



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 north-eastward 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

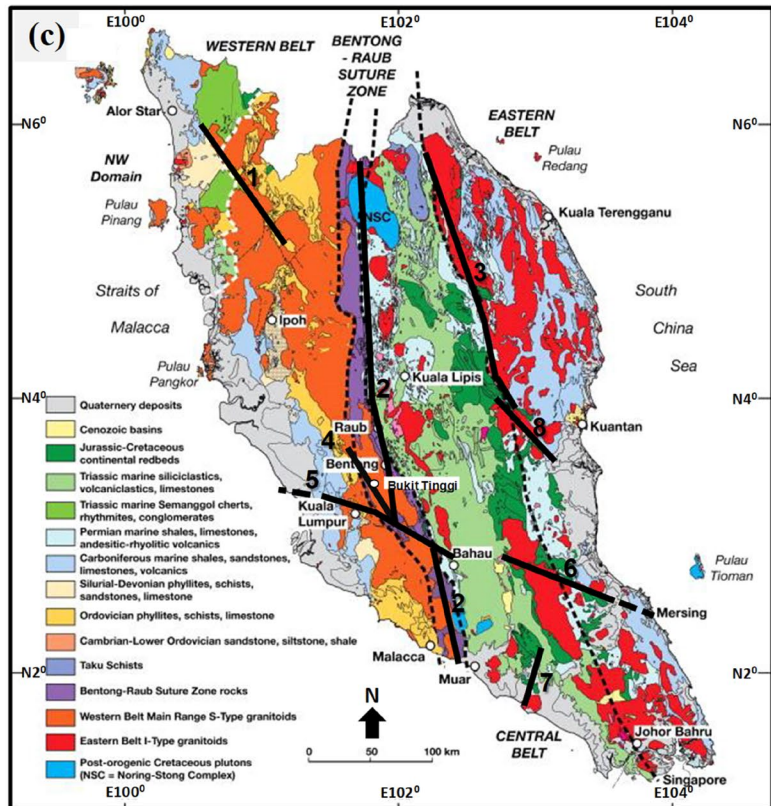
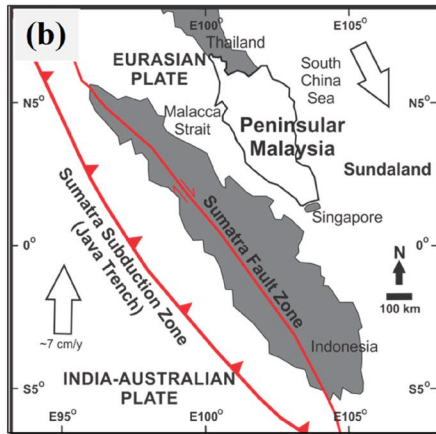
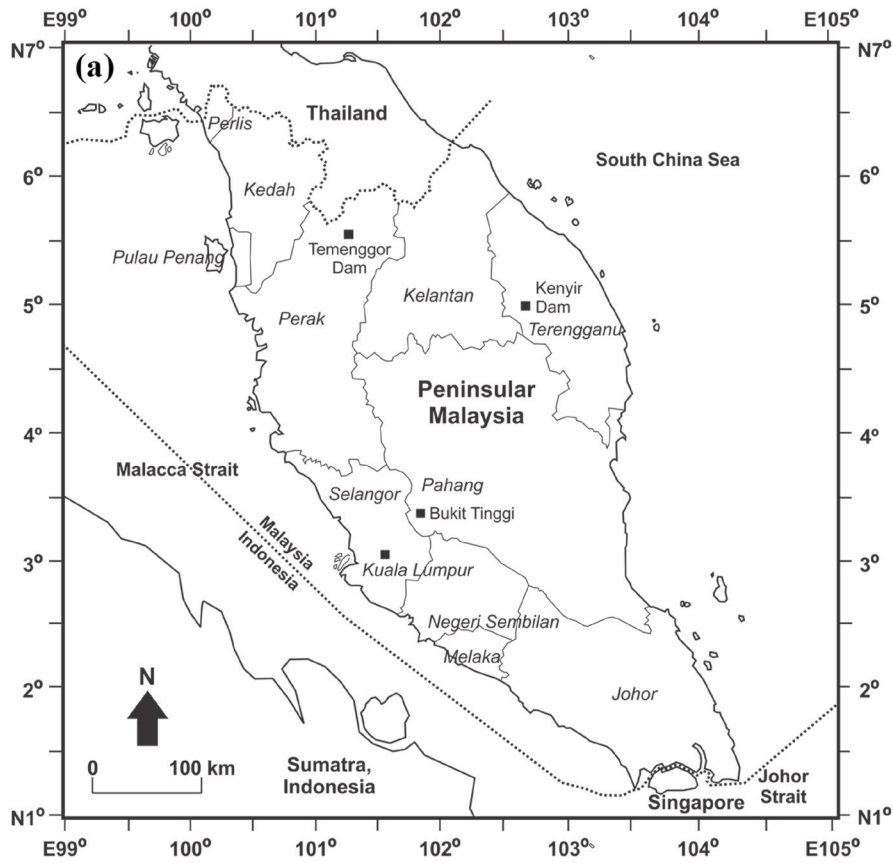


