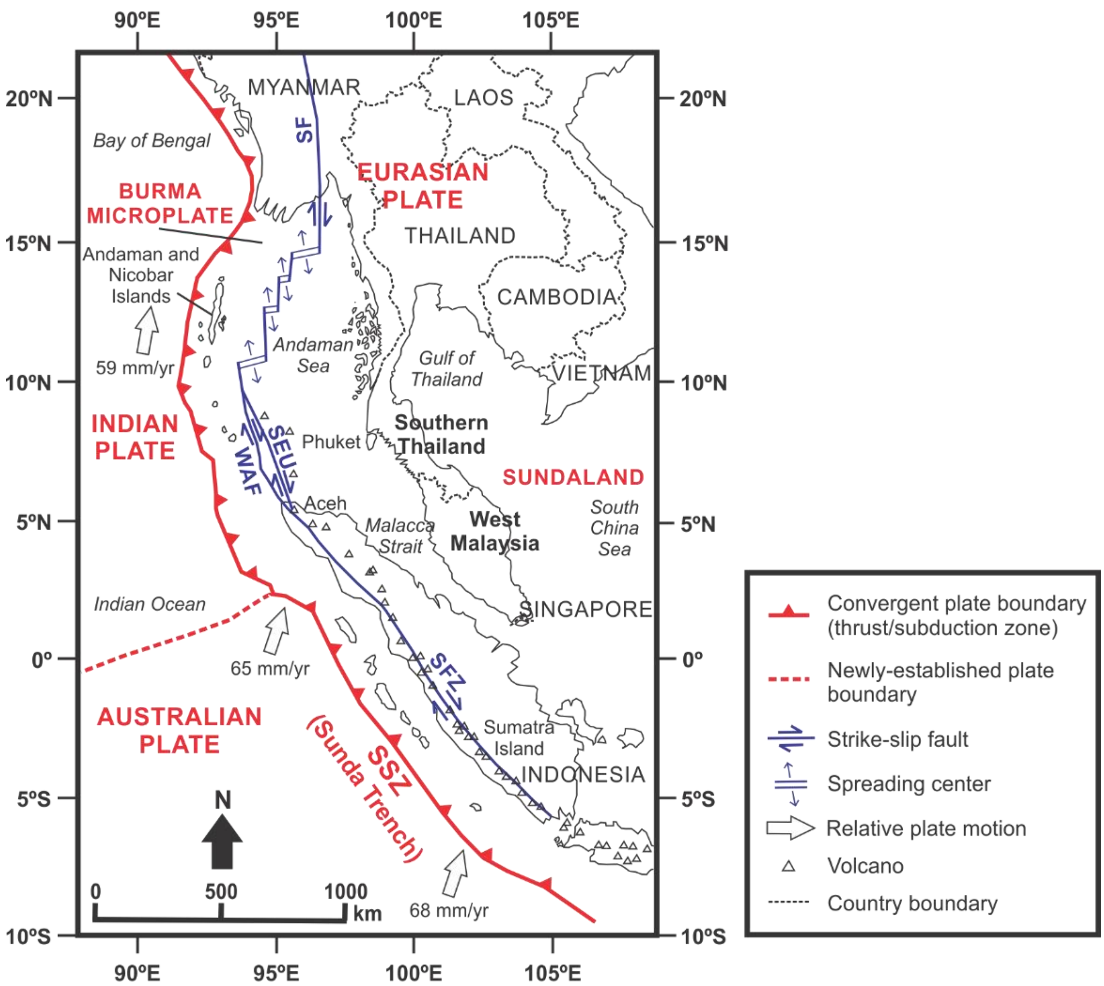


Figure 1.1 Regional tectonic setting surrounding Southern Thailand and West Malaysia where the Indian and Australian Plates subduct under the Burma Microplate and the larger Eurasian Plate forming the Sunda Subduction Zone (SSZ) or Sunda Trench, and other major tectonic features such as Sumatra Fault Zone (SFZ), West Andaman Fault (WAF), Seuliman Fault (SEU) and Sagaing Fault (SF) (Adapted from Curray, 2005).

Studies of seismic tomography (Hall and Spakman, 2015; Liu et al., 2018; Liu et al., 2019; Loi et al., 2018; Pesicek et al., 2008; Richards et al., 2007) revealed that the subducting slab of the SSZ extends until beneath Peninsular Malaysia at Upper Mantle depths (more than 600 km). In addition to the SSZ, there is a diffuse plate boundary between Indian and Australian Plates which is also regionally closed to Southern Thailand and Peninsular Malaysia and becomes one of regional earthquake sources. Nearby this nascent and newly-established plate boundary, there are reactivated fracture zones where several large earthquakes (M>8) occurred there, such as the two 11 April 2012 subsequent events in East Indian Ocean (M 8.6 and M 8.2). Last but not least, the volcanic arc in Sumatra is another seismic source that can cause volcanic earthquakes (Coudurier-Curveur et al., 2020; Hayes et al., 2017; Wah, 2011).

The two study areas are parts of the Thai-Malay Peninsula. The first study area is Southern Thailand, one of four regions and the southernmost part of Thailand. This region is situated between the latitude 5° N and 13° N and the longitude 97° E and 103° E. It elongates in a NNE-SSW direction in its upper part and bends into a NNW-SSE in its lower part. It has the maximum length of almost 1,000 km and breadth of ~220 km. This region is surrounded by the Andaman Sea in the west, the Gulf of Thailand in the east, the Central Thailand region in the north and extends south to the border with Malaysia. Meanwhile the second study area, West Malaysia, is one of Malaysia’s two regions and is located between the latitude 1° N and 7° N and the longitude 99° E and 105° E. It is elongated in a general NNW-SSE direction (parallel to its main structural trend) with a maximum length of ~750 km and breath of ~330 km. It is surrounded by the Malacca Strait and the South China Sea in the west and the east, respectively. West Malaysia extends to the north to the border with Southern Thailand and to the south with the narrow Johor Strait. Figure 1.2 shows the detailed geographic location of both areas.

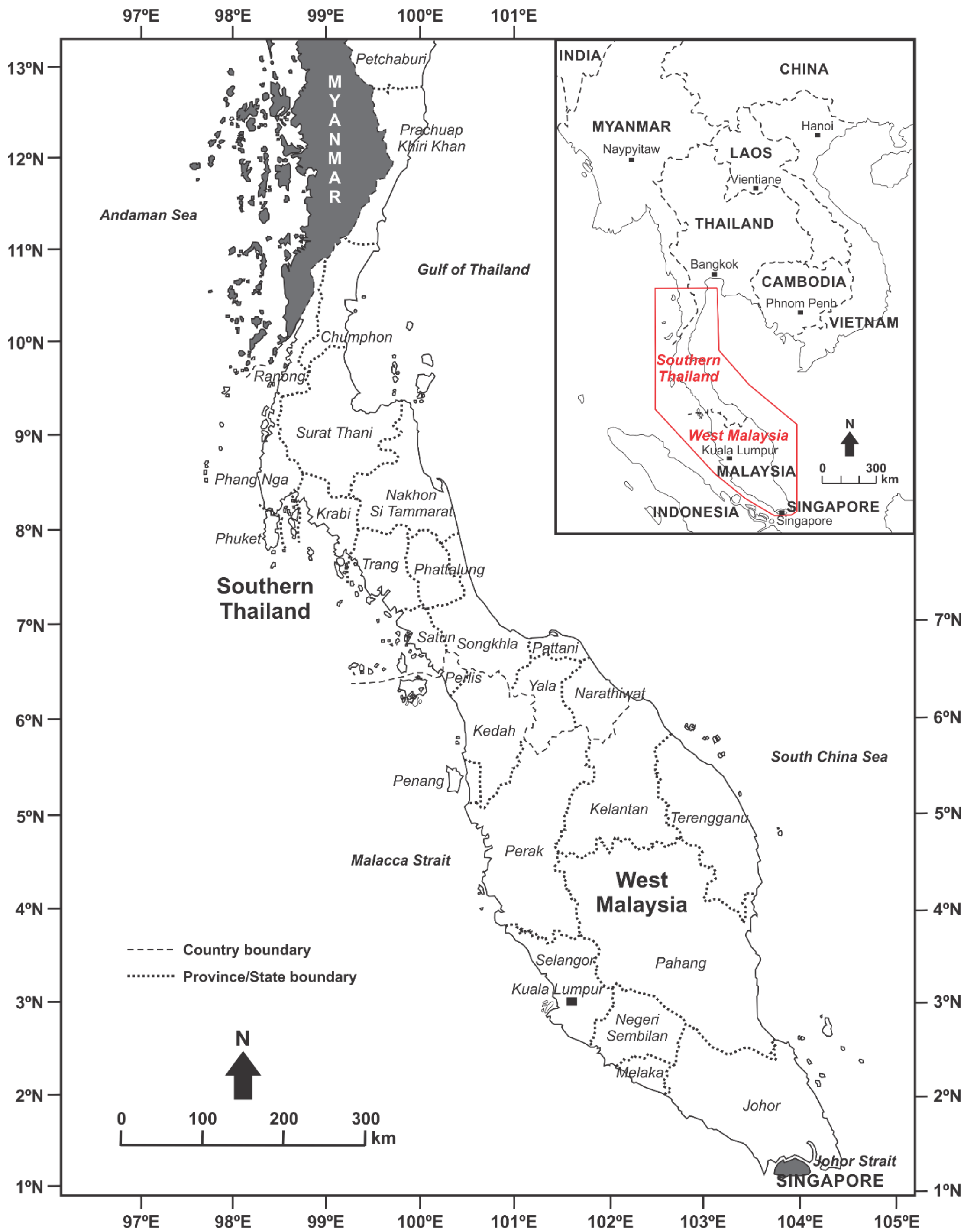


Figure 1.2 Location map of Southern Thailand and West Malaysia including their provinces or states.

1.1.2 Local Tectonics

For local earthquake origins, there are several local active faults (and fault zones) in both study areas. Charusiri et al. (1999) revealed that there are several active fault zones in Southern Thailand, such as Ranong, Khlong Marui, and Khlong Thom Fault Zones in the central Southern Thailand, and Khok Po, Saba Yoi, Yala, and Betong Fault Zones in the southernmost of Thailand. However, the Ranong and Khlong Marui Fault Zones (RFZ and KMFZ) are the most major and prominent active fault zones which associate with the seismic hazard in Southern Thailand. These two active strike-slip fault zones cross the region extending from the Andaman Sea to the Gulf of Thailand in the relatively NNE-SSW direction. Although they have not been traced well offshore, the two fault zones appear to intersect or converge in the northern Gulf of Thailand under a thick cover of late Tertiary sedimentary rocks (Maliwan et al., 2015; Morley et al., 2011; Ridd et al., 2011; Watkinson et al., 2008). Prior to the 2004 Sumatra-Andaman earthquake, these two fault zones were considered as dormant (Duerrast et al., 2007). Figure 1.3 shows the KMFZ and RFZ in the geological map of Southern Thailand.

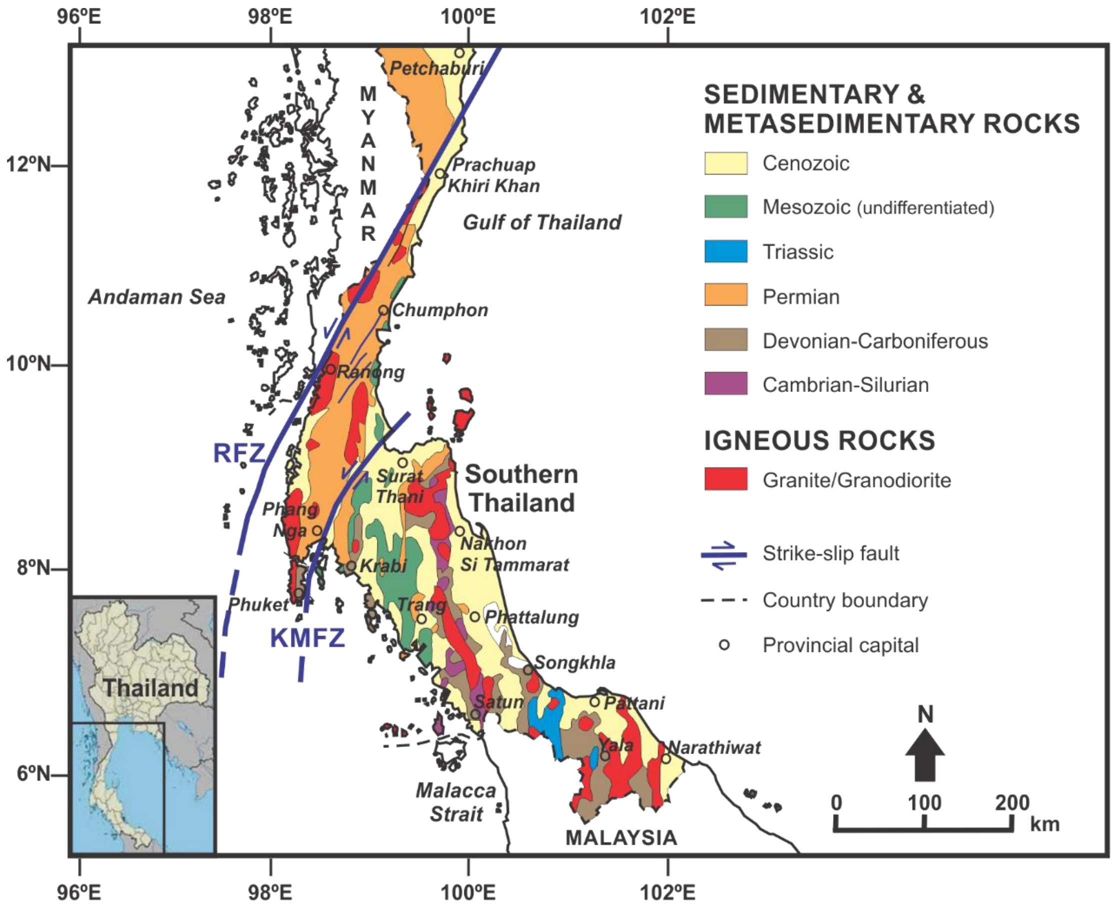


Figure 1.3 Geological map of Southern Thailand region (modified from Ridd et al., 2011).

Faults and fault zones in West Malaysia are commonly in NW-SE trends and previously stated inactive. Tjia (1978, 1999) recognized eight large, potentially active strike-slip faults within this region: Bok Bak Fault, Kelau–Karak Fault, Lebir Fault, Bukit Tinggi Fault, Kuala Lumpur Fault, Mersing Fault, Ma Okil Fault, and Lepar Fault. All these fault lines are shown in the geological map of West Malaysia (Figure 1.4). Meanwhile, the Department of Mineral and Geoscience Malaysia (2014) listed seven major faults within the region: Bok Bak Fault, Lebir Fault, Terengganu Fault, Bukit Tinggi Fault, Kuala Lumpur Fault, Lepar Fault, and Mersing Fault. According to Shuib et al. (2009, 2017a), the Bukit Tinggi and Kuala Lumpur Fault Zones (BTFZ and KLFZ) formed the most active fault zones that lay within this region.

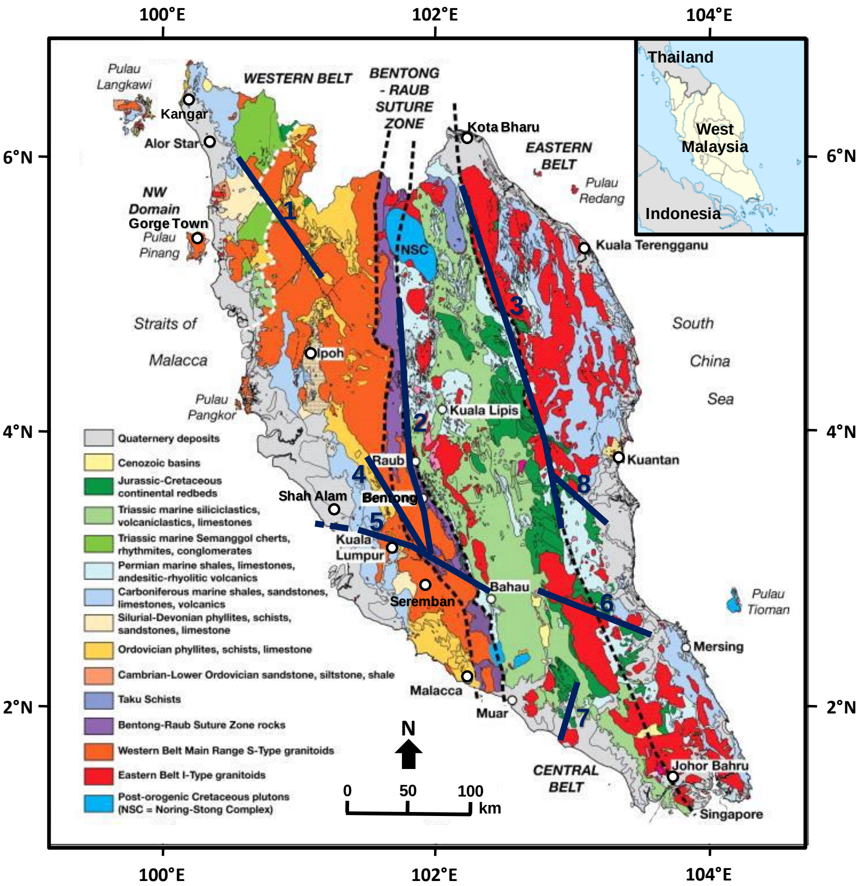


Figure 1.4 Geological map of West Malaysia region (Metcalfe, 2012) with the local faults (adapted from Tjia, 1978, 1999) (1 = Bok Bak Fault; 2 = Kelau-Karak Fault; 3 = Lebir Fault; 4 = Bukit Tinggi Fault; 5 = Kuala Lumpur Fault; 6 = Mersing Fault; 7 = Ma Okil Fault; 8 = Lepar Fault).

1.2 Data Sources

Each region in the world has a specific seismicity chronology which is usually subdivided into three types: paleoseismicity, historical seismicity (both happened in the pre-instrumental period), and instrumental seismicity. The seismicity study and seismic hazard assessment in a region could be more reliable if the seismic monitoring taking all these types of seismicity.

1.2.1 Pre-Instrumental Period

Other than observing the instrumental seismicity, earthquakes of the pre-instrumental period are also essential to the evaluation of seismicity in a region. This period comprises paleo- and historical earthquakes which hold clues about future earthquakes in a region. Paleoearthquakes (or past/ancient earthquakes that occurred in the prehistorical time) and paleoseismicity have been studied in the field of paleoseismology, with emphasize on their location, timing, and size (McCalpin and Nelson, 2009). Paleoseismology works with geological evidences created during each paleoearthquake including the past behavior of active faults. Therefore, paleoseismology is essential for characterizing those faults. Exploring of fault zones and their exposures by trenching method has become a common practice in this field (Wallace, 2009).

Meanwhile, the historical earthquakes are a list of significant earthquakes took place before the instrumental recording era. The earthquake parameters were only deduced from historical sources and not instrumental recordings. The parameters generally include the occurring time, epicenter location, magnitude, and maximum intensity (Wang et al., 2017). The knowledge basis on historical earthquakes is the contemporary written documentation. Many historical earthquakes were mentioned in various sources written immediately after the quakes, or years or centuries later, and most of them did not include any analysis or deeper scientific study (Eisinger et al., 1992). Sources of historical earthquakes include eyewitness accounts, local and regional newspapers, archival documents, history books, various reposts by government agencies, and travellers’ diaries (Bilham, 2019;

Rubenach et al., 2020). This study compiled and analyzed all literatures discussing on paleo- and historical earthquakes in both Southern Thailand and West Malaysia.

1.2.2 Instrumental Period

This study provides earthquake catalogues of instrumental period which are the compilation of local event data from several seismological networks in both Southern Thailand and West Malaysia regions. Shortly after the occurrence of the Mw 9.1 Sumatra-Andaman earthquake on 26 December 2004, earthquake monitoring in Southern Thailand have been conducted since early 2005 by a four-station temporary network established by the Geophysics Research Center – Prince of Songkla University (GRC–PSU; http://geophysicspsu.sci.psu.ac.th/index.php) in collaboration with the Thailand's Department of Mineral Resources (DMR; http://www.dmr.go.th/main.php?filename=Index___En). Two agencies in Thailand, the Royal Irrigation Department (RID; https://www.rid.go.th/eng/) and Thai Meteorological Department (TMD; https://www.tmd.go.th/en/), have also monitored earthquake activity in Thailand through their own permanent networks. RID has the Royal Irrigation Department network (with International Federation of Digital Seismograph Networks/FDSN code of TG) consisting of five stations installed in Southern Thailand. Meanwhile, TMD operates Thai Seismic Monitoring Network (with FDSN code of TM) comprising ten stations operated in the southern part of the country. TMD's earthquake catalogue can also be accessed at http: https://earthquake.tmd.go.th/inside.html. The first seismological (analog) station of TMD was installed at Chiang Mai (CHG) in 1963; meanwhile the first station installed in Southern Thailand is in 1965 at Songkhla (SKLT). Later, the department has improved and expanded its network in the region by installing other (analog) stations in Phuket and Prachuap Khiri Khan. After 2004, TMD has established a new automatic earthquake monitoring system in the whole Thailand within two phases, phase 1 (in 2006) with 15 stations and phase 2 (in 2009) with 25 stations. From totally 40 digital stations, ten stations were set up in Southern Thailand (Sitthiworanun, 2010; Vanichnukhroh, 2013). Earthquake data including digital seismograms of Southern Thailand have been requested officially and collected from all above-mentioned agencies.

The Malaysian Meteorological Department (MMD, previously the Malaysian Meteorological Service or MMS, now famously called MetMalaysia; https://www.met.gov.my/) is the government agency which is responsible for the earthquake monitoring in Malaysia. The MMD started the instrumental recording of seismic events in Malaysia in 1975 by installing three seismological stations in West Malaysia at Petaling Jaya (KLM), Kluang (KGM), and Ipoh (IPM), and a station in East Malaysia at Kota Kinabalu (KKM). Kuala Terengganu (KTM) and Kuala Lumpur (FRM) stations were installed later in 1986 and 1992, respectively (Che Abas, 2001). The department has improved its network by installing other stations, mainly after 2004. The department operates Malaysian National Seismic Network (with FDSN code of MY) currently consisting of 30 stations already installed in West Malaysia. For this study, local earthquake data has been requested from the department. According to MMD (personal communication), no calibration has been done for their stations. Some of the stations are sitting on rocks and some others on soft soils and built on vaults. Loi et al. (2018) listed several stations installed on rocks and soft soils as follow: hard rock/granite (FRM, IPM, KGM, KOM, KTM, KUM, BRSM, DTSM, GTSM, JBSM, PYSM_B0, SRSM), sandstone (JRM), and soft soil (BKSM, KNSM, PJSM, SASM, UYSM).

This study analyzed digital seismograms from all these data sources both from Southern Thailand and West Malaysia. Only seismogram data recorded by three or more stations were selected to be analyzed in this study. Table 1.1 contains information on seismological stations in both regions used in this study. Locations of all stations in these regions are shown in Figure 1.5 and 1.6, respectively.

Table 1.1 Information on seismological stations for the monitoring of earthquake activities in Southern Thailand and West Malaysia (for this study) (Duerrast et al., 2007; MMD, personal communication; RID, personal communication; Vanichnukhroh, 2013).

No.	**Station Code**	**Location**	**Lat. (°N)**	**Long. (°E)**	**Elevation (m)**
GRC-PSU and DMR network					
1	PSUHY	Muang District, Phang Nga	8.4343	98.5068	85

		Province			
2	PNG2	Thap Put District, Phang Nga Province	8.5576	98.6604	55
3	PSUNM	Prince of Songkla University, Phuket Campus, Khatu District, Phuket Province	7.891361	98.3511	4
4	TBK	Tanbokkoranee National Park, Ao Luek District, Krabi Province	8.388967	98.736239	60
RID network					
1	TSJK	Khlong Cha Kra Reservoir, Thap Sakae District, Prachuap Khiri Khan Province	11.540260	99.495789	77
2	TSKA	Khuring Sub-district, Tha Sae District, Chumphon Province	10.716182	99.161580	78
3	TSKT	Khuring Sub-district, Tha Sae District, Chumphon Province	10.716182	99.161580	78
4	TSLC	Lam Chu Weir, Bang Saphan Noi District, Prachuap Khiri Khan Province	11.019690	99.424271	14
5	TSPJ	Kra Buri District, Ranong Province	10.522430	98.905159	44
TMD network					
1	KRAB	Krabi Province	8.2215	99.631013	58
2	PHET	Phetchaburi Province	12.91331	99.62675	101
3	PKDT	Phuket Province	7.892	98.335	53
4	PRAC	Prachuap Khiri Khan Province	12.47263	99.79288	54
5	RNTT	Ranong Province	9.3904	98.4778	38
6	SKLT	Songkhla Province	7.1735	100.6188	14
7	SRIT	Nakhon Si Tammarat Province	8.59549	99.60196	58
8	SURA	Surat Thani Province	9.16634	99.62945	-5
9	SURT	Surat Thani Province	8.9577	98.795	26
10	TRTT	Trang Province	7.8362	99.6912	71
MMD network					
1	BKM	Batu Kikir, Kuala Pilah, Negeri Sembilan	2.858	102.271	135
2	FRM	FRIM Kepong, Kuala Lumpur	3.237	101.625	97
3	IPM	Ipoh, Perak	4.480	101.025	247
4	JRM	Jerantut, Pahang	3.887	102.477	55

5	KGM	Kluang, Johor	2.016	103.319	103
6	KOM	Kota Tinggi, Johor	1.792	103.847	49
7	KRM	Kuala Krai, Kelantan	5.515	102.193	95
8	KTM	Kuala Terengganu, Terengganu	5.328	103.136	33
9	KUM	Kulim, Kedah	5.290	100.649	74
10	TGM	Temenggor, Perak	5.411	101.293	280
11	BHSM	Behrang, Perak	3.766	101.514	90
12	BKSM	Bukit Kiara, Kuala Lumpur	3.147	101.645	66
13	BRSM	Beranang, Selangor	2.902	101.863	73
14	BUSM	Bukit Mertajam, Penang	5.397	100.501	17
15	DTSM	Dusun Tua, Selangor	3.132	101.840	67
16	GTSM	Goh Tong Jaya, Pahang	3.390	101.775	844
17	JBSM	Janda Baik, Pahang	3.320	101.863	577
18	JPSM	Jempol, Negeri Sembilan	2.899	102.408	62
19	KNSM	Kundang, Selangor	3.270	101.515	27
20	KPSM	Kuala Pilah, Negeri Sembilan	2.727	102.249	109
21	KUSM	Kuala Nerang, Kedah	6.252	100.611	27
22	LGSM	Langkawi, Kedah	6.305	99.781	66
23	PJSM	Wetland, Putrajaya	2.968	101.695	45
24	PYSM_B0	Perbadanan Putrajaya – Basement, Putrajaya	2.918	101.684	74
25	PYSM_B9	Perbadanan Putrajaya – Level 9, Putrajaya	2.918	101.684	74
26	SASM	Shah Alam, Selangor	3.097	101.512	28
27	SRSM	Serendah, Selangor	3.365	101.618	61
28	TPSM	Taiping, Perak	4.867	100.759	255
29	TRSM	Tanah Rata, Cameron Highlands, Pahang	4.472	101.377	1,398
30	UYSM	Ulu Yam, Selangor	3.272	101.685	84

Other than the aforementioned networks, the composite earthquake catalogues for this study have been complimented by earthquake data from global networks, such as the International Seismological Centre (ISC; http://www.isc.ac.uk/), United State Geological Survey–National Earthquake Information Center (USGS-NEIC; https://www.usgs.gov/natural-hazards/earthquake-hazards/national-earthquake-information-center-neic), and the European Mediterranean Seismological Centre

(EMSC; https://www.emsc-csem.org/). Table 1.2 summarizes all information about datasets of local events used in this study.

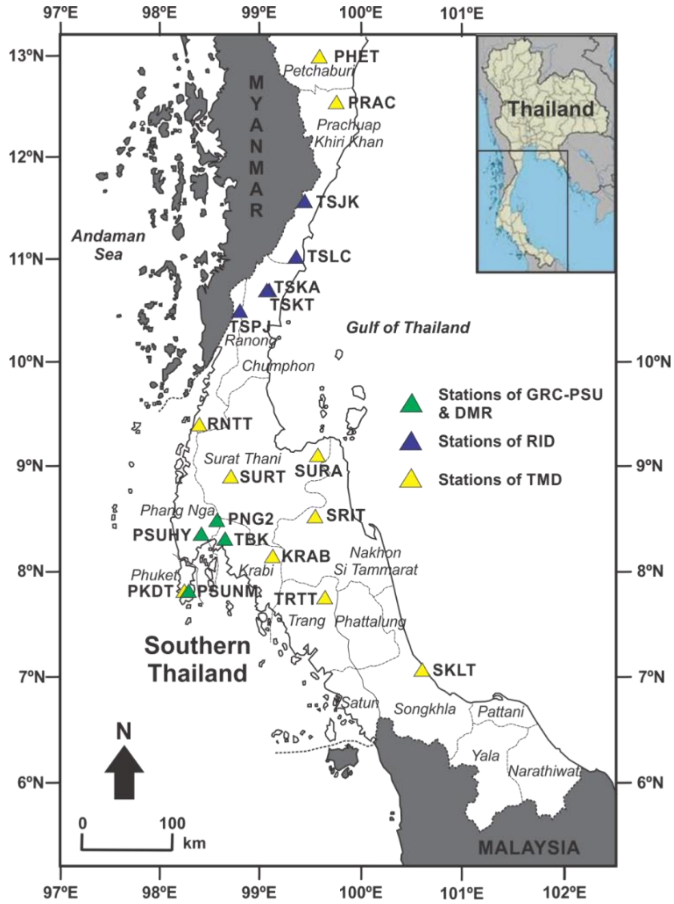


Figure 1.5 Location map of seismological stations in Southern Thailand.

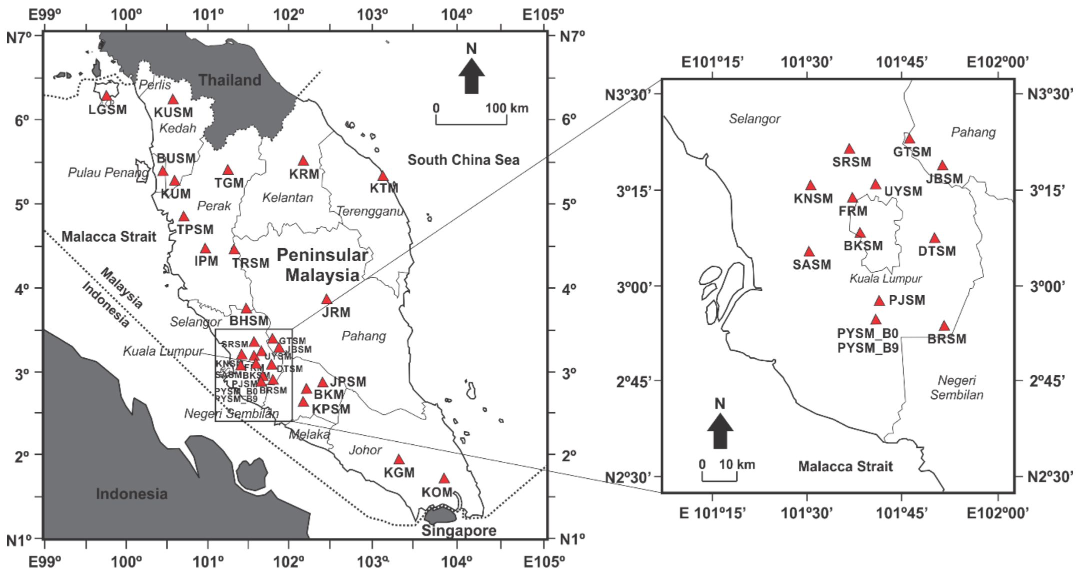


Figure 1.6 Location map of MMD's seismological stations in West Malaysia.

Table 1.2 Information on datasets of local earthquakes used in this study.

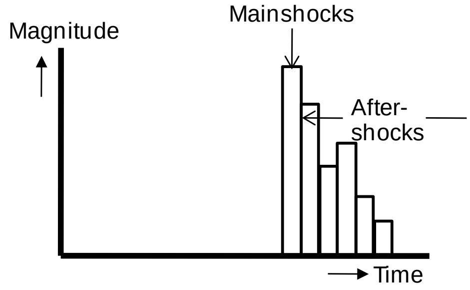
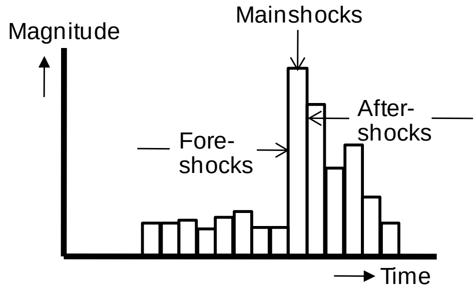
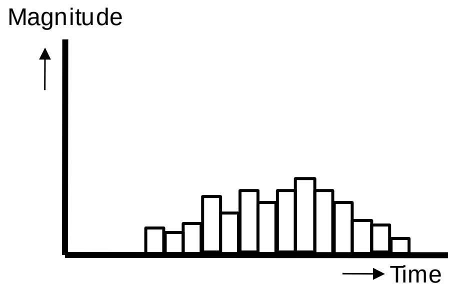
Area	**Dataset**	**Data Period**	**No. of Events**	**No. of analyzed Seismograms**
Southern Thailand	Dataset 1: GRC-PSU & DMR	14 Jan 2005 – 11 Apr 2005	111	111
	Dataset 2: RID	12 May 2008 – 24 May 2013	4	4
	Dataset 3: TMD	4 May 2008 – 2 Jul 2020	96	59
	Additional dataset: previous studies, ISC, USGS-NEIC, and EMSC	19 Jan 1970 – 22 May 2019	16	0
	Total		*227*	*174*
West Malaysia	Dataset 4: MMD	30 Nov 2007 – 23 Feb 2016	33	20
	Additional dataset: previous studies, ISC, USGS-NEIC, and EMSC	31 Jan 1922 – 26 Feb 2020	25	0
	Total		*58*	*20*

1.3 Earthquake Swarm

There are at least three different types of earthquake sequences: the mainshock-aftershock (MS-AS), the foreshock-mainshock-aftershock (FS-MS-AS), and the earthquake swarm (ES). The MS-AS sequence is a multiple earthquake with one prominent larger event (the mainshock) followed by a series of smaller aftershocks as the Earth adjusts the stress changes caused by the mainshock. This is the most common type of earthquake sequences. Similar to this but with smaller events take place before the mainshock, it is called a FS-MS-AS sequence. Meanwhile, an ES is a sequence or a group of earthquakes occurring in a certain region within a certain period of time (mostly days or months, but even several years) without a predominant principle earthquake or mainshock (Mogi, 1963; 1967). The term “earthquake swarm” has been used and well documented since the early of the 19th Century. Credner (1876) and Knett (1899) used the term *“Erdbebenschwarm”* and *“Schwarmbeben”* (both in German, to refer the “earthquake swarm”) to describe the seismicity in West Bohemia and Vogtland at the border of Czech Republic and Germany in 1875 and 1824, respectively. They used the terms due to the distribution of the earthquakes giving the impression of an accumulation like a bee swarm when plotted on a map, a cross section, or a 3D model. Mogi (1963, 1967) carried out experimental studies on fracture phenomena which seem to have close relations with the earthquake occurrence. Experimental results showed that the differences between these types of earthquake sequences are due to the structural states of the medium and the distribution of the applied stress. The MS-AS sequence takes place in a homogeneous medium under the uniform applied stress. The FS-MS-AS sequence happens when the medium and the applied stress are not uniform. The ES occurs in a highly heterogeneous medium (i.e. highly fractured area) under the application of a concentrated stress (Table 1.3).

Earthquake swarms happened globally in a variety of geological settings and with different origins. Volcanic or magmatic activities can generate earthquake swarms, such as the 1960 Chile (Tillotson, 1962), the 2000 Izu Islands, Japan (Toda et al., 2002), the 2008 West Bohemia/Vogtland, Czech Republic/Germany (Fischer et al., 2010), the 2011 El Hierro, Canary Islands, Spain (López et al., 2017), the 2015-2016 West Halmahera, Indonesia (Passarelli et al., 2018), and the 2018 Yellowstone, USA (Ghose, 2018) earthquake series. Tectonic activities can also trigger earthquake swarms, such as the 1965-1967 Matsushiro, Japan (Ichikawa, 1969; Mogi, 1988), the 1969 Gulf of California, USA (Thatcher and Brune, 1971), the 2003-2004 and 2012-2015 Ubaya Valley, French (Jenatton et al., 2007; Thouvenot et al., 2016), the 2017 Maurienne Valley, French (Langlais et al., 2019), and the 2018 Maharashtra, India (Mahesh et al., 2020) earthquakes. Another origin of earthquake swarms is a combination of volcanic and tectonic activities, such as the 1994-1995 Hengill triple junction, Iceland (Sigmundsson et al., 1997), the 2005 Andaman Sea (Kundu et al., 2012) and the 2018-2019 east of Mayotte, Comoros islands (Lemoine et al., 2019) earthquakes.

Table 1.3 Main types of earthquake sequences and their relations to structures of medium and applied stress (adapted from Mogi, 1963, 1967).

Type of Earthquake Sequence	**Pattern of Earthquake Sequence**	**Structure of Material**	**Applied Stress**
Type-1 (MS-AS)		Homogenous	(Nearly) uniform
Type-2 (FS-MS-AS)		Heterogeneous	Not uniform
Type-3 (ES)		Highly heterogeneous	Very concentrated

Earthquake swarms have also been widely associated with the presence of fluid or groundwater intrusion (overpressure) to the faults, such as the 1989 earthquake swarm beneath the Mammoth Mountain, California, USA (Špičák, 2000) and the 2000 Vogtland/NW Bohemia (Hainzl, 2004). Meanwhile, several artificially induced earthquake swarms occurred due to man-made management of fluids (e.g. water pumping, injection, and production), such as the Larderello (Italy) and the Coso (California, USA) geothermal fields, and the NE Bavaria deep drilling project, Germany (Špičák, 2000).

Qualitatively, earthquake swarms are different from other earthquake sequences due to their unique seismicity patterns such as they are a cluster of relatively similar-sized earthquakes (commonly small to moderate earthquakes) rather than only one clear mainshock, the highest magnitude event usually happens later in the sequence, and they mostly take place in shallow depths (Horálek et al., 2015; Roland and McGuire, 2009).

The ES type has been distinguished from other earthquake sequences by the following quantitative empirical measure: 1) Total number of earthquakes in a sequence exceeds 10, and 2) $Nm/\sqrt{T} > 2$, where Nm is the maximum daily number of events and T is the duration of the earthquake sequence (in days) (Mogi, 1963). Another quantitative way to identify an ES should be conducted by calculating the skewness of the seismic moment release history. To calculate a skew value for a swarm, the duration of the swarm as the period of time during which the seismicity rate is at least 20 per cent of its maximum value should be defined. This 20 per cent seismicity rate provides a consistent way to define the start (t_1; the occurrence time since the beginning of the sequence) and end of the swarm. The seismicity rate is calculated using 2-hr time bins (Roland and McGuire, 2009). The moment for each event M_o (i) is estimated from $M_o\ (i) = 10^{(1.5*ML(i)+9.1)}\ Nm$ using the definition of Mw (Kanamori, 1977), assuming that the ML is equivalent to Mw. The individual moment is normalized to the sum of the moments of all events [m_o (i)] and the centroid time of moment release is obtained from the weighted mean time (t; representing the centroid time of moment release) with the respective equations:

$$m_0\,(i) = \frac{M_o\,(i)}{\sum_1^N M_o\,(I)}$$

$$t = \frac{\sum_1^N t_i \,.\, M_o\,(i)}{\sum_1^N M_o\,(I)}$$

The third central moment of the sequence (μ_3) and the standard deviation (σ) are determined by the respective equations:

$$\mu_3 = \sum_{1}^{N} (t_i - t)^3 \, m_o \, (i)$$

$$\sigma = \sqrt{\sum_{1}^{N} (t_i - t)^2 \, m_o \, (i)}$$

So, the skewness or skew value (S) of seismic moment release history for an earthquake sequence can be calculated as:

$$\mathrm{S} = \frac{\mu_3}{\sigma^3}$$

Mesimeri et al. (2019) proposed a new approach to distinguish the common MS-AS sequence from the ES by extending quantitative criteria. In addition to the value of skewness of seismic moment release history which characterizes the timing of the moment release in an earthquake sequence, the value of kurtosis needs also to be considered to quantify the distribution of moment for all events. The forth central moment of the sequence (μ_4) is determined by the following equation:

$$\mu_4 = \sum_{1}^{N} (t_i - t)^4 \, m_o \, (i)$$

So, the kurtosis (K) of seismic moment release history for an earthquake sequence can be calculated as:

$$\mathrm{K} = \frac{\mu_4}{\sigma^4}$$

The ES sequences commonly have negative to low positive values of Skewness and low positive values of Kurtosis, meanwhile the MS-AS sequences commonly have higher values of Skewness and Kurtosis. Several studies discovered the values of S and K to distinguish the ESs from the MS-AS sequences. Mesimeri et al. (2013, 2015, 2017) showed that ESs have low values of Skewness (S<2) and Kurtosis (K<10) contrary to MS-AS sequences which have higher values (S>25 and K>700). Mesimeri et al. (2019) found that the ESs have the values of -3.5<S<3.5 and K<10, whereas the MS-AS sequences have the values of S>3.5 and K>22. Several other studies revealed that the ESs have the S values between -11.1 to 33.3 (Roland and McGuire, 2009), $-10<S<4$ (Chen and Shearer, 2011), and $-5<S<5$ (Zhang and Shearer, 2016). The discrimination is then validated by taking into consideration the occurrence time of the largest event in the sequence and the difference in magnitude between the two largest events (Mesimeri et al., 2019; Roland and McGuire, 2009). In the MS-AS sequences, the magnitudes of the aftershocks are usually lower one or more unit than that of the mainshock, meanwhile in the swarm sequence the magnitude difference between two largest events is usually less than one unit (Jakoubková, 2018).

An ES can occur as a single phase during a very short period, e.g. the 6-day 2005 Andaman Sea (Kundu et al., 2012). An ES can also occur as several phases based on its temporal and spatial distribution with days to months of gap durations between phases, e.g. the 1965-1967 Matsushiro (Japan) swarm with four phases (Mogi, 1988), the 2003-2004 Ubaye (French Alps) swarm with 14 phases (Jenatton et al., 2007), the 2008 West Bohemia/Vogtland (Czech/Germany) swarm with nine phases (Fischer et al., 2010), and the 2015-2016 Jailolo Volcano (Halmahera, Indonesia) swarm with two phases (Passareli et al., 2018).

In addition to the earthquake swarms, there is a swarm-like activity called a “mini swarm”. Although earthquake swarms and mini swarms have similarity in general characteristics and origins, however, mini swarms are different from the common swarms due to their lesser number of event and lower magnitude values (Fischer and Horálek, 2003; Jakoubková, 2013). Mini swarms can also appear as compliments of the normal swarms (e.g. Čermáková and Horálek, 2015; Jakoubková, 2013). Several examples of mini swarms are as follows: six earthquakes shook the River City in the SW Wanganui (New Zealand) on 29 October 2012 with the largest magnitude of M 4.4 (Emerson, 2012); three earthquakes (M 3.7, M 3.4, and M 3.1) rattled an area in NW of Mount St. Helens (USA) on 23 August 2013 due to tectonic origin (Bowder, 2013); and eight earthquakes happened in Rotorua (New Zealand) on 30 August 2013 with the largest magnitude of 2.7 (Radio New Zealand, 2013). Fischer and Horálek (2003) and Grimwood (2017) used the term “micro swarm” for the swarm-like sequences took place in the NW Bohemia/Vogtland (Czech-German border) for the period 1991-2001 and near Stroud in Lincoln County (USA) on 14 July 2017, respectively.

1.4 Previous Studies

For a long time, Southern Thailand and West Malaysia have been recognized as low seismicity regions. These areas are only occasionally affected by tremors originating from regional earthquake sources, such as the SSZ and the SFZ. The motions produced by these distant earthquakes were attenuated through distances up to 1,000 km and still can be felt particularly by residents of high-rise buildings. Local events were still relatively less and local faults were relatively not too active in these two regions. Therefore, the study about earthquakes in these neighboring regions was not a popular topic previously. Otherwise, the Northwestern Thailand and East Malaysia regions are subjected to the highest seismic hazard in respective countries (Adnan et al., 2002, 2004; Araghi et al., 2014; Balendra and Li, 2008; Charusiri et al., 1999; Che Abas, 2001; Lat, 2007; Lukkunaprasit, 1993; Marto et al., 2013; Nabilah and Balendra, 2012; Ornthammarath et al., 2010; Pailoplee, 2014; Raj, 1994; Shoushtari et al., 2018; Sun and Pan, 1995; Sutiwanich et al., 2012; Wah, 2011). However, after the 2004 Sumatra-Andaman earthquake (M 9.1), the local seismicity in both regions have increased significantly by the occurrence of plenty of local events mostly took place in the vicinity of their respective local active fault zones.

1.4.1 Previous Studies on Seismicity in Southern Thailand

There were several previous studies on paleoseismology have been carried out in Southern Thailand, such as RID (2009), Sutiwanich (2010), Keawnaungmoon (2010), Pananont et al. (2010), Thipyopass (2010), and Noppradit (2013). However, there was no large significant earthquake happened in this region during the historical period as stated by Nutalaya and Sodsri (1983), Nutalaya et al. (1985), and Prachuab (1988). Meanwhile, there were only a few local earthquakes recorded instrumentally in this region before 2004 as reported by Nutalaya and Sodsri (1983) and Shrestha (1987). Sections 3.1 and 3.2 discuss in details about the pre-instrumental and instrumental seismicity of this region, respectively. Charusiri et al. (1999) created seismic zoning map of Thailand and showed that the lower Southern Thailand was categorized as Zone 0 which corresponds to no seismicity and the upper part of this region as Zone 1 which corresponds to mild quake intensity.

After the 26 December 2004 earthquake, a number of small events (micro earthquakes) have been recorded in Southern Thailand due to possible reactivation of its faults and fault zones (Duerrast et al., 2007; Morley et al., 2011). Therefore, this region is not tectonically stable anymore as had previously been thought (Sutiwanich et al., 2012). Department of Mineral Resources (2014) produced seismic hazard map of the country in which the two active fault zones in the region (KMFZ and RFZ) are categorized as Zone 4 which is a zone of seismic hazard intensity level VII of Modified Mercalli Intensity (MMI) scale. This zone, which is the highest intensity in Thailand, is defined as a zone of intermediate and high risk.

Several other researchers have studied the inter-relationships between active faults, seismicity and seismic hazard in Thailand and Southern Thailand region, such as Lukkunaprasit (1993), Charusiri et al. (1999), Duerrast et al. (2007), Pailoplee et al. (2009), Ornthammarath et al. (2010), Sutiwanich et al. (2012), Kosuwan et al. (2013), and Pailoplee (2014). Pongvithayapanu and Teachavorasinskun (2010) studied earthquakes with the epicenters off the east coast of Prachuab Khiri Khan in the Gulf of Thailand (within the RFZ and previously classified as the low seismic area) in between September 2006 to March 2007 with the magnitude M=3.5-5.0. Pornsopin et al. (2012) analyzed the 16 April 2012 earthquake (M 4.3) in Phuket. Kosuwan et al. (2013) stated that the biggest earthquake in Southern Thailand occurred on 7 October 2006 at 21:12 UTC offshore (in the east of) Prachuap Khiri Khan Province in the Gulf of Thailand, which was associated with the RFZ. Meanwhile, among the biggest earthquake corresponds to the KMFZ took place on 16 April 2012 (M 4.3) in Thalang district, Phuket which can be felt throughout the island. Saetang et al. (2014) studied the faults in the KMFZ and stated that the recent seismic hazard map for Southern Thailand shows the maximum ground motion is located along the KMFZ.

1.4.2 Previous Studies on Seismicity in Peninsular Malaysia

Paleoseismological investigations in Peninsular Malaysia have been conducted by a few researchers, such as Ng et al. (2009), Shuib (2013), and Shuib et al. (2017b). Meanwhile, the historical seismicity of this region has been compiled and summarized by a few researchers such as Leyu et al. (1985) and Tongkul (2020). Martin et al. (2020) exposed historical seismicity in this region focusing on a pair of moderate earthquakes in 1922. Previous seismological studies carried out in West Malaysia also revealed that this region has experienced several reservoir-induced earthquakes around the Kenyir Dam in Terengganu state in between 1984 and 1988 with the local magnitude ranging from 2.4 to 4.6 (Che Abas, 2001; Fatt et al., 2011; Lat, 1997a, b, 2002; Mat Said, 2011; Raj, 1994).

