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Earthquake Science in Malaysia

Status, Challenges and Way Forward

FELIX TONGKUL

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INAUGURAL LECTURE

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Lastly, I wish to dedicate this lecture to all the families who lost their loved ones during the 2015 Ranau Earthquake. I hope that such episodes will not be repeated again in the future.

SYNOPSIS

Earthquake hazard is regarded as low throughout Malaysia, with the exception of Sabah where it is considered moderate. This elevated level of hazards was reinforced on 5 June 2015 when a magnitude 6.0 Richter Scale (Mw) earthquake struck Ranau, killing 18 climbers on nearby Mount Kinabalu. Despite this and other recent sizeable earthquakes, seismic hazard in Malaysia is poorly understood, yet the population is increasing and growth in buildings and infrastructure is rising. In the face of such rapid expansion, it is crucial that earthquake hazard is properly quantified in order to minimize future risk. The science of earthquake that deals with a scientific understanding of earthquake processes, their consequences and mitigation need to be constantly improved. This lecture highlights the level of earthquake hazard in Malaysia, the challenges in mitigating earthquake hazards and the way forward to strengthen earthquake science in Malaysia. Based on the 2015 Ranau earthquake experience, it is clear that we still have a long way to go in mitigating earthquake hazard in Malaysia. There is an urgent need to carry out comprehensive geological, geotechnical and engineering mapping of earthquake-prone areas and to carry out coordinated monitoring of earthquake events and crustal plate movements. Such tasks require planned human resource capacity building by related government agencies and universities, and the allocation of special research and development grant. Ideally, these tasks should be coordinated by a national earthquake research centre. Apart from the rigorous scientific activities, a coordinated public education programme on earthquake hazards and preparedness should be intensified and carried out continuously.

SINOPSIS

Bahaya gempa bumi di seluruh Malaysia dianggap sebagai rendah kecuali di Sabah di mana ia adalah sederhana. Peningkatan tahap bahaya ini diperkukuhkan oleh kejadian gempa bumi bermagnitud 6 Skala Richter (Mw) yang melanda Ranau pada 5 Jun 2015 di mana 18 pedaki Gunung Kinabalu terkorban. Walaupun kejadian gempa bumi ini dan begitu juga dengan beberapa kejadian gempa bumi lain bermagnitud sederhana yang berlaku kebelakangan ini, pemahaman bahaya gempa bumi di Malaysia masih rendah sungguhpun bilangan penduduk meningkat dan bangunan infrastruktur terus berkembang. Dalam berhadapan dengan pembangunan yang sangat pesat ini adalah sangat penting agar bahaya gempa bumi diukur secara terperinci untuk mengurangkan risiko pada masa hadapan. Sains gempa bumi yang merangkumi pemahaman saintifik berkaitan dengan proses gempa bumi, impak serta mitigasinya perlu sentiasa dipertingkatkan. Syarahan ini akan menekankan tahap bahaya gempa bumi di Malaysia, cabaran yang dihadapi untuk mengurangkan kesan gempa bumi dan bagaimana memperkukuhkan sains gempa bumi di Malaysia. Berdasarkan pada kejadian gempa bumi di Ranau pada 2015, agak jelas bahawa kita masih mempunyai perjalanan yang jauh untuk mengurangkan bahaya gempa bumi di Malaysia. Terdapat keperluan mendesak untuk menjalankan pemetaan geologi, geoteknik dan kejuruteraan yang komprehensif bagi kawasan yang kerap dilanda gempa bumi serta membuat pemantauan kejadian gempa bumi dan pergerakan plet bumi yang terselaras. Tanggungjawab tersebut memerlukan pembangunan kapasiti sumber manusia yang terancang oleh agensi-agensi kerajaan dan universiti-universiti yang berkaitan serta peruntukan khas dana penyelidikan dan pembangunan. Secara idealnya, tanggungjawab ini boleh diselaraskan oleh pusat kajian gempa bumi kebangsaan. Selain dari mempergiatkan aktiviti saintifik, program pendidikan awam berkaitan bahaya gempa bumi dan persediaan untuk menghadapi gempa bumi perlu dipertingkatkan dan dianjurkan secara berterusan.

Earthquake Science in Malaysia

Status, Challenges and Way Forward

by

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INTRODUCTION

Earthquake science deals with the scientific understanding of earthquake processes (origin and properties), their consequences and mitigation. Earthquake science encompasses the multidisciplinary field of geology, geodesy, rock mechanics and physics of complex system apart from seismology.

The main goal of earthquake research is to learn how to predict the behaviour of earthquake systems. The prediction has come to mean the accurate forecasting of time, place, and size of specific large earthquakes, ideally in a short time to allow nearby communities to prepare for a calamity. Unfortunately, accurate prediction of an earthquake is still not possible at this stage due to the complexity of earthquake systems. No clear signals before the occurrence of a large earthquake have been identified.

However, many aspects of earthquake behaviour can be anticipated with enough precision to be useful in mitigating risk. The potential of near-surface faults to cause future earthquakes can be assessed by combining geological field studies of the previous slippage with seismic and geodetic monitoring of current activity.

Seismologists are learning how geological complexity controls the strong ground motion during earthquakes, and engineers are learning how to predict the effects of seismic waves on buildings, lifelines, and critical facilities such as large bridges, dams and nuclear plants. Together, geologists, seismologists and engineers have quantified long-term expectations for potentially destructive shaking in the form of seismic hazard maps.

Earthquake science in Malaysia is still in its infancy and exploratory stage. Geologists, seismologists and engineers are talking to each other only recently, when “forced” to produce a seismic hazard map of Malaysia. Thus, opportunities for research in the field of earthquake science in Malaysia are wide open.

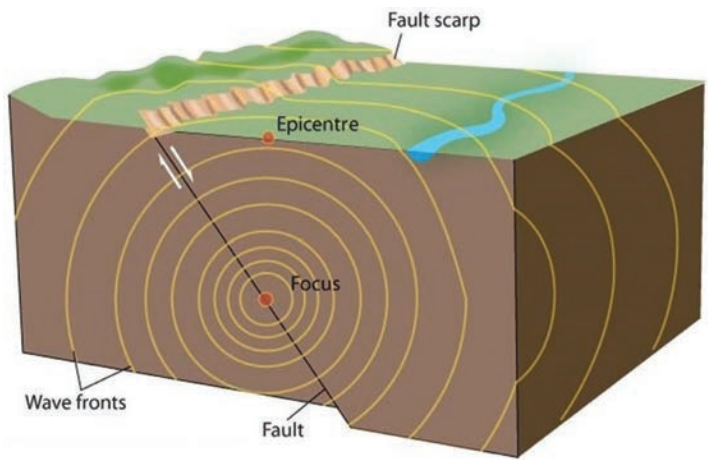
This lecture highlights the current status and challenges in earthquake science in Malaysia and proposes some strategic plans to strengthen earthquake science in Malaysia. It is hoped that some of these plans can be the basis for disaster risk reduction (DRR) programme on earthquakes in Malaysia.

EARTHQUAKE SCIENCE PRIMER

In this section, a brief introduction of earthquake science is provided to explain how and why an earthquake happens, how to measure its strength, and how to estimate the hazards associated with the earthquake.

What is an Earthquake?

An earthquake is a vibration, sometimes violent, of the Earth's surface that follows a release of energy in the Earth's crust. This energy can be generated by a sudden slip on a fault or fracture on the Earth's crust. During the sudden slip, vibrations called "seismic waves" are generated. These waves travel outward from the source of the earthquake along the surface and through the Earth at varying speeds depending on the material through which they move (Figure 1). Some of the vibrations are of high enough frequency to be audible, while others are of very low frequency. These vibrations cause the entire planet to quiver or ring like a bell.



(Image: Copyright of University of Waikato)

Figure 1 Vibrations called seismic wave generated by a sudden slip on the fault

What Causes an Earthquake?

An earthquake can be caused by tectonic plate movement, volcanic eruption, giant landslide or man-made explosion. Most destructive earthquakes, however, are caused by tectonic plate movements. Tectonic plates represent the outer layer of the earth. The internal structure of the Earth is layered in spherical shells: an outer solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core (Figure 2).

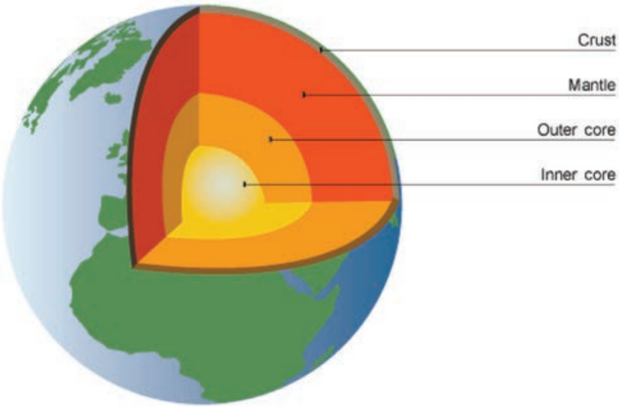


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Figure 2 Internal structure of the earth showing the four layers

The tectonic plates, consisting of the solid crust and upper mantel, known as lithosphere are roughly 100 km thick and consist of two principal types of material: oceanic lithosphere and continental lithosphere. Convection currents within the Earth's mantle drive plate movements (Figure 3). Tectonic plates are like pieces of a puzzle of different sizes, floating on top of the mantle. There are 9 major plates that move slowly relative to each other, they collide with each other at subduction zones, moves in a different direction at the mid-oceanic ridge and pass each other at transform fault (Figure 4). Plate movements cannot be felt by human because of its extremely slow movement, around 1 – 10 cm/year. Tectonic plates can be destroyed at a subduction zone and new tectonic plates generated at mid-oceanic ridge zone.

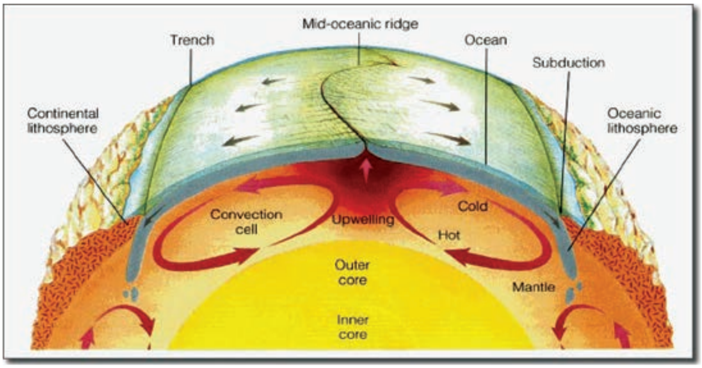

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Figure 3 Convection currents in the mantle move the plates as the core heats the slowly-flowing upper mantle

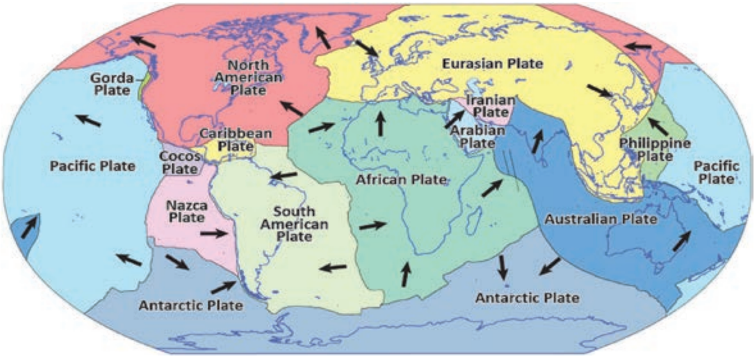

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Figure 4 Major plate movements. Notice that Malaysia is within the Eurasian Plate

Although tectonic plates are constantly moving relative to one another, their edges are usually locked together by friction, causing stress to build up along the plate boundaries. For example, where tectonic plates are colliding with each other, the plate boundaries comprise many individual features known as faults, each of which separates different blocks of the Earth's crust (Figure 5). Eventually, the frictional strength of one or several faults is overcome and the blocks on either side of the fault move suddenly, with the built-up energy released as an earthquake.

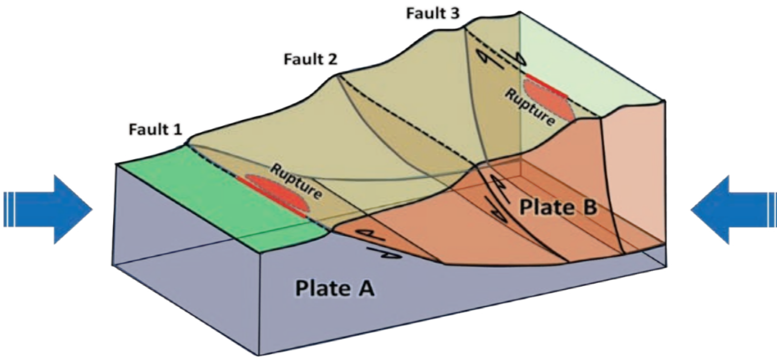


Figure 5 Schematic of plate boundary where two plates (A and B) are colliding. Earthquakes are generated along thrust fault planes in the rupture zone within Plate B

During a single earthquake, a section or 'patch' of Fault 1 or Fault 3 can slip tens of metres, while the rupture can extend for up to several hundred kilometres along the fault. The rupture can be several square kilometres in area. Earthquakes typically last for a few seconds to a few minutes, but the time between earthquakes on a single fault – sometimes called the 'recurrence interval' – can range from a few years up to tens of thousands of years.

What are the Different Types of Faults?

The interaction of the tectonic plates can produce horizontal force such as compression, extension or shearing on the earth's crust. There are three different types of faults – normal fault, thrust fault and strike-slip fault (Figure 6). Normal fault form due to extension along the mid-oceanic ridge, thrust fault due to compression along subduction zones and strike-slip fault due to shearing along transform faults. All three can produce an earthquake.

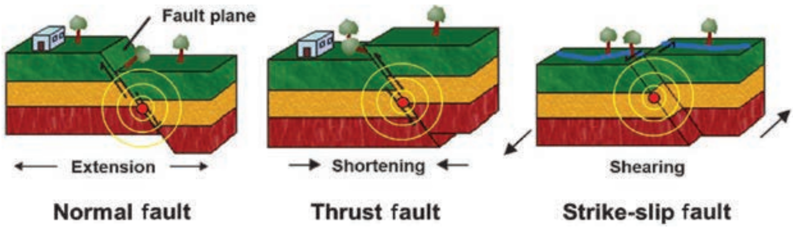
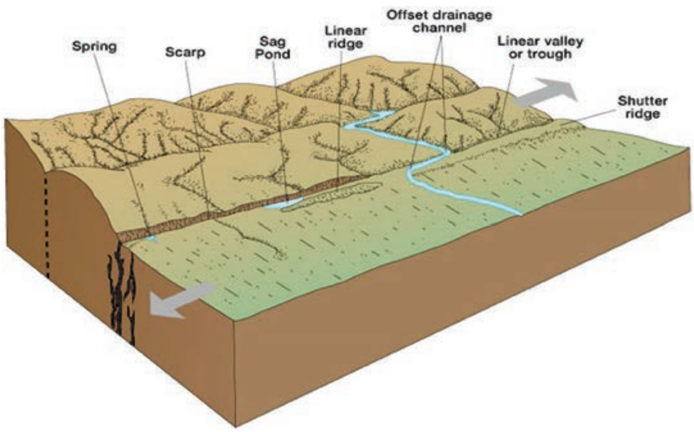


Figure 6 Three types of faults associated with extension and compression

What is an Active Fault?

Active faults are defined as linear areas where ground movement occurs systematically and continuously over a large area. Faults are commonly considered to be active if there has been movement observed or evidence of seismic activity during the last 10,000 years (Holocene age). Active fault movements are usually manifested on the Earth's surface as a scarp, facet, sag pond, linear ridge, shutter ridge, linear valley and offset drainage channel (Figure 7). River incision and triangular facet indicate continuous vertical movement. The presence of persistence landslides, damaged roads and mud volcanoes are other indicators of active fault movements.



(Source: Vedder & Wallace, 1970)

Figure 7 Geomorphological features associated with active fault movements

Active faults provide concrete evidence that a region is still undergoing tectonic stress. Active faults are a potential source of earthquakes. The larger the fault displacement the bigger the earthquake generated. Active faults thus play a very crucial role in the development of a seismic hazard map. When active faults have not been adequately mapped (e.g. unknown slip rate movement) they can be referred to as potential active faults.

How are Earthquakes Recorded?

During the sudden movement on a fault, two different types of seismic waves are generated: body waves called *P*-waves and *S*-waves, and surface waves called Raleigh wave and Love wave (Monroe & Wicander, 2001). The speed of the waves depends on wave type and the properties of the rock; the denser the rock, the faster the waves travel. In the Earth's crust, *P*-waves travel at around 6 – 7 km/s, while *S*-waves travel at around 3.5 – 4.0 km/s. *P*-waves travel fastest. They consist of successive contractions and expansions, just like sound waves in air. The motion of the particles in the rocks that the waves travel through is parallel to the direction of the wave. *S*-waves are slower than *P*-waves. They are transverse waves, which means that the particle motion is at right angles to the direction of travel. *S*-waves cannot travel through air or liquids. Surface waves travel just below or along the ground's surface. They are slower than body waves; rolling and side-to-side movement and especially damaging to buildings (Figure 8).

A seismogram is a record of the seismic waves from an earthquake. A seismograph or seismometer is the measuring instrument that creates the seismogram. Almost all seismometers are based on the principle of inertia: a suspended mass tends to remain still when the ground moves. The relative motion between the suspended mass and the ground will then be a measure of the ground's motion (Figure 9).

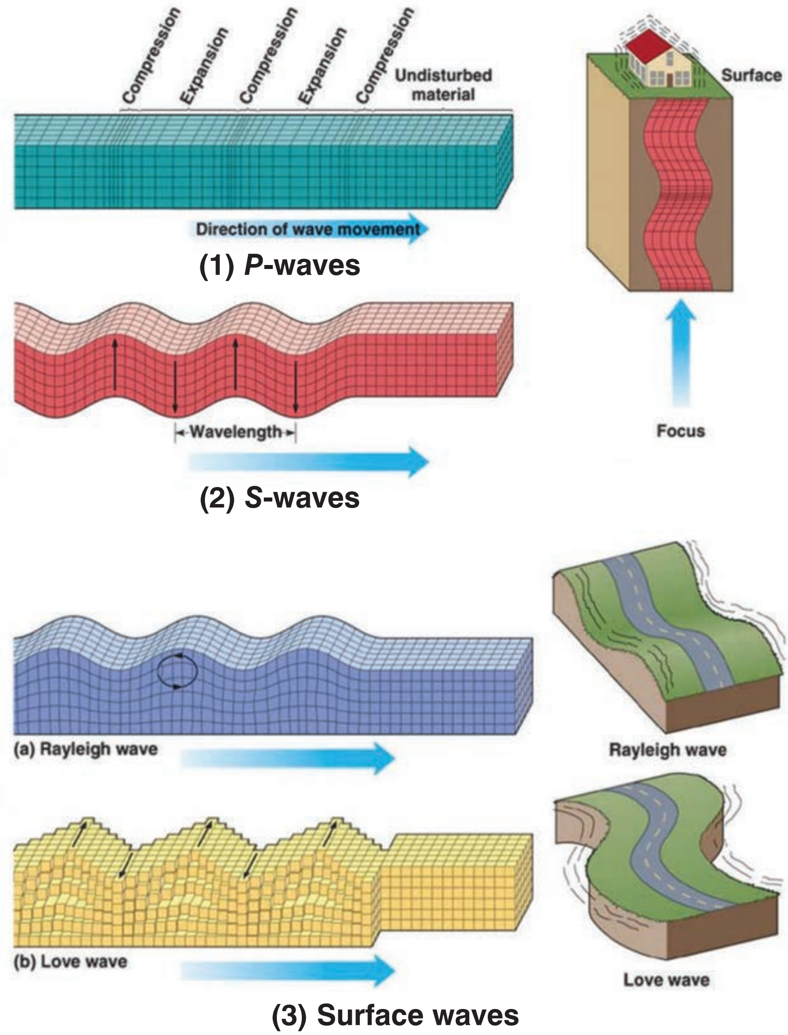
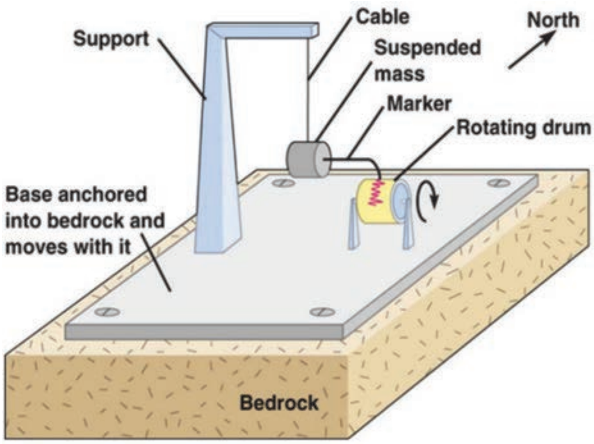
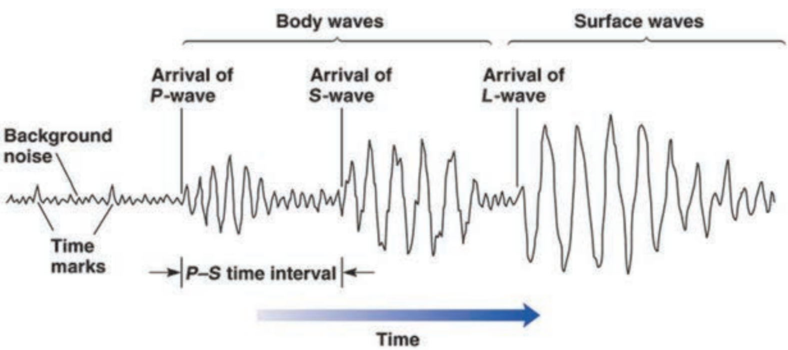


Figure 8 The movements of the three types of seismic waves – *P*-waves, *S*-waves and surface waves (Source: Monroe & Wicander, 2001)



(Source: Monroe & Wicander, 2001)

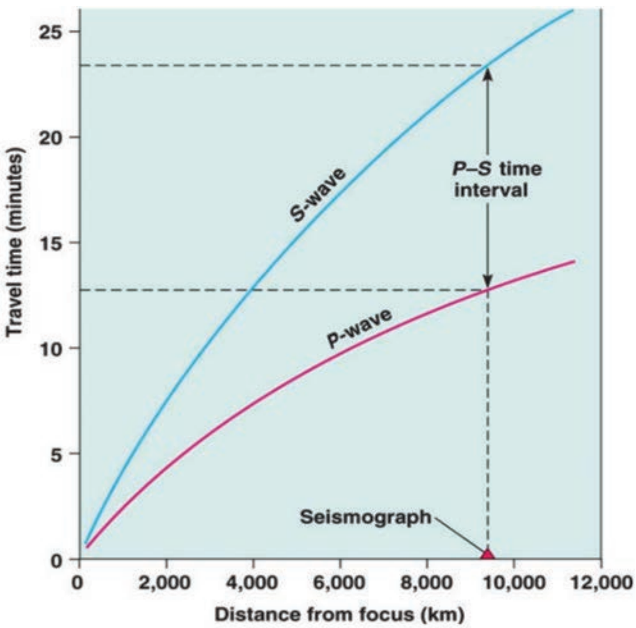
Figure 9 A typical seismograph. The suspended mass remains still during horizontal movement of the bedrock



(Source: Monroe & Wicander, 2001)

Figure 10 An example of a seismogram recorded by a seismometer. *P*-wave arrives first followed by *S*-wave and surface waves

On a seismogram from an earthquake, the *P*-wave is the first signal to arrive, followed by the slower *S*-wave, then the surface waves (Figure 10). The arrival times of the *P*-wave and *S*-wave at different seismographs are used to determine the location of the earthquake. Given that we know the relative speed of *P*-wave and *S*-wave, the time difference between the arrivals of the *P*-wave and *S*-wave determines the distance the earthquake is from the seismograph (Figure 11). To determine the location of an earthquake, the distance of the earthquake must be determined from at least three seismic recording stations. Circles with the appropriate radius are then drawn around each station. The intersection of three circles uniquely identifies the earthquake epicentre (Figure 12). The amplitude of the largest seismic wave is used to determine the strength of the earthquake (Figure 13).