Fig. 1 **a** Location map of Peninsular Malaysia; **b** regional tectonic setting of Peninsular Malaysia; **c** general geology of Peninsular Malaysia [24] with local faults, adopted from Tjia [20, 21], (1=Bok Bak Fault; 2=Kelau-Karak Fault; 3=Lebir Fault; 4=Bukit Tinggi Fault; 5=Kuala Lumpur Fault; 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

Ottmöller [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 V_p/V_s 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

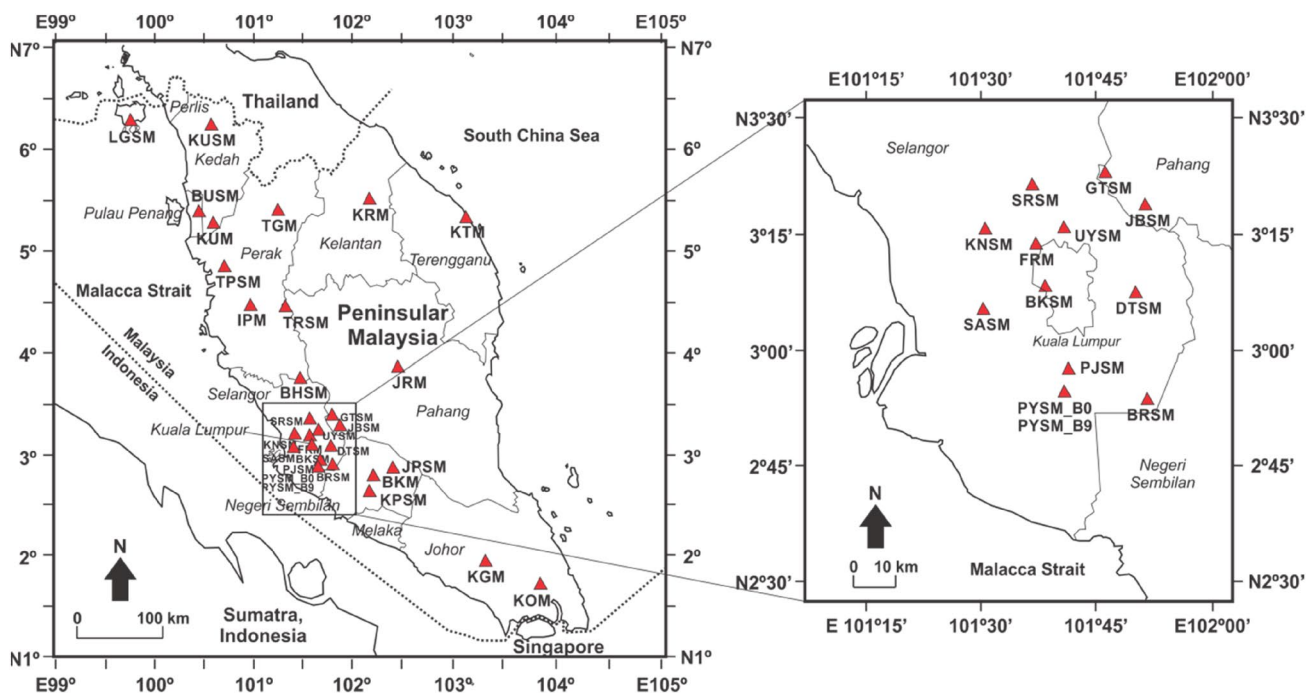


Fig. 2 Location map of all permanent, local seismological stations used in this study to monitor earthquakes in Peninsular Malaysia during 2007–2016. Triangles indicate locations of seismological stations operated by MMD (MetMalaysia). Note: Created with CorelDraw

