

The recent Bukit Tinggi earthquakes and their relationship to major geological structures

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Abstract— This paper presents the study on the cause of the recent, small and shallow intraplate earthquakes in the Bukit Tinggi area. It discusses the correlation between the earthquake localities and the regional lineaments/structures of the area interpreted from SRTM digital elevation model. The results of the study show that the earthquakes are located at or near to the intersection of three sets of major lineaments trending N-S, NW-SE and NE-SW. This corresponds to the N-S faults, the NW-SE Bukit Tinggi and Kuala Lumpur fault zones and the NE-SW faults, respectively. It is interpreted that the earthquakes are due to the reactivation of the above faults. The fault reactivations are believed to be the result of stress build-up due to the present-day tectonics in SE Asia (Sundaland), especially the oblique, NNE-oriented subduction of the Indo–Australian plate under the Sundaland. The earthquake occurrences indicate that the core of Sundaland is also deforming and that earthquakes do occur in Peninsular Malaysia. It is implied that the intraplate deformation zone associated with the Sumatran Subduction Zone is wide, encompassing Peninsular Malaysia. Hence, it is suggested that the design of large engineering structures in Peninsular Malaysia must take into consideration the possible seismicity due to the reactivation of ancient major faults zones, the seismicity due to tremors from seismic waves generated with epicentres located in Sumatra and rarely, major dam-induced seismicity.

Abstrak— Kertas kerja ini mengemukakan kajian terhadap punca gempa bumi intraplat bermagnitud kecil dan cetek yang berlaku baru-baru ini di sekitar Bukit Tinggi. Kertas ini membincangkan korelasi antara kedudukan gempa bumi dengan lineamen dan struktur rantau dengan menggunakan model aras digital SRTM. Hasil kajian menunjukkan gempa bumi-gempabumi ini terletak pada atau berhampiran dengan persilangan antara tiga lineamen utama yang menjurus U-S, BL-TG dan TL-BD yang berpadanan dengan zon-zon sesar Bukit Tinggi – Kuala Lumpur serta sesar menjurus U-S dan TL. Ditafsirkan bahawa gempa bumi-gempabumi ini disebabkan oleh pengaktifan semula sesar-sesar atas. Pengaktifan semula ini disebabkan oleh peningkatan tegasan intraplat berpunca daripada aktiviti tektonik kini di Asia Tenggara (Pentas Sunda), terutamanya subduksi menyerong Plat Indo-Australia ke bawah Sundaland. Maka disyorkan rekabentuk struktur-struktur kejuruteraan besar di Semenanjung Malaysia mesti mengambil kira kesan seismik akibat pengaktifan semula sesar-sesar kuno tempatan, kesan dari gempa bumi yang berpunca dari Sumatra dan gegaran akibat daripada pembebanan empangan major tempatan.

Keywords: intraplate, earthquakes, seismicity, lineaments, tectonics, Bukit Tinggi

INTRODUCTION

The recent, small intraplate earthquakes in the Bukit Tinggi area, along the Selangor-Pahang boundary (Figure 1), have been enigmatic. The paradigm of plate tectonics predicts concentrations of earthquakes, volcanism, and other tectonic activity within narrowly-defined plate boundaries, but no significant deformation within the rigid plates. Thus the $M_w = 1.7$ to 3.7 earthquake near Bukit Tinggi, Malaysia, which occurred from November 2007 to May 2008, has stimulated considerable interest and debate.

To get to the heart of this debate, this paper discusses the relationship between the earthquakes and the regional structures of the Bukit Tinggi area. It attempts to address the question of what caused the Bukit Tinggi earthquakes. Numerous hints have been provided by geological observations. The Bukit Tinggi earthquakes occurred in a region of an abnormally high concentrations of major ancient faults and hotspots.



Figure 1: Map showing the locations of the recent Bukit Tinggi earthquakes.