(Source: Monroe & Wicander, 2001)

Figure 11 Time-distance graph showing the average travel times for *P*-wave and *S*-wave. The farther away a seismograph is from the focus of an earthquake, the longer the interval between the arrivals of the *P*-wave and *S*-wave

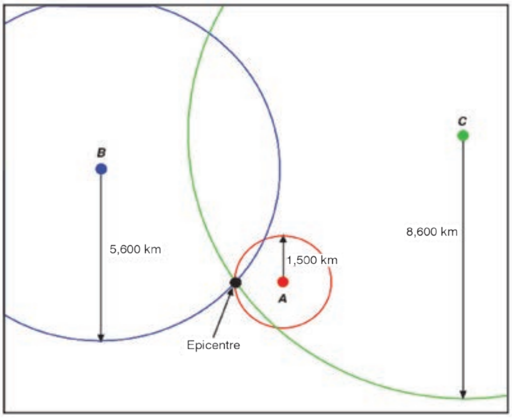


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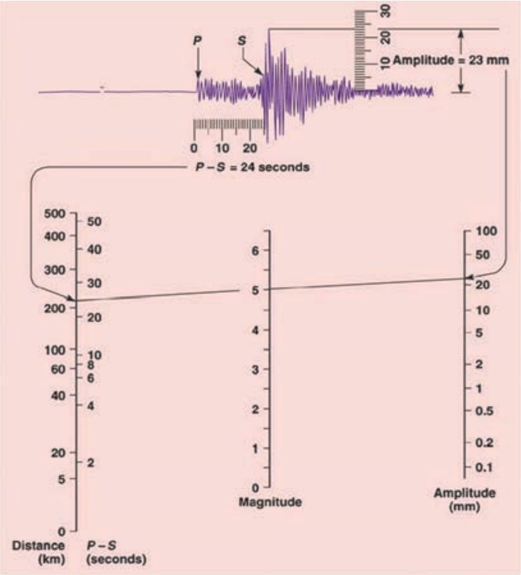
Figure 12 Epicentre of an earthquake is determined by a triangulation technique from at least three seismic stations (*A* located 1500 km, *B* located 5,600 km and *C* located 8,500 km from the earthquake source)

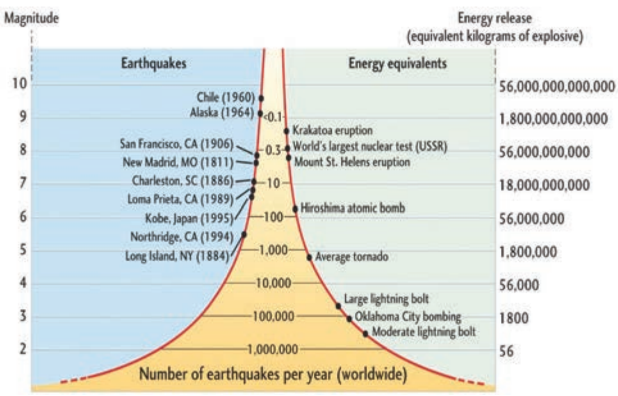


(Source: Monroe & Wicander, 2001)

Figure 13 Magnitude of an earthquake determined by the amplitude of the seismic wave. The amplitude of the largest wave produced by an event is corrected for distance and assigned a value on an open-ended logarithmic scale

What Determines the Size or Magnitude of an Earthquake?

The size or magnitude of an earthquake, usually expressed as its seismic moment (quantity used by seismologists), is defined by the amount of energy that is released (Figure 14). This is determined by the area of the fault that ruptured during the earthquake, the amount of slip on the fault, and the physical properties of the rocks involved. Seismic moment is then converted into a Moment Magnitude Scale (MMS), commonly abbreviated as Mw or just M, which provides a simple and convenient numerical scale with which to compare earthquakes. The Mw scale was developed in the 1970s to succeed in the 1930s-era Richter Magnitude Scale or Local Magnitude Scale (ML). The Richter Magnitude Scale is effective for nearby earthquakes below magnitude 4, but not for larger earthquakes. Two other types of magnitude are used depending on the size and depth of the earthquake. For large earthquake occurring near the surface, the Surface Magnitude (Ms) is used. For small-medium earthquake occurring deep within the earth, the Body Magnitude (Mb) is used. With the use of certain formula, the three different magnitude types can be converted to Mw.



(Image: Copyright of USGS)

Figure 14 The left side of the chart shows the magnitude of the earthquake and the right side represent the amount of high explosive required to produce the energy released by the earthquake. The middle of the chart shows the relative frequencies

Magnitudes are based on a logarithmic scale (base 10). What this means is that for each whole number that goes up on the magnitude scale, the amplitude of the ground motion recorded by a seismograph goes up ten times. Using this scale, a magnitude 5 earthquake would result in ten times the level of ground shaking as a magnitude 4 earthquake (and 32 times as much energy would be released) (Stein & Wysession, 2003).

What is the Difference between Magnitude and Intensity?

Moment magnitude measures the energy released by an earthquake and is expressed as an Arabic number (e.g. Mw 8.2). Intensity is a measure of how that energy release is experienced at the surface, and how it affects people and infrastructure at a given location (Table 1). It is ranked on a qualitative scale, based for example on observations of damage to different types of buildings, and is sometimes expressed as a Roman numeral (e.g. intensity IX), commonly known as Mercalli Scale. Importantly, the magnitude of a particular earthquake is the same, irrespective of location, whereas the intensity of the earthquake varies from place to place. This means that a location can experience the same intensity from a large-magnitude earthquake that is far away or a smaller earthquake that is nearby.

The Mercalli scale is not considered as scientific as the Richter scale, though. Some witnesses of the earthquake might exaggerate just how bad things were during the earthquake and may not find two witnesses who agree on what happened; everybody will say something different. The amount of damage caused by the earthquake may not accurately record how strong it was either.

Some things that affect the amount of damage that occurs are: (a) the building designs, (b) the distance from the epicentre, and (c) the type of surface material (rock or dirt) the buildings rest on.

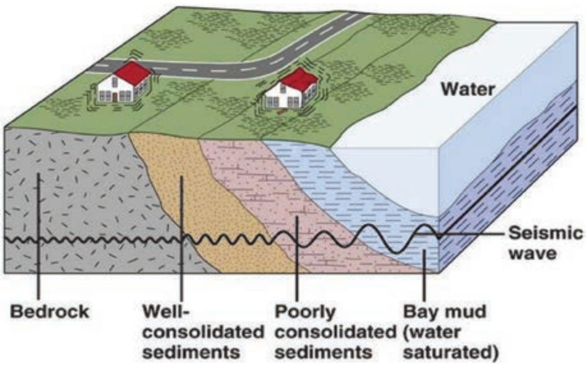
Different building designs hold up differently in an earthquake and the further you are from the earthquake, the less damage you will usually see. Whether a building is built on solid rock or sand makes a big difference in how much damage it takes. A solid rock usually shakes less than sand, so a building built on top of the solid rock should not be as damaged as it might if it was sitting on a sandy lot.

Table 1 Relationship between magnitude and intensity of the earthquake

Magnitude (Richter scale)	Intensity (Mercalli scale)	Earthquake Effects
1.0 – 2.9	I	Generally, not felt
3.0 – 3.9	II – III	Quite noticeable by people on rest, particularly by people on the upper floor
4.0 – 4.9	IV – V	Usually felt indoors. Breaking down of windowpanes and dishes
5.0 – 5.9	VI – VII	Felt by mostly all, movement of furniture expected, negligible damages to property likely
6.0 – 6.9	VII – IX	Considerable damage in ordinary substantial buildings with partial collapse, great damages to poorly constructed buildings, a threat to life
7.0 and higher	VIII or higher	Total damage, objects are thrown into the air, massive destruction and threat to human life

How does Local Geology Affect Shaking?

Shaking during an earthquake is caused by the passage of seismic waves through the Earth. These waves are produced by slip on the fault and travel away from the fault in all directions. The shaking at any particular point depends on the size of the waves, and thus in part on the conditions along the pathway that the waves take to that point (Figure 15). Different types of rock and the interactions between the waves and topography can cause the waves to either be amplified (leading to locally greater shaking and intensity) or attenuated (leading to decreased shaking and intensity). For example, buildings built in basins filled with soft sediment (e.g. Kota Kinabalu International Airport), often experience greater intensities than nearby buildings on bedrock (e.g. Universiti Malaysia Sabah), both because the seismic waves are amplified by the sediment and the waves are reflected off the bedrock at the edges of the basin.



(Source: Monroe & Wicander, 2001)

Figure 15 Amplification of seismic waves on different surface material condition. Poorly consolidated and water-saturated sediment tend to amplify the waves several times

How are the Likely Size and Frequency of Future Earthquakes Estimated?

The size and frequency of future earthquakes can be estimated by either examining the size and frequency of past earthquakes from historical and instrumental records and from pre-historical geological evidence (paleoseismology) or by using measuring techniques – such as GPS or satellite radar interferometry – to estimate the rates at which plates are moving and thus infer how and where stress is accumulating. Both approaches provide some insights into the potential size of future earthquakes and how often they may be expected to occur on average. It is not currently possible, however, to predict where and when a particular earthquake will happen, or how large it will be. Instead, scientists may be able to use these techniques to identify specific areas where stress is likely to be accumulating and therefore where the likelihood of an earthquake may be higher.

What is Seismic Hazard and How is it Measured?

Seismic hazard is a measure of the potentially damaging effects of some future earthquake at a specific location. These effects are often, but not exclusively, due to the shaking caused by the earthquake. Besides ground shaking, other processes, such as landslides and liquefaction, can form important 'secondary hazards' triggered by the earthquake. Shaking can be expressed qualitatively in terms of intensity, or quantitatively in terms of peak ground acceleration (PGA).

Table 2 Relationship between intensity and PGA values

Intensity	PGA (%g)	Perceived shaking	Potential damage
I	< 0.05	Not felt	None
II – III	0.3	Weak	None
IV	2.8	Light	None
V	6.2	Moderate	Very light
VI	12	Strong	Light
VII	22	Very strong	Moderate
VIII	40	Severe	Moderate/ heavy
IX	75	Violent	Heavy
X+	> 139	Extreme	Very heavy

Note: Scale based upon Worden et al., 2012

PGA is the maximum acceleration that the ground surface experiences during an earthquake and is usually given as a fraction of the Earth's gravitational acceleration (g). Generally speaking, a PGA of about 0.001 g (0.01 m/s) is perceptible by people, a PGA of around 0.2 g (0.02 m/s) causes most people to lose their balance, and a PGA of around 0.7 g (7 m/s) will cause the collapse of all but the best-designed buildings. Table 2 shows a rough relationship between PGA and intensity values.

What is Involved in a Seismic Hazard Assessment?

An assessment of seismic hazard involves understanding the sources that generate earthquakes in a region (i.e. the location, size and type of fault), and the characteristics of those earthquakes (e.g. frequency of occurrence and maximum magnitude). Data from past earthquakes are then used to predict how those sources produce shaking at a particular location. Seismic hazard assessment often takes one of two forms:

- Deterministic seismic hazard assessment (DSHA) consists of estimating the level of ground shaking associated with a particular earthquake – for example, the PGA associated with a 6 Mw earthquake on a particular section of the Mount Kinabalu Normal fault. This approach is scenario-specific, which can help decision-makers visualise the potential impacts of an earthquake. A problem with this approach, however, is that there are many candidate faults that could affect a given location, so it is difficult to design a comprehensive set of scenarios.

- Probabilistic seismic hazard assessment (PSHA) consists of estimating the probability that a certain level of ground shaking will be exceeded within a given time period at the location of interest. Unlike DSHA, PSHA takes into account multiple scenarios associated with earthquakes on multiple faults, and so must express the hazard in probabilistic terms. For example, a given location might have a 10% probability that PGA will exceed 0.1 g within 50 years, or in other words, the return period for shaking greater than 0.1 g is 500 years (usually referred to as 475 years). PSHA can be conducted for a single location or a larger area, depending on its intended use (e.g. to inform building codes).

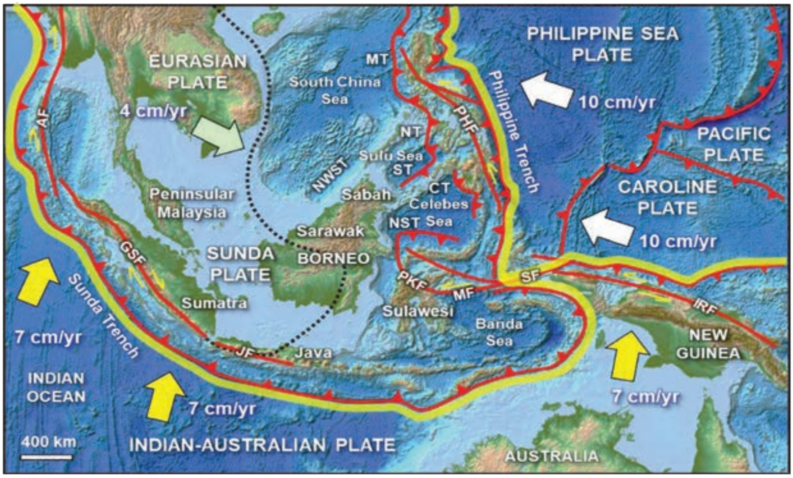
What is Probabilistic Seismic Risk?

To understand the full effects of an earthquake, seismic hazard assessment must be combined with some understanding of how the earthquake will impact upon people and infrastructure to create risk. Probabilistic seismic risk is the probability of some adverse consequence (e.g. damage to buildings, human casualties or monetary losses) occurring due to the hazard. Accurate assessments of risk depend on reliable estimates of seismic hazard, exposure and vulnerability.

STATUS OF EARTHQUAKE SCIENCE IN MALAYSIA

In this section, the state of scientific understanding of earthquakes in Malaysia in terms of how and why earthquake happens, the consequences of an earthquake on the natural environment and the people who live in it and their mitigation is reviewed.

Plate Tectonic Movements Around Malaysia



Legend: MT: Manila Trench, NT: Negros Trench, ST: Sulu Trench, CT: Cotabato Trench, NST: North Sulawesi Trench, NWST: NW Sabah Trough, PHF: Philippine Fault, PKF: Palu-Koro Fault, MF: Matano Fault, SF: Sorong Fault, IRF: Irian Fault, AF: Andaman Fault, GSF: Great Sumatran Fault, JF: Java Fault

Figure 16 Tectonic setting of Malaysia showing major plate boundaries (thick yellow line) and movements. Malaysia lies away from the active plate boundaries along the Sunda Trench and Philippine Trench. The Indian-Australian Plate moving northwards (7 cm/yr). The Philippine-Caroline-Pacific Plate moving relatively faster towards the west (10 cm/yr)

Malaysia which lies on the stable Sunda Plate and semi-stable stretched South China Sea is only mildly susceptible to earthquake (Figure 16). Peninsular Malaysia sitting on the Sunda Shelf lies passively behind the active Great Sumatran Fault (GSF) Zone and Sunda Trench Subduction Zone. Global Positioning System (GPS) measurements indicate rates of movements of between 2 – 5 cm/yr along the Great Sumatra Fault Zone (Natawidjaja & Triyoso, 2007). Sabah and Sarawak sitting on the semi-stable South China Sea are to a certain extent influenced by the active mobile belts in Sulawesi and Philippines. The active Sulu Trench subduction zone continues into East Sabah (Tongkul, 1991). Similarly, the movement along the Palu-Koro Fault (PKF) in Sulawesi appears to affect Southeast Sabah (Rangin et al., 1990). GPS measurement of movement across the Palu-Koro Fault showed 3.4 cm/yr left-lateral strike-slip movement (Walpersdorf, Vigny, Subarya, & Manurung, 1998). In the South China Sea, the NW Sabah Trough (NWST) which was probably once associated with subduction zone is not seismically active. Active thrust faults found along the trough may mostly be associated with sedimentary loading and slumping or crustal shortening (Sapin, Hermawan, Pubellier, Vigny, & Ringenbach, 2013; Hall, 2013; King, Backé, Morley, Hillis, & Tingay, 2010; Hesse, Back, & Franke, 2009).

Earthquake Hazards in Malaysia

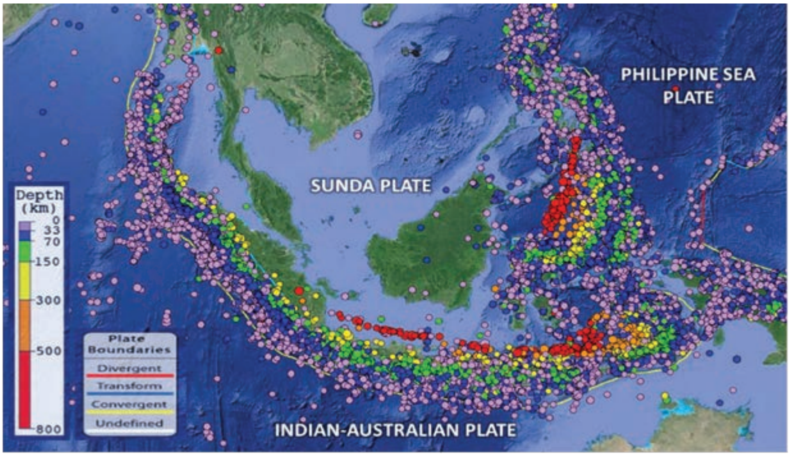


Figure 17 Distribution of regional earthquake (magnitude more than 5 Mw) surrounding Malaysia associated with the interaction of the three major plates, Sunda, Philippines Sea and Indian-Australian. The colour of the dots corresponds to the depth of the earthquake: Purple (0 – 33 km), Blue (33 – 70 km), Green (70 – 150 km), Yellow (150 – 300 km), Orange (300 – 500 km) and Red (500 – 800 km). Earthquakes generated from USGS Database (1900 – 2018)

Malaysia is affected by both regional and local earthquakes. Significant earthquakes from West Sumatra have been felt several times in Peninsular Malaysia (Figure 17). The USGS earthquake data shows about 50 earthquakes with magnitude scale more than 6 (Mw) lies within 1,000 km from Kuala Lumpur since 1973. Although the effect is small, it is still of concern, especially to vulnerable high-rise buildings. Similarly, earthquakes from the Sulu and Celebes seas are periodically felt as slight tremors in Sabah. The USGS earthquake database shows a total of 221 earthquakes with magnitude scale more than 6 (Mw) within 1,000 km from Kota Kinabalu since 1973. Rare earthquake from Kalimantan is felt as slight tremors in Sarawak.

Earthquakes in Peninsular Malaysia

Earthquakes felt in Peninsular Malaysia since the early 1800s are mostly related to earthquakes from Sumatra and Andaman Islands (Leyu et al., 1985, Table 3). In all these tremors, no casualties or damages to houses were recorded. The most severe cases reported objects falling from shelves. Since 1970, earthquake records available from Incorporated Research Institutions for Seismology (IRIS) Earthquake Database shows local earthquakes in Peninsular Malaysia. Since 2007, the Malaysian Meteorological Department (MetMalaysia) recorded several small local earthquakes in Peninsular Malaysia (Figure 18, Appendix 1). These earthquakes, mostly less than 4 Mw in magnitude are located in Bukit Tinggi, in Pahang, Kuala Pilah in Negeri Sembilan and Tasik Temenggor in Perak, and occurred after 2006 (Figure 19). Except for creating some minor tremors and shaking of high-rise buildings, these earthquakes have not resulted in any significant damage.