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. HYPYOCENTER 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:

$$ML = \log A_{\max} - \log A_0 \quad (1)$$

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 $((-4.5) - (-2.8)) \times (100 - 60) / (400 - 60) - 2.8 = -3.0$. 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:

$$Ms = 1.1198mb - 0.7796 \quad (2)$$

and

$$Mw = 0.8693Ms + 0.9135 \quad (3)$$

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

$$Mw = 0.9734mb + 0.2358 \quad (4)$$

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),

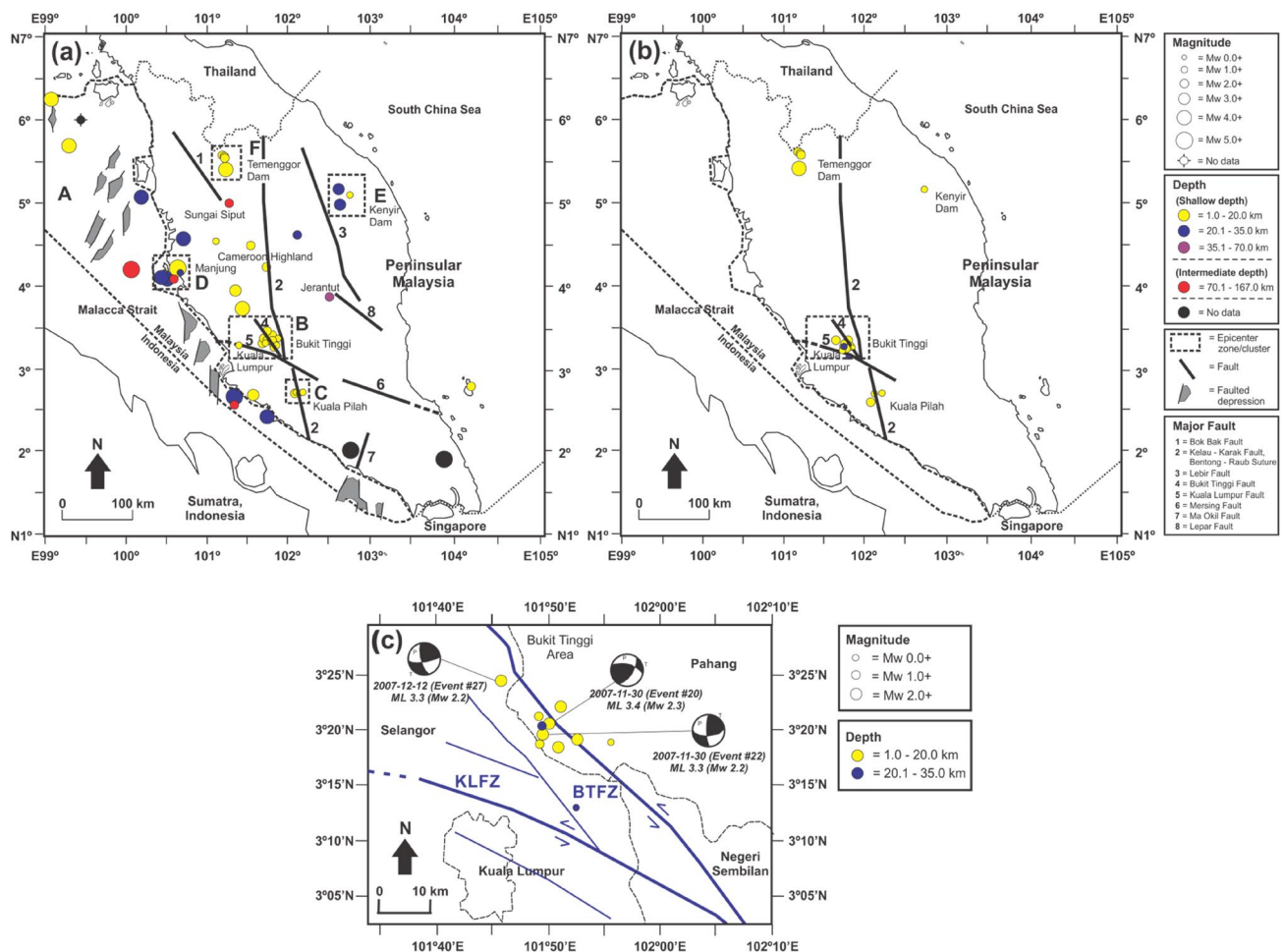


Fig. 3 **a** Epicenter map of Peninsular Malaysia shows the spatial distribution of recorded earthquakes from several international and national agencies during 1922–2020 in relation to the Mw (symbolized by dots with different sizes) and focal depth (symbolized by different colors). Zones of earthquake 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 Temenggong 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,