After 2004, the first occurrence of tectonic earthquake in West Malaysia was recorded on 30 November 2007 and followed by other local events until 25 May 2008 with the epicenters in Bukit Tinggi area and its surroundings, along the Selangor-Pahang state boundary. These earthquakes were interpreted to be associated with the reactivation of the BTFZ and KLFZ. Both fault zones cover an area of about 80 km long (N-S) and 40 km wide (W-E). The reactivation of these fault zones has produced a series of small earthquakes with the magnitude of 2.5 to 3.5 Richter Scale. It is believed that the fault reactivations were the result of regional stress build-up due to the present-day tectonics post-2004 Sumatra-Andaman earthquake. These Bukit Tinggi earthquakes happened in an area with high concentrations of ancient faults and hot springs. When earthquakes took place, residents of the areas reported hearing loud noises like a truck coming towards them before they felt the tremors and others felt the ground shaking and rolling. However, there is no any surface trace of rupture or any surface movement related to fault activity has been observed in this area (Lat and Ibrahim, 2009; Shuib, 2009). Mat Said and Hara (2012) determined focal mechanisms of a few Bukit Tinggi earthquakes. Rahim et al. (2015) conducted a study to identify active faults in Malaysia from remote sensing and field survey analysis in tectonically active areas, including Bukit Tinggi area. Shuib (2017a) investigated geomorphic features of active faults in West Malaysia, mainly Bukit Tinggi area, using IFSAR and field verification.

In addition to Bukit Tinggi area, other parts of West Malaysia have also been investigated for their earthquake potentials. Shuib (2011) revealed the evidences of recent seismicity and radiocarbon dating of active faulting in NW Peninsular Malaysia, specifically in Bok Bak Fault Zone. Shuib (2013) studied paleoearthquake and active faulting in Cameron Highlands using remote sensing and field investigations. Shuib (2017b) identified active faults surrounding Manjung area in the south of Perak which are considered capable of generating earthquakes. Avar et al. (2019) presented an overview of geological and tectonic settings of Penang Island on the NW of Peninsular Malaysia, and summarized the earthquake risk and seismic hazards of the island.

For other seismic hazard studies in this region, the Malaysian Meteorological Department and Academy of Sciences Malaysia (2009) carried out the seismic and tsunami hazards and risks study in Malaysia, including the West Malaysia. Wah (2011) studied the geological assessment of earthquake sources and hazard in Malaysia and revealed the occurrence of several sinkholes in NW of Peninsular Malaysia (mainly in Perak and Kedah) as impacts of large earthquakes near Sumatra. Manafizad et al. (2016) estimated the Peak Ground Acceleration (PGA) produced by the subduction zone and fault zones for Peninsular Malaysia using the geospatial approach. Lam et al. (2016) and Looi et al. (2018) explained the seismic hazard model for different parts of Malaysia with very different seismicity conditions. West Malaysia is subject to a combination of earthquake hazards generated from distant and local sources. According to the Department of Standards Malaysia (2017), the seismic hazard map of this region has been created by the Department of Mineral and Geoscience. Liew et al. (2017) contributed on the study of seismic hazard analysis method and ground motion prediction equations for Malaysia, mainly Peninsular Malaysia. Loi et al. (2018) have also studied the seismic hazard assessment for this region using deterministic and probabilistic approaches. Shoushtari et al. (2018) presented the new probabilistic seismic ground-motion hazard maps of Peninsular Malaysia by incorporating local faults effects with far-field seismic sources. Abd Razak et al. (2018) reviewed the history of significant earthquakes in Malaysia and surrounding regions where increasing earthquake activities with higher frequency and intensity in and around Malaysia have also reactivated many fault lines previously considered dormant. Ramli (2019) mapped the earthquake hazard in Malaysia based on the active fault zones throughout the country. Tongkul (2020) highlighted the earthquake hazard throughout Malaysia (including Peninsular Malaysia), the challenges in mitigating the hazard, and the way forward to strengthen the earthquake science in Malaysia.

2. OBJECTIVES

Since Southern Thailand and Peninsular Malaysia were previously categorized as low seismicity regions, there are still not enough comprehensive and updated studies regarding local seismicity of these two neighboring regions. After the occurrence of the 2004 Sumatra-Andaman earthquake and several other regional events, there was a significant increase in the seismicity of both regions. The quantity and quality of earthquake data in Southern Thailand and Peninsular Malaysia have also improved considerably after 2004 due to the increase in the number of seismological stations in both areas, thus further improve their earthquake monitoring. There have been plenty of local events recorded in the regions.

This study aims to achieve several objectives. This study firstly analyzed the seismicity in Southern Thailand and Peninsular Malaysia, majorly on the temporal-spatial distribution and magnitude variation of local earthquakes, as well as their relationship with local active faults. In the study of seismicity, it is important to have several earthquake parameters for each event, such as origin time, location, magnitude, and focal depth. The earthquake distribution is then observed in relation to preexisting faults of the study areas.

Secondly, this study investigated characteristics of earthquake swarms happened in both regions. The earthquake swarm is an unusual seismological behavior which is different from common multiple earthquakes either the MS-AS or FS-MS-AS sequences. Thirdly, this study evaluated the impacts of several large regional earthquakes on the local seismicity and crustal deformation in both regions in terms of geodynamic implications. The link between the occurrences of several large distant earthquakes (primarily took place near Sumatra region) and local events have been evaluated to see how these regional earthquakes affecting the local seismicity and crustal deformation. It is expected that this study will contribute to a deeper understanding of seismicity in these regions as a basis for seismic hazard and risk assessment studies in both regions.

3. METHODOLOGY

This work uses several comprehensive methods dealing the seismicity study including seismological data compilation, processing, products, as well as seismicity analysis. Figure 3.1 summarized all above-mentioned methodology used in this study.

3.1 Seismological data compilation

Seismological data of pre-instrumental period were compiled from literature reviews of previous studies on paleoseismology and historical earthquakes in Southern Thailand and Peninsular Malaysia. Meanwhile, instrumental earthquakes data were obtained from networks of local (GRC-PSU&DMR), national (RID, TMD, MMD), and international (ISC, USGS-NEIC, and EMSC) agencies.

3.2 Seismological data processing

In this study, available digital seismograms recorded by several seismological networks in both Southern Thailand (GRC-PSU & DMR, RID and TMD) and West Malaysia (MMD) were processed or analyzed by using SEISAN earthquake analysis software (Havskov and Ottemöller, 1999; ftp://ftp.geo.uib.no/pub/seismo/SOFTWARE/SEISAN/) following standard and routine procedures (Bormann et al., 2014; Havskov and Ottemöller, 2010). This analysis determines source parameters such as the time of occurrence (origin time), location, focal depth, and magnitude. The origin time, location, and focal depth are determined by arrival times of seismic waves (e,g. P and S waves), meanwhile the magnitude is determined from the maximum amplitude for each event. Since the structures of the crust and upper mantle beneath both regions are not well-established yet, this study used the IASP91 velocity model (Kennett and Engdahl, 1991).

3.3 Seismological data products

All earthquake datasets were used to generate several earthquake data products such as earthquake catalogues and seismicity maps. An earthquake catalogue contains information on date and origin time, latitude and longitude of epicenter, magnitude, focal depth of all local earthquakes located in Southern Thailand and Peninsular Malaysia. According to Dattatrayam et al. (2014), the earthquake catalogue is the basic data input or reference for seismicity analysis and comprehensive seismic hazard assessment of any region. However, the completeness of an earthquake catalogue in space and time often becomes a discussion and debate matter. Meanwhile, a seismicity map shows the distribution of earthquakes (epicenters) in space, time, and magnitude.

3.4 Seismicity analysis

Several aspects need to be considered to analyses the seismicity of both regions. The temporal-spatial distribution and magnitude variation of local earthquakes were analyzed from the seismicity maps. Although focal mechanism solutions were not created in this study due to limited geographical distribution of seismological stations around the epicenters, the focal mechanisms among the largest events in both regions were obtained from other sources and previous studies. The occurrence of earthquake swarms and mini swarms was identified and characterized by several criteria (Mesimeri et al., 2019; Mogi, 1963; Roland and McGuire, 2009) as explained in the Section 1.3 (Earthquake Swarm) in the Introduction. The relationship between seismicity and tectonics (such as local active faults) were analyzed in the seismotectonic framework. In addition, seismicity of both regions can be analyzed from the regional geodynamic implications to see how regional earthquakes give impacts on the local seismicity and crustal deformation to the regions.

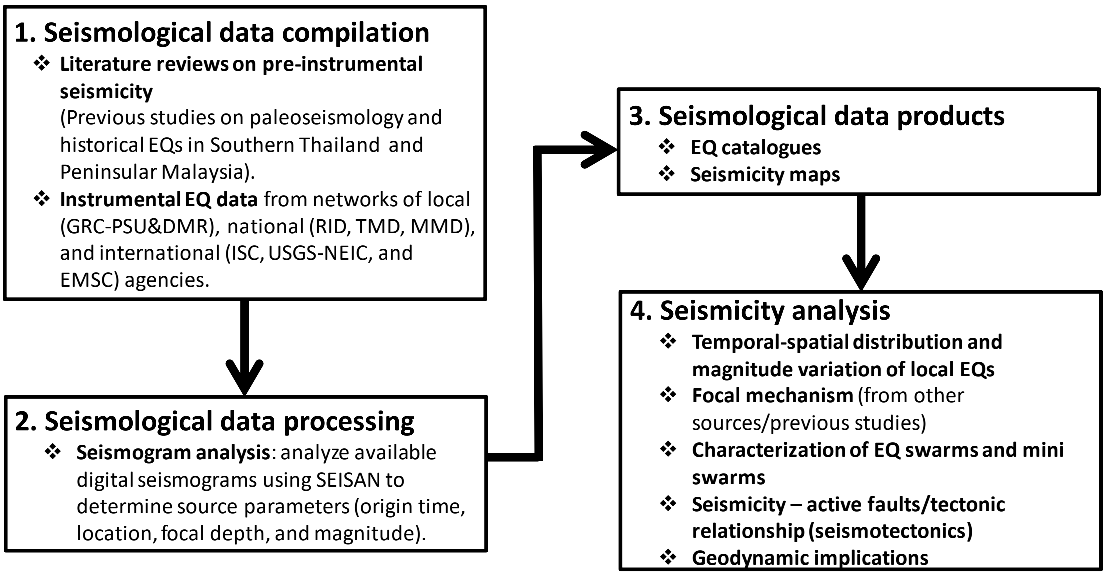


Figure 3.1 Summary of methodology used in this study.

4. RESULTS AND DISCUSSION

This part discusses the seismicity in Southern Thailand and Peninsular Malaysia started from the pre-instrumental (paleo- and historical) seismicity, and followed by the instrumental seismicity with the emphasis on their temporal and spatial distributions and magnitude variation. This study also observes unique seismological phenomena of earthquake sequences occurred in Phuket in Southern Thailand (2012) and Bukit Tinggi in Peninsular Malaysia (2007-2009). In addition, this study relates the seismicity in both regions to their respective local tectonics.

4.1 Seismicity in Southern Thailand

4.1.1 Brief History on Pre-Instrumental Seismicity in Southern Thailand

Several paleoseismological studies have been conducted in Southern Thailand by different researchers. RID (2009) reported its paleoseismological project in 11 sites (no. 45-55) in this region. Three sites (no. 45-47) focused on the RFZ revealing the fault slip rate of 0.18 – 0.7 mm/year. Eight other sites (no. 48-55) focused on the KMFZ reporting the fault slip rate of 0.01 – 0.5 mm/year. Sutiwanich (2010) studied paleoearthquake activity of the KMFZ and RFZ and stated that the two fault zones have ever produced the maximum paleomagnitude of around Mw 6.6 and Mw 6.2 at 2,000 and 9,000 years ago, respectively. The KMFZ and RFZ have the mean recurrence interval of 2,200 and 8,300 years, and the slip rate of 0.1 – 0.5 mm/year and 0.04 – 0.17 mm/year, respectively. Another paleoseismological study was carried out by Keawnaungmoon (2010) to evaluate the paleoearthquake occurrence in the KMFZ and indicated four paleoearthquake events with the maximum magnitude of Mw 7.1 with the latest movement taking place around 2,000 years ago, the slip rate was estimated as 0.4 – 0.5 mm/year. Pananont et al. (2010) conducted a paleoseismological study in an excavated trench on a segment of the RFZ in Prachuap Khiri Khan Province and reported evidences of the faults' offsets up to 50 cm through a series of bedrock. It was also estimated that larger earthquakes have happened in this region with the magnitude values between Mw 6.1 to 6.6. The age of these earthquakes obtained by the thermoluminescence (TL) dating is around between 12.4±1.3 ka and 9.6±0.7 ka B.P. Thipyopass (2010) carried out a paleoearthquake investigation along the RFZ and concluded that there are at least six paleoearthquake events and the latest movement took place at around 2,000 years. The RFZ has triggered the largest earthquake with the magnitude Mw 7.4 and the maximum slip rate of 0.7 mm/year. Noppradit (2013) conducted a paleoseismological investigation in the eastern part of the KMFZ and managed to identify several locations with paleoearthquake evidences. The TL and optically stimulated luminescence (OSL) dating methods revealed that there were at least three periods of paleoearthquakes occurred in this area, viz. 33–112 ka, 2.5–10 ka, and younger than 2.5 ka. The investigation has also shown that the KMFZ has generated earthquakes with the magnitude Mw 6.6 to 7.8. All in all, these paleoseismological evidences have proven that both fault zones (KMFZ and RFZ) have been active since ancient time and they have the potential to generate earthquakes in the future with much higher magnitudes than what is recorded by the current network of stations.

Since the first seismological station in Thailand was installed in 1963 marking the beginning of the instrumental period of the country and the end of the historical earthquakes for this region. However, there is no large earthquake happened in Southern Thailand during the historical period. Nutalaya and Sodsri (1983), Nutalaya et al. (1985), and Prachuab (1988) confirmed that no large significant earthquake occurred in this region reported as a historical earthquake. However, a lot of large earthquakes were recognized to take place in surrounding regions, such as the Andaman Sea, Andaman and Nicobar Islands, Sumatra, and Myanmar as the historical felt earthquakes.

4.1.2 Instrumental Seismicity in Southern Thailand

This study compiled earthquake data of the instrumental period in Southern Thailand to create a composite earthquake catalogue. In total, as many as 227 local events have been compiled from local, national, and global networks and complimented from other previous research works. Nutalaya and Sodsri (1983) for the first time published the instrumental earthquakes in the region. Prior to the 2004 Sumatra-Andaman earthquake, there were at least four local earthquakes (events no. 1 and 4 in Table 4.1) occurred in this region in 1970s and recorded instrumentally. However, earthquake parameters of these earthquakes are not complete. The first and second events happened on 19 January 1970 03:20:38 UTC and 28 March 1971 01:17:13 UTC with the epicenters on the coordinates of 7.6°N 99.7°E (in Trang Province) and 9.1°N 97.0°E (in Andaman Sea, offshore Ranong Province), respectively, with no information on the magnitude and focal depth. The third event took place on 7 April 1976 at 15:27:12 UTC with the epicenter on 7.2°N 98.6°E (in Andaman Sea, offshore Trang Province), focal depth of 33 km, and no magnitude reported. Meanwhile, the fourth event occurred on 30 September 1978 at 09:30:52 with the epicenter on 11.0°N 99.0°E (near the border between Chumphon and Prachuap Khiri Khan Provinces and Myanmar) and the magnitude M 5.6. Shresta (1987) stated that the 1978 earthquake happened along the RFZ. With the magnitude M 5.6 (Mw = 5.6), it is assumed as the largest instrumental earthquake ever recorded in Southern Thailand so far. In addition, there are two other records of local events before 2004, which both took place in August 1999 (events no. 5 and 6 in Table 4.1). The first one occurred on 17 August 1999 at 23:39 local time (16:39 UTC) and the second one happened on 29 August 1999 at 07:41 local time (00:41 UTC) with both have the same magnitude ML 2.1. Both events were located in the Andaman Sea off Phuket, around 10 km SW from Phuket Airport. Tremors can be felt in Phuket and

Phang Nga areas (source: Earthquake Statistics of TMD; www.earthquake.tmd.go.th/earthquakestat.html).

After the 2004 megathrust earthquake (Mw 9.1), the seismicity of the region increases significantly with earthquakes of mostly micro (ML<3) to light (ML=4-5) magnitude scale (events 7 – 227 in Table 4.1) recorded in line with the improvement of seismic networks and stations in the region. A temporary earthquake monitoring in Southern Thailand have been carried out right after the occurrence of the 2004 earthquake by the GRC–PSU and DMR during the period January to July 2005 (Duerrast et al., 2007). From numerous earthquakes recorded during the monitoring period, only those recorded by at least three stations were selected for this study, which are 111 micro earthquakes took place in Southern Thailand during 14 January to 11 April 2005. Digital seismograms of these 111 events have been analyzed in this study.

Two national institutions, RID and TMD, which concern on earthquake activity in Thailand, also conduct the earthquake monitoring by their respective networks. RID contributed earthquake data of four local events happened during 12 May 2008 to 24 May 2013, where digital seismograms of all these events have also been analyzed. Meanwhile, from 94 local events occurred during 4 May 2008 to 2 July 2020 and recorded by TMD, digital seismograms of 59 events have been analyzed. The composite earthquake catalogue created in this study has also been complimented by earthquake data from previous studies and global networks such as ISC, USGS-NEIC, and EMSC. Table 4.1 summarizes all data of local earthquakes in the region of Southern Thailand during the instrumental period.

Different from the earthquake catalogue of West Malaysia, in this study, the catalogue of Southern Thailand (Table 4.1) was added by earthquake data from local temporary network operated by GRC-PSU and DMR in early 2005. Consequently, a significant number of micro earthquakes (ML<3), which is as many as 111 events or almost half of total events, compiled in the catalogue. With this earthquake catalogue, the temporal and spatial distributions of local earthquakes in Southern Thailand will be analyzed in the following sections.

Table 4.1 Earthquake data of instrumental period in Southern Thailand from various local, regional/national, and international seismological networks and previous studies.

Event No.	Date and Original Time (yyyy-mm-dd hh:mm:ss UTC)	Lat. (ºN)	Long. (ºE)	Mag. (calcu-lated/ reported)	Mag. Scale	Con-verted into Mw	Focal Depth (km)	Data source (agency)
1	1970-01-19 03:20:38	7.6	99.7	No report	-	-	No report	Nutalaya & Sodsri (1983)
2	1971-03-28 01:17:13	9.1	97.0	No report	-	-	No report	Nutalaya & Sodsri (1983)
3	1976-04-07 15:27:12	7.2	98.6	No report	-	-	33	Nutalaya & Sodsri (1983)
4	1978-09-30 09:03:52	11.0	99.0	5.6	M	5.6	No report	Nutalaya & Sodsri (1983), Shrestha (1987)
5	1999-08-17 16:39:00	8.1	98.3	2.1	ML	1.3	No report	Earthquake Statistics of TMD; www.earthquake. tmd.go.th/ earthquakestat.html
6	1999-08-29 00:41:00	No report on coordinates (~ 10 km SW from Phuket Airport)		2.1	ML	1.3	No report	Earthquake Statistics of TMD; www.earthquake. tmd.go.th/ earthquakestat.html
7*	2005-01-14 03:54:27	8.396	98.743	0.9	ML	0.5	8.1	GRC-PSU & DMR
8*	2005-01-14 10:08:49	8.145	98.643	0.8	ML	0.5	1.0	GRC-PSU & DMR
9*	2005-01-15 21:54:46	8.174	98.549	-0.2	ML	-0.1	2.2	GRC-PSU & DMR
10*	2005-01-16 02:47:32	9.635	99.500	1.4	ML	0.8	26.1	GRC-PSU & DMR
11*	2005-01-16 04:03:08	8.401	98.581	0.7	ML	0.4	1.1	GRC-PSU & DMR
12*	2005-01-16 13:01:21	8.241	97.506	1.2	ML	0.7	1.2	GRC-PSU & DMR
13*	2005-01-16 20:57:28	8.566	98.818	0.0	ML	0.0	1.0	GRC-PSU & DMR
14*	2005-01-17 04:03:25	8.529	98.628	0.8	ML	0.5	4.1	GRC-PSU & DMR
15*	2005-01-17 12:01:29	9.060	99.056	1.2	ML	0.7	1.0	GRC-PSU & DMR
16*	2005-01-17 12:08:57	8.324	97.571	1.0	ML	0.6	15.0	GRC-PSU & DMR
17*	2005-01-17 17:20:57	8.756	98.476	0.5	ML	0.3	64.2	GRC-PSU & DMR
18*	2005-01-17 23:00:57	8.246	98.073	0.6	ML	0.4	78.4	GRC-PSU & DMR
19*	2005-01-18 21:39:13	8.142	98.166	0.5	ML	0.3	1.6	GRC-PSU & DMR
20*	2005-01-20 04:11:32	8.634	98.549	0.6	ML	0.4	1.0	GRC-PSU & DMR

21*	2005-01-20 09:48:20	7.658	97.854	1.0	ML	0.6	27.4	GRC-PSU & DMR
22*	2005-01-21 22:23:02	8.281	98.026	0.9	ML	0.5	9.9	GRC-PSU & DMR
23*	2005-01-22 04:07:35	8.679	98.445	0.6	ML	0.4	1.0	GRC-PSU & DMR
24*	2005-02-05 12:46:04	8.134	98.650	0.3	ML	0.2	17.5	GRC-PSU & DMR
25*	2005-02-05 18:07:41	7.722	98.352	0.8	ML	0.5	9.6	GRC-PSU & DMR
26*	2005-02-09 21:04:08	8.209	100.422	1.2	ML	0.7	16.8	GRC-PSU & DMR
27*	2005-02-15 13:09:32	8.350	98.656	0.3	ML	0.2	11.4	GRC-PSU & DMR
28*	2005-03-01 01:02:29	7.363	99.448	0.3	ML	0.2	1.4	GRC-PSU & DMR
29*	2005-03-01 04:08:30	7.887	98.349	0.6	ML	0.4	1.0	GRC-PSU & DMR
30*	2005-03-01 09:27:41	8.758	98.944	0.7	ML	0.4	5.4	GRC-PSU & DMR
31*	2005-03-01 09:35:29	8.121	98.454	0.6	ML	0.4	1.8	GRC-PSU & DMR
32*	2005-03-01 09:57:45	8.453	98.595	0.3	ML	0.2	1.9	GRC-PSU & DMR
33*	2005-03-01 17:42:38	8.549	98.532	-0.1	ML	-0.1	27.2	GRC-PSU & DMR
34*	2005-03-02 04:14:23	8.475	98.657	0.4	ML	0.2	1.4	GRC-PSU & DMR
35*	2005-03-02 04:35:37	8.709	98.156	0.5	ML	0.3	1.0	GRC-PSU & DMR
36*	2005-03-02 04:46:05	8.527	99.616	0.8	ML	0.5	1.2	GRC-PSU & DMR
37*	2005-03-02 06:07:12	9.783	97.970	1.7	ML	1.0	16.3	GRC-PSU & DMR
38*	2005-03-02 08:38:02	7.362	99.609	1.1	ML	0.7	17.0	GRC-PSU & DMR
39*	2005-03-02 09:13:38	7.954	98.415	-0.2	ML	-0.1	15.0	GRC-PSU & DMR
40*	2005-03-02 14:25:24	8.393	98.652	0.2	ML	0.1	20.4	GRC-PSU & DMR
41*	2005-03-03 00:10:46	8.527	99.595	0.4	ML	0.2	14.9	GRC-PSU & DMR
42*	2005-03-03 00:15:58	8.689	99.603	0.9	ML	0.5	15.8	GRC-PSU & DMR
43*	2005-03-03 04:13:41	8.489	98.648	0.8	ML	0.5	17.7	GRC-PSU & DMR
44*	2005-03-03 06:57:41	9.163	98.489	1.2	ML	0.7	1.5	GRC-PSU & DMR
45*	2005-03-03 09:12:59	9.474	98.926	1.0	ML	0.6	10.0	GRC-PSU & DMR
46*	2005-03-03 09:15:30	9.411	98.880	1.0	ML	0.6	8.0	GRC-PSU & DMR
47*	2005-03-03 10:01:46	9.064	98.718	1.3	ML	0.8	1.0	GRC-PSU & DMR
48*	2005-03-03 10:20:52	9.396	98.907	1.0	ML	0.6	10.2	GRC-PSU & DMR
49*	2005-03-03 10:24:47	8.625	98.616	0.3	ML	0.2	22.0	GRC-PSU & DMR
50*	2005-03-03 11:54:01	9.428	98.840	2.0	ML	1.2	15.5	GRC-PSU & DMR
51*	2005-03-03 13:54:38	7.890	98.749	0.0	ML	0.0	12.8	GRC-PSU & DMR
52*	2005-03-03 14:15:24	8.485	99.450	0.8	ML	0.5	7.6	GRC-PSU & DMR
53*	2005-03-03 15:23:05	8.996	98.749	1.2	ML	0.7	1.1	GRC-PSU & DMR
54*	2005-03-04 02:48:48	7.456	99.767	0.8	ML	0.5	5.8	GRC-PSU & DMR
55*	2005-03-04 07:52:54	9.521	98.741	1.6	ML	1.0	4.4	GRC-PSU & DMR
56*	2005-03-04 08:32:12	9.406	98.840	1.5	ML	0.9	13.9	GRC-PSU & DMR
57*	2005-03-04 09:36:12	8.348	99.594	1.1	ML	0.7	2.8	GRC-PSU & DMR
58*	2005-03-04 09:46:36	8.203	98.620	0.1	ML	0.1	1.0	GRC-PSU & DMR
59*	2005-03-04 10:33:04	7.500	99.446	1.9	ML	1.1	15.0	GRC-PSU & DMR
60*	2005-03-04 12:31:16	7.470	99.683	1.5	ML	0.9	15.0	GRC-PSU & DMR
61*	2005-03-04 21:35:34	9.535	98.636	0.5	ML	0.3	1.0	GRC-PSU & DMR

62*	2005-03-04 22:47:02	9.467	98.816	0.8	ML	0.5	13.9	GRC-PSU & DMR
63*	2005-03-05 09:52:17	9.442	98.804	1.4	ML	0.8	14.8	GRC-PSU & DMR
64*	2005-03-06 23:19:32	7.183	98.032	1.3	ML	0.8	1.0	GRC-PSU & DMR
65*	2005-03-06 23:21:50	7.147	98.011	1.6	ML	1.0	15.0	GRC-PSU & DMR
66*	2005-03-06 23:30:25	7.162	97.994	1.5	ML	0.9	15.0	GRC-PSU & DMR
67*	2005-03-06 23:45:20	7.160	98.022	1.1	ML	0.7	1.0	GRC-PSU & DMR
68*	2005-03-07 09:02:33	7.270	98.954	0.9	ML	0.5	9.6	GRC-PSU & DMR
69*	2005-03-07 11:31:26	9.519	98.711	1.1	ML	0.7	12.3	GRC-PSU & DMR
70*	2005-03-07 15:23:28	7.359	99.101	0.9	ML	0.5	8.7	GRC-PSU & DMR
71*	2005-03-08 14:01:20	8.797	99.246	0.8	ML	0.5	1.4	GRC-PSU & DMR
72*	2005-03-08 16:26:42	10.688	99.143	1.5	ML	0.9	15.0	GRC-PSU & DMR
73*	2005-03-09 00:52:16	9.418	98.861	1.0	ML	0.6	1.0	GRC-PSU & DMR
74*	2005-03-09 00:53:17	9.399	98.865	0.9	ML	0.5	10.1	GRC-PSU & DMR
75*	2005-03-09 06:20:51	7.706	98.284	0.9	ML	0.5	1.1	GRC-PSU & DMR
76*	2005-03-09 06:25:53	8.713	98.118	0.6	ML	0.4	1.0	GRC-PSU & DMR
77*	2005-03-09 07:06:23	7.239	98.002	1.1	ML	0.7	1.0	GRC-PSU & DMR
78*	2005-03-09 07:33:48	8.548	98.208	0.9	ML	0.5	1.2	GRC-PSU & DMR
79*	2005-03-09 14:09:20	8.213	98.411	0.1	ML	0.1	67.7	GRC-PSU & DMR
80*	2005-03-09 14:56:22	8.876	98.366	-0.1	ML	-0.1	1.0	GRC-PSU & DMR
81*	2005-03-10 03:07:57	8.743	98.116	0.9	ML	0.5	7.0	GRC-PSU & DMR
82*	2005-03-19 03:57:35	8.374	98.408	1.0	ML	0.6	13.1	GRC-PSU & DMR
83*	2005-03-19 04:10:17	8.351	98.719	1.0	ML	0.6	1.0	GRC-PSU & DMR
84*	2005-03-20 04:04:00	8.355	98.699	1.0	ML	0.6	1.0	GRC-PSU & DMR
85*	2005-03-20 10:19:42	8.437	98.570	0.3	ML	0.2	2.5	GRC-PSU & DMR
86*	2005-03-20 12:03:12	8.484	98.016	0.5	ML	0.3	1.0	GRC-PSU & DMR
87*	2005-03-21 00:49:39	7.956	99.570	0.9	ML	0.5	7.2	GRC-PSU & DMR
88*	2005-03-21 03:53:47	8.572	98.594	0.6	ML	0.4	1.0	GRC-PSU & DMR
89*	2005-03-21 06:14:15	9.550	98.747	1.4	ML	0.8	1.7	GRC-PSU & DMR
90*	2005-03-21 10:39:06	8.280	98.236	0.4	ML	0.2	4.0	GRC-PSU & DMR
91*	2005-03-21 23:37:47	8.072	98.549	1.1	ML	0.7	35.4	GRC-PSU & DMR
92*	2005-03-22 04:11:34	8.889	99.496	1.0	ML	0.6	30.7	GRC-PSU & DMR
93*	2005-03-22 05:03:43	9.604	98.842	0.9	ML	0.5	12.4	GRC-PSU & DMR
94*	2005-03-22 06:01:03	7.555	98.820	0.8	ML	0.5	22.4	GRC-PSU & DMR
95*	2005-03-23 04:09:28	8.488	98.654	0.2	ML	0.1	15.0	GRC-PSU & DMR
96*	2005-03-23 04:19:20	8.377	98.486	0.9	ML	0.5	6.6	GRC-PSU & DMR
97*	2005-03-23 08:52:24	8.422	98.753	0.5	ML	0.3	28.5	GRC-PSU & DMR
98*	2005-03-23 10:25:15	8.481	98.521	0.4	ML	0.2	9.0	GRC-PSU & DMR
99*	2005-03-24 04:10:55	8.655	98.557	0.5	ML	0.3	1.0	GRC-PSU & DMR
100*	2005-03-24 09:53:30	8.579	98.567	0.3	ML	0.2	1.0	GRC-PSU & DMR
101*	2005-03-26 14:11:54	8.732	98.153	0.7	ML	0.4	1.0	GRC-PSU & DMR
102*	2005-03-26 16:36:43	7.830	98.687	0.0	ML	0.0	31.5	GRC-PSU & DMR

103*	2005-03-26 17:30:10	7.831	98.687	0.4	ML	0.2	12.6	GRC-PSU & DMR
104*	2005-03-26 17:49:11	8.936	98.621	0.5	ML	0.3	1.0	GRC-PSU & DMR
105*	2005-03-26 19:23:25	7.899	98.486	0.2	ML	0.1	54.0	GRC-PSU & DMR
106*	2005-03-27 02:29:50	8.134	98.450	-0.1	ML	-0.1	1.0	GRC-PSU & DMR
107*	2005-03-27 09:56:34	8.428	98.604	0.2	ML	0.1	1.0	GRC-PSU & DMR
108*	2005-04-03 03:58:17	8.397	98.722	0.5	ML	0.3	1.3	GRC-PSU & DMR
109*	2005-04-06 04:13:22	8.233	98.726	0.6	ML	0.4	26.2	GRC-PSU & DMR
110*	2005-04-06 11:32:21	7.074	98.601	0.8	ML	0.5	8.2	GRC-PSU & DMR
111*	2005-04-06 16:08:55	8.508	98.395	0.2	ML	0.1	8.7	GRC-PSU & DMR
112*	2005-04-07 04:06:24	8.402	98.713	0.4	ML	0.2	15.0	GRC-PSU & DMR
113*	2005-04-08 04:19:27	8.205	98.706	0.6	ML	0.4	33.5	GRC-PSU & DMR
114*	2005-04-08 08:58:11	7.964	97.936	0.9	ML	0.5	1.2	GRC-PSU & DMR
115*	2005-04-08 10:55:30	8.094	98.721	1.0	ML	0.6	1.0	GRC-PSU & DMR
116*	2005-04-10 09:35:44	8.644	98.642	0.2	ML	0.1	1.0	GRC-PSU & DMR
117*	2005-04-11 04:53:07	8.390	98.698	0.8	ML	0.5	1.0	GRC-PSU & DMR
118	2005-09-06 23:21:17	8.245	97.457	4.5	M	4.5	10.0	USGS-NEIC, ISC
119	2006-02-09 00:18:00	7.668	98.494	3.9	mb	4.3	35.0	ISC
120	2006-09-27 13:27:42	11.697	99.955	4.1	M	4.1	29.4	USGS-NEIC, ISC
121	2006-09-27 15:57:30	11.720	99.866	4.5	M	4.5	10.0	USGS-NEIC, ISC
122	2006-09-27 17:38:34	11.788	100.005	4.2	M	4.2	18.5	USGS-NEIC, ISC
123	2006-09-27 17:40:17	11.744	99.933	4.3	M	4.3	10.0	USGS-NEIC, ISC,
124	2006-09-27 18:46:02	11.816	100.145	4.7	M	4.7	10.0	USGS-NEIC, ISC
125	2006-09-28 09:48:01	11.749	99.987	4.5	M	4.5	22.3	USGS-NEIC, ISC
126	2006-10-07 21:12:25	11.743	100.179	5.0	M	5.0	10.0	USGS-NEIC, ISC, EMSC
127	2007-06-06 04:00:48	7.433	98.138	3.6	mb	4.1	1.0	ISC
128	2008-05-04 07:55:34	8.640	98.740	2.7	ML	1.6	1.0	TMD
129*	2008-05-12 06:32:14	12.010	99.972	3.5	ML	2.1	1.0	RID
130	2008-05-24 10:14:54	8.830	98.890	1.0	ML	0.6	1.0	TMD
131	2008-09-04 02:56:23	9.260	98.620	3.1	ML	1.9	1.0	TMD
132	2008-12-23 06:38:41	8.650	98.990	4.1	ML	4.1	1.0	TMD
133*	2009-08-10 19:57:11	11.352	99.974	3.6	ML	2.2	17.6	RID
134*	2010-06-12 19:26:22	9.870	99.554	3.2	ML	1.9	13.7	RID
135*	2010-08-01 21:14:31	7.971	98.957	1.9	ML	1.1	1.0	TMD
136*	2010-09-30 23:42:45	8.915	99.382	3.1	ML	1.9	1.0	TMD
137	2011-04-30 11:12:16	7.390	97.760	4.4	ML	4.4	1.0	TMD, ISC
138	2011-04-30 13:03:35	7.570	97.550	3.1	ML	1.9	1.0	TMD
139*	2011-06-24 15:33:51	7.349	99.682	3.7	ML	2.2	1.0	TMD
140*	2011-06-24 16:42:44	7.385	99.647	4.4	ML	4.4	1.0	TMD
141*	2011-07-25 10:37:17	8.814	98.937	4.0	ML	4.0	1.0	TMD
142	2012-02-19 20:48:39	8.853	98.602	2.8	ML	1.7	1.0	TMD

143	2012-04-16 00:37:00	7.974	98.319	2.2	ML	1.3	7.5	TMD
144	2012-04-16 03:20:00	7.969	98.323	1.7	ML	1.0	8.0	TMD
145	2012-04-16 09:44:25	8.021	98.347	4.1	M	4.1	4.5	USGS-NEIC, ISC, EMSC, TMD
146	2012-04-16 10:12:00	7.979	98.386	2.3	ML	1.4	2.0	TMD
147	2012-04-16 10:30:00	7.972	98.343	2.4	ML	1.4	8.0	TMD
148	2012-04-16 11:43:00	7.967	98.400	1.9	ML	1.1	1.0	TMD
149	2012-04-16 11:47:00	7.870	98.250	1.8	ML	1.1	7.0	TMD
150	2012-04-16 12:25:00	7.989	98.340	1.7	ML	1.0	2.0	TMD
151	2012-04-16 12:50:00	7.989	98.335	1.7	ML	1.0	2.0	TMD
152	2012-04-16 13:02:00	7.964	98.403	1.8	ML	1.1	1.0	TMD
153	2012-04-16 13:03:00	7.972	98.344	1.7	ML	1.0	8.0	TMD
154*	2012-04-16 13:30:27	8.038	98.328	2.3	ML	1.4	4.0	TMD
155	2012-04-16 13:56:00	7.984	98.365	2.1	ML	1.3	1.0	TMD
156*	2012-04-16 14:17:54	8.015	98.343	2.8	ML	1.7	5.0	TMD
157	2012-04-16 14:23:00	7.969	98.328	1.9	ML	1.1	8.0	TMD
158	2012-04-16 14:25:00	7.966	98.359	2.6	ML	1.6	4.1	TMD
159	2012-04-16 14:37:00	7.986	98.332	1.8	ML	1.1	3.5	TMD
160	2012-04-16 14:50:00	8.000	98.343	2.2	ML	1.3	2.0	TMD
161	2012-04-16 15:54:00	7.977	98.311	1.5	ML	0.9	6.5	TMD
162*	2012-04-16 16:01:39	8.069	98.332	2.1	ML	1.3	5.5	TMD
163*	2012-04-16 16:03:00	8.025	98.329	2.3	ML	1.4	5.0	TMD
164*	2012-04-16 16:48:12	8.021	98.312	1.5	ML	0.9	7.0	TMD
165	2012-04-16 17:16:00	7.981	98.369	2.2	ML	1.3	5.0	TMD
166*	2012-04-16 18:00:52	8.083	98.369	1.8	ML	1.1	6.0	TMD
167*	2012-04-16 19:02:01	7.910	98.331	3.4	ML	2.0	4.5	TMD
168	2012-04-16 20:11:00	7.986	98.358	2.0	ML	1.2	1.0	TMD
169	2012-04-16 20:12:00	7.985	98.347	1.4	ML	0.8	3.5	TMD
170*	2012-04-17 01:31:50	8.023	98.378	1.8	ML	1.1	2.0	TMD
171*	2012-04-17 05:18:40	8.091	98.351	2.9	ML	1.7	8.5	TMD
172*	2012-04-17 14:56:55	8.000	98.374	2.7	ML	1.6	5.8	TMD
173*	2012-04-17 17:49:23	8.016	98.300	2.2	ML	1.3	6.0	TMD
174*	2012-04-17 21:15:18	8.019	98.294	2.9	ML	1.7	6.0	TMD
175*	2012-04-17 21:19:55	8.054	98.327	1.8	ML	1.1	19.7	TMD
176*	2012-04-18 12:48:10	8.017	98.368	2.3	ML	1.4	9.3	TMD
177*	2012-04-18 12:53:00	8.087	98.363	3.5	ML	2.1	1.5	TMD
178*	2012-04-18 13:38:49	8.084	98.379	2.9	ML	1.7	1.0	TMD
179*	2012-04-19 01:13:20	8.082	98.386	1.7	ML	1.0	18.5	TMD
180*	2012-04-19 10:13:57	8.069	98.396	1.7	ML	1.0	4.1	TMD
181*	2012-04-19 14:20:12	8.073	98.331	2.6	ML	1.6	33.1	TMD
182*	2012-04-19 19:43:41	8.015	98.328	2.9	ML	1.7	1.2	TMD

183*	2012-04-20 02:57:24	8.048	98.386	2.4	ML	1.4	1.0	TMD
184*	2012-04-20 06:18:30	8.074	98.322	2.7	ML	1.6	1.0	TMD
185*	2012-04-20 08:10:48	8.025	98.352	3.0	ML	1.8	6.9	TMD
186*	2012-04-20 08:42:10	8.038	98.385	2.2	ML	1.3	36.0	TMD
187*	2012-04-21 21:07:45	8.022	98.359	1.9	ML	1.1	1.0	TMD
188*	2012-04-22 01:42:40	8.024	98.331	2.5	ML	1.5	1.0	TMD
189*	2012-05-03 21:54:44	8.056	98.391	2.0	ML	1.2	5.0	TMD
190*	2012-05-05 23:21:24	8.052	98.348	2.1	ML	1.3	1.0	TMD
191*	2012-06-04 05:48:48	9.804	98.535	3.4	ML	2.0	1.0	TMD
192*	2012-06-25 10:17:44	8.859	99.190	3.0	ML	1.8	1.0	TMD
193*	2012-06-25 10:21:37	8.758	99.073	3.9	ML	2.3	1.4	TMD
194	2012-09-18 17:40:04	8.220	97.820	2.5	ML	1.5	1.0	TMD
195*	2013-05-24 05:53:51	11.513	99.905	4.0	ML	4.0	15.0	RID
196*	2013-09-09 05:18:44	9.264	98.886	3.0	ML	1.8	1.0	TMD
197*	2013-10-25 09:04:19	7.664	99.450	2.7	ML	1.6	1.0	TMD
198*	2013-10-25 14:58:59	8.231	98.162	2.4	ML	1.4	1.1	TMD
199*	2014-01-16 05:18:29	8.950	98.599	4.3	ML	4.3	1.0	TMD, ISC
200*	2015-02-20 06:02:09	7.473	98.481	4.7	ML	4.7	1.0	TMD
201*	2015-03-24 22:32:21	7.848	98.407	3.5	ML	2.1	10.0	TMD, USGS-NEIC, ISC, EMSC
202*	2015-05-05 21:18:05	7.869	98.527	4.3	ML	4.3	10.0	TMD, USGS-NEIC, EMSC, ISC
203*	2015-05-06 05:25:56	7.737	98.599	4.1	ML	4.1	1.0	TMD
204*	2015-05-06 17:30:12	7.861	98.537	4.5	ML	4.5	10.0	TMD, USGS-NEIC, ISC, EMSC
205*	2015-05-08 05:14:56	7.798	98.566	3.7	ML	2.2	1.0	TMD
206*	2015-05-09 11:15:02	7.796	98.416	3.7	ML	2.2	21.9	TMD
207*	2015-05-11 03:49:46	7.780	98.391	3.6	ML	2.2	23.3	TMD
208*	2015-09-10 16:22:20	8.140	99.319	3.1	ML	1.9	1.0	TMD
209*	2016-03-20 15:04:24	9.364	98.884	3.7	ML	2.2	1.0	TMD
210*	2016-03-25 11:24:31	7.939	98.482	3.4	ML	2.0	1.0	TMD
211*	2016-03-28 19:10:04	9.446	98.842	3.2	ML	1.9	1.0	TMD
212*	2016-03-31 02:26:10	7.839	98.440	3.9	ML	2.3	19.6	TMD
213*	2016-03-31 19:44:59	9.487	98.784	3.5	ML	2.1	1.0	TMD
214*	2016-05-08 04:06:40	8.065	98.689	3.0	ML	1.8	1.0	TMD
215*	2016-06-17 22:17:29	7.833	98.515	3.8	ML	2.3	1.0	TMD
216*	2017-04-06 11:24:41	10.030	99.160	2.9	ML	1.7	15.0	TMD
217	2017-04-11 10:56:33	8.120	97.530	3.2	ML	1.9	1.0	TMD
218*	2017-05-01 08:43:07	7.183	100.627	2.6	ML	1.6	1.0	TMD
219*	2017-05-24 05:58:40	7.991	98.453	3.6	ML	2.2	1.0	TMD
220	2019-02-03 01:28:14	9.430	99.190	2.3	ML	1.4	10.0	TMD

221	2019-05-22 12:03:00	7.510	102.380	4.3	M	4.3	10.0	EMSC
222	2019-10-05 12:09:52	7.660	97. 900	2.8	ML	1.7	10.0	TMD, ISC
223	2020-01-25 17:41:54	8.853	98.384	2.1	ML	1.3	1.0	TMD
224	2020-01-25 17:42:49	8.863	98.383	2.2	ML	1.3	1.0	TMD
225	2020-02-06 11:10:32	11.460	99.410	2.8	ML	1.7	3.0	TMD, ISC
226	2020-07-02 05:18:29	8.999	97.797	2.7	ML	1.6	2.0	TMD, ISC
227	2020-07-02 05:22:03	9.006	97.757	2.9	ML	1.7	3.0	TMD, ISC

*Analysis of seismograms conducted by this study; GRC-PSU: Geophysics Research Center – Prince of Songkla University; DMR: Department of Mineral Resources; RID: Royal Irrigation Department; TMD: Thai Meteorological Department; USGS-NEIC: United States Geological Survey National Earthquake Information Center; ISC: International Seismological Center; EMSC: European-Mediterranean Seismological Center.

Temporal Distribution

The graph of temporal distribution of local earthquakes with the cumulative number of earthquakes in Southern Thailand can be seen in Figure 4.1. The graph shows that the temporal distribution of the earthquakes in this region is not balanced. There is an obvious gap in the earthquake recorded before and after 2004. This gap might relate to either hiatus in seismicity or no recorded data. After 2004, the seismicity of Southern Thailand increased significantly due to the occurrence of the 26 December 2004 Sumatra-Andaman earthquake. The seismicity of the region increased again following the 11 April 2012 East Indian Ocean earthquakes with the occurrence of a series of Phuket earthquakes during 16 April 2012 to 5 May 2012.

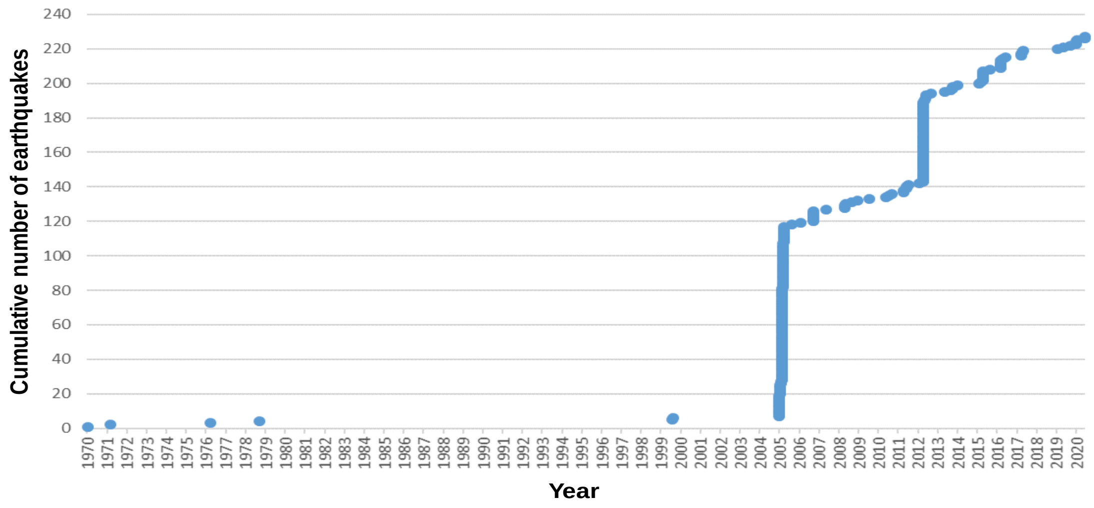


Figure 4.1 Temporal distribution of local earthquakes in the instrumental period in Southern Thailand (1970-2020).

Spatial Distribution

From the composite earthquake catalogue of Southern Thailand (Table 4.1), the epicenter map was created to show the lateral distribution of local earthquakes in the region during the instrumental period (1970 – 2020) in relation to the magnitude and focal depth (Figure 4.2). Earthquakes generally occurred in both onshore and offshore of the region, predominantly happened in the central part of the region in the vicinity of KMFZ and RFZ. These local events were scattered in a relatively NNE-SSW trend following the direction of the two major fault zones. Several events were recorded in the northern part, meanwhile, there were fewer earthquakes recorded in southern part and no record in the southernmost part of the region. The spatial distribution of earthquakes in this region reveals that a lot of micro and macro earthquakes were associated with the two prominent fault zones and some others were located in areas surrounding other fault lines/zones. On the land, they were distributed in some provinces i.e. Trang, Krabi, Phuket, Phang Nga, Nakhon Si Thammarat, Surat Thani, Ranong, Chumphon, and Prachuap Khiri Khan. There were also a few clusters of relatively N-S-trending epicenters in Trang and Nakhon Si Thammarat Provinces which, based on the fault maps (Charusiri et al., 1999; Watkinson et al., 2008) can be interpreted due to the existence of other fault zones in granitic bodies in the region, such as the Khlong Tom Fault Zone (KTFZ; Figure 4.2). Meanwhile, several concentrations of epicenter can also be found in the Andaman Sea and the Gulf of Thailand which were scattered offshore of Trang, Krabi, Phuket, Phang Nga, Ranong, Songkhla, Nakhon Si Tammarat, Surat Thani, and Prachuap Khiri Khan Provinces. There was also a cluster of earthquake swarm took place in Phuket Island from 16 April to 5 May 2012 (Nazaruddin and Duerrast, 2021a; Figure 4.3) as discussed in details in Section 4.1.3.