THE EARTHQUAKE FACTS

Since 30 November 2007, 23 earthquakes have occurred in Bukit Tinggi and the surrounding areas. Table 1 shows the characteristics of the earthquakes as released by the Meteorological Department of Malaysia (MMD). These earthquakes were mild. Residents reported minor tremors but there were no reports of property damage. The shallow (1.2 to 6.7 km depth) and mild $M_w = 1.7$ to 3.7 earthquakes (MMD, 2008) which occurred from November 2007 to May 2008, have stimulated considerable interests and debate. Located about 600 km away from the plate boundary (Figure 2), the Bukit Tinggi earthquakes share significant similarities with other intraplate earthquakes in that there are a lack of surface ruptures.

TECTONIC SETTING OF PENINSULAR MALAYSIA

Peninsular Malaysia is located in the southern part of the stable microcontinent/block called Sundaland, with the E-dipping subduction of Indo-Australian plate in the W and the S, and the W-dipping Philippine plate in the E (Figure 3). Before the Bukit Tinggi earthquakes, Peninsular Malaysia was experiencing only low seismic activity level tremors due to seismic waves generated by earthquakes with epicentres located in Sumatra, or rarely, the induced seismicity near Kenyir Dam (Raj, 1994; Che Noorliza Lat, 1997a & b, 1999, 2002). The maximum observed intensities of the tremors that originate from the Sumatran epicenters on the Modified Mercalli (MM) scale are VI for Peninsular Malaysia (Mohd Rosaidi bin Che Abas, 2001). Thus the earthquakes that gave rise to tremors in the Bukit Tinggi area, along the Selangor-Pahang boundary and just north of Kuala Lumpur (Figure 1) are enigmatic.

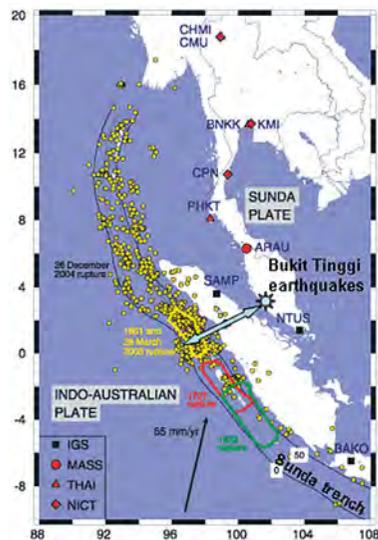


Figure 2: Map showing the distance between the Bukit Tinggi earthquake localities in relation to the Sunda Trench.

GEOLOGY AND FAULTS

The Bukit Tinggi area is dissected by several intersecting lineaments/fault zones (Figure 4). These were mapped from remote sensing imagery of the surface (topography, SRTM digital elevation model, and aerial photos), and have been subject to rigorous verification with field-mapped fault data by various geologists (Shu, 1969; Ng, 1994; Zaiton Harun, 2002). Lineaments on the SRTM DEM correlate with faults mapped in the field and show spatial continuity between and beyond mapped faults, thereby providing a fuller coverage of regional structural patterns than previously known. The topography of the area is dominated by 5 sets of distinct lineaments. These are the 1) NW-SE, 2) N-S, 3) NE-SW, 4) ENE-WSW sets, and 5) a less prominent E-W set as shown in Figure 2.

The above lineaments can be corresponded to five sets of steeply dipping mesoscopic brittle faults and shear zones. These are the sinistral NW-SE (the Kuala Lumpur and Bukit Tinggi fault zones) and N-S faults, dextral NE-SW faults and ENE-WSW faults, and a less prominent normal to sinistral E-W faults as shown in Figure 4. These faults were said to be active until the Tertiary. The major faults in the area are described below.

