RELOCATION OF LARGE EARTHQUAKES ALONG THE SUMATRAN FAULT AND THEIR FAULT PLANES

Biana Rahayu Wulandari* **Supervisor: Nobuo HURUKAWA****
MEE11605

ABSTRACT

In order to identify fault planes of large eartquakes along the Sumatran Fault in Sumatra, western Indonesia, fifteen M ≥ 6.0 earthquakes and their aftershocks, from 1964 to 2011, were relocated using the Modified Joint Hypocenter Determination (MJHD) method. The results of earthquake relocation in northern, central and southern Sumatra for this period, show that the fault planes of M ≥ 6.0 mainshocks, with a few exceptions, were along the Sumatran Fault. We found that in many cases mainshocks originated near the segment boundaries and propagated to the end of the fault segments. The 1967 (M 6.1) and 2003 (M 6.0) earthquakes that occurred in northern Sumatra are off-Sumatran fault earthquakes.

We also relocated eleven M ≥ 6.8 earthquakes from 1900 to 1963, and their aftershocks, together with the above-mentioned 15 M ≥ 6.0 earthquakes from 1964 to 2011 in order to obtain precise hypocenter locations of all earthquakes and identify the fault planes of M ≥ 7.0 events. It was possible to relocate hypocenters precisely except for the 1900, 1907 and 1909 events. We found that fault segments related to M ≥ 7.0 events are Kumering for 1933 (M 7.5), Tripa for 1935 (M 7.0) and 1936 (M 7.2), Ketaun for the first event of 1943 (M 7.4), Sumani and Suliti for the second event of 1943 (M 7.6). We considered fault segments related to the 1900 ad 1909 event are Dikit and Siulak, respectively.

From the results of earthquake location between 1900 and 2011 and the expected fault lengths of M ≥ 7.0 earthquakes, we obtain earthquake history along the Sumatran fault since the 1892 (M 7.3) event that occurred along the Angkola segment. Possible seismic gaps along the Sumatran Fault are Sunda, Semangko, Manna, Musi, Sianok, Sumpur, Barumun, Toru, Renun, central part of the Tripa, Aceh, and Seulimeum segments.

1. INTRODUCTION

The Sumatran Fault is formed as a result of the oblique subduction of the Indo-Australian plate beneath the Sunda plate. The 1900 km long structure of the right lateral strike slip Sumatran Fault is parallel to the oblique convergence of the Sumatran Subduction on the western coast of Sumatra (Sieh and Natawidjaja, 2000). Many large earthquakes occurred along the Sumatran Fault (Figure 1).

By comparing fault segments and historical large earthquakes, Sieh and Natawidjaja (2000) and Natawidjaja and Triyoso (2007) identified unbroken fault segments, where future large earthquakes are expected. In a study by Aydan (2007) on crustal deformation and straining of Sumatra island by using GPS deformation rates, it is found three high stress rate concentration regions along the Sumatran Fault, which are Sunda, Semangko, Kumering, Ketaun, Dikit, Sianok, Sumpur, Barumun, Angkola, and Toru.

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*Agency for Meteorology, Climatology and Geophysics, Indonesia.
** Building Research Institute, Japan.

In northernmost of the Sumatran Fault, Aceh and Seulimeum segments, has not experienced a major eartquake at least last 170 years. Therefore, a seismic gap is considered there (Bellier *et al.*, 1997; Petersen *et al.*, 2004; Sorensen, 2008). In a very recent study by Ito *et al.* (2012) on the Aceh segment, which contains 200-km-long segment, found shallow creeping and locked zone that appears to be capable of producing a significant earthquake. Their estimation of locking depth and slip deficit rate in this segment suggested that the accumulated seismic moment in 170 years correspond to an earthquake of magnitude 7.