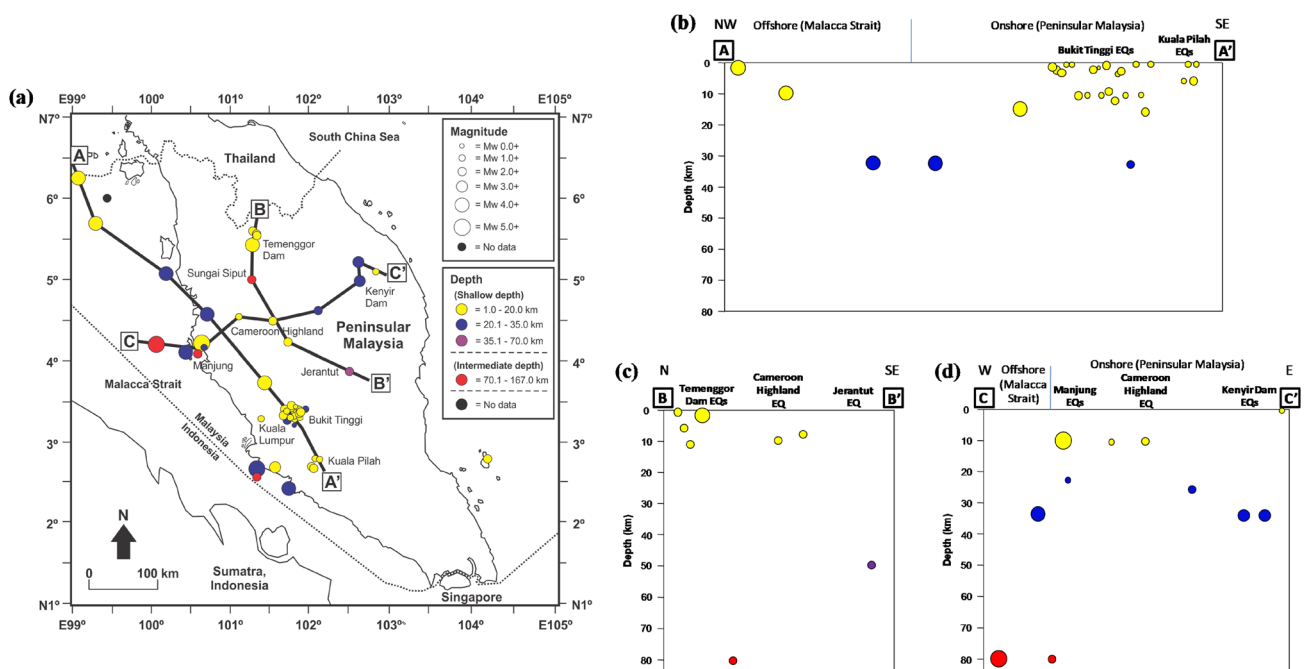


Fig. 4 Vertical sections of focal depth distribution in Peninsular Malaysia during the period 1922–2020. **a** Epicenter map with three cross sections (A–A', B–B', and C–C'). **b** Depth profile A–A' with the

