Plate Tectonics and Seismic Activities in Sabah Area

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Received: ***27 November 2015***
Revised: ***25 December 2015***
Accepted: ***7 January 2016***
In press: ***8 January 2016***
Online: ***1 April 2016***

Keywords:
Arc and Trench System, Tectonic earthquake, Seismic zoning, GM（1,1）model, Seismic potential assessment

Abstract
Ever since the Pliocene which was 1.6 million years ago, the structural geology of Sabah is already formed; it is mainly influenced by the early South China Sea Plate, which is subducted into the Sunda Plate. However, since the Cenozoic, the Sunda Plate is mainly influenced by the western and southern of the Sunda-Java Arc and Trench system, and the eastern side of Luzon Arc and Trench system which has an overall impact on the tectonic and seismic activity of Sunda plate. Despite the increasing tectonic activities of Sunda-Java Arc and Trench System, and of Luzon Arc and Trench System since the Quaternary, which cause many large and frequent earthquakes. One particular big earthquake is the M9.0 one in Indian Ocean in 2004, leading to more than two hundred and ninety thousand deaths or missing by the tsunami caused by the earthquake. As for Borneo island which is located in residual arc, the impact of tectonic earthquake is trivial; on the other hand, the Celebes Sea which belongs to the back-arc basin is influenced by the collision of small plates, North Sulawesi, which leads to two M≧7 earthquakes (1996 M7.9 and 1999 M7.1) in the 20th century. In Sabah, there is a complete record of earthquake catalog for more than 40 years. The major earthquake affected Sabah area is from the northwest to the southeast of the seismic zone. The present study is based on the 66 earthquakes (M≧3.7) occurred in Sabah areas since 1974. With the use of seismic zoning method, Sabah area is divided into eight seismic zones. The study uses two predictive models, GM (1,1) model and GM (1,1) Verhulst model of Grey Forecasting theory in Grey System Theory, to evaluate these eight seismic potential zones of future earthquakes. The result shows that Sandakan, Semporna and Celebes Sea have reached a critical point of accumulating seismic energy. If any trigger factor appears, there is a high possibility for moderate to heavy earthquakes to occur. Additionally, there will be high earthquake potential in Lahad Datu, Tawau, Kudat, Ranau, Tarakan and Sitangkai within the next seven years (2015-2022). Possible disaster reduction is needed.

Introduction

Plate tectonic theory has revolutionized the study of earth science since 19th century. It describes the outer rigid layer of the earth is divided into a dozen of plates that move across the earth's surfaces relative to each other. These plates basically separate lithosphere and asthenosphere. Lithosphere is the rigid and brittle shell of the earth. Asthenosphere is the hot, plastic interior of the earth. Within the asthenosphere are convection cells that bring heat from the earth's interior out the surface in a very slow pace of about 10 centimeters a year. Over a long period of time, when the convection cells reach the base of lithosphere, they release heat to the surface causing the cooled plastic rock turns sideways and moves parallel to the earth's surface. In back and forth movement, they descend back into earth at the subduction zones to become reheated and eventually drives the plate movements.

In cross section, there are three kinds of plate boundaries namely convergent, divergent and transform. Convergent boundaries are where two tectonic plates are colliding to form subduction zones. This collision can occur between oceanic crust and continental crust, or together within each other. Divergent boundaries are where two tectonic plates are moving apart to create a space filled with new crustal sourced from molten magma. Transform boundaries are where plates slide passed each other in horizontal motion. Because of friction, the plates cannot simply glide past each other. Rather, stress builds up in both plates during the collision and when it exceeds the threshold of the rocks, the energy is released and eventually causing earthquake.

Recently, an earthquake struck Ranau, Sabah with a magnitude of 6.0 on 5^{th} June 2015, which lasted for 30 seconds, was one of strongest earthquakes recorded in Malaysia (Earthquake Track, 2015). The news has drawn enormous attentions from the local government and related agencies around the world to study the seismic activities in Sabah area. In this work, potential zones of future earthquakes are evaluated using two predictive models in Grey System Theory. The evaluation is based on the 66 earthquakes ($M \geqq 3.7$) occurred in Sabah areas since 1974. The result shows that Sandakan, Semporna and Celebes Sea have reached a critical point of accumulating seismic energy. If any trigger factor appears, there is a high possibility for moderate to heavy earthquakes to occur. Additionally, there will be high earthquake potential in Lahad Datu, Tawau, Kudat, Ranau, Tarakan and Sitangkai within the next seven years (2015-2022).

Plate tectonic setting

Sunda-Java Arc and Trench System

In recent years, the India-Australian Plate is to the north of Sunda-Java Trench and is subducted beneath the Sunda Plate which causes the increasing seismic activity in the Sunda Strait and the Lesser Sunda islands which locate in fore-arc basin. The M9 earthquake in 2004 was one particular example.