Table 3 Historical earthquakes felt in Peninsular Malaysia

No.	Event date	Areas affected	Origin
1	06-12-1815	Penang – minor tremor	Uncertain
2	24-11-1833	Penang, Malacca – minor tremor	Indonesia
3	06-01-1843	Penang, Singapore – slight tremor	Uncertain
4	22-06-1846	Penang – minor tremor	Uncertain
5	16-02-1861	Singapore, Malacca, Penang – Minor tremor	Indonesia
6	23-02-1861	Malacca – slight tremor	Uncertain
7	26-04-1861	Penang – minor tremor	Uncertain
8	19-08-1973	Penang – minor tremor	Uncertain
9	26-08-1883	Whole Peninsular – ground shaking, heard a loud explosion	Krakatoa explosion, Indonesia
10	17-05-1892	Singapore, Johor, Malacca, Penang – strong tremors, buildings shook, loose objects removed from shelves	Sumatra
11	03-06-1909	Malacca, Singapore – violent shaking, clocked stopped in Singapore, whole house shaking	Upper Padang, Sumatra
12	25-06-1914	Singapore – minor tremor	Bencoolen, Sumatra
13	29-02-1916	Kapar – minor tremor	Uncertain
14	27-07-1916	Kapar, Klang – minor tremor	Sumatra
15	31-01-1922	West Peninsular – minor tremor	Uncertain
16	07-02-1922	West Peninsular – minor tremor	Uncertain
17	28-06-1926	Singapore – minor tremor	Sumatra
18	20-01-1931	Selangor – minor tremor	Sumatra
19	03-08-1935	Penang – minor tremor	Sumatra
20	28-12-1935	Singapore – minor tremor	Sumatra
21	19-09-1936	Selangor, Penang – minor tremor	Sumatra
22	24-05-1942	Kuala Lumpur – slight tremor lasted 15 seconds, buildings shake slightly	Sumatra
23	13-01-1948	Singapore – minor tremor	Sumatra
24	24-08-1948	Teluk Anson – minor tremor	Uncertain
25	10-03-1949	Singapore – minor tremor	Uncertain
26	15-03-1952	Singapore – minor tremor	Sumatra
27	31-12-1962	Singapore, Kuala Lumpur – slight tremor	Sumatra
28	12-04-1967	West Peninsular – high buildings in Penang, Kuala Lumpur, Alor Star and Ipoh swayed alarmingly	North Sumatra
29	21-08-1967	Penang, Ipoh, Kuala Lumpur – minor tremor	Sumatra
30	04-02-1971	Singapore, Kuala Lumpur – minor tremor, affected tall buildings	Uncertain
31	20-06-1976	Penang, Kulim – minor tremor, shook some high-rise buildings	Sumatra
32	08-03-1977	Kuala Lumpur, Malacca, Muar – minor tremor	Sumatra
33	16-03-1979	Penang – minor tremor	Sumatra
34	01-04-1980	Penang – minor tremor	Sumatra
35	24-02-1982	Penang – minor tremor	Sumatra
36	04-04-1983	Penang, Petaling Jaya, Kedah – minor tremor	Sumatra

Source: Leyu et al., 1985

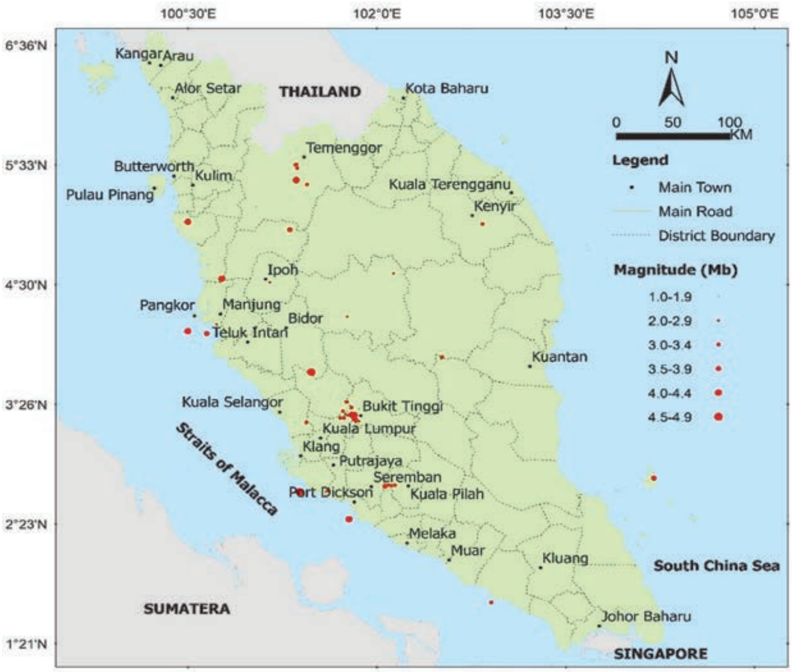


Figure 18 Earthquake distribution in Peninsular Malaysia based on MetMalaysia and IRIS Earthquake Databases (1970 – 2018). The earthquakes are concentrated in Bukit Tinggi, Kuala Pilah, Manjung, Temenggor and Kenyir

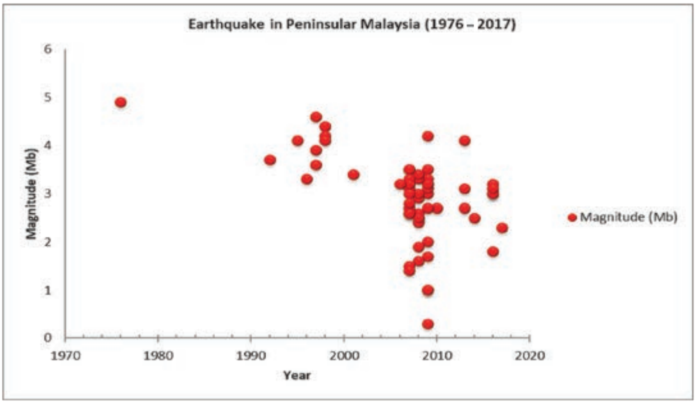


Figure 19 Time series earthquake distribution in Peninsular Malaysia based on MetMalaysia and IRIS Earthquake Databases (1970 – 2018). Most of the earthquakes occurred after 2006, following the large 2004 earthquake in Sumatra

Earthquakes in Sarawak

Earthquakes felt in Sarawak are mostly related to local earthquakes. Leyu et al. (1985) documented several historical minor earthquakes around Kuching, Samarahan, Bintulu, Bekenu and Niah areas (Table 4). These earthquakes caused minor damage to buildings. During the period from 1970 to May 2019, about 20 light to moderate (magnitude larger than 3 Mw) earthquakes were recorded onshore Sarawak (Figure 20, Appendix 2). Most of the earthquakes have a magnitude less than 5 Mw except for two which were recorded at Batu Niah and Bukit Mersing. Most of the earthquakes were recorded after 2006 (Figure 21).

Table 4 Historical earthquakes felt in Sarawak

No.	Event date	Areas affected	Origin
1	26-06-1874	Simunjan – mild tremor	Uncertain
2	24-06-1876	Kuching – slight tremor	Uncertain
3	26-08-1883	Kuching – minor tremor	Krakatoa eruption, Indonesia
4	07-03-1910	Simanggang, Sadong, Kuching – minor tremor	Uncertain
5	07-04-1910	Samarahan to Serian – minor tremor	Uncertain
6	19-11-1953	Kuching – airport shaken, bungalows rocked	Uncertain
7	16-07-1965	Bintulu, Miri, Lutong – light tremor	Central Sarawak
8	21-07-1965	Bekenu and Niah areas – smashed windows and slammed doors, very large limestone stalactite broke from below the ceiling in Niah Cave	Central Sarawak
9	04-07-1970	Bekenu area – tremors lasted for 10 seconds, government quarters and wooden houses slightly damaged	Central Sarawak

Source: Leyu et al., 1985

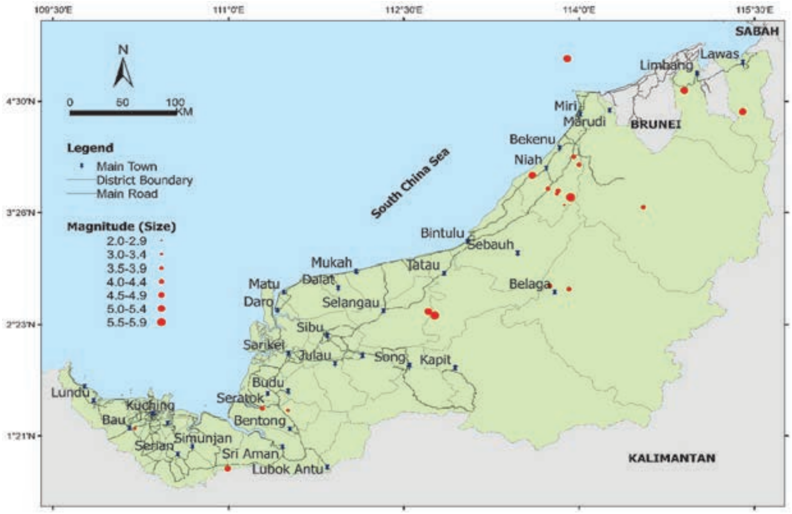


Figure 20 Distribution of earthquakes in Sarawak based on MetMalaysia and IRIS Databases. The earthquakes are mostly located around Niah and Selangau

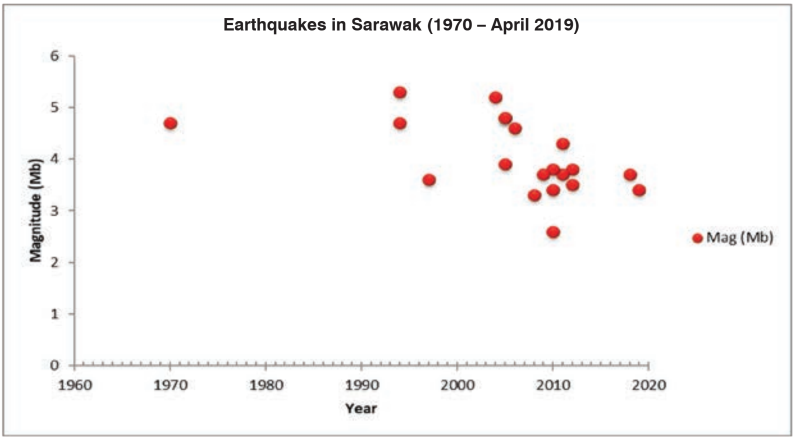


Figure 21 Time series earthquakes in Sarawak based on MetMalaysia and IRIS Databases. The higher number of earthquake record after 2006 is due to better seismic instrumentation coverage in Sarawak.

Earthquakes in Sabah

Earthquakes in Sabah are mostly generated locally and regionally from the Philippines (Sulu and Celebes Seas) and Indonesia (Kalimantan). Wilford (1967) records several historical earthquakes that were felt in Sabah that are not well documented in the USGS Earthquake Database. Some of the significant earthquakes reported in the British North Borneo Herald newspaper are shown in Table 6. These historical earthquakes occurred mostly in Tawau, Lahad Datu, Sandakan, Kudat and Keningau.

Table 5 Historical earthquakes felt in Sabah

No.	Event date	Areas affected	Origin
1	21-09-1897	Sandakan – house cracked, clock tower stopped	Philippines
2	05-04-1902	Tawau – severe tremor	Kalimantan
3	01-10-1902	Sandakan – caused fissure on the ground	Philippines
4	02-05-1903	Tawau – minor tremor	Uncertain
5	31-12-1908	Kalabakan, Tawau – S.S. Victoria heeled over	Kalimantan
6	15-05-1909	Tawau – damaged to crockery	Uncertain
7	27-07-1911	Ranau – weak tremor	Ranau
8	06-06-1912	Timbang Batu, Marudu Bay – house shook violently	Kudat
9	19-04-1923	Tawau-Cowie Harbour – tremor lasting for 20 seconds	Tarakan
10	11-08-1923	Lahad Datu – tremor lasting 30 seconds, buildings shook and swayed, window rattled	Sulawesi Sea
11	25-01-1928	Bengkoka area – severe tremor	Pitas
12	27-03-1932	Pingan-Pingan area – strong tremor	Pitas
13	17-10-1932	Keningau – minor tremors	Keningau
14	04-12-1932	Sandakan – slight tremor	Celebes Sea
15	02-06-1951	Kudat – several strong tremors, crevasse appear in the street of Kudat, cracks appeared on road, sea wall collapsed, water pipes burst	Kudat
16	30-10-1958	Keningau to Sapong – severe tremor, things falling	Tenom
17	28-06-1964	Kennedy Bay – violent tremor	Lahad Datu
18	24-01-1965	Kennedy Bay – minor tremor	Lahad Datu
19	15-02-1965	Bakapit area – minor tremor	Lahad Datu
20	03-03-1965	Bakapit area – minor tremor	Lahad Datu
21	18-10-1965	Ranau – weak tremor	Ranau
22	19-05-1966	Ranau – strong tremor with slight intensity, rattling of windows and doors and cookery, houses shook violently, felt in Kota Kinabalu, Papar, Penampang, Tuaran, Kota Belud and Tambunan	Ranau

Source: Wilford, 1967; Leyu et al., 1985

Based on USGS Earthquake Database, during the period from 1900 to May 2019, about 67 light to moderate (magnitude larger than 3.5 Mw) earthquakes were recorded onshore and offshore Sabah (Figure 22, Appendix 3). Most of the earthquakes in Sabah have a magnitude less than 5, apart from the four earthquakes with magnitude 6 and above, such as the 2015 Ranau earthquake, 1976 Lahad Datu earthquake, 1951 Kudat earthquake and 1923 Lahad Datu Earthquake. The epicentres of the earthquakes are concentrated on the east coast of Sabah, around Lahad Datu-Kunak area, and around Kundasang-Ranau area.

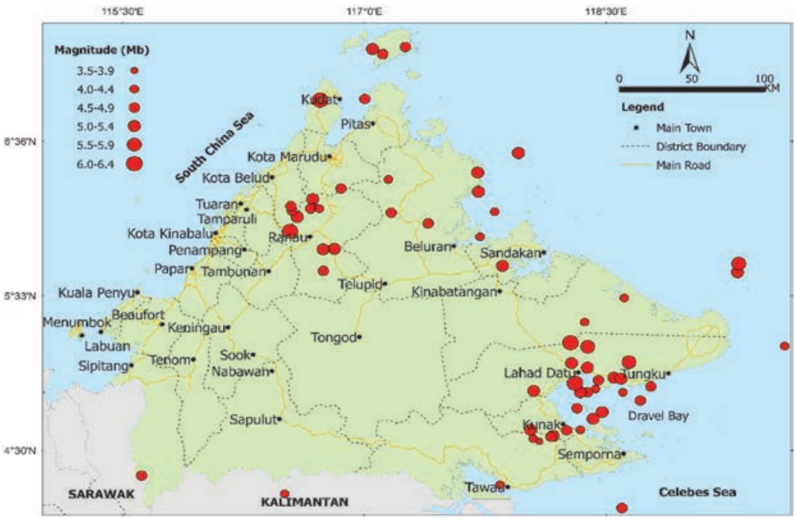


Figure 22 Earthquake distribution in Sabah (1900 – 2018) extracted from the USGS database

The relatively small number of earthquakes shown by the USGS database is due partly to the detection limit of older seismographs in Sabah. However, since the establishment of new seismographs in 2019 in Sabah more microearthquakes has been recorded in Sabah (Figure 23). For example, during 2015 alone, MetMalaysia recorded 155 small earthquakes (magnitude larger than 2 Mw) in Sabah. The historical earthquake record is still patchy but has improved after 1970 (Figure 24). Since 2005, the earthquake record in Sabah is almost complete (Figure 25). For the last 100 years, there has been a regular occurrence of an earthquake with a magnitude greater than 5 Mw (Figure 26).

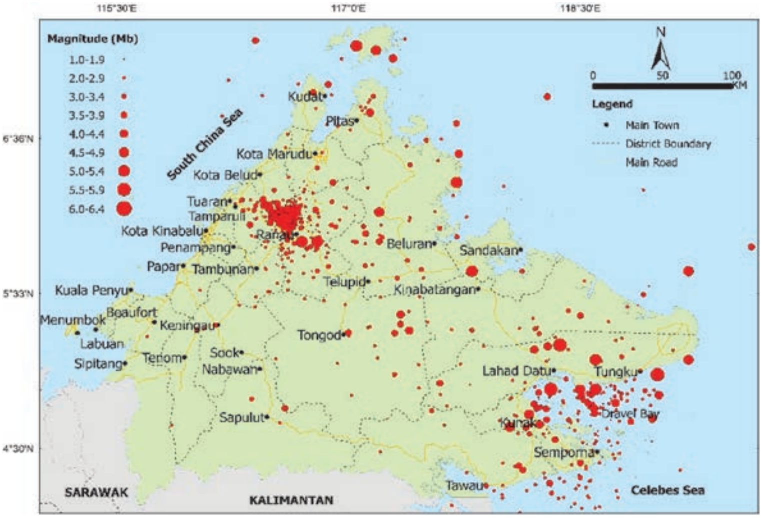


Figure 23 Earthquake distribution in Sabah (1966 – 2019) based on the database of MetMalaysia (2019). There is a heavy concentration of very small earthquakes in Ranau and Darvel Bay areas

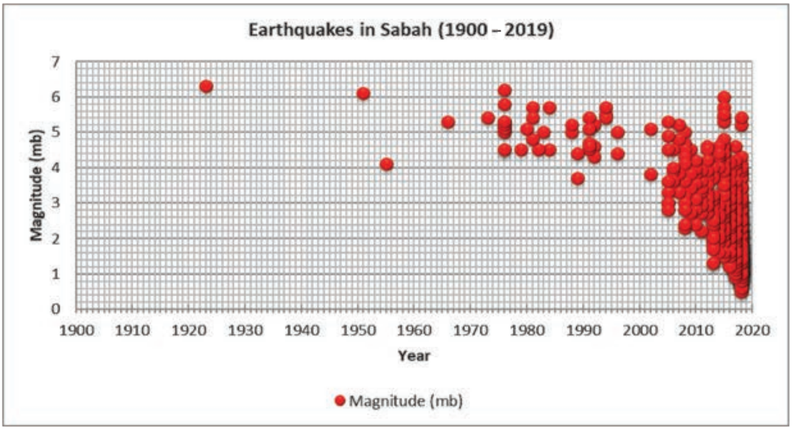


Figure 24 Time series of the earthquake in Sabah (1900 – 2019) based on MetMalaysia (2019) and USGS databases showing the incomplete record of Sabah earthquake. Data of magnitude 3.5 – 5.0 missing from 1940 – 1957 and data of magnitude more than 6.0 complete since 1923

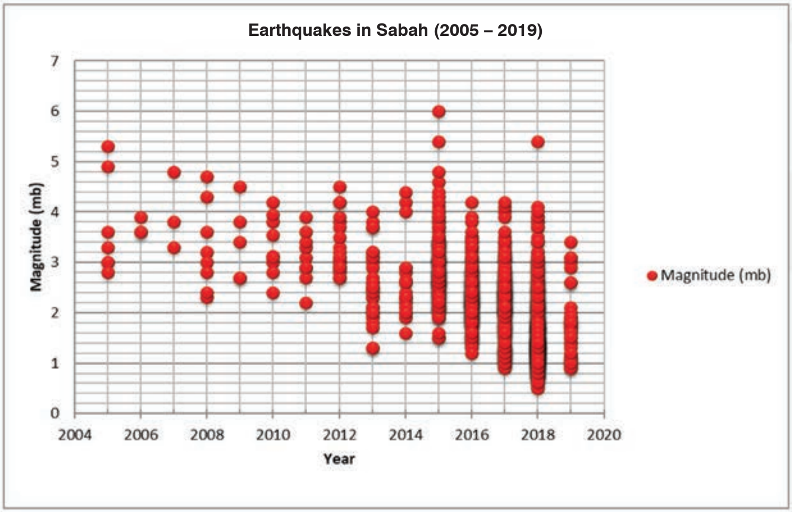


Figure 25 Time series of earthquakes in Sabah after 2005 based on Malaysia Meteorological Department (2019) database. Since 2015 a complete range of magnitudes have been recorded

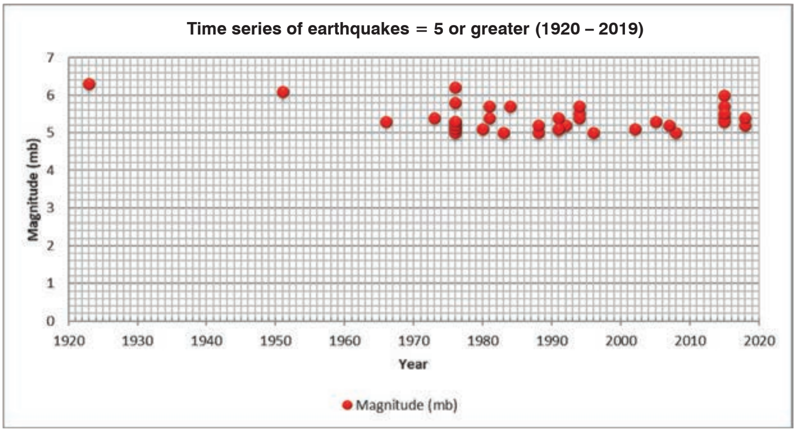


Figure 26 Time series of earthquakes with a magnitude more than 5 (1920 – 2019) based on Malaysia Meteorological Department (2019) and USGS database. There is a regular occurrence of the earthquake (Mag 5 – 6) for the last 100 years in Sabah.

Potential Source of Regional Earthquakes

The source of regional earthquake for Peninsular Malaysia comes from the active Great Sumatra Fault Zones and Sunda Trench Subduction Zone (or Sunda megathrust) which extends across the Andaman Sea (Figure 27). The Sunda megathrust is the plane of contact between the Indian Ocean Plate descending beneath the Sunda Plate (Sundaland) at a rate of about 7 cm/yr. Rupture of a 1,600-km length of the megathrust caused the great magnitude 9.2 (Mw) earthquake of 26 December 2004. Tens of metres of sudden slip relieved centuries of slowly accumulating strain across the plate boundary. Another rupture of 350-km length at the southern end of the 2004 rupture occurred 3 months later on 23 March 2005, causing another great earthquake (Sieh, 2007). There are also historical accounts of great earthquakes along the rupture, but the accounts are too sparse to tell us much about the details of these large ancient earthquakes. Fortunately, however, corals have been used to characterize in detail some of these events that occurred in 1797 and 1833 (Natawidjaja et al., 2006). Modern GPS geodesy to measure the current accumulation of strains that are building toward the next big megathrust failures have also been used by Sieh (2007). Based on the current rates of strain accumulation, Sieh believes there is a high likelihood that the region will generate a great earthquake within the next few decades.

The Great Sumatra Fault (GSF) which occur along the length of Sumatra is a right-lateral strike-slip fault, absorbing the oblique subduction of the Indian Ocean Plate towards the north under the Sunda Plate. Numerous earthquakes measuring up to magnitude 7 (Mw) and depth of less than 100 km occur along the Great Sumatra Fault. The small earthquake in Peninsular Malaysia may also be related to the shear stress generated by the oblique subduction. GPS data in Peninsular Malaysia indicate intra-plate crustal deformation (Abdul Rahim Samsudin et al., 2014).