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 Corel-Draw

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

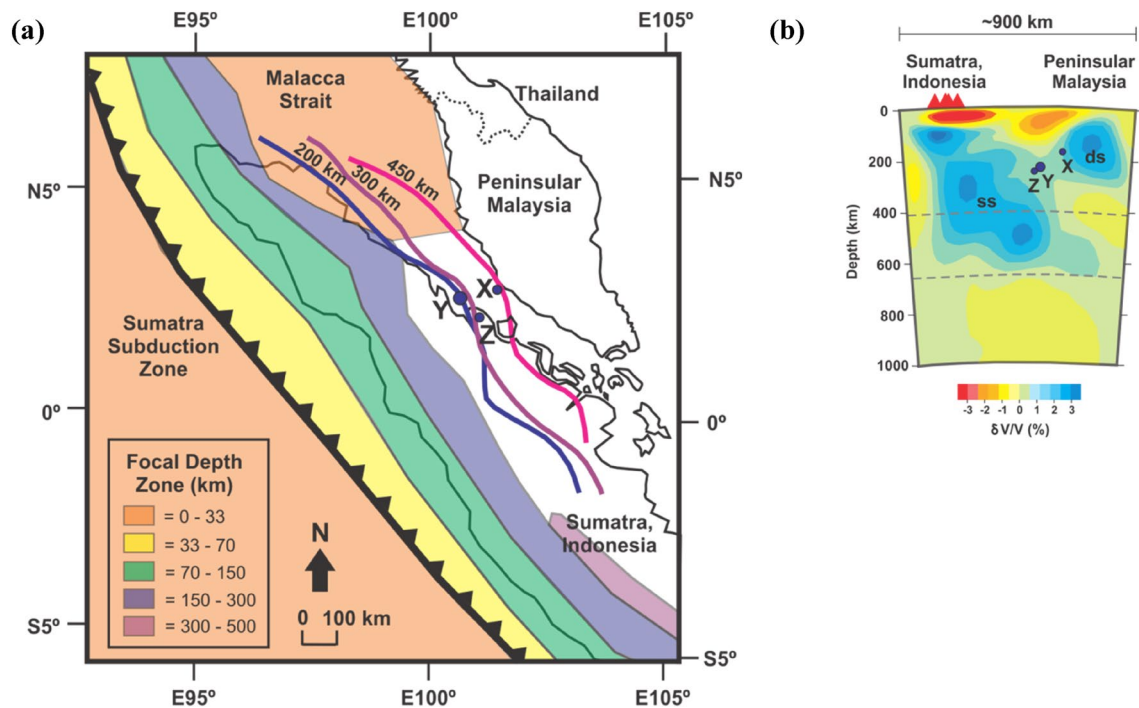


Fig. 5 Deeper earthquakes. **a** Focal depth zones in the SSZ and its surrounding regions (over the period 100 years: 1919–2019; redrawn from the seismicity map obtained from USGS Earthquake Catalog, <https://earthquake.usgs.gov/earthquakes/search>) with slab contours at selected depths redrawn from 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

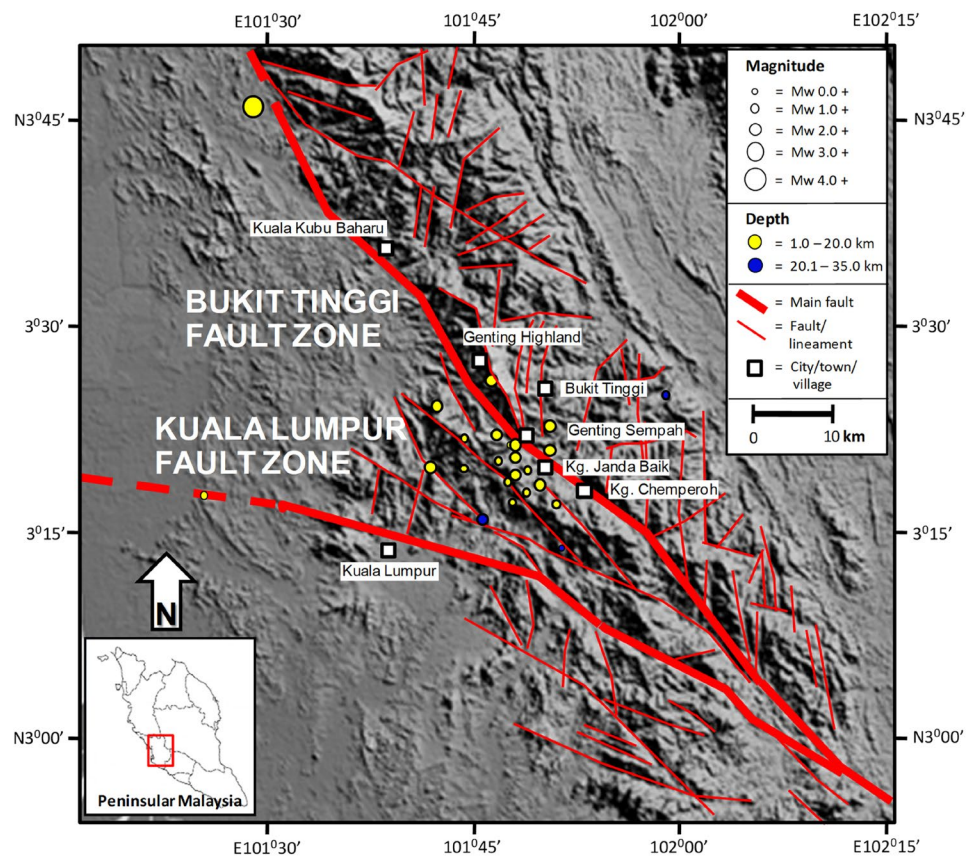
offshore Peninsular Malaysia (ML 3.1, 1992-09-25 earthquake); meanwhile, Y and Z are locations of two nearby earthquakes in the Malacca Strait of Indonesian territory, the 2004-04-29 (ML 4.8) and 1992-11-02 (ML 3.1) earthquakes, which have focal depths of 220 km and 235 km, respectively. “ss” is the 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 Tinggi and 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