Luzon Arc and Trench System

The Philippine Sea Plate is on the northwest direction underneath from the Manila trench to Sunda Plate, causing a series of deep earthquakes and a considerable number of M7 shallow earthquakes in Sulu Sea and Celebes Sea of back-arc basin. It appears that the tectonic and seismic activity not only is increasing but also is enhancing. However, concerning these two subduction zones to the same residual arc of Borneo State, the influence of tectonic earthquake is minimal.

North Sulawesi Plate (Molucca Sea Plate)

The Celebes Sea which belongs to the back-arc basin is influenced because of the small plate collision in the south of North Sulawesi Trench. It is also influenced by the active tectonic in Bayan ng arc island, making the occurrence of multiple M7 shallow earthquakes. As for the eastern district of Sabah State, the near and far of epicenter will cause a number of damages to a certain extent. Tectonic Sunda Plate environment can be concerned by Figure 1.

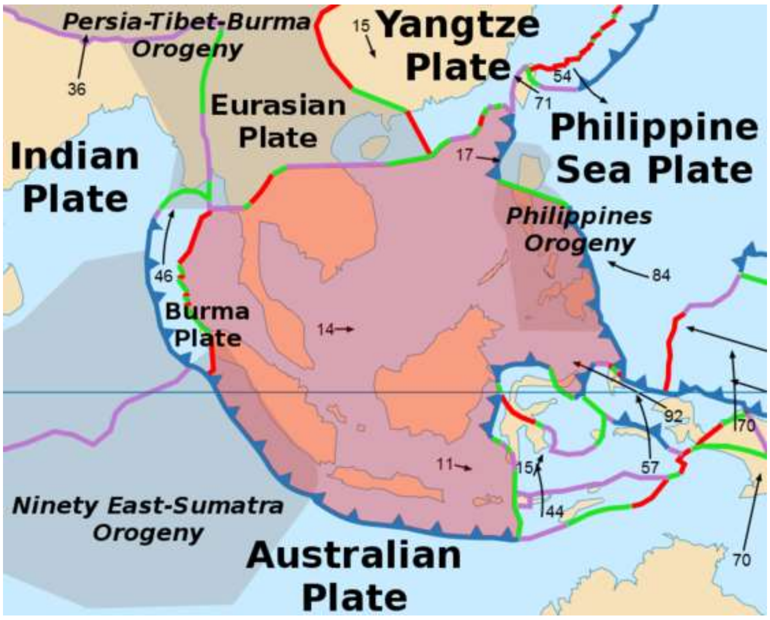

Figure l: Tectonic Sunda plate diagram. (Wikipedia, 2015）

Since 1973, the 26 pieces of M7.5 to 9.0 earthquakes occurred in the tectonic Sunda Plate boundaries were showed of their distribution in Figure 2. The tectonic earthquakes induced by Sunda Trench and Manila Trench on the Sunda Plate boundary and by the four small plates in the southeast (MS, BS, TI and BH) are shown in Figure 3.

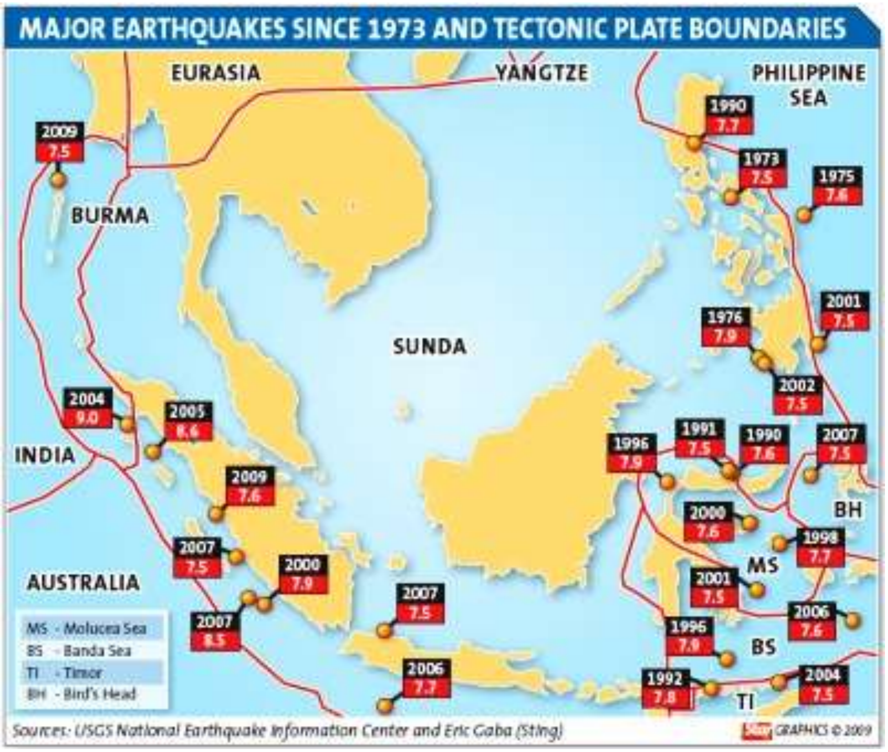

Figure 2: Major earthquakes since 1973 which occurred in Tectonic Sunda Plate boundaries (USGS, 2015)