2. DATA

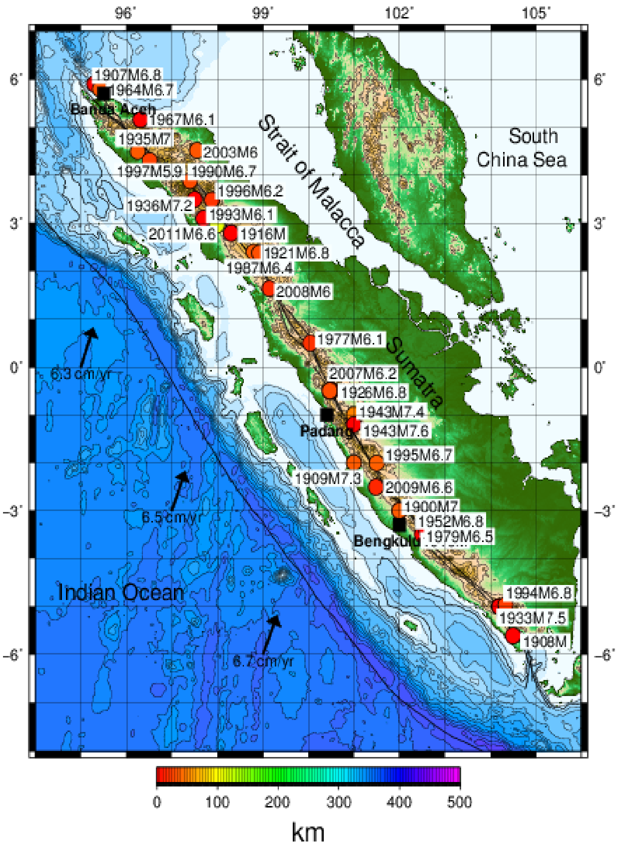

Figure 1. Epicenters of M ≥ 6.0 earthquakes near the Sumatran Fault from 1900 to 2011.

We relocated large earthquakes and their aftershocks along the Sumatran Fault from 1900 to 2011. We selected area 8ºS – 7ºN and 94ºE – 106ºE for all strike-slip inland earthquakes with shallow depths (Figure 1).

According to the purposes, two data set were used in this study. Firstly, earthquakes with M ≥ 6.0 and their aftershocks from 1964 – 2011 were relocated in order to identify their fault planes. Secondly, earthquakes with M ≥ 6.8 from 1900 – 2011 and aftershocks available in ISS bulletins were relocated in order to identify the fault planes of old earthquakes and obtain earthquake history.

The intial P-wave arrival times at worldwide stations are taken from various references as British Association for the advancement of Science, Seismology Committee; ISS (International Seismological Summary); ISC (International Seimological Centre); USGS (United States Geological Survey). Note that Global CMT solutions after 1976 were used as Mw magnitude. Since the CMT solution of the 2003 event is not available, this event used Ms magnitude from ISC.

3. THEORY AND METHODOLOGY

The Modified Joint Hypocenter Determination (MJHD) method was used for a precise relocation of earthquakes along the Sumatran Fault. The MJHD method was developed by Hurukawa and Imoto (1990, 1992) and Hurukawa (1995) from the Join Hypocenter Determination (JHD) method. The MJHD method calculates hypocenters of a group of earthquakes and station corrections simultaneously. Station corrections remove the effects of lateral heterogeneity and reflect a travel-time difference between the assumed velocity structure and the actual one.

They used constraints that station correction is independent of distance and azimuth from the center of the region to each station, then minimizes their absolute values. Although sometimes this will sacrifice absolute hypocenters, it makes the method stable.

Since we used only P-arrival times and no nearby station, sometimes the focal depth become deeper than it should be and this is inaccurate. We already know that the focal depths of earthquakes at the Sumatran Fault are about 0 – 20 km. We can improve the focal depth by changing the additional coefficient a_1 in the MJHD method proposed by Hurukawa *el al.* (2008). Therefore, the group of earthquakes become shallower.

4. RESULTS AND DISCUSSION

4.1 Relocation of M ≥ 6.0 Earthquakes between 1964 – 2011 and their Fault Planes

In this study, mainshocks of M ≥ 6.0 and their immediate aftershocks after 1964 along the Sumatran Fault were relocated. In order to know relative locations of large earthquakes and their fault planes, we relocated all earthquakes simultaneously. Sumatra, however, is a large region and about fifteen earthquakes of M ≥ 6.0 occurred in this region. Therefore, to facilitate the process of relocation, it was devided into three regions: Northern, Central and Southern Sumatra.

4.1.1 Northern Sumatra

There were six earthquakes of M ≥ 6.0 occurred in the Norhern Sumatra (Figure 2). The 1964 earthquake occurred close to the Simeuleum segment. The 1990 and 1996 mainshock and its aftershocks event occured on the Tripa segment. The 1997 occured near the Renun segment. The fault plane of 1964, 1990, 1996 and 1997 are in the Sumatran Fault. The 1967 and 2003 events are off Sumatran Fault. The fault plane of 1967 is in Nortwest (NW) – Southeast (SE) direction, which is parallel to the Sumatran Fault.