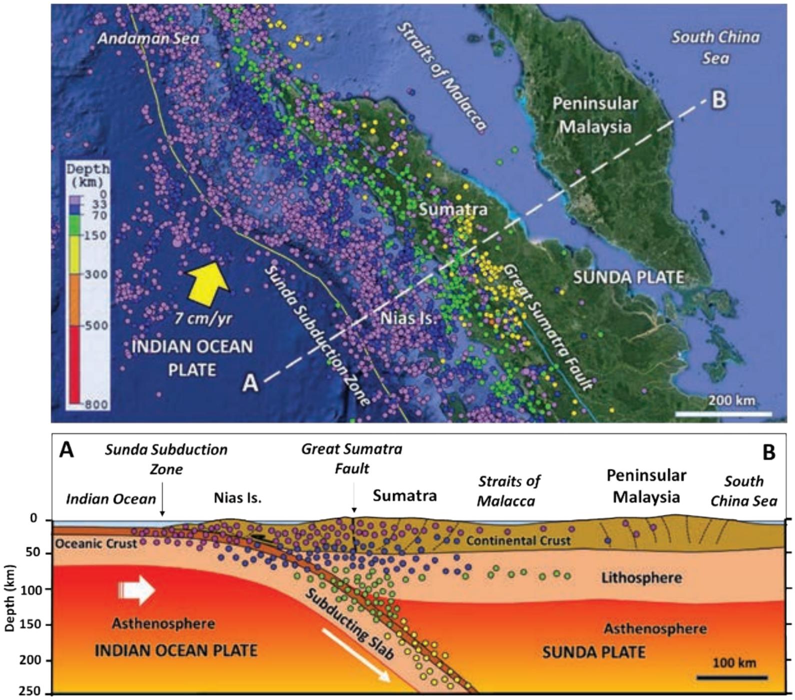


Figure 27 The interaction between the Indian Ocean Plate and Sunda Plate along the Sunda Subduction Zone. The subducting Indian Ocean slab under Sumatra generates numerous large earthquakes up to Magnitude 9 (Mw) in Sumatra and minor earthquakes in Peninsular Malaysia. Earthquakes generated from USGS Database (1900 – 2018). The colour of the dots corresponds to the depth of the earthquake: purple (0 – 33 km), blue (33 – 70 km), green (70 – 150 km), yellow (150 – 300 km)

The source of regional earthquakes for Sabah comes from the active subduction zones marked by the Philippine Trench, Manila Trench (MT), Negros Trench (NT), Sulu Trench (ST), Cotabato Trench (CT) and North Sulawesi Trench (NST) (see Figure 16). The Philippine Subduction Zone is the plane of contact between the Philippine Sea Plate descending beneath the extended Sunda Plate at a rate of about 10 cm/yr. The Philippine Sea Plate descends up to 600 km deep under the Celebes Sea and Sulu Sea areas (Figure 28). The stress generated by the westward subducting slab of the Philippine Sea Plate is being absorbed by shallow faults in the Philippines, Sangihe Islands and Sabah. GPS measurement in Sabah indicates intra-plate crustal deformation which may be related to the Sunda-Philippine sea plate convergence (Mohamad, Simons, Kamaludin Omar, & Ambrosius, 2014; Mohamad et al., 2017).

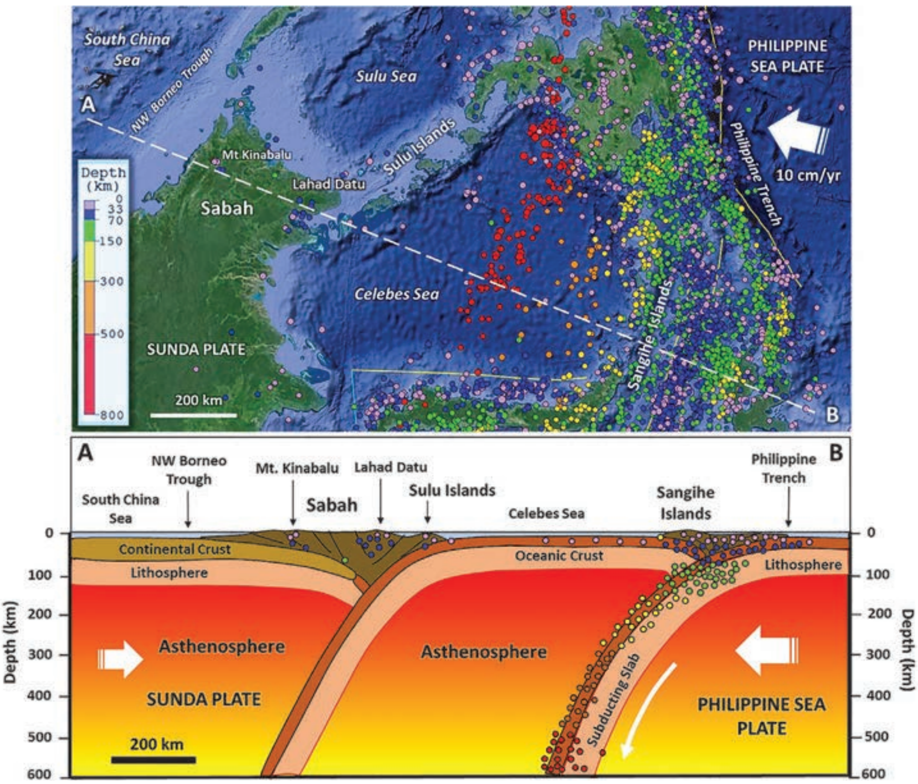


Figure 28 The subducting Philippine Sea slab under the Celebes Sea generates numerous large earthquakes in the Philippines and moderate earthquakes in Sabah and Sarawak. Earthquakes generated from USGS Database (1900 – 2018). The colour of the dots corresponds to the depth of the earthquake: purple (0 – 33 km), blue (33 – 70 km), green (70 – 150 km), yellow (150 – 300 km), orange (300 – 500 km), red (500 – 800 km)

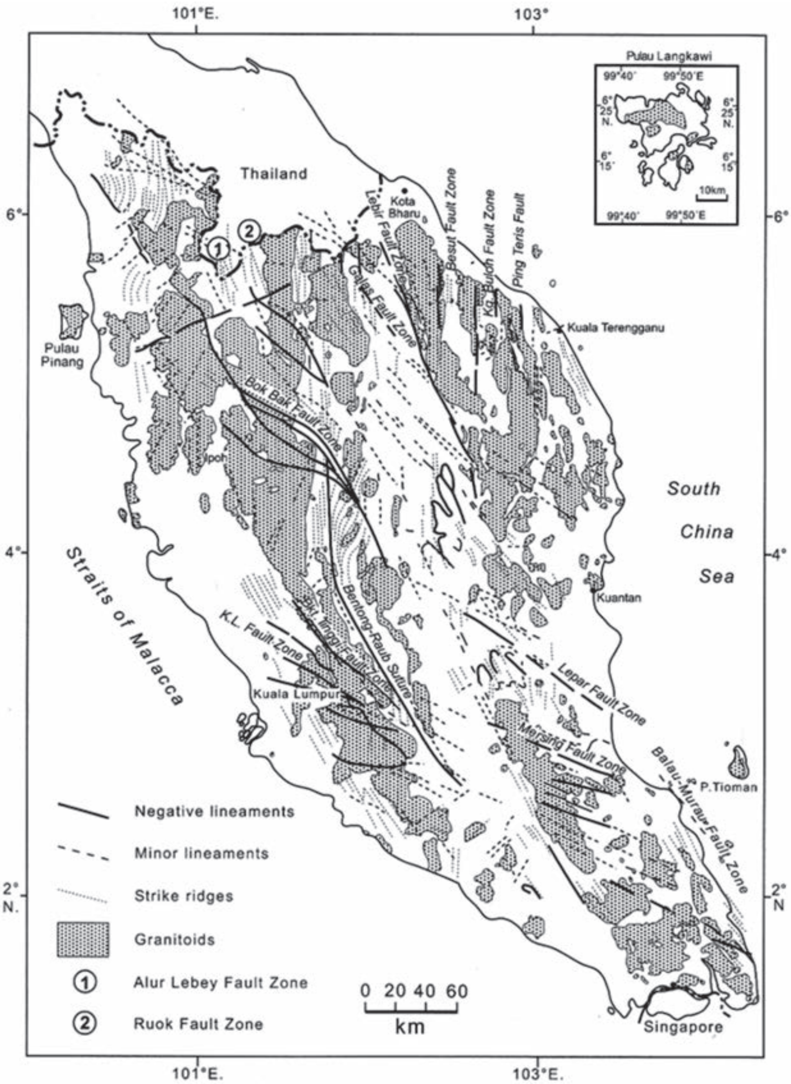
Potential Source of Local Earthquakes

Local earthquakes are caused by active faults in Malaysia. There are several potential active faults mapped in Peninsular Malaysia, Sarawak and Sabah (Ismail et al., 2015). These potential active faults may have utilised existing ancient faults, which are quite numerous in Malaysia.

Active Faults in Peninsular Malaysia

In Peninsular Malaysia, the potential active faults appear to be related to major ancient faults. Hutchison and Tan (2009) provided a summary of the major ancient's faults trending N-S, NW-SE, NNE-SSW, and E-W in Malaysia. Some of the well-known faults include the Bak-bak Fault, Lepar Fault, KL Fault, Bukit Tinggi Fault, Mersing fault, Galas Fault, Besut Fault, Kg. Buloh Fault, Ping Teris Fault and Balau-Murau Fault (Figure 29).

The occurrence of small earthquakes in the Bukit Tinggi, Kuala Pilah, Manjong, Temenggor and Kenyir areas indicates the presence of potentially active faults in these areas. A recent study by Ismail et al. (2015) identified several potential active fault zones in these areas (Figure 30). The occurrence of induced light earthquakes with a maximum magnitude of 4.6 during the flooding of the Kenyir Dam in Terengganu in 1984 – 1987 may be associated with the reactivation of old N-S and NW-SE strike-slip faults in the region. In Bukit Tinggi, the earthquakes appear to be associated with the NW-SE Bukit Tinggi Fault Zone (Figure 31).



Source: Hutchison & Tan, 2009

Figure 29 Location of major ancient faults in Peninsular Malaysia trending NW-SE, N-S and NNE-SSW

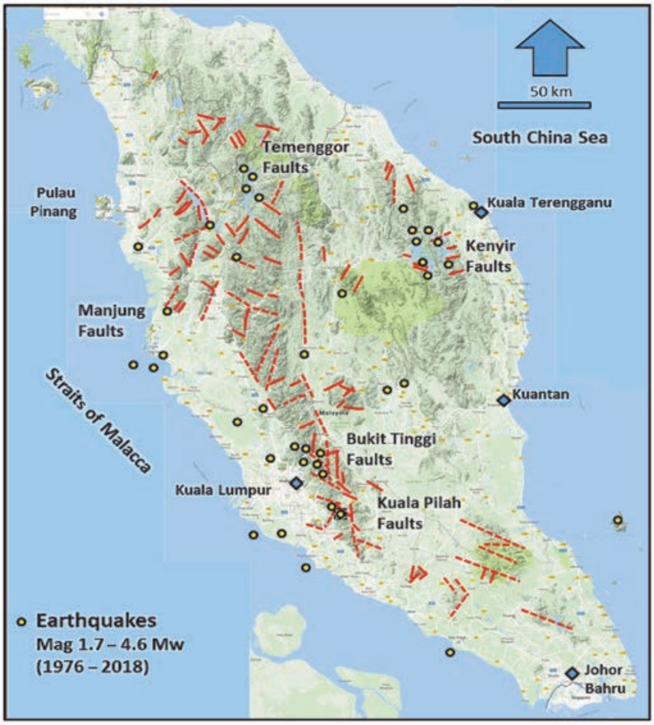


Figure 30 Potential active faults (red lines) in Peninsular Malaysia. The potential active faults trending NW-SE, N-S and NNE-SSW are possibly reactivated ancient faults (modified from Ismail et al., 2015)

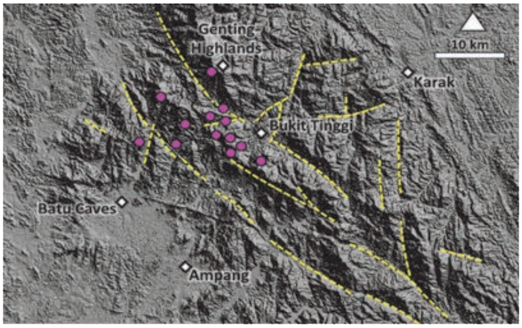


Figure 31 Potential Bukit Tinggi active faults trending NW-SE, N-S and NE-SW and cluster of small earthquakes (magnitude less than 3.5) (modified from Ismail et al., 2015). The reactivation of the NW-SE trending Bukit Tinggi Fault Zone may have produced the earthquakes

Active Faults in Sarawak

In Sarawak, the potential active faults are also associated with ancient faults (Figure 32). Several major ancient thrust faults oriented approximately E-W occur in Sri Aman, Gunung Sebangkoi, Kanowit, Selangau and Tatau oriented parallel to the structural grain. These thrust faults change in orientation from E-W to N-S towards North Sarawak. The thrust faults are dissected by a series of NW-SE and N-S strike-slip faults, showing left-lateral and right-lateral movements, respectively (Tongkul, 1997).

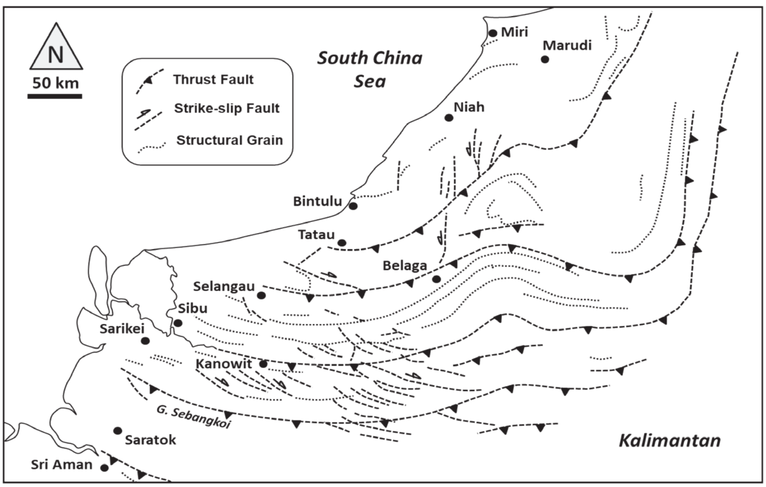


Figure 32 Locations of ancient faults in Sarawak trending NW-SE and N-S are possibly reactivated ancient faults (modified from Tongkul, 1997)

Potential active faults located near Niah and Selangau has generated earthquakes up to magnitude 5.4 (Mw) (Figure 33). The potential active left-lateral strike-slip faults in Niah appears to be associated with the Tubau Fault Zone (Figure 34). The potential active right-lateral strike-slip faults in Selangau appears to be associated with the Mersing Fault Zone (Figure 35). The potential active faults near Sri Aman appears to be associated with the Sungai Lupar Fault Zone. The reactivation of ancient faults in Sarawak may be due to stress generated by the subduction of the Philippine Sea Plate under the Sunda Plate.

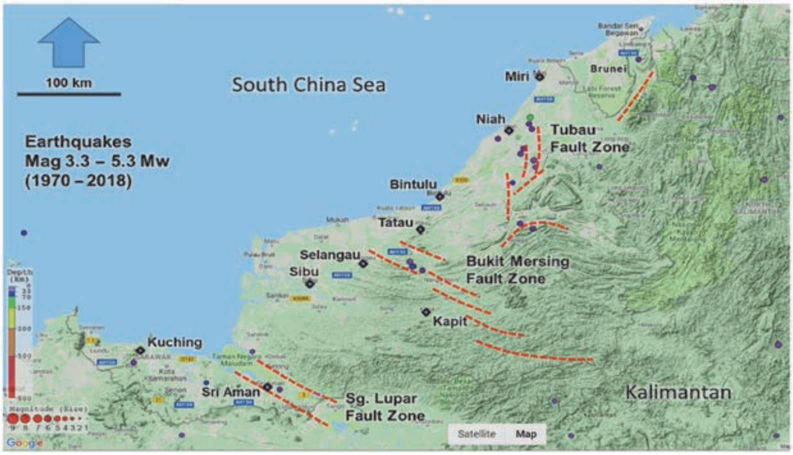


Figure 33 Potential active faults in Sarawak associated with minor earthquake activities. The potential active faults trending NW-SE and N-S are possibly reactivated ancient faults

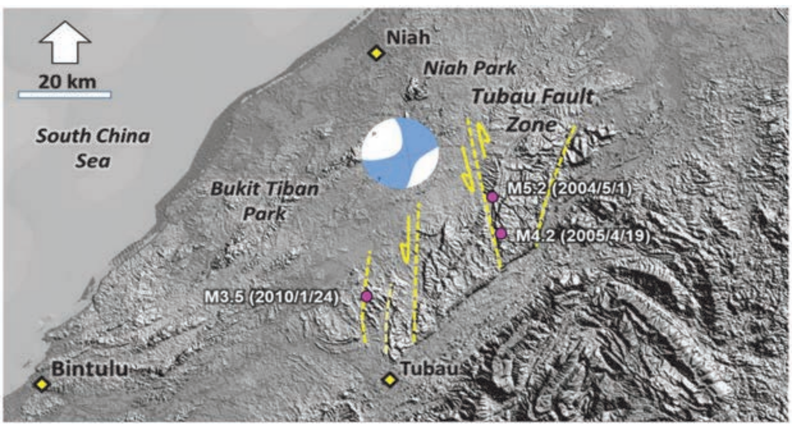


Figure 34 Potential active N-S strike-slip faults (yellow line) near Niah National Park. Three earthquakes occurred in this area (purple circle). The focal mechanism (beach ball) indicates N-S left-lateral strike-slip fault

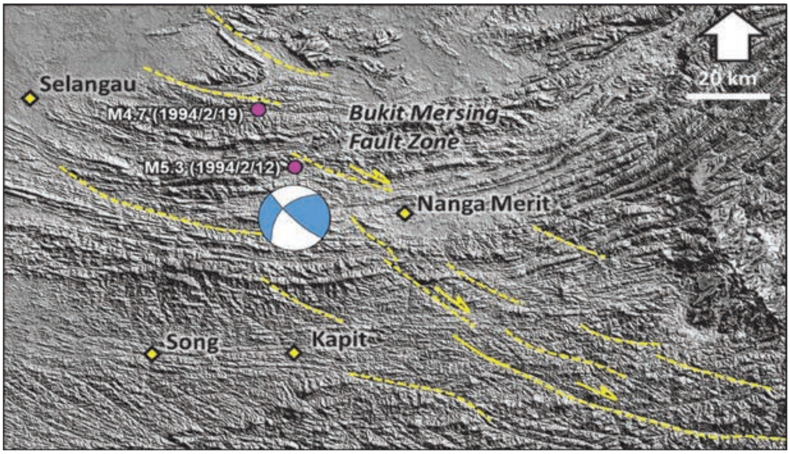
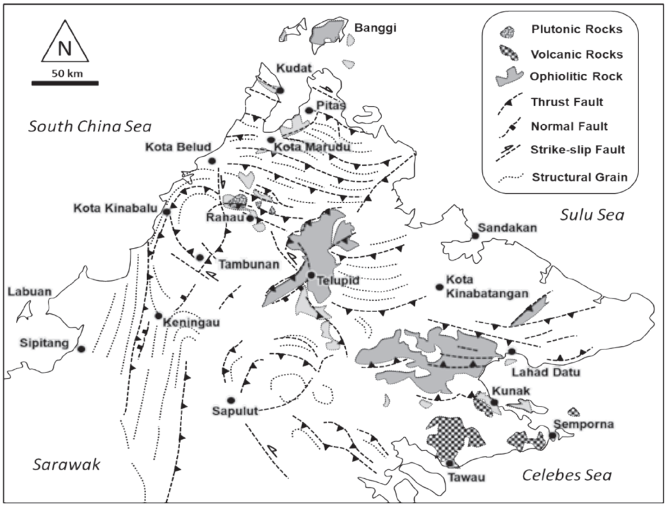


Figure 35 Potential active NW-SE strike-slip faults (yellow line) near Selangau-Nanga Merit. Two earthquakes occurred in this area (purple circle). The focal mechanism (beach ball) indicates right-lateral NW-SE strike-slip fault

Active Faults in Sabah

In Sabah, the potential active faults are also associated with ancient faults (Figure 36). The ancient faults comprised of thrust faults, strike-slip faults and normal faults associated with past tectonic compression in Sabah. The thrust faults follow the structural grain and occur all over Sabah. The strike-slip faults occur mostly in Ranau and Telupid whereas the normal faults occur in Tambunan and Keningau valleys.

Potential active faults are mostly concentrated in Ranau, Kudat, Sandakan, Lahad Datu and Kunak areas. Earthquake focal mechanism solutions provided by USGS shows both compressional stress regime (thrust faults and strike-slip faults) and extensional stress regime (normal faults) in Sabah (Figure 37). The compressional stress regime is mostly recorded in Southeast Sabah, whereas the extensional regime is mostly recorded in West and North Sabah. The compressional and extensional stress directions are mostly oriented WNW-ESE. These potential active faults are associated with the crustal shortening of Sabah due to the westward movement of the Philippine Sea Plate.