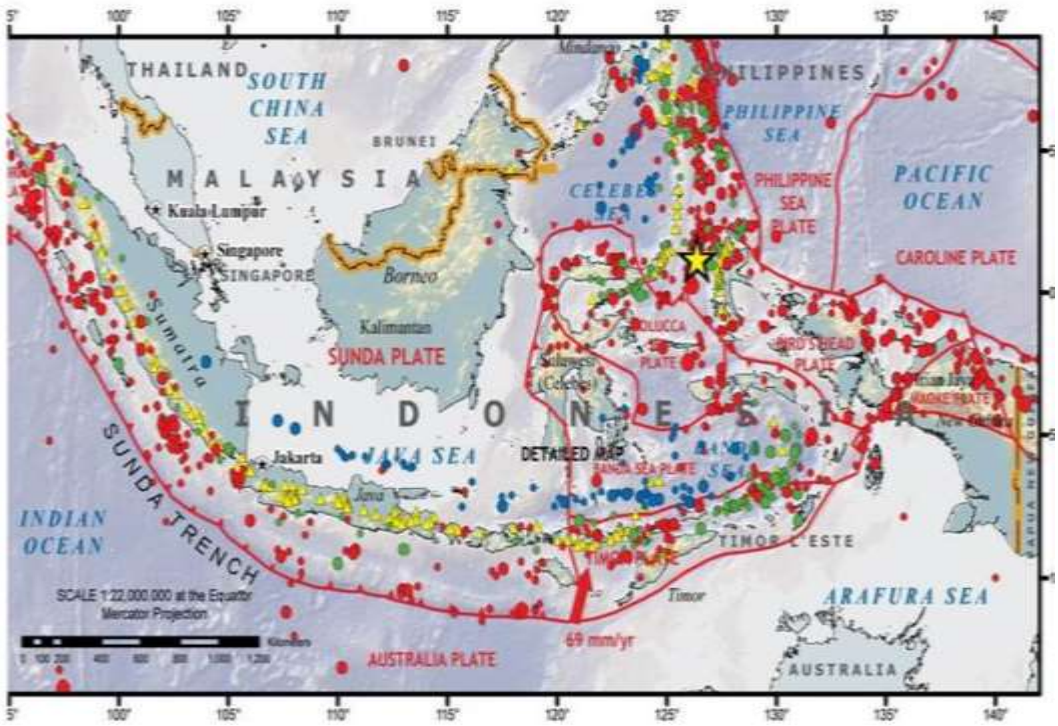

Figure 3: The tectonic earthquakes in Sunda Plate (Scientific Malaysian, 2015).

The Borneo Arc

According to the GPS data from Simons *et al.* (2007), the Borneo areas slow movement may be influenced by the important movement in the North Sulawesi (Molucca Sea Plate), the South Sulawesi (Banda Sea Plate), and the South Philippines as the Figure 4 shown. The GPS motion and structural scheme of Sabah area from Ego *et al*., (2006) is also shown in another diagram in Figure 5.

