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2012 Earthquake Swarm in Phuket, Southern Thailand

Dony Adriansyah Nazaruddin and Helmut Duerrast*

Geophysics Research Center, Department of Physics, Faculty of Science, Prince of Songkla University, Hat Yai, 90112, Thailand.

*Author for correspondence; e-mail: helmut.j@psu.ac.th

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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

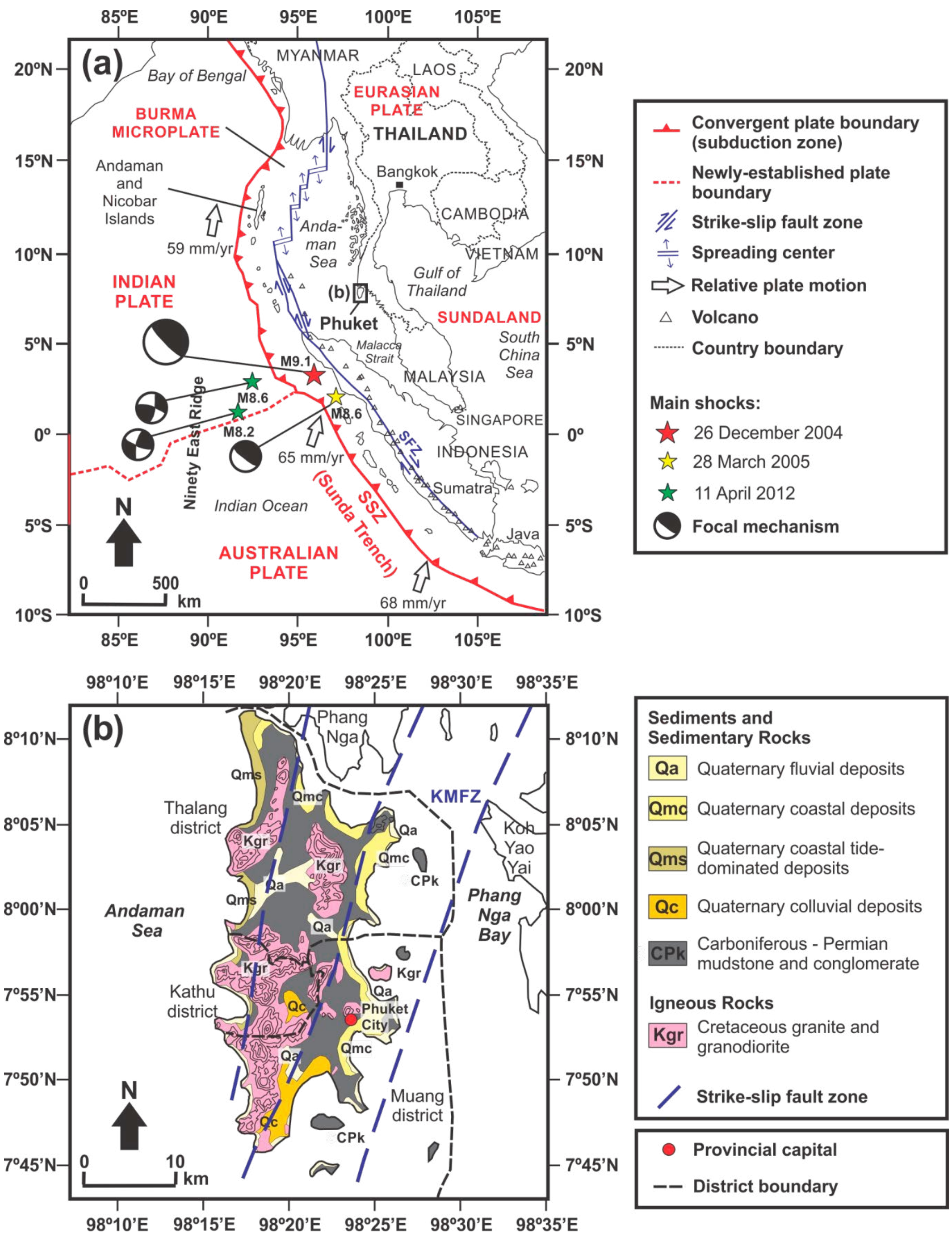


Figure 1. Regional tectonics of the Sunda Subduction Zone (SSZ) and surrounding regions (a), after [17, 20]; Geology and local tectonics of Phuket Island (b). SFZ = Sumatra Fault Zone; KMFZ = Khlong Marui Fault Zone. Geological map of Phuket was redrawn from [16]. Several faults within KMFZ were redrawn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