Bukit Tinggi Fault Zone

The NE-SE trending, predominantly sinistral Bukit Tinggi Fault Zone is situated just north of the Kuala Lumpur Fault Zone (Figure 4; Stauffer, 1968). The fault can be traced up to Kuala Kubu Bharu (Shu, 1969). Unlike the Kuala Lumpur Fault Zone, the surface trace of this curvilinear fault zone is distinct and strongly expressed. On the SRTM DEM and StereoSAR imageries, the surface trace of the fault zone is well expressed with excellent continuity for

Table 1: Characteristics of earthquakes around Bukit Tinggi (Source: MMD, 2008).

No.	Date	Time (MST)	Lat.	Long.	Mag. (M_w)	Depth (km)
	30/11/2007	10.13 am	3.36°N	101.80°E	3.5	2.3 km
	30/11/2007	10.42 am	3.34°N	101.80°E	2.8	<10 km
	30/11/2007	8.42 pm	3.31°N	101.84°E	3.2	6.7 km
	4/12/2007	6.12 pm	3.40°N	101.80°E	3.0	<10 km
	5/12/2007	3.57 am	3.37°N	101.81°E	3.3	<10 km
	6/12/2007	11.23 pm	3.36°N	101.81°E	2.7	<10 km
	9/12/2007	8.55 pm	3.33°N	101.82°E	3.5	4.9 km
	12/12/2007	6.01 pm	3.48°N	101.76°E	3.2	<10 km
	31/12/2007	5.19 pm	3.32°N	101.81°E	2.5	<10 km
	10/01/2008	9.26 pm	3.17°N	101.61°E	1.7	1.2
	10/01/2008	11.38 pm	3.39°N	101.80°E	2.5	3.0
	13/01/2008	10.24 am	3.30°N	101.90°E	2.9	<10 km
	13/01/2008	6.18 pm	3.30°N	101.80°E	2.5	<10 km
	13/01/2008	11.59 pm	3.40°N	101.86°E	1.9	3.0
	14/01/2008	11.45 pm	3.42°N	101.79°E	3.4	<10 km
	15/01/2008	6.24 am	3.63°N	101.24°E	2.9	<10 km
	15/01/2008	12.41 pm	3.35°N	101.77°E	2.5	<10 km
	10/01/2008	11.38 pm	3.39°N	101.73°E	3.0	<10 km
	15/03/2008	8.50 am	3.30°N	101.70°E	3.3	<10 km
	15/03/2008	7.35 am	3.50°N	101.80°E	1.8	<10 km
	15/03/2008	7.16 am	3.30°N	101.70°E	2.8	<10 km
	27/03/2008	9.46 am	3.80°N	102.40°E	3.0	<10 km
	25/05/2008	9.36 am	3.31°N	101.65°E	3.0	<10 km

a distance of at least 120 km. It can be shown to extend further northwards along the boundary between granite and country rock up to the Bujang Melaka stock in Perak.

The fault is characterized by mylonite zones, fault breccias and large quartz veins. Microscopic and field studies on the mylonites show that the early ductile microstructures were superimposed by later brittle-ductile and brittle structures. Within the mylonites, a distinct foliation and stretching lineation defined by symmetric to asymmetric lenses of feldspar and elongated quartz are commonly found. The sub-horizontal to moderately inclined stretching lineations in the mylonites along the fault zone shows that it is a strike-slip fault zone with a significant dip-slip component. Fault kinematic studies on the mylonites at Bukit Tinggi show that the early ductile movement had a dextral sense of shear (Ng, 1994) but at Kuala Kelawang and along the Karak Highway, Zaiton Haron (2002) shows that the movements were sinistral. This is attributed to the reactivation of the early dextral Bukit Tinggi Fault Zone by later sinistral fault movements.

A zone of protomylonite at km 32 of the Karak Highway exhibits only plastic microstructures indicating deformation at 450°C, probably occurring shortly after the emplacement of the Late Triassic granite, before complete cooling (Ng 1994). This shows that the Bukit Tinggi Fault Zone may have been initiated as early as Late Triassic to Jurassic. The superimposition of brittle deformations on the fault zone may indicate that the fault zone had suffered several episodes of brittle-ductile reactivation. This is confirmed by the age of faulting determined by Zaiton Haron (2002) on the sinistral mylonitic fault zone at Kuala Kelawang, which gives a Late Cretaceous age (83.6 Ma). Movements along the fault may have occurred with dextral sense in the Late Triassic-Jurassic, sinistral sense in the Late Cretaceous and brittle sinistral faulting up to the Tertiary.