In terms of the focal depth, the minimum and maximum depths of earthquake have ever recorded in this region are 1 km and 78.4 km, respectively. Thus, local earthquakes were categorized into shallow (1 – 70 km deep) and intermediate earthquakes (70 – 78.4 km deep). Several depth profiles showing the vertical distribution of epicenters are represented in Figure 4.4. Previous studies on the crustal thickness beneath Thailand revealed that South Thailand has the average crustal thickness of around 20–30 km (Tadapansawut et al., 2012) or around 25–35 km (Naisagool et al., 2014; Wongwai, 2011;). Considering that the most common depth for the intraplate earthquakes in any region is around 10-20 km (Havskov and Ottemöller, 2010) and the maximum crustal thickness in Southern Thailand is 35 km, thus for this study, the dominant shallow earthquakes can be categorized into three classes of focal depth (symbolized by three different colors of dots in the epicenter map): 1 – 20 km (yellow), 20.1 – 35 km (dark blue), and 35.1 – 70 km (purple). Most of the recorded earthquakes in this region have very shallow depths (1 – 20 km) with 198 events scattered in and around the fault zones as well as offshore areas. As many as 18 earthquakes with the depths of 20.1- 35 km were distributed randomly in the fault zones and its surroundings. The focal depths of 35.1- 70 km of five events were scattered in the western part of Thai Peninsula i.e. in Phang Nga and Phuket Provinces. Meanwhile, one event with the depth of 78.4 km (categorized as the intermediate earthquake; symbolized by a red dot) occurred offshore Phang Nga Province is the deepest earthquake ever detected so far in the region. Three events in the 1970s and two events in 1999 have no data of focal depth. Figure 4.4 shows several depth profiles of local earthquakes in this region.

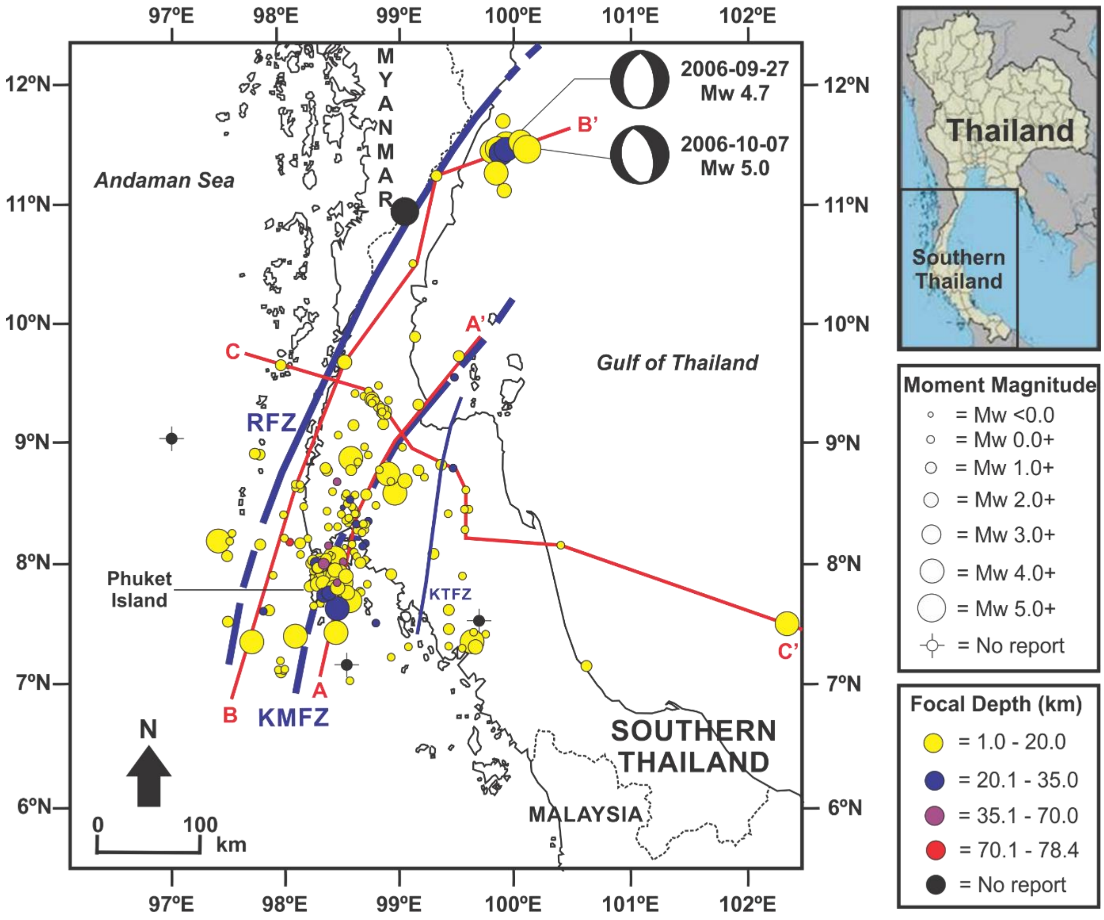


Figure 4.2 Epicenter map of Southern Thailand showing the earthquake distribution during the period 1970 – 2020 with different magnitude and focal depth values. Focal mechanisms of two largest events happened offshore Prachuap Khiri Khan (source: http://www.globalcmt.org/CMTsearch.html) were added. Red lines (A-A', B-B', and C-C') indicate the lines of cross section. Depth profiles of these lines can be seen in Figure 4.4 (a-c).

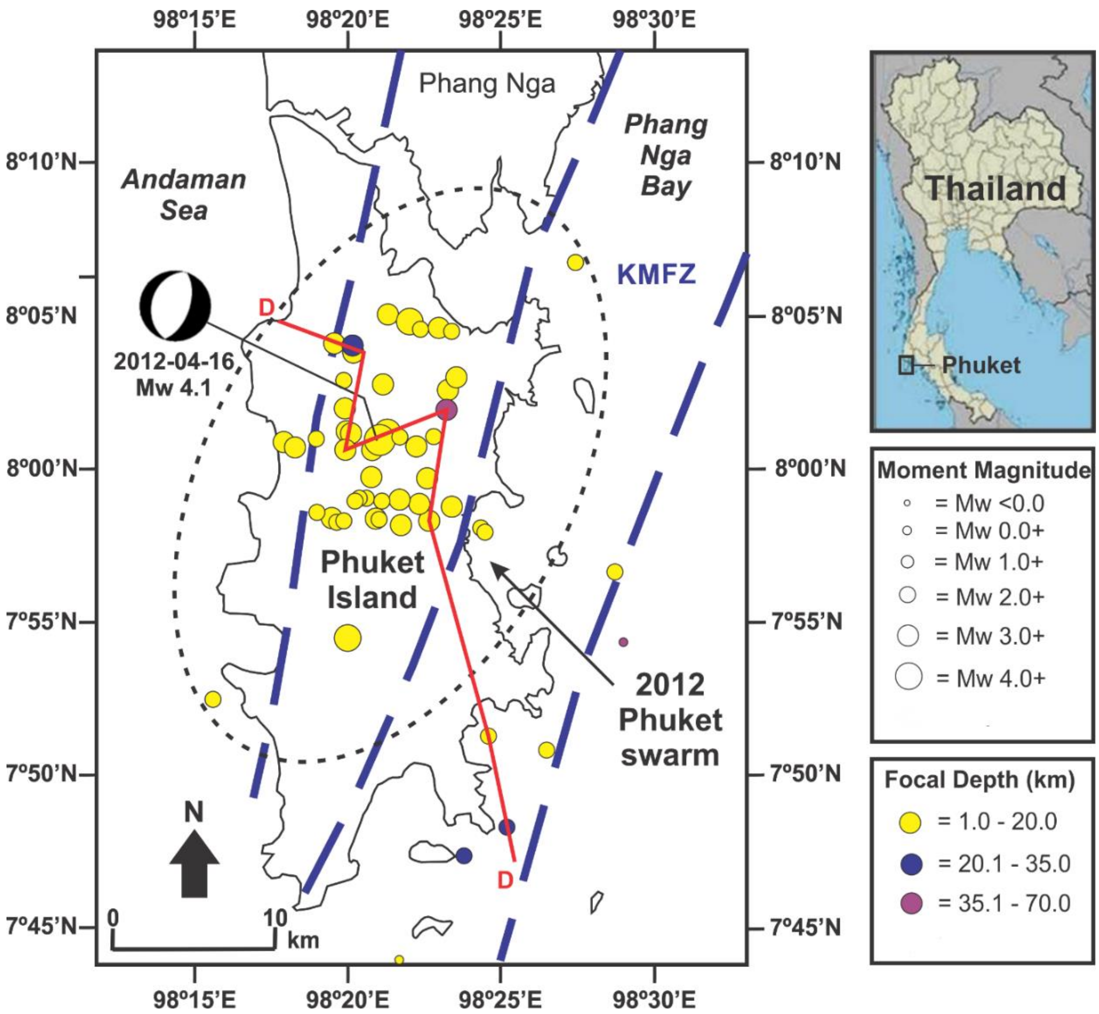


Figure 4.3 Epicenter map of Phuket Island showing the 2012 earthquake swarm and other earthquake events. A focal mechanism of the swarm's largest event occurred onshore the island (Pornsopin et al., 2012) was added. The red line (D-D') indicates the lines of cross section. Depth profiles can be seen in Figure 4.4 (d).

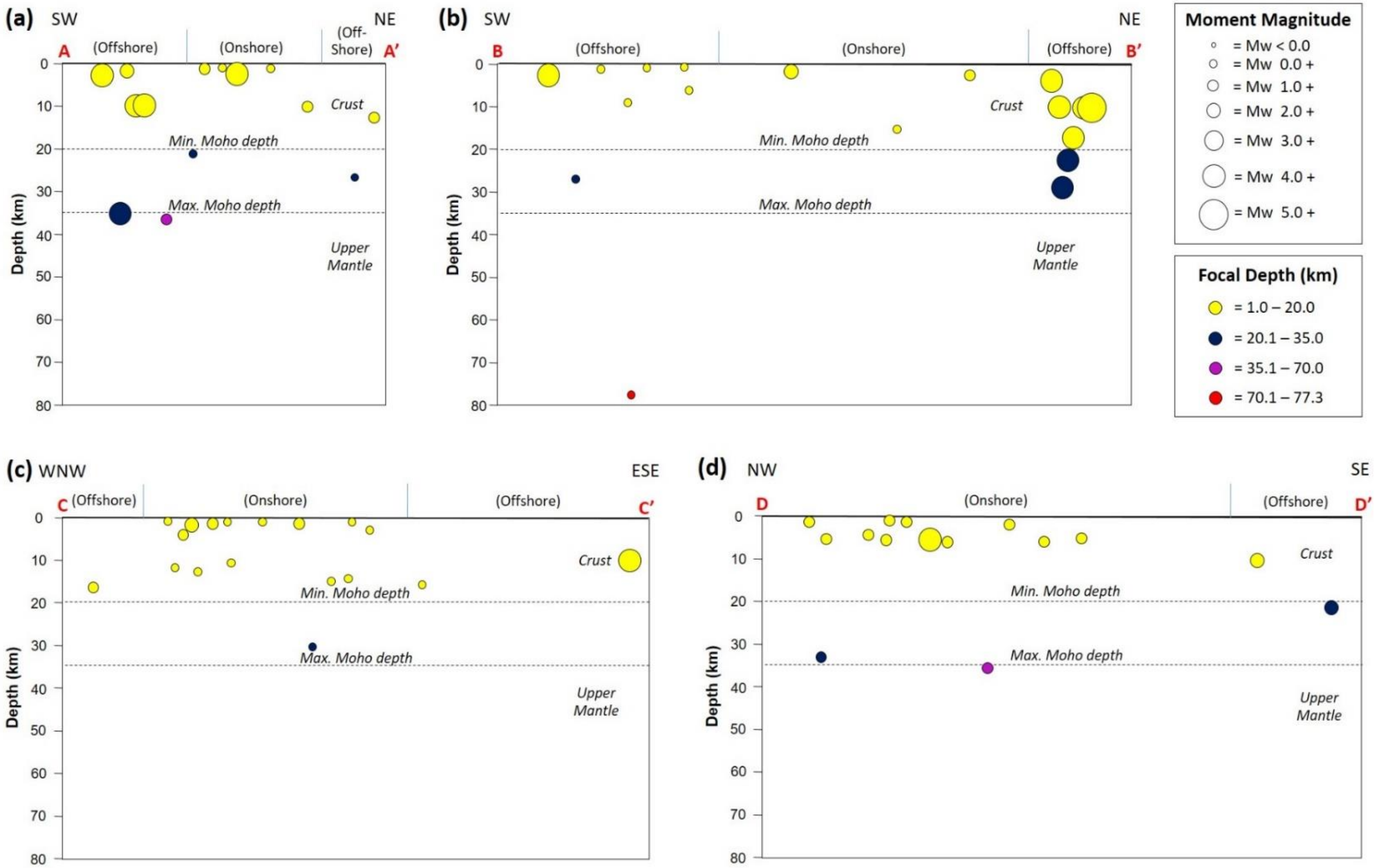


Figure 4.4 Vertical sections (depth profiles) of seismicity in Southern Thailand during the instrumental period from several lines: (a) Along the KMFZ, (b) Semi-parallel to and in between the KMFZ and RFZ, (c) Perpendicular to the RFZ and KMFZ, and (d) Across Phuket Island. The map showing cross section lines can be seen in Figures 4.2 and 4.3. The depth of Moho in this region was obtained from Naisagool et al. (2014), Tadapansawut et al. (2012), and Wongwai (2011).

Based on the fault map by Watkinson et al. (2008), the occurrence of deeper earthquakes in the western part of the KMFZ (mainly in Phuket and Phang Nga Provinces) was interpreted to be related to the deformation of the metamorphic rocks (such as migmatite, granite mylonite and biotite mylonite which form deep under the surface with high temperature and pressure) which were sheared and exhumed at the surface of the western part of KMFZ. Therefore, most local earthquakes in the region are of crustal depths and only some events happened in the upper mantle. The focal depth distribution reveals that the numbers of earthquakes are decreasing with the increasing of focal depths, as shown in Table 4.3 later.

Focal Mechanism

Due to limited geographical distribution of seismological stations around the epicenters, this study did not create the focal mechanism solution (FMS, or "beach ball"). However, the FMS of among two largest events were obtained from the Global Centroid Moment Tensor (GCMT; http://www.globalcmt.org/CMTsearch.html). Both events took place offshore Prachuap Khiri Khan on 27 September 2006 (Mw 4.7) and 7 October 2006 (Mw 5.0). GCMT catalogue displays the "beach balls" in two nodal planes and shows that both events are the normal faulting (see Figure 4.2). Pornsopin et al. (2012) provided the FMS to the largest event of the 2012 earthquake swarm in Phuket (ML 4.1 = Mw 4.1). The FMS was displayed by a "beachball" in two nodal planes where the selected solution shows the slightly oblique normal faulting (see Figure 4.3). Table 4.2 summarizes the FMS of three events in Southern Thailand. From the FMS, it can be observed that the three earthquakes occurred because of normal faulting possibly took place on several sub-fault lines in RFZ and KMFZ, instead of the main fault lines.

Table 4.2 Focal mechanism determination with the strikes, dips, and rakes for the two fault plane solutions (FP1 and FP2) for three local earthquakes in Southern Thailand (http://www.globalcmt.org/CMTsearch.html; Pornsopin et al., 2012).

Event No.	**Origin time (yyyy-mm-dd hh:mm:ss; UTC)**	**Location**	**Mw**	**FP1 strike (degree)**	**FP1 dip (degree)**	**FP1 rake (degree)**	**FP2 strike (degree)**	**FP2 dip (degree)**	**FP2 rake (degree)**
124	2006-09-27 18:46:02	Offshore Prachuap Khiri Khan	4.7	191	41	-77	353	50	-101
126	2006-10-07 21:12:25	Offshore Prachuap Khiri Khan	5.0	171	37	-84	344	53	-94
145	2012-04-16 09:44:25	Phuket	4.1	019	57	-87	-	-	-

Magnitude Variation

Although the magnitude values of local earthquakes in Southern Thailand were reported and analyzed in different magnitude scales (M, ML, and mb), for uniformity, this study converted all these magnitude scales into the moment magnitude (Mw). This study has used a lot of micro earthquakes obtained from the earthquake monitoring of the local temporary network in 2005. There were 105 out of 227 local events in this region has the Mw between 0.0 to 0.9 which happened mostly in 2005 and several others took place afterward. They were concentrated mostly in the central part of the region both onshore and offshore in the vicinity of the KMFZ and RFZ. As many as five earthquakes of lowest magnitude with negative values (Mw < 0) i.e Mw -0.1 occurred in 2005 and were concentrated in some areas in Phang Nga and Phuket. Other earthquakes have Mw 1.0+ with 74 events, Mw 2.0+ with 17 events, and Mw 4.0+ with 21 events. Meanwhile, there were only two events with

Mw 5.0+. The highest magnitude value is Mw 5.6 happened in the border between Chumpon, Prachuap Khiri Khan and Myanmar on 30 September 1978. The Mw variation in this region during the instrumental period can be seen in Table 4.3.

Table 4.3 Numbers of local earthquakes in Southern Thailand during the instrumental period (1970 – 2020) based on their focal depth distribution and moment magnitude variation.

Number of local earthquakes based on focal depths			**Number of local earthquakes based on moment magnitudes**	
Focal depth (km)	**No. of earthquakes**		**Moment magnitude (Mw)**	**No. of earthquakes**
1.0 – 20.0	198		<0.0	5
20.1 – 35.0	18		0.0+	105
35.1 – 70.0	5		1.0+	74
70.1 – 78.4	1		2.0+	17
No report	5		3.0+	0
			4.0+	21
			5.0+	2
			No report	3
Total	**227**		**Total**	**227**

4.1.3 Earthquake Swarm in Phuket (2012)

A series of local earthquakes occurred in Phuket (events no. 145 – 190 in Table 4.1), the only island province in Southern Thailand, mainly in its northern part, during 16 - 22 April 2012 (in the first phase), even likely until the second phase on 5 May 2012. Analysis on this earthquake sequence revealed that the first phase of this sequence is considered as the main earthquake swarm, meanwhile the second phase is assumed as the mini swarm and as the compliment to the first phase. Most results of the 2012 Phuket swarm have been published in a paper by Nazaruddin and Duerrast (2021a; Appendix 1). From the distribution of epicenters (Figure 4.3), it can be seismotectonically interpreted that this multiple earthquake is associated with the NNE-SSW trending KMFZ, likely due to fluid intrusions into fault planes of the positive flower structure as revealed by focal mechanism of Pornsopin et al. (2012). Chronology of this swarm is summarized in Table 4.4. Figure 4.5 displays a graph of number of earthquakes per day and local magnitude variation during the full 20-day duration of the 2012 Phuket swarm and a graph of cumulative number of earthquakes.

Table 4.4 Chronology of the 2012 Phuket earthquake swarm activity.

Date	**ML (Mw)**	**No. of event**	**Remark**
16 April 2012	1.5 - 4.1 (0.9 – 4.1)	27	Initiation of the swarm (the first phase); the weakest and largest events occurred this day
17 April 2012	1.8 - 2.9 (1.1 – 1.7)	6	Swarm activity decreased
18 April 2012	2.3 - 3.5 (1.4 – 2.1)	3	Swarm activity decreased, but the range of magnitude increased
19 April 2012	1.7 - 2.9 (1.0 – 1.7)	4	Swarm activity slightly increased, but the range of magnitude decreased
20 April 2012	2.2 - 3.0 (1.3 – 1.8)	4	Range of magnitude increased
21 April 2012	1.9 (1.1)	1	Swarm activity decreased, only one event detected
22 April 2012	2.5 (1.5)	1	Only one event detected with higher magnitude from previous day (the end of the first phase)
23 April – 2 May 2012	-	0	*Hiatus (no event detected) for 10 consecutive days*
3 May 2012	2.0 (1.2)	1	Only one event detected (the initiation of the second phase/the mini swarm)
4 May 2012	-	0	*Hiatus (no event detected)*
5 May 2012	2.1 (1.3)	1	Termination of the second phase/the mini swarm

Based on the criteria of an earthquake swarm (Horálek et al., 2015; Mogi, 1963, 1967; Roland and McGuire, 2009), these earthquakes are suitable to be categorized as an earthquake swarm by considering several reasons. They are a multiple earthquake (not a single event) with total 46 events (in the first phase). They took place in a certain local area in Phuket and within a certain period of time (7 days). They have no an obvious mainshock like other common earthquake sequences. In addition, they have also relatively similar-sized earthquakes (as small to moderate earthquakes) and mostly occurred in shallow depths.

Quantitative analysis shows that the first phase of these earthquakes has been categorized as an earthquake swarm based on the empirical measure of Mogi (1963): 1) The number of earthquakes in this sequence is 46 events, which is more than 10, and 2) The maximum daily number of earthquakes (Nm) is 27 (in the first day; 16 April 2012) and the duration of the earthquake sequence (T) is 7 days, so that the calculation of $Nm/\sqrt{T}$ is 10.205 which is greater than 2. Meanwhile, the second phase is assumed as a mini swarm with only two events during only two days and become a compliment to the first phase.

For the statistical analysis of the calculation of skewness and kurtosis (Table 4.5), the maximum value of seismicity rate for this earthquake sequence is six events per 2-hr time bins, so that the 20% of this maximum value is 1.2. This 20% seismicity rate value ends with the 27th event after 19:35 hrs or 1,175 minutes. With the standard deviation (σ) obtained as 157.99, the third central moment (μ_3) of 10,454,109.19, and the forth central moment (μ_4) of 5,596,998,402.13, the calculation of skewness ($S = \mu_3/\sigma^3$) and kurtosis ($K = \mu_4/\sigma^4$) from the 1st – 27th events of this earthquake sequence gives their values of S = 2.65 and K = 8.98, respectively. These skew and kurtosis values indicate that this earthquake sequence is an earthquake swarm. This result can be validated by considering that the largest earthquake happened as the 3rd event in the sequence, not the first one (like MS-AS sequence) and the local magnitude difference between the two largest events is small, only 0.6.

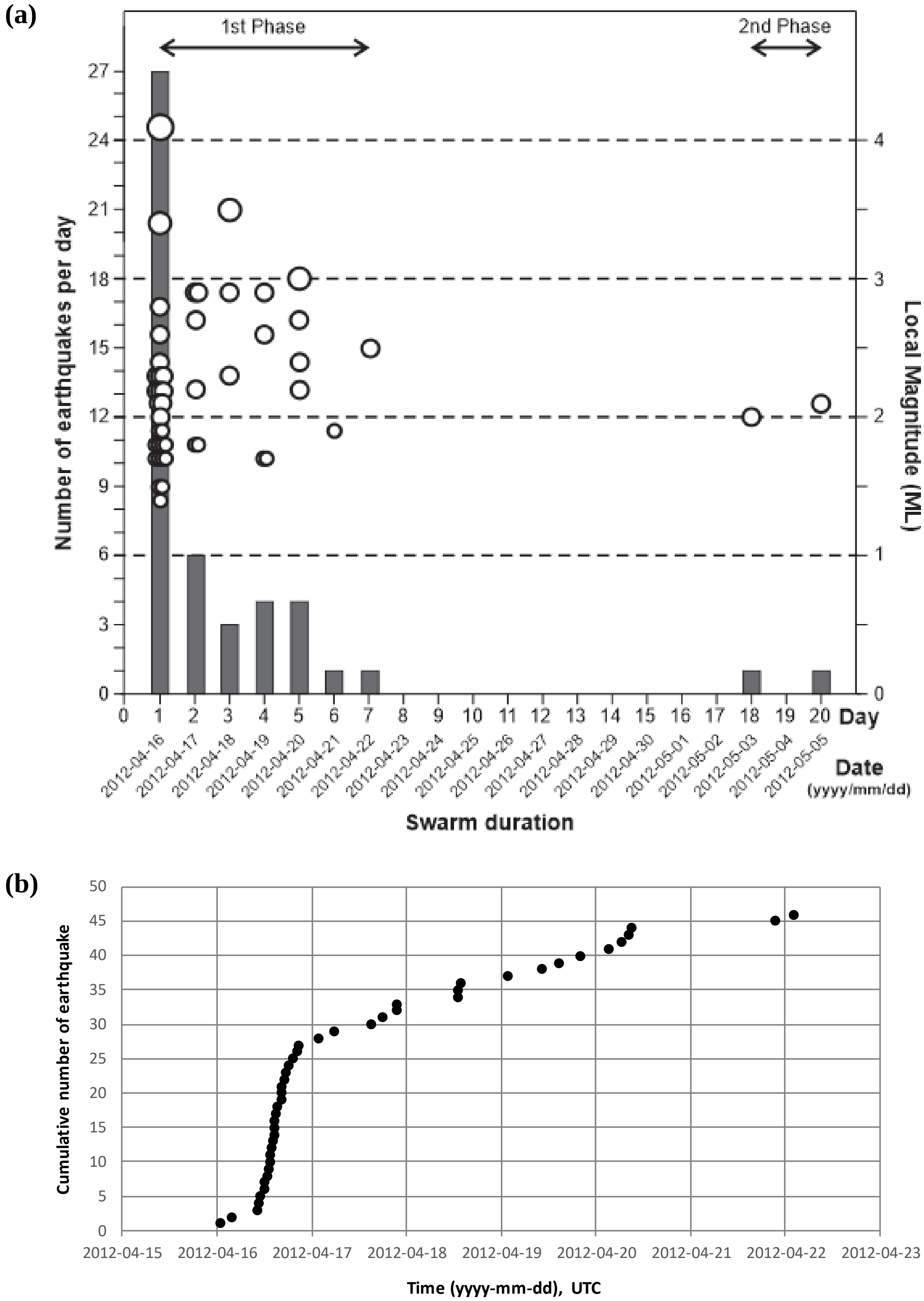


Figure 4.5 (a) Number of earthquakes per day (grey bars; lower left-hand side scale) and local magnitude variation (circles; right-hand side scale) during the 2012 Phuket swarm; (b) Cumulative number of earthquakes (black dots) for the first seven days (first phase) of the swarm.

Table 4.5 Calculation of skewness (S) and kurtosis (K) of the 2012 Phuket earthquake swarm.

Event No.	Date (mm-dd-yy hh:mm)	2-hr time bins	No. of EQs per time bins	From first event		Mag. (ML)	Moment Mo (Nm) (Mw = ML)	Normalized Mo/ mo	Event time x Normalized Mo	Std. Dev. (min)	Third central moment (min^3)	Forth central moment (min^4)
				hrs	min							
1	2012-04-16 00:37	0:00 - 2:00	1	0:00	0	2.2	2.51189E+12	0.00125505	0.00000000	449.3757	-268895.9779	160901121.2131
2	2012-04-16 03:20	2:00 - 4:00	1	2:43	163	1.7	4.46684E+11	0.00022318	0.03637874	42.3049	-18418.5711	8019018.9651
3	2012-04-16 09:44	8:00 - 10:00	1	9:07	547	4.1	1.77828E+15	0.88850528	486.01238900	2345.2790	-120492.9866	6190546.9413
4	2012-04-16 10:12	10:00 - 12:00		9:35	575	2.3	3.54813E+12	0.00177280	1.01936064	0.9688	-22.6473	529.4221
5	2012-04-16 10:30	10:00 - 12:00		9:53	593	2.4	5.01187E+12	0.00250415	1.48495984	0.0724	-0.3893	2.0930
6	2012-04-16 11:43	10:00 - 12:00		11:06	666	1.9	8.91251E+11	0.00044531	0.29657480	2.0363	137.7040	9311.9852
7	2012-04-16 11:47	10:00 - 12:00	4	11:10	670	1.8	6.30957E+11	0.00031525	0.21121989	1.6172	115.8299	8296.1065
8	2012-04-16 12:25	12:00 - 14:00		11:48	708	1.7	4.46684E+11	0.00022318	0.15801316	2.6820	294.0134	32230.6852
9	2012-04-16 12:50	12:00 - 14:00		12:13	733	1.7	4.46684E+11	0.00022318	0.16359273	4.0448	544.5271	73305.9700
10	2012-04-16 13:02	12:00 - 14:00		12:25	745	1.8	6.30957E+11	0.00031525	0.23486391	6.7774	993.7288	145703.6752
11	2012-04-16 13:03	12:00 - 14:00		12:26	746	1.7	4.46684E+11	0.00022318	0.16649410	4.8637	717.9987	105993.2465
12	2012-04-16 13:30	12:00 - 14:00		12:53	773	2.3	3.54813E+12	0.00177280	1.37037525	54.0585	9439.8624	1648418.7548
13	2012-04-16 13:56	12:00 - 14:00	6	13:19	799	2.1	1.77828E+12	0.00088851	0.70991572	35.7620	7174.6929	1439409.6861
14	2012-04-16 14:17	14:00 - 16:00		13:40	820	2.8	1.99526E+13	0.00996919	8.17473845	489.6552	108518.9387	24050311.8795
15	2012-04-16 14:23	14:00 - 16:00		13:46	826	1.9	8.91251E+11	0.00044531	0.36782400	23.0724	5251.8154	1195434.8989
16	2012-04-16 14:25	14:00 - 16:00		13:48	828	2.6	1E+13	0.00499643	4.13704601	263.4459	60493.2857	13890660.3911
17	2012-04-16 14:37	14:00 - 16:00		14:00	840	1.8	6.30957E+11	0.00031525	0.26481300	18.4051	4447.0886	1074519.6689
18	2012-04-16 14:50	14:00 - 16:00		14:13	853	2.2	2.51189E+12	0.00125505	1.07055515	81.3684	20718.2852	5275355.5899
19	2012-04-16 15:54	14:00 - 16:00	6	15:17	917	1.5	2.23872E+11	0.00011186	0.10257212	11.3557	3618.1961	1152841.1345

20	2012-04-16 16:01	16:00 - 18:00		15:24	924	2.1	1.77828E+12	0.00088851	0.82097888	94.2086	30676.5092	9988982.3685
21	2012-04-16 16:03	16:00 - 18:00		15:26	926	2.3	3.54813E+12	0.00177280	1.64161382	190.2871	62342.4496	20424831.3488
22	2012-04-16 16:48	16:00 - 18:00		16:11	971	1.5	2.23872E+11	0.00011186	0.10861236	15.5310	5787.2148	2156450.3696
23	2012-04-16 17:16	16:00 - 18:00	4	16:39	999	2.2	2.51189E+12	0.00125505	1.25379202	201.4337	80699.0130	32329894.9114
24	2012-04-16 18:00	18:00 - 20:00		17:23	1043	1.8	6.30957E+11	0.00031525	0.32880947	62.3224	27709.9859	12320501.9231
25	2012-04-16 19:02	18:00 - 20:00	2	18:25	1105	3.4	1.58489E+14	0.07918812	87.50286881	20324.9797	10297105.7701	5216752431.0968
26	2012-04-16 20:11	20:00 - 22:00		19:34	1174	2.0	1.25893E+12	0.00062901	0.73846193	208.4186	119970.5993	69057857.4226
27	2012-04-16 20:12	20:00 - 22:00	2	19:35	1175	1.4	1.58489E+11	0.00007919	0.09304604	26.3296	15182.2555	8754440.3865
28	2012-04-17 01:31	0:00 - 2:00	1			1.8						
29	2012-04-17 05:18	4:00 - 6:00	1			2.9						
30	2012-04-17 14:56	14:00 - 16:00	1			2.7						
31	2012-04-17 17:49	16:00 - 18:00	1			2.2						
32	2012-04-17 21:15	20:00 - 22:00				2.9						
33	2012-04-17 21:19	20:00 - 22:00	2			1.8						
34	2012-04-18 12:48	12:00 - 14:00				2.3						
35	2012-04-18 12:53	12:00 - 14:00				3.5						
36	2012-04-18 13:38	12:00 - 14:00	3			2.9						
37	2012-04-19 01:13	0:00 - 2:00	1			1.7						
38	2012-04-19 10:13	10:00 - 12:00	1			1.7						
39	2012-04-19 14:20	14:00 - 16:00	1			2.6						
40	2012-04-19 19:43	18:00 - 20:00	1			2.9						
41	2012-04-20 02:57	2:00 - 4:00	1			2.4						
42	2012-04-20 06:18	6:00 - 8:00	1			2.7						
43	2012-04-20 08:10	8:00 - 10:00				3.0						
44	2012-04-20 08:42	8:00 - 10:00	2			2.2						

45	2012-04-21 21:07	20:00 - 22:00	1			1.9						
46	2012-04-22 01:42	0:00 - 2:00	1			2.5						
47	2012-05-03 21:54	20:00 - 22:00	1			2.0						
48	2012-05-05 23:21	22:00 - 24:00	1			2.1						
	For events# 1-27 (using 20% max. seismicity rate)		Max. = 6 20% = **1.2**				Sum Mo (events# 1-27) = 2.00143E+15	Sum normalized Mo = m_o = **1.00000000**	Sum = 598.37682379 Weighted mean time (in min)= t = **598.37682379**	Sum = 24960.6563 Std. dev.= σ= **157.9894**	Sum 3rd central moment = μ_3 = **10454109.1922**	Sum 4th central moment = **5596998402.1341**
											S = 2.65	**K = 8.98**

4.1.4 Relations between Seismicity and Local Tectonics in Southern Thailand

This study creates an opportunity to analyze the relations between the seismicity in Southern Thailand and the local tectonics through earthquake occurrence since the pre-instrumental period until the current modern instrumental period. As stated in the previous section, paleoseismological studies have revealed that there were paleoearthquake activities with the magnitude more than Mw 6.0 have been recorded from the fault zones, mainly the KMFZ and RFZ, showing that the fault zones have been active during the ancient time.

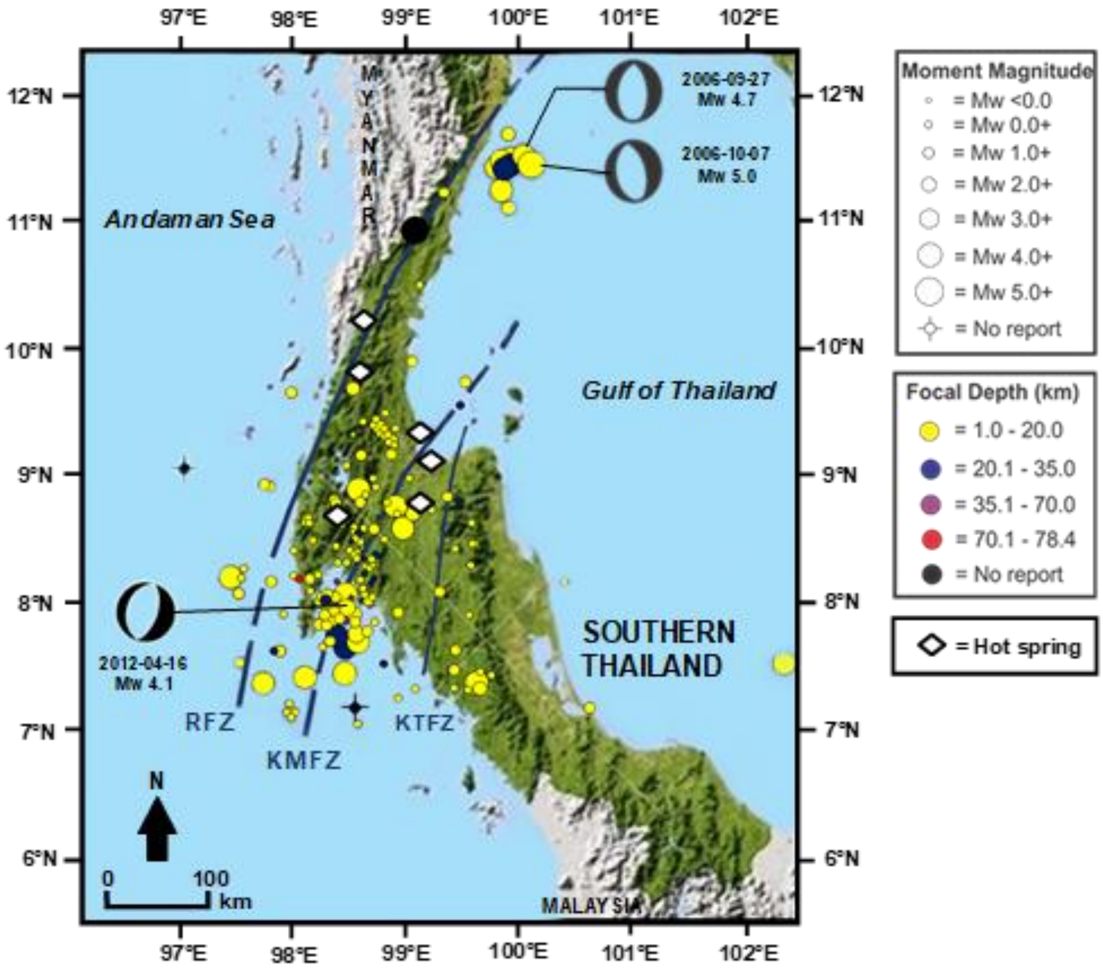
The present study shows the correlation between the seismicity in this region with local tectonics, mainly faults (and lineaments) obtained from the geological map. The result show that the seismicity did correlate with some mapped faults (and lineaments). Figure 4.6 shows this relation in a seismotectonic map of Southern Thailand. Most epicenters were located in the vicinity of the fault zones, such as KMFZ and RFZ, and the trend of most epicenters is parallel to these two fault zones as well as other minor or smaller fault zones. Among the two fault zones, more earthquakes were located within the KMFZ than the RFZ. However, the two largest earthquakes (Mw 5.6 and Mw 5.0) took place within the RFZ in 1978 and 2006, respectively, specifically in the north segment of the fault zone. Meanwhile, Figure 4.3 shows the spatial distribution of earthquakes in Phuket in relation to the KMFZ, where epicenters were located in the south segment of the fault zone.

Based on this result, it can be interpreted that the earthquakes were attributed to the reactivations or movements of fault lines within these fault zones. The major fault zones in Southern Thailand generally appeared to be inactive or dormant for a long time until the occurrence of several large regional earthquakes in Sumatra region, started by the 2004 Sumatra-Andaman earthquake. It is believed that the fault reactivations are the results of intraplate stress release after its prolonged accumulation due to the present-day tectonics in the Sundaland. Sibson (1989) elaborated that the existence of structural controls (such as faults) governs the initiation and termination of earthquake ruptures at particular locations. Faulting occurs to release the accumulated shear stress on faults.

Trends of the fault planes from the focal mechanisms (source: http://www.globalcmt.org/CMTsearch.html) show that several earthquakes which happened offshore Prachuap Khiri Khan originated from the sub-faults within the RFZ. Meanwhile, the focal mechanism also reveals that the trend of the fault plane for the largest event of the 2012 Phuket swarm (Pornsopin et al., 2012) with ML 4.1 (= Mw 4.1) was consistent with the trend of the KMFZ in this island. Focal mechanisms also show that all these earthquakes triggered by the normal faulting.

The existence of these fault zones is also associated with geothermal (hot) spring manifestations in some parts in Southern Thailand. Previous studies show that several hot springs are located in and associated with the fault zones, such as RN1 and RN2 (Ranong), PG1 (Phang Nga), SR3, SR7, and SR9 (Surat Thani) (Ngansom and Duerrast, 2019; Ngansom et al., 2020; Subtavewung et al., 2005).

Figure 4.6 *(Next page)* Seismotectonic map of Southern Thailand showing the relation between the seismicity with local tectonics. Faults and fault zones were mapped by Charusiri (1999). Focal mechanisms for several events (http://globalcmt.org/CMTsearch.html; Pornsopin et al., 2012) and hot spring manifestations (Ngansom and Duerrast, 2019) were added. RFZ=Ranong Fault Zone, KMFZ=Khlong Marui Fault Zone, KTFZ=Khlong Thom Fault Zone.



4.2 Seismicity in Peninsular Malaysia

4.2.1 Brief History on Pre-Instrumental Seismicity in Peninsular Malaysia

There are very few studies on paleoseismology carried out in West Malaysia so far. These studies only revealed the evidences of paleoearthquakes in this region without estimating paleoearthquake parameters. Ng et al. (2009) disclosed evidences of paleoearthquake in Bukit Tinggi area (in the state of Pahang) comprising the fault rocks and other materials related to dislocation along the fault planes. Shuib (2013) have identified faults displaying evidences of Late Pleistocene to Holocene movements in Cameron Highland (in Pahang) from the remote sensing and field investigations. These active faults are considered capable of generating large earthquakes. Shuib et al. (2017b) have also identified active faults displaying evidences of Quaternary movements in coastal plains in the south of state of Perak through the remote sensing, geological and geomorphological mapping, and geophysics. The alluvial sediments showed the existence of seismites suggesting paleoearthquake activity during sedimentation. These faults are also considered capable of producing large earthquakes.

The instrumental period of Malaysia started in 1975 since the installation of the first seismological station in the country by the MMD, hence the end of historical earthquakes for this region. Leyu et al. (1985) for the first time compiled historical earthquakes in and around West Malaysia. However, only very few events were reported as the historical earthquakes originated from this region and otherwise most of the events are historical felt earthquakes with the epicenters located in surrounding areas mainly around Sumatra. Tongkul (2020) summarized all these historical felt earthquakes in West Malaysia. There are at least three earthquakes reported as historical earthquakes in West Malaysia which took place on 31 January 1922 and 7 February 1922 in the state of Johor in the southern part of this region, and 16 June 1927 in the Malacca Strait off Kedah (events no. 1 – 3 in Table 4.6). Leyu et al. (1985) labeled the two earthquakes occurred in 1922 as the minor tremors felt in many parts of Peninsular Malaysia until Singapore in the south. In a current paper, Martin et al. (2020) elaborated that this pair of moderate earthquakes were felt more strongly in the southern part of West Malaysia than in Sumatra; therefore they concluded that both the 1922 historical earthquakes originated from the southern part of West Malaysia causing a light grade of damage. However, what caused these earthquakes is still enigmatic. The first event happened at 09:10 local time (01:10 UTC) in the east of Muar, Johor (2.0°N; 102.8°E) with the intensity magnitude (M_I) of 5.4 (= Mw 5.4). The second one took place at 12:15 local time (04:15 UTC) in the west of Batu Pahat, Johor (1.9°N; 103.8°E) with the M_I of 5.0 (= Mw 5.0). The earthquakes could probably have originated in the lower crust (Z = 25 – 30 km). The 31 January 1922 earthquake is the largest earthquake (M_I 5.4 = Mw 5.4) have ever reported in West Malaysia region. Such a large earthquake is rare within the intraplate regions. The 16 June 1927 earthquake occurred at 02:40 UTC in the coordinates

6.0°N 99.5°E (in the Malacca Strait off Kedah near Langkawi Island) as reported by ISC and without information on magnitude and focal depth known.

4.2.2 Instrumental Seismicity in Peninsular Malaysia

The earthquake catalogue of West Malaysia created for this study comprises three historical events (events no. 1 – 3 in Table 4.6) and 56 local events of the instrumental period (events no. 4 – 59 in Table 4.6). The instrumental data have been compiled from national and global networks. Early instrumental earthquakes in the region were reported by ISC and other agencies during the period 1978 to 2006. The first event of instrumental period in West Malaysia is the 31 May 1978 earthquake which happened in the Malacca Strait off Selangor (2.6754°N 101.3871°E) at 04:20:25 UTC with the reported magnitude mb 4.9 (= Mw 5.0). Meanwhile, the last event recorded so far in West Malaysia is the 26 February 2020 earthquake which took place at 21:46:09 UTC in the state of Perak (3.9689°N 101.4237°E) with the reported magnitude mb 3.6 (= Mw 3.7).

The MMD as the national seismological agency started to record seismological data from the 1970s (around 1975) onward (MMD, personal communication). However, there was no any significant earthquake originating from within West Malaysia and no record by the MMD until the occurrence of the 30 November 2007 Bukit Tinggi earthquake. Before the 2004 Sumatra-Andaman earthquake, there were still less number of seismological stations in this region. After 2004, the number of stations increases in this region so that the earthquake monitoring improves, thus further enhances the quantity and quality of earthquake data. The seismicity in West Malaysia increases post-2004 with a number of earthquakes of mostly micro (ML<3) to minor magnitude scale (ML=3-4). From 33 local events recorded by MMD and happened during 30 November 2007 to 23 February 2016, only digital seismograms of 20 events have been analyzed in this study (Table 4.6). The earthquake catalogue has also been complimented by earthquake data from global networks, such as ISC, USGS-NEIC, and EMSC. All data of local earthquakes in West Malaysia region were summarized in Table 4.6.

Table 4.6 Earthquake data in West Malaysia compiled from various catalogues of national and international seismological networks and previous studies.

Event No.	**Date and Original Time (yyyy-mm-dd hh:mm:ss UTC)**	**Lat. (ºN)**	**Long. (ºE)**	**Mag. (calcu-lated/ reported)**	**Mag. Scale**	**Con-verted into Mw**	**Focal Depth (km)**	**Data source (agency)**
1	1922-01-31 01:10:00	2.0	102.8	5.4	M_I	5.4	25-30 (estimated)	Martin et al. (2020)
2	1922-02-07 04:15:00	1.9	103..8	5.0	M_I	5.0	25-30 (estimated)	Martin et al. (2020)
3	1927-06-16 02:40:12	6.000	99.500	No report	-	-	No report	ISS/ISC
4	1978-05-31 04:20:25	2.6754	101.3871	4.9	mb	5.0	35.0	ISC
5	1985-04-06 13:34:37	5.1913	102.6242	3.8	mb	3.9	33.0	ISC
6	1987-06-23 16:06:28	4.9564	102.6379	3.8	mb	3.9	33.0	ISC
7	1992-02-08 00:55:33	2.800	104.200	3.7	ML	2.5	12.0	ISC
8	1992-09-25 11:40:32	2.6291	101.3829	3.1	ML	2.1	167.0	ISC
9	1995-06-10 09:13:53	5.0544	100.2510	4.1	mb	4.2	33.0	ISC
10	1996-04-21 07:34:44	2.6900	101.6100	3.3	mb	3.4	1.0	ISC
11	1997-07-25 03:00:53	4.0710	100.6540	3.9	ML	2.6	80.0	ISC
12	1997-11-02 10:56:52	4.9781	101.3126	3.6	ML	2.4	80.0	ISC
13	1997-11-27 03:59:01	3.7348	101.4787	4.6	ML	4.6	15.0	ISC
14	1998-03-01 05:57:56	4.1888	100.1420	5.0	ML	5.0	80.0	ISC
15	1998-03-26 08:00:17	6.2543	99.1030	4.3	ML	4.3	1.0	ISC
16	1998-08-22 08:11:46	4.0893	100.5039	4.1	ML	4.1	33.0	ISC
17	1998-08-25 05:55:47	2.4380	101.7840	4.2	ML	4.2	32.0	ISC
18	1998-09-14 07:45:03	4.5543	100.7663	4.4	ML	4.4	33.0	ISC
19	2006-05-18 18:06:43	3.2826	101.4359	2.3	ML	1.5	1.0	ISC
20*	2007-11-30 02:13:30	3.350	101.837	3.4	ML	2.3	2.7	MMD
21	2007-11-30 02:42:00	3.340	101.800	2.8	ML	1.9	10.0	MMD
22*	2007-11-30 12:42:57	3.331	101.823	3.3	ML	2.2	8.2	MMD
23*	2007-12-04 10:11:52	3.377	101.852	3.0	ML	2.0	9.4	MMD
24	2007-12-04 19:57:00	3.370	101.800	3.3	ML	2.2	10.0	MMD
25*	2007-12-06 15:23:37	3.343	101.829	2.7	ML	1.8	21.1	MMD
26*	2007-12-09 12:55:41	3.319	101.848	3.7	ML	2.4	15.9	MMD
27*	2007-12-12 10:01:55	3.416	101.746	3.3	ML	2.2	17.2	MMD
28	2007-12-31 09:19:00	3.320	101.810	2.6	ML	1.7	3.0	MMD
29	2008-01-10 15:38:00	3.390	101.730	3.0	ML	2.0	1.2	MMD
30	2008-01-13 02:24:00	3.310	101.830	2.5	ML	1.7	10.0	MMD
31	2008-01-13 10:18:00	3.330	101.830	2.4	ML	1.6	10.0	MMD
32	2008-01-14 15:45:00	3.420	101.800	3.4	ML	2.3	2.1	MMD

33	2008-03-14 23:16:18	3.330	101.740	2.9	ML	1.9	1.0	MMD
34	2008-03-14 23:35:34	3.300	101.860	2.5	ML	1.7	1.0	MMD
35	2008-03-15 00:50:57	3.330	101.710	3.3	ML	2.2	1.0	MMD
36	2008-05-25 01:36:22	3.360	101.750	2.6	ML	1.7	1.0	MMD
37	2009-03-27 01:46:25	3.862	102.519	3.0	ML	2.0	50.0	MMD
38	2009-04-29 13:53:54	4.150	100.729	2.5	ML	1.7	23.0	MMD
39*	2009-10-07 21:21:50	3.305	101.815	1.7	ML	1.1	3.3	MMD
40*	2009-10-07 21:26:08	3.328	101.922	0.9	ML	0.6	2.0	MMD
41*	2009-10-07 21:51:12	3.330	101.868	3.0	ML	2.0	2.4	MMD
42*	2009-10-07 22:09:47	3.357	101.820	2.8	ML	1.9	2.8	MMD
43*	2009-10-08 04:05:43	3.226	101.864	1.1	ML	0.7	32.0	MMD
44*	2009-11-29 06:26:58	2.796	102.098	2.8	ML	1.9	6.5	MMD
45*	2009-11-29 16:15:05	2.703	102.056	3.0	ML	2.0	1.0	MMD
46*	2009-11-30 01:12:42	2.799	102.185	2.9	ML	1.9	3.0	MMD
47*	2009-11-30 06:29:49	2.704	102.054	3.1	ML	2.1	7.0	MMD
48	2010-04-16 08:32:07	4.5200	101.1500	2.7	ML	1.8	10.0	ISC
49 (X)	2013-02-13 05:10:54	4.2000	100.7000	5.1	mb	5.2	10.0	ISC
50*	2013-08-20 00:26:49	5.418	101.342	3.8	ML	2.5	1.2	MMD
51	2013-12-18 05:49:10	4.5980	102.1340	2.7	mb	2.9	26.6	ISC
52	2013-12-26 05:51:31	4.4750	101.5840	2.6	mb	2.8	10.0	ISC
53	2014-01-02 05:46:00	4.2180	101.7650	2.5	mb	2.7	8.7	ISC
54*	2016-01-03 16:23:03	5.5213	101.3686	3.0	ML	2.0	15.3	MMD
55*	2016-01-03 17:33:15	5.5537	101.3622	3.2	ML	2.1	12.0	MMD
56*	2016-01-03 21:07:55	5.5498	101.3538	3.1	ML	2.1	10.9	MMD
57*	2016-02-23 13:25:36	5.0316	102.8402	2.6	ML	1.7	2.4	MMD
58	2019-02-17 15:14:01	5.690	99.350	4.5	M	4.5	10.0	EMSC
59	2020-02-26 21:46:09	3.9689	101.4237	3.6	mb	3.7	1.0	ISC

*Analysis of seismograms conducted by this study; MMD: Malaysia Meteorological Department; ISC: International Seismological Center; EMSC: European-Mediterranean Seismological Center. (X): This event was assumed as not a real earthquake, recorded by ISC (obtained from BMKG Indonesia), and it will not be used later in this study.