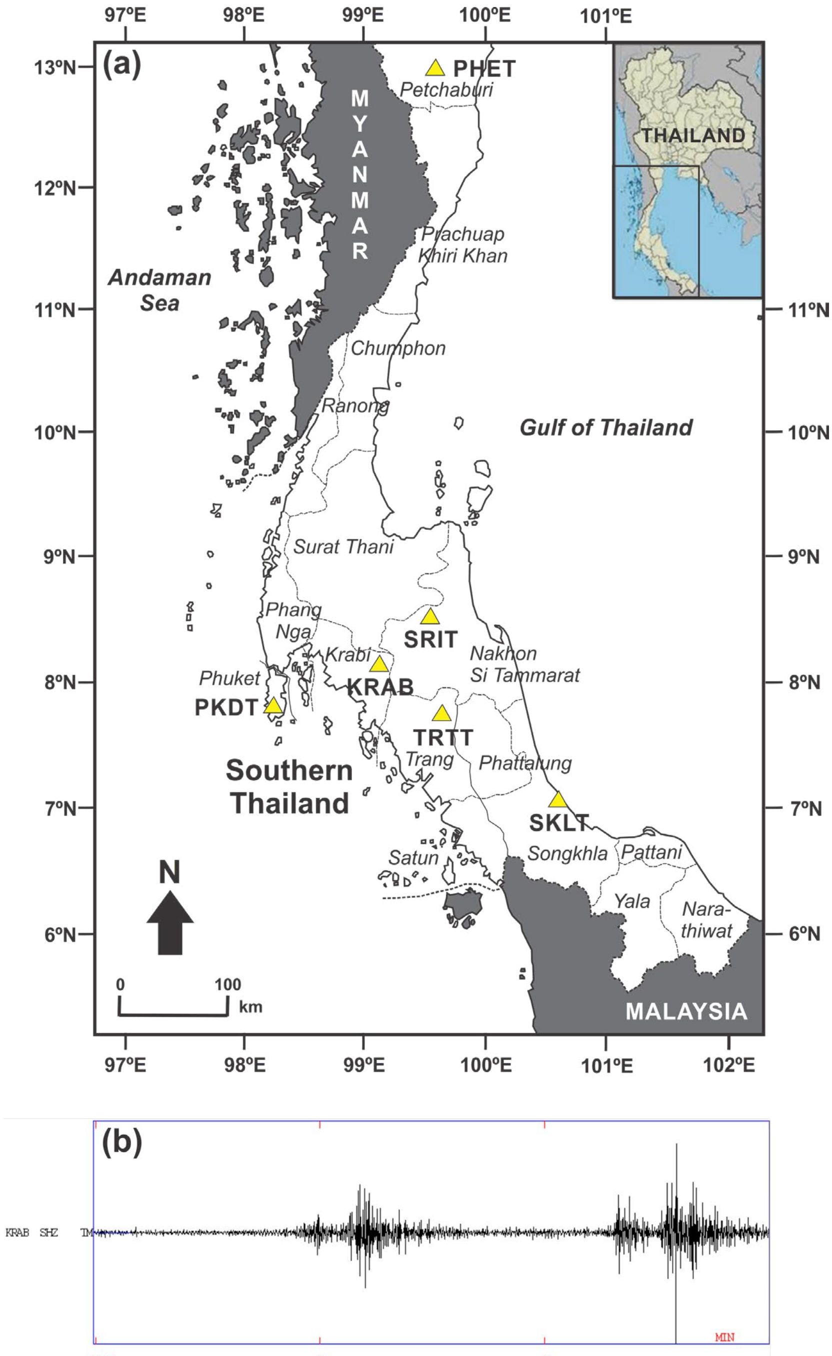


Figure 2. Location map of TMD's stations (yellow triangles) in Southern Thailand used in this study (a). Detailed information of all these stations refer to Table S1 (supplementary material); An example of digital seismogram for this swarm activity is shown by two events on 16 April 2012 with the original 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 $1.5 \leq ML \leq 4.1$. 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 $2.0 \leq ML \leq 3.0$ and a few events with $ML \leq 2.0$ and $ML \geq 3.0$. No event detected with $ML \leq 1.0$. 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).