Kuala Lumpur Fault Zone

The Kuala Lumpur Fault Zone is well established. On SRTM DEM, Landsat imagery, and the StereoSAR DEM, the surface expression of the fault zone is indistinct, broad and diffuse. The fault zone has a minimum width of 10 km and a total displacement of more than 20 km. The fault zone is made up of five main strands, each defined by steep mesoscopic brittle faults and shear zones. These are the sinistral NW–SE and N–S, dextral NE–SW, and ENE–WSW sets and a less prominent normal to sinistral E–W set. Four hot springs at Setapak and Selayang are within the Kuala Lumpur Fault Zone.

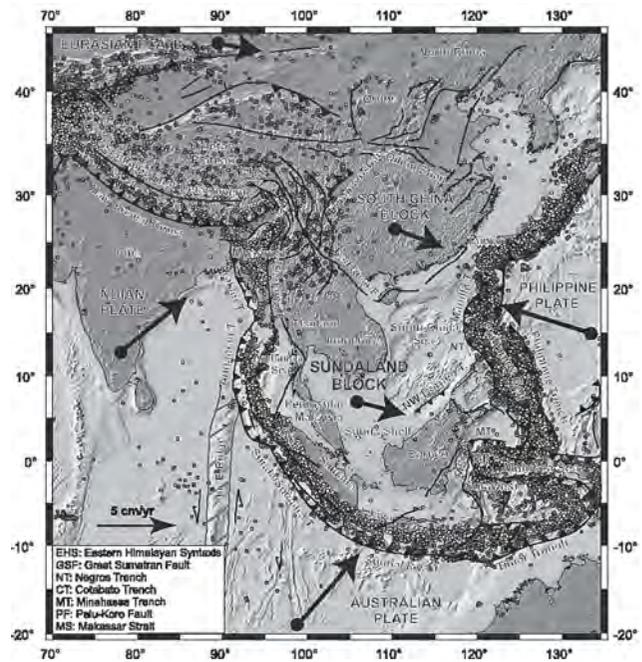


Figure 3: The tectonic setting of Peninsula Malaysia showing the Sundaland block/microcontinent (after Simons *et al.*, 2007).

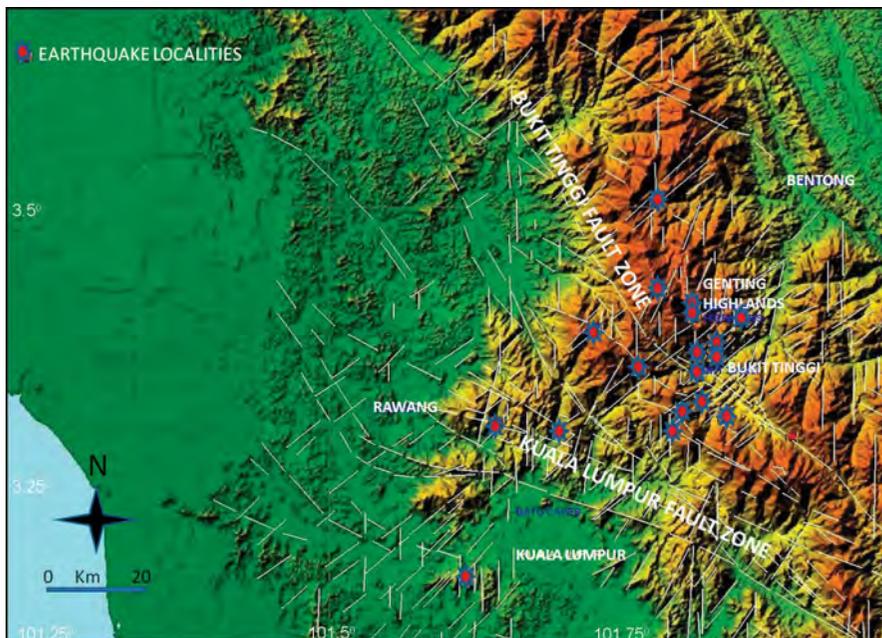


Figure 4: Map showing the spatial relationship between the Bukit Tinggi earthquakes and the lineaments of the surrounding area.