Source: Tongkul, 2017

Figure 36 Locations of ancient faults in Sabah trending NW-SE, N-S and NE-SW

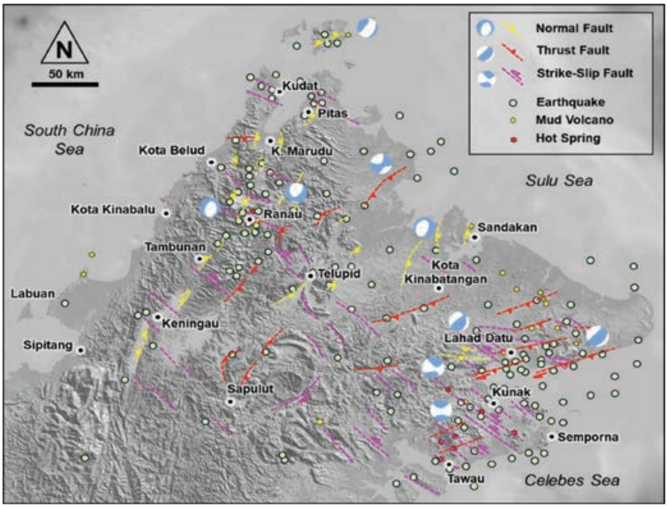


Figure 37 Locations of potential active faults in Sabah. The potential active faults trending NE-SW in West Sabah are mostly normal faults whereas the faults trending NW-SE and NE-SW in East Sabah are strike-slip faults and thrust faults (based on Tongkul, 2017). The corresponding focal mechanism (beach ball) indicates both extension and compression regime in Sabah

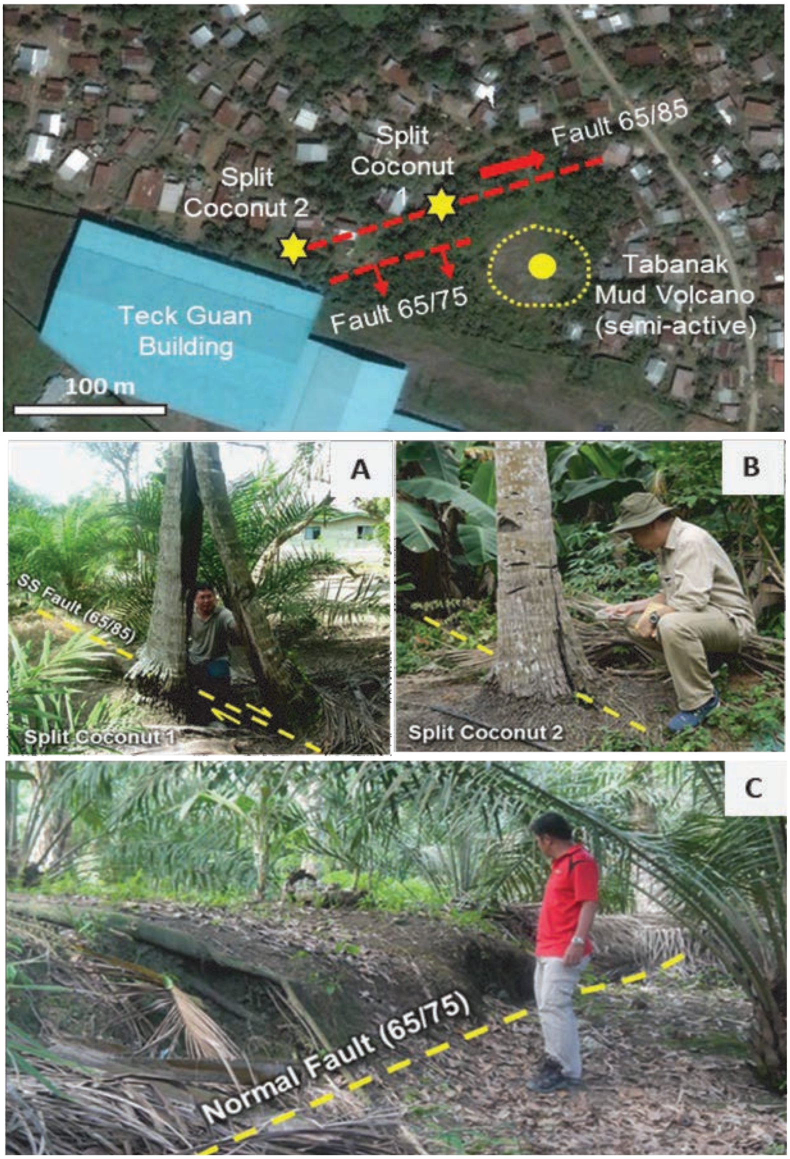


Figure 38 Active strike-slip faults oriented N65E caused a split in the trunk of two coconut trees (A and B). The strike-slip fault is associated with a normal fault (C) and a semi-active mud volcano located near Lahad Datu Airport

Figure 39 Active mud volcanoes associated with active fault movements at Binuang Oil Palm Plantation, Kunak

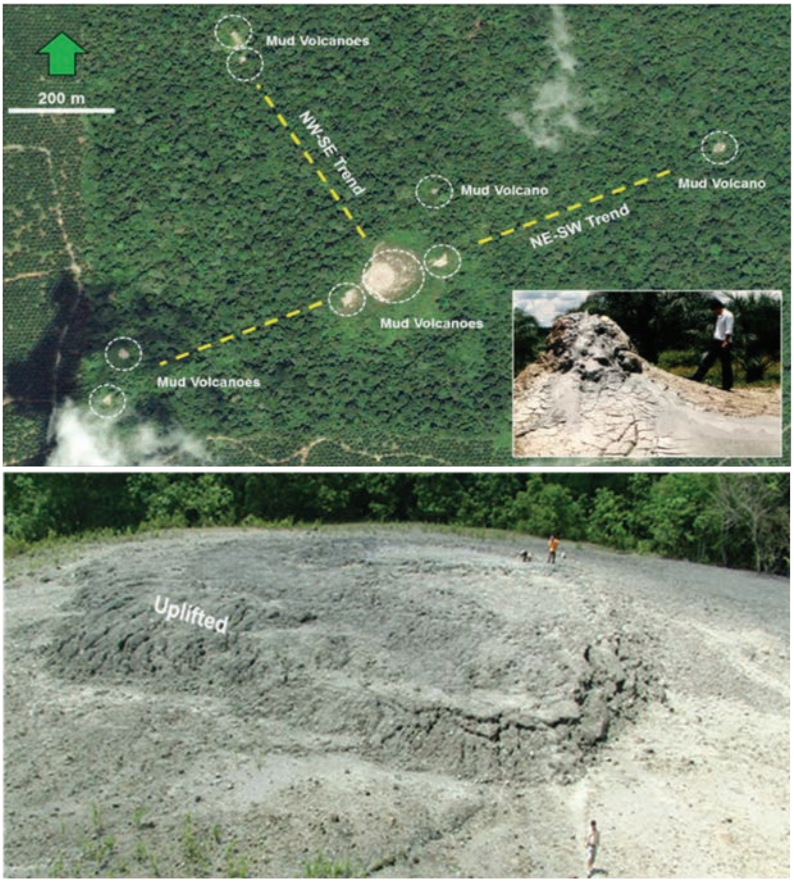


Figure 40 Several active mud volcanoes aligned NE-SW and NW-SE associated with active fault movements near Tabin, Lahad Datu. The Lipad Mud Volcano near Tabin shows recent uplift

Minor ground movements due to active faults are clearly observed in Lahad Datu and Kundasang areas (Tongkul, 2017; Ismail et al., 2015; Tongkul & Omang, 2010; Tjia, 2007). In Lahad Datu area, the manifestation of the active faults can be seen from ground movement causing a split in coconut tree trunks and presence of a mud volcano near Lahad Datu Airport (Figure 38). The presence of mud volcanoes in Kunak (Figure 39) and Tabin (Figure 40) is a clear indicator of active ground movement in the areas.

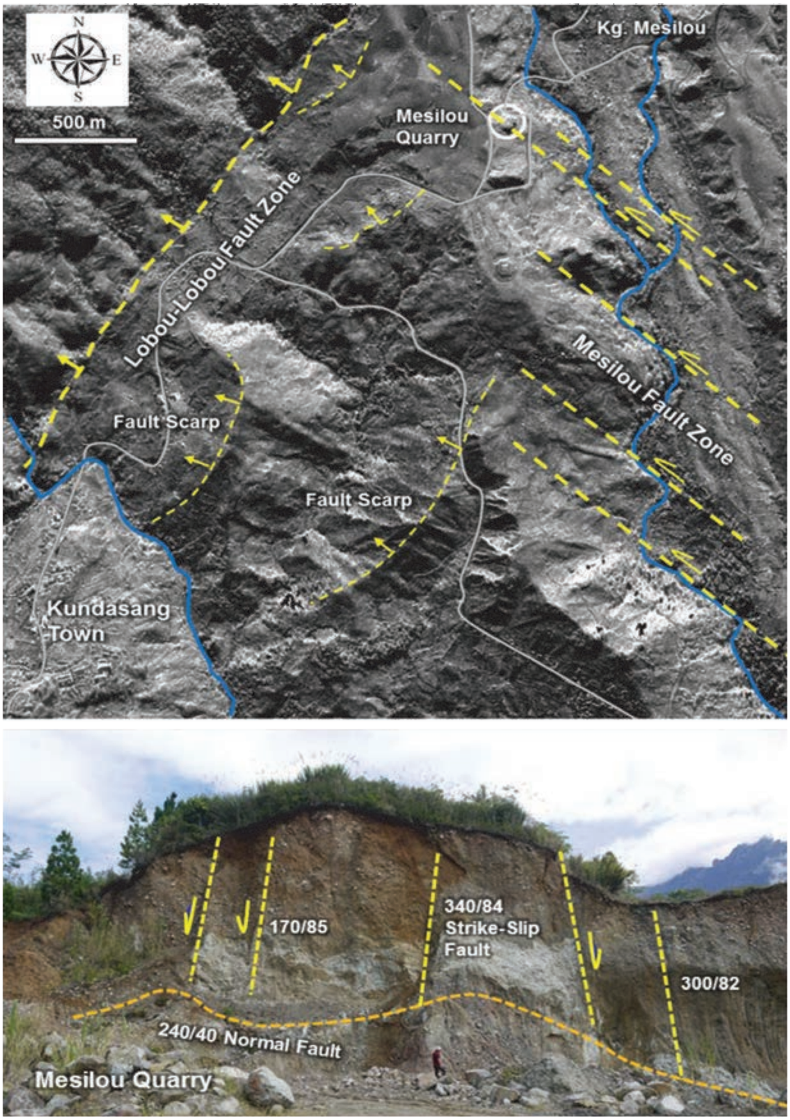


Figure 41 Radar image showing fault scarps due to normal faults associated with the Lobou-Lobou Fault Zone oriented N40E around Kundasang. Active left-lateral strike-slip fault oriented N130E associated with Mesilou Fault Zone also occurs here displacing the Mesilou River. Both types of faults can be observed at Mesilou Quarry.

Figure 42 Active left-lateral strike-slip fault oriented N130E affecting the concrete bridge along Kibbas-Mohimbayan road, Kundasang

Figure 43 Active thrust fault with right-lateral movement-oriented N60E affecting the road near Kibbas, Kundasang

In Kundasang and Ranau, active normal faults have produced fault scarps near Kundasang town area and left-lateral horizontal displacement of the Mesilou River. Both these faults can be observed at Mesilou Quarry (Figure 41). Active left-lateral strike-slip fault can also be seen causing minor displacement of the bridge along Jalan Kibbas-Mohimbayan (Figure 42). Along Jalan

Kundasang-Kibbas, persistent road damage is possibly related to active thrust fault, with right-lateral horizontal component (Figure 43). The active normal fault has resulted in the vertical displacement of Quaternary gravel deposits near Ranau town (Figure 44).

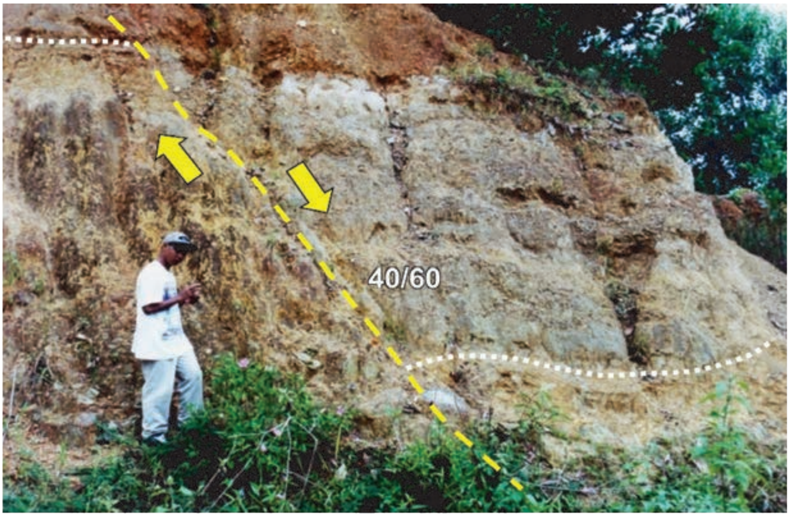


Figure 44 Active normal fault oriented N40E displacing the layers of the Quaternary Pinousuk Gravel by 3.5 m at Taman Pasir Puteh, near Ranau town

Impact of Earthquake in Malaysia

So far, the impact of earthquakes in Malaysia is mostly seen in Sabah due to the higher number of local earthquakes in this region, compared to Sarawak and Peninsular Malaysia. The effects of large earthquakes in the active regions surrounding the Sunda Shelf could extend to Peninsular Malaysia, Sarawak and Sabah. In Peninsular Malaysia, the epicentres of these earthquakes are located mainly to the west in Sumatra or northwest in the Andaman Islands. In all these tremors, no casualties or damage to houses were recorded. The most severe cases reported objects falling from shelves. Seismic effects, as experienced in West Sarawak, are almost identical to those of the Peninsula. However, in Central-North Sarawak and Sabah local earthquakes gave rise to stronger felt intensities. The larger earthquakes resulted in minor cracks in masonry walls, narrow fissures in the ground, and partial damage to a number of buildings and roads. The significant earthquakes and their impact are described below.

Three incidences caused considerable damage to buildings, which occurred in 1976 in Lahad Datu area and 1991 and 2015 in Ranau area (Tjia, 1978; Lim, 1976, 1985; Lim & Godwin, 1992; Tongkul, 1992, 2016). Another incidence caused minor damage to buildings in May 2008 in Kunak. These four events are elaborated below.

1976 Lahad Datu Earthquake

The July 1976 Lahad Datu Earthquake swarm with a magnitude of 5.8 Mb (6.2 Ms) and intensity of VIII (Table 6, Figure 45), caused considerable damage to property especially in the epicentral region in Lahad Datu and Kunak (Lim, 1976, Tjia, 1978). The walls of the ground floor of the new police complex at Lahad Datu were badly damaged; cracks appeared in other buildings including the Fire Department Flat, Telecom building and low-cost houses (Figure 46). The cracks indicated vertical and lateral movements. Steel rails buckled, snapped and were displaced laterally for 4 cm and north-south cracks 1.5 cm wide appeared in the ground at a rubber factory. The jetty at Kunak was cracked, water pipes burst, and five houses collapsed causing injury to two people. In Tawau, cracks appeared in the general hospital and in the Residence's office. Near Lahad Datu Airport, a mud volcano erupted and became active for several years after the event (Tongkul, 1989). The earthquake may be related to the active Sulu Trench (Lim, 1986). The focal mechanism solutions provided by USGS indicate two possible strike-slip fault-plane solutions, NW-SE left-lateral slip and NE-SW right-lateral slip. The NE-SW cluster of aftershocks suggests that the mainshock may have been due to NE-SW right-lateral strike-slip fault zone in the Darvel Bay.

Table 6 The main shock and aftershocks of the 1976 Lahad Datu Earthquake swarm

No.	Date	Time (Local)	Depth (km)	Mag	Mag type
1	25-07-1976	10:03 p.m.	33	5.3	Mb
2	26-07-1976	10:56 a.m.	33	5.8 /6.2	Mb /Ms
3	26-07-1976	11:03 a.m.	33	5.3	Mb
4	26-07-1976	1:35 p.m.	33	5.2	Mb
5	26-07-1976	4:36 p.m.	33	5.3	Mb
6	26-07-1976	4:49 p.m.	33	5.3	Mb
7	26-07-1976	5:43 p.m.	33	5.1	Mb
8	26-07-1976	9:12 p.m.	33	4.5	Mb

Source: USGS Earthquake Database

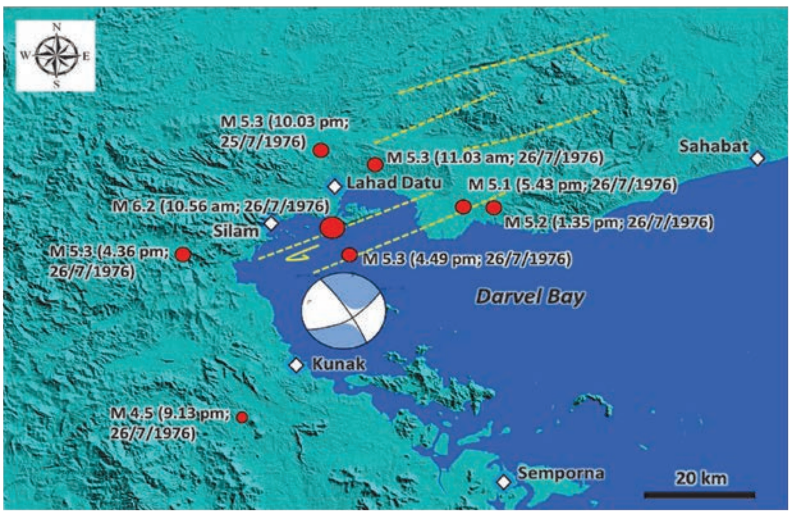


Figure 45 Epicentres of the 1976 Lahad Datu Earthquake swarm with a magnitude more than 4.5 based on USGS database. The foreshock with magnitude 5.3 occurred at 10.03 p.m. on 25 July 1976. The main shock with magnitude 6.2 occurred at 10.56 a.m. on 26 July 1976, followed by seven aftershocks of magnitude more than 5 on the same day. The focal mechanism (beach ball) indicates possible NE-SW right-lateral strike-slip fault zone (yellow line) producing the earthquakes

Figure 46 Damages caused by the 1976 Lahad Datu Earthquake swarm on buildings
(a) Minor rupture to the concrete floor of the Fire Department building
(b) Serious crack on walls and floor of Fire Department's Flat (totally abandoned)
(c) Serious crack on Telecom's newly completed building (totally abandoned)
(d) Minor crack on JKR building

1991 Ranau Earthquake

The 26 May 1991 Ranau Earthquake swarm with a magnitude of 5.1 Mb (5.4 Mw) and intensity VII produced substantial damage to property in the Ranau area, close to the epicentral region (Table 7, Figure 47). The 4-storey teacher's quarters at SMK Mat Salleh, Ranau suffered considerable structural damage – brick walls collapsed, cracks appeared in several parts of the buildings (Figure 48). A landslide was also triggered near Kg. Perapot. Tension cracks (en-echelon) appeared on the ground near Kg. Gaur, Bt. Kambura and Bt. Mitabang in the epicentral region (Lim & Godwin, 1992). The earthquake was also felt over a wide area on the west coast (Papar, Kota Belud, Kota Kinabalu, Tuaran and Tambunan). One death related to shock from ground shaking was reported in Tuaran. The earthquake may be related to reactivation of major faults in the Ranau area (Tongkul, 1992; JMG, 2006). The focal mechanism solutions provided by USGS indicate two possible normal fault-plane solutions-oriented NE-SW. Based on the geomorphological features such as the presence of linear structures and fault scarps, the main shock was probably due to NNW-SSE normal fault.

Table 7 The foreshocks and mainshock of the 1991 Ranau Earthquake swarm

No.	Date	Time (Local)	Depth	Mag	Mag type
1	26-05-1991	10:30 a.m.	33	4.6	Mb
2	26-05-1991	6:59 p.m.	33	5.1	Mb
3	26-05-1991	7:14 p.m.	33	4.7	Mb
4	26-05-1991	7:16 p.m.	18	5.4	Mw

Source: USGS Earthquake Database

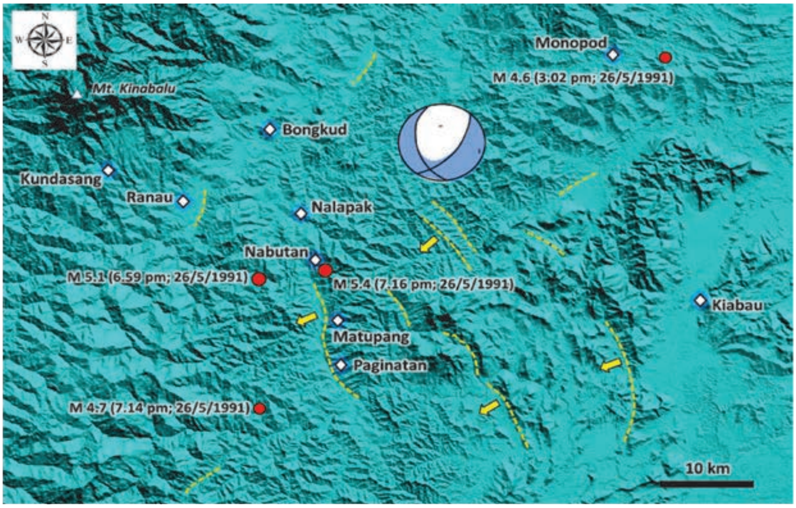


Figure 47 Epicentres of the 1991 Ranau Earthquake swarm with a magnitude more than 4.5 Mw based on USGS database. The foreshocks with magnitude 4.3 Mw occurred at 3.02 p.m. on 25 May 1992 near Monopod, followed by a magnitude of 5.1 Mw and 4.1 Mw at 6.59 p.m. then at 7.14 p.m. The main shock with magnitude 5.4 occurred several minutes later at 7.16 p.m. on the same day. The focal mechanism (beach ball) indicates two possible normal fault planes, NE-SW and NNW-SSE (yellow line)

Figure 48 Damages caused by the 1991 Ranau earthquake on SMK Mat Salleh Teacher's Quarters. The column of the flat suffered serious shear fractures and the flat have to be abandoned

2008 Kunak Earthquake

A moderate earthquake of magnitude 5 (Mw) occurred in Kunak District on 18 May 2008 around 2.26 p.m. The epicentre of the earthquake was located near Kg. Tun Fuad at a very shallow depth of about 10 km (Figure 49). The earthquake was felt as far as Lahad Datu and Tawau town areas. Some of the sites which incurred minor damages included stone wall houses in Bukit Tajam Estate, minarets in a mosque in Kampung Tun Fuad, concrete floor of Giram Oil Palm Mill and concrete floor and walls of Millimewa Supermarket in Kunak town (Figure 50). A mud volcano near Binuang Estate appeared to have been activated by the tremor. The focal mechanism solutions provided by USGS indicated two possible strike-slip fault-plane solutions, NW-SE left-lateral slip and NE-SW right-lateral slip. Based on the geomorphological features, such as the presence of linear structures and mud volcanoes, the earthquake was probably due to an NW-SE right-lateral strike-slip fault.