The earthquake catalogue of West Malaysia comprises 58 local earthquakes took place during the historical and instrumental periods which are during the past almost 100 years, 1922 to 2020. Following sections analyses temporal and spatial distributions of local earthquakes in this region.

Temporal Distribution

The temporal distribution of local earthquakes in West Malaysia with the cumulative number of earthquakes is shown by a graph in Figure 4.7. The graph shows the temporal distribution of the local earthquakes recorded during pre-instrumental and instrumental periods. There is a clear gap in the graph between the pre-instrumental and instrumental periods which might relate to either seismicity hiatus or no recorded data. The seismicity of West Malaysia increased significantly following the 12 September 2007 Bengkulu earthquake in Sumatra with the occurrence of Bukit Tinggi earthquakes during 30 November 2007 – 25 May 2008. The seismicity of the region increased again after the 30 September 2009 West Sumatra earthquake with the occurrence of the second phase of Bukit Tinggi earthquakes during 7 – 8 October 2009.

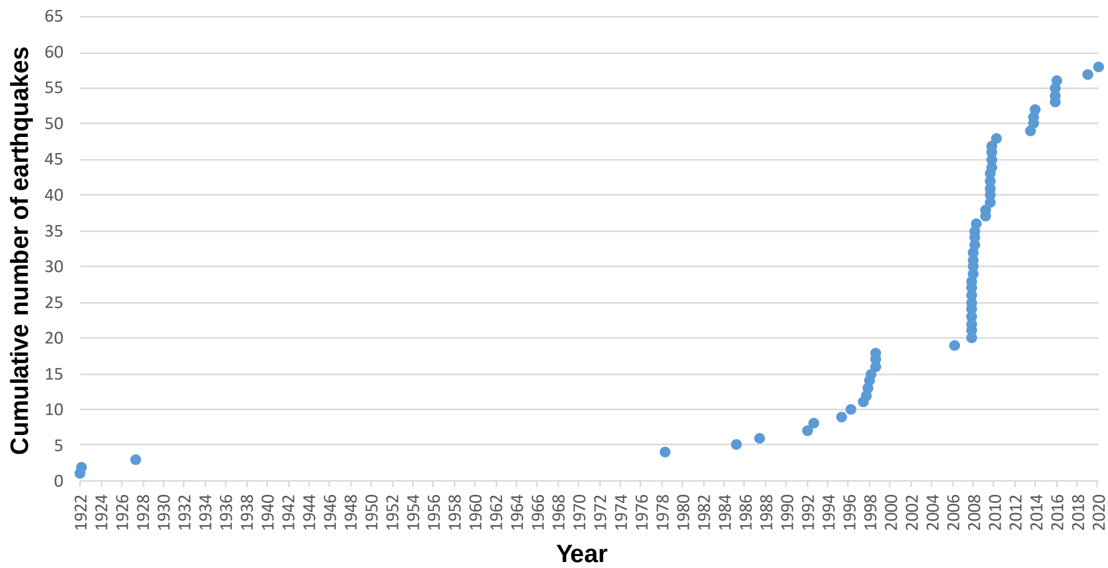


Figure 4.7 Temporal distribution of local earthquakes in the pre-instrumental period (recorded in 1922 and 1927) and in the instrumental period (recorded during 1978 to 2020) in Peninsular Malaysia.

Spatial Distribution

There were 58 earthquakes scattered spatially within the region of West Malaysia during 1922 to 2020 as summarized in the earthquake catalogue (Table 4.6). The epicenter map was created from the catalogue to show the lateral distribution of local earthquakes in the region in relation to the magnitude and focal depth (Figure 4.8a). In general, earthquake epicentres were distributed in both onshore (more dominant) and offshore of the region with predominantly occurred in the western and northern parts. Meanwhile, earthquake occurrences in eastern and southern parts are sparse. Earthquake epicenters on the land were distributed in some states i.e. Johor, Negeri Sembilan, Selangor, Kuala Lumpur, Pahang, Perak, and Terengganu. Meanwhile, there was also a cluster of earthquakes scattered along the Melacca Strait. Nazaruddin and Duerrast (2021b) have delineated the spatial distribution of local earthquakes in West Malaysia into six zones based on the geological interpretation: Malacca Strait (zone A), BTFZ and KMFZ (zone B), Kuala Pilah area (zone C), Manjung area (zone D), Kenyir Dam area (zone E), and Temenggor area (zone F). Four of them (zones A to D) are zones of local tectonic earthquakes where a number of earthquakes were associated with local fault zones which have the potential to be reactivated and become sources of local intraplate earthquakes. Two other zones (zones E and F) are considered as reservoir-induced earthquakes where epicenters were located beneath the two man-made reservoirs. A significant number of local earthquakes happened in the vicinity of BTFZ and KLFZ during 2007 to 2009 which is assumed as an earthquake mini swarm (Figure 4.8b). This series of earthquakes will be discussed in details in Section 4.2.3.

Focal depths of earthquakes in West Malaysia range from 1 to 167 km, with most earthquakes have shallow depths of 1 – 20 km (symbolized by yellow dots in the epicenter map) distributed in all spatial zones in and around fault lines and fault zones. Focal depths of 20 – 35 km (symbolized by dark blue dots) are scattered randomly along fault zones and beyond. Earthquakes with depths of 35 – 70 km (symbolized by purple dots) took place only once, which was in Jerantut and associated to the Lepar Fault. Intermediate earthquakes occurred in the range 70 – 167 km ((symbolized by red dots) distributed in four different locations, including the deepest focus recorded in this region so far (167 km) located in the Malacca Strait. Deeper earthquakes are still possible to happen in the region due to its position within the intraslab of the SSZ (Nazaruddin and Duerrast, 2021b). Later, Table 4.8 summarized the focal depths of of all these local earthquakes in West Malaysia. Figure 4.9 shows several depth profiles of local earthquakes in this region.

Focal Mechanism

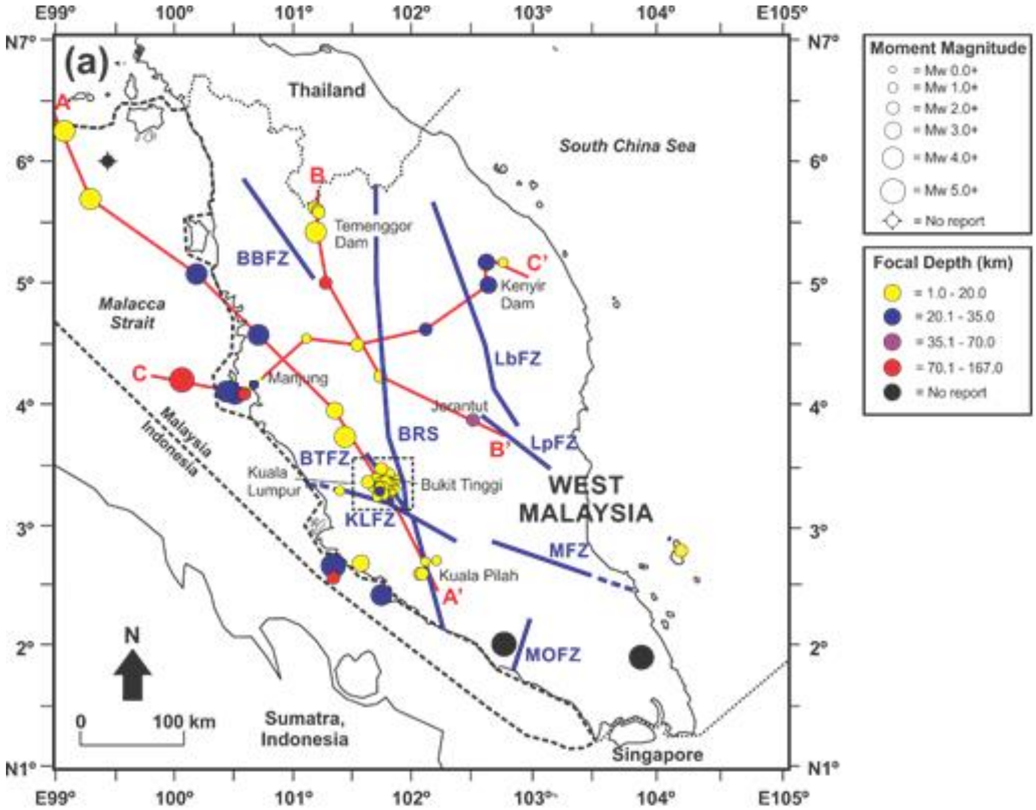
Similar to the earthquakes in Southern Thailand, this study also did not create the FMS for local earthquakes in West Malaysia because of limited distribution of stations around the epicenters and low values of magnitude. GCMT also did not provide any FMS for earthquakes in this region. However, the FMS of four local events which are parts of the Bukit Tinggi earthquake sequence (2007 and 2008) and are associated with the BTFZ and KLFZ were determined by Mat Said and Hara (2012; Figure 4.8b; Table 4.7). The FMS reveals that all four earthquakes took place due to strike-slip faultings on several sub-fault lines within the BTFZ and KLFZ.

Magnitude Variation

Converted magnitudes of local earthquakes are ranging from Mw 0.6 to 5.4. The highest magnitude so far is Mw 5.4 and occurred on 31 January 1922 in the east of Muar, Johor in southern of the region. Meanwhile, the lowest magnitude so far is Mw 0.6 which happened on 7 October 2009 in Bukit Tinggi area, Pahang. Majority of the magnitude is Mw 1.0+ and 2.0+ with 16 and 24 events, respectively. There were two events with Mw 0.0+ (i.e. Mw 0.6 and 0.7) which both took place in Bukit Tinggi area in 2009. Other earthquakes have Mw 3.0+ with 4 events, Mw 4.0+ with 7 events and Mw 5.0+ with 5 events. This magnitude variation is summarized in Table 4.8.

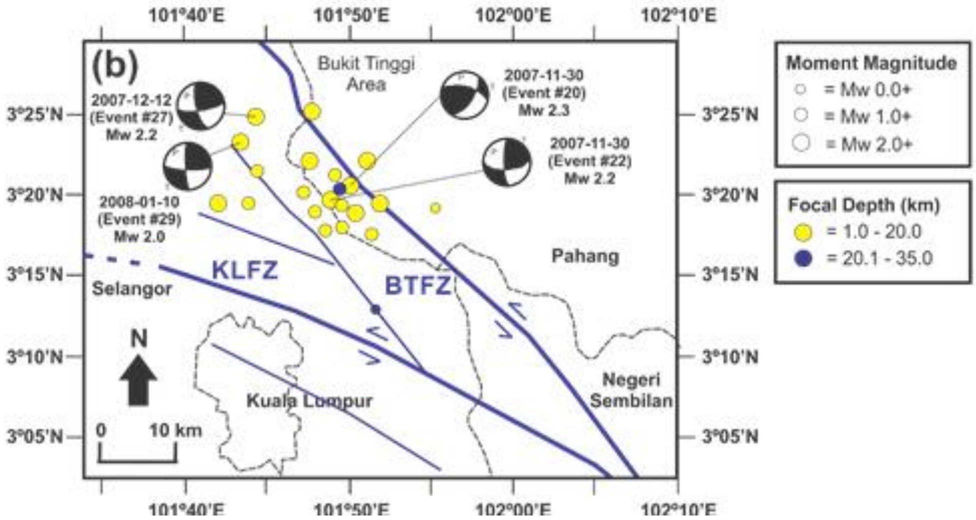
Figure 4.8 *(Next page)* (a) Epicenter map of West Malaysia (1922 – 2020); (b) Epicenter map of Bukit Tinggi earthquakes (2007 – 2009) with focal mechanisms of four events (Mat Said and Hara, 2012). Red lines (A-A’, B-B’, and C-C’) indicate the lines of cross section. Depth profiles can be seen in Figure 4.9. Note: BBFZ = Bok Bak Fault Zone; BRS = Bentong – Raub Suture (Kelau-Karak Fault Zone); LbFZ = Lebir Fault Zone; BTFZ = Bukit Tinggi Fault Zone; KLFZ = Kuala Lumpur Fault Zone; MFZ = Mersing Fault Zone; MOFZ = Ma Okil Fault Zone; LpFZ = Lepar Fault Zone).

(a)



E99°
100°
101°
102°
103°
104°
E105°
N7°
6°
5°
4°
3°
2°
N1°
(a)
Thailand
South China Sea
A
A'
B
B'
C
C'
Temenggor Dam
Kenyir Dam
BBFZ
LbFZ
Malacca Strait
Manjung
Jerantut
LpFZ
BRS
BTFZ
Kuala Lumpur
Bukit Tinggi
KLFZ
WEST MALAYSIA
MFZ
Malaysia
Indonesia
Kuala Pilah
MOFZ
N
0
100 km
Sumatra, Indonesia
Singapore
Moment Magnitude
= Mw 0.0+
= Mw 1.0+
= Mw 2.0+
= Mw 3.0+
= Mw 4.0+
= Mw 5.0+
= No report
Focal Depth (km)
= 1.0 - 20.0
= 20.1 - 35.0
= 35.1 - 70.0
= 70.1 - 167.0
= No report

(b)



101°40'E
101°50'E
102°00'E
102°10'E
3°25'N
3°20'N
3°15'N
3°10'N
3°05'N
(b)
Bukit Tinggi Area
2007-12-12 (Event #27) Mw 2.2
2008-01-10 (Event #29) Mw 2.0
2007-11-30 (Event #20) Mw 2.3
2007-11-30 (Event #22) Mw 2.2
Pahang
Selangor
KLFZ
BTFZ
N
Kuala Lumpur
Negeri Sembilan
0
10 km
Moment Magnitude
= Mw 0.0+
= Mw 1.0+
= Mw 2.0+
Focal Depth (km)
= 1.0 - 20.0
= 20.1 - 35.0

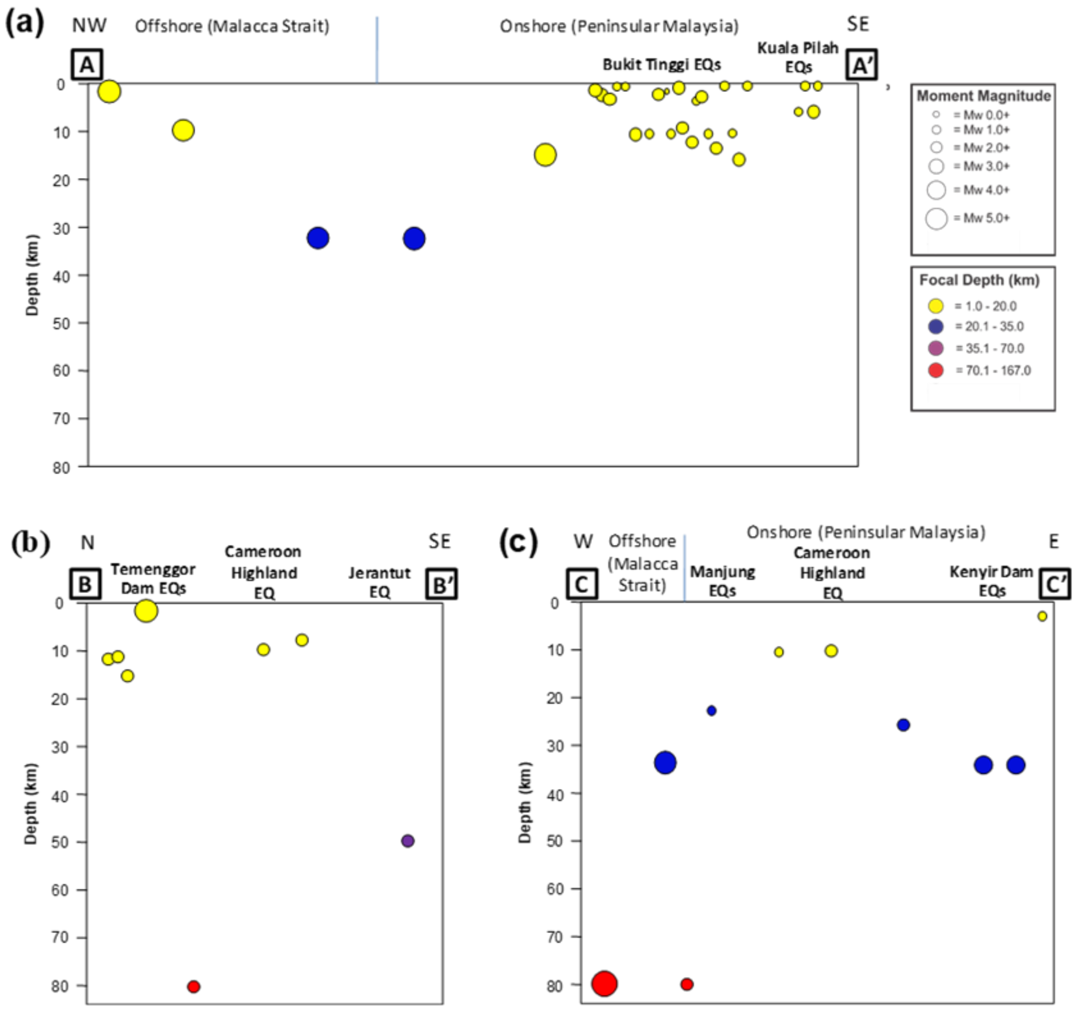


Figure 4.9 Vertical sections of seismicity in West Malaysia during 1922 - 2020 from several lines (A-A', B-B', and C-C'): (a) Depth profile A-A' with the trend NW-SE in the west of the region; (b) Depth profile B-B' with N-S-SE direction in the central part; and (c) Depth profile C-C' with W-E direction. The map showing cross section lines can be seen in Figures 4.8 (a).

Table 4.7 Focal mechanism determination with the strikes, dips, and rakes for the two fault plane solutions (FP1 and FP2) for four local earthquakes in West Malaysia (Mat Said and Hara, 2012).

Event No.	Origin time (yyyy-mm-dd hh:mm:ss)	Location	Mw	FP1 strike (degree)	FP1 dip (degree)	FP1 rake (degree)	FP2 strike (degree)	FP2 dip (degree)	FP2 rake (degree)
20	2007-11-30 02:13:00	Bukit Tinggi area	2.3	010 – 060	45 – 75	20 – 50	270 – 310	50 – 70	130 – 170
22	2007-11-30 12:42:00	Bukit Tinggi area	2.2	170 – 190	72 – 85	(-40) – 0	080 – 110	58 – 82	180 – (-160)
27	2007-12-12 10:01:00	Bukit Tinggi area	2.2	150 – 180	70 – 82	(-10) – (-40)	070 – 090	55 – 80	(-150) – (-180)
29	2008-01-10 15:38:00	Bukit Tinggi area	2.0	170 – 180	80 – 85	(-10) – (-20)	090 – 100	75 – 80	(-170) – (-180)

Table 4.8 Numbers of local earthquakes in West Malaysia during the period 1922 – 2020 based on their focal depth distribution and moment magnitude variation.

Number of local earthquakes based on focal depths			**Number of local earthquakes based on moment magnitudes**	
Focal depth (km)	**No. of earthquakes**		**Moment magnitude (Mw)**	**No. of earthquakes**
1.0 – 20.0	39		<0.0	0
20.1 – 35.0	13		0.0+	2
35.1 – 70.0	1		1.0+	16
70.1 – 167.0	4		2.0+	24
No report	1		3.0+	4
			4.0+	7
			5.0+	4
			No report	1
Total	**58**		**Total**	**58**

4.2.3 Earthquake Swarm in Bukit Tinggi (2007-2009)

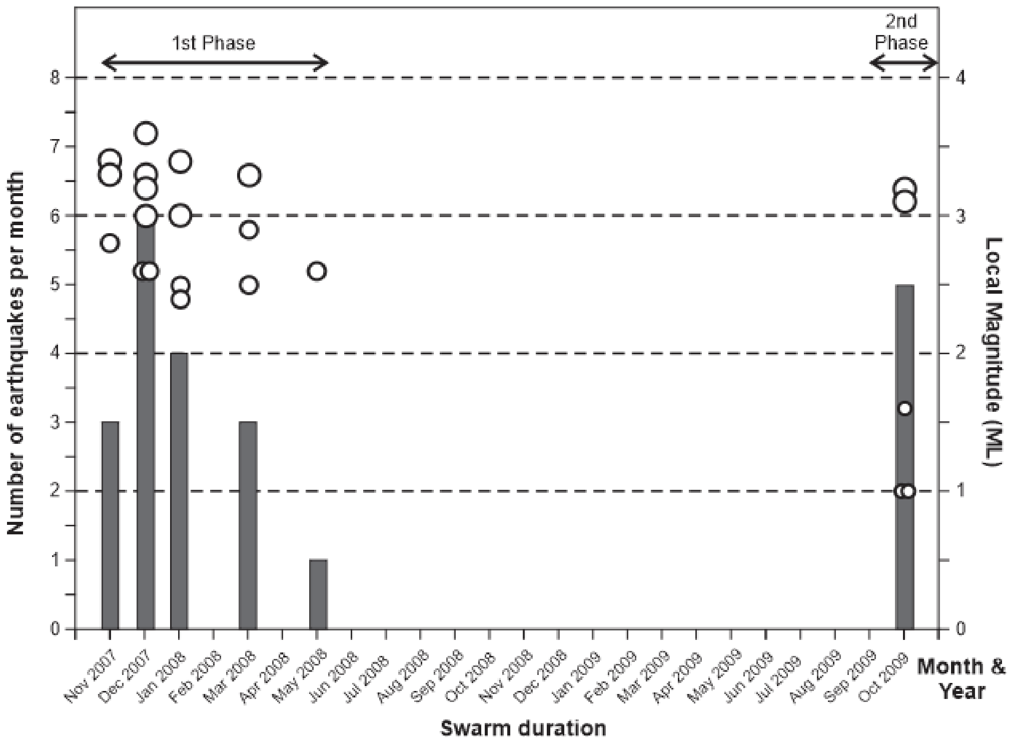
A group of multiple earthquakes occurred in Bukit Tinggi area near the border between two states, Selangor and Pahang, during 30 November 2007 – 25 May 2008 (first phase) and 7 – 8 October 2009 (second phase). This earthquake sequence consists of 17 events in the first phase and 5 events in the second phase. Based on the quantitative measure of Mogi (1963), this first and second phases are suitable to be categorized as an earthquake swarm and a mini swarm due to their total number of earthquakes are 17 (more than 10) and 5 (less than 10) events, respectively. These earthquakes happened within a duration of 178 days (or 5 months and 25 days) for the first phase and only two days for the second phase. They are of small to moderate earthquakes without a mainshock and mostly shallow earthquakes. Chronology of this earthquake sequence is summarized in Table 4.9. Figure 4.10 displays the graph of the number of earthquakes per month and local magnitude of the full duration of the sequence.

Due to less number of earthquakes in this sequence, for calculating the skewness and kurtosis of this earthquake sequence, this study used all events in the first phase instead of using the 20% of the maximum seismicity rate. Meanwhile, five events in the second phase (the mini swarm) are assumed as the compliments of the first phase (the swarm). With the standard deviation (σ) obtained as 98,890.42, the third central moment (μ_3) of 1.90E+15, and the forth central moment (μ_4) of 5.99E+20, the calculation of skewness ($S = \mu_3/\sigma^3$) and kurtosis ($K = \mu_4/\sigma^4$) from the 1st – 17th events of this earthquake sequence gives their values of S = 1.96 and K = 6.27, respectively (Table 4.10). These skew and kurtosis values indicate that the first phase of this earthquake sequence is an earthquake swarm, meanwhile the second phase is suitable to be decided as a mini swarm. Different from the common MS-AS sequence which has the largest earthquake took place in the first event, the largest event of this sequence is the 7th event. The local magnitude difference between the two largest events is too small, i.e 0.3.

Table 4.9 Chronology of the 2007-2009 Bukit Tinggi swarm activity per month.

Date	**ML (Mw)**	**No. of event per month**	**Remark**
30 November 2007	2.8 - 3.4 (1.9 – 2.3)	3	Initiation of the first phase of the swarm
4,6,9,12,31 December 2007	2.6 - 3.7 (1.7 – 2.4)	6	Earthquake activity increased this month
10,13,14 January 2008	2.4 - 3.4 (1.6 – 2.3)	4	Earthquake activity and strength decreased this month
February 2008	-	-	*Hiatus for this month*
14,15 March 2008	2.5 - 3.3 (1.7 – 2.2)	3	Earthquake activity resumed this month
April 2008	-	-	*Hiatus for this month*
25 May 2008	2.6 (1.7)	1	One event detected The end of the first phase
June 2008 – September 2009	-	-	*Hiatus for 16 months*
7,8 October 2009	0.9 - 3.0 (0.6 – 2.0)	5	Initiation of the second phase or the mini swarm (7 October 2009) and termination of the (mini) swarm activity (8 October 2009)

(a)



(b)

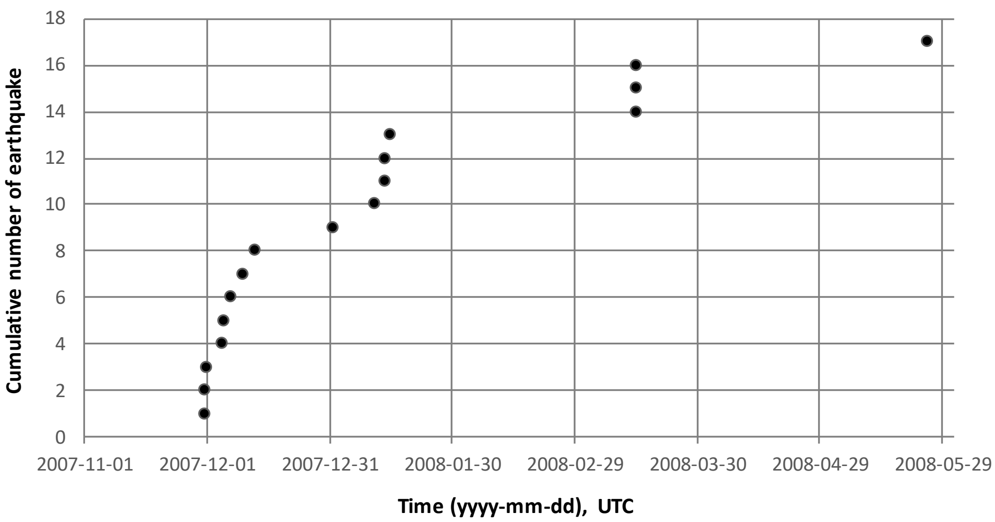


Figure 4.10 (a) Number of earthquakes per month (grey bars; lower left-hand side scale) and local magnitude variation (circles; right-hand side scale) during the Bukit Tinggi swarm (2007-2009); (b) Cumulative number of earthquakes (black dots) for the first phase of the swarm (2007-2008).

Table 4.10 Calculation of skewness (S) and kurtosis (K) of the 2007-2009 Bukit Tinggi earthquake swarm.

Event No.	Date (yyyy-mm-dd hh:mm)	2-hr time bins	No. of EQs per time bins	From first event			Mag. (ML)	Moment Mo (Nm) (Mw = ML)	Normalized Mo/ mo	Event time x Normalized Mo	Std. Dev. (min)	Third central moment (min^3)	Forth central moment (min^4)
				day	hrs	min							
1	2007-11-30 02:13	02:00 - 04:00		0	00:00	0	3.4	1.58489E+14	0.11373278	0.00000000	536589932.76	-3.68571E+13	2.53163E+18
2	2007-11-30 02:42	02:00 - 04:00	2	0	00:29	29	2.8	1.99526E+13	0.01431811	0.41522515	67495640.60	-4.63416E+12	3.18175E+17
3	2007-11-30 12:42	12:00 - 14:00	1	0	10:29	629	3.3	1.12202E+14	0.08051664	50.64496763	372951072.50	-2.53825E+13	1.7275E+18
4	2007-12-04 10:11	10:00 - 12:00	1	4	07:58	11998	3.0	3.98107E+13	0.02856838	342.76345362	91810565.09	-5.20471E+12	2.95053E+17
5	2007-12-04 19:57	18:00 - 20:00	1	4	17:44	12584	3.3	1.12202E+14	0.08051664	1013.22141919	253435434.61	-1.42186E+13	7.97717E+17
6	2007-12-06 15:23	14:00 - 16:00	1	6	13:10	18070	2.7	1.41254E+13	0.01013644	183.16555449	25971019.66	-1.31459E+12	6.65415E+16
7	2007-12-09 12:55	12:00 - 14:00	1	9	10:42	26562	3.7	4.46684E+14	0.32054252	8514.25052533	568824313.69	-2.39621E+13	1.00942E+18
8	2007-12-12 10:01	10:00 - 12:00	1	12	07:48	35028	3.3	1.12202E+14	0.08051664	2820.33692556	91222911.44	-3.07053E+12	1.03353E+17
9	2007-12-31 09:19	08:00 - 10:00	1	31	07:06	89706	2.6	1.00000E+13	0.00717605	643.73503242	3170183.18	66632132032	1.4005E+15
10	2008-01-10 15:38	14:00 - 16:00	**1**	41	13:25	118885	3.0	3.98107E+13	0.02856838	3396.35215734	71985967.72	3.61351E+12	1.81389E+17
11	2008-01-13 02:24	02:00 - 04:00	1	44	00:11	126731	2.5	7.07946E+12	0.00508026	643.82600469	17115560.39	9.93445E+11	5.76629E+16
12	2008-01-13 10:18	10:00 - 12:00	**1**	44	08:05	127205	2.4	5.01187E+12	0.00359655	457.49866883	12315597.31	7.20677E+11	4.21721E+16
13	2008-01-14 15:45	14:00 - 16:00	1	45	13:32	130412	3.4	1.58489E+14	0.11373278	14832.11922345	433310488.89	2.67458E+13	1.65087E+18
14	2008-03-14 23:16	22:00 - 24:00		105	21:03	303663	2.9	2.81838E+13	0.02022487	6141.54347819	1116684257.91	2.62393E+14	6.1656E+19
15	2008-03-14 23:35	22:00 - 24:00	2	105	21:22	303682	2.5	7.07946E+12	0.00508026	1542.78249802	280543767.35	6.59262E+13	1.54923E+19
16	2008-03-15 00:50	00:00 -02:00	1	105	22:37	303757	3.3	1.12202E+14	0.08051664	24457.49353367	4449157667.28	1.04586E+15	2.4585E+20
17	2008-05-25 01:36	00:00 - 02:00	1	176	23:23	508283	2.6	1.00000E+13	0.00717605	3647.46587167	1386729971.88	6.096E+14	2.67977E+20
18	2009-10-07 21:21	20:00 - 22:00		677	19:08	1950908	1.7	4.46684E+11	0.00032054	625.34897462	1135603174.64	2.13746E+15	4.02316E+21
19	2009-10-07 21:26	20:00 - 22:00		677	19:13	1950913	0.9	28183829313	0.00002022	39.45695396	71652097.02	1.34865E+14	2.53847E+20
20	2009-10-07 21:51	20:00 - 22:00		677	19:38	1950938	3.0	3.98107E+13	0.02856838	55735.14308065	101213965820.18	1.9051E+17	3.58588E+23
21	2009-10-07 22:09	22:00 - 24:00	4	677	19:56	1950956	2.8	1.99526E+13	0.01431811	27933.99990236	50728117748.06	9.54839E+16	1.79726E+23

22	2009-10-08 04:05	04:00 - 06:00	1	678	01:52	1952752	1.1	5.62341E+10	0.00004035	78.80118415	143244228.53	2.69881E+14	5.08474E+20
	For events# 1-17 (using the first phase events)							Sum Mo (events# 1-17) 1.39352E+15	**Sum normalized Mo = 1.00000000**	Sum = 68687.61453925 **Weighted mean time (in min) = t = 68687.61453925**	Sum = 9779314352.26 **Std. dev. = σ = 98890.4159**	**Sum 3rd central moment = μ_3 1.90128E+15**	**Sum 4th central moment = μ_4 5.99758E+20**
												S = 1.96	**K = 6.27**

4.2.4 Relations between Seismicity and Local Tectonics in Peninsular Malaysia

Although paleoseismological studies in West Malaysia are still in the preliminary stage, Shuib et al. (2017b) believed that active faults in this region are capable of generating large earthquakes. The current study shows that there is relationship between the seismicity in West Malaysia with mapped faults and lineaments. Figure 4.11 shows the seismotectonic map of Peninsular Malaysia. From this maps, it can be observed that most epicenters were scattered in the vicinity of the several fault zones. More earthquakes occurred within the BTFZ and KLFZ compared to other fault zones. They are the micro earthquakes which contributed significantly to the local seismicity in this region. The largest local earthquake in this region so far reported as a historical earthquake happened in 31 January 1922 with Mw 5.4, and along with another larger earthquake in 7 February 1922 (Mw 5.0) both occurred in the south of this region (Martin et al., 2020). These two earthquakes are interpreted to be associated with the Ma' Okil Fault Zone and the Mersing Fault Zone, respectively (Figure 4.11). Shuib (2009) revealed that there was the relationship between the Bukit Tinggi earthquake (2007-2008) and the major geological structures in the area. Samsudin et al. (1997) and Shuib (2009) found that there are high concentrations of faults and associated hot springs in the vicinity of BTFZ and KLFZ, such as hot springs in Kuala Kubu Baharu, Batang Kali, Hulu Yam, Selayang (Gombak), Dusun Tua (Hulu Langat) and Semenyih in Selangor, Setapak in Kuala Lumpur, and Sg. Bujang and Bt.7 Bentong in Pahang. The available FMS (Mat Said and Hara, 2012) shows the trends of the fault planes from the focal mechanisms of several earthquakes took place in Bukit tinggi area originated from the sub-faults within the BTFZ and KLFZ. Focal mechanisms also show that all these earthquakes triggered by the strike-slip faulting.

Based on these results, the local intraplate earthquakes were interpreted to be predominantly associated to the reactivations or movements of fault lines or lineaments within several fault zones, such as the BTFZ and KLFZ. The major fault zones in West Malaysia are generally also considered as dormant for a long period until the occurrence of several large regional earthquakes in Sumatra region started by the 2004 Sumatra-Andaman earthquake. Most of the results of this study have been published by Nazaruddin and Duerrast (2021b) who studied the intraplate earthquakes and their distribution in Peninsular Malaysia including the relationship between the earthquakes with faults and lineaments observed from the shuttle radar topography mission – digital elevation model (SRTM-DEM).

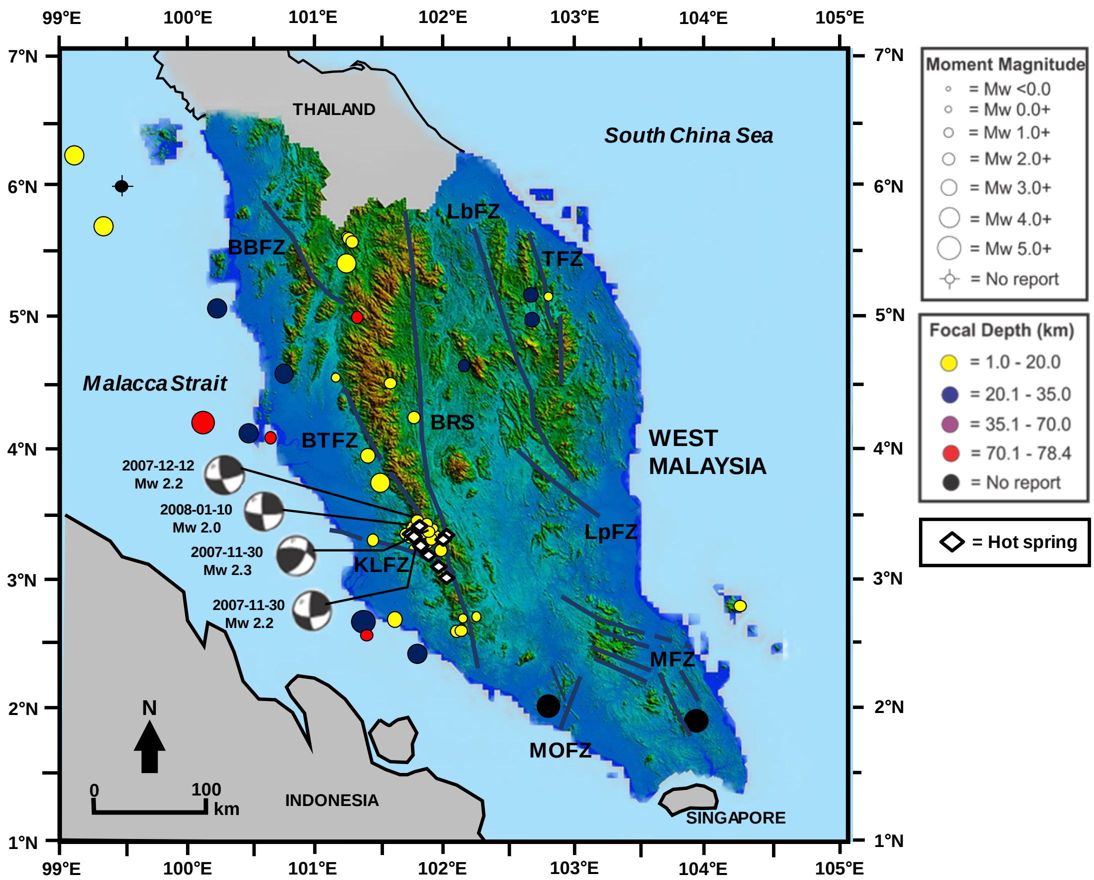


Figure 4.11 Seismotectonic map of Peninsular Malaysia showing the relation between the seismicity and local tectonics. Faults and fault zones were mapped by Tjia (1978; 1999) and Department of Mineral and Geoscience Malaysia (2014). Focal mechanisms for several events in Bukit Tinggi area (Mat Said and Hara, 2012) and hot spring manifestations (Samsudin et al., 1997; Shuib, 2009) were added. BBFZ=Bok Bak Fault Zone; BRS=Bentong-Raub Suture (Kelau-Karak Fault Zone); LbFZ=Lebir Fault Zone; TFZ=Terengganu Fault Zone; LpFZ=Lepar Fault Zone; BTFZ=Bukit Tinggi Fault Zone; KLFZ=Kuala Lumpur Fault Zone; MFZ=Mersing Fault Zone; MOFZ=Ma Okil Fault Zone.

4.3 Implications of Regional Geodynamics

When earthquakes occur, forces and motions are fundamental to the physics of the earthquakes. The forces generated in the Earth's interior are described in terms of the stress and strain. The stress is the force per unit are applied tangent to a plane, meanwhile the strain is the distortion of a body as a response to a stress. When the stress exceeds a critical value (called the local strength), a sudden failure initiated at the focus and happens along the fault plane, and the elastic waves are radiated. During an earthquake event, the sudden crustal motion excites seismic waves that travel through the Earth and recorded at seismological stations on the surface. These waves bring the information about the movement at the seismic source (Kanamori and Brodsky, 2011). In order to support the study of seismicity, more investigations in the regional scale are needed to observe the crustal deformation, such as the geodetic method (GPS) to measure the crustal motion and the Gravity Recovery and Climate Experiment (GRACE) satellite to monitor the gravity changes, both are associated with large earthquakes (Tronin, 2010).

The present study of seismicity in Southern Thailand and West Malaysia shows that generally there was a significant increase of the local seismicity in both regions after the 2004 Sumatra-Andaman earthquake. This result is consistent with Zheng (2019) who revealed that the 2004 megathrust earthquake marked the beginning of active seismological period in the Sundaland. In Southern Thailand, the increasing seismicity was due to the occurrence of micro to moderate earthquakes. Meanwhile, the increasing seismicity in West Malaysia was mainly due to the occurrence of micro to minor earthquakes. This study also links the earthquake cycle of Sumatra region to the local seismicity in both regions and the regional crustal deformation. The earthquake cycle mainly consists of three phases, namely the inter-seismic phase, a period between two large earthquakes during which the stress accumulation occurs; the co-seismic phase, a short period where the accumulated stress is released during an earthquake; and the post-seismic phase, the period immediately after an earthquake. The crustal deformation in both regions involves Indian-Australian Plates move constantly to the NNE until today (Figure 4.12). Other than the 2004 megathrust earthquake, there were several other large regional earthquakes affecting the seismicity and deformation in Southern Thailand and West Malaysia. A few of these regional earthquakes have contributed to accumulate the stress in both regions, meanwhile a few others have triggered the release of the stress in these regions through the reactivation of local faults thus increasing the local seismicity. A few earthquakes also affected the crustal deformation; however, a few others did not. The following sections discuss the relationship between the cycle of large regional earthquakes in Sumatra and the seismicity as well as the regional crustal deformation in Southern Thailand and West Malaysia.

The 2004 Sumatra-Andaman earthquake and other regional earthquakes near Sumatra, which produced large stress changes in the lithosphere surrounding the rupture zones, are expected to be followed by viscoelastic relaxation during the post-seismic deformation (Pollitz et al., 2006; Wiseman et al., 2015).

Effects of the 26 December 2004 Sumatra-Andaman Earthquake (Mw 9.1)

Prior to the 2004 megathrust earthquake (inter-seismic phase), the Indian-Australian Plates and the Burma Microplate were locked and the elastic strain was accumulated slowly in the subduction zone which is suddenly released during an earthquake. In this phase, the Indian-Australian Plates continuously pushed the Burma Microplate and Eurasian Plate into the east direction and therefore Southern Thailand and West Malaysia constantly moved horizontally to the east with a small strain rate i.e. around 3 cm/yr (Abu Bakar, 2006; Kee et al., 2005; Royal Thai Survey Department, 2011; Simon et al., 2019). Southern Thailand and West Malaysia were then assumed as regions with very low seismicity indicated by the rarity of local earthquakes and the dormancy of local fault zones.

Known as one of the world’s largest earthquakes ever recorded, the 26 December 2004 Sumatra-Andaman earthquake (Mw 9.1) occurred at 00:58 UTC at the source of rupture of 3.316°N, 95.854°E with the focal depth of 30 km beneath the Indian Ocean off the west coast of Aceh, Indonesia. This earthquake was triggered by a thrust faulting on the interface of the Indian Plate and the Burma Microplate (Hayes et al., 2017). The occurrence of this earthquake (co-seismic phase) was due to the sudden rupture in the SSZ in view of the strain build-up exceeded the ability of the frictional forces that lock plates to prevent slip. This has unlocked the Indian-Australian Plate and the Burma Microplate and significantly turned the direction of the overall plate movement towards the 2004 earthquake rupture zone. This moved the Southern Thailand and West Malaysia generally to the southwest and west, respectively. These movements have caused the extensional deformation or expansion of the plate and consequently the reactivation of existing faults and fault zones. Global Positioning System (GPS) observations showed displacements of Phuket Island (Southern Thailand) and Langkawi Island (West Malaysia) horizontally ~27 cm to the southwest and ~17 cm to the west, respectively (Subarya et al., 2006; Vigny et al., 2005; Zheng, 2019), the biggest magnitudes of displacement in respective countries. After the occurrence of the 2004 megathrust earthquake (post-seismic phase), the involved tectonic plates adjusted the stress caused by the earthquake. The GRACE satellites also observed the expansion of the crust due to the 2004 earthquake by showing a negative gravity change related to density changes in the crust (Han et al., 2006). Although there are no any large earthquakes took place in both regions right after the megathrust earthquake, however, plenty of micro earthquakes have been recorded in Southern Thailand showing the increasing seismicity in an extensional stress regime. In addition, another phenomenon also occurred due to the 2004 earthquake, where an increasing number of sinkholes was reported in Southern Thailand such as in Trang and Satun, and West Malaysia such as in Perak (DMR, 2005; Giao et al., 2011; Termizi et al., 2018).

Effects of the 28 March 2005 Nias Earthquake (M 8.6)

Crustal deformation in the post-seismic period of the 2004 earthquake was distinct from that in the inter-seismic period forming an integral part of the earthquake cycle (Catherine and Gahalaut, 2007). The second major earthquake occurred a few months later, i.e. the 28 March 2005 Nias earthquake (the largest event after the 2004 earthquake; Mw 8.6), another thrust-faulting earthquake occurred at 16:09 UTC at the source of rupture of 2.074°N, 97.013°E with the depth of 30 km (Hayes et al., 2017). The co- and post-seismic phases of this earthquake were accompanied by a slight impact to crustal deformations in both regions. GPS data indicated that both regions moved towards the 2005 earthquake rupture zone in smaller changes (i.e. less than 10 cm) generally to the southwest (Simon et al., 2019; Zheng, 2019). This earthquake had also accumulated the stress without increasing the seismicity in both regions.

Effects of the 12 September 2007 Bengkulu Earthquake (Mw 8.4)

Another large regional earthquake happened later in the southern part of Sumatra i.e. the 12 September 2007 Bengkulu earthquake (Mw 8.4) at 11:10 UTC at the source of rupture of 4.520°N, 101.374°E off the west coast of Bengkulu Province, Indonesia with the depth of 34 km beneath the Indian Ocean. This thrust faulting earthquake took place on the boundary between the Australian and Eurasian Plates (Hayes et al., 2017). This regional earthquake had given no significant impact on crustal deformations where its co- and post-seismic deformations moved Southern Thailand and West Malaysia to the south towards the rupture zone with a very small magnitude of displacement (Simon et al., 2019; Zheng, 2019). This earthquake did not also affect to the seismicity in Southern Thailand, otherwise it contributed a significant impact on the seismicity in West Malaysia. After this earthquake, the seismicity in West Malaysia increased significantly marked by the occurrence of a series of about 17 local earthquakes detected in Bukit Tinggi area during 30 November 2007 – 25 May 2008 which is decided as a mini swarm in this study. The GRACE observation on the post-seismic phase indicated the expansion of the crust from a negative gravity change in Bukit Tinggi area in West Malaysia associated with the 2007 Bengkulu earthquake (Zheng et al., 2018). This extensional deformation can be considered as a trigger to the occurrence of Bukit Tinggi earthquakes (2007-2008).