4.1.2 Central Sumatra

Four of the M ≥ 6.0 earthquakes occurred in the Central Sumatra region. They are the 1987 (M 6.4), 2008 (M 6.0) and the 2007 doublet earthquakes (M 6.4 and M 6.3) (Figure 3).

The fault planes of 1987 and 2008 events are along the SE end of the Renun segment and NW end of the Toru segment in the Sumatran Fault, respectively. However, it is still difficult to judge the fault plane of the 2007 doublet from the immediate aftershocks distribution because standar errors of aftershock location are large. Although we could confirm that the doublet occured at the boundary between the Sianok and Sumani segments, we could not identify the fault where the doublet occured. However, our relocation result does not consistent to previous studies. Therefore, further study necessary for the 2007 doublet.

4.1.3 Southern Sumatra

There are four earthquakes of M ≥ 6.0 occurred in Southern Sumatra region as shown in Figure 4. The 1995 earthquake of M 6.7 occurred along the SE end of the Siulak segment. The 2009 earthquake of M 6.6 occurred on the NW end of the Dikit segment. The 1979 earthquake of M 6.5 occurred near the Ketaun segment. Then, the 1994 earthquake of M 6.8 occurred near the Kumering segment.

The fault plane of 1979, 1994, 1995 and 2009 are on the Sumatran Fault. The 1994 earthquake have no immediate aftershocks. Though the fault plane of 1994 earthquake difficult to determine. According to Widiwijayanti *et al.* (1996) who caried out local temporal aftershock observation of the 1994 earthquake, most of events were located in the broad zone of 55 x 20 km^2 along to the Kumering segment of the Sumatran Fault. By comparing their locations and the relocated 1994 earthquake in this study, we can conclude that the 1994 earthquake was mislocated about 30 km NE and apart of the Kumering segment. In the same manner, there is high possibility that other events, 1979, 1995 and 2009 were also mislocated about 30 km NE. If we correct about 30 km for them, they situated very close to the Sumatran Fault.

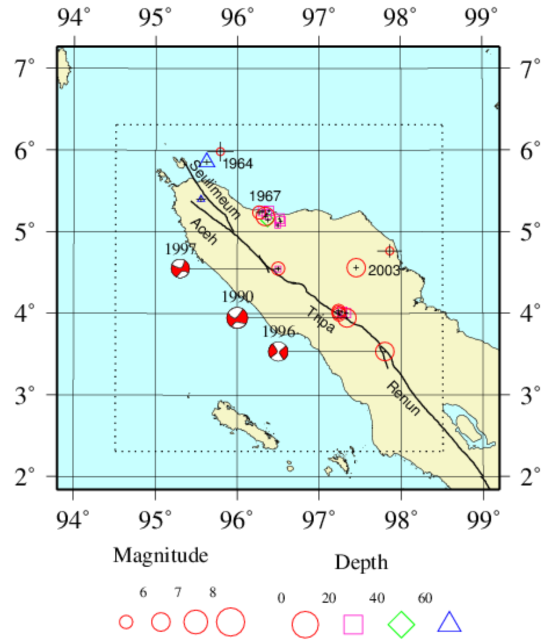

Figure 2. Distribution of relocated M ≥ 6.0 earthquakes in Northern Sumatra region between 1964 and 2011 using MJHD. The magnitude and depth of the earthquakes are represented by different sizes of circle and colored shapes, respectively. The mooment tensor solutions are taken from Global CMT catalog. Cross indicates standard errors of hypocenters.

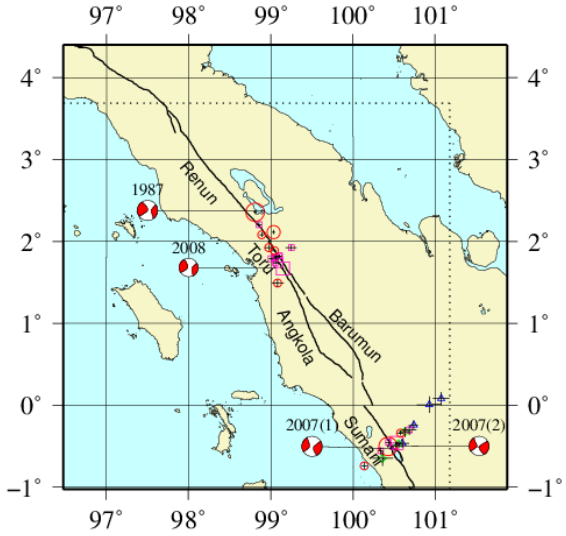

Figure 3. Distribution of relocated M ≥ 6.0 earthquakes distribution in Central Sumatra region between 1964 and 2011 using MJHD. Symbols are same as in Figure 2.