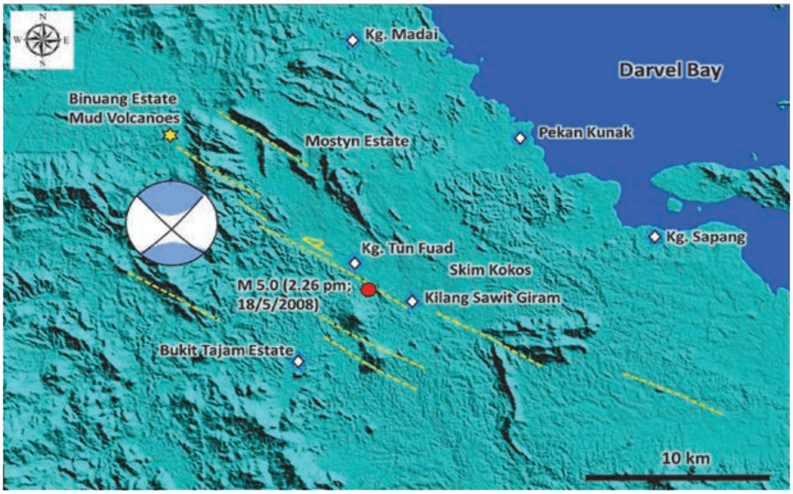


Figure 49 Epicentre of the earthquake located around 12 km Southwest of Kunak town based on the USGS database. The earthquake affected nearby areas at Tun Fuad Village, Bukit Tajam Settlement and Giram palm oil mill. The focal mechanism (beach ball) indicates two possible strike-slip fault planes, NW-SE and NE-SW (yellow line)

Figure 50 Damages caused by the 2008 Kunak Earthquake on buildings
(a) Wall collapsed at a house in Bukit Tajam
(b) Palm oil storage tank pipe bent at Giram
(c) Minor cracks on the floor of Milimewa Supermarket in town
(d) The base of palm oil storage tank uplifted by several centimetres at Giram
(e) Minarets fell at Tun Fuad Mosque

2015 Ranau Earthquake

The 5 June 2015 Ranau Earthquake with a magnitude of 6.0 (Mw) occurred at the foot of Mount Kinabalu near the highland town of Kundasang in the district of Ranau (Table 8, Figure 51). The earthquake which lasted for about 30 seconds was the strongest to affect Malaysia since the last 1976 earthquake in Lahad Datu. Tremors were also felt all over Sabah and as far afield as Federal Territory of Labuan, Miri in Sarawak as well as Brunei. During a period of 3 months after the mainshock, more than 120 aftershocks were recorded by Malaysia Meteorology Department located on a narrow zone stretching from Ranau to Tuaran. However, only 5 were of significant magnitude (larger than 4). The frequency of aftershocks was most intense during the first month (Figure 52).

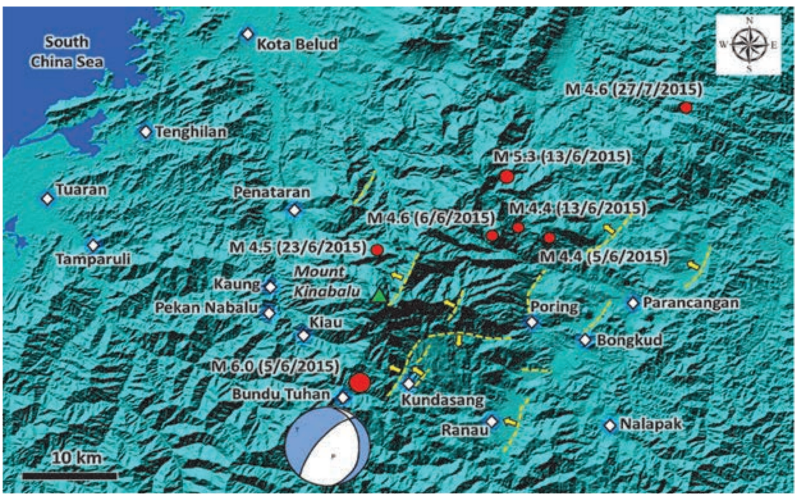


Figure 51 Epicentre of the earthquake mainshock and aftershocks (magnitude larger than 4 Mw) located around Mount Kinabalu during the first month based on the USGS database. The focal mechanism (beach ball) indicates two possible normal fault planes trending NE-SW (yellow line)

Table 8 Earthquake mainshock and aftershocks (more than 4) during the first month of the 2015 Ranau Earthquake

No.	Date	Time (Local)	Depth (km)	Mag	Mag type
1	05-06-2015	7:15 a.m.	10	6	Mw
2	05-06-2015	11:35 p.m.	18.23	4.4	Mb
3	06-06-2015	1:45 p.m.	10	4.6	Mb
4	13-06-2015	2:25 a.m.	15.01	4.4	Mb
5	13-06-2015	2:29 a.m.	7.25	5.3	Mb
6	23-06-2015	5:32 p.m.	15.32	4.5	Mb
7	27-07-2015	0.11 a.m.	14.96	4.6	Mb

Source: USGS Earthquake Database

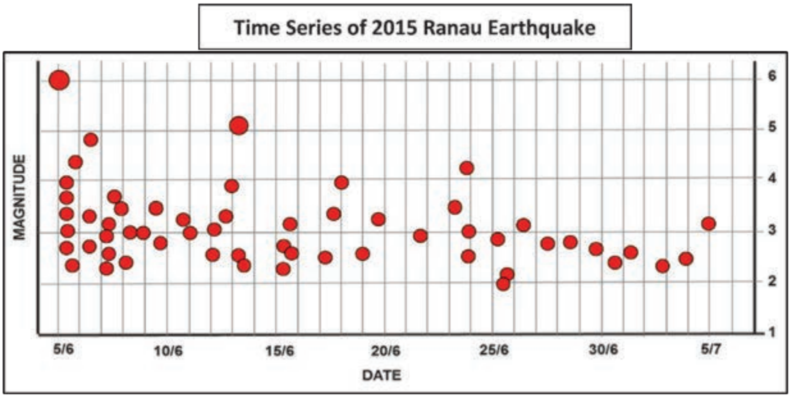


Figure 52 Time series of Ranau earthquakes based on MetMalaysia database. The first month was the most intense

Based on focal mechanism solution provided by USGS, the fault plane that has produced the main shock was interpreted to be a normal fault, where its strike was oriented NE-SW and dipping around 70 degrees to the NW. Based on field observations, apart from minor cracks on sealed roads and soil surface (mm scale), no significant surface rupture was recorded to clearly indicate where the earthquake-generating fault was located (Figure 53). It is possible that the fault displacement at the hypocentre, located around 11 km down, was probably very small, between 1 – 2 m only and therefore did not reach the surface, possibly a blind fault (Wang et al., 2017). The distribution of aftershocks, which is confined to a narrow zone indicates that the length of the earthquake-generating faults was approximately 20 km. The depth of the aftershocks which gradually increased towards the NW indicates that the fault plane dips NW towards Tuaran. Based on the location and depth of the hypocentre and the parameter of the earthquake-generating fault plane, the fault responsible for the mainshock is projected to have occurred approximately 5 km southeast of the epicentre, around Mesilou plain. Coincidently, NW dipping active normal faults trending NE-SW occur around Kundasang and Mesilou area collectively called the Lobou-Lobou Fault Zone. This fault zone is characterized by the presence of fault scarps (Figure 54) and damaged roads (Figure 55). The 2 km wide Lobou-Lobou Fault Zone extending from Mesilou to Kundasang and comprising of several parallel normal faults, is therefore interpreted to have caused the mainshock and some of the aftershocks (Figure 56). The fault planes trending NE-SW within the Lobou-lobou fault zone appears to undercut the Mount Kinabalu pluton (Figure 57). This may explain why Mount Kinabalu was violently shaken during the mainshock and aftershocks during the first day of the event. The Lobou-lobou Fault Zone is part of a regional extensional zone trending NE-SW along the west coast of Sabah related to gravitational sliding on an uplifted mountain belt (Tongkul, 2017).

Figure 53 Minor cracks on ground and road produced by the Ranau earthquake-generating fault

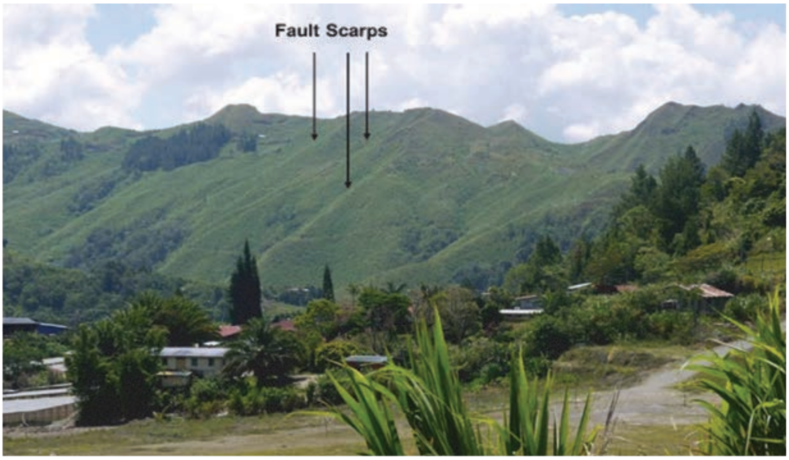


Figure 54 Fault scarps dipping towards the NW as seen from the Kundasang main road

Figure 55 Damaged road located within the NE-SW trending Lobou-Lobou Fault Zone near Kundasang

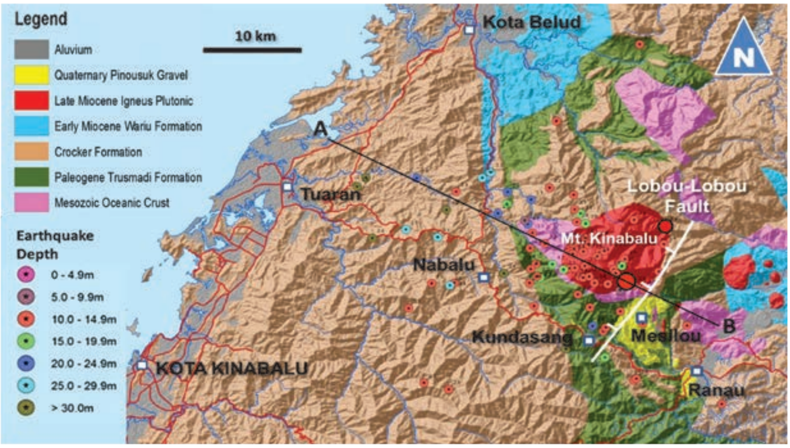


Figure 56 Location of the approximately 20 km length Lobou-Lobou Fault Zone southeast of the mainshock epicentre (big red circle) and significant aftershock epicentres (smaller circles of different colours indicating depth). The aftershocks are confined to a narrow zone. The aftershocks depth increased up to 30 km towards the NW. The geological cross-section A-B is shown in Figure 57 (Tongkul, 2016)

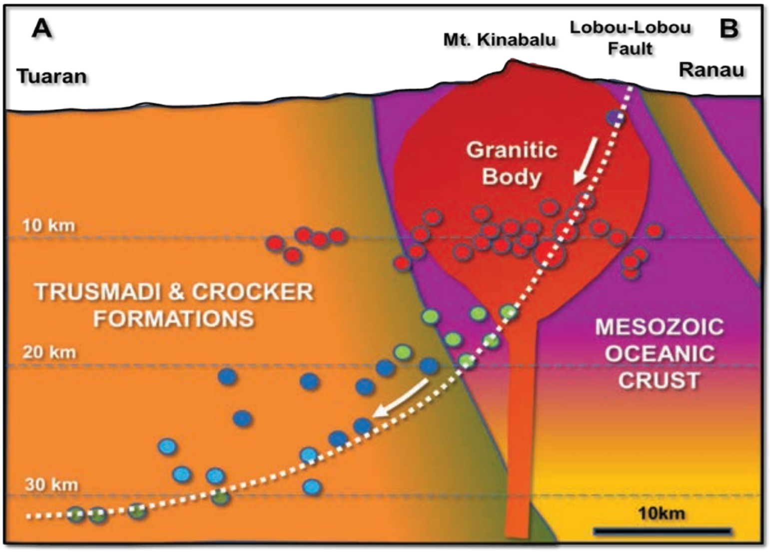


Figure 57 Geological cross-section showing the main earthquake-generating fault plane dipping steeply towards the NW cutting through the granitic Kinabalu body (Tongkul, 2016)

Figure 58 Damages caused by the 2015 Ranau Earthquake on buildings in Ranau town area
(a) The broken glass wall of a local bank
(b) Cracked wall of a coffee shop in town
(c) Shear fracture of the SMK Mat Salleh Teacher's Quarters' column
(d) Collapsed ceiling at Ranau Mosque
(e) Cracked walls at the Ranau Police Quarters

The surface movement due to the Ranau Earthquake mainshock (peak ground acceleration up to 14% (0.14 g) caused physical damages to infrastructures. Public buildings (schools, hostels, teacher's quarters, hospital, police quarters, mosque and temple), drainage pipes, water tanks, water intakes and private buildings (shops and houses) around Ranau and Kundasang areas suffered moderate damage (Figure 58). Damaged pipes resulted in water shortage in Kundasang and Ranau for several days. As a result of the shaking, rockfalls and landslides caused severe damage to public and private buildings. The Kinabalu Park facilities (hostels and climbing trails) near the summit of Mount Kinabalu suffered most from rockfalls and landslides. Houses in Kg. Kiau Nulu was also affected by landslides. Eighteen people died on Mount Kinabalu due to rockfalls with most of the deaths being Singaporean students while about 137 other people who were climbing the mountain were stranded but were subsequently rescued. As a result of the rockfalls and landslides, most areas in the Kinabalu Park was closed temporarily. The mountain was partially reopened on 1 September 2015 for climbers to go up to Panar Laban Resthouse (3,272 m) and a new route to the highest point at Low Peak (4,095 m) was officially opened on 1 December 2015. The shaking caused some form of liquefaction in Poring Hot Spring area. The hot water coming out from underground turned black as a result of mud ejected out from underneath. The shaking appears to have dislodged silts and muds that got stuck inside fractures or faults, enabling more hot water from underground to flow out. The shaking has thus rejuvenated the ageing hot spring, one of the positive impacts of the earthquake.

The shaking from the mainshock and aftershocks has caused extensive rockfalls and landslides around Mount Kinabalu. The landslide has practically scraped off about 1,500 hectares (15 km^2) of soils, rocks and vegetation cover, drastically reducing the capability of the water catchment to capture and store rainwater (Figure 59). The loose materials from the landslides which have accumulated on the slopes, in gullies and river valleys not only provided abundant source materials for debris flow during heavy rain but has affected the flow of water. Temporary reservoirs were created upstream when landslide materials dammed several river valleys, which eventually triggered debris flows after the dams were breached. The force of the debris flows, which carried a mixture of sand, muds, rocks and trees, like a river of concrete, resulted in deep scouring of river beds and banks up to bedrocks (Figure 60). This has drastically altered the river channels of all the major river system around Mount Kinabalu, especially the rivers of Sg. Mesilou West and Sg. Mesilou East in Ranau District; and Sg. Kadamaian, Sg. Tohabang, Sg. Kilambun and Sg. Penataran in Kota Belud District. Almost all living organisms in these rivers were wiped out by the debris flows (Figure 61).

The debris flows washed away several roads, Bailey bridges and hanging bridges, and inundated farmlands and villages, leaving behind thick layers of debris deposits (Figure 62). The Public

Works Department [Jabatan Kerja Raya (JKR)] estimated the cost of repairing the damaged infrastructures in the region of around RM100 million.

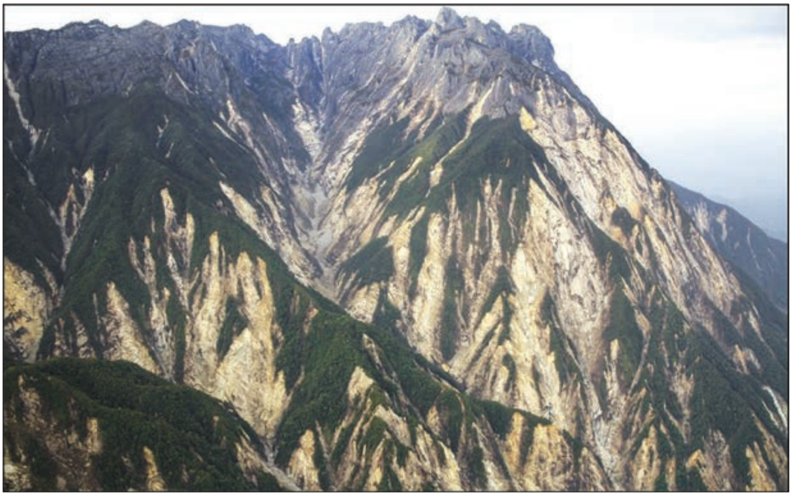


Figure 59 Extensive rockfalls and landslides occurred at the foot of Mount Kinabalu due to several aftershocks causing extensive damage to the water catchment

Figure 60 Deepening of river valleys due to the erosive force created by the extremely viscous debris flow

Figure 61 Impact of debris flow in Ranau and Kota Belud
(a) Riverbank erosion caused a house to slide down at Mesilou
(b) Debris flow deposit affected SK Kiau
(c) Fish died due to extremely high concentration of mud in the Kadamaian River

Figure 62 Penataran Village seriously affected by the debris flow

The enormous amount of loose materials washed into the river systems by rain, resulted in high turbidity and has rendered most of the affected rivers unfit for human use for several weeks after the massive landslide. Several water intake points along the rivers of Sg. Mesilou in Ranau District and Sg. Kadamaian in Kota Belud District were repeatedly shut down to avoid damaging the water treatment plants. As a result, both districts suffered a shortage of drinking water for several weeks. In Ranau, the water intake point was clogged by logs brought down by the debris flow. In Kota Belud, the irrigation system for paddy fields was also shut down for several weeks to avoid contamination from the muddy rivers.

The huge amount of sediments washed from the foot of Mount Kinabalu resulted in extremely heavy siltation to the Kadamain River, all the way to its estuary at Kuala Abai. The abnormal amount of siltation has resulted in the frequent flooding in Kota Belud area (Figure 63).

Figure 63 Recurrent flooding in Kota Belud area due to serious siltation of the river. Drone photo was taken on 21 Nov 2017

Earthquake Vulnerability in Malaysia

So far, the fatalities and damages to properties caused by the earthquakes in Malaysia are comparatively low compared to other earthquake-prone countries such as Indonesia, Philippines, Taiwan and Japan. This is due to the low earthquake intensity observed and because there are fewer major structures (such as tall concrete buildings, bridges, dams) and the urban areas are less populated in the earthquake-prone areas in Malaysia. However, Malaysia is fast developing, and urban areas are becoming more populated and more major structures have been erected in earthquake-prone areas. Most of these buildings were built without considering the effect of earthquake shakings which can cause vertical and lateral movements.

In Sabah, the effect is more pronounced as the earthquake intensity reached up to VII. In Lahad Datu, the newly established Palm Oil Industrial Cluster (POIC), housing several mills, factories and offices have changed the local landscape and will be quite vulnerable to future earthquakes. Similarly, in Ranau and Kundasang several new buildings (schools, shops and hotels) have also been erected.

In Peninsular Malaysia, the effect of regional earthquakes from Sumatra has been quite minimal (Maximum intensity of about IV). For example, on 6 March 2007, a 6.3 magnitude earthquake which hit the island of southern Sumatra sent tremors through the west coast states of Peninsular Malaysia. Incidences of people fleeing shaking buildings were reported in the Klang Valley, Seremban, Malacca, Johor as well as in Singapore. Similarly, the 26 December 2004 Magnitude 9.1 – 9.3 Mw earthquake in Sumatra generated tremors that were felt by many in the western part of Peninsular Malaysia. Hundreds of civilians and patients were evacuated from hospitals, police stations, hotels and apartments. Most of the structures affected by the vibration were high-rise buildings.

A study by JKR and UTM (Universiti Teknologi Malaysia) to determine the vulnerability of selected public buildings to earthquakes in Malaysia shows that most of our public buildings structural system are not critical to earthquake load (Selvanayagam, Zamri, Azlan, Mohd Noor Azudin, & Ch'ng, 2007). At least 50% of the selected building in Sabah and Sarawak were found to suffer from concrete deterioration problems, whereas in Peninsular Malaysia most of the buildings were in good condition. There were indications that showed that the vertical element design provision was inadequate for at least 50% of buildings evaluated. This will translate to a higher earthquake damage risk.

A study conducted by Ismail, Adnan and Ibrahim, (2011) on eight low-rise, medium-rise, and high-rise buildings in Sabah (Bangunan Telekom Kota Kinabalu, Sekolah Kebangsaan Bombalai Tawau, Wisma Dang Bandung Kota Kinabalu, Wisma Persekutuan Sandakan, Labuan Airport, Wisma Persekutuan Tawau, Perumahan

Kastam Kudat and Hospital Duchess of Kent Sandakan) using different intensities of earthquake load, 0.05 g, 0.10 g, 0.15 g and 0.20 g indicates that all the buildings in Sabah can resist up to 0.15 g. All the buildings were categorised in the moderate damage level where there is no structural damage but only obtained some non-structural damages. Similarly, an analytical vulnerability assessment carried out by Ahmadi, Mulyani, Nazri, Pilakoutas and Hajirasouliha (2014) on an industrial building in Peninsular Malaysia based on 0.13 g peak ground acceleration found that the MINTec-SINAGAMA building is considered safe.

Following the 2015 Ranau Earthquake, a seismic vulnerability study on existing buildings in Sabah was conducted by JKR (Mansor, Siang, Ahwang, Saadun and Dumatin, 2017). A total of 54 government buildings from 12 districts were evaluated. The results show that from 54 buildings selected for this study, 4 buildings were ranked as the most vulnerable building having insufficient capacity to resist earthquake forces and need to be further investigated for their strength requirement and suggested to be retrofitted.

Mitigation of Earthquake in Malaysia

Mitigation of earthquake involves receiving, analysing, maintaining, and distributing data on earthquake activity in Malaysia. This work is basically carried out by MetMalaysia through their network of seismograph stations. They provide rapid notification of earthquake events to civil defence and government officials in the affected area, and to the public through the news media. Mitigation also involves producing regional assessments of earthquake hazards in conjunction with State and local governments. The Minerals and Geoscience Department of Malaysia [Jabatan Mineral dan Geosains Malaysia (JMG)] produce the regional Seismic Hazard Map of Malaysia. This map is used by local planners and building officials in setting appropriate building and retrofitting standards in an area, government and civil defence officials in planning for disaster recovery, and professionals conducting detailed site assessments.

Basic research to learn more about the nature of earthquake activity is also part of the mitigation strategy. This research is mostly carried out by local universities in collaboration with foreign institutions. Apart from the scientific studies, education on earthquake hazards and safety to the public by publishing and distributing literature, and through a variety of other outreach efforts is a must to mitigate earthquake. This public education is carried out by MetMalaysia, JMG and local universities in collaboration with the Malaysian National Disaster Management Agency (NADMA).