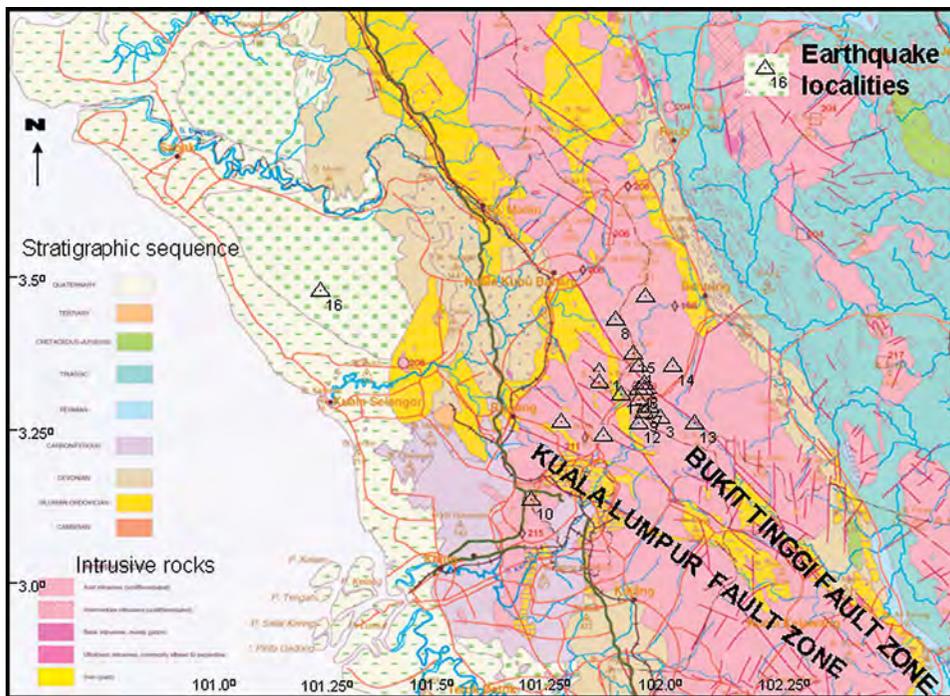


Figure 5: Map showing the relationship between the earthquake localities and the regional geology (geological map after GSD, 1985)

The N-S Faults

A broad zone of distinct and straight but discontinuous lineaments define the N-S fault zones. The N-S lineament trend can be traced from Sungai Bentong in the N to Janda Baik in the S. It also cut the Kuala Lumpur area. To the E, the N-S faults can be traced from Tampin in the S to Karak in the N. Other smaller parallel lineaments can also be traced. These give rise to a 25 km wide zone of N-S lineaments cut across the Main Range. The largest earthquake in the Bukit Tinggi area occurred on or near this lineament (magnitude 3.5) and more recently, smaller magnitude earthquakes have occurred along this lineament. In the field they are expressed as a wide zone of breccias, laced with some quartz veins. The N-S faults are also identified as forming the major structure that controlled the distribution of the Straits of Malacca Tertiary basins.

The NE-SW Faults

The third set of lineaments are distinct and straight but discontinuous. This broad zone of lineaments cuts through the Main Range Granite. It is associated with quartz reefs or pegmatite dykes. The Dusun Tua and Semenyih hot springs occur along this fault zone.