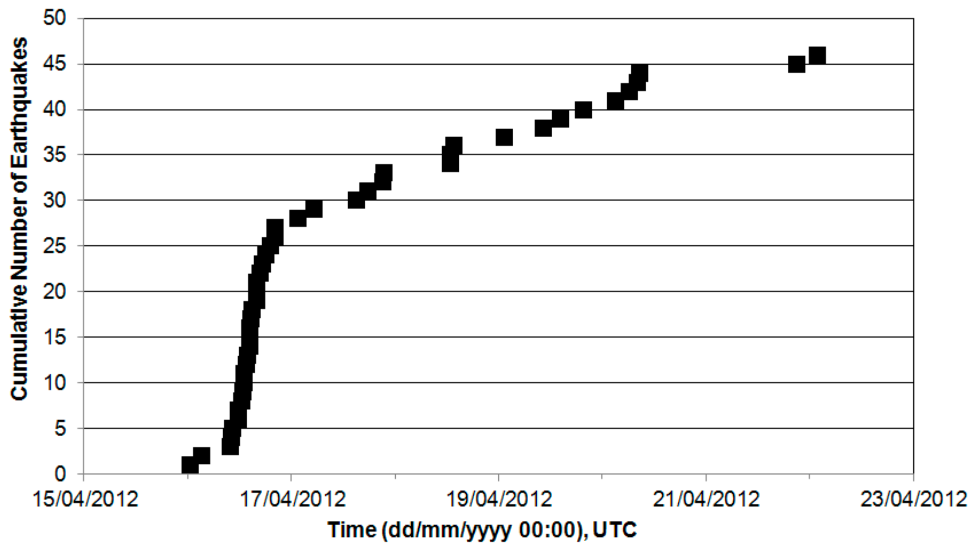
Event No.	Origin Date (UTC) (yyyy-mm-dd)	Origin Time (UTC) (hh:mm)	Latitude (N)	Longitude (E)	Magnitude (ML)	Focal Depth (km)	Recorded by stations	RMS Residual (s)
6*	2012-04-16	11:43	7.967	98.400	1.9	1.0	PKDT, KRAB, SRIT, TRTT, SKLT, PHET (6)	-
7*	2012-04-16	11:47	7.870	98.250	1.8	7.0	PKDT, KRAB, SRIT, 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].