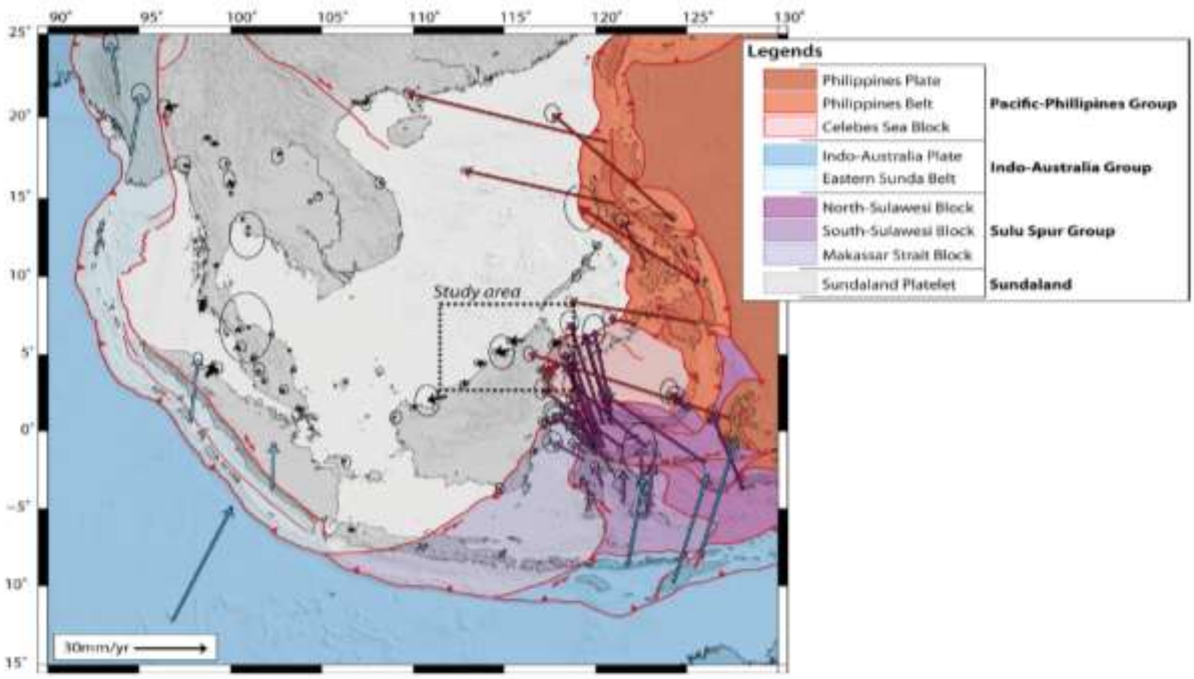

Figure 4: Sundaland geodynamic settings (Sapin *et al*., 2013).

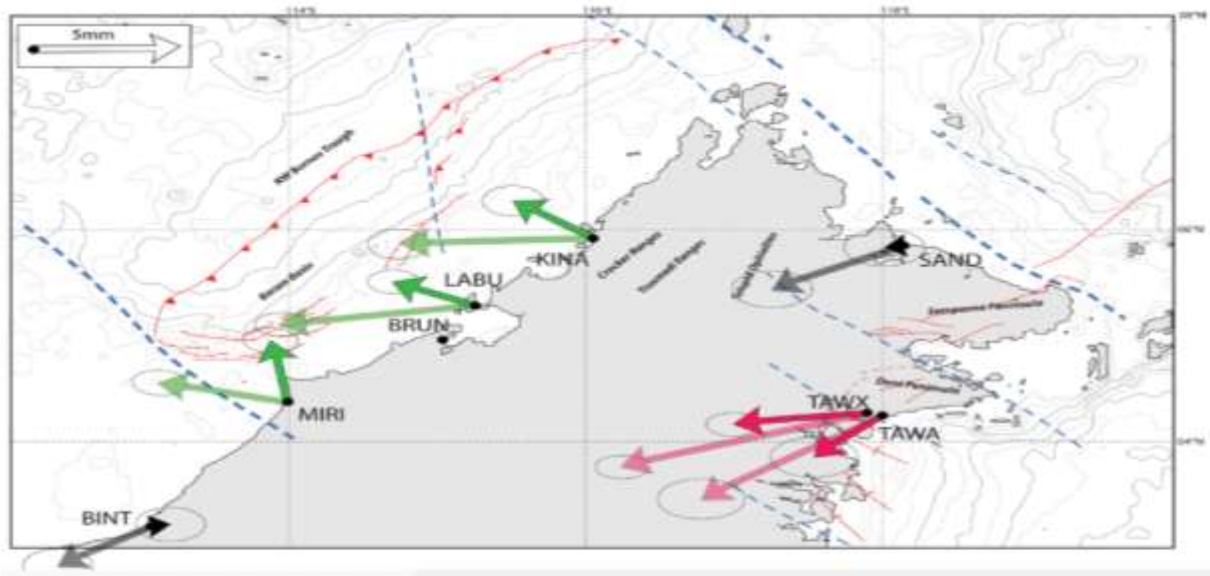

Figure 5: NW Borneo GPS motion and structural scheme (Ego *et al*., 2006).

Data

The district of earthquakes in Sabah

The seismic zoning method is used to record the 66 pieces of M≧3.7 earthquakes (see as Table 1) occurred from 1974 to 2015 in Sabah area, as depicted in Figure 6.

Table 1: Earthquake catalogs in Sabah area

No	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
1	2015	26-Jul	16:10	6.224, 116.868	15	4.6	Ranau
2	2015	23-Jun	09:32	6.159, 116.606	15	4.5	Ranau
3	2015	12-Jun	18:29	6.182, 116.651	11	5.3	Ranau
4	2015	6-Jun	05:45	5.956, 116.608	10	4.5	Ranau
5	2015	4-Jun	23:15	5.979, 116.529	10	6.0	Ranau
6	2015	25-Feb	01:31	6.089, 119.844	24	5.6	Jolo
7	2015	19-Jan	17:19	4.624, 119.761	11	5.5	Sitangkai
8	2014	8-Nov	20:07	3.594, 117.603	43	4.4	Tarakan
9	2014	24-Oct	05:40	7.194, 117.247	14	4.6	Kudat
10	2014	1-Feb	11:35	6.157, 116.589	17	4.7	Ranau
11	2013	5-Jun	19:23	2.984, 117.561	16	4.9	Tarakan
12	2012	28-May	16:44	4.786, 118.321	39	4.6	Lahad Datu
13	2010	21-Aug	19:43	5.370, 118.368	54	4.2	Lahad Datu
14	2009	4-Sep	04:49	7.191, 117.115	35	4.5	Kudat
15	2008	18-May	06:26	4.598, 118.173	10	5.0	Tawau
16	2008	9-Apr	00:51	4.838, 118.713	27	4.5	Semporna