EARTHQUAKES RELATIONSHIP TO GEOLOGY AND FAULTS

Figure 5 shows the surface location of the earthquakes in relation to the lineaments, geology and faults respectively. With the exception of the earthquake locality near Sabak Bernam (in alluvium), all earthquakes were located in granite bedrock. Each individual epicenter is located at the intersection of 2 to 3 major lineaments/faults.

The close correspondence between the ancient fault traces and present-day seismicity in the Bukit Tinggi area is

intriguing. Most of the earthquakes with magnitudes around 3.0 to 3.7 occurred along the NNW-SSE lineaments which correspond to the Bukit Tinggi Fault Zone. Two earthquakes of magnitude around 2.5 to 3.0 occurred along the NW-SE lineaments which correspond to the Kuala Lumpur Fault Zone. A few other earthquakes with magnitudes 2.5 to 3.5 are found located in between these fault zones. Most of them are aligned in a N-S direction along prominent N-S lineaments. A weak northeasterly trend is also discernable (Figure 4).

At least three sets of prominent topographic lineaments correspond to zones of seismicity in the Bukit Tinggi area. The earthquakes were located at or near to the intersection of regional lineaments/faults. They seem to have occurred at the intersection of 3 cross-cutting trends as shown in Figure 6. They are the Kuala Lumpur – Bukit Tinggi trend, N-S trend and NE-SW trend, which corresponds to the NW-SE Bukit Tinggi and Kuala Lumpur Fault Zones, the N-S faults and the NE-SW faults, respectively.

A DISCUSSION ON THE CAUSE OF THE EARTHQUAKES

The occurrence of earthquakes in the Bukit Tinggi area apparently violates the plate tectonic model. However, it may be possible to explain the occurrence of earthquakes within the framework of the present-day tectonics. The challenge in figuring out why the earthquakes occur in Bukit Tinggi area is that the earthquake process in plate interior is more complex than at plate boundaries. Unlike the situation in Sumatra, since there are no surface ruptures, the relationship between earthquakes and geologically mapped faults in Bukit Tinggi area cannot be proven.

The present study noted a spatial association of the intraplate earthquakes with fault intersections. Based on this

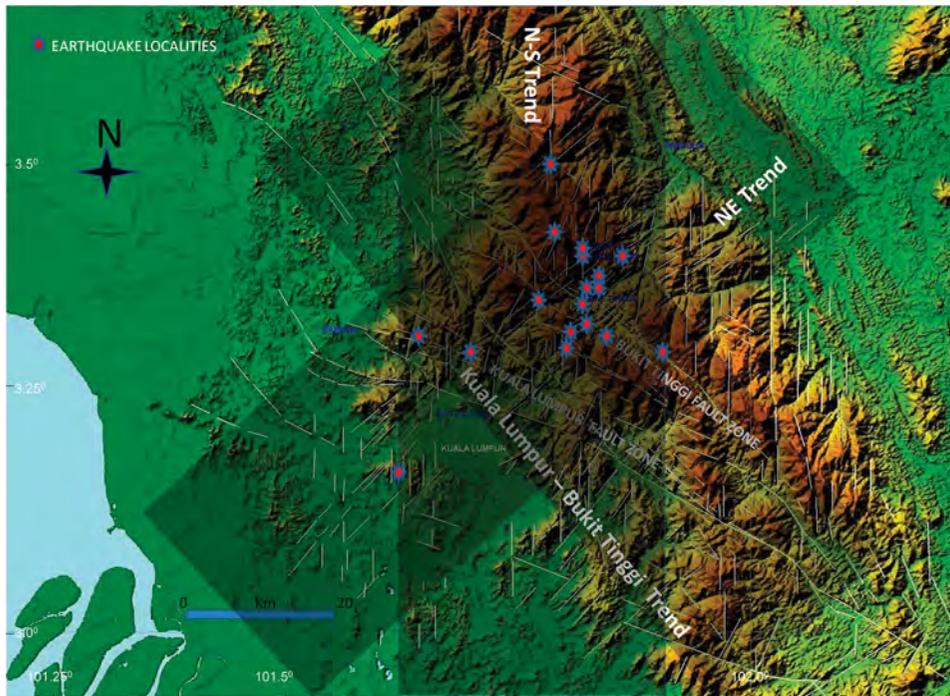


Figure 6: SRTM shaded relief map showing the three seismogenic zones.