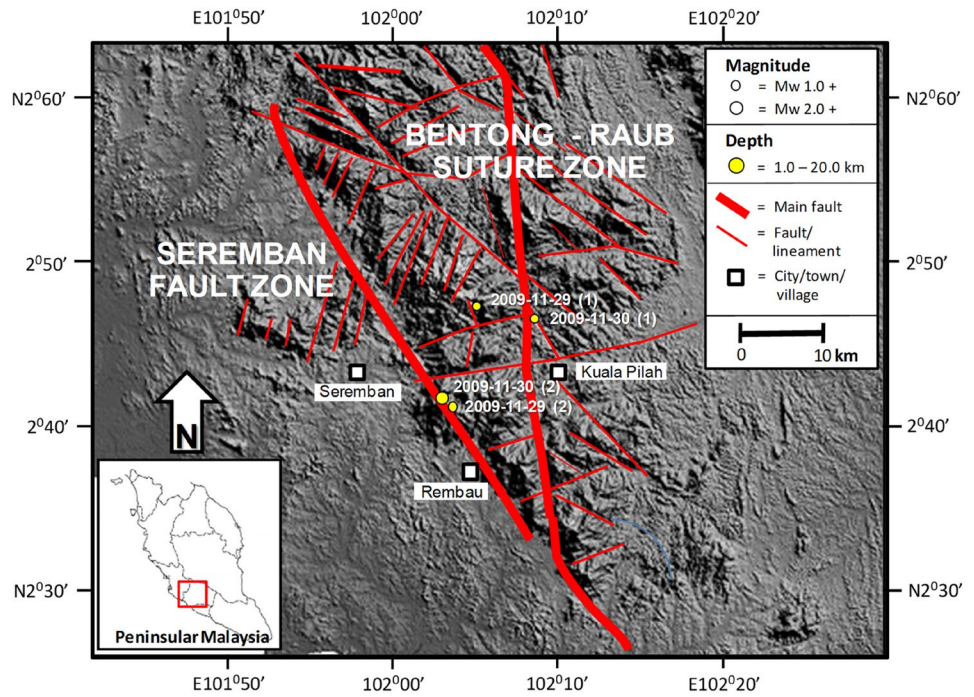
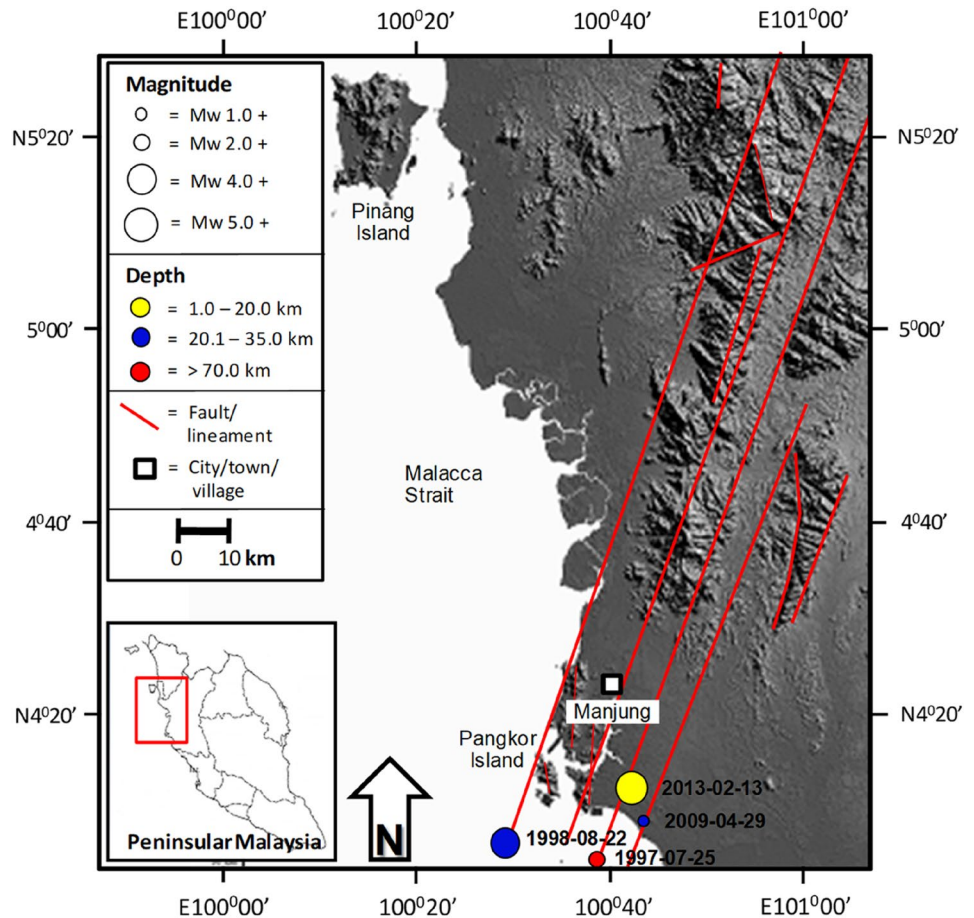