17	2008	10-Jan	13:18	4.205, 116.508	10	4.1	Keningau
18	2007	23-Oct	20:34	5.710, 119.316	48	5.2	Sitangkai
19	2006	28-Sep	15:11	6.041, 117.398	10	4.5	Ranau
20	2006	22-Apr	02:01	6.121, 117.810	70	4.0	Sandakan
21	2005	30-Jun	18:09	4.329, 115.620	24	4.5	Limbang
22	2005	23-May	19:58	6.256, 117.709	19	5.3	Sandakan
23	2003	3-Aug	18:44	3.694, 118.759	33	4.9	Semporna
24	2002	7-Apr	01:03	7.225, 117.052	33	5.1	Kudat
25	2001	31-Jul	16:41	8.023, 117.466	33	5.5	Pulot
26	1999	4-Mar	08:52	5.397, 121.937	33	7.1	Seit
27	1996	6-Dec	12:42	4.894, 118.605	33	4.4	Lahad Datu
28	1996	7-Feb	22:42	5.208, 119.609	33	4.4	Sitangkai
29	1996	1-Jan	08:05	0.729, 119.931	24	7.9	Palu
30	1995	11-Aug	06:21	6.340, 117.150	33	4.1	Ranau
31	1995	6-Mar	18:43	2.690, 118.226	16	6.1	Tarakan
32	1994	8-Dec	08:30	1.967, 120.844	38	5.7	Gorontalo
33	1994	27-Nov	18:27	5.768, 119.324	27	5.5	Sitangkai
34	1994	2-Nov	01:43	5.099, 118.643	55	5.7	Lahad Datu
35	1992	4-Jul	22:33	4.976, 118.454	10	4.6	Lahad Datu
36	1992	4-Jul	18:19	4.579, 118.049	50	4.3	Tawau
37	1992	22-Feb	00:39	5.415, 114.546	40	5.2	Labuan
38	1991	25-Aug	07:15	4.636, 118.256	33	4.5	Semporna
39	1991	26-May	11:16	5.869, 116.815	18	5.1	Ranau
40	1991	26-May	11:14	5.718, 116.748	33	4.7	Ranau
41	1991	26-May	10:59	5.865, 116.746	33	5.1	Ranau
42	1991	26-May	07:02	6.130 , 117.168	33	4.6	Ranau
43	1989	9-Oct	15:58	3.455, 117.674	10	3.7	Tarakan
44	1989	13-Feb	20:24	4.265, 117.843	32	4.4	Tawau
45	1989	5-Feb	18:32	4.560, 118.089	24	3.7	Tawau
46	1988	14-Dec	17:06	5.753, 117.859	79	5.1	Sandakan
47	1984	24-May	14:56	4.108, 118.600	33	4.5	Semporna
48	1984	14-Mar	00:39	5.203, 118.387	50	5.6	Lahad Datu
49	1983	22-Mar	22:44	3.835, 118.862	57	5.0	Semporna
50	1982	26-Nov	19:29	4.895, 118.387	33	4.5	Lahad Datu
51	1981	25-Dec	00:28	4.760, 118.477	39	5.4	Semporna
52	1981	9-Dec	19:24	3.796, 117.319	57	4.8	Tarakan
53	1980	23-Oct	14:00	6.519, 117.957	51	5.1	Sandakan
54	1979	30-May	14:06	6.886, 117.004	33	4.5	Kudat

55	1976	18-Sep	07:54	4.639, 118.033	33	5.0	Tawau
56	1976	14-Aug	11:10	4.714, 118.421	36	5.1	Semporna
57	1976	26-Jul	13:12	4.592, 118.160	33	4.5	Tawau
58	1976	26-Jul	09:43	4.994, 118.550	33	5.1	Lahad Datu
59	1976	26-Jul	08:49	4.894, 118.342	33	5.3	Lahad Datu
60	1976	26-Jul	08:36	4.904, 118.052	33	5.3	Lahad Datu
61	1976	26-Jul	05:35	4.986, 118.594	33	5.2	Lahad Datu
62	1976	26-Jul	03:03	5.062, 118.385	33	5.3	Lahad Datu
63	1976	26-Jul	02:56	4.956, 118.308	33	6.2	Lahad Datu
64	1976	25-Jul	14:03	5.092, 118.287	33	5.3	Lahad Datu
65	1976	18-Jun	18:40	6.041, 119.771	33	4.5	Jolo
66	1974	12-Nov	22:13	2.316, 121.129	54	5.8	Gorontalo