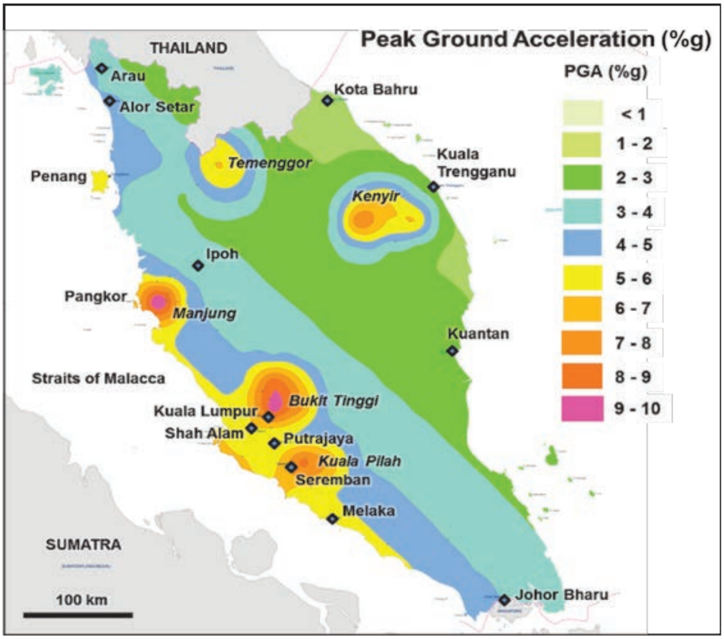
Development of National Seismic Hazard Map

Seismic hazard is the hazard associated with potential earthquakes in a particular area, and a seismic hazard map shows the relative hazards in different areas. The maps are made by considering what we currently know about: (i) Past faults and earthquakes, (ii) The behaviour of seismic waves as they travel through different parts of the crust, and (iii) The near-surface site conditions at specific locations of interest. Hazard maps can be used for land-use planning, mitigation, and emergency response.

In late 2017, the first edition of the seismic hazard map of Malaysia (JMG, 2018) was published by JMG and used in the Malaysia National Annex MS EN1998: 2015 Eurocode 8; Design for Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings. The seismic hazard map shows the probable peak ground acceleration (PGA) values for different parts of Malaysia. The seismic hazard map was developed by a group of local experts on earthquake comprising of various government agencies, non-government agencies and universities. The analysis is based on Probabilistic Seismic Hazard Assessment (PSHA) using active fault lines mapped by the Department of Minerals and Geosciences (JMG) and earthquakes from the

MetMalaysia database and the United States Geological Survey (USGS) earthquake database.

An earlier seismic hazard map of Peninsular Malaysia was produced by Azlan et al. (2008) based on regional earthquakes from Indonesia. Similarly, JMG (2006 & 2008) also produced a seismotectonic map in Malaysia. However, both studies were quite regional in nature and could not be used in formulating building codes. A global and regional seismic hazard map of Asia, which includes Malaysia was produced by Giardini, Grunthal, Shedlock and Zhang (1999) and Petersen et al. (2007). Both maps show PGA values which are not very different from the PGA values of the latest seismic hazard map of Malaysia. Another recent global seismic hazard map produced by the Global Earthquake Model (GEM) (Pagani et al., 2018) also shows nearly similar PGA values for Sabah.

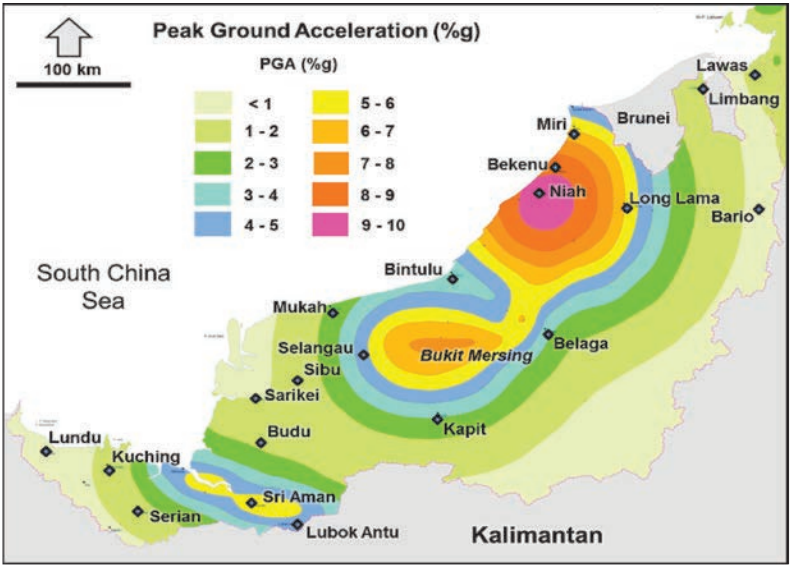


Source: JMG, 2018

Figure 64 Seismic hazard map of 475-year return period Peak Ground Acceleration (PGA) on the rock for Peninsular Malaysia

The latest seismic hazard map shows that not all parts of Malaysia are exposed to significant peak ground acceleration of more than 4%. In Peninsular Malaysia, low PGA values make up around 60% of the total land area (Figure 64). The higher PGA values are concentrated in five areas, in Kuala Pilah, Bukit Tinggi, Manjung, Temenggor and Kenyir, coinciding with the presence of potential active faults in these areas. The highest PGA value of 9% (0.09 g) is located in Bukit Tinggi.

In Sarawak, low PGA values make up around 50% of the total area (Figure 65). The higher PGA values are concentrated in three areas, in Miri, Bukit Mersing (near Selangau) and Sri Aman, coinciding with the presence of potential active faults in these areas. The highest PGA value of 9% (0.09 g) is located in the Niah area.

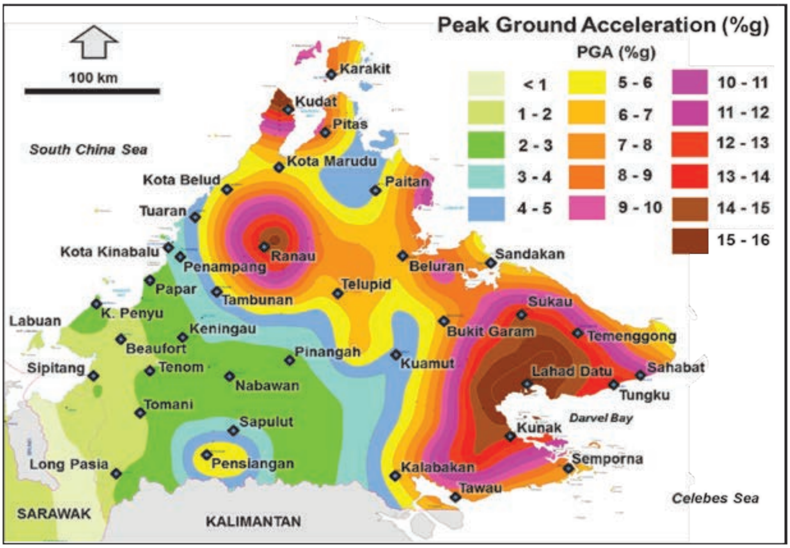


Source: JMG, 2018

Figure 65 Seismic hazard map of 475-year return period Peak Ground Acceleration (PGA) on the rock for Sarawak

In Sabah, low PGA values make up around 30% of the total area (Figure 66). The low PGA values are located in the southwest (e.g. Papar, Beaufort, Kuala Penyu, Sipitang and Tenom) whereas the higher values are located in north (e.g. Kudat, Pitas and Kota

Marudu), northeast (e.g. Paitan, Beluran, Sandakan and Sukau) and southeast (Lahad Datu, Kunak, Semporna and Tawau). The higher PGA values of more than 12% (0.12 g) are concentrated in three areas, in Ranau, Kudat and Lahad Datu, coinciding with the presence of potential active faults in these areas. The highest PGA value of 16% (0.16 g) is located in Lahad Datu. During the 2015 Ranau Earthquake, the PGA value recorded by MMD for Ranau is 12.9% (0.129 g), whereas for Tuaran is 4.4% (0.044 g).



Source: JMG, 2018

Figure 66 Seismic hazard map of 475-year return period Peak Ground Acceleration (PGA) on the rock for Sabah

Development of National Seismic Building Code

Building codes are designed to create quality assurance and durability, with the objective to minimise economic loss due to material and structural deterioration and to provide basic comfort and safety conditions. In earthquake-prone areas, building codes are complemented by seismic codes, specifying the calculation methods and strength values of key structural elements to avoid building collapse during an earthquake. In countries where building and seismic codes have not been implemented (Haiti, Pakistan, China and Nepal), large loss of life and economic set-back has occurred, compared to countries where seismic codes are strictly enforced (Peru, Chile, New Zealand and Japan) and the loss of life has been minimal.

In 2015, Malaysia adopted the MS EN1998: Eurocode 8; Design for Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings. However, the annexe to the Eurocode 8 was only completed and published by the Department of Standards Malaysia (JSM) in late 2017. The annexe was prepared by a group comprising officials from relevant government agencies such as MetMalaysia, JMG, Public Works Department (JKR), Sabah Housing and Real Estate Developers Association, Institution of Engineers Malaysia (IEM), Association of Consulting Engineers Malaysia and other seismic experts. With the publication of the Malaysian Annex to MS EN1998: 2015 Eurocode 8, new buildings are expected to follow this code to better withstand earthquakes. However, it is not mandatory for all buildings to follow as it is up to the local authorities to impose such standards. Among the features that can be incorporated into buildings to help it weather quakes are the use of reinforced concrete and seismic rubber bearings. For existing buildings, it will be up to the owners' discretion to seek advice from professional engineers to assess whether such structures need to be upgraded or retrofitted to comply with the code.

Development of Planning Guideline in High-risk Earthquake Area

Following the physical impact of the 2015 Ranau Earthquake (6.0 Mw), the Department of Town and Country Planning under the Ministry of Housing and Local Government (KPKT) was tasked with preparation of a development guideline in high-risk earthquake area as a reference for state government, local government, implementing agencies, developers and consultants. The guideline which was completed in June 2018 provides a list of high-risk earthquake areas in Malaysia and proposed several mitigation measures in terms of planning and management of new developments in these areas. The guideline emphasised the importance of using the Seismic Hazard Map prepared by JMG in the preparation of development plan and approval of the development plan.

Public Education and Awareness Programme

Public education and awareness on earthquake is currently carried out by the MetMalaysia through their website. Information on the occurrence and records of an earthquake around Southeast Asia is readily available on their website. A recently developed shake map called myGempa provides detailed information on the intensity of an earthquake. The department also routinely issue statements on the occurrence of earthquake within 8 minutes to the disaster management agency and the public via TV crawler, website, media statement and Facebook. The department also organises seminars and workshops to share and disseminate earthquake-related studies and findings to the public.

Apart from MetMalaysia, public education and awareness on earthquake is an ongoing activity by UMS under the Natural Disaster Research Centre (NDRC). This seminar is carried out periodically with collaboration from MetMalaysia and the National Disaster Management Agency (NADMA) in Sabah (Figure 67).

In 2017, NDRC and UNICEF Malaysia with the support of the Ministry of Education of Malaysia embarked on a two-year earthquake education programme among schoolchildren and teachers in Ranau and Lahad Datu districts (Figure 68 and Figure 69). This programme produced a teacher training package including a DVD and a children booklet on earthquake preparedness (Figure 70). All the 82 schools in Ranau and 53 schools in Lahad Datu benefited from this programme.

Figure 67 Public education seminar on earthquake science and earthquake preparedness. (a) Kudat in 2017, (b) Kunak in 2018

Figure 68 Schoolchildren in Ranau learning about earthquake science and earthquake drill in 2018

Figure 69 Teachers from Ranau District learning the basics of earthquake science and earthquake preparedness. The teachers are expected to be facilitators of earthquake education and preparedness in their respective schools

Figure 70 Teaching materials for teachers and schoolchildren on earthquake science and earthquake preparedness

Figure 71 Posters on earthquake preparedness distributed to schools in Ranau and Lahad Datu

Since the publication of the Malaysian seismic building code in late 2017, the Department of Standards [Jabatan Standard Malaysia (JSM)] has organised several seminars to educate the public on the building code, especially those professionals involved in the designs of the building. The seminar provides participants with an introduction to the seismic hazard map and the critical standards inside the Malaysian Annex to the Eurocode 8. Apart from JSM, Universiti Teknologi Malaysia (UTM) has also been actively promoting the use of the Eurocode 8 through their short courses, organised individually or co-organised by the Institution of Engineers Malaysia (IEM).

CHALLENGES IN EARTHQUAKE SCIENCE IN MALAYSIA

Earthquake hazard is still poorly understood and yet to be properly quantified in Malaysia. This is due to the lack of critical basic scientific data. For example, during the 2015 Ranau Earthquake, there was no usable earthquake hazard model or map which could be referred to for mitigation planning and reduction of impacts. Basic scientific data such as Peak Ground Acceleration (PGA) of the Ranau Earthquake and past earthquakes was inadequate and not readily available for formulating a building code. The lack of engineering data on the strength of existing buildings adds to the problem of coming up with realistic guidelines for earthquake resistant building. The communities affected by the 2015 Ranau Earthquake did not know what to do for several days as they were totally unprepared for the earthquake. Timely and appropriate information on the earthquake aftershocks was lacking from MetMalaysia and unfounded statements from the public regarding an impending large earthquake that went viral did not help calm the affected communities.

Lack of Seismic, Geological, Geodetic and Engineering Data

In other to properly quantify earthquake hazard, three basic pieces of information are needed: the model of future earthquakes, attenuation relations, and geologic site conditions. To come up with a model of a future earthquake, information such as the past history of earthquakes, active faults (cause of earthquakes) and present crustal deformation (geodetic data) are required. In Malaysia, historical earthquakes are not well documented and archived. For example, in Sabah only earthquake records after 2004 are complete. The older earthquake records are very patchy (see Figure 24).

Conventional mapping of active faults has been on-going for the past few years in Malaysia, primarily carried out by the Department of Minerals and Geosciences Malaysia (JMG) and UMS. Unfortunately, the precise location, rate of movement and detailed characteristics of active faults are still lacking. No attempt has yet been carried out to apply satellite remote sensing technology such as Interferometry Synthetic Aperture Radar (InSAR) to determine ground movement and thereby locate active faults.

To determine how the earthquake ground motion propagates from an earthquake source, strong motion recordings close to the earthquake are required. In Malaysia strong motion seismic stations are already available in several locations. However, in other to estimate the surface ground motion of earthquake waves it is necessary to know the geologic site condition. In Malaysia, such geological information is also still lacking. An on-going study by Cambridge University and University of Aberdeen in collaboration with UMS and MetMalaysia to model the crustal velocity is currently limited to Sabah (Pilia, Rawlinson, Gilligan, & Tongkul, 2019).

Due to incompleteness of available seismic, geological and geodetic data, the seismic hazard map of Malaysia produced by JMG in 2017 can be considered a preliminary map that requires further revisions in the near future.

In other to mitigate the impact of the future earthquake on buildings basic information on the strength of existing buildings is needed. At the same time, appropriate designs of the earthquake-resistant building are required. To achieve this an earthquake engineering laboratory is needed to carry-out appropriate simulations and testing. Currently, such a facility is only available at Universiti Teknologi Malaysia (UTM). Even then, the facilities at UTM is inadequate and are quite old.

Insufficient Seismic and Geodetic Monitoring System

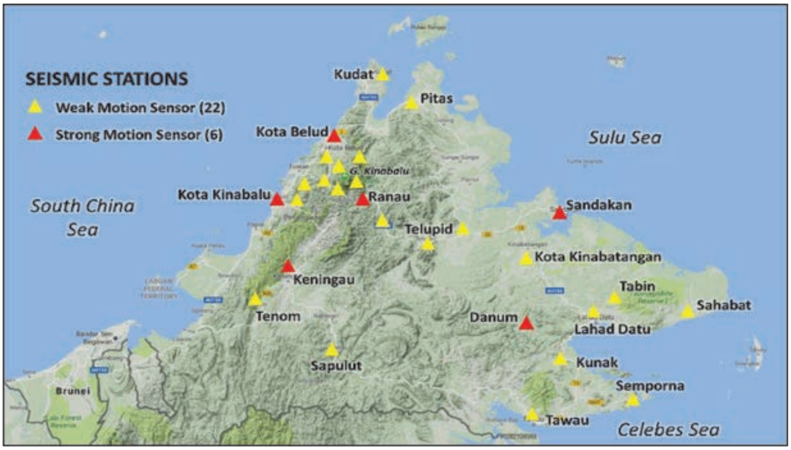
Data generated from continuous monitoring of earthquake activities and crustal movements can provide important clues as to where the next potential earthquakes will be located, apart from being used to update the existing seismic hazard map of Malaysia.

Monitoring of earthquake in Malaysia is solely carried out by MetMalaysia. During the 2015 Ranau Earthquake, some of the seismic stations in Sabah experienced technical problems. As a result, critical data were missing as there is no complementary seismic monitoring system in place. Although there are now 28 seismic stations installed and monitored by MetMalaysia in Sabah (Figure 72), these are still not dense enough to provide accurate information, for research purpose (e.g. generating Focal Mechanism Solution – FMS). Blind spots exist in many places especially in the Lahad Datu and Kunak areas.

Except for the MetMalaysia seismic data centre in Petaling Jaya, other seismological data centres are practically non-existent in Malaysia. A mirror site for earthquake monitoring was established by MetMalaysia in Kota Kinabalu since 2017 but is not well maintained due to lack of capable human resource.

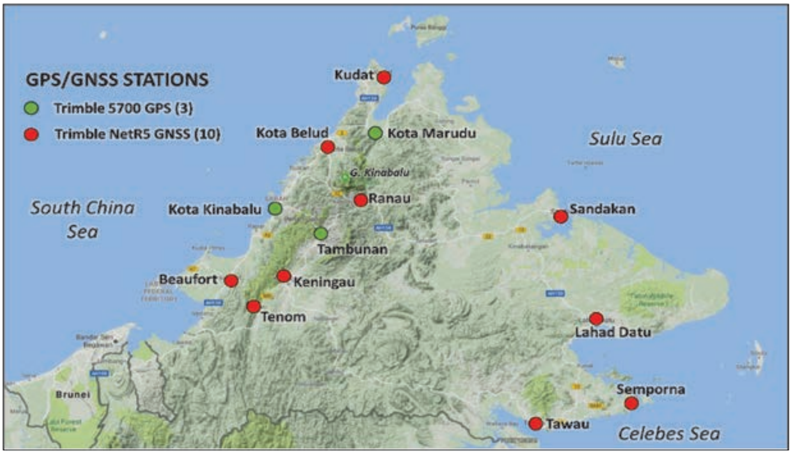
In terms of crustal deformation information on Malaysia, 78 real-time Global Navigation Satellite System (GNSS) stations have been installed by the Department of Survey and Mapping Malaysia (JUPEM) for the past few years. In Sabah, there are 13 stations

(Figure 73). However, the small number of stations, which is located tens of kilometres from each other do not provide high-resolution crustal movement, associated with active faults and strained crustal areas. A pilot study to monitor crustal movement in Kundasang by JUPEM yielded some results but was discontinued after a few years due to lack of funding (Azhar, 2012).



Source: MetMalaysia

Figure 72 Distribution of 28 seismic stations in Sabah where 15 new stations were installed in 2017



Source: JUPEM

Figure 73 Distribution of 13 GPS/GNSS stations in Sabah

Lack of Trained Human Resource

Currently, the number of expertise in the field of earthquake-related science and engineering is very small in local universities. They are distributed in different universities (e.g. UMS, UTM, UiTM, UPM and USM), carrying out their own limited research based on their individual expertise. JMG has only recently started to train their geologists to carry out mapping and monitoring of active faults.

The human resource in relevant departments, like MetMalaysia and JUPEM, are mostly focused on gathering data with limited capacity for data analysis (advanced research). Trained technicians in handling earthquake monitoring instrumentations are also limited. Local graduate students pursuing earthquake science and earthquake engineering degrees are very few.

Lack of Public Awareness

Educating people about earthquakes can effectively reduce human and economic losses during seismic disasters. The issues encompass the delivery of earthquake information to the public, earthquake-oriented curricula in schools at all levels; career focus for young researchers, and the transfer of knowledge to engineers, emergency managers, and government officials. During the 2015 Ranau Earthquake, communities affected were traumatized and their daily activities stopped for several days as they do not know how to cope with the hazard.

Coordinated and sustained effort to educate the public is still weak. Currently, public education on natural hazards including earthquake carried out by relevant agencies like NADMA, MetMalaysia and UMS is carried out based on the availability of funding. Studies in the field of earth science that includes earthquake processes and active tectonics are limited to undergraduate students in higher education.

WAY FORWARD IN EARTHQUAKE SCIENCE IN MALAYSIA

To ensure that the science of earthquake in Malaysia is up-to-date and is able to respond to the current and future needs, some steps have to be taken by all stakeholders involved in looking after the well-being of the people. The following are strategic suggestions to address the existing gaps, some which could be carried out immediately and others on a medium or long-term basis.

Comprehensive Geological and Engineering Studies

- Embark on using InSAR and GNSS to monitor minute (cm scale) surface ground deformation and crustal strain accumulation in earthquake-prone areas in Sabah. This could be quite useful in identifying active fault zones and locations of future earthquakes.
- Embark on crustal velocity studies using mathematical modelling for the whole country. This crustal velocity models could be useful in estimating surface ground motion of an earthquake.
- Embark on soil studies in high-risk areas to determine soil amplification values for generating appropriate response spectrum acceleration (RSA) for a specific location.
- Map potential earthquake-induced landslides and ground settlement due to liquefaction in high-risk areas.
- Prepare hazard maps for earthquake-prone areas like Ranau and Lahad Datu (showing where landslides may occur and evacuation information). The map could be used for improving facilities for preventive and emergency measures.
- Develop a guideline for planning development of land on or close to active faults.

- Identify cost-effective and easy methods to build earthquake-resistant houses in rural areas.
- Undertake seismic vulnerability studies of existing important buildings or structures, particularly in high-risk areas.
- Promote earthquake-resistant construction in high-risk areas and encourage retrofitting for critical buildings
- Improve the National Seismic Hazard Maps and provide revision periodically (based on new earthquake science findings).