Fig. 8 Plot of earthquake epicenters during the studied period on the SRTM–DEM image in Manjung area. Red thinner lines here are lineaments indicating possible faults. Note: Created with CorelDraw



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.

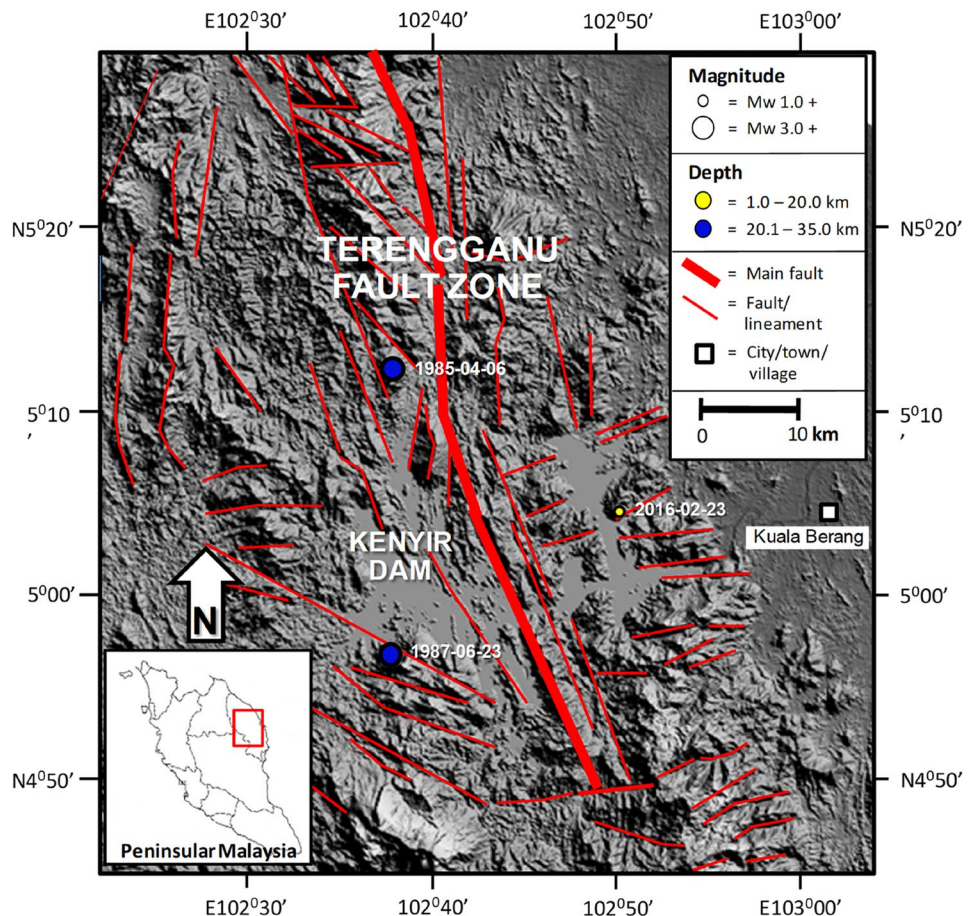
A previous study by Shuib et al. [68] identified active faults by using remote sensing, geophysics, geomorphology, and geological mapping and showed that there are several lineament sets with the NE-SW and N-S trends displaying evidences of Quaternary movements in this coastal area. There were few earthquakes 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 km² 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 km³ 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