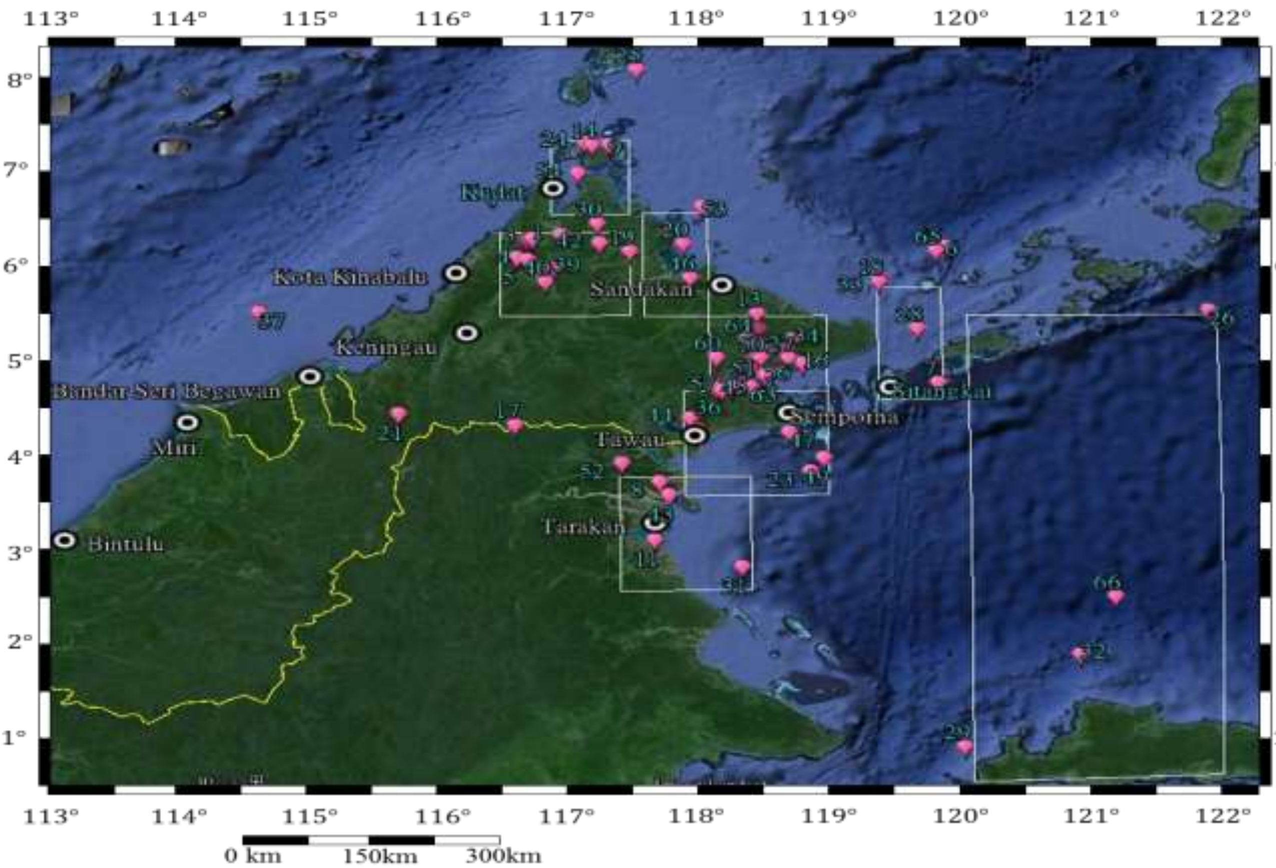

Figure 6: The seismic epicenter distribution diagram from 1974 to 2015 in Sabah area.

The 60 records of the eight seismic zones are shown in Table 2.

Table 2: Seismic zoning and range statistics table

No.	District	Quake no.	M max	Longitude (°)	Latitude (°)	Area (km^2)
1	Ranau	12	M6.0	116.4~117.4	5.5~6.4	100*90
2	Kudat	4	M5.1	116.8~117.4	6.6~7.4	60*80
3	Sandakan	4	M5.3	117.5~118.0	5.5~6.6	50*110
4	Lahad Datu	17	M6.2	118.0~118.9	4.7~5.5	90*80
5	Tawau	10	M5.0	117.8~118.9	3.6~4.7	110*110
6	Tarakan	5	M6.1	117.3~118.3	2.6~3.8	100*120
7	Sitangkai	4	M5.5	119.3~119.8	4.6~5.8	50*120
8	Collision Zone	4	M7.9	120.0~122.0	0.5~5.5	200*500

Future seismic potential assessment in Sabah area

Based on seismic zoning, we use these 60 pieces of earthquake catalog from the upper section of Table 1 in Sabah, to summarize into eight different districts as follows in Table 3 - 10.