Effects of the 30 September 2009 West Sumatra Earthquake (Mw 7.6)

The Mw 7.6 earthquake occurred on 30 September 2009 10:16 UTC at the source of rupture of 0.725°N, 99.856°E offshore West Sumatra Province near the Australian and Eurasian plate boundary. This earthquake occurred as a result of an oblique reverse faulting at the depth of 81 km representing deformations within the subducted Australian Plate (Hayes et al., 2017). Similar to the 12 September 2007 Bengkulu earthquake, the 2009 West Sumatra earthquake were not accompanied by a significant change in crustal deformations in Southern Thailand and West Malaysia, where co- and post-seismic deformations indicated a movement generally to the south towards the rupture zone with very small displacements (Simon et al., 2019; Zheng, 2019). This earthquake did not increase the seismicity in Southern Thailand. However, it increased the seismicity in West Malaysia, where about five local earthquakes recorded in Bukit Tinggi during 7-8 October 2009 and considered as the second phase of the Bukit Tinggi mini swarm.

Effects of the 11 April 2012 East Indian Ocean Earthquakes (Mw 8.6 and Mw 8.2)

Two subsequent earthquakes (Mw 8.6 and Mw 8.2) occurred in the same day on 11 April 2012 in East Indian Ocean within the oceanic lithosphere of the Indian Plate and nearby a nascent plate boundary between Indian and Australian Plates. The first event (Mw 8.6) occurred at 08:38 UTC and the source of rupture at 2.311°N, 93.063°E with the depth of 20 km. Meanwhile, the second event (Mw 8.2) occurred at 10:43 UTC and the source of rupture at 0.773°N, 92.452°E with the depth of 25.1 km (Hayes et al., 2017). These 2012 earthquakes are considered as the largest strike-slip and intraplate events that have been seismologically recorded (Pollitz et al., 2012). Both earthquakes affected sizeable crustal deformations in Southern Thailand and West Malaysia. GPS data showed a significant jump where both regions turned their movements from the south into the northeast directions. Due to these earthquakes, the seismicity in Southern Thailand increased mainly in Phuket where an earthquake swarm occurred in the island during 16 April – 5 May 2012 (Nazaruddin and Duerrast, 2021a). Meanwhile, there was no change in seismicity of West Malaysia due to these earthquakes.

Current GPS measurements reveal that the Sundaland changed its movement into the southeast direction since the subducting Indian-Australian Plates push the overriding Burma Microplate (and Eurasian Plate) moves to the southeast direction. Therefore, the Indian-Australian Plates and the Burma Microplate might have locked again. This already changed the geodynamic situation of the Burma Plate from extension to compression again. Figure 4.12 and 4.13 show the GPS time series data of horizontal displacements in Phuket (Southern Thailand) and Langkawi

(Peninsular Malaysia) along with their graphs of cumulative number of earthquakes, respectively. Meanwhile, Figure 4.14 illustrates the development of geodynamic implications of several large earthquakes near Sumatra towards Southern Thailand and West Malaysia in terms of their earthquake cycle.

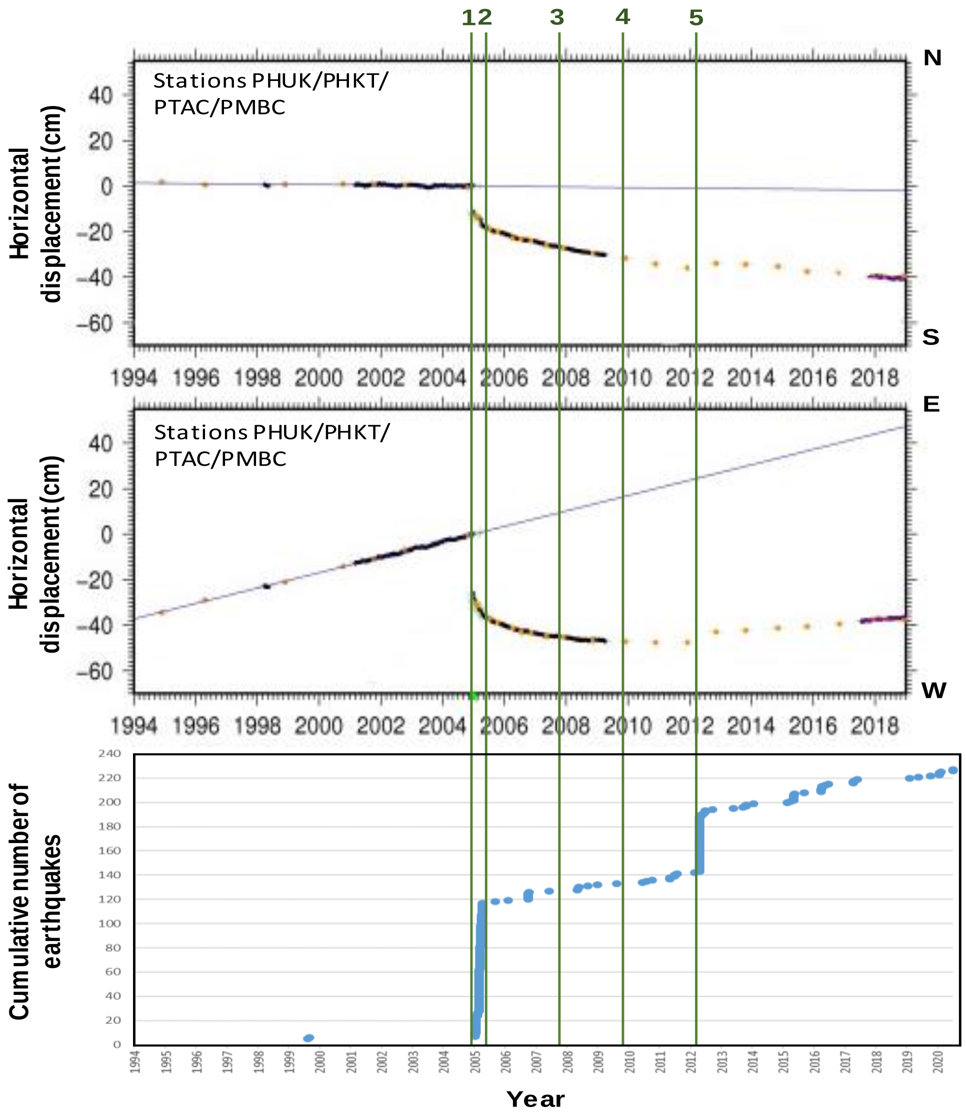


Figure 4.12 Graphs of time series of horizontal displacements in Phuket, Southern Thailand (1994-2018; Simons et al., 2019) and their relations with several large regional earthquakes near Sumatra and the cumulative number of local earthquakes. Numbers on top indicate the regional earthquakes: 1 = 2004 Sumatra-Andaman earthquake, 2 = 2005 Nias earthquake, 3 = 2007 Bengkulu earthquake, 4 = 2009 West Sumatra earthquake, and 5 = 2012 East Indian Ocean earthquakes.

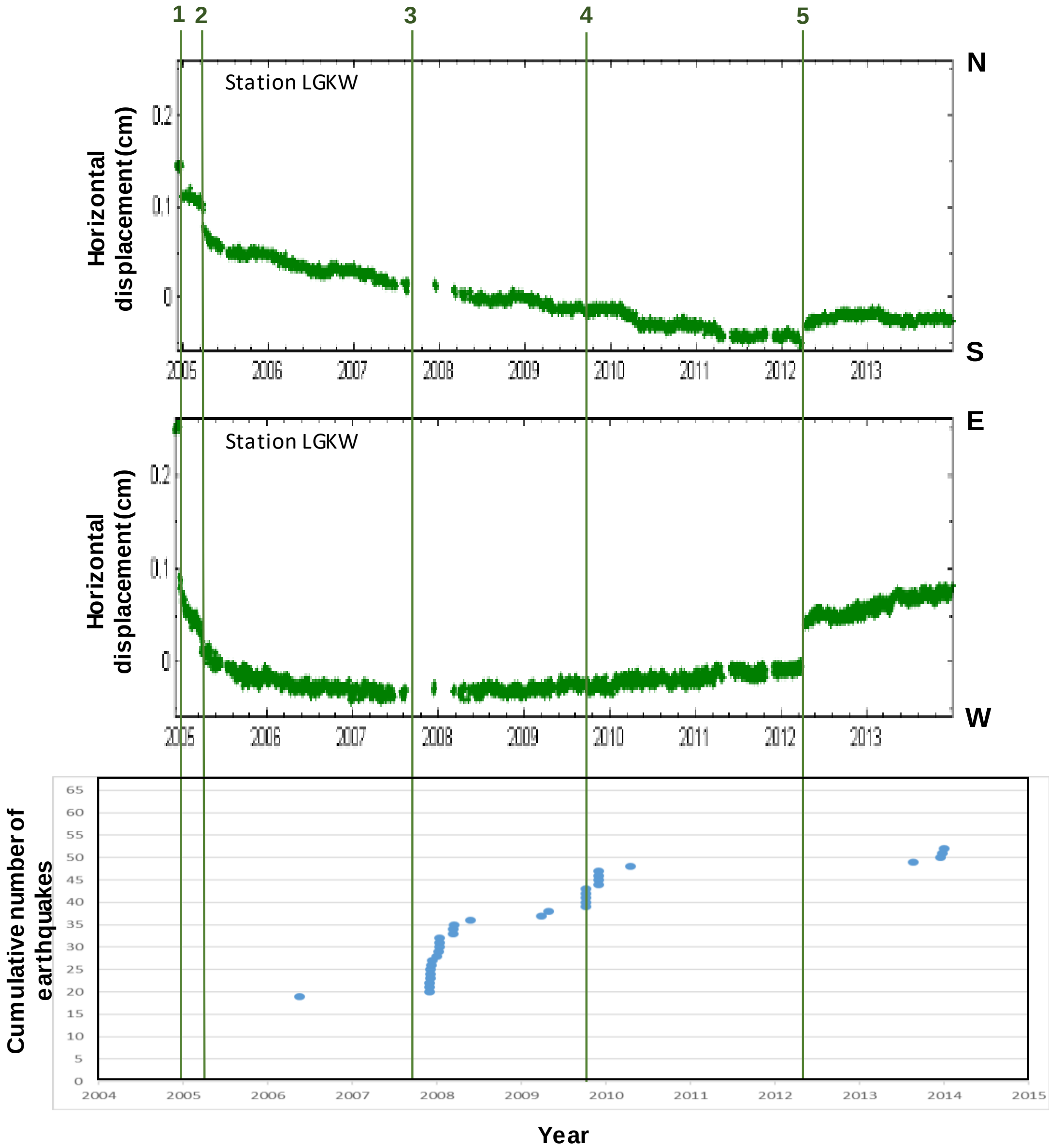


Figure 4.13 Graphs of time series of horizontal displacements in Langkawi, Peninsular Malaysia (December 2004-January 2014; Gill et al., 2015) and their relations with several large regional earthquakes near Sumatra and the cumulative number of local earthquakes. Numbers on top indicate the regional earthquakes: 1 = 2004 Sumatra-Andaman earthquake, 2 = 2005 Nias earthquake, 3 = 2007 Bengkulu earthquake, 4 = 2009 West Sumatra earthquake, and 5 = 2012 East Indian Ocean earthquakes.

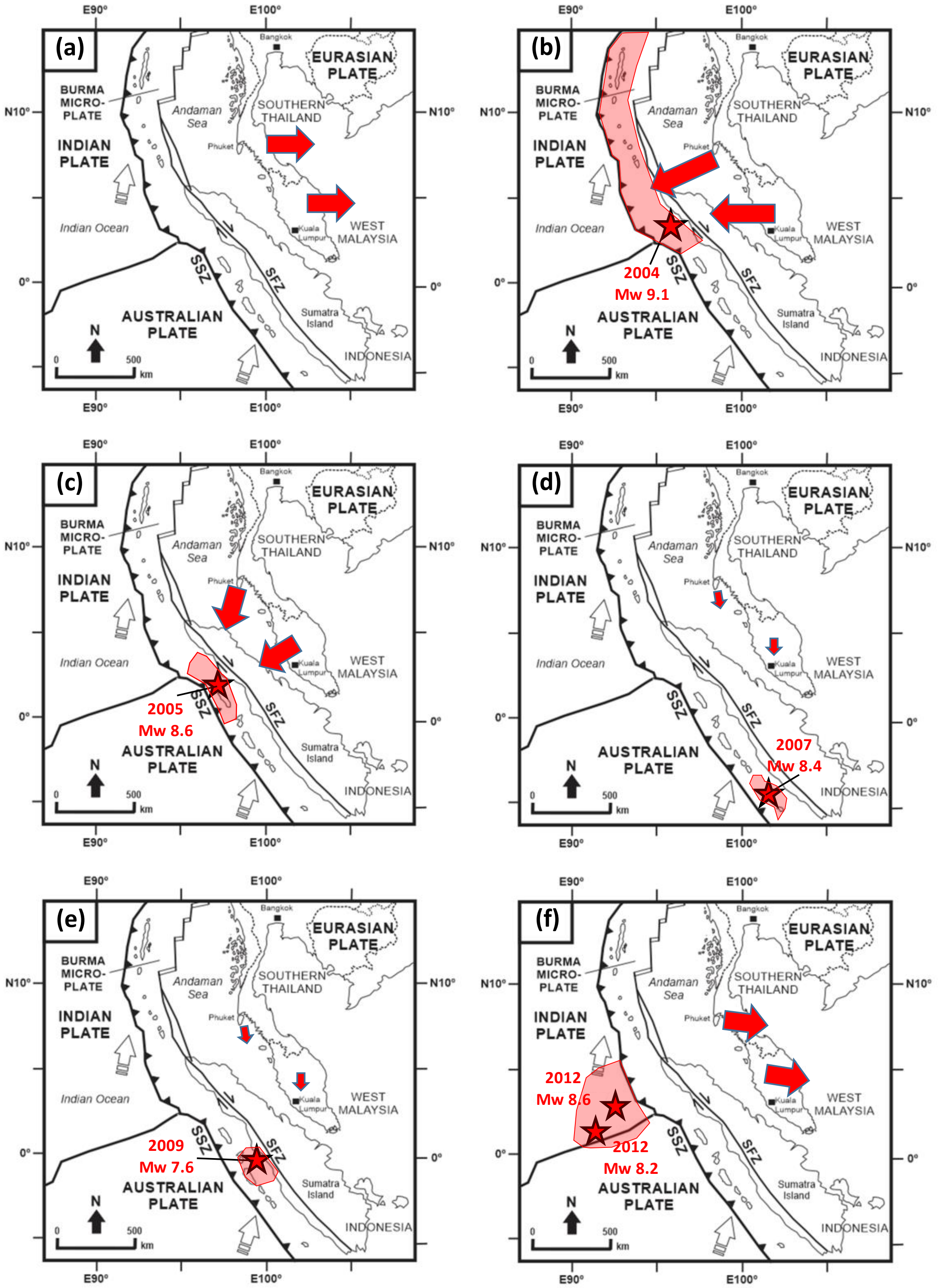
4.4 Comparisons of Seismicity between Southern Thailand and Peninsular Malaysia

This study finally compared between Southern Thailand and Peninsular Malaysia in terms of their seismicity. There are several similarities and differences on the seismicity of both regions as stated in Table 4.11.

Table 4.11. Comparisons between Southern Thailand and Peninsular Malaysia in terms of their seismicity

No.	**Similarity**	**No.**	**Difference**
1	Experienced the seismicity increase after 2004 Sumatra-Andaman earthquake	1	Southern Thailand has experienced larger magnitude earthquakes than Peninsular Malaysia has done after 2004
2	Local earthquakes are distributed mostly in the vicinity of fault zones	2	Peninsular Malaysia has deeper earthquakes than Southern Thailand due to the existence of the subducting slab of SSZ extending until beneath Peninsular Malaysia
3	Experienced at least an earthquake swarm and mini swarm		
4	Several regional earthquakes near Sumatra affected the local seismicity and crustal deformation		

Figure 4.14 *(Next page)* Maps of regional geodynamic situation in Southern Thailand and West Malaysia associated with several large earthquakes near Sumatra region: (a) Prior to the 2004 Sumatra-Andaman earthquake (inter-seismic); (b) Co- and post-seismic of the 2004 earthquake; (c) Co- and post-seismic of the 2005 Nias earthquake; (d) Co- and post-seismic of the 2007 Bengkulu earthquake; (e) Co- and post-seismic of the 2009 West Sumatra earthquake; and (f) Co- and post-seismic of the 2011 earthquakes. Red arrows indicate the directions of plate movements. Red areas indicate the rupture zones of regional earthquakes: 2004 (Ammon et al., 2005), 2005 (Walker et al., 2005), 2007 (Tsang et al., 2016), 2009 (Wiseman et al., 2012), and 2012 (Pollitz et al., 2012).


(a)
(b)
(c)
(d)
(e)
(f)
E90°
E100°
N10°
0°
EURASIAN PLATE
BURMA MICRO-PLATE
INDIAN PLATE
AUSTRALIAN PLATE
Andaman Sea
SOUTHERN THAILAND
Bangkok
Phuket
Kuala Lumpur
WEST MALAYSIA
Indian Ocean
SSZ
SFZ
Sumatra Island
INDONESIA
N
0
500
km
2004
Mw 9.1
2005
Mw 8.6
2007
Mw 8.4
2009
Mw 7.6
2012
Mw 8.6
2012
Mw 8.2

5. CONCLUSION

This part summarizes and concludes the whole study while indicating the novelty of the findings and providing recommendations for further research works.

5.1 Conclusion

Previous studies on paleoseismology in Southern Thailand and West Malaysia revealed that both regions had experienced paleoearthquake activities and have the potential to generate large earthquakes in the future. Meanwhile, historical earthquakes were very rare in these regions. Results of this study show that local seismicity in both regions generally increased after the 2004 Sumatra-Andaman earthquake with the occurrence of plenty of local earthquakes. The increasing seismicity in Southern Thailand was indicated by the occurrence of generally micro (ML<3) to light (ML=4-5) earthquakes. Moreover, there was a significant increase to local earthquakes with ML≥4 (Mw≥4) in this region. Meanwhile, the seismicity in West Malaysia increased by the occurrence of mostly micro (ML<3) to minor (ML=3-4) earthquakes without a significant increase to local earthquakes with ML≥4 (Mw≥4). Spatial distribution of local earthquakes in these regions shows that most epicenters were scattered along and in the vicinity of the fault zones, so that it can be interpreted that most earthquakes were associated with the movements or reactivations of major faults or sub faults within the fault zones, mainly KMFZ and RFZ in Southern Thailand, and BTFZ and KLFZ in West Malaysia. From these results, it can be concluded that although Southern Thailand and West Malaysia are located in the interior of the plate, they are still facing earthquake risks, not only from regional tectonics, but also from local tectonics. Therefore, this study also emphasizes the importance in understanding both regional and local tectonics.

This study also reveals that a unique seismological behavior of earthquake sequences took place in Phuket Island (Southern Thailand) in 2012 and in Bukit Tinggi (West Malaysia) in 2007-2009. Based on the qualitative and quantitative analyses, the 2012 Phuket and 2007-2009 Bukit Tinggi earthquake sequences can be categorized as earthquake swarms (in their first phases) with the compliments of mini swarms (in their second phases). The calculation of the skewness (S) and kurtosis (K) resulted the values of S = 2.65 and K = 8.98 for the 2012 Phuket swarm, meanwhile S = 1.96 and K = 6.27 for the 2007-2009 Bukit Tinggi swarm.

This study evaluates that several regional earthquakes near Sumatra region have affected the local seismicity and/or crustal deformation in Southern Thailand and West Malaysia. Regional tectonics near Sumatra occasionally produces large earthquakes and follows the earthquake cycle. Other than the 26 December 2004 Sumatra-Andaman Earthquake (Mw 9.1), several other earthquakes have also implications for regional geodynamic situations, including the 28 March 2005 Nias Earthquake (M 8.6), the 12 September 2007 Bengkulu Earthquake (Mw 8.4), the 30 September 2009 West Sumatra Earthquake (Mw 7.6), and the 11 April 2012 East Indian Ocean Earthquakes (Mw 8.6 and Mw 8.2). Therefore, seismic hazard studies in Southern Thailand and West Malaysia have to look the broader scale beyond their geographical boundaries.

5.2 Novelty

This section emphasizes the novelty of findings in this study which contribute to the body of the knowledge as follow:

1). This is the first study that compares the seismicity of Southern Thailand and West Malaysia comprehensively with updated data compiled during pre-instrumental until instrumental periods.

2). This study revealed that Peninsular Malaysia, even situated in the interior of the plate, has experienced deeper earthquakes which are affected by the subducting slab of SSZ which reach until beneath this region.

3). This study considers the 2012 Phuket (Southern Thailand) earthquakes and the 2007-2009 Bukit Tinggi (Peninsular Malaysia) earthquakes as the first tectonic swarms recorded in both regions, respectively.

4). There is significant relationship between large regional earthquakes, mainly occur near Sumatra, and local seismicity and deformation in Southern Thailand and West Malaysia.

5.3 Recommendation

It is expected that this study can provide a basis for further seismological or broader geophysical research to establish intercorrelations between regional tectonic near Sumatra and local seismicity and deformation in Southern Thailand and West Malaysia. This study can also be used for further works mainly to evaluate seismic hazards assessment in both regions.

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APPENDICES

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Contributed Paper

2012 Earthquake Swarm in Phuket, Southern Thailand

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ABSTRACT

An earthquake swarm occurred at Phuket Island, located in the western part of Southern Thailand, from 16 April to 22 April 2012, likely even until 5 May 2012. The earthquakes have caused slight damages to buildings on the island, and the largest event on the first day has been felt by local people and tourists prompting them to flee buildings in panic. For this study, digital seismograms recorded by seismological stations in Southern Thailand under the Thai Meteorological Department (TMD)'s network were analyzed; some event data from a previous study were added. Results show that the Phuket swarm is relatively short in duration (7 days/20 days) with 46/48 earthquakes, respectively. Seismotectonically the Phuket swarm can be linked to the active and NNE-SSE trending Khlong Marui Fault Zone, precisely to ESE dipping fault planes of its positive flower structure. Further, through GPS data the Phuket swarm might be linked to two M8+ earthquakes, which occurred five days earlier east of the Sunda Subduction Zone at the nascent plate boundary inside the Indian Australian Plate.

Keywords: earthquake swarm, local seismicity, crustal deformation, 2012 East Indian Ocean earthquakes, Khlong Marui Fault Zone, Phuket

1. INTRODUCTION

Earthquakes in general appear and are recognized as single events or as sequences known as main-shock-aftershock or foreshock-mainshock-aftershock sequences, mostly along tectonic boundaries or in volcanic areas. Another type with a less frequent occurrence are earthquake swarms, which are characterized by a sequence of earthquakes that occur in a relatively defined (local) area within a relatively short period of time (days, months, or even years) without an obvious mainshock [1]. The terminology "earthquake swarm" was introduced by [2] and [3] who used the term *Erdbebenschwarm* and *Schwarmbeben* (in German) to describe the seismicity in West Bohemia and Vogtland (at the border of Czech Republic and Germany) in 1875 and 1824, respectively, and it typically refers to a cluster of moderate earthquakes that occur over a period of hours to days (or even longer, weeks and months, [4]) with magnitudes usually less than M 4.5, e.g. [5]. Swarms frequently originate in the upper part of the crust (<20 km), which deeper swarms rather infrequently exist. Most swarm events are located around 10 km and shallower [4].

Single earthquakes in a swarm follow the same physical principles than earthquakes in general [6] and swarms originate along tectonics boundaries as well as in volcanic regions [7]. For most intraplate earthquake swarms, fluid intrusions into pre-existing faults of a regional tectonic stress system are seemingly the trigger, which can be natural or man-made by water injection (anthropogenic or induced earthquakes) [8] which now becomes a great concern in seismology. Work done by [5] however suggests that swarms on strike-slip faults are primarily driven by processes of shallow aseismic creep transients. A number of studies utilizing high-quality earthquake catalogues have shown that swarms are a common feature of various large-scale tectonic fault systems [9].

For the distinction of mainshock-aftershock (MS-AS) sequences from swarms, which have no distinct mainshock, e.g. [10], certain parameters were proposed over time. [11] applied following empirical measure based on [1] with 1) Total number of earthquakes in a sequence exceeds 10, and 2) $Nm/\sqrt{T} > 2$, where Nm is the maximum daily number of earthquakes and T is the duration of the earthquake sequence (in days). According to [5] swarms are characterized by their unique seismicity patterns, which makes them distinguishable from typical MS-AS sequences as the highest magnitude event usually occurs later in the swarm sequence, and swarms contain several large events rather than a clear mainshock, and the swarm seismicity tends to be longer. Therefore, they proposed a quantitative method to identify swarms through characterizing the timing of the largest earthquakes relative to the rest of the seismicity. This is done by calculating the skew of the seismic moment release history. A larger positive skew value is observed for pure aftershock sequences, whereas a lower or even negative value indicates a swarm (-5.0 to 5.0).

Phuket Island, which is located in the western part of Southern Thailand, experienced an earthquake swarm from 16 April to 5 May 2012, with overall 48 seismic events during 20 days. The maximum magnitude recorded was ML 4.1 according the website of the Earthquake Surveillance Division of the Thai Meteorological Department (TMD; http://earthquake.tmd.go.th/). TMD also indicated that some of the local earthquakes during the 2012 Phuket swarm generated vibrations that have been felt by people in Phuket, and that this earthquake swarm with a maximum VI on the MMI intensity scale has caused slight damages to buildings on the island [12]. A Thailand national daily newspaper, the Bangkok Post, on 18 April 2012 has reported that the largest event on the first day has been felt by local people and tourists prompting them to flee buildings in panic. As many as 33 houses in Si Sunthon Sub-district, Thalang District, sustained cracks. There were no injuries or death reported [13; https://www.bangkokpost.com/learning/learning-news/289304/phuket-shaken-by-earthquakes].

To the best of our knowledge, the 2012 Phuket earthquake swarm was the first of its kind in Southern Thailand, so that the further understanding of this event is required, which is the objective of this work. Digital seismograms of 29 events of the 2012 Phuket swarm recorded at stations of the Earthquake Surveillance Division of the TMD were used for this study. Further, 19 event data were added from a previous work [12] as well as geodetic data (time series for Phuket stations) to explain the Phuket swarm in a larger geotectonic setting.

2. GEOLOGICAL SETTING

Phuket Island (known as *Pearl of the Andaman*) is the largest island in Thailand surrounded by the Andaman Sea with the Phang Nga Bay in the east, and within the latitudes 7º43'–8º12'N and longitudes 98º15'–98º30'E (Figure 1). Phuket is divided into three districts, Thalang in the north, Kathu in the west, and Muang in the south. The provincial capital Phuket City is situated in the southeast of the island.

2.1 Regional Geological Setting

Phuket Island, like all regions of Thailand, is tectonically located in the interior of the Eurasian Plate (intraplate), around 600-700 km east of the Sunda Subduction Zone (SSZ, Figure 1a) in the Eastern Indian Ocean. The SSZ is the zone

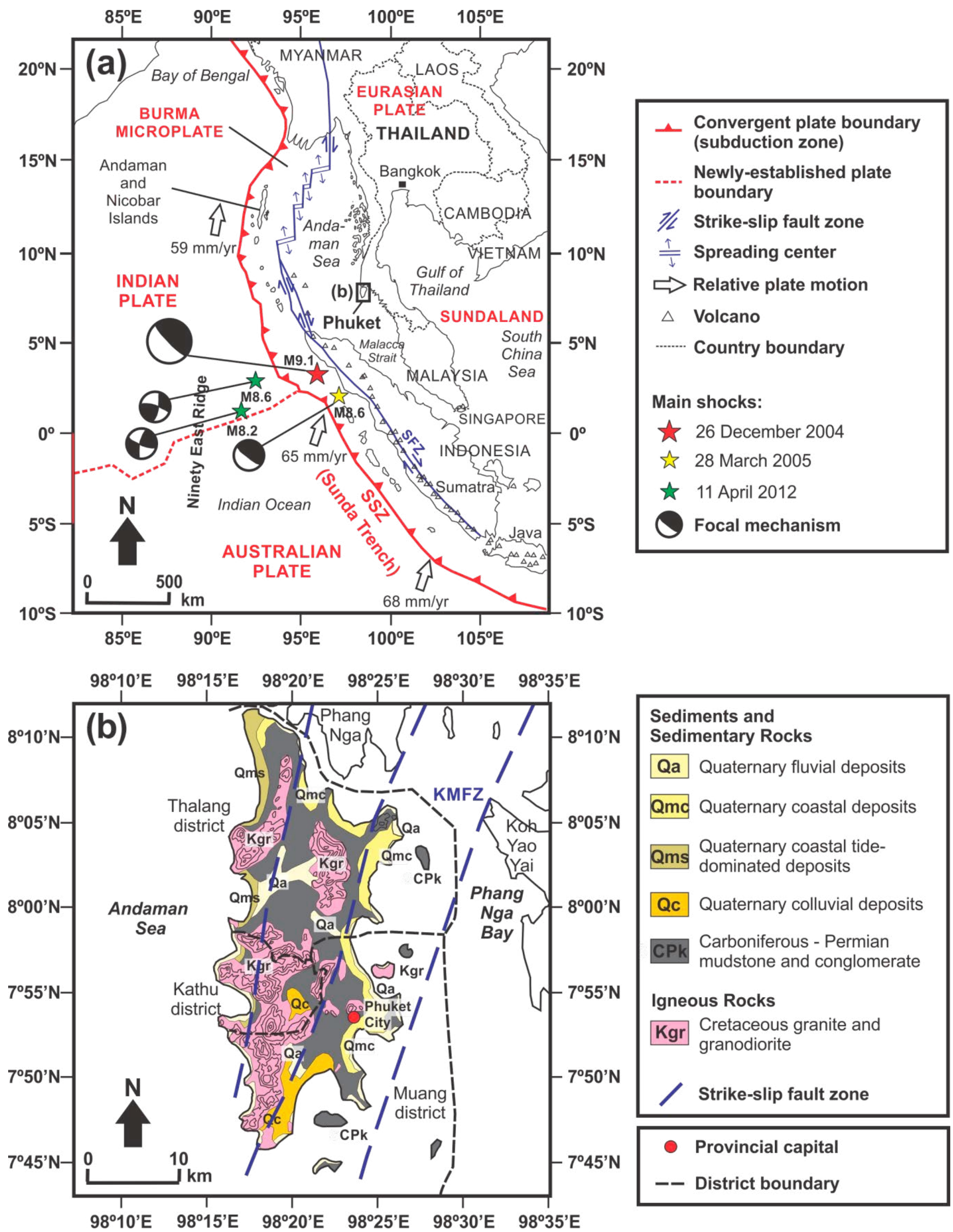


Figure 1. Regional tectonics of the Sunda Subduction Zone (SSZ) and surrounding regions (a), after [17, 20]; Geology and local tectonics of Phuket Island (b). SFZ = Sumatra Fault Zone; KMFZ = Khlong Marui Fault Zone. Geological map of Phuket was redrawn from [16]. Several faults within KMFZ were redrawn from [17, 18].

where the Indian-Australian Plate subducts under the overriding Burma Microplate and Eurasian Plate. This contact formed the Sunda Trench or the Sunda megathrust, which elongates from Bangladesh southwards along the Andaman and Nicobar Islands and continues offshore west of Sumatra, south of Java, Bali, and Sumba Islands and further east, with a total length of about 5,500 km [14, 15]. This megathrust is so far the principal source of large earthquakes (and tsunamis) in the Indian Ocean, such as the 26 December 2004 Sumatra-Andaman earthquake (M 9.1) and the 28 March 2005 Nias earthquake with a magnitude of 8.6 (see Figure 1a).

2.2 Local Geological Setting

Phuket Island is composed of Carboniferous-Permian sedimentary rocks with significant Cretaceous granitic intrusive bodies scattered over the island, and overlain by Quaternary deposits [16]. For local tectonics, the island is affected by the major NNE-SSW-trending Khlong Marui Fault Zone (KMFZ, Figure 1b) [17, 18], a strike-slip fault zone with a left-lateral offset crossing Phuket, Phang Nga Bay, and partly passes the Khlong Marui channel to Surat Thani province and Bandon Bay, and continues into the Gulf of Thailand. This fault zone occupies the bend of the Thai Peninsula separating it into an upper and lower part with the distance of 210 km [19, 20]. The transpressive faulting during the deformation history of this fault zone has formed an elevated topography within positive flower structures [17]. Before the 26 December 2004 Sumatra-Andaman earthquake, the KMFZ and other major fault zones in Southern Thailand i.e. the Ranong Fault Zone (RFZ) further north, were considered dormant [21]. However, seismological monitoring after the 2004 great earthquake in the region has revealed an increase of local seismicity indicating a reactivation of these local fault zones [21, 22, 23].

3. DATA AND METHODS

This study analyzed digital seismograms of 29 local earthquakes occurred at Phuket Island from 16 April until 5 May 2012, obtained from the Earthquake Surveillance Division of the TMD. Each event was recorded by four to six permanent, three-component, digital seismological stations distributed over Southern Thailand under the TMD's network (Figure 2a), including one station located on the island, Phuket station (PKDT). An example of a digital seismogram for this swarm activity is shown in Figure 2b. Other stations are located around 90–550 km from Phuket Island. Detailed information on these stations was obtained from [24, 25] (Table S1).

Digital seismograms were analyzed by using SEISAN software (ftp://ftp.geo.uib.no/pub/seismo/SOFTWARE/SEISAN/) following standard and routine procedures [26, 27], mainly the manual picking of P and S phases as well as the maximum amplitude for each event in order to generate earthquake parameters such as origin time, location, magnitude, and focal depth. Earthquakes are usually located using P and S arrival times from a set of stations that recorded the events (called single-event location) resulting in a fixed geographical coordinates and a fixed time base. Earthquake locations were determined simultaneously by using HYPOCENTER program running under SEISAN. Focal depths were obtained through iterations with the starting depths adjusted to around 10-20 km for the local earthquake [26]. For this study, the starting depth was fixed to 15 km and the minimal focal depth was fixed at 1 km (similar to that in TMD's earthquake catalog). The IASP91 velocity model was used in this study, where the crust consists of uniform layers with discontinuities at depths of 20 km (Conrad discontinuity, upper and lower crust) and 35 km (Moho discontinuity, lower crust and upper mantle) [28], which is in accordance with results from [29]. Seismological data from seismogram analysis of 29 events were incorporated with other data of 19 earthquake events obtained from [12].

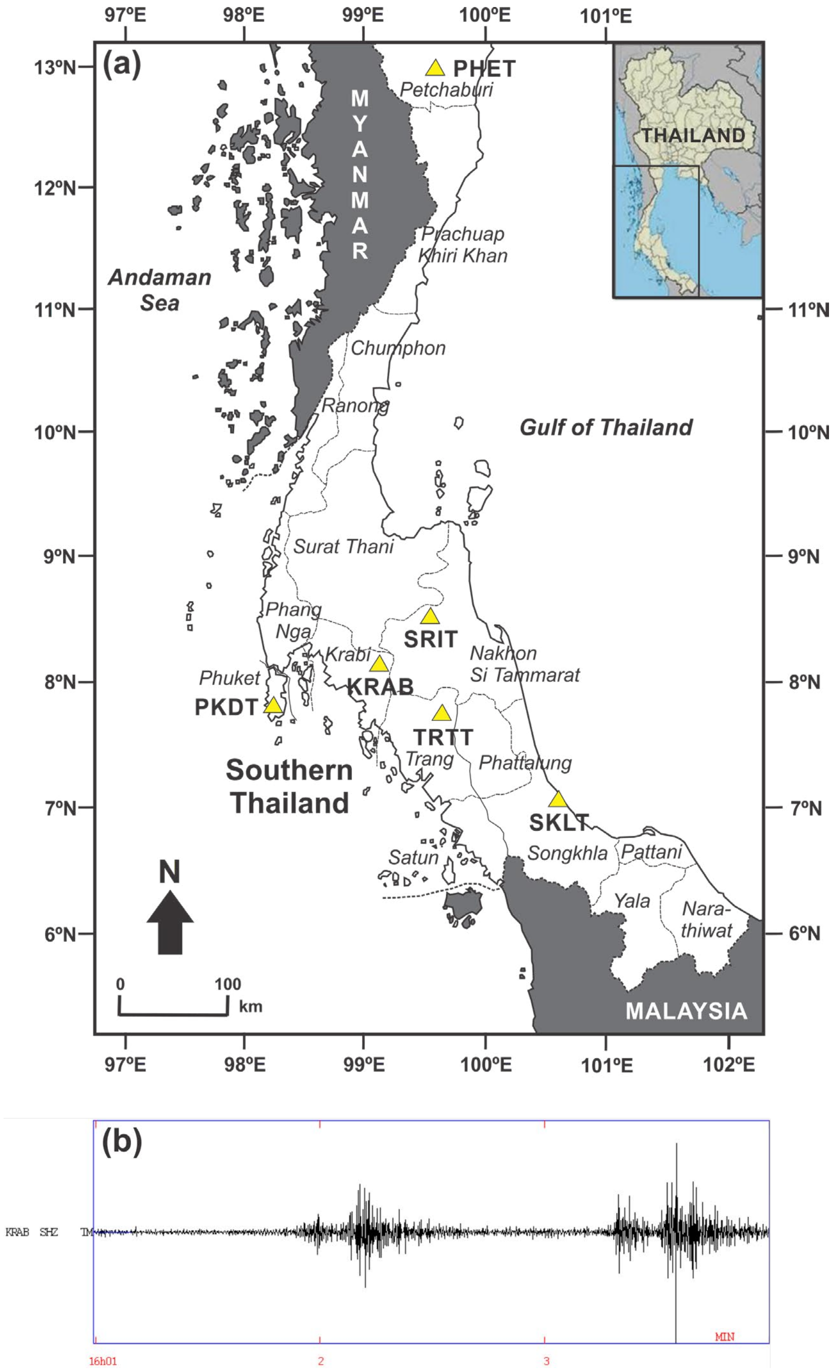


Figure 2. Location map of TMD's stations (yellow triangles) in Southern Thailand used in this study (a). Detailed information of all these stations refer to Table S1 (supplementary material); An example of digital seismogram for this swarm activity is shown by two events on 16 April 2012 with the original times of 16:01 and 16:03 UTC (b) (the vertical component [Z] from KRAB station).

For calculating the empirical swarm value after [11] dates were taken from Table 1 with the maximum daily number determined. Here, for the swarm duration seven days were used, from 16 to 22 April 2012. [5] calculated the skew value for a given swarm sequence from its moment release history by first defining the duration of the swarm as the period of time during which the seismicity rate is at least 20% of its maximum value, with the seismicity rate being calculated using 2-hr time bins. For the Phuket swarm the 20% seismicity rate value ends with the 27th event after 19:35 hrs; however here we additionally also calculated for all 46 events (145:05 hrs). The detailed calculation procedure is described by [5], and accordingly here it was also assumed that ML is equivalent to Mw. The skew of the seismic moment release is represented by the standardized third central moment, which is equal to the third central moment divided by the standard deviation cubed.

4. Results

The empirical swarm values determined here, first, show that the earthquake number is higher than 10, and, second, the maximum of the daily number of events in the swarm (27 events for 16 April 2012) is greater than twice the square root of the swarm duration in days (5.29). The skew of the seismic moment release for the 20% seismicity rate value is 2.65 and for all 46 events 2.35, respectively. Both criteria therefore indicate that the Phuket earthquake sequence is a swarm. Seismogram analysis shows that travel times of this swarm event increase with the increase of epicentral distances, e.g. the average travel times for KRAB, SRIT, TRTT, and SKLT stations (see Figure 2a) are 16 s, 23 s, 26 s, and 45 s, respectively. The earthquake catalog for this study consists of 48 local earthquakes of the 2012 Phuket swarm event in the period of 16 April to 5 May 2012 (Table 1). During this 20-day duration, the first day (16 April 2012) was the most active one with 27 recorded earthquakes with local magnitudes 1.5 ≤ ML ≤ 4.1. The weakest and strongest magnitudes of the overall swarm are ML 1.5 and ML 4.1, respectively, both occurred on the first day. This swarm has a predominant magnitude of 2.0 ≤ ML ≤ 3.0 and a few events with ML ≤ 2.0 and ML ≥ 3.0. No event detected with ML ≤ 1.0. Figure 3 shows the relations between cumulative number of earthquakes, number of earthquakes per day, and local magnitudes of the 2012 Phuket swarm and Figure 4 the relation between location, depth, and magnitude.

Table 1. Earthquake parameters of the 2012 Phuket swarm (16 April – 5 May 2012) from seismogram analysis (this study) and a previous study.

Event No.	Origin Date (UTC) (yyyy-mm-dd)	Origin Time (UTC) (hh:mm)	Latitude (N)	Longitude (E)	Magnitude (ML)	Focal Depth (km)	Recorded by stations	RMS Residual (s)
1*	2012-04-16	00:37	7.974	98.319	2.2	7.5	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
2*	2012-04-16	03:20	7.969	98.323	1.7	8.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
3	2012-04-16	09:44	8.021	98.347	4.1	4.5	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.35
4*	2012-04-16	10:12	7.979	98.386	2.3	2.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
5*	2012-04-16	10:30	7.972	98.343	2.4	8.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-

* Earthquake data from [12].

Table 1. (Continued).

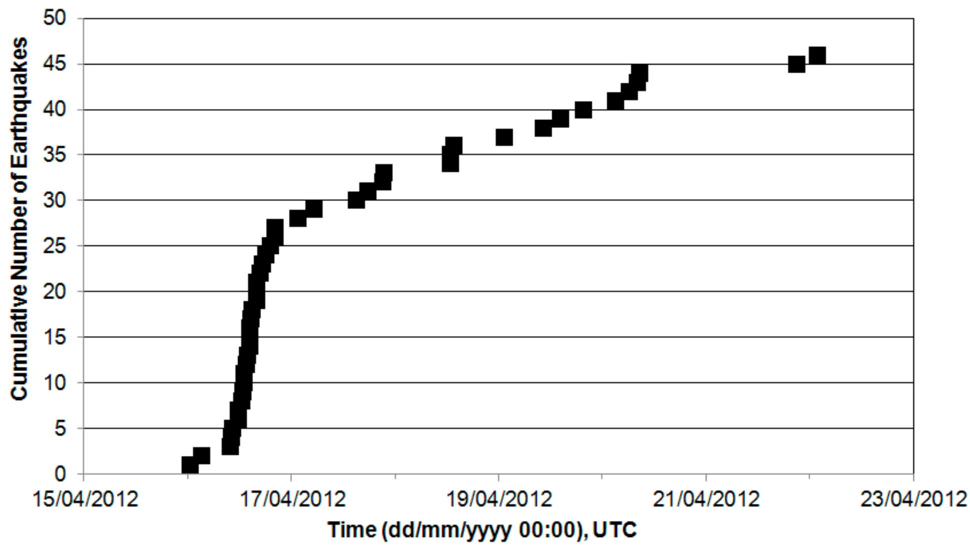
Event No.	Origin Date (UTC) (yyyy-mm-dd)	Origin Time (UTC) (hh:mm)	Latitude (N)	Longitude (E)	Magnitude (ML)	Focal Depth (km)	Recorded by stations	RMS Residual (s)
6*	2012-04-16	11:43	7.967	98.400	1.9	1.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
7*	2012-04-16	11:47	7.870	98.250	1.8	7.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
8*	2012-04-16	12:25	7.989	98.340	1.7	2.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
9*	2012-04-16	12:50	7.989	98.335	1.7	2.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
10*	2012-04-16	13:02	7.964	98.403	1.8	1.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
11*	2012-04-16	13:03	7.972	98.344	1.7	8.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
12	2012-04-16	13:30	8.038	98.328	2.3	4.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	1.56
13*	2012-04-16	13:56	7.984	98.365	2.1	1.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
14	2012-04-16	14:17	8.015	98.343	2.8	5.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.58
15*	2012-04-16	14:23	7.969	98.328	1.9	8.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
16*	2012-04-16	14:25	7.966	98.359	2.6	4.1	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
17*	2012-04-16	14:37	7.986	98.332	1.8	3.5	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
18*	2012-04-16	14:50	8.000	98.343	2.2	2.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
19*	2012-04-16	15:54	7.977	98.311	1.5	6.5	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
20	2012-04-16	16:01	8.069	98.332	2.1	5.5	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.96
21	2012-04-16	16:03	8.025	98.329	2.3	5.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.99
22	2012-04-16	16:48	8.021	98.312	1.5	7.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.37
23*	2012-04-16	17:16	7.981	98.369	2.2	5.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
24	2012-04-16	18:00	8.083	98.369	1.8	6.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.66
25	2012-04-16	19:02	7.910	98.331	3.4	4.5	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.89
26*	2012-04-16	20:11	7.986	98.358	2.0	1.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
27*	2012-04-16	20:12	7.985	98.347	1.4	3.5	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
28	2012-04-17	01:31	8.023	98.378	1.8	2.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	1.00
29	2012-04-17	05:18	8.091	98.351	2.9	8.5	KRAB, SRIT, TRTT, SURA, SKLT (5)	1.95
30	2012-04-17	14:56	8.000	98.374	2.7	5.8	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.58

* Earthquake data from [12].

Table 1. (Continued).

Event No.	Origin Date (UTC) (yyyy-mm-dd)	Origin Time (UTC) (hh:mm)	Latitude (N)	Longitude (E)	Magnitude (ML)	Focal Depth (km)	Recorded by stations	RMS Residual (s)
31	2012-04-17	17:49	8.016	98.300	2.2	6.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	1.05
32	2012-04-17	21:15	8.019	98.294	2.9	6.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.58
33	2012-04-17	21:19	8.054	98.327	1.8	19.7	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.15
34	2012-04-18	12:48	8.017	98.368	2.3	9.3	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.59
35	2012-04-18	12:53	8.087	98.363	3.5	1.5	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.40
36	2012-04-18	13:38	8.084	98.379	2.9	1.0	KRAB, SRIT, TRTT, SKLT (4)	0.33
37	2012-04-19	01:13	8.082	98.386	1.7	18.5	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.41
38	2012-04-19	10:13	8.069	98.396	1.7	4.1	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.40
39	2012-04-19	14:20	8.073	98.331	2.6	33.1	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.08
40	2012-04-19	19:43	8.015	98.328	2.9	1.2	KRAB, SRIT, TRTT, SURA, SKLT (5)	1.00
41	2012-04-20	02:57	8.048	98.386	2.4	1.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.15
42	2012-04-20	06:18	8.074	98.322	2.7	1.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.41
43	2012-04-20	08:10	8.025	98.352	3.0	6.9	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.97
44	2012-04-20	08:42	8.038	98.385	2.2	36.0	KRAB, SRIT, TRTT, SURA, SKLT (5)	0.10
45	2012-04-21	21:07	8.022	98.359	1.9	1.0	KRAB, SRIT, TRTT, SKLT (4)	0.19
46	2012-04-22	01:42	8.024	98.331	2.5	1.0	KRAB, SRIT, TRTT, SKLT (4)	0.03
47	2012-05-03	21:54	8.056	98.391	2.0	5.0	KRAB, SRIT, TRTT, SKLT (4)	0.37
48	2012-05-05	23:21	8.052	98.348	2.1	1.0	KRAB, SRIT, TRTT, SKLT (4)	0.75

* Earthquake data from [12].