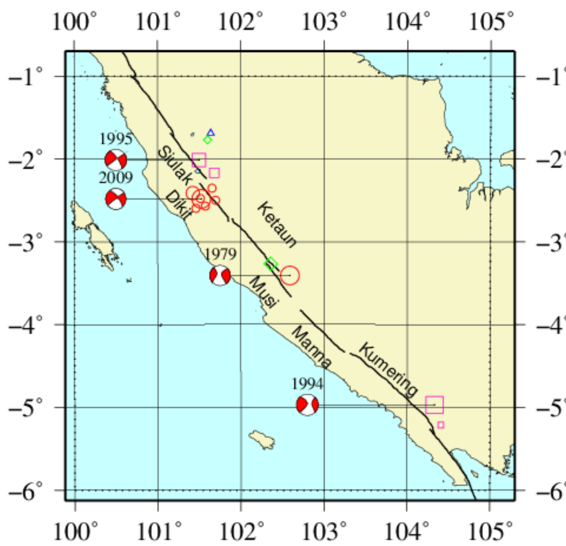

Figure 4. Distribution of relocated M ≥ 6.0 earthquakes distribution in Southern Sumatra region between 1964 and 2011 using MJHD. Symbols are same as in Figure 2.

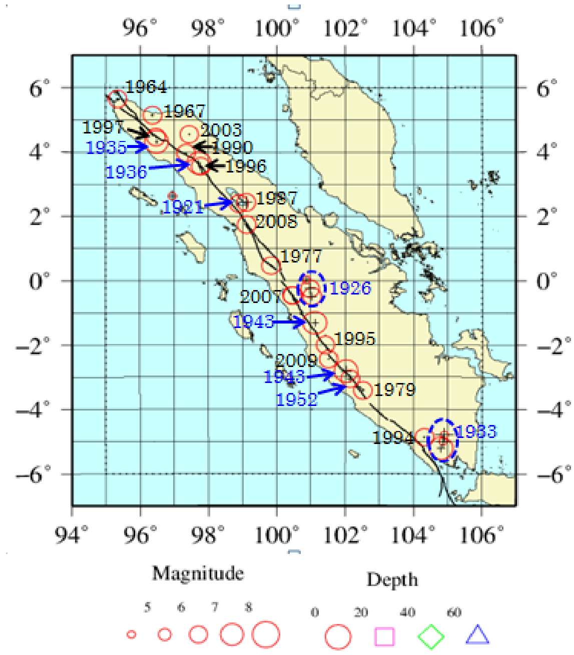

Figure 5. Distribution of relocated earthquakes in Sumatra between 1900 and 2011.

4.2 Relocation of large Earthquakes between 1900-2011

We tried to relocate all earthquakes. However, since travel time residuals of P-arrival times for the 1900 (M 7.0), 1907 (M 6.8), 1909 (M 7.3) earthquakes were too large, these earthquakes were excluded from MJHD relocation.

As there are no nearby stations and only P-arrival time readings are available, we fixed focal depths of all earthquakes to be 15 km in this relocation. Figure 5 shows MJHD hypocenters. Almost all earthquakes were located on the Sumatran Fault.