Table 3: Ranau area earthquakes list

No.	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude(M)	District
1	2015	26-Jul	16:10	6.224, 116.868	15	4.6	Ranau
2	2015	23-Jun	09:32	6.159, 116.606	15	4.5	Ranau
3	2015	12-Jun	18:29	6.182, 116.651	11	5.3	Ranau
4	2015	6-Jun	05:45	5.956, 116.608	10	4.5	Ranau
5	2015	4-Jun	23:15	5.979, 116.529	10	6.0	Ranau
10	2014	1-Feb	11:35	6.157, 116.589	17	4.7	Ranau
19	2006	28-Sep	15:11	6.041, 117.398	10	4.5	Ranau
30	1995	11-Aug	06:21	6.340, 117.150	33	4.1	Ranau
39	1991	26-May	11:16	5.869, 116.815	18	5.1	Ranau
40	1991	26-May	11:14	5.718, 116.748	33	4.7	Ranau
41	1991	26-May	10:59	5.865, 116.746	33	5.1	Ranau
42	1991	26-May	07:02	6.113, 117.168	33	4.6	Ranau

Table 4: Kudat area earthquakes list

No.	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
9	2014	24-Oct	05:40	7.194, 117.247	14	4.6	Kudat
14	2009	4-Sep	04:49	7.191, 117.115	35	4.5	Kudat
24	2002	7-Apr	01:03	7.225, 117.052	33	5.1	Kudat
54	1979	30-May	14:06	6.886, 117.004	33	4.5	Kudat

Table 5: Sandakan area earthquakes list

No.	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
20	2006	22-Apr	02:01	6.121, 117.810	70	4.0	Sandakan
22	2005	23-May	19:58	6.256, 117.709	19	5.3	Sandakan
46	1988	14-Dec	17:06	5.753, 117.859	79	5.1	Sandakan
53	1980	23-Oct	14:00	6.519, 117.957	51	5.1	Sandakan

Table 6: Lahad Datu area earthquakes list

No	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
12	2012	28-May	16:44	4.786, 118.321	39	4.6	Lahad Datu
13	2010	21-Aug	19:43	5.370, 118.368	54	4.2	Lahad Datu
16	2008	9-Apr	00:51	4.838, 118.713	27	4.5	Semporna
27	1996	6-Dec	12:42	4.894, 118.605	33	4.4	Lahad Datu
34	1994	2-Nov	01:43	5.099, 118.643	55	5.7	Lahad Datu
35	1992	4-Jul	22:33	4.976, 118.454	10	4.6	Lahad Datu
48	1984	14-Mar	00:39	5.203, 118.387	50	5.6	Lahad Datu
50	1982	26-Nov	19:29	4.895, 118.387	33	4.5	Lahad Datu
51	1981	25-Dec	00:28	4.760, 118.477	39	5.4	Semporna
56	1976	14-Aug	11:10	4.714, 118.421	36	5.1	Semporna
58	1976	26-Jul	09:43	4.994, 118.550	33	5.1	Lahad Datu
59	1976	26-Jul	08:49	4.894, 118.342	33	5.3	Lahad Datu
60	1976	26-Jul	08:36	4.904, 118.052	33	5.3	Lahad Datu
61	1976	26-Jul	05:35	4.986, 118.594	33	5.2	Lahad Datu
62	1976	26-Jul	03:03	5.062, 118.385	33	5.3	Lahad Datu
63	1976	26-Jul	02:56	4.956, 118.308	33	6.2	Lahad Datu
64	1976	25-Jul	14:03	5.092, 118.287	33	5.3	Lahad Datu

Table 7: Tarakan area earthquakes list

No	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
8	2014	8-Nov	20:07	3.594, 117.603	43	4.4	Tarakan
11	2013	5-Jun	19:23	2.984, 117.561	16	4.9	Tarakan
31	1995	6-Mar	18:43	2.690, 118.226	16	6.1	Tarakan
43	1989	9-Oct	15:58	3.455, 117.674	10	3.7	Tarakan
52	1981	9-Dec	19:24	3.796, 117.319	57	4.8	Tarakan