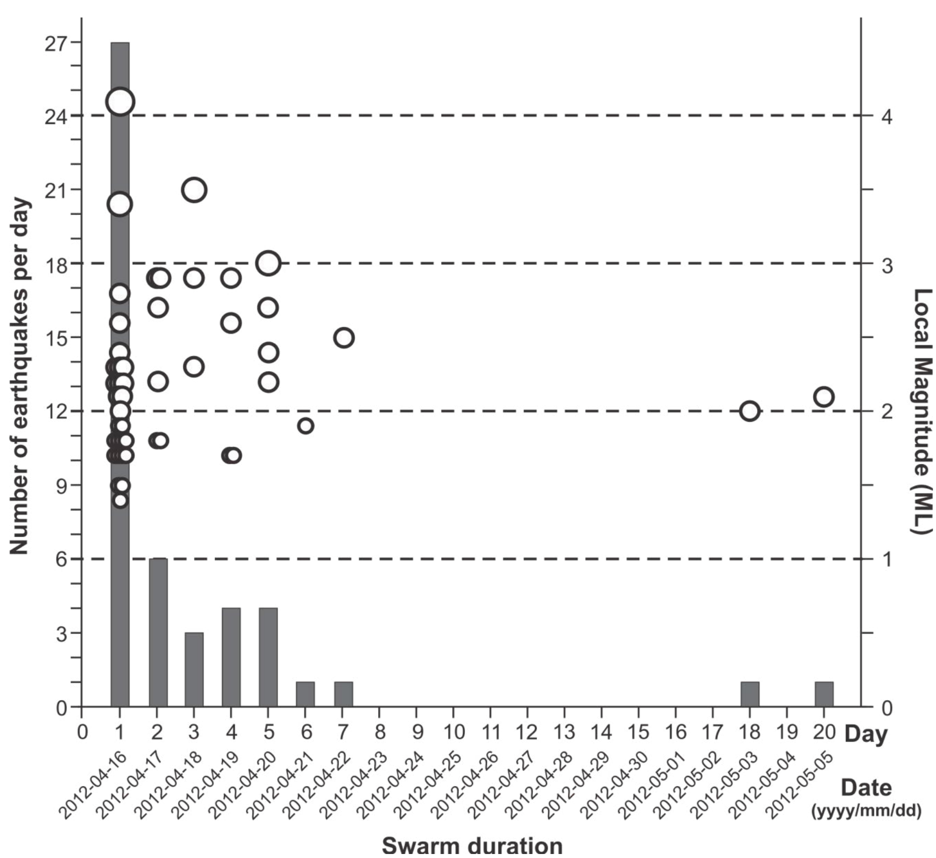


Figure 3. Cumulative number of earthquakes (black squares) for the first seven days of the swarm (top); Number of earthquakes per day (grey bars; lower left-hand side scale) and local magnitude variation (bottom) (circles; right-hand side scale) during the full 20-day duration of the 2012 Phuket swarm.

The excitation of the swarm started on 16 April 2012 with the first event occurred at 00:37 UTC and magnitude ML 2.2, and followed around three hours later by the second event of ML 1.7 [7] (see Table 1). These earthquakes were followed by other events on the first day (UTC time) including the largest event (ML 4.1). The two earlier earthquakes (ML 2.2 and ML 1.7) in the first day of the swarm are considered belong to this swarm since they occurred in the starting day of seismic excitation which occurred only a few hours before the largest magnitude earthquake (ML 4.1). There have been no events recorded for a long time before 16 April 2012 in the same area (Phuket). The swarm activity decreased on the following days with the 2nd and 3rd days recorded six and three events, respectively, and the 4th and 5th days recorded four events each. The swarm activity decreased again on the 6th and 7th day with each day only one recorded event. There was no earthquake event detected during 23 April to 2 May 2012 (8th to 17th day) and on 4 May 2012 (19th day). One event was detected on 3 May 2012 (18th day) and on 5 May 2012 (20th day). The 5th May 2012 event with ML 2.1 was the last event of this sequence (Table 2). Both earthquake events in May were not used for the determination of the swarm criteria (see above). The next reported earthquake for Phuket was in March 2015 (see Figure 5a).

Figure 4a shows the lateral distribution of the swarm epicenters which are concentrated mostly onshore in the northern part of Phuket Island, more precisely in Thalang District, and only two events occurred in the neighboring Kathu District. The earthquake epicenters of the swarm are located within latitude 7°52’to 8°08’N and longitude 98°15’ to 98°28’E, clustered in the vicinity of several faults within the active KMFZ. In the vertical distribution, earthquake hypocenters are ranging from 1.0 km down to 36.0 km depth, respectively, with the majority in the shallow part of the upper crust and a few further down to the crust-mantle boundary (Figure 4b; Table 1).

Table 2. Chronology of the 2012 Phuket swarm activity.

Date	ML	No. of event	Remark
16 April 2012	1.5 - 4.1	27	Swarm initiation, the weakest and largest events occurred this day
17 April 2012	1.8 - 2.9	6	Swarm activity decreased
18 April 2012	2.3 - 3.5	3	Swarm activity decreased, but the range of magnitude increased
19 April 2012	1.7 - 2.9	4	Swarm activity slightly increased, but the range of magnitude decreased
20 April 2012	2.2 - 3.0	4	Range of magnitude increased
21 April 2012	1.9	1	Swarm activity decreased, only one event detected
22 April 2012	2.5	1	Only one event detected with higher magnitude from previous day
23 April – 2 May 2012	-	0	*Hiatus (no event detected) for 10 consecutive days*
3 May 2012	2.0	1	Only one event detected
4 May 2012	-	0	*Hiatus (no event detected)*
5 May 2012	2.1	1	End of swarm activity

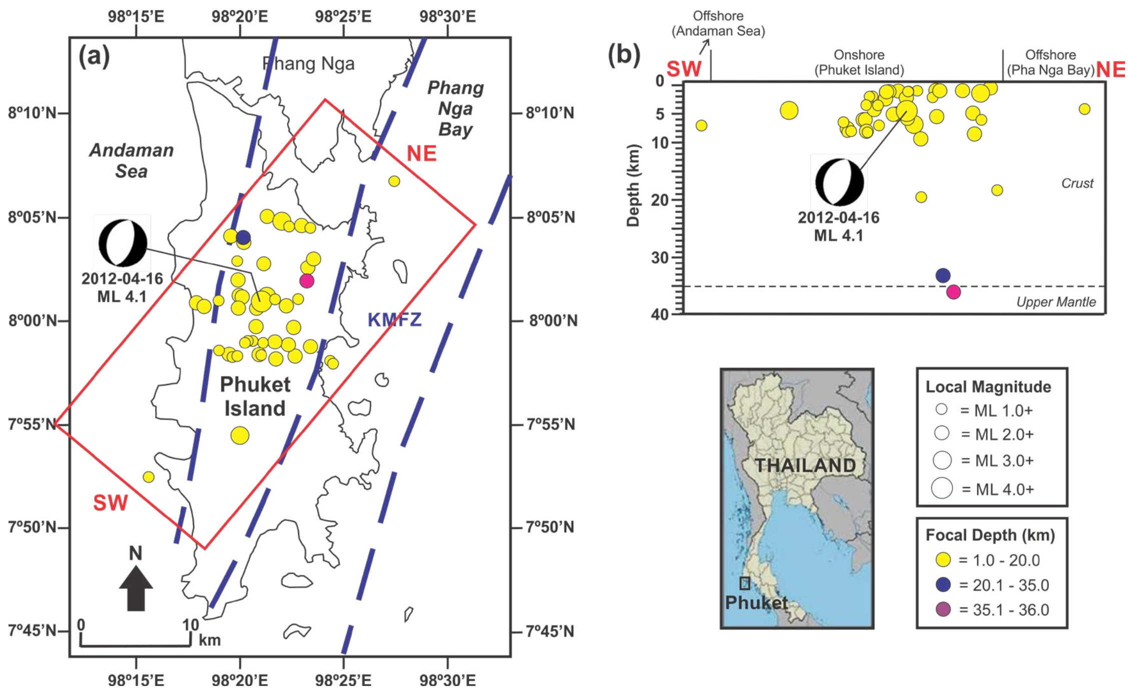


Figure 4. Epicenter map (a) of the 2012 Phuket swarm (period 16 April to 5 May 2012) shows the distribution of epicentral locations in the vicinity of the several faults (blue dashed lines) within the Khlong Marui Fault Zone (KMFZ). The focal mechanism of the largest event of the swarm obtained from [12]. The red rectangle indicates the area of cross section; Depth profile indicates that the 2012 Phuket swarm consists of shallow earthquakes (b). The Moho depth for Phuket Island is 35 km (black dotted line) [29].

5. Discussion

Similar to other earthquake swarms, the 2012 Phuket swarm has mostly low magnitude earthquakes with no foreshock, mainshock, and aftershock. The Phuket swarm is different from other common swarms, mainly in terms of duration and number of events. The Phuket swarm lasted over a relatively short time duration (within only 20 days) compared to other longer period swarms, such as the 2012-2015 Ubaya Valley Swarm in France [30]. The Phuket swarm occurred with fewer number of events (only 46, respectively, 48 recorded local earthquakes) compared to other swarms, which can reach until tens of thousands events, such as the 1965-1967 Matsushiro Swarm in Japan with more than 60,000 events [31]. In terms of origin, earthquake swarms are often found in volcanic areas, such as the 2000 Izu Islands, Japan [32], or along active tectonic belts or boundaries, such as the 1965-1967 Matsushiro Swarm in Japan [31], or a combination of both (volcano-tectonic swarm), such as the 2005 Andaman Sea Swarm [7]. The Phuket swarm occurred in an intraplate area which is around 600-700 km from an active subduction zone (SSZ) and within a non-volcanic area, suggesting that also here, according to [8], fluids intruded into the preexisting fault planes of the KMFZ and by this triggering the earthquake swarm. Although geothermal (hot) springs are not known on Phuket, several can be found along the Khlong Marui Fault Zone and main parts of Southern Thailand [33].

The focal mechanism of the largest event (ML 4.1) created by [12] is displayed by two nodal planes (see Figure 4a) where the selected solution shows the slightly oblique normal faulting with a strike direction of the planes 19º in NNE which is parallel to the main strike direction of the KMFZ, a dip of 57º to the ESE, and a rake of -87º. This is very likely the fault plane, thus also confirming the current sinistral strike slip faulting of the KMFZ in a transtensional regime [34]. Following [17], the KMFZ has a positive flower structure where Phuket and the swarm area are located on the west of the main fault (see Figure 4a). Further, a few deeper earthquakes with epicenters at the crust mantle boundary, as shown in Figure 4b, support the assumption by [17] that the KMFZ is a crustal-scale strike-slip fault zone with metamorphism and migmatization along ductile shear zones, which were found further east in Southern Thailand.

Five days before the Phuket swarm started the 11 April 2012 East Indian Ocean (EIO) doublet earthquakes occurred [35], located within the oceanic lithosphere nearby a diffuse boundary between Indian and Australian Plates which is assumed as a newly-established plate boundary [36-38]. The first event of the 2012 EIO earthquakes occurred at 08:38:36 UTC with the epicenter at 2.311 °N and 93.063 °E or about 100 km to the SW from the SSZ with the focal depth of 20 km and the magnitudes of M8.6. Meanwhile, the second event (the largest aftershock) occurred two hours later at 10:43:10 UTC and located at 0.773 °N and 92.452 °E or about 200 km to the SW from the SSZ with the depth of 25.1 km and the magnitudes of M8.2 (Figure 1a). The two earthquakes were the result of conjugate strike-slip faults with left-lateral slip on a NNE-trending fault [37]. The rupture zone of these earthquakes was in the oceanic lithosphere within the Wharton Basin, and extended into the adjacent Ninety East Ridge (NER) with an average slip of ~15 km, a depth of 40 km, and a length of 500 km [37-38].

Both earthquakes were accompanied by sizeable crustal deformations measured at several GPS stations in the region, on Phuket Island (combined data from four stations) by [39] as shown in Figure 5a, on Sumatra (ACEH) by [40], and by a station in Bangkok (CUSV; 13.73591°N, 100.53392°E; http://sideshow.jpl.nasa.gov/post/links/CUSV.html). Before the 2012 EIO earthquakes, GPS data indicated a movement to the SW (Figure 5a,b). During the earthquakes then Phuket Island has experienced a significant jump in the horizontal components (N-S and E-W) according to the GPS data before and after the 11 April 2012 earthquakes (Figure 5a), although the GPS stations on the Island did not cover the displacement data around the earthquakes. The GPS station in Bangkok has covered the data showing also a significant jump in the measurement in April 2012. Based on the trend lines constructed by [39] and this study, the 2012 EIO earthquakes have changed the magnitude of the horizontal displacements by about 3.3 cm to the North and 3.8 cm to the East directions, respectively. It also changed the movement of the E-W-component from West to East, whereas the movement direction of the N-S-component towards the South direction continued. Current GPS measurements reveal that Phuket Island is still moving in SE direction (Figure 5a,b). This change in movement shortly after the 2012 EIO earthquakes resulted in a variation and change of the stress patterns around Phuket Island and the KMFZ. The SE movement created an extensional stress regime along the KMFZ allowing geothermal fluids moving upwards into the fault zone and thus triggering the swarm; a process described [41] for the Yellowstone volcano-tectonic system. Although [5] indicated that aseismic creep transients are the primary process driving swarms on strike-slip faults here the changes in movement direction indicated by the GPS data are seemingly a main process in the swarm occurrence. Further investigations of

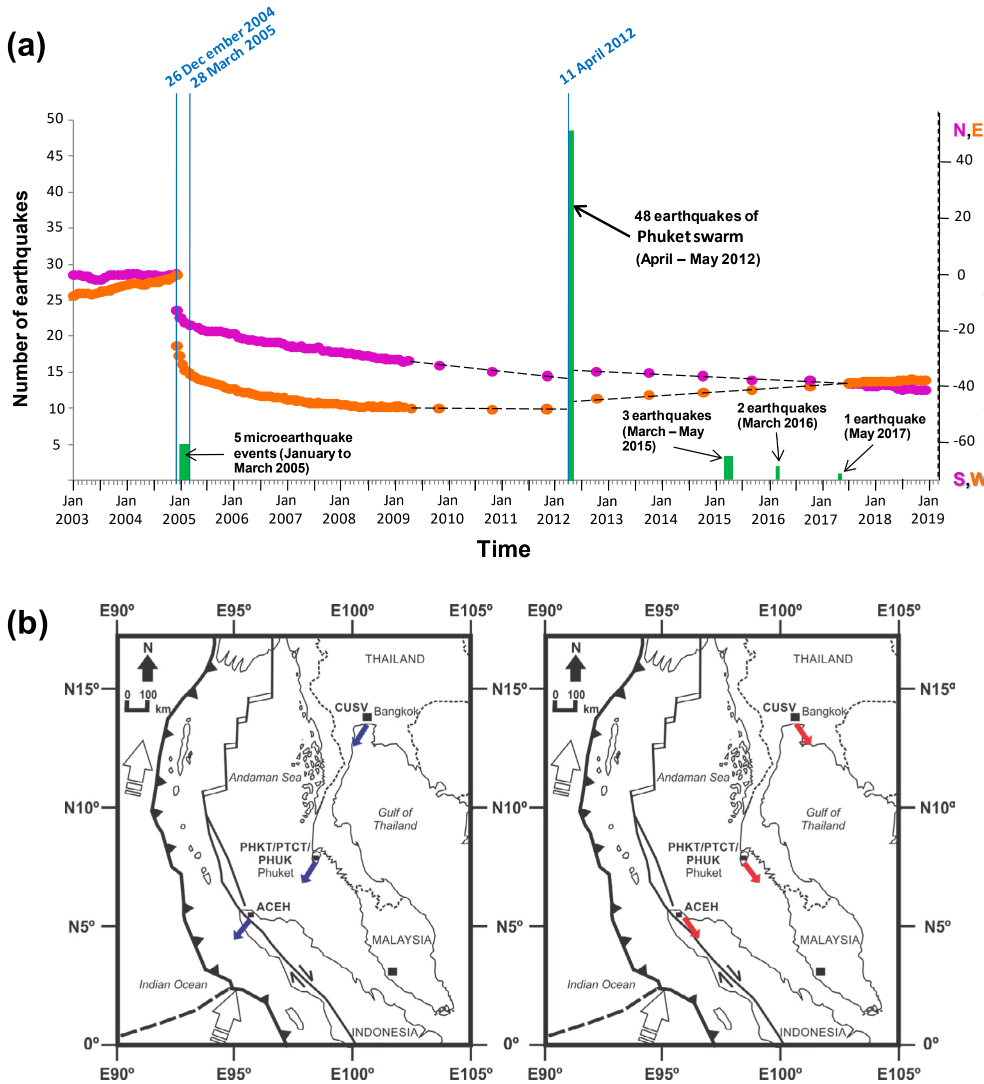


Figure 5. Graph showing relations between large regional earthquakes (a) i.e the 26-12-2004 Sumatra-Andaman (M9.1), the 28-03-2005 Nias (M8.6), and the 11-04-2012 EIO (M8.6 & M8.2) earthquakes (blue lines), the numbers of earthquakes ever recorded in Phuket Island since 2003 until recent time (green bars), and two time series of horizontal displacements in Phuket Island in N-S (purple charts/dots) and E-W (orange charts/dots) directions measured by [39]. Micro-earthquakes occurred in Phuket during January to March 2005 were recorded by the temporary network of the Geophysics Research Center at Prince of Songkhla University (GRC-PSU) in collaboration with the Department of Mineral Resources (DMR) [21]. Other earthquake events (after 11-04-2012 until recent time) were recorded by TMD's stations; Crustal deformation measured at several GPS stations (b) on Phuket (PHKT/PTCT/PHUK; [39]) and nearby areas e.g. Aceh (ACEH; [40]) and Bangkok (CUSV) before and after the 11-04-2012 EIO earthquakes indicated by blue and red arrows, respectively.

possible interrelations and driving processes are part of ongoing research.

6. CONCLUSIONS

The 2012 Phuket swarm is assumed to be the first earthquake swarm during the instrumental period of seismological observations in Southern Thailand. In comparison to other swarms across the globe it is relatively short in duration (20 days) and with a total number of 48 earthquakes relatively small. Seismotectonically the Phuket swarm can be linked to the active and NNE-SSE trending Khlong Marui Fault Zone, likely due to fluid intrusions into ESE dipping fault planes of its positive flower structure as revealed by focal mechanism analysis of previous work [12], which subsequently triggered the earthquake swarm. Time correlated GPS data revealed that the occurrence of the Phuket swarm might be linked to two M8+ earthquakes, which occurred five days earlier east of the Sunda Subduction Zone at the nascent plate boundary inside the Indian Australian Plate.

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Intraplate earthquake occurrence and distribution in Peninsular Malaysia over the past 100 years

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Research Article

Intraplate earthquake occurrence and distribution in Peninsular Malaysia over the past 100 years

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Abstract
Peninsular Malaysia is tectonically situated on a stable craton (intraplate) and so far experiences relatively little earthquake activities, thus considered as a region with low seismicity. This study uses earthquake data from 59 events obtained from various sources in the period 1922 to 2020. The overall seismicity in the study area is low as expected due to the general intraplate setting. Earthquakes occurred onshore and offshore of Peninsular Malaysia between latitudes 1° and 7° N and longitudes 99° and 105° E. The seismicity pattern shows that the epicenters are distributed spatially in some parts of the peninsula and in the Malacca Strait with several epicenter zones. Most of earthquakes are associated with several preexisting faults and fault zones indicating that they are the major contributor to the local seismicity. Meanwhile, some further earthquakes were caused by activities related to reservoirs. Magnitudes are ranging from Mw 0.7 to 5.4 with the majority is Mw 1.0 + and 2.0 +. Hypocenters are located in between 1 and 167 km deep (shallow to intermediate earthquakes) with the majority being shallow earthquakes (1–70 km). The deepest earthquake located in the Straits of Malacca can be associated with a slab detachment broken off from the Sumatran Subduction Zone. Finally, this study contributes to the understanding of the intraplate seismicity of Peninsular Malaysia as a basis for seismic hazard and risk assessment.

Article Highlights

- Earthquake assessment over the last 100 year reveals low but clear seismicity with an associated seismic hazard and risk for certain areas.
- Shallow, low-magnitude earthquakes associated with reservoir activities and preexisting faults reactivated by the nearby subduction zone.
- A deeper, low-magnitude earthquake can be related to slab detachment from the Sumatran subduction zone toward the east.

Keywords Intraplate earthquake · Low seismicity · Active faults · Local magnitude · Peninsular Malaysia

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42452-021-04686-2.

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1 Introduction

Intraplate earthquakes are less numerous than those along active plate boundaries, as only around 10% of all worldwide earthquakes occur in the interiors of lithospheric plates [1]. However, intraplate earthquakes must also be taken into account for seismic hazard assessment, especially if they occur in a populated area equipped with critical facilities and other man-made structures. Peninsular Malaysia, a region located in the interior of Sundaland (part of Eurasian Plate), is facing this situation and thus it becomes the study area.

Peninsular Malaysia (also called West Malaysia) is situated between latitude 1 and 7°N and longitude 99 and 105°E (Fig. 1a), and it is surrounded by the Malacca Strait and the South China Sea in the west and in the east, respectively. Lat [2], Balendra and Li [3], and Wah [4] stated that Peninsular Malaysia extends to the north to the border with Southern Thailand and to the south with the Johor Strait. Peninsular Malaysia is tectonically located on a stable craton outside the "*Ring of Fire*," thus it experiences only relatively little earthquake activities and therefore considered as a region in Malaysia with low seismicity. However, earthquake data obtained from databases of international and national seismological centers, i.e., International Seismological Center (ISC), European Mediterranean Seismological Centre (EMSC), and Malaysian National Seismic Network operated by Malaysian Meteorological Department (MMD or MetMalaysia) show that at least as many as 59 earthquake events have been recorded in Peninsular Malaysia region from 1922 to 2020. MetMalaysia has started to record seismological data from the 1970s onward (MMD, personal communication).

The Malaysian National Seismic Network (FDSN code: MY) was operated by MMD since 2003. However, there were no significant tectonic earthquakes originating from within West Malaysia and no records by MMD until the occurrence of the November 30, 2007, Bukit Tinggi earthquakes, which were generated by a strike-slip fault along the Bukit Tinggi Fault Zone [5]. Lat and Ibrahim [6] stated that these earthquake occurrences were associated with the reactivation of preexisting faults and produced a series of weak earthquakes with local magnitudes ranging from ML 2.5 to 3.5.

The 2007-11-30 local earthquakes in Bukit Tinggi area and other local earthquakes have revealed that there are a number of active fault zones in Peninsular Malaysia, which can be considered potential near-field (local) earthquake sources, mainly the Bukit Tinggi and the Kuala Lumpur Fault Zones (BTFZ and KLFZ).They were assumed to be dormant before 2007 and have become active with around 22 events during 2007 to 2009. Most of the earthquakes in Peninsular Malaysia are located in and around the BTFZ and KLFZ, mainly in the Bukit Tinggi area (near the boundary between Pahang and Selangor states; Fig. 1a). Other than tectonic earthquakes, several reservoir-induced earthquakes, which were generated by reservoir related activities, e.g., infilling of a dam has occurred previously around the Kenyir Dam in Terengganu state (Figs. 1a, 3a) in between 1984 and 1988 with local magnitude values ranging from 2.4 to 4.6 [5, 7–12].

In addition to compile all necessary earthquake data from international and national seismological centers, this study also analyzed digital seismograms of local earthquake events recorded by MMD from 2007 to 2016 by reprocessing them according to standard and routine procedures using freely available SEISAN software to estimate earthquake source parameters, which include origin times, locations, magnitudes, as well as focal depths. This study also assesses the spatial (lateral and vertical) distribution and magnitude variations of local earthquakes as well as evaluates the relationship between the earthquakes and geological structures in this region. For this, shuttle radar topography mission (SRTM)–digital elevation model (DEM) images were also analyzed.

2 Seismotectonic and geological setting

Peninsular Malaysia (or West Malaysia) is located in Sundaland, the South East Asian part of the Eurasian Plate. The peninsula is generally elongated in NNW–SSE direction (parallel to its main structural trend) and has a maximum length of 750 km and a width of 330 km. The tectonic setting that influences the earthquake activities of this region can be divided into two types: regional and local. Regional tectonics influences West Malaysia where the India-Australian Plate moves northeastward and subducts under the Eurasian Plate forming the Sunda Trench, part of the larger Sunda-Java-Sumatra Trench. This Sumatra Subduction Zone (SSZ, about 500–600 km to the Peninsula's nearest coastline; Fig. 1b) has an approximate convergence direction of N010E and an average velocity of about 7 cm/yr. This subduction zone is one of the most active plate margins globally, and its complex geomechanical setting also has yielded the occurrence of the Sumatra Fault Zone (SFZ, around 250–300 km to the nearest coastline of the Peninsula; Fig. 1b), an active dextral strike slip fault zone [10, 13]. Balendra and Li [3] emphasized that historical evidences showed that West Malaysia was influenced by earthquakes from these two far-field (regional) sources, the SSZ and the SFZ. Such earthquakes, which originated from Sumatra region, one of the main islands of

Indonesia with very frequent earthquake experiences, were seismically attenuated through distances up to 1000 km and still have created panic situations among the public in Peninsular Malaysia due to tremors being felt mainly by people who were living in high-rise buildings, and also have reportedly caused cracks at buildings [3, 14–16]. Major earthquakes from Sumatra, with long period surface waves, have been felt in Peninsular Malaysia particularly along its west coast with intensity values of up to V on the modified Mercalli intensity scale [4, 5]. Magnitudes of earthquakes from the SSZ are higher than those from the SFZ; however, effects of major ruptures of the latter can still be felt in Peninsular Malaysia [17].

Other than the regional tectonic, West Malaysia is also affected by local tectonics, which are major faults and fault zones. Several fault lines in West Malaysia have been delineated, commonly in NW–SE trend, and previously stated inactive. However, a sequence of large earthquakes near Sumatra, which started by the December 26, 2004 (M 9.2) earthquake, have altered the tectonic setting in the South East Asian region, including West Malaysia, reactivating major fault lines in the area [18, 19]. Tjia [20, 21] listed eight large, potentially active strike-slip faults that have been recognized in West Malaysia (Fig. 1c): (1) Bok Bak Fault Zone in the state of Kedah and Perak; (2) Kelau–Karak Fault Zone in Pahang; (3) Lebir Fault Zone in Kelantan-Terengganu-Pahang; (4) Bukit Tinggi Fault Zone in Selangor-Pahang; (5) Kuala Lumpur Fault Zone in Kuala Lumpur–Selangor–Negeri Sembilan; (6) Mersing Fault Zone in Johor; (7) Ma Okil Fault Zone in Johor; and (8) Lepar Fault Zone in Pahang. Shuib et al. [22] revealed that these fault zones show prominent lineaments but do not show any surface rupture caused by recent earthquakes. Marto et al. [13] stated that the Bukit Tinggi and Kuala Lumpur Faults (fault lines 4 and 5, respectively, in Fig. 1c) form the main and most active fault zones within West Malaysia.

Geologically, West Malaysia can be divided into three relatively N-S oriented major belts: Western Belt, Central Belt, and Eastern Belt; each of them possesses its own distinctive geological characteristics [23, 24]. Two main boundaries distinctly separate each belt, the Bentong–Raub Suture Zone and the Lebir Fault Zone (Fig. 1c). West Malaysia is composed of a great variety of rock types (Fig. 1c) reflecting various environments in space and time. Shuib [25] stated that structures in all three belts are complex; however, outcrops are less and major structures are also not easy to be detected in the field, so that their interpretations became difficult and depends mainly on aerial photographs and satellite imageries.

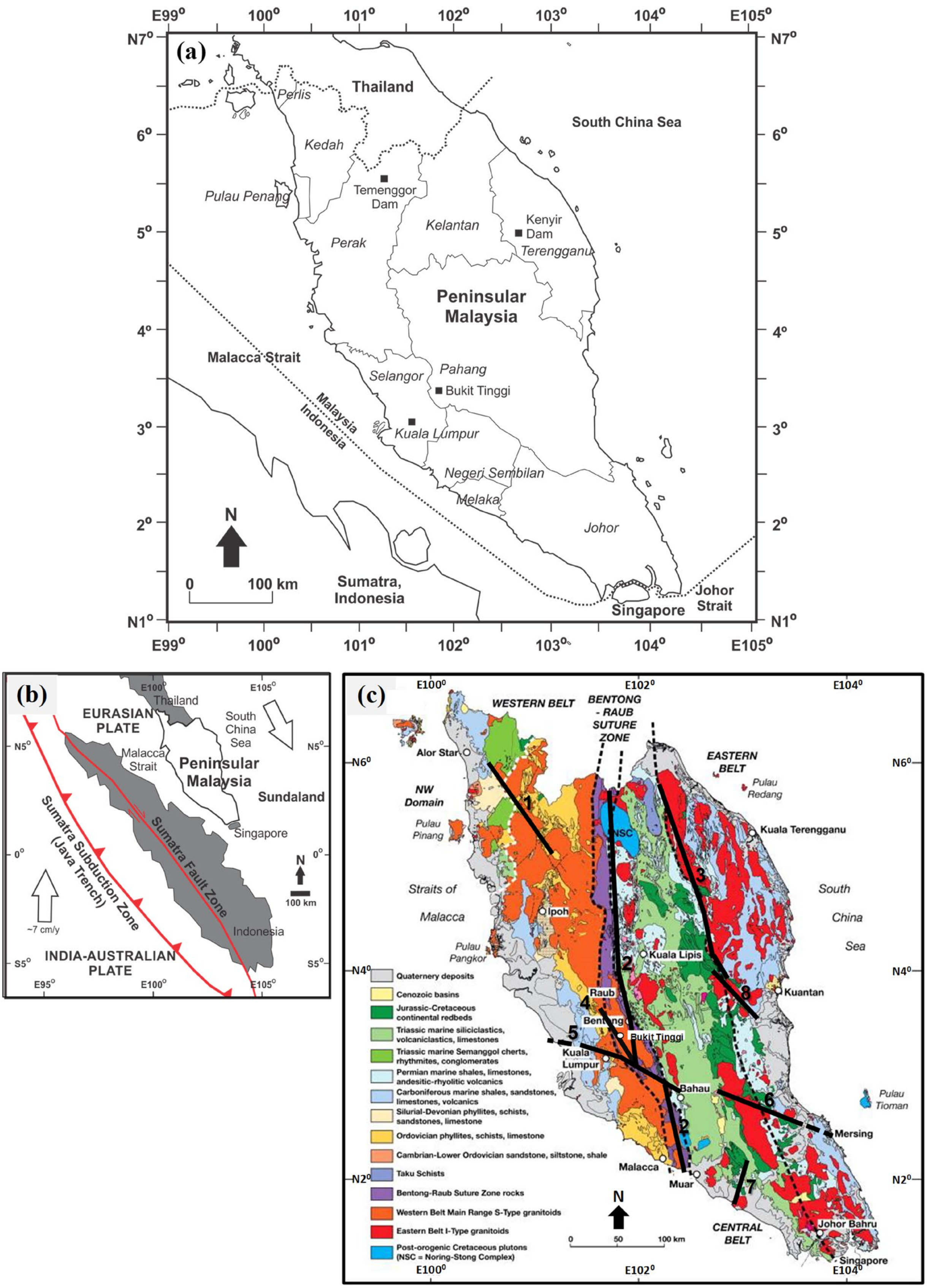
3 Data and methodology

3.1 Data sources

This study has been conducted based on all available earthquake data compiled from several international and national seismological centers for the study area, and no further data are available due to the nature of the seismicity of Peninsular Malaysia. With all data available a comprehensive analysis was attempted. The earthquake catalog created for this study comprises data from following three databases: (a) International Seismological Centre (ISC), local earthquakes recorded from June 16, 1927 to February 26, 2020; (b) Malaysian Meteorological Department (MMD), November 30, 2007 to February 23, 2016; and (c) the European-Mediterranean Seismological Centre (EMSC), data as of February 17, 2019. Two earthquakes on January 31, 1922 and February 7, 1922 were added [26]. A total of 59 earthquakes have been retrieved within the Peninsular Malaysia region, which have occurred from 1922 to 2020. As many as 23 records were collected from the ISC Bulletin comprising earthquakes occurred in the region since 1927 and mostly before 2007 as well as several events between 2010 and 2020. ISC (http://www.isc.ac.uk/iscbulletin/search/bulletin/) collected earthquake data from several institutions from various countries, such as BMKG (Meteorological, Climatological, and Geophysical Agency, Indonesia), EIDC (Experimental International Data Center, USA), and IDC (International Data Center, Austria). The last event in 2019 was retrieved from EMSC through the link https://www.emsc-csem.org. The MMD has recorded 33 local earthquakes which occurred from 2007 to 2016.

For this study, digital seismograms of the 33 local earthquakes, which were recorded by totally 30 seismological stations scattered over Peninsular Malaysia, have been requested officially from MMD. From these 33 local events, this study analyzed digital seismograms (in MiniSEED) of 20 events which were recorded by at least three or more stations. As many as 13 events were recorded by less than three stations due to following possible reasons: (1) Other stations did not detect the events; (2) Other stations did not work at the time of such events; and (3) Other newer stations have not yet been finished at that time (MMD, personal communication).

The MMD (or MetMalaysia) is a government institution under the Ministry of Science, Technology and Innovation (MOSTI), which is responsible for the monitoring of earthquake activity in Malaysia. This agency is currently operating around 30 seismological stations in West Malaysia and 21 stations in East Malaysia, while its headquarter is in Petaling Jaya, Selangor (West Malaysia), operating as


(a)
Thailand
Perlis
Kedah
South China Sea
Temenggor Dam
Pulau Penang
Kenyir Dam
Kelantan
Perak
Terengganu
Peninsular Malaysia
Malacca Strait
Pahang
Selangor
Bukit Tinggi
Malaysia
Indonesia
Kuala Lumpur
Negeri Sembilan
Melaka
Johor
N
0 100 km
Sumatra, Indonesia
Singapore
Johor Strait
(b)
EURASIAN PLATE
Thailand
South China Sea
Malacca Strait
Peninsular Malaysia
Sundaland
Singapore
Sumatra Subduction Zone (Java Trench)
Sumatra Fault Zone
~7 cm/y
Indonesia
INDIA-AUSTRALIAN PLATE
100 km
(c)
WESTERN BELT
BENTONG - RAUB SUTURE ZONE
EASTERN BELT
Alor Star
NW Domain
Pulau Redang
Pulau Pinang
Kuala Terengganu
NSC
Straits of Malacca
South China Sea
Ipoh
Kuala Lipis
Pulau Pangkor
Kuantan
Raub
Bentong
Bukit Tinggi
Kuala Lumpur
Bahau
Pulau Tioman
Mersing
Malacca
Muar
Johor Bahru
Singapore
CENTRAL BELT
0 50 100 km
Quaternery deposits
Cenozoic basins
Jurassic-Cretaceous continental redbeds
Triassic marine siliciclastics, volcaniclastics, limestones
Triassic marine Semanggol cherts, rhythmites, conglomerates
Permian marine shales, limestones, andesitic-rhyolitic volcanics
Carboniferous marine shales, sandstones, limestones, volcanics
Silurial-Devonian phyllites, schists, sandstones, limestone
Ordovician phyllites, schists, limestone
Cambrian-Lower Ordovician sandstone, siltstone, shale
Taku Schists
Bentong-Raub Suture Zone rocks
Western Belt Main Range S-Type granitoids
Eastern Belt I-Type granitoids
Post-orogenic Cretaceous plutons (NSC = Noring-Stong Complex)

◂**Fig. 1** **a** Location map of Peninsular Malaysia; **b** regional tectonic setting of Peninsular Malaysia; **c** general geology of Peninsular Malaysia [24] with local faults, adopted from Tjia [20, 21], (1 = Bok Bak Fault; 2 = Kelau-Karak Fault; 3 = Lebir Fault; 4 = Bukit Tinggi Fault; 5 = Kuala Lumpur Fault; 6 = Mersing Fault; 7 = Ma Okil Fault; 8 = Lepar Fault). Note: Created with CorelDraw

the central recording site and the national seismological center as well. At each seismological station different sensor types were installed, three-component weak-motion seismometers or strong-motion accelerometers. All seismograms are digitally recorded at the seismological stations and transmitted in near real time to the central recording site for processing, analysis, and dissemination. Locations of all seismological stations used in this study are shown in Fig. 2, and their detailed information is given in the supplementary material, Table S1. Most of these stations are situated in the west coast of the peninsula which are closer to the seismically active Sumatra region and where major cities are located.

3.2 Methodology

Earthquake data in this study compiled from ISC, EMSC, and MMD databases were used as reported (Table S2). However, the available digital seismograms of 20 events recorded by at least three MMD stations have been reanalyzed using SEISAN software developed by Havskov and Ottemöller [27]. Seismogram analysis was conducted following routine earthquake data processing [28, 29] to recalculate relevant parameters including origin time, magnitude, location, and focal depth (hypocenter). This study used the IASP91 velocity model by Kennett and Engdahl [30] since the structure of crust and upper mantle beneath Peninsular Malaysia are not precisely studied yet.

For the determination of the hypocenter locations all possible phases, P and S, in the available seismograms were identified and their arrival times picked by hand. Hence, P was the most unambiguous phase to pick; however, all possible S-phases were also identified and their arrival times picked by hand; not calculated by SEISAN from the Vp/Vs ratio of the velocity model [31]. The average number of phases picked for one event was 27, with a minimum of six (here only data from three stations; 2 events) and a maximum of 31 (more than five stations). Picking of the S-phase was done quite carefully as it has a larger influence on the location than the P-phase due to its lower velocity [28]. For all phases, the picking itself is inherently associated with an uncertainty in the phase arrival times, which will lead to errors in the resulting event locations [32]. Closer stations to the epicenter however usually provide more accurate data than stations farther away [28], which especially applies for the larger Bukit Tinggi–Kuala Lumpur zone. Another error is related to the velocity model of the layered Earth used, which might be not reflecting true ground. However, especially for the

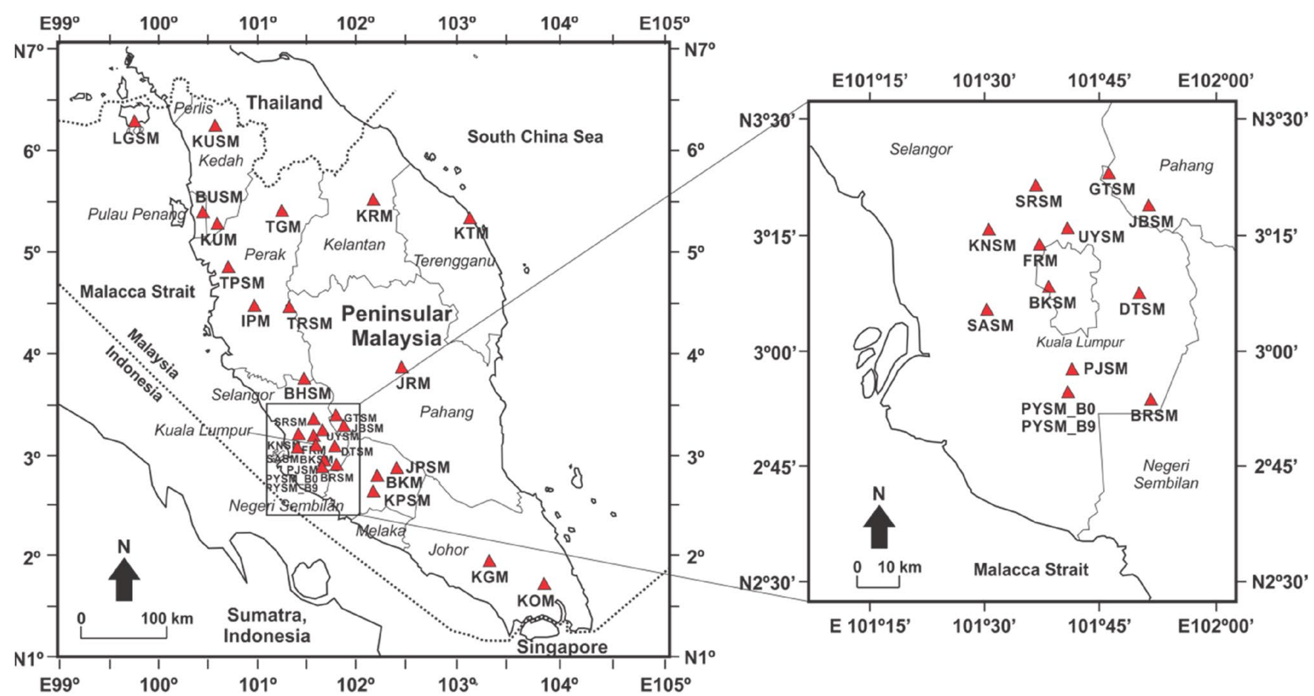


Fig. 2 Location map of all permanent, local seismological stations used in this study to monitor earthquakes in Peninsular Malaysia during 2007–2016. Triangles indicate locations of seismological stations operated by MMD (MetMalaysia). Note: Created with CorelDraw

depth determination uncertainties in the local velocity model have less effect on the results for events at shorter distances to seismic stations than at larger ones [28]. The hypocenter location was determined with the HPYOCENTER software in SEISAN. It is using the Jacobi method for matrix inversion with centered, scaled, and adaptively damped least squares [32]. For the location estimation the least squares solution looks for a minimum of the sum of the squared residuals from the number of phases or observations used. RMS, the root means square value, is commonly used as parameter for the location accuracy. Here, the average RMS value for all 20 stations is 0.44 with a range from 0.13 to 0.85. However, a low RMS value does not necessarily indicate a 'good' hypocenter depth. HYPOCENTER also provides errors in latitude, longitude, and depth (all in km). The maximal depth error was 8.3 km for an estimated depth of 9.4 km (event 23, Table S3). A further indicator of the reliability of the hypocenter inversion is the minimum RMS test [31]. The derived DRMS values (D for distance, d) indicate changes in RMS relative to the hypocenter when the hypocenter is moved 5 km up (+), down (–), east (+), west (–), north (+), or south (–). The average value of all 20 events for depth-d (minus d) is 0.04 (max. 0.25) and for depth + d (plus d) 0.07 (max 0.27).

Magnitude nomenclature is following IASPEI [33]. According to [28], the local magnitude (ML) is for earthquakes with magnitudes less than 6–7 and distances < 1500 km, meanwhile the body-wave magnitude (mb) is for teleseismic earthquakes with magnitudes < 7 and distances 20°–100°, the surface-wave magnitude (Ms) is for teleseismic recordings of surface waves with magnitudes up to 8 and distances 20°–160°, and the moment magnitude (Mw) is for any earthquake at any distance. There are two historical events in 1922 reported in the intensity magnitude (M_I), which according to [34] is the magnitude determined from seismic intensity data.

The ML calculation of the MMD standard procedure is similar to the original ML using the following formula:

$$\mathrm{ML} = \log A_{\max} - \log A_0. \tag{1}$$

where $A_{\max}$ (in mm) is the maximum amplitude in a Wood–Anderson seismogram, and A_0 (in mm) is the empirical calibration function, which is a function of epicentral distance. This ML calculation used the magnification of Wood–Anderson of 2080 [35]. The calibration function has been configured for Peninsular Malaysia using following fixed interval corner values (MMD, personal communication): at 0 km: – 1.3; at 60 km: – 2.8; at 400 km: – 4.5; and at 1000 km: – 5.85. Within each interval, values are computed by linear interpolation, e.g., at a epicentral distance of 100 km, the log A_0 would be ((– 4.5) – (– 2.8)) × (100 – 60)/(400 – 60) – 2.8 = -3.0. Therefore, at 100 km distance, the ML would be log $A_{\max}$ – (– 3) or log $A_{\max}$ + 3.

In this study, most of events were reported in ML and only some events from ISC database were reported in mb. Two events were reported in M_I which is equal in the mean to Mw [34]. For uniformity, all magnitudes (ML and mb) were converted to Mw following Kanamori [36]. From Kanamori's graphs, it is observed that for ML = 4–6, Mw = ML, however, for smaller ML (ML < 2–4), Mw ≈ 0.67 ML [27]. Meanwhile, to convert mb to Mw, Ismaili and Majid [37] developed empirical relationships for magnitude conversion specifically for Malaysia using regression method and the relationship of Ms, mb, and Mw as following:

$$Ms = 1.1198mb - 0.7796. \tag{2}$$

and

$$Mw = 0.8693Ms + 0.9135 \tag{3}$$

From Eq. (2) and (3), mb can be converted into Mw by the as following:

$$Mw = 0.9734mb + 0.2358. \tag{4}$$

Earthquake origin time (yyyy-mm-dd hh:mm:ss) is in Universal Time Coordinates (UTC), with Malaysia time being UTC + 8. The epicenter coordinate is in decimal degrees (DD), and focal depth is in kilometer (km). Spatial distribution of all earthquakes was displayed laterally by using the epicenter map and vertically by using depth profiles of seismicity in the region, and the magnitude variation was displayed in a frequency–magnitude histogram.

In order to relate the earthquake distribution with known geological structures in the area, major faults and fault zones were drawn after Tjia [20, 21]. Further, SRTM–DEM images of Peninsular Malaysia were analyzed to depict lineaments, which might be interpreted but not confirmed as possible fault lines in the study area as no ground control was done or available.

4 Results

During the past almost 100 years, 1922 to 2020, there were 59 earthquakes reported within the Peninsular Malaysia region (see Fig. 3, Tables S2 and S3). The first two historical earthquakes were reported by Martin et al. [26] which occurred in the southern part of the region; however, all information were estimated based on intensity observations, and no depth values are available. Event no. 3 in the earthquake catalog of this study (1927-06-16) was reported by the International Seismological Summary (ISS, a global earthquake catalog covering the period from 1918 to 1963 and published as the ISC Bulletin since 1964),

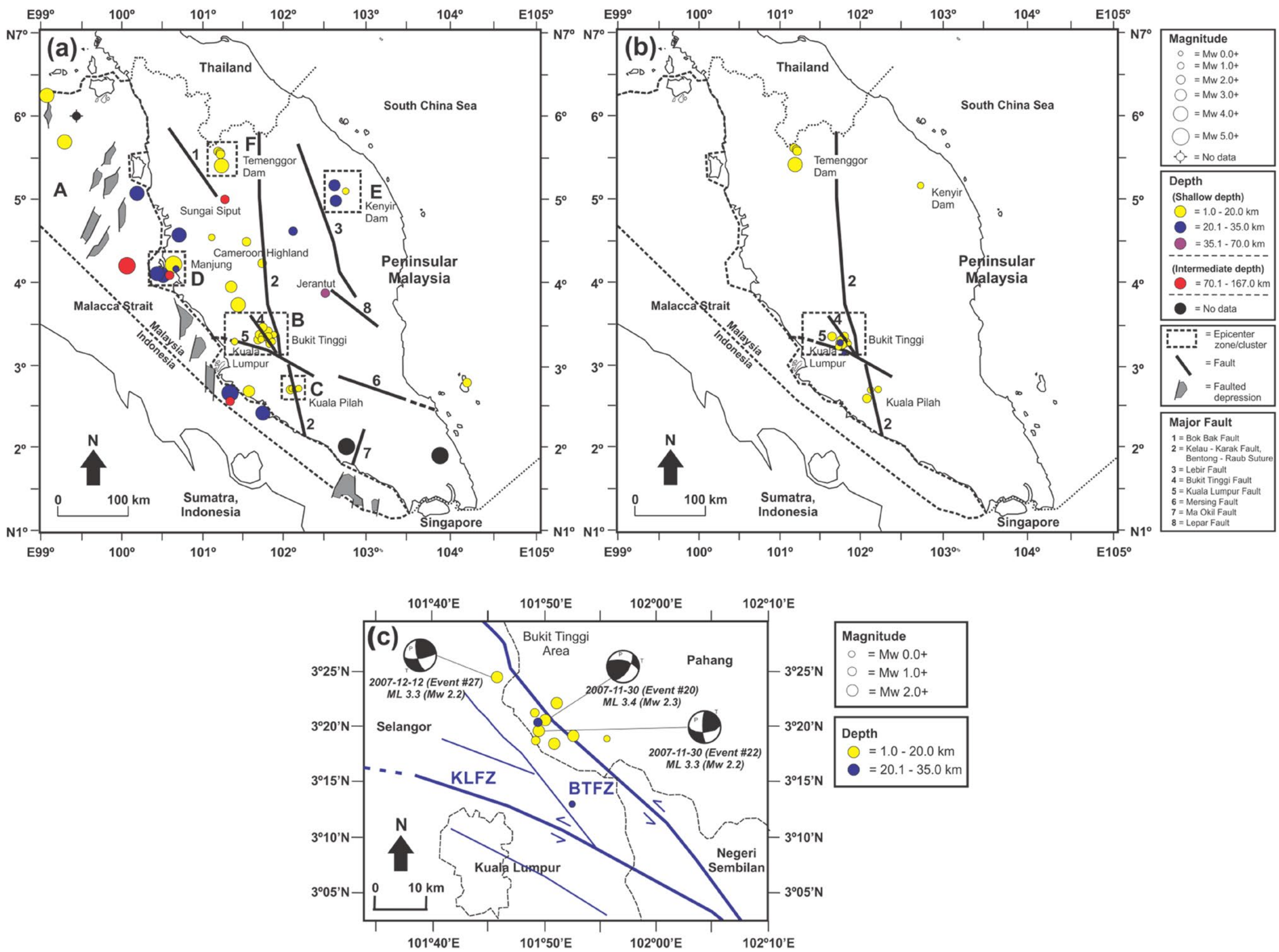


Fig. 3 **a** Epicenter map of Peninsular Malaysia shows the spatial distribution of recorded earthquakes from several international and national agencies during 1922–2020 in relation to the Mw (symbolized by dots with different sizes) and focal depth (symbolized by different colors). Zones of earthquake epicenters are symbolized by A to F: A = Malacca Strait zone; B = Bukit Tinggi–Kuala Lumpur zone; C = Kuala Pilah zone; D = Manjung zone; E = Kenyir Dam zone; and F = Temenggor Dam zone. **b** Epicenter distribution resulted from re-analysis of seismograms (obtained from MMD) in this study; and **c** detailed epicenter distribution of BTFZ and KLFZ as the result of relocation of several local earthquakes with a few focal mechanisms determined by [64]; Geological structures onshore and offshore Peninsular Malaysia were obtained from [20, 21] and [43], respectively; (BTFZ = Bukit Tinggi Fault Zone, KLFZ = Kuala Lumpur Fault Zone). Note: Created with CorelDraw

and was labeled 'with poor determination'. Other events were reported by ISC, EMSC, and MMD. 20 events with seismograms from MMD were reanalyzed in this study. A comparison of location estimates of this study with MMD data for the locations as well for the depth values of these earthquakes indicates in general similarities but with some events differ. Maximum deviation in longitude and latitude distance was 0.61 degrees. For the depth solutions some events show significant differences, e.g., no 54, with 1 km depth for this study and 15.3 km from MMD. However, MMD did not provide any error values for their hypocenter locations. Information of all events is summarized in the supplementary material, Tables S2 and S3.