4.3 Earthquake History and Seismic Gaps Along The Sumatran Fault

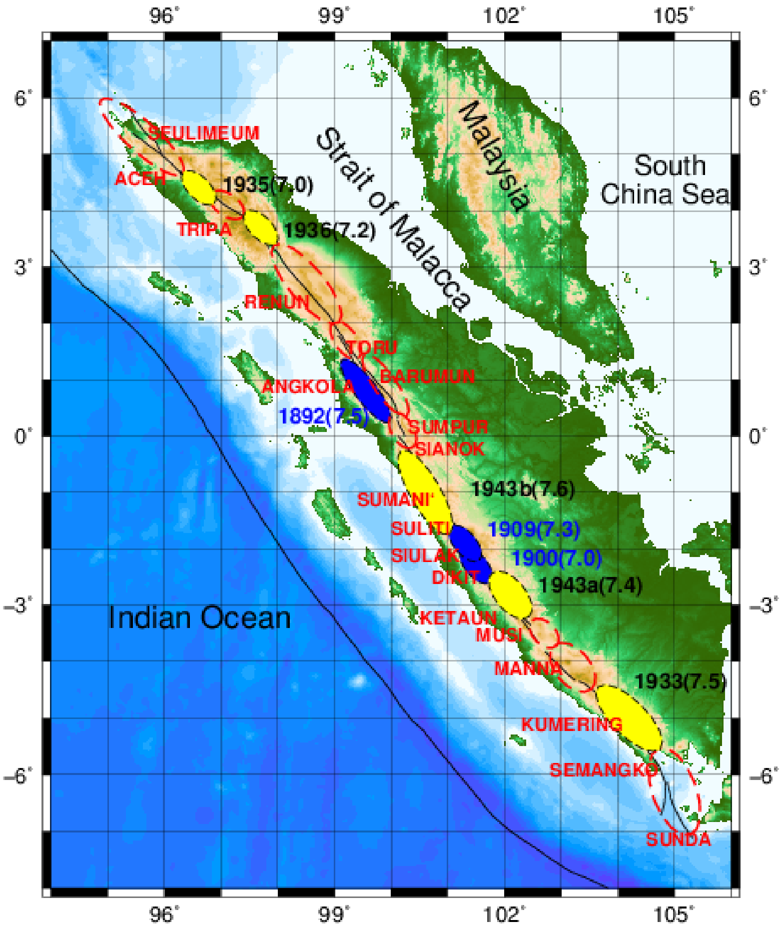

Figure 6 Earthquake history and the Sumatran Fault. Yellow ellipses indicated M≥7.0 earthquakes after 1930. Blue ellipses represent M ≥ 7.0 earthquakes before 1930. Red ellipses with dashed lines indicate possible seimic gaps. Segment names of the Sumatran Fault was taken from Sieh and Natawidjaja (2000).

There are eight M ≥ 7.0 occurred along the Sumatran Fault since 1892 . They are 1892 (M 7.5), 1900 (M 7.0), 1909 (M 7.3), 1933 (M 7.5), 1935 (M 7.0), 1936 (M 7.2), and the doublet of 1943 (M 7.4, M 7.6). Since we need to know the fault length corresponding earthquake magnitude in order to identify fault segment and to obtain the seismic gaps, fault lengths of the magitude ≥ 7.0 earthquakes are estimated by the equation for large earthquakes in the Sagaing Fault in Myanmar (Hurukawa and Phyo, 2011). From the equation, we obtain the faulth length of M 7.0, M 7.2, M 7.3, M 7.4, and M 7.6 earthquakes are 62 km, 84 km, 97 km, 113 km, 132 km and 153 km, repectively. These lengths were used in Figure 6.

Seven earthquakes with M ≥ 7.0 have occured along the Sumatran Fault and rupture the fault segments between 1900 - 2011. On 1933, an earthquake with M 7.5 has ruptured all part of the Kumering segment in the Southern Sumatra. On 1935, an earthquake with M 7.0 ruptured northmost part of the Tripa segment in Northern Sumatra. On 1936, another earthquake with M 7.2 ruptured southmost part of the Tripa segment. On 1943, doublet earthquakes occured in the Cental Sumatra. The first earthquake with M 7.4 has ruptured the Ketaun segment, while the second earthquake with M 7.6 has ruptured the Sumani and Suliti segments. Concerning two M ≥ 7.0 events on 1900 and 1909, we considered from catalog locations that these two events ruptured the Dikit and Siulak segments, respectively. In addition, the 1892 earthquake occurred along the Angkola Segment (Prawirodirjo, 2000).

The above results and expected fault length of M ≥ 7.0 earthquakes, we obtain earthquake history since 1892 and possible seismic gaps along the Sumatran fault in Sunda, Semangko, Manna, Mussi, Sianok, Sumpur, Barumun, Toru, Renun, center part of the Tripa, Aceh and Seulimeum segment.

These results are different from the recent study of Aydan (2007) on crustal deformation and starining of Sumatra island using GPS deformation rates. It is pointed out that there are three high stress rate concentration along the Sumatran Fault. They are Sianok, Sumpur, Barumun, Angkola, Toru, Dikit, Ketaun, Sunda, Semangko, and Kumering segment.

5. CONCLUSIONS

We relocated M $\geq$ 6.0 earthqukes and their immediate aftershocks near the Sumatran Fault from 1964 – 2011 by using Modified Joint Hypocenter Determination (MJHD) metthod. The fault plane of 1964, 1979, 1987, 1990, 1994, 1995, 1