Table 8: Tawau area earthquakes list

No	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
15	2008	18-May	06:26	4.598, 118.173	10	5.0	Tawau
23	2003	3-Aug	18:44	3.694, 118.759	33	4.9	Semporna
36	1992	4-Jul	18:19	4.579, 118.049	50	4.3	Tawau
38	1991	25-Aug	07:15	4.636, 118.256	33	4.5	Semporna
44	1989	13-Feb	20:24	4.265, 117.843	32	4.4	Tawau
47	1984	24-May	14:56	4.108, 118.600	33	4.5	Semporna
49	1983	22-Mar	22:44	3.835, 118.862	57	5.0	Semporna
45	1989	5-Feb	18:32	4.560, 118.089	24	3.7	Tawau
55	1976	18-Sep	07:54	4.639, 118.033	33	5.0	Tawau
57	1976	26-Jul	13:12	4.592, 118.160	33	4.5	Tawau

Table 9: Sitangkai area earthquakes list

No	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
7	2015	19-Jan	17:19	4.624, 119.761	11	5.5	Sitangkai
18	2007	23-Oct	20:34	5.710, 119.316	48	5.2	Sitangkai
28	1996	7-Feb	22:42	5.208, 119.609	33	4.4	Sitangkai
33	1994	27-Nov	18:27	5.768, 119.324	27	5.5	Sitangkai

Table 10: Collision Zone earthquakes list

No	Year	Date-month	Time	Epicenter	Depth (km)	Magnitude (M)	District
26	1999	4-Mar	08:52	5.397, 121.937	33	7.1	Seit
29	1996	1-Jan	08:05	0.729, 119.931	24	7.9	Palu
32	1994	8-Dec	08:30	1.967, 120.844	38	5.7	Gorontalo
66	1974	12-Nov	22:13	2.316, 121.129	54	5.8	Gorontalo

Results & discussion

We use the method of assessing future seismic potential at different seismic zones in Sabah area, and the study can get analytical results in each area as follows:

Ranau Area

According to Tongkul's estimation (Tongkul, 2015) from the Universiti Malaysia Sabah, the M≧5 earthquake cycle of Ranau area is 25 years which means that there will be another M5.5 earthquake around 2040. However, based on the present study which uses the two gray prediction model, GM (1.1) and GM Verhulst, the next M≧5.0 earthquake will be occurred around 2019-2020 in Ranau area.

Kudat Area

Based on GM (1,1) model estimation, the next two earthquakes will occur around 2017-2018 and 2020-2021 respectively in Kudat area.

Sandakan Area

A M5 earthquake whose depth is 70 km will occur in Sandakan area in 2015.

Lahad Datu Area

Based on GM (1,1) model estimation, whether to ignore the M4.6 earthquake at a depth of 10 km in1992 or not, another earthquake will occur earliest around 2016-2017 and slowest in 2026. And the next earthquake at the depth of 33km will occur around 2021-2022.

Tawau Area

An earthquake will occur around 2017 in the Tawau area. But the Semporna area has already reached the critical point, in theory, an earthquake is very likely to occur at any time.

Tarakan Area

Based on GM (1,1) model estimation, the next earthquake in Tawau area will be around 2019-2020. But if based on the GM(1,1) Verhulst model, the next earthquake will occur around 2021-2022.

Sitangkai Area

Based on the GM (1,1) model estimation of Sitangkai area, the next M> 5 earthquake will occur around 2020-2021. As for the estimation of GM Verhulst model, the date will be two years earlier.

Celebes Sea Collision Zone

As for the Collision Zone of the Celebes Sea, the next M≥6.0 earthquake has now entered the critical range of earthquakes using the GM (1,1) model estimation. Theoretically, M≧6.0 earthquake will occur at any time in this region. If we take the above eight sections of future potential earthquakes in Sabah State, the present study can get future seismic potential assessment in Sabah area as shown in Table 11:

Table 11: Future seismic potential in Sabah area

No.	Year	Magnitude (M)	Depth (km)	District
1	~now	M5.0	70km	Sandakan
2	~now	4.5≦M≦5.0	~33km	Semporna
3	~now	M≧6.0		Celebes Sea
4	2017	4.5≦M≦6.0	~33km	Lahad Datu
5	2017	4.5≦M≦5.0		Tawau
6	2018	4.5≦M≦5.0		Kudat
7	2020	4.5≦M≦6.0		Ranau
8	2020	4.5≦M≦6.0		Tarakan
9	2021	4.5≦M≦5.0		Sitangkai
10	2021	4.5≦M≦5.0		Kudat
11	2022	4.5≦M≦5.0		Tawau
12	2022	4.5≦M≦6.0	~33km	Lahad Datu

Conclusion

The high seismic potential region in Sabah State in the next three years (2015-2017) are Sandakan, Semporna, and the Celebes Sea. These three areas have currently accumulated enough strain energy. As long as the trigger factors take place, it will cause the fault dislocation and induce earthquakes. Another higher seismic potentials areas are Lahad Datu and Tawau. According to the high seismic potential areas in Sabah State in the next seven years (2015-2022), in addition to the above five regions, other areas such as Kadat, Ranau, Tarakan, Sitangkai, Lahad Datu, and Tawau areas are also included.

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