Based on the data available, time occurrences of earthquake show no certain pattern or trend. The earthquake distribution was subsequently zoned based on the distribution of epicenter locations for seismic hazard assessment [38]. Earthquake occurrence and possible sources are discussed for each zone in the following section.

5 Discussion

The 59 earthquake data used in this study were collected from various sources with only 20 of them reanalyzed here based on available seismograms. All earthquake parameters naturally and inherently contain errors as outlined in Sect. 3.2 due to phase picking and uncertainties in the velocity model used, with likely different models used over time. For 39 events, error data are sparse or not available.

For the 20 reanalyzed events, location processing results also indicate errors but they are reasonably small regarding the objective of this study. Some depth values show significant difference between this study and MMD, but as MMD did not provide any error data, an improvement in hypocenter location cannot be documented here.

For Peninsular Malaysia in general, earthquake epicenters were found both onshore and offshore as shown in the epicenter map (Fig. 3a) with a dominant occurrence in the western and northern part. Meanwhile, earthquake records in the eastern and southern parts are sparse. Gill et al. [39] and Yong et al. [40] supported these evidences by their analyses on the tectonic deformation by using GPS data and revealed that due to large magnitude regional earthquakes the average displacements of the northern (NW and NE) and central west of Peninsular Malaysia were higher than its southern and central east parts.

For the geological interpretation of the earthquake occurrence six zones were delineated from the spatial distribution of earthquakes in Peninsular Malaysia (Fig. 3a). Four of them are zones of local tectonic earthquakes where a number of earthquakes were located in the vicinity of known fault zones, which have the potential to be reactivated and become sources of intraplate earthquakes, e.g., [41]. Meanwhile, two other zones are considered to enclose reservoir-induced earthquakes where epicenters were located below two larger man-made reservoirs in the region, i.e., the Kenyir Dam in Terengganu and the Temenggor Dam in Perak (Fig. 1a). Gibson and Sandiford [42] revealed that this type of earthquake is triggered by groundwater pore pressure increase due to the reservoir loading; compression under the weight of the reservoir water. Although there are a number of mines and quarries in the region, there are no specific records of mining-induced earthquakes so far.

Many researchers believed that fault reactivations in Peninsular Malaysia are associated with several major earthquakes near Sumatra. According to [19] and [22], local (intraplate) earthquakes, which occurred in Bukit Tinggi area (between November 30, 2007 to May 25, 2008 and October 7–8, 2009), Jerantut area (March 27, 2009), Manjung area (April 29, 2009 and February 13, 2013), and Kuala Pilah area (November 29–30, 2009) (Fig. 3a) were considered as indications of the reactivation of major faults/fault zones in the region, which were associated with several major earthquakes along the Sumatra Subduction Zone, such as the Mw 9.2 Sumatra-Andaman Earthquake (December 26, 2004), the Mw 8.6 Nias Earthquake (March 28, 2005), the Mw 8.4 Bengkulu Earthquake (September 12, 2007), and the Mw 7.6 Southern Sumatra Earthquake (September 30, 2009).

Intraplate earthquakes exhibit differences from interplate earthquakes in terms of their distribution of epicenters and depths of foci. Epicenters of interplate earthquakes concentrate along the plate boundaries,

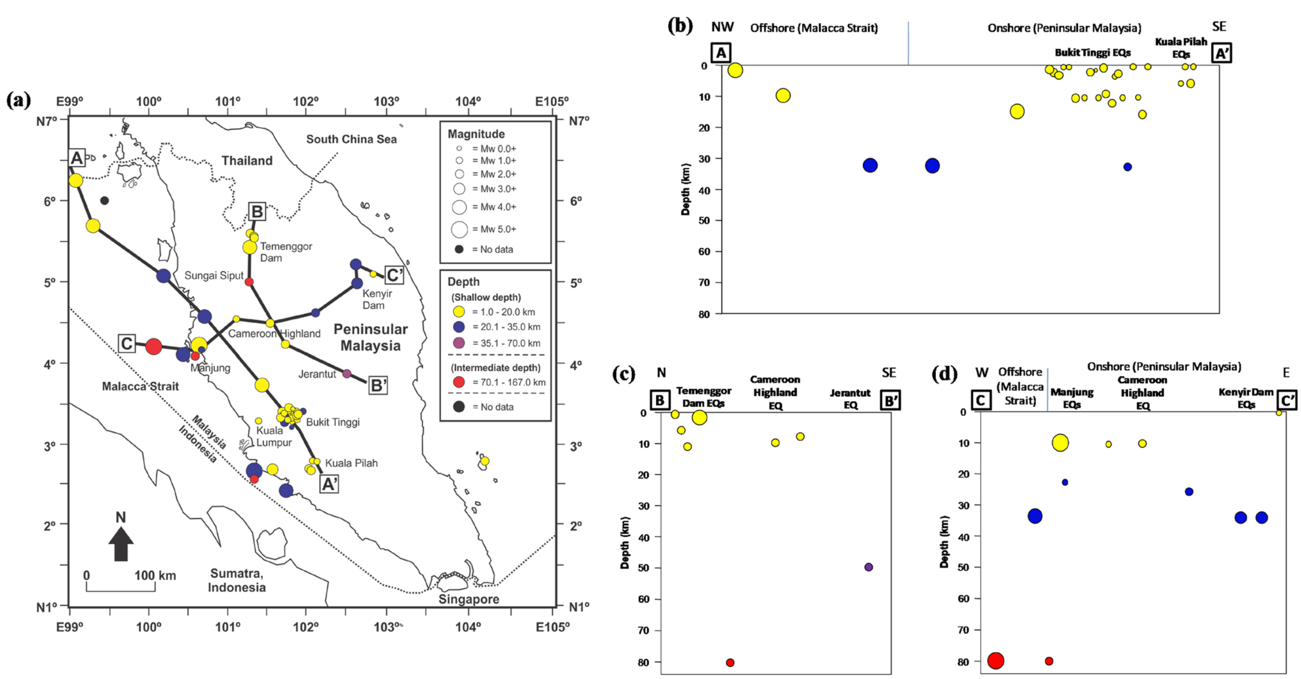


Fig. 4 Vertical sections of focal depth distribution in Peninsular Malaysia during the period 1922–2020. **a** Epicenter map with three cross sections (A–A′, B–B′, and C–C′). **b** Depth profile A–A′ with the trend NW–SE. **c** Depth profile B–B′ with the trend N–S–SE; and **d** depth profile C–C′ with the trend W–E. Note: Created with CorelDraw

where at subduction zones their hypocenters image the subducting slab. For intraplate earthquakes, like in this study, it can be observed that the earthquake epicenters in Peninsular Malaysia are scattered spatially and do not concentrate only along fault lines, and their focal depths are mostly shallow (0–70 km) (Fig. 4). Liu et al. [44] provided a conceptual model for these differences. For interplate earthquakes, the interaction between plates at a constant rate causes earthquakes to concentrate along the plate boundary. However, for intraplate earthquakes, the regional tectonic loading is shared by a complex system of preexisting faults where the loading rate may be variable on each fault causing earthquakes may quit on a fault and/or migrate to another fault.

In terms of focal depth, earthquakes can be divided into shallow earthquakes (0–70 km), intermediate earthquakes (71–300 km), and deep earthquakes (301–700 km) [45]. Here, the depths are min. 1 km and max. 167 km, with most earthquakes have shallow depths of 1 to 20 km (symbolized by yellow dots in the epicenter map) scattered in all spatial zones in and around faults/fault zones. Epicenters with the depth more than 20 km to 35 km (symbolized by dark blue dots in the epicenter map) are distributed randomly along fault zones, but also beyond. Focal depths of more than 35–70 km (indicated by purple dots in the epicenter map) occurred only once, which was in Jerantut area and was related to the Lepar Fault. In this region, intermediate earthquakes occurred in the range more than 70 km to 167 km (symbolized by red dots in the epicenter map) located in four different localities, including in the Malacca Strait. There are three events (event no. 1 to 3; occurred in 1922 and 1927) with no report of the focal depth due to the poor determination. The September 25, 1992 earthquake located in offshore Selangor (in the Malacca Strait) occurred in the focal depth of 167 km, the maximum depth of hypocenter has recorded in the region so far.

Several former studies on the crustal thickness beneath Peninsular Malaysia revealed that the region has an average crustal thickness of around 30–35 km [46, 47]; thinning in the NW and in western parts (28–32 km), thickening in the southern part (30–35 km), and around 31 km in the central part, with the lithosphere–asthenosphere boundary in this region at around 70 km depth [48–50]. Therefore, local earthquakes of this region occurred in the hypocenter more than the crustal thickness (> 35 km) are considered as upper-mantle earthquakes. According to Goldbaum [51], intraplate earthquakes, which occur inside instead of at the boundaries of the plates can be affected by the convection of the molten mantle beneath the crust. The convecting mantle causes convection currents to flow slowly within it and pushes the overlying rocks in the crust causing tremors.

Following sections discuss correlations between spatial earthquake zones/clusters and local geological structures.

5.1 Malacca strait (Zone A)

Although the shallow Malacca Strait was considered of less to no tectonic significance [52], ten earthquakes have been recorded to occur in the strait (Figs. 3a and 4), mostly during the period 1927 to 1998 and one event of the latest record of this study (2019-02-17). Magnitudes of earthquakes in this area were recorded in the ranges of Mw 2.1–5.0. Meanwhile, the focal depths were recorded in between 1 and 167 km; 167 km is the deepest hypocenter in Peninsular Malaysia reported so far.

In an intraplate region like Peninsular Malaysia, it is very likely to have local earthquakes with shallow crustal depths. However, deeper earthquakes are still possible to occur in the region, mainly in the Malacca Strait due to its location within the intra slab of the SSZ. The seismicity map of the SSZ and its surrounding region obtained from the USGS Earthquake Catalog (https://earthquake.usgs.gov/earthquakes/search) shows focal depth zones revealing that deeper hypocenters are generally distributed in the subducting slab areas (Fig. 5a). Analysis of seismic tomography [53–57] suggested that the subducting slab of the SSZ extends beneath Peninsular Malaysia at upper mantle depths (more than 600 km). Epicenter locations of the ML 4.8, 2004-04-29 (2.5297°N, 101.5516°E) and ML 3.1, 1992-11-02 (2.1000°N, 101.1000°E) earthquakes in Malacca Strait of Indonesia territory with depths of 220 km and 235 km (indicated by Y and Z in Fig. 5b, respectively) indicate the earthquakes occurred in the subducting slab. Meanwhile, slab detachment (breakoff) can also be observed from tomographic images in Liu et al. [56, 57] further east of the subduction slab at relative shallower depths. In a profile from Sumatra (Indonesia) through Peninsular Malaysia in SW-NE direction [57] (Fig. 5b), the ML 3.1, 1992-09-25 earthquake as indicated by X (2.6291°N, 101.3829°E) in the Malacca Strait of Malaysia territory with a focal depth of 167 km lies well within the slab detachment. Therefore, it is very likely that deeper earthquakes (focal depths more than shallow crustal depths) can occur in Peninsular Malaysia, but likely of lower magnitude as they are not part of the active subducting slab of the SSZ further southwest. Epicenter distances between X, Y, and Z are less than 100 km.

The reactivation of faults is another important factor that contributes to earthquakes in the strait. According to [21, 43], the Malacca Strait in Malaysia territory consists

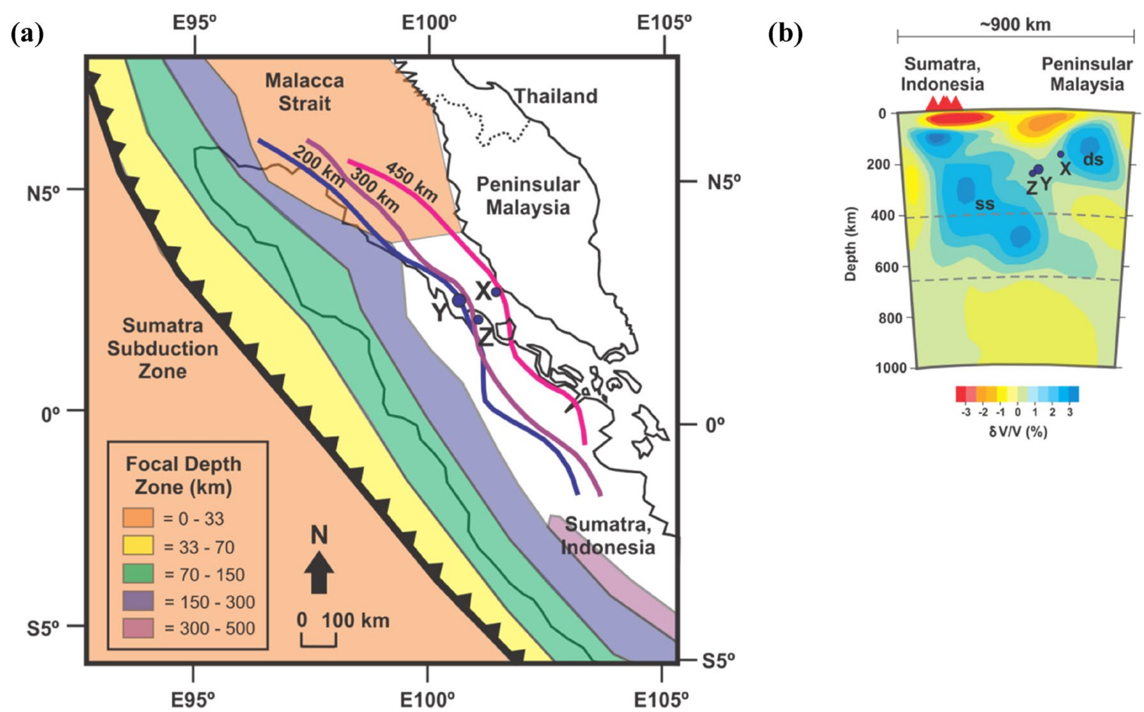


Fig. 5 Deeper earthquakes. **a** Focal depth zones in the SSZ and its surrounding regions (over the period 100 years: 1919–2019; redrawn from the seismicity map obtained from USGS Earthquake Catalog, https://earthquake.usgs.gov/earthquakes/search) with slab contours at selected depths redrawn from Liu et al. [57] indicating the subducting slab morphology beneath northern Sumatra until Peninsular Malaysia. **b** Vertical cross section of one of P-wave tomographic images reproduced from Fig. 9 in Liu et al. [51]. X indicates the location of the deepest (167 km) local earthquake offshore Peninsular Malaysia (ML 3.1, 1992-09-25 earthquake); meanwhile, Y and Z are locations of two nearby earthquakes in the Malacca Strait of Indonesian territory, the 2004-04-29 (ML 4.8) and 1992-11-02 (ML 3.1) earthquakes, which have focal depths of 220 km and 235 km, respectively. "ss" is the subducting slab, while "ds" is the detached slab. Earthquake data occurred in the Malacca Strait both in Malaysia and Indonesian territories were obtained from ISC Online Bulletin (http://www.isc.ac.uk/iscbulletin/search/bulletin/). Note: Created with CorelDraw

of at least 15 small, faulted depressions, i.e., grabens and half-grabens (see Fig. 3a) in the pre-Tertiary basement, which were produced by the regional tension in the Late Oligocene. In addition, submarine landslides are assumed to be another cause of earthquakes, mainly shallow earthquakes occurred in the strait. Lin et al. [58] studied submarine landslides along the Malacca Strait–Mergui Basin shelf margin and revealed some mechanisms of underwater landslides in the strait area. During periods of low sea level (sea level low stands), slumping occurred when a large amount of sediments were being deposited onto the shelf margin (the Malacca Strait). Such rapid and huge accumulations result in high pore pressures in the unconsolidated, young sediments triggering submarine landslides along the strait. Another precondition for submarine landslides in the strait is the existence of regionally, parallel-bedded, clay-rich sediment sequences as potential slide surfaces supporting slope failure. More precipitation process due to the higher Asian monsoon intensity leads to higher rates of erosion and sediment influx triggering underwater landslides. In additions, strong earthquakes from other areas may also trigger landslides in the Strait.

5.2 Bukit Tinggi–Kuala Lumpur fault zones (BTFZ and KLFZ; Zone B)

Among the seismogenic faults/fault zones, the BTFZ and KLFZ have received much attention lately because of the occurrences of several local earthquakes in between and around the two fault zones (Fig. 6). These two major fault zones are considered as the most active fault zones in Peninsular Malaysia. The BTFZ is a NW–SE trending, left lateral (sinistral) strike-slip fault zone with fault strikes 310–325 and a width of about 7 km. Field observations of this fault zone show evidences of faulting such as steep escarpment, deformed alluvium, linear scarp, and abandoned sigmoidal stream. This fault zone consists of mylonite, fractured granite, and large quartz dykes for a distance of 110 km from Kuala Kubu Bharu (Selangor) in NW to Bahau (Negeri Sembilan) in SE. The fault zone is interpreted to have a displacement of two kilometers from the disposition of the granite bodies on either side of the lineament. South of the BTFZ, the KLFZ elongates with a length of more than 60 km and a width of 15 km, extending around Kuala Lumpur and Kajang (Selangor). SE- and SSE-striking faults are

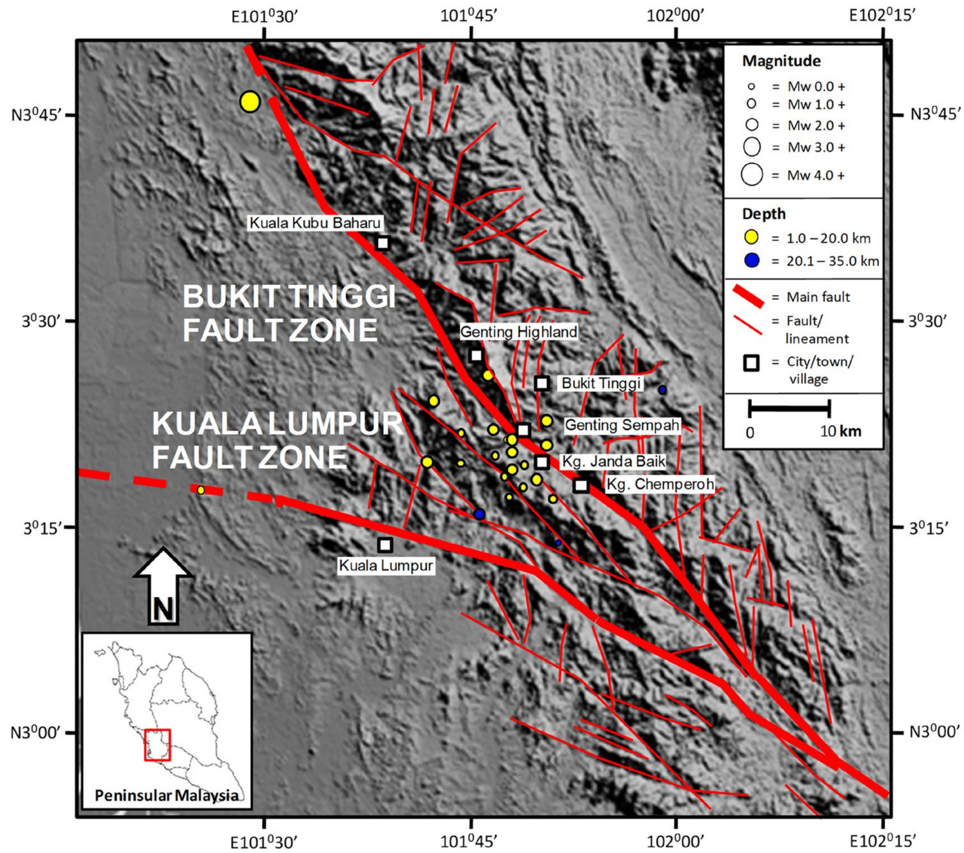


Fig. 6 SRTM–DEM image of Bukit Tinggiand Kuala Lumpur Fault Zones with the earthquake distribution in between and around these two most active seismogenic faults in Peninsular Malaysia. Red thicker lines indicate main known faults; while red thinner lines are lineaments indicating possible faults. Note: Created with CorelDraw

dominant in this fault zone and are frequently filled with vein quartz. The largest of these quartz dykes is the Klang Gate Quartz Ridge standing out around 250 m from the surface. This fault zone has 13 km left-lateral offsets which are shown by some rocks, such as the Main Range Granite, the Bentong Group, and others [19, 59]. The KLFZ can be traced westward into the Malacca Strait [60]. Rahim et al. [19] and Shuib et al. [22] used IFSAR (interferometric synthetic aperture radar) data and field verifications to provide evidences for active faulting of this zone, such as: (1) The fault zone displays geomorphic features indicative of recent fault activity, such as steep-sided Quaternary alluvial basins, triangular facets, steep scarps, shifted streams etc.; (2) It shows displacements in young (Late Quaternary) deposits; and (3) It is associated with a pattern of micro earthquakes.

Structural analysis conducted on the SRTM–DEM image shows the distribution of Bukit Tinggi and Kuala Lumpur Faults and a number of intersecting conjugate faults/lineaments in the vicinity of these two main faults with several trends: N–S, W–E, NW–SE, NE–SW, WNW–ESE, and NNE–SSW (Fig. 6). Fatt et al. [18] stated that the Bukit Tinggi Fault and Kuala Lumpur Fault are NW–SE-striking faults and dipping toward NE and SW, respectively. Shuib [61] studied the 2007–2008 earthquakes in BTFZ and KLFZ, especially in Bukit Tinggi area, and revealed that there are high concentrations of faults and hot springs in the area. Raj [62] studied several quaternary faults from outcrops in Kuala Lumpur–Karak Highway which are probably related to quaternary activity or movement of faults in Bukit Tinggi area. Evidence of paleoseismic activities in Bukit Tinggi area was also disclosed by [63] who described the fault rocks and other materials related to dislocation along fault planes.

The highest number of tectonic earthquakes in Peninsular Malaysia was found in this zone. There were 22 local earthquakes that occurred so far in Bukit Tinggi area (along the boundary of Selangor–Pahang states), where nine earthquakes were recorded in 2007, eight events in 2008, and five events in 2009. The epicenters are aligned on, in between and around the BTFZ and KLFZ or located in an area within the latitude of 3°15′N–3°50′N and the longitude of 101°20′ E–102°00′ E (Fig. 6). Local magnitude values range from ML 1.0 to 3.6 (Mw 0.7–2.4), where the magnitude ML 1.0 (Mw 0.7) being the lowest magnitude detected in Peninsular Malaysia so far. Meanwhile, focal depths are ranging from 1 to 32 km. Most earthquakes occurred along and in between the faults/lineaments which correspond to those fault zones. Shuib [61] explained the cause of the earthquakes in these fault zones as a reactivation of preexisting faults. The stress build-up in this region is related to the recent tectonics in

SE Asia (Sundaland), mainly the subduction of the Indo-Australian Plate under the Sundaland (Eurasian Plate). Lat and Ibrahim [6] elaborated several mechanisms of the reactivation of these seismogenic faults/fault zones: firstly, the extensional movement of Sundaland toward the west on top of the Indo-Australian Plate causing a weak zone to rupture; secondly, the compressional movement of the Indo-Australian Plate toward the Sundaland, which increases stress in the Peninsular Malaysia; and thirdly, effects of the 2004 Sumatra-Andaman Earthquake, which resulted in an increasing trend of seismicity in the SE Asia region due to lithosphere deformation/relaxation.

In Bukit Tinggi–Kuala Lumpur area focal mechanisms of four local earthquakes were determined by [64] (Fig. 3b) by using polarity data of the first motions of P and S waves and their amplitude ratios. Table 1 provides the values of the dip, strike, and rake angles for both fault planes (FP1, FP2) for all four events. Although according to [64] the analysis obtained relatively well-constrained solutions, a comparison of the nodal planes with the fault orientations and the strike of the Bukit Tinggi fault and the Kuala Lumpur fault were not clear [64].

Earthquakes occurred in these fault zones were felt in some nearby areas such as Genting Highland, Bukit Tinggi, Genting Sempah, Kampung Janda Baik, and Kampung Chemperoh. Local residents were reportedly feeling the tremors after they heard loud noises. Others felt the ground shaking and rolling. However, there is no any surface trace of rupture or any surface movement correspond to fault activity has been revealed in this area [6]. Shuib [60] described that the similarity among the intraplate earthquakes is that there are a lack of surface ruptures. Shoushtari et al. [65] observed that there were several cracks at the police headquarters and secondary school buildings in Bukit Tinggi area as a result of these tremors.

5.3 Kuala Pilah area (Zone C)

Kuala Pilah (in the state of Negeri Sembilan) is located at the elongation of the Bentong–Raub Suture Zone, one of the major structural zones in Peninsular Malaysia, and is also close to the Seremban Fault Zone, one of fault systems in the region. Lineament analysis using the SRTM–DEM image combined with epicenter locations (Fig. 7) revealed that four local earthquakes which occurred during November 29–30, 2009, near Kuala Pilah area apparently correspond to both structural zones. Magnitudes of these events are ML 2.8–3.1 (Mw 1.9–2.1) and the focal depths are 1–7 km.

The Bentong–Raub suture zone is the boundary between the Sibumasu (Western Belt of Peninsular Malaysia) and Indochina (Central and Eastern Belts of Peninsular Malaysia) continental terranes. The N–S trending suture zone extends from Thailand in the north to the south through Raub and Bentong, two towns in the state of Pahang. This suture zone represents the part of the Paleo–Tethys before the collision of the Sibumasu and Indochina terranes of SE Asia [66]. Meanwhile, the Seremban Fault Zone is a curvilinear NW–SE striking fault zone which lies within the granite intrusion of the Western Belt in the south of KLFZ [67]. Shuib [60] elaborated that the fault shows a distinct sinistral strike-slip displacement. The fault zone passes through the city of Seremban (in the state of Negeri Sembilan).

5.4 Manjung area (Zone D)

Based on MMD database, Manjung area, one of coastal areas in the south of Perak state, was hit by a mild tremor of ML 2.5 (Mw 1.7) on April 29, 2009, at 13:53:54 UTC. ISC database shows that another earthquake with the higher magnitude (mb 5.1 = Mw 5.2) occurred in the area on February 13, 2013, at 05:10:53:50 UTC. Further, the ISC database also shows that there were previously two

Table 1 Focal mechanism determination with dip, strike, and rake angles for the two fault plane solutions (FP1 and FP2) for four earthquake events; from [64]

Event no	Origin time (UTC) (yyyy-mm-dd hh:mm:ss)	FP 1 dip (degree)	FP 1 strike (degree)	FP 1 rake (degree)	FP 2 dip (degree)	FP 2 strike (degree)	FP 2 rake (degree)
20	2007-11-30 02:13:00	45–75	010–060	20–50	50–70	270–310	130–170
22	2007-11-30 12:42:00	72–85	170–190	(−40)-0	58–82	080–110	(180)-(−160)
27	2007-12-12 10:01:00	70–82	150–180	(−10)-(−40)	55–80	070–090	(−150)-(−180)
29	2008-01-10 15:38:00	80–85	170–180	(−10)-(−20)	75–80	090–100	(−170)-(−180)

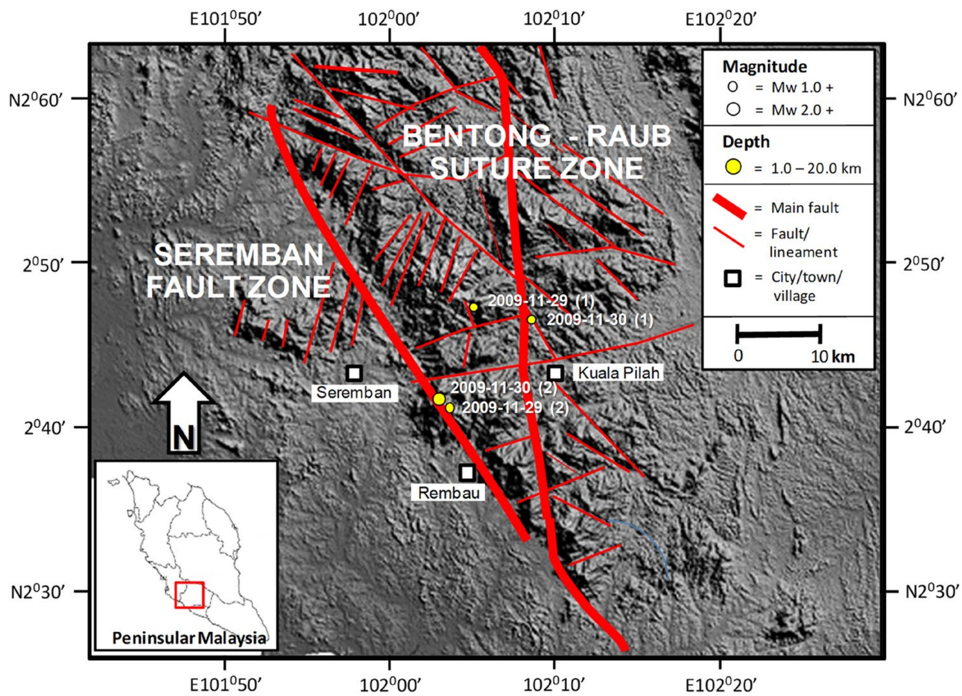


Fig. 7 Four local earthquakes, which occurred on November 29 and 30, 2009, were plotted on SRTM–DEM image of Seremban-Kuala Pilah area. These events were interpreted as the result of the reactivation of the Bentong–Raub Suture Zone and Seremban Fault Zone. Red thicker lines indicate known main faults, while red thinner lines are lineaments indicating possible faults. Note: Created with CorelDraw

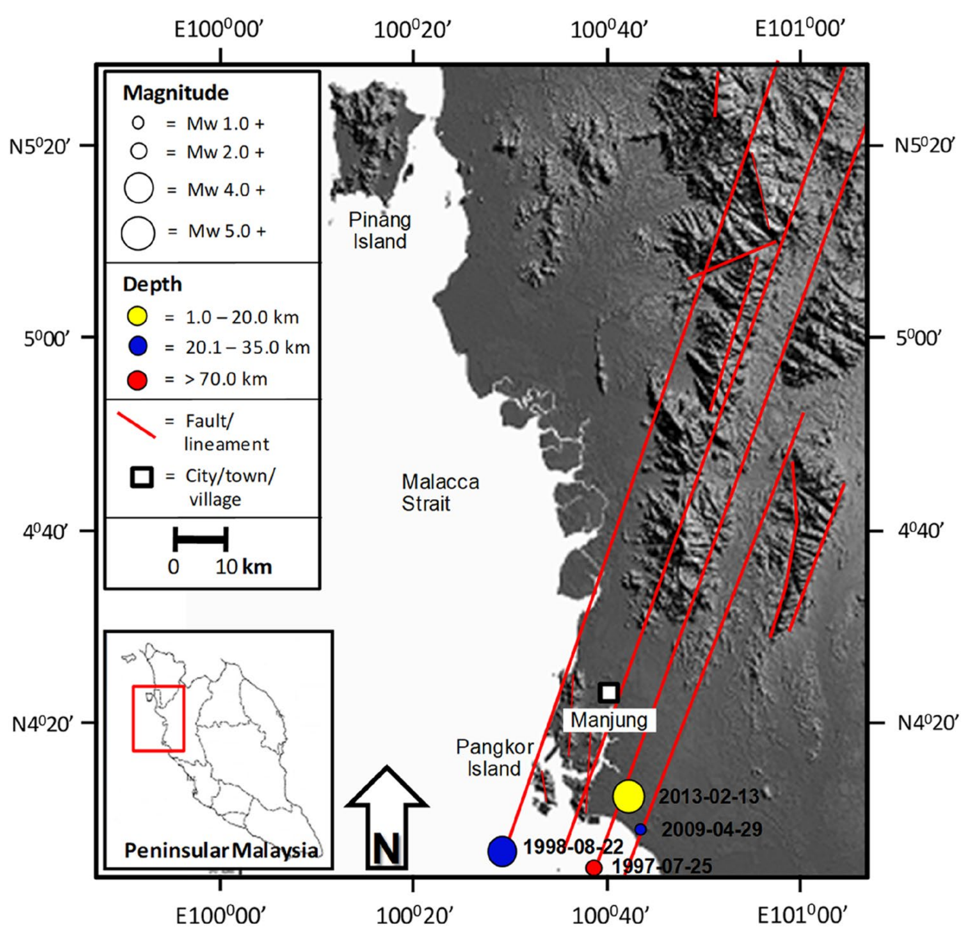


Fig. 8 Plot of earthquake epicenters during the studied period on the SRTM–DEM image in Manjung area. Red thinner lines here are lineaments indicating possible faults. Note: Created with CorelDraw

earthquake events which occurred in offshore Manjung area in the Malacca Strait on July 25, 1997, with ML 3.9 (Mw 2.6) and on August 22, 1998 ML4.1 (Mw 4.1).

Based on the lineament analysis using the SRTM–DEM image and combined with the epicenter distribution in this area, it might be interpreted that the earthquakes in Manjung area occurred parallel to faults with a NE–SW trend (Fig. 8). Manjung and its vicinity are surrounded by coastal plains composed of quaternary deposits, so that active faults in Manjung area can be considered as the prolongation of active faults in the NE area.

A previous study by Shuib et al. [68] identified active faults by using remote sensing, geophysics, geomorphology, and geological mapping and showed that there are several lineament sets with the NE-SW and N-S trends displaying evidences of Quaternary movements in this coastal area. There were few earthquakes with epicenters around onshore and offshore Manjung area. To confirm a possible correlation between structural trends and epicenter distribution in this area as shown in Fig. 8 more earthquake data would be needed.

5.5 Kenyir Dam area (Zone E)

The Kenyir Dam is located in Kuala Berang area in the upstream Terengganu state, NE of Peninsular Malaysia. Its construction was started in 1978 and completed in 1985. This dam is the location where the first reservoir-induced earthquake occurred in the region in 1985 after the establishment of the dam. This rock-fill dam is the largest reservoir in Malaysia and in SE Asia covering an area of 370 km^2 with the maximum water depth of 125 m and is underlie by granite [69, 70]. The Kenyir Dam started filling up in 1984 and there was a series of light earthquakes due to the water impounding processes in 1985 [18]. According to Lat [8, 9, 71], a total of 27 tremors from the dam site occurred during 1985–1987 with the magnitude ranging from mb 2.5 to 4.6. The dam was built with a height of 150 m and a storage capacity of 13.6 km^3 in a previously aseismic area. Tremors from this area can be felt at a distance of more than 50 km. Since there was no any report on earthquake activity prior to the dam construction, the earthquakes occurred in the vicinity of the dam were assumed to be generated by the dam-related activities.

The Kenyir Dam has been hit by local earthquakes three times with low magnitudes: 1985-04-06 and

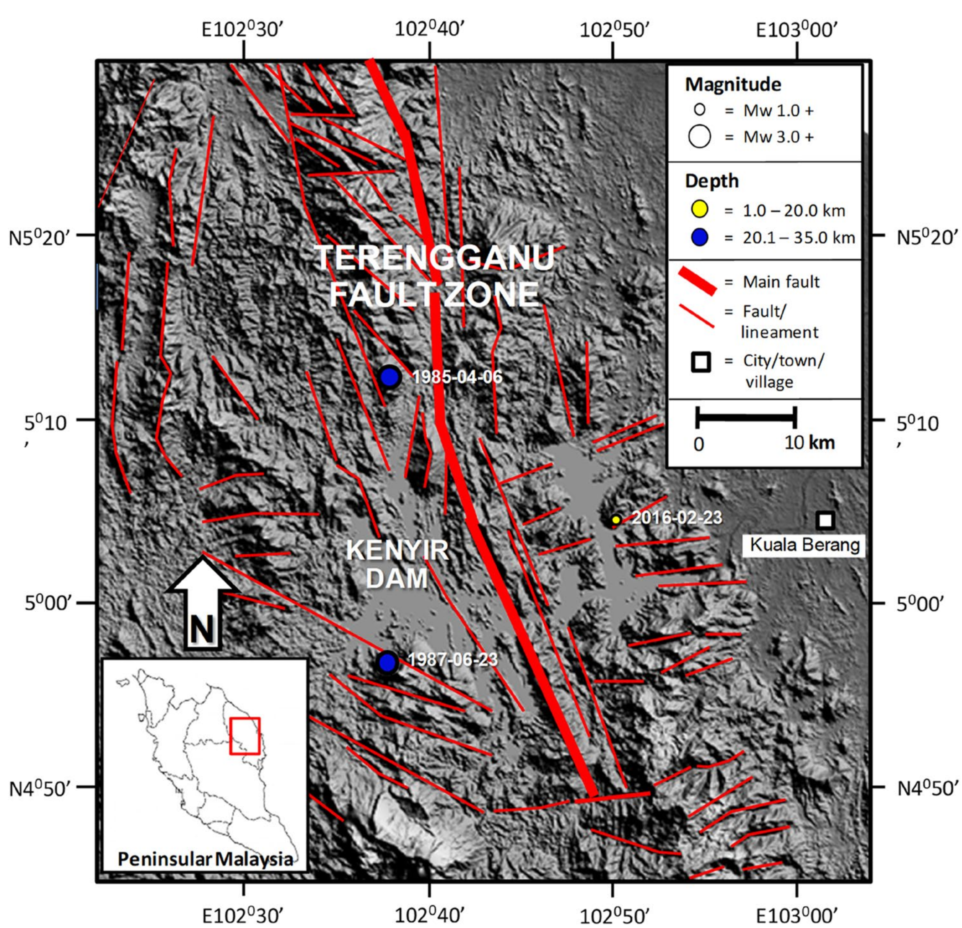


Fig. 9 Epicenters of the local origin earthquakes in the Kenyir Dam area superimposed on the SRTM–DEM image. Red thicker lines indicate known main faults (Terengganu Fault), while red thinner lines are lineaments indicating possible faults. Note: Created with CorelDraw

1987-06-23 events with the magnitude both mb 3.8 (Mw 3.9), and the latest event on 2016-02-23 with the magnitude ML 2.5 (Mw 1.7). In a closer look by using the SRTM–DEM image, the epicenters are located in the vicinity of Terengganu Fault Zone (Fig. 9). From the lineament analysis using the SRTM–DEM image, the main fault, i.e., the Terengganu Fault is shown in the northern part by an obvious N–S lineament and changes into NNW-SSE-trending lineament in the southern end. This sinistral strike-slip fault zone has a total length of 150 km [60]. Other minor faults within this fault zones commonly have the trend N–S, W–E, and NW–SE. The induced earthquakes may have triggered the reactivation of faults in the reservoir area due to increasing stress and pore pressure under the reservoir. Shuib et al. [22] stated that like other faults, Terengganu Fault also shows a prominent lineament but does not show any surface rupture related to the recent earthquake.

The earthquake tremors that occurred in the vicinity of this large and deep lake can be felt in Kuala Berang area. In the 2016-02-23 event, local people reported having heard a loud noise or a sound like an explosion followed by tremors at 9:25 pm local time without knowing that those were from an earthquake (https://www.malaysiakini.com/news/331459). Tenaga Nasional Berhad (TNB, the Malaysia's national electric-generating company), which built the dam as the home for the Sultan Mahmud Hydro Electric Power Station reported that there was no physical or structural damage that affected the dam. The dam was designed to withstand low-to-moderate earthquake activities (https://www.tnb.com.my/highlights/earthquake-no-signs-of-structural-damage-to-kenyir-dam).

5.6 Temenggor Dam area (Zone F)

Another reservoir in Peninsular Malaysia which is associated with few epicenters is the Temenggor Dam (or Temenggor Lake, also known as Banding Lake). This second largest reservoir in Peninsular Malaysia (after the Kenyir Dam) is located in the upstream Perak state near Gerik area. Similar to the Kenyir Dam, the Temenggor Dam (Temenggor Hydro-Electric Project or Temenggor Power Station), is operated by TNB to generate the electric power. Its construction was started in 1974 to impound the Temenggor Lake and the Perak River, and the project was completed in 1978.

There is no record of an earthquake in the early establishment of this dam until the year 2013 where the first detected earthquake in the vicinity of this dam occurred in 2013-08-20 measuring ML 3.8 (Mw 2.5) with the epicenter in the southern part of the lake. Later on in 2016, there was a cluster of three events with epicenters in the central part of the lake and magnitudes ranging ML 3.1–3.2 (Mw 2.0–2.1). All these four detected earthquakes in this dam area have shallow depth ranging 1.0–10.2 km. Lineament analysis using the SRTM–DEM image shows that the reservoir area is controlled by dense faults or lineaments mainly with the orientation trends NNW-SSE, NW–SE, and N–S. All epicenters are located on and close to the surface trends of the lineaments (Fig. 10).

5.7 Other areas

Other than the aforementioned zones, there are also other areas in Peninsular Malaysia where earthquake events have occurred in the region, such as Jerantut and Cameroon Highland (both are located in the state of Pahang) and Sungai Siput (Perak). However, they occurred each as a single event and scattered separately.

The 2009-03-27 Jerantut earthquake has been instrumentally detected and recorded by MMD occurring on 01:46:25 UTC with the local magnitude ML3.0 (Mw 2.0) and the focal depth 50.0 km. The epicenter map (Fig. 3) shows that the epicenter of this event was located near the Lepar Fault (Zone), one of major faults in Peninsular Malaysia. It can be interpreted that the event was triggered by the reactivation of this NW–SE trending fault. Fatt et al. [18] stated that there was only a single earthquake in Jerantut and the epicenter was located a few kilometers from the Lepar Fault. Furthermore about the fault, Shuib [60] and Kong [72] explained that the Lepar Fault is a left lateral strike-slip fault which is located in the south of the Lebir Fault. The Lepar Fault Zone consists of a series of several NW–SE striking faults with the width of 18 km and the length along the Lepar River around 45 km.

In the ISC database the 2013-12-26 earthquake in Cameroon Highland on 05:51:31 UTC was reported with a magnitude of mb 2.6 (Mw 2.8) and a focus depth of 10 km. This area is also interpreted to be affected by active faults where the earthquake occurred. According to [73], the eastern part of the highland crosses the Bentong–Raub Suture with at least 18 km wide. A paleoearthquake and active fault study in Cameroon Highlands using remote sensing and field investigations conducted by Shuib [74] has identified faults displaying evidences for Quaternary activity or movements, which are considered capable of generating earthquakes.

The 1997-11-02 earthquake near Sungai Siput area with the magnitude ML 3.6 (Mw 2.4) and the depth of 80 km is interpreted to be caused by the reactivation of the Bok Bak Fault, another major fault in Peninsular Malaysia. This NW–SE-trending sinistral fault crosses in the NW of

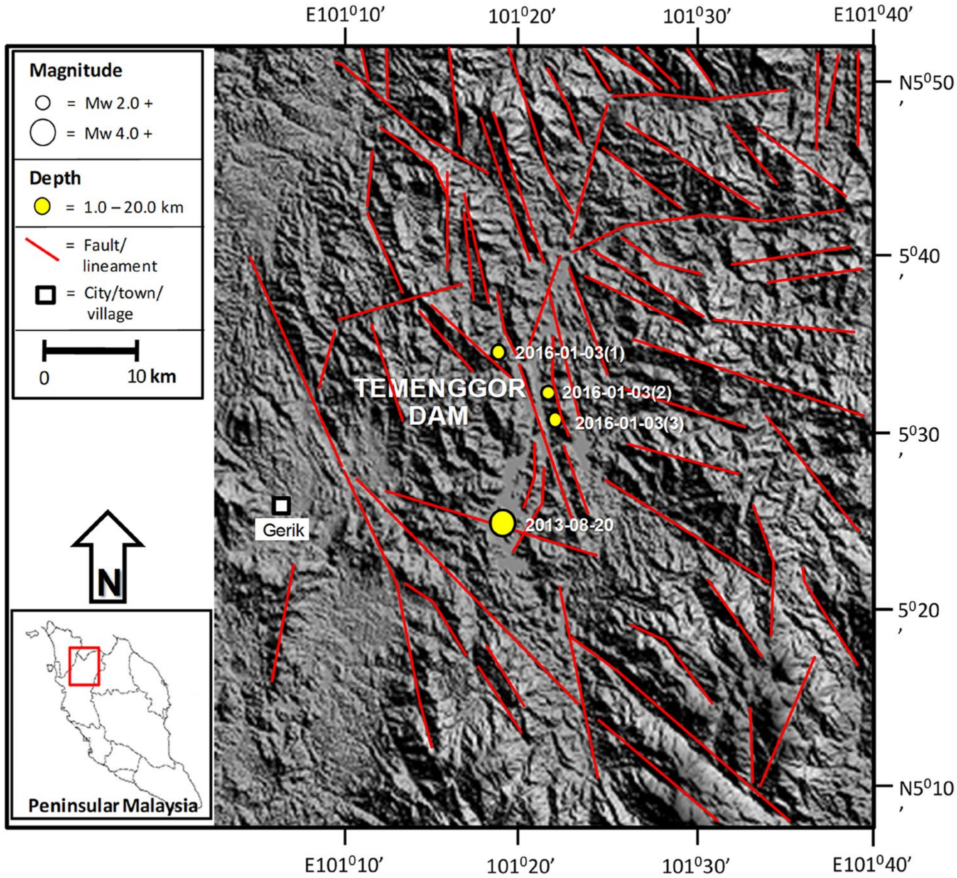


Fig. 10 Epicenters distribution of the Temenggor Dam earthquakes in 2013 and 2016 plotted on the SRTM–DEM image. Red thinner lines here are lineaments indicating possible faults. Note: Created with CorelDraw

Peninsular Malaysia and can be traced northward to the Thailand border in Wang Kelian (Perlis) and southeastward to Sungai Siput (Perak). The fault zone has a width of around 10 km [60]. Sahat [75] discovered a linear drainage system together with quartz reefs and outcrops of cataclasite, mylonites, and a shear zone near Sungai Siput area. Almashoor [76, 77] confirmed that the length of the fault is around 215 km and the displacement is 10 km. Like the Jerantut earthquake, which occurred deeper than the crustal thickness of the region, this earthquake is also assumed to be originated from the upper mantle.

The epicenter zonation resulted from this study is consistent with the finding of the Department of Mineral and Geoscience Malaysia which created the seismic hazard map of Peninsular Malaysia in 2017. The map shows several areas (zones) with higher PGA (%g) with 10% probability of exceedance in 50 years [78] as follows: the BTFZ and KMFZ (9%, the highest), Seremban/Kuala Pilah area (8%), the Malacca Strait (8%), Manjung area (7%), the Kenyir Dam area (7%) and the Temenggor Dam area (6%).

5.8 The 1922 earthquakes

In a recent paper by [26] two earthquakes that occurred in the southern part of the Malay Peninsula in 1922 were analyzed. The first one occurred on January 31, 1922, and the second one on February 7, 1922, with an M_l 5.4 and M_l 5.0, respectively. The estimated depth is in the lower crust of about 25–30 km based on intensity analyses. Comparing both earthquakes with events from this study the first event could be related to the Ma Okil Fault; however, no seismicity is so far reported there. No faults mapped and no seismicity describes the surrounding area of the second earthquake in 1922. However, hypothetically assuming that both earthquakes might have had larger depths they might be related to detached slab parts of the Sunda Subduction Zone; similar to the situation described in Zone A, Malacca Strait (Sect. 5.1). Seismic tomography results in [56] indicate a lower P- and S-wave velocity zone beneath the southern part of the Malayan Peninsula, but at depths of at least around 100 km or deeper. As the depth values of both 1922 earthquakes will likely never be resolved, this scenario remains speculative.