observed spatial association, the relation of the earthquakes to the regional faults is taken to show that “ancient zones of weakness” are being reactivated in the present-day stress field. The preexisting faults and/or other geological features formed during ancient geological episodes persist in the intraplate crust, and by way of analogy with plate boundary seismicity, earthquakes occur when the present-day stress is released along these zones of weakness.

IMPLICATION FOR SUNDALAND DEFORMATION

Before the Mw 9.3, 26 December 2004, devastating Sumatran earthquake, Simons *et al.* (2004) show that Sundaland was relatively stable with a rigid core, and deformation occurring only at the edges. During the Mw 9.3 earthquake, Sundaland deformed more than 2000 km inside the core. Co-seismic displacements were up to 20 cm/min. After Mw 9.0 earthquake, Sundaland continues to deform significantly. The high interplate deformation rate resulted in a wide intraplate deformation zone. This wide intraplate deformation zone encompasses Peninsular Malaysia which is situated more than 600 km away from the Sumatran trench. The presence of earthquakes in Bukit Tinggi area supports the notion that the Sundaland core is deforming.

CONCLUSION

The relationship between the location of the Bukit Tinggi earthquakes, known major faults and hot springs is intriguing. The earthquake occurrences in the Bukit Tinggi area were the result of fault reactivation due to intraplate stress build-up. The stress build-up is due to the present-day tectonics in SE Asia (Sundaland), especially the oblique, NNE-oriented subduction of the Indo–Australian

plate under the Sundaland. The earthquake occurrences support the notion that Sundaland core is deforming. It implied that the intraplate deformation zone associated with the Sumatran Subduction Zone is wide and encompasses Peninsular Malaysia.

The earthquake occurrences in Bukit Tinggi area indicated that ancient faults in Peninsular Malaysia can be reactivated. A recent version of the National Seismic Hazard Maps developed by the Azlan *et al.* (2005) showed that the Peak Ground Acceleration (PGA) across the Peninsular Malaysia range between 10 and 25 gal for 10% probability of exceedance, and between 15 and 35 gal for 2% probability of exceedance in 50 years hazard levels. The hazard maps take into consideration only the tremors that were derived from Sumatra. Due to the presence of earthquakes that originate within the peninsula, a new seismic hazard map should be drawn to include the potential hazards along the active faults.

Hence, it is suggested that the design of large engineering structures must take into consideration the possible seismicity due to reactivation of ancient major faults zones, the seismicity due to tremors from seismic waves generated with epicentres located in Sumatra and rarely, the induced seismicity near major dams.

Consequently, a study should be undertaken to determine active faults and major ancient faults that can potentially be reactivated. An inventory showing the location and characteristics of these faults should be made available to the public. This type of information can be used as input for the design and construction of buildings and for public policy decisions requiring an assessment of earthquake risk.

In conclusion, the better we can understand the cause of earthquakes in the Bukit Tinggi area and the nature of ground motion generated by those earthquakes, the better we will be able to provide the necessary information to evaluate and plan for earthquake risk in Malaysia.

ACKNOWLEDGMENT

The author would like to thank Pn. Irene Eu Swee Neo and En. Muhammad Nazri Noordin from the MMD for contributing the earthquake data. Discussions with my colleagues especially Prof. Dr. JK Raj and Assoc. Prof. Dr. Ng Tham Fatt and the critical reviews by Mr. Loganathan and Assoc. Prof. Dr. Tajul Anuar Jamaludin helped to improve the paper significantly.

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Manuscript received 3 March 2008
Revised manuscript received 20 July 2009