Coordinated Seismic and Geodetic Monitoring

- Strengthen and improve seismic observation network under MetMalaysia by adding more sensitive seismic stations in strategic areas.
- Improve accuracy, timeliness and content of earthquake information products.
- Set up building acceleration instrumentation devices to obtain the acceleration at different storey height.
- Incorporate global seismic data, seismic hazard models and earthquake predictions to enhance local seismic models.
- Strengthen and improve GPS/GNNS observation network under JUPEM by adding more GPS stations in strategic areas.
- Set up a complementary seismological and GPS data centre, not only to process data but to carry out serious earthquake-related research (ideally located in Sabah).

Human Resource Capacity Building

- Develop human resource in the field of earthquake science and safety. Train more seismologists, earthquake scientists, earthquake engineers and earthquake technicians in relevant departments and universities to handle and interpret seismic instrumentations and to increase their capacities on these three aspects; (i) mitigation and adaptation, (ii) forecasting and (iii) impact assessment on earthquake.
- Introduce earthquake science and earthquake engineering education curriculum in local institutions of higher learning.
- Capacity building of relevant government administration at all levels, but especially in relation to the seismic code requirements, on-site supervision and enforcement.

Coordinated Public Education

- Increase public awareness of earthquake hazards and risks through a coordinated effort among institutions to ensure they are better prepared (more resilient) to respond to future earthquakes (during night-time or daytime).
- Implement seismic safety programmes in schools.
- Awareness-raising of the population on matters relating to earthquake-resistant building techniques, preventive measurements, and the fact that many multi-storey buildings need structural retrofitting.

Special Research and Development Fund

- Provide support for basic research in geosciences, engineering, and social sciences phenomena, on earthquake impacts, and means to reduce earthquake effects. This is essential to form the knowledge base from which targeted applied research and mitigation practices and policies can be developed.
- Provide support for advanced scientific and engineering knowledge of earthquake effect on the built environment. This research will contribute to developing cost-effective design methodologies and technologies for mitigating these effects on soils, existing structures and new construction. This will also contribute to the formulation of building codes.
- Provide support to determine the available strength of various building types prevalent in the country, to identify their deficiencies and weaknesses from a seismic behaviour point of view, and to work out how such deficiencies and weaknesses can be eliminated or minimized by feasible and economic actions in the field. The objective of such an intervention would be to reduce the risk of total collapse and prevent the loss of life as well as the loss of contents in future earthquake occurrences.
- Provide support to develop building code versions which are understandable and affordable to local village craftsmen in rural areas who normally build their houses without plans or calculations using self-help methods.
- Support the development of guidelines and instructions for community-based assessment of seismic hazards.

National Earthquake Research Centre

- Set-up a national earthquake research centre dedicated to the teaching, research and mitigation of earthquake hazards (equipped with earthquake science and engineering laboratories).
- Earthquake science and earthquake engineering expertise could be pooled together at this centre to serve a common goal.

CONCLUDING REMARKS

The occurrence of a large earthquake in Malaysia in the future can have devastating consequences, especially in urban areas. As more remote areas are built, the risk is also increasing. To mitigate the impact of future large earthquakes, scientific knowledge on the behaviour of earthquakes needs to be improved and mitigation strategies properly put in place. In short, earthquake science needs to be given serious support in terms of funding and appropriate infrastructures. The current seismic hazard map needs to be updated soon, and local earthquake scientists and engineers need to collaborate with international scientists to work towards the production of better seismic hazard maps.

Prompt implementation of construction code for earthquake resistant building will reduce the impact of the earthquake. For example, the recent Mexico earthquakes (8.2 Mw) on 8 September 2017 only killed 58 people compared to 10,000 during the earthquake (8.0 Mw) on 19 September 1995, after construction codes were reviewed and stiffened – now as strict as those in US and Japan. Similarly, the large Chile earthquakes on 16 September 2015 in Illapel (8.3 Mw) shows the positive effect of applied seismic codes where the casualties are only 15 and 270 building collapsed. The 2011 New Zealand Christchurch earthquake (6.3 Mw) event also demonstrates the small number of casualties (185 deaths) and the small number of the collapsed building (2) when building and seismic codes are properly adhered to. In contrast, the 2015 Nepal Earthquake (7.8 Mw) killed 8,790 people and destroyed 605,253 buildings where the seismic building code was not implemented. Earthquake-prone areas like Sabah should seriously start implementing the newly developed earthquake resistance building code (Eurocode-8).

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APPENDICES

Appendix 1 Local Earthquakes in Peninsular Malaysia based on MetMalaysia and IRIS Earthquake Database

No.	Date	Latitude	Longitude	Depth	Mag (Mb)	Location
1	01-05-2017	5.2103	102.8671	650	2.3	Kuala Berang, Terengganu
2	24-03-2016	5.184	101.043	10	1.8	Temenggor
3	23-02-2016	5.0316	102.8402	2.4	3.0	Tasik Kenyir, Terengganu
4	03-01-2016	5.5498	101.3538	10.9	3.0	Temenggor, Perak
5	03-01-2016	5.5537	101.3622	12.0	3.2	Temenggor, Perak
6	03-01-2016	5.5213	101.3686	15.3	3.1	Temenggor, Perak
7	02-04-2014	4.2184	101.7653	8.7	2.5	Sungai Koyan, Pahang
8	18-12-2013	4.5982	102.1335	26.6	2.7	Sungai Tabung, Pahang
9	25-09-2013	5.378	101.447	20.0	3.1	Tasik Temenggor, Perak
10	20-08-2013	5.416	101.360	1.6	4.1	Tasik Temenggor, Perak
11	16-04-2010	4.52	101.15	10	2.7	Gopeng, Perak
12	04-12-2009	3.373	101.804	5.0	2.0	Bukit Tinggi, Pahang
13	30-11-2009	2.731	102.067	14.7	3.5	Kuala Pilah, N. Sembilan
14	30-11-2009	2.738	102.143	4.0	3.0	Kuala Pilah, N.Sembilan
15	29-11-2009	2.736	102.117	1.7	3.3	Kuala Pilah, N. Sembilan
16	29-11-2009	2.739	102.091	3.0	3.1	Kuala Pilah, N. Sembilan
17	08-10-2009	3.270	101.827	10.0	1.0	Bukit Tinggi, Pahang
18	07-10-2009	3.344	101.814	1.9	0.3	Bukit Tinggi, Pahang
19	07-10-2009	3.303	101.834	10.0	3.2	Bukit Tinggi, Pahang
20	07-10-2009	3.354	101.822	3.0	4.2	Bukit Tinggi, Pahang

21	07-10-2009	3.389	101.902	10.0	1.0	Bukit Tinggi, Pahang
22	07-10-2009	3.349	101.809	1.9	1.7	Bukit Tinggi, Pahang
23	29-04-2009	4.150	100.729	22.5	2.7	Manjung, Perak
24	27-03-2009	3.862	102.519	50.0	3.2	Jerantut, Pahang
25	25-05-2008	3.360	101.750	< 33.0	2.6	Bukit Tinggi, Pahang
26	15-03-2008	3.330	101.710	< 33.0	3.3	Bukit Tinggi, Pahang
27	14-03-2008	3.300	101.860	< 33.0	2.5	Bukit Tinggi, Pahang
28	14-03-2008	3.330	101.740	< 33.0	2.9	Bukit Tinggi, Pahang
29	03-02-2008	3.240	101.870	10.0	1.6	Bukit Tinggi, Pahang
30	14-01-2008	3.350	101.770	10.0	2.5	Bukit Tinggi, Pahang
31	14-01-2008	3.420	101.800	< 33.0	3.4	Bukit Tinggi, Pahang
32	13-01-2008	3.410	101.860	10.0	1.9	Bukit Tinggi, Pahang
33	13-01-2008	3.330	101.830	< 33.0	2.4	Bukit Tinggi, Pahang
34	13-01-2008	3.310	101.830	< 33.0	2.5	Bukit Tinggi, Pahang
35	10-01-2008	3.390	101.730	3.0	3.0	Bukit Tinggi, Pahang
36	31-12-2007	3.320	101.810	< 33.0	2.6	Bukit Tinggi, Pahang
37	12-12-2007	3.470	101.760	< 33.0	3.2	Bukit Tinggi, Pahang
38	09-12-2007	3.350	101.800	< 33.0	3.1	Bukit Tinggi, Pahang
39	09-12-2007	3.330	101.820	4.9	3.5	Bukit Tinggi, Pahang
40	06-12-2007	3.360	101.810	< 33.0	2.7	Bukit Tinggi, Pahang
41	05-12-2007	3.370	101.800	< 33.0	2.6	Bukit Tinggi, Pahang
42	05-12-2007	3.300	101.800	< 33.0	1.5	Bukit Tinggi, Pahang

43	04-12-2007	3.350	101.800	< 33.0	1.4	Bukit Tinggi, Pahang
44	04-12-2007	3.370	101.800	< 33.0	3.3	Bukit Tinggi, Pahang
45	04-12-2007	3.360	101.810	< 33.0	3.0	Bukit Tinggi, Pahang
46	30-11-2007	3.310	101.840	6.7	3.2	Bukit Tinggi, Pahang
47	30-11-2007	3.340	101.800	< 33.0	2.8	Bukit Tinggi, Pahang
48	30-11-2007	3.360	101.800	2.3	3.5	Bukit Tinggi, Pahang
49	18-05-2006	3.29	101.44	0	3.2	Batu Arang, Selangor
50	03-09-2001	1.71	102.91	0	3.4	Off Batu Pahat, Johor
51	14-09-1998	4.55	100.77	33	4.4	Batu Gajah, Perak
52	25-08-1998	2.44	101.78	0	4.2	Off Port Dickson, N.S.
53	22-08-1998	4.09	100.5	33	4.1	Off Port Dickson
54	27-11-1997	3.73	101.48	15	4.6	Tg. Malim, Perak
55	02-11-1997	4.98	101.31	80	3.6	Perak
56	25-07-1997	4.07	100.65	80	3.9	Off Setiawan
57	21-04-1996	2.69	101.61	0	3.3	Sepat, Selangor
58	10-06-1995	5.05	100.5	33	4.1	Off Bagai Serai, Perak
59	08-02-1992	2.8	104.2	12	3.7	Pulau Tioman, Johor
60	31-05-1976	2.68	101.39	35	4.9	Off Tg. Sepat

Appendix 2 Earthquakes in Sarawak based on MetMalaysia, USGS and IRIS Earthquake Databases

No.	Date	Latitude	Longitude	Depth	Mag (Mb)	Location
1	20-04-2019	1.59	111.51	10.0	3.4	Sri Aman
2	07-05-2018	3.6751	113.7348	16.9	3.7	Niah
3	12-05-2012	2.734	113.914	40.6	3.5	Bakun
4	09-05-2012	2.763	113.750	20.9	3.8	Bakun
5	08-10-2011	1.61	111.29	0	3.7	Pasu
6	15-07-2011	1.040	110.993	55.7	4.3	Sebuyau
7	24-01-2010	3.626	113.810	9.7	3.4	Batu Niah
8	24-01-2010	3.520	113.875	2.0	2.6	Batu Niah
9	24-01-2010	3.654	113.821	10.0	3.8	Batu Niah
10	23-12-2009	3.975	113.955	50.0	3.7	Miri
11	19-03-2008	1.420	110.200	50.0	3.3	Semenggok
12	17-02-2006	4.600	114.900	< 33.0	4.6	Limbang
13	02-09-2005	3.900	114.000	< 33.0	3.9	Batu Niah
14	30-06-2005	4.400	115.400	< 33.0	4.8	Limbang
15	19-04-2005	3.800	113.600	15.0	4.8	Batu Niah
16	01-05-2004	3.593	113.927	10	5.2	Batu Niah
17	16-01-1997	3.5	114.55	33	3.6	Long Pelutan
18	19-02-1994	2.522	112.710	33.0	4.7	Bukit Mersing
19	12-02-1994	2.485	112.765	28.9	5.3	Bukit Mersing
20	02-07-1970	4.9	113.9	149	4.7	Bekenu

Appendix 3 Earthquakes (magnitude more than 4) onshore and offshore Sabah based on USGS Earthquake Database

No.	Date	Time (UTC)	Latitude	Longitude	Depth	Mag (Mb)	Location
1	08-03-2018	13:06:13.46	6.0846	116.5853	10	5.2 Mw	Ranau
2	05-01-2018	00:40:33.14	5.9504	117.7198	10	4.3	Labuk
3	26-03-2017	09:30:48.32	4.9334	118.7791	33.96	4.6	Lahad Datu
4	04-03-2016	00:43:35.70	4.9182	118.4359	34.96	4.1	Lahad Datu
5	26-07-2015	16:10:11.82	6.2782	116.8568	14.96	4.6	Ranau
6	23-06-2015	09:32:30.95	6.1277	116.5537	15.32	4.5	Ranau
7	12-06-2015	18:29:15.95	6.2053	116.6814	7.25	5.3	Ranau
8	12-06-2015	18:25:36.92	6.1504	116.692	15.01	4.4	Ranau
9	06-06-2015	05:45:15.47	6.1416	116.6689	10	4.6	Ranau
10	05-06-2015	15:13:35.65	6.1402	116.7228	18.23	4.4	Ranau
11	04-06-2015	23:15:43.91	5.9867	116.5409	10	6 Mw	Ranau
12	19-03-2015	21:56:06.66	5.5346	118.6135	50.77	4.1	Kretam
13	25-02-2015	01:31:41.50	6.0816	119.8398	9	5.7 Mw	Sulu Sea
14	19-01-2015	17:19:45.65	4.6079	119.7571	11	5.5 Mw	Celebes Sea
15	24-10-2014	05:40:34.03	7.2393	117.256	15.69	4.6	Banggi
16	05-09-2014	01:15:54.55	4.6396	118.3414	12.43	4.3	Semporna
17	01-02-2014	11:35:10.75	6.1586	116.5453	17.28	4.6	Ranau
18	28-05-2012	16:44:14.17	4.786	118.321	39.5	4.6	Kunak
19	21-08-2010	19:43:33.69	5.37	118.368	54.1	4.2	Sukau
20	04-09-2009	04:49:12.56	7.191	117.115	35	4.5	Banggi
21	18-05-2008	06:26:41.31	4.598	118.173	10	5 Mwc	Kunak
22	09-04-2008	00:51:44.44	4.838	118.713	27.8	4.5	Lahad Datu
23	10-01-2008	13:18:36.78	4.205	116.508	10	4.1	Klagan
24	23-10-2007	20:34:37.29	5.71	119.316	48.8	5.2 Mwc	Sulu Sea
25	28-09-2006	15:11:35.40	6.041	117.398	10	4.5	Lingkabau
26	22-04-2006	02:01:34.24	6.121	117.81	70.8	4	Labuk
27	30-06-2005	18:09:48.74	4.329	115.62	24.7	4.5	Long Miao
28	23-05-2005	19:58:09.66	6.256	117.709	19	5.3 Mwc	Labuk

29	07-04-2002	01:03:57.81	7.225	117.052	33	5.1 Mwc	Banggi
30	06-12-1996	12:42:25.96	4.894	118.605	33	4.4	Lahad Datu
31	07-02-1996	22:42:48.77	5.208	119.609	33	4.4	Celebs Sea
32	11-08-1995	06:21:02.09	6.34	117.15	33	4.1	Lahad Datu
33	27-11-1994	18:27:08.01	5.768	119.324	27.3	5.5 Mw	Sulu Sea
34	02-11-1994	01:43:55.54	5.099	118.643	55.2	5.7 Mw	Lahad Datu
35	04-07-1992	22:33:02.32	4.976	118.454	10	4.6	Lahad Datu
36	04-07-1992	18:19:33.81	4.579	118.049	50	4.3	Kunak
37	22-02-1992	00:39:53.83	5.415	114.546	40.4	5.2	South China Sea
38	25-08-1991	07:15:10.22	4.636	118.256	33	4.5	Kunak
39	26-05-1991	11:16:59.11	5.869	116.815	18	5.4 Mw	Ranau
40	26-05-1991	11:14:31.05	5.718	116.748	33	4.7	Ranau
41	26-05-1991	10:59:48.95	5.865	116.746	33	5.1	Ranau
42	26-05-1991	07:02:33.51	6.113	117.168	33	4.6	Lingkabau
43	13-02-1989	20:24:01.81	4.265	117.843	32.5	4.4	Tawau
44	05-02-1989	18:32:54.82	4.56	118.089	24.4	3.7	Kunak
45	14-12-1988	17:06:28.07	5.753	117.859	79.4	5.2 Mw	Sandakan
46	24-05-1984	14:56:37.33	4.108	118.6	33	4.5	Celebes Sea
47	14-03-1984	00:39:18.15	5.203	118.387	50.3	5.7 Mw	Lahad Datu
48	22-03-1983	22:44:24.87	3.835	118.862	57.6	5	Celebes Sea
49	26-11-1982	19:29:35.49	4.895	118.387	33	4.5	Lahad Datu
50	25-12-1981	00:28:15.79	4.76	118.477	39.1	5.4	Darvel Bay
51	09-12-1981	19:24:59.17	3.796	117.319	57.3	4.8	Kalimantan
52	23-10-1980	14:00:21.40	6.519	117.957	51	5.1	Sulu Sea
53	30-05-1979	14:06:44.30	6.886	117.004	33	4.5	Pitas
54	18-09-1976	07:54:44.90	4.639	118.033	33	5	Kunak
55	14-08-1976	11:10:28.00	4.714	118.421	36	5.1	Kunak
56	26-07-1976	13:12:11.00	4.592	118.16	33	4.5	Kunak
57	26-07-1976	09:43:50.60	4.994	118.55	33	5.1	Lahad Datu
58	26-07-1976	08:49:34.60	4.894	118.342	33	5.3	Darvel Bay

59	26-07-1976	08:36:12.20	4.904	118.052	33	5.3	Lahad Datu
60	26-07-1976	05:35:10.30	4.986	118.594	33	5.2	Lahad Datu
61	26-07-1976	03:03:15.10	5.062	118.385	33	5.3	Lahad Datu
62	26-07-1976	02:56:39.30	4.956	118.308	33	6.2 ms	Lahad Datu
63	25-07-1976	14:03:17.80	5.092	118.287	33	5.3	Lahad Datu
64	18-06-1976	18:40:39.70	6.041	119.771	33	4.5	Terusan
65	28-04-1973	20:39:43.90	6.386	117.704	33	5.4	Kudat
66	02-06-1951	06:47:56.00	6.878	116.727	15	6.1 Mw	Kudat
67	11-08-1923	00:54:43.00	5.231	118.28	35	6.3 Mw	Lahad Datu

BIODATA

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Before joining UMS, Felix was an Associate Professor at Earth Science Department of Universiti Kebangsaan Malaysia (Sabah Campus) for the period of 1987 – 1996 and Universiti Kebangsaan Malaysia main campus in Bangi from 1996 – 1998.

Felix received his primary and secondary education at SK St. Theresa, Inobong, Penampang (1967 – 1972) and SM St.

Michael, Penampang (1973 – 1977), respectively. After completing his Matriculation course at SMK Menggatal (1977 – 1981), he continued his undergraduate study in the field of Geology at UKM main campus in Selangor (1979 – 1983). After graduating from UKM, he continued his postgraduate study, first at the Chelsea College, London, then at the Royal Holloway and Bedford New College of University of London and obtained his PhD in Geology in 1987.

By virtue of being the Director of PPI, Felix was a member of the Senate, the highest academic body of the university. He has carried out many responsibilities that generally go with such position especially related to the development of research and innovation in UMS.

Felix has been involved in the development of modules and teaching of several undergraduate courses including Structural Geology, Sedimentology, Geological Mapping, Regional Geology and Malaysian Geology, Photogeology and Remote Sensing, and Geotourism. He was also involved in teaching postgraduate courses such as Geological Hazards and Management. He has been actively involved in the supervision of postgraduate (Master of Science and PhD) degree programmes, some in collaboration with other foreign universities, leading to the award of degree to 5 PhDs and 13 Masters.

For the past 30 years, Felix has been doing research on the geological evolution of Sabah and Sarawak in collaboration with local and international researchers. Since 1996, he has been involved in research related to the promotion of geological and landscape heritage for geotourism in Sabah. He played a key role in the establishment of the Kinabalu Geopark. Since 2004, he has been actively involved in geological hazards studies, such as earthquake, tsunami, landslide and flood in Sabah. He has completed 30 research projects on regional geology and sedimentation of Northwest Borneo; conservation geology; and geological hazards. He has also completed 20 field workshops on the geology of Sabah for various organizations, especially international oil companies; and completed 32 geotechnical assessment projects for various companies. Felix has coordinated 5 scientific expeditions to Maliau Basin, Lake Linumunsut, Imbak Canyon and Kawag Danum Rainforest.

Felix is a member of the National Working Group on Earthquake Monitoring and Active Faults in Malaysia and also a member of the National Working Group on Modelling and Impact of Tsunami in Malaysia. He is a member of the Local Experts on Earthquake for the Development of Seismic Building Codes in Malaysia. He was a member of the Scientific Expert Panel Committee on Natural Disaster under the Prime Minister Department before it was disbanded in July 2018.

Felix has published and reviewed scientific papers extensively. He has published 52 papers in international journals, 7 papers in national jurnal, 25 papers in conference proceedings, 29 chapters in books, 53 technical reports, 2 books and 4 booklets. He is a reviewer of research papers for 12 journals, including Journal of Asian Earth Science, Bulletin of Geological Society of Malaysia, Indonesian Journal of Geology, Journal of Seismology, International Journal of Digital Earth, Global and Planetary Change, Geoheritage, Sains Malaysiana, Borneo Science, Transactions of Science and Technology, Geological Behaviour and Malaysian Journal of Geology.

Felix has attended a number of the local and international seminars as a presenter, invited speaker and keynote speaker. He has presented 39 papers in International Conference and 70 papers in National Conference, out of which 15 are keynote papers.

Felix actively participates in community service which includes public outreach programmes, popular lectures and knowledge transfer programmes. He has been instrumental in providing timely and appropriate information on the 2015 Ranau Earthquake disaster. Since 2017, he has been involved in earthquake education among schoolchildren in Ranau and Lahad Datu.

Felix is actively involved in several professional bodies. He is a Fellow of the Science Academy of Malaysia (ASM), the ‘Think Tank’ of the nation for matters related to science, engineering, technology and innovation, Member of the Malaysian Board of Geology, Member of the Institute of Geology Malaysia (IGM) and Life Member of the Geological Society of Malaysia (GSM). He is also involved in public interest organisation. He is the Chairperson of the Board of Trustee of Partners of Community Organisations

(PACOS Trust), Member of the Board of Trustee of Yayasan Perpaduan Malaysia (YPM), and Member of the Advisory Council of World Wildlife Fund Malaysia (WWF).

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