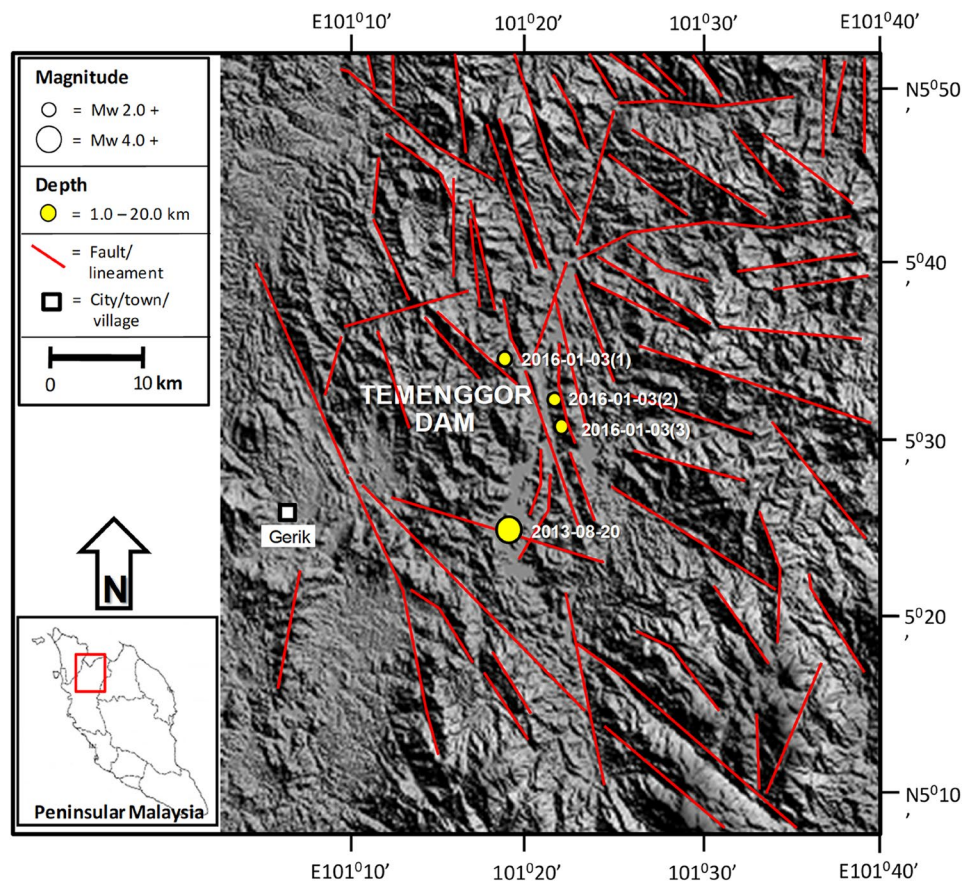
Other than the aforementioned zones, there are also other areas in Peninsular Malaysia where earthquake events have occurred in the region, such as Jerantut and Cameron Highland (both are located in the state of Pahang) and Sungai Siput (Perak). However, they occurred each as a single event and scattered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

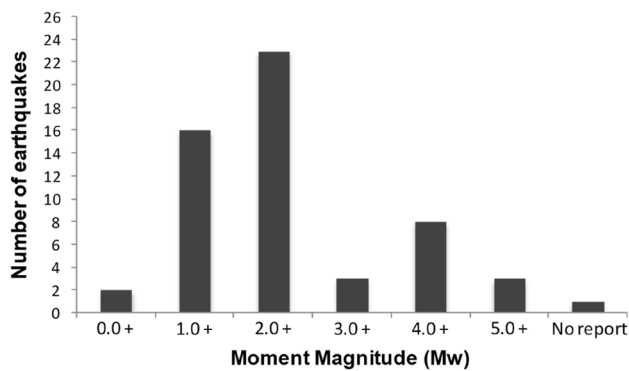


Fig. 11 Magnitude variation of local earthquakes in Peninsular Malaysia during the period 1922–2020. Note: Created with MS Office

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.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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