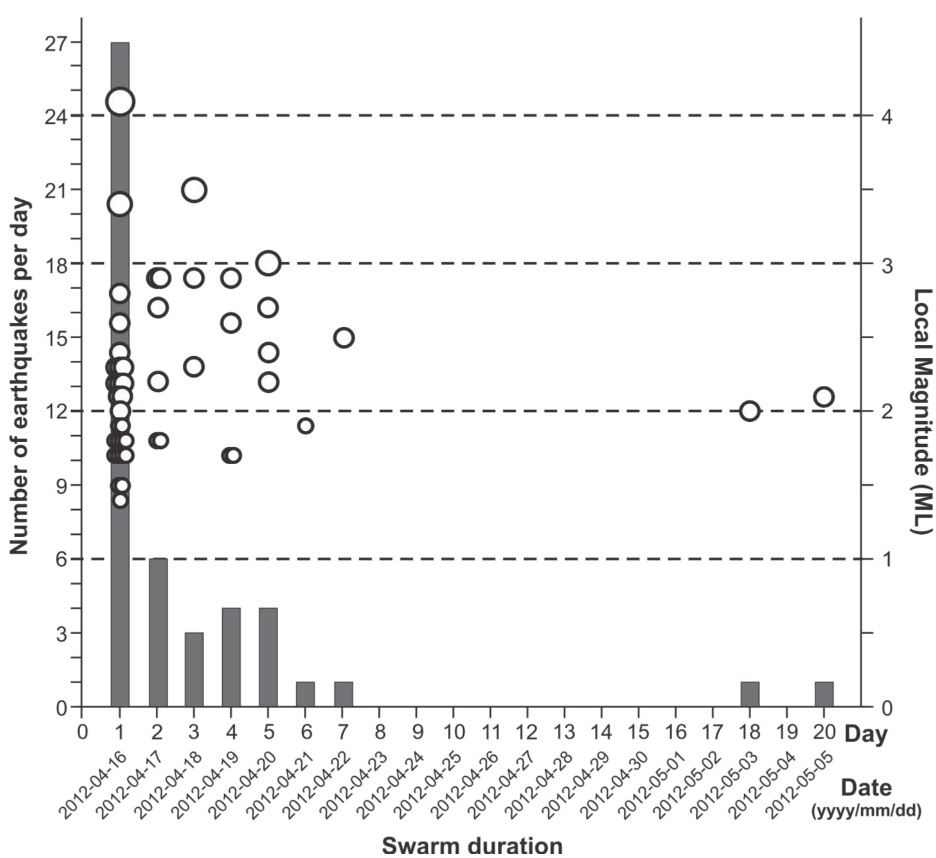


Figure 3. Cumulative number of earthquakes (black squares) for the first seven days of the swarm (top); Number of earthquakes per day (grey bars; lower left-hand side scale) and local magnitude variation (bottom) (circles; right-hand side scale) during the full 20-day duration of the 2012 Phuket swarm.

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

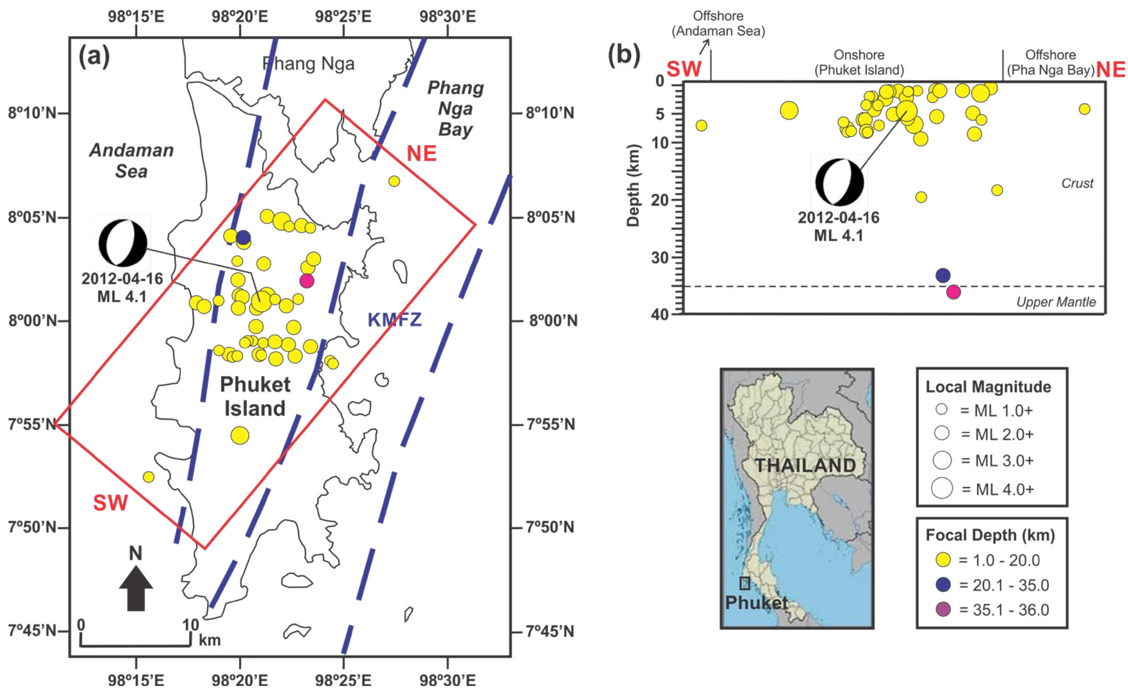


Figure 4. Epicenter map (a) of the 2012 Phuket swarm (period 16 April to 5 May 2012) shows the distribution of epicentral locations in the vicinity of the several faults (blue dashed lines) within the Khlong Marui Fault Zone (KMFZ). The focal mechanism of the largest event of the swarm obtained from [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