5.9 Magnitude variation

Converted magnitudes ranging from Mw 0.6 to 5.4 with the majority of the magnitude is Mw 1.0+and 2.0+. The lowest magnitude so far is Mw 0.6 (equivalent to ML 0.9

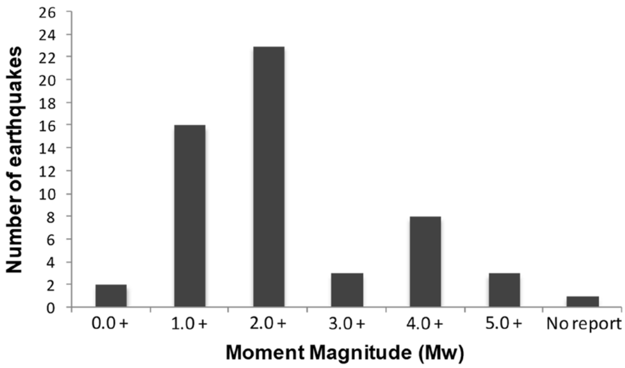


Fig. 11 Magnitude variation of local earthquakes in Peninsular Malaysia during the period 1922–2020. Note: Created with MS Office

and can be categorized as micro earthquake) and has been recorded in one event, 2009-10-07 Bukit Tinggi earthquakes. Meanwhile, the highest magnitude is Mw 5.4 (categorized as moderate earthquake) and has been recorded from the 1922-01-31 earthquake in east of Muar, Johor in southern of the peninsula. Figure 11 shows the histogram of the moment magnitude distribution of earthquakes in the region during the studied period (1922–2020). It reveals that the majority of the magnitude is Mw 1.0+and 2.0+(equivalent to ML 2.0+and 3.0+) and can be categorized as micro- to minor earthquakes.

6 Conclusion

It can be concluded that although Peninsular Malaysia is situated in the interior of the plate and is considered as a region in Malaysia with low seismicity, this area is still facing earthquake risks, not only from regional tectonics but also from local tectonics. For the local tectonic setting, there are a number of preexisting, assumed dormant faults (and fault zones), which have been reactivated causing local tectonic earthquakes. In addition, reservoir-induced earthquakes have also occurred in several reservoirs in the region.

This study compiled earthquake data from international and national seismological networks (ISC, EMSC, and MMD) and analyzed a number of digital seismograms obtained from the national agency (MMD). There are at least 59 earthquake events have been recorded in Peninsular Malaysia during 1922 to 2020; however two earthquakes from 1922 are based on macroseismic intensity analyses. Observations on earthquake occurrence in the region during the studied period have shown that earthquakes are dominant in the western and northern parts of the region, and sparse in the eastern and southern area. Epicenters are scattered laterally both onshore (Peninsular Malaysia) and the adjacent offshore areas in the Malacca Strait. Most of the recorded earthquakes were located on and near surface traces of faults and fault zones or lineaments as assumed faults. For the vertical (focal depth) distribution, the majority of recorded earthquakes were categorized as shallow earthquakes (occurred at 1–70 km); most of them even very shallow earthquakes which occurred at 1–10 km. The deepest earthquake with 167 km depth located in the Street of Malacca can be associated with a slab detachment broken off from the Sumatran Subduction Zone. Earthquakes in this region have varied magnitudes with a minimum magnitude of Mw 0.6 and a maximum of Mw 5.4.

Intraplate earthquake activities in this region have revealed that Peninsular Malaysia has a relatively low seismicity with 59 earthquakes over 98 years and all with magnitudes below 5.4. However, locally, in certain zones, there is an elevated vulnerability related to earthquakes originating from active and/or reactivated faults/fault zones due to movements and earthquakes along the SSZ. The reactivation of local faults/fault zones is considered capable of generating larger magnitude earthquakes and contributing to seismic hazards in this region. Due to relatively low magnitudes (and intensities), earthquakes occurred in Peninsular Malaysia have so far caused no fatalities and injuries, and only minor structural damages happened near epicenters. However, the reactivation of local faults and earthquake activities in this region still should be taken into future consideration. Thus, monitoring and documenting earthquake activities and conducting detailed research works on local earthquakes in this region is very essential for many purposes such as to understand about the dynamic geological processes of the region, to determine the frequency of earthquake occurrences, and earthquake recurrence intervals, to estimate earthquake hazards, and subsequently to evaluate earthquake risks.

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Data availability All data made available through the manuscript or are publicly available with sources stated in the manuscript.

Code availability Software used in this study is publicly available and the source stated in the manuscript.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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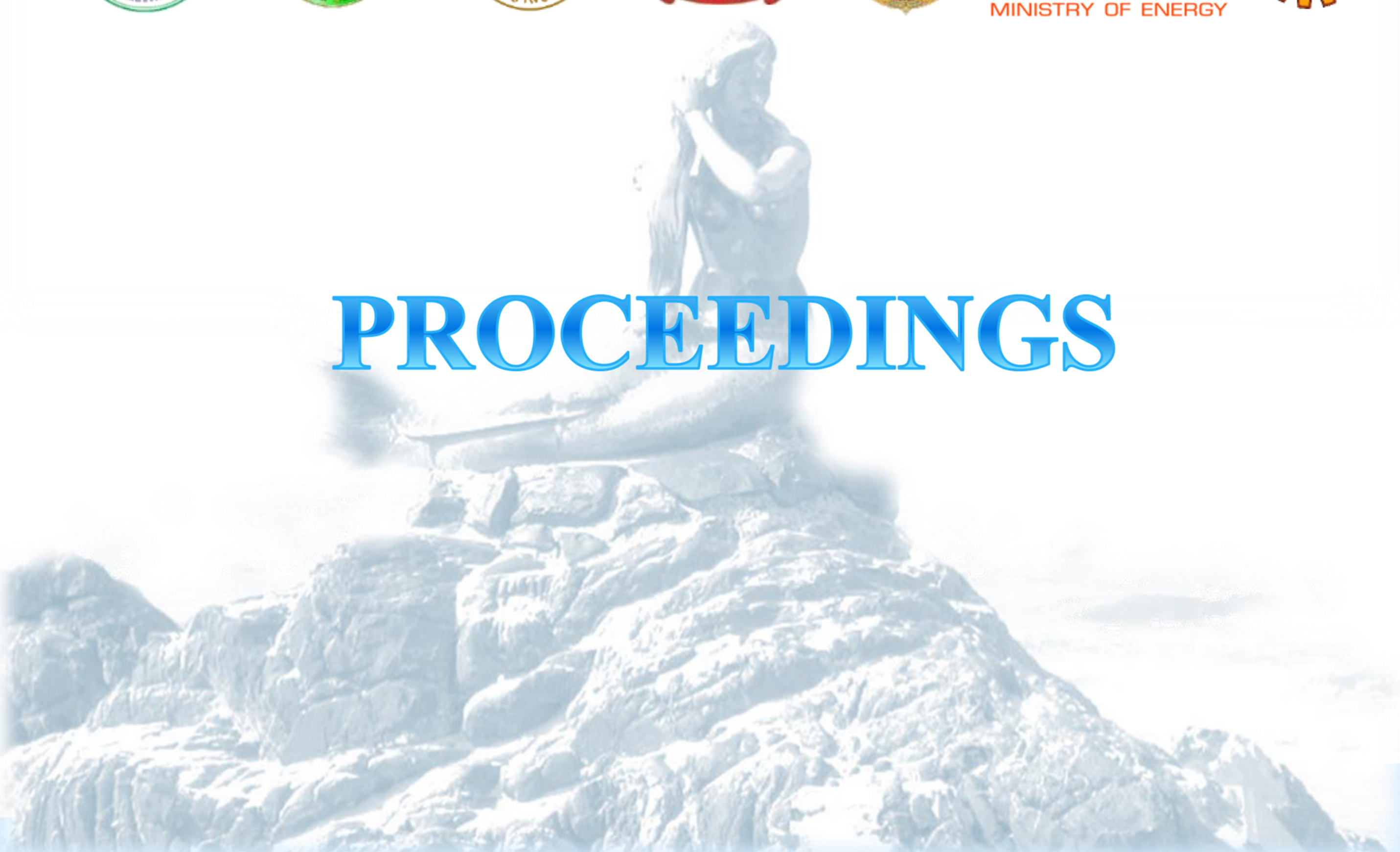

PROCEEDINGS

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Spatial Distribution of Shallow and Intermediate Earthquakes in Southern Thailand after the 26 December 2004 Sumatra – Andaman Earthquake

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ABSTRACT- The observation of seismicity in Southern Thailand has been actively conducted in the aftermath of the 26 December 2004 Sumatra – Andaman Earthquake. In this study, seismogram records of 172 earthquakes were collected during 2005 to 2017 from two sources: A temporary seismological network operated by the Geophysics Research Center – Prince of Songkla University (GRC–PSU) in collaboration with the Department of Mineral Resources (DMR) with 111 earthquakes recorded by at least 3 stations in the region during January to April 2005; and Some permanent local stations of the Thai Meteorological Department (TMD) installed in the region recorded 61 events during 2010 to 2017. Some previous studies have analyzed earthquake data in the region to determine earthquake source parameters; however not the focal (hypocentral) depths. Therefore, the purpose of this study was to determine the focal depths and the spatial distribution of earthquakes in Southern Thailand. All available digital seismograms were processed and interpreted following standard procedures by using SEISAN software to produce information on source parameters (origin times, locations, magnitudes, and focal depths). Focal depths were obtained by using the software through iterations with the starting/trial depth of 15 km; then this depth was used to give the best fit to the data. All recorded earthquakes are considered local earthquakes which occurred onshore and offshore of Thai Peninsula within an area between 7°00’N to 10°45’N and 97°30’E to 100°45’E with local magnitudes ML -0.2 to 4.8 (micro to light earthquakes), including earthquake swarms in Phuket Island in 2012. This study also reveals that the hypocenters (focal depths) are located between 0 – 80 km deep where most of the events are categorized as shallow earthquakes and only a few as intermediate earthquakes. The lateral distribution of shallow-depth events within this region is scattered in and around two major fault zones in Southern Thailand, which are the Ranong and Khlong Marui Fault Zones; whereas intermediate-depth events are clustered in the western part of the region.

Keywords: Earthquakes, 2004 Sumatra–Andaman Earthquake, Southern Thailand, focal depth

1. INTRODUCTION

Southern Thailand, one of four regions and the southernmost part of Thailand, is surrounded by the Andaman Sea and the Gulf of Thailand in the west and the east respectively forming a part of the Thai Peninsula which extends south to the border with Malaysia. This region is tectonically located intraplate of the Eurasian Plate and regionally close to the Sumatra-Andaman Subduction Zone (about 600-800 km between the coast line to the plate boundary), which is the regional source of earthquakes. For local setting, there are a series of active fault zones mainly the Ranong and the Khlong Marui Fault Zones (RFZ and KMFZ) which, according to Duerrast et al. (2007), were considered as dormant by Thailand’s Department of Mineral Resources (DMR) before the Mw 9.2 Sumatra-Andaman Earthquake on 26 December 2004.

Before the 2004 great earthquake, there was no or little awareness on seismic hazards in Southern Thailand until the region experienced the impact of the 2004 earthquake. Since then until now, seismic hazards and the potential for the movement and reactivation of existing faults and fault zones in the region have been studied. As stated by Morley et al. (2011), since the occurrence of the 2004 Sumatra-Andaman Earthquake, the two major faults and fault zones (RFZ and KMFZ) have attracted much attention from geologists, seismologists, and people from other related fields because of their increasing reactivation. Duerrast et al. (2007) conducted an earthquake study in the region and revealed that after the 26 December 2004 earthquake, the existing faults zones might be reactivated in a compressional stress regime, increasing the probability of higher magnitude earthquakes. Sutiwanich et al. (2012) concluded that Southern Thailand or Thai Peninsula is not tectonically stable anymore as had previously thought. Some other researchers have also analyzed earthquake data from this region to identify source parameters including origin times, locations, and magnitudes. However, there is still no study on the determination of earthquake focal depths (depths of hypocenters) in this region after the 2004 earthquake.

This study observed the seismicity in Southern Thailand from 2005 to 2017. Digital seismograms from 172 earthquake events in the region have been processed and interpreted according to standard procedures using the freely available SEISAN (Seismic Analysis) software to produce earthquake source parameters which include origin times, locations, magnitudes as well as focal depths. This paper also emphasized the determination of focal depths and their spatial distribution in this region.

2. TECTONIC SETTING AND GENERAL GEOLOGY

Southern Thailand is regionally affected by the interaction of the plate boundary between the India Plate and Burma Microplate (considered a part of the larger Eurasian Plate), one of most seismically active plate boundaries, mainly in the Andaman Sea. In local tectonic setting, the RFZ and KMFZ which cross the Thai Peninsula from Andaman Sea to the Gulf of Thailand in the relatively NNE-SSW direction are two prominent fault zones that have long and complex history extending back to Paleozoic Era (Morley et al., 2011; Figure 1a).

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. It has also a number of scattered and less linear granitic bodies (Ridd et al., 2011; Figure 1b).

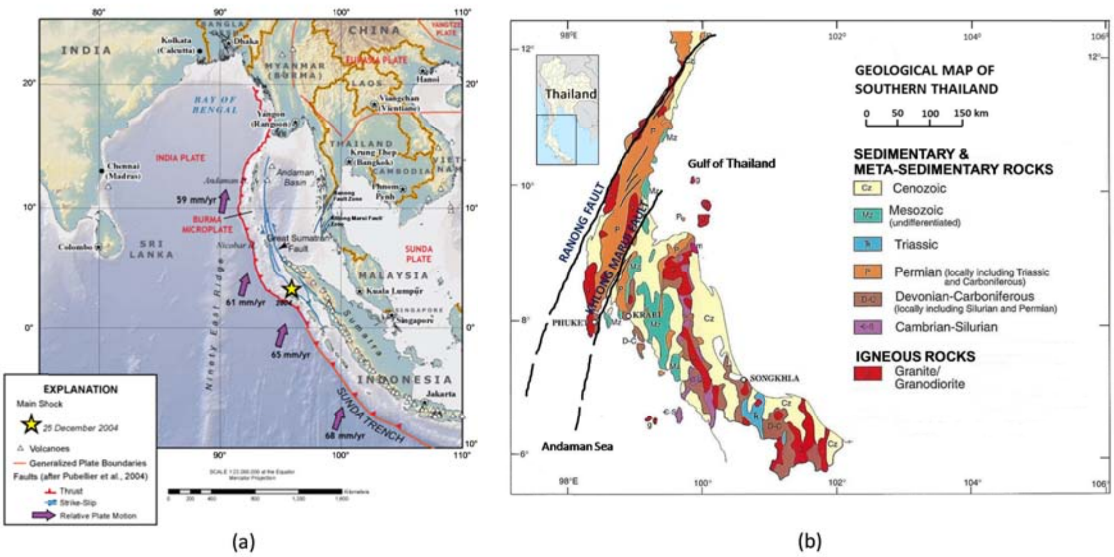

Figure 1. (a) Regional tectonic setting of Sumatra–Andaman subduction zone showing relative motion between the India Plate and the Burma Microplate, major fault zones, and location of the 26 December 2004 earthquake (Source: http://walrus.wr.usgs.gov/tsunami/sumatraEQ/tectonic.html); (b) Geological Map of Southern Thailand (Modified from Ridd et al., 2011)

3. DATA AND METHODOLOGY

3.1 Datasets

In total, there are 172 local earthquake events were used in this study and can be categorized into two datasets based on their sources. The first dataset was collected from a temporary seismological network comprising four short-period (SP) three-component (Z, N, and E) seismometers operated by GRC-PSU and DMR from January to June 2005 in Phang Nga (2 stations), Phuket (1 station), and Krabi (1 station). From numerous earthquakes recorded during the six-month monitoring, only those recorded by at least 3 seismic stations were selected for this study, which are 111 local earthquakes occurred between 14 January and 11 April 2005. The second dataset was taken from 10 permanent local stations in Southern Thailand operated by TMD. This dataset contains 61 local earthquakes occurred during 2010 – 2017 in the region. This study was carried out in Southern Thailand region, situated between latitude of 5°30'-12°30'N and 97°30'-102°30'E. Locations of all seismic stations used in this study are given in Table 1 and shown in Figure 2.

Table 1. Information on Seismic Stations for Earthquake Monitoring in Southern Thailand during 2005–2017 (for this study)

Data-set	Station No.	Station Code	Lat.	Long.	Location
1	1	PSUHY	8°26'3.48"N	98°30'24.48"E	Muang District, Phang Nga Province
1	2	PNG2	8°33'27.36"N	98°39'37.44"E	Thap Put District, Phang Nga Province
1	3	PSUNM	7°53'28.90"N	98°21'3.96"E	Prince of Songkla University, Phuket Campus, Khatu District, Phuket Province
1	4	TBK	8°23'20.28"N	98°44'10.46"E	Tanbokkoranee National Park, Ao Luek District, Krabi Province
2	5	KRAB	8°13'17.40"N	99°11'49.92"E	Krabi Province
2	6	PHET	12°54'47.92"N	99°37'36.30"E	Phetchaburi Province
2	7	PKDT	7°53'31.20"N	98°20'6.00"E	Phuket Province
2	8	PRAC	12°28'21.47"N	99°47'34.37"E	Prachuap Kirikhan Province
2	9	RNTT	9°23'25.44"N	98°28'40.08"E	Ranong Province
2	10	SKLT	7°10'24.60"N	100°37'7.68"E	Songkhla Province
2	11	SRIT	8°35'43.76"N	99°36'7.06"E	Nakhon Si Tammarat Province
2	12	SURA	9°9'58.82"N	99°37'46.02"E	Surat Thani Province
2	13	SURT	8°57'27.72"N	98°47'42.00"E	Surat Thani Province
2	14	TRTT	7°50'10.32"N	99°41'28.32"E	Trang Province

Reference: Duerrast et al. (2007), Vanichnukhroh (2013)

3.2 Methodology

In seismogram analysis, the first step was to identify the seismic phases associated with each earthquake and to determine their arrival times. Seismic phases for local earthquakes (mainly P and S waves) and their arrival times, and maximum amplitudes (from horizontal components: N and E) have been measured. Information of earthquake source parameters consists of origin time, location (epicentral coordinates), magnitude and focal depth; focal depth has not been determined in the earlier study (Duerrast et al., 2007). Seismogram analysis was done by SEISAN, open-source software developed by Havskov and Ottemöller (1999) which can be downloaded at: ftp://ftp.geo.uib.no/-pub/seismo/SOFTWARE/SEISAN/. For this study, SEISAN version 10.4 (the latest version) was used.

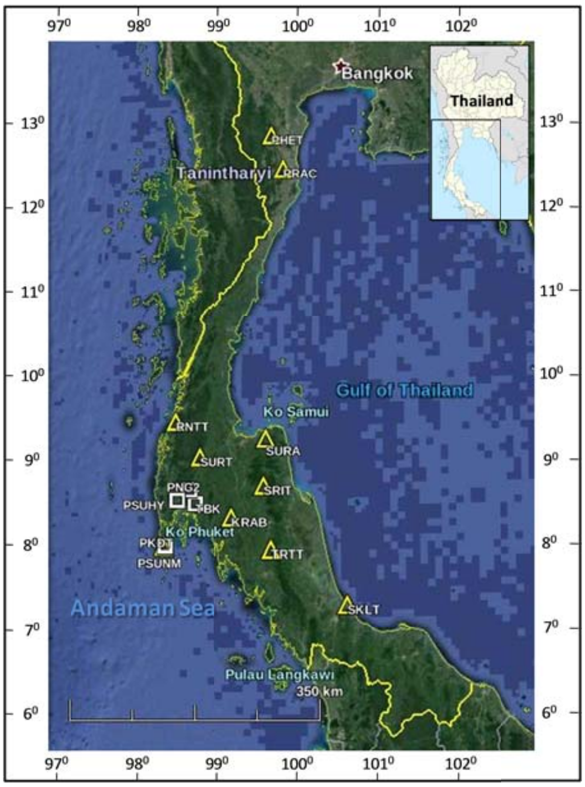

Figure 2. Location map of all seismic stations used in this study to monitor earthquakes in Southern Thailand during 2005–2017. The squares indicate the temporary network/stations (operated by GRC-PSU and DMR for data collection in 2005) and consist of 4 stations (PSUHY, PNG2, PSUNM, and TBK) and the triangles show permanent local stations (operated by TMD for data collection in 2010 - 2017) and consist of 10 stations (KRAB, PHET, PKDT, PRAC, RNTT, SKLT, SRIT, SURA, SURT, and TRTT)

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. This study used the IASP91 velocity model (Kennett and Engdahl, 1991). 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 (Bormann et al., 2013) with:

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

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).

Based on Rafferty (2018), earthquakes can be categorized into six classes based on the magnitude (Richter scale): micro (less than 1.0 – 2.9), minor (3.0 – 3.9), light (4.0 – 4.9), moderate (5.0 – 5.9), strong (6.0 – 6.9), major (7.0 – 7.9), and great (8.0 and higher).

3.3 Focal (Hypocentral) Depth

Spence et al. (1989) divided the earthquake focal depths into three zones: shallow earthquakes (0-70 km deep), intermediate earthquakes (70 - 300 km deep), and deep earthquakes (300 - 700 km deep). In this study, focal depths were obtained by using SEISAN software through iterations with the starting/trial depths adjusted to all events. The starting depth is usually a fixed parameter and adjusted to the most likely depth for the region which is around 10-20 km for the local earthquake (Havskov and Ottemöller, 2010). In this study, the software/program first iterated with the depth fixed to the starting depth of 15 km and then used this depth to give the best fit to the data.

4. SPATIAL DISTRIBUTION OF EARTHQUAKES

This study revealed that, during 2005 – 2017, the earthquake locations are distributed in a relatively 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 was also a cluster of relatively 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 (Watkinson et al., 2008), can be interpreted due to the existences of some faults in granitic bodies in the areas. During this period, the earthquakes in Southern Thailand occurred mainly on land in some provinces of the region, i.e. Chumpon, Ranong, Surat Thani, Phang Nga, Nakhon Si Thammarat, Krabi, Phuket, and Trang. However, there are also clusters of epicenter in the Andaman Sea and the Gulf of Thailand, scattered in many locations offshore of Trang, Krabi, Phang Nga, Phuket, and Ranong, and a few locations in Surat Thani, Nakhon Si Tammarat, and Songkla. There was also a cluster of earthquake swarms in the northern part of Phuket Island, where the island experienced sequences of many earthquakes striking in a relatively short period of time in April – May 2012.

Most of local earthquakes occurred during 2005 - 2017 have their local magnitude (ML) between 0.1 to 1.0 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 -1.0 to 0.0) are concentrated in some areas in Krabi, Phang Nga, and Phuket. The maximum magnitudes are ML 4.8 located near Phuket and Ko Yao Yai islands in the western part of Thai Peninsula.

In term of the focal depth, most of the recorded earthquakes in Southern Thailand have very shallow depths (depth = 0.0 – 20.0 km, symbolized by white circles in the following maps) scattered in and around the fault zones. Epicenters with the depth of 21.0 – 35.0 km (symbolized by yellow circles) are distributed randomly in the fault zones and its surroundings. Deeper hypocenters with 35.0 – 70.0 km depth (indicated by blue circles) and the deepest category (depth = 70.0 – 80.0 km, symbolized by red circles) are all located in the western part of Thai Peninsula, mainly in Phang Nga and Phuket provinces.

Figure 3 and 4 shows the maps of lateral distribution of epicenters in Southern Thailand region and Phuket Island area respectively during 2005 – 2017 in relation to the magnitude and depth. The vertical distribution of epicenters is represented by some depth profiles in Figure 5.

5. CONCLUSION

The results of this study have shown that after the 26 December 2004 Sumatra-Andaman Earthquake, the increasing numbers of earthquake events occurred in Southern Thailand. Based on the distribution of epicenters during 2005 - 2017, it can be interpreted that most of the recorded earthquakes are related to the existing faults and fault zones, mainly the Ranong and Khlong Marui Fault Zones. The 2004 devastating earthquake has reactivated the fault zones in this region with subsequent earthquake occurrences.

Most recorded earthquakes are categorized as microearthquakes (ML≤2.0) and mostly have very shallow depth of sources (0.0 – 20.0 km). This study revealed that the number of earthquakes decreased with the increasing of the focal depths. Most of shallower earthquakes occurred on land, meanwhile most of deeper events occurred offshore of the study area.

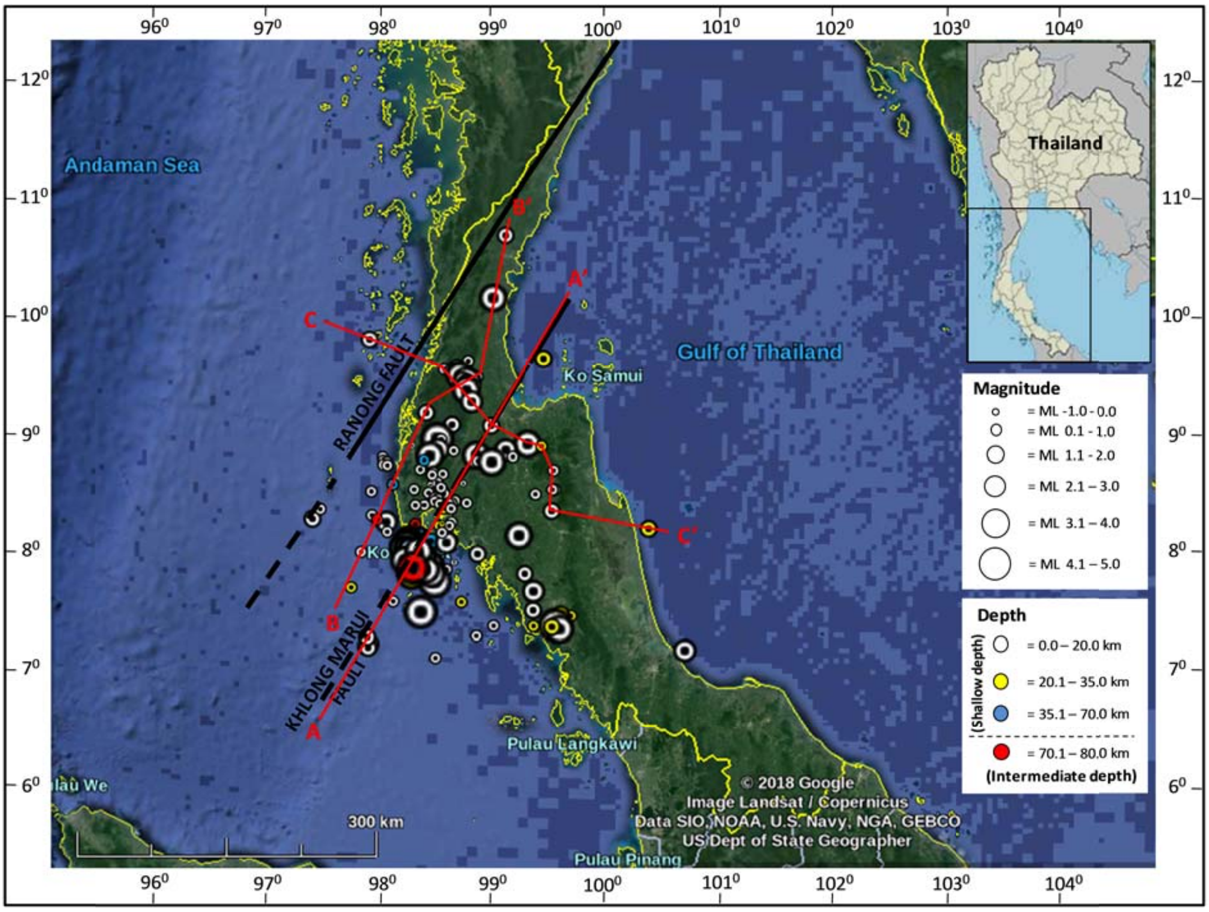

Figure 3. Epicenter Map of Southern Thailand Showing the Distribution of Earthquakes during 2005 - 2017 with Different Magnitudes and Depths. Red lines (A – A', B – B', and C – C') indicate the lines of cross section (see Figure 5 a-c)

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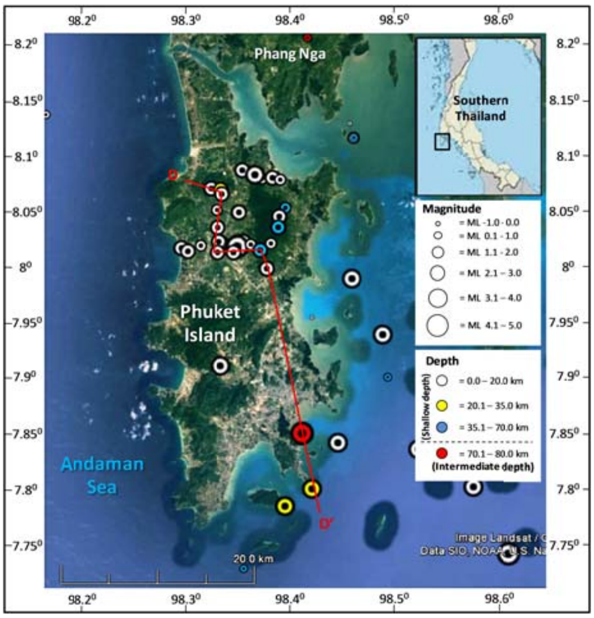

Figure 4. Epicenter Map of Phuket Island and Its Surroundings during 2005 - 2017 with Different Magnitudes and Depths. Earthquake swarms in 2012 can be seen in the northern part of the island. The red line (D – D') shows the line of cross section (see Figure 5d)

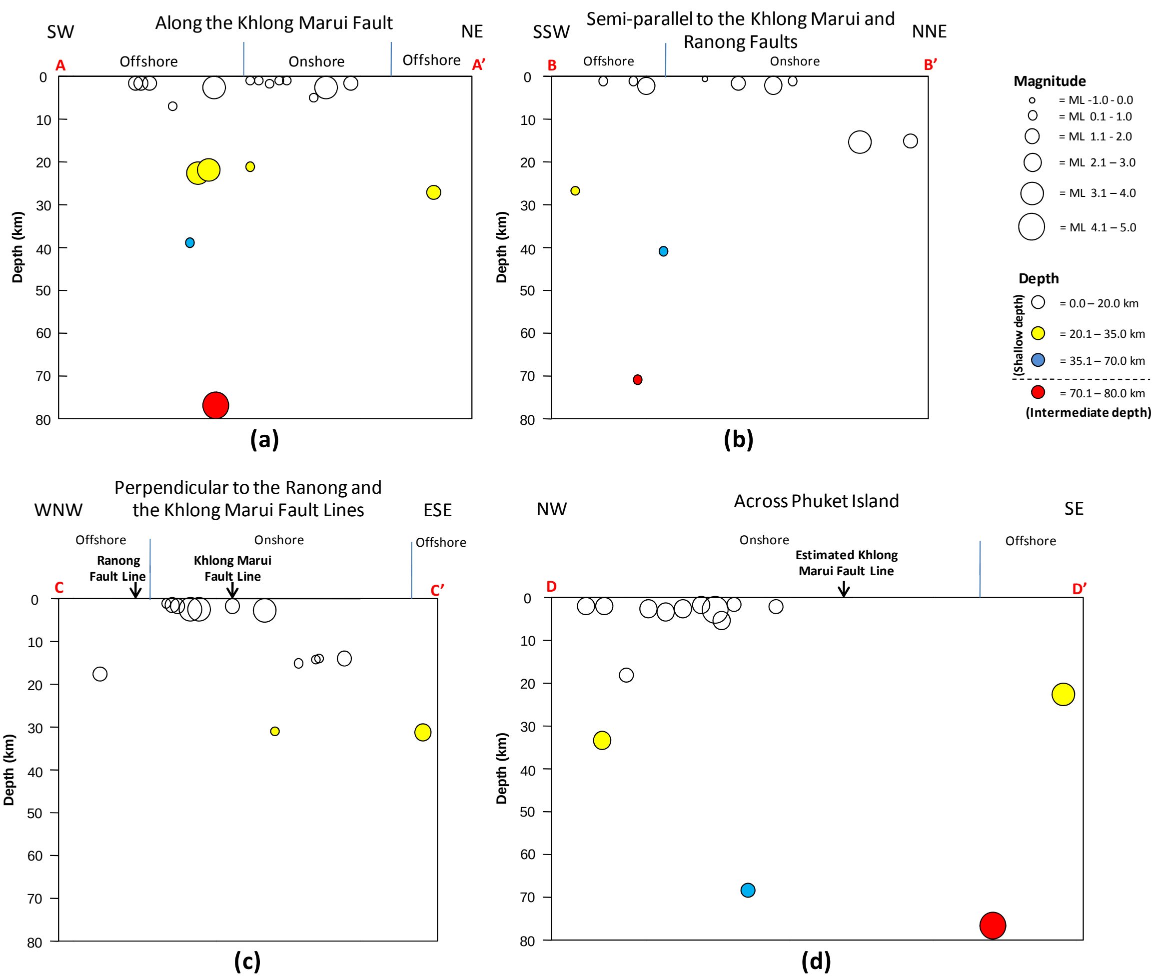

Figure 5. Vertical sections (depth profiles) of seismicity in Southern Thailand during 2005 – 2017 from some lines: (a) Along the Khlong Marui Fault, (b) Semi-parallel to the Khlong Marui and Ranong Faults, (c) Perpendicular to the Ranong and the Khlong Marui Fault Lines, and (d) Across Phuket Island

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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].

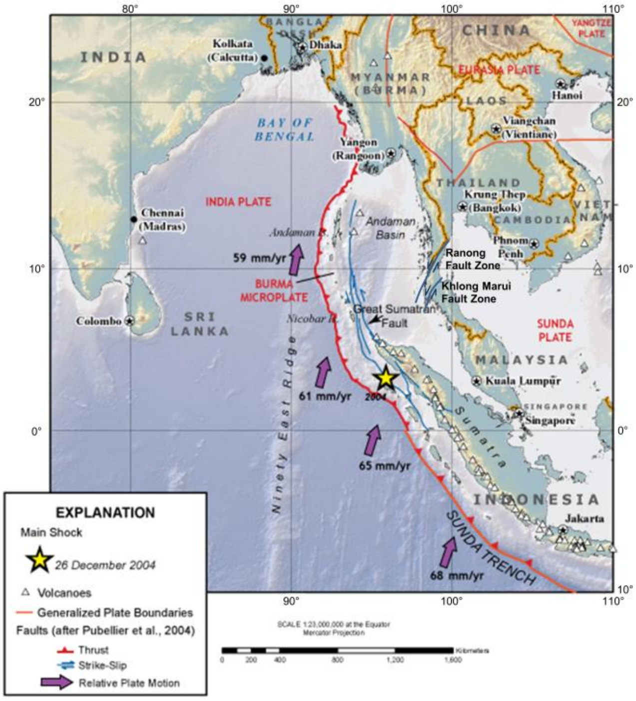

Fig. 1. *Regional tectonic setting of Sumatra–Andaman subduction zone showing relative motion between the India Plate and the Burma Microplate, major fault zones, and location of the 26 December 2004 earthquake (Source: http://walrus.wr.usgs.gov/tsunami/sumatraEQ/tectonic.html)*

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.

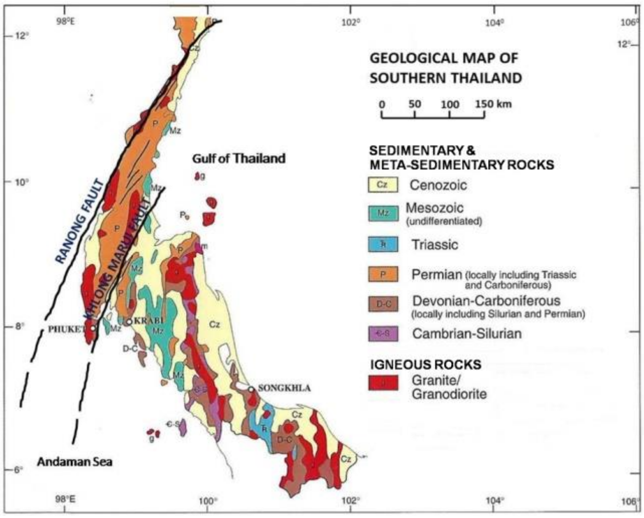

Fig. 2. *Geological map of Southern Thailand (modified from [5])*

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

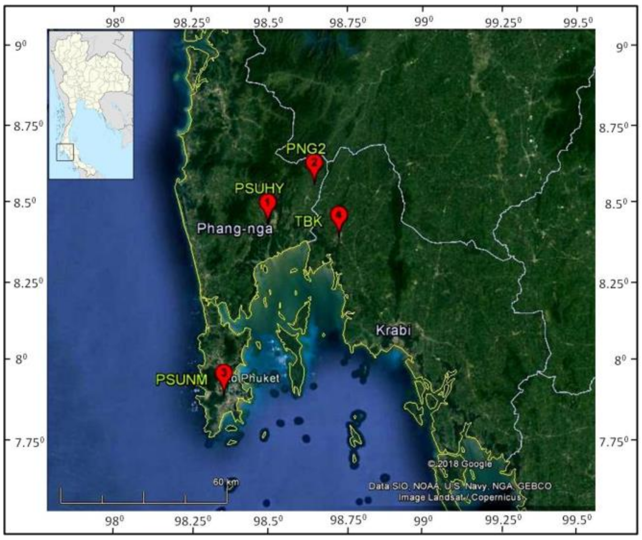

Fig. 3. *Location of 4 seismic stations (PSUHY, PNG2, PSUNM, and TBK) for earthquake monitoring in Southern Thailand in early 2005*

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.

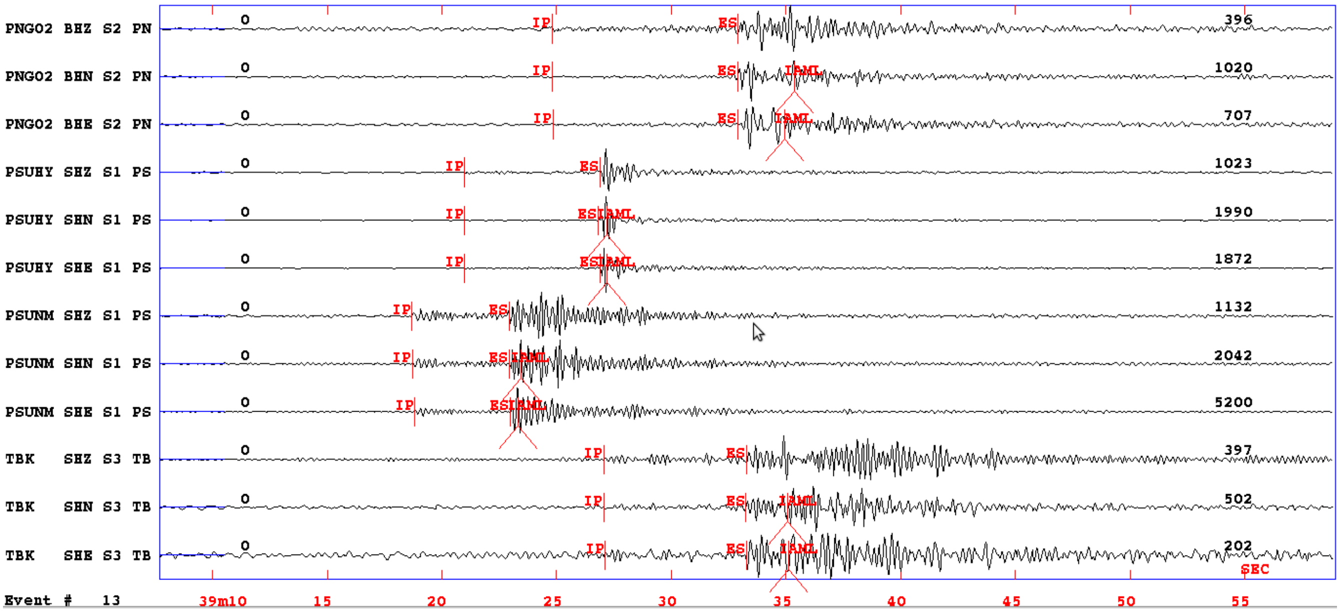

Fig. 4. *Seismogram analysis of event no.13 recorded on 18 January 2005 by 4 seismic stations (Station 1/PSUHY, Station 2/PNG02, Station 3/PSUNM, and Station 4/TBK) with three-component seismographs (Z, N, and E). (IP = P phase; ES = Sphase; IAML = Maximum amplitude)*

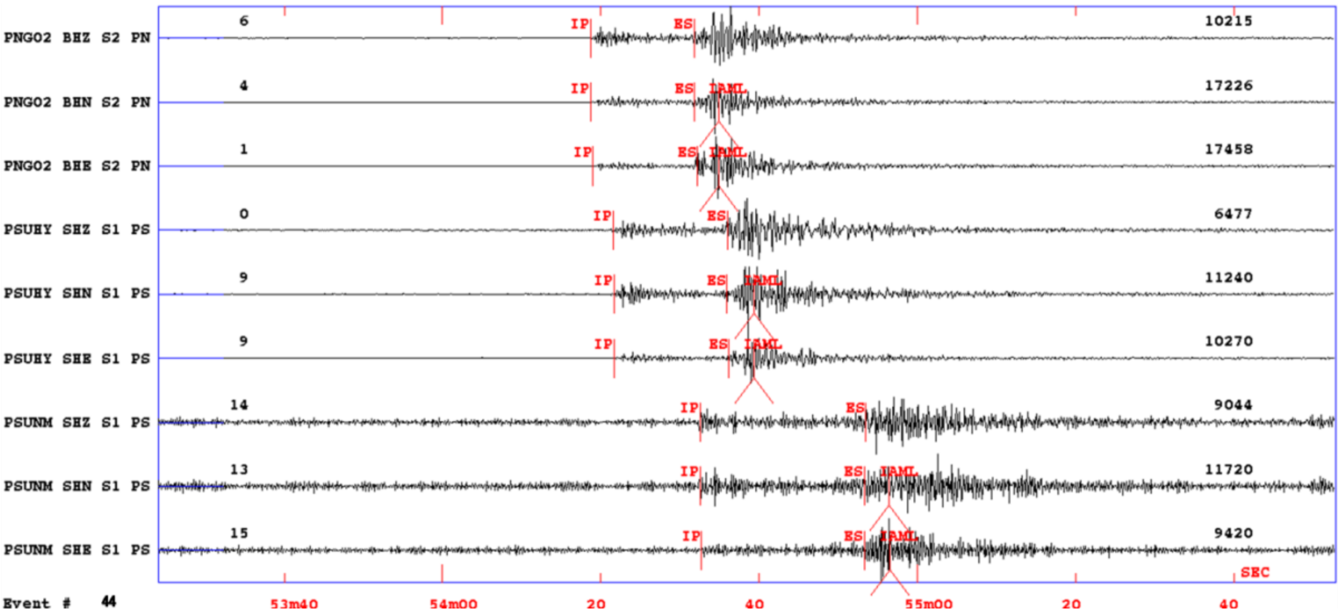

Fig. 5. *Seismogram analysis of event no.44 recorded on 3 March 2005 by three-component seismographs (Z, N, and E) in 3 seismic stations (Station 1/PSUHY, Station 2/PNG02, and Station 3/PSUNM). (IP = P phase; ES = S phase; IAML = Maximum amplitude)*

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	

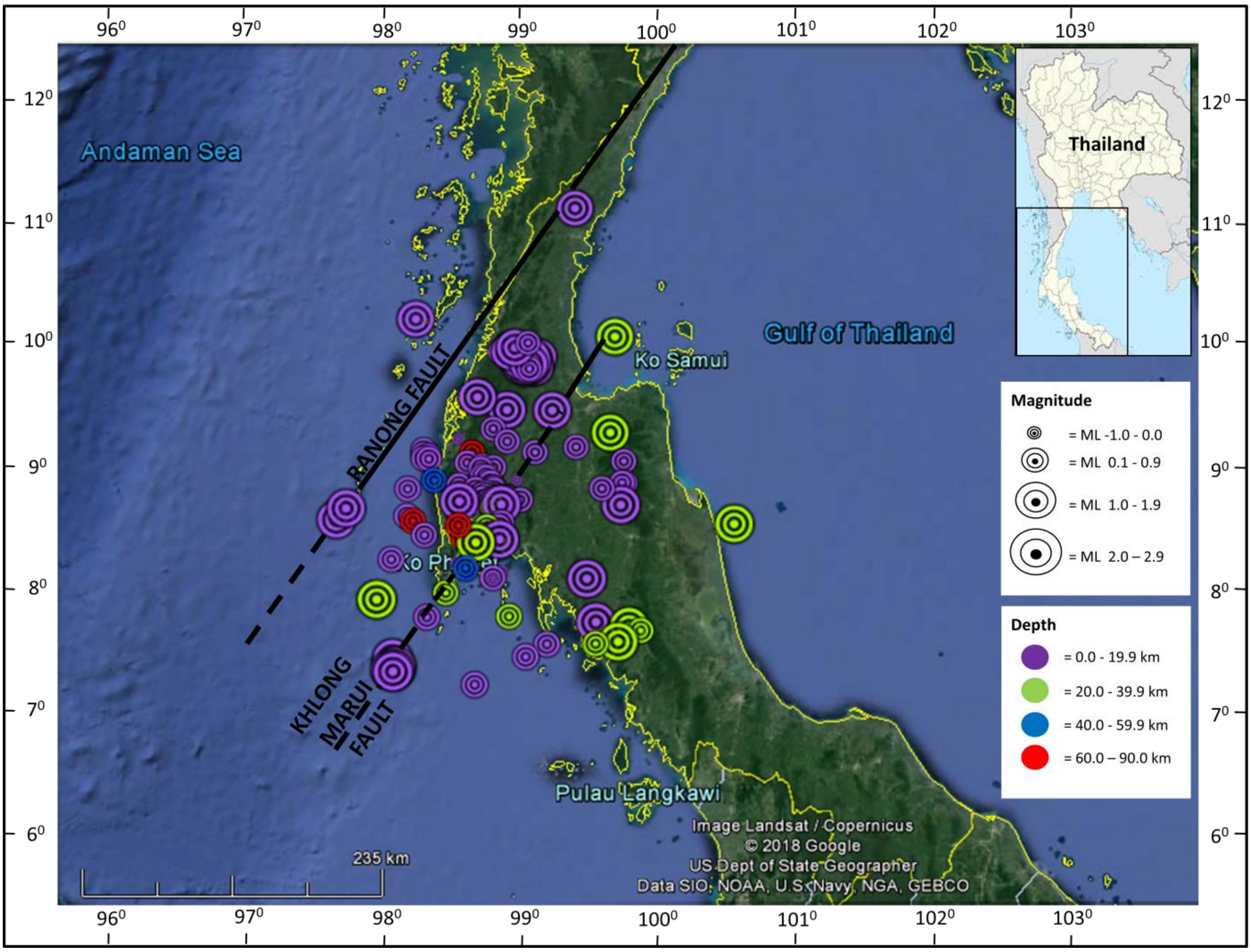

Fig. 6. *Map of earthquake locations (epicenters) in Southern Thailand from January 14th to April 11th, 2005*

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.

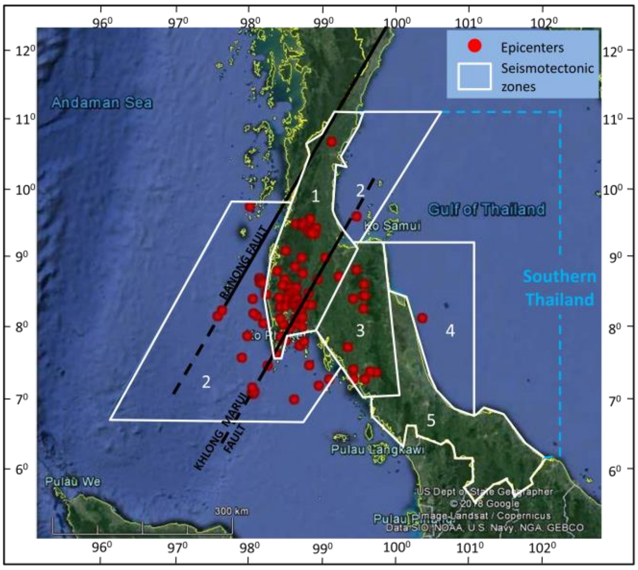

Fig. 7. *Seismotectonic zones of Southern Thailand based on earthquake activities recorded from 14 January to 11 April 2005*

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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List of Publication and Proceeding

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2. Nazaruddin, D.A. and Duerrast, H. (2021b). Intraplate earthquake occurrence and distribution in Peninsular Malaysia over the past 100 years. *SN Applied Sciences*, 3, 693. DOI: 10.1007/s42452-021-04686-2.

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1. Nazaruddin, D.A. and Duerrast, H. (2018a). Spatial distribution of shallow and intermediate earthquake in Southern Thailand after the 26 December 2004 Sumatra-Andaman earthquake. *Proceedings of the 8th International Conference on Applied Geophysics (Geophysics Songkhla 2018)*, 8-10 November 2018, Songkhla, Thailand.
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