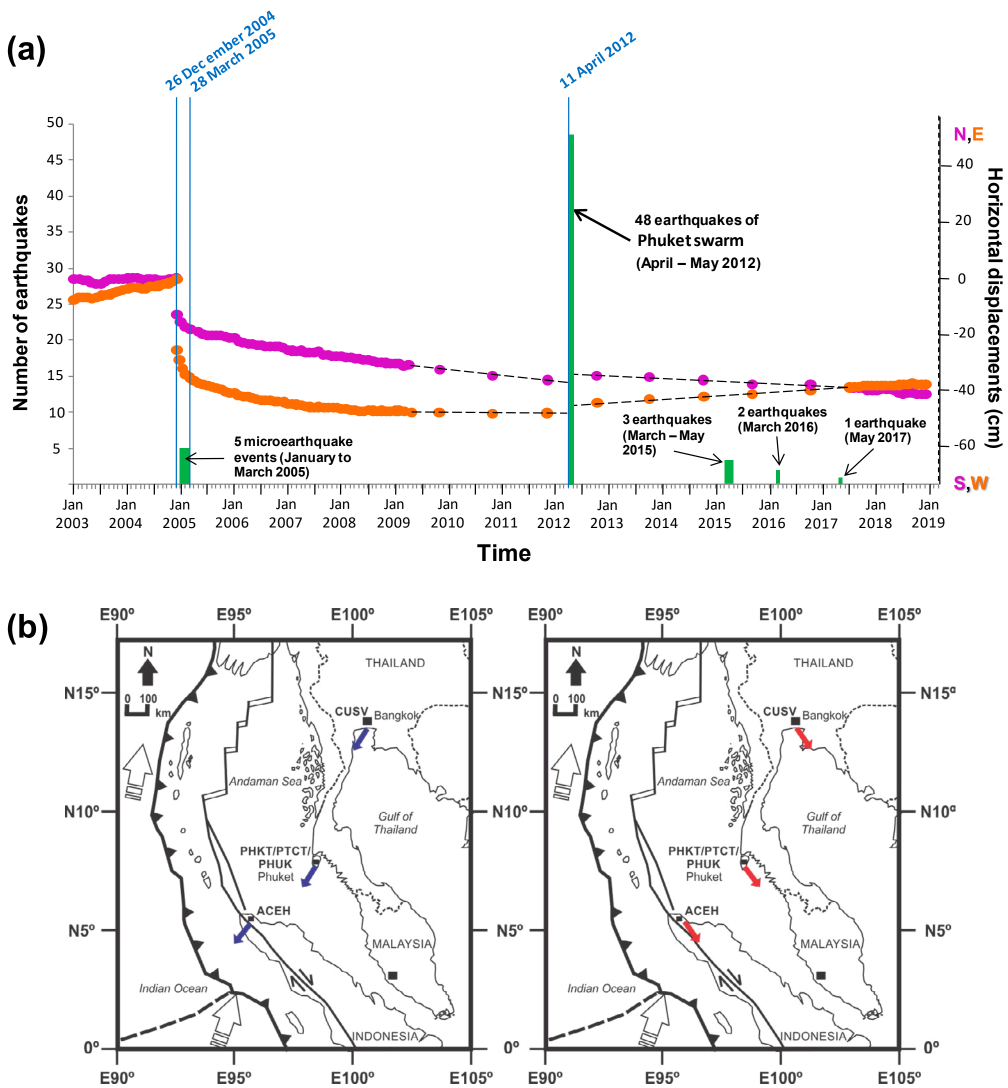


Figure 5. Graph showing relations between large regional earthquakes (a) i.e the 26-12-2004 Sumatra-Andaman (M9.1), the 28-03-2005 Nias (M8.6), and the 11-04-2012 EIO (M8.6 & M8.2) earthquakes (blue lines), the numbers of earthquakes ever recorded in Phuket Island since 2003 until recent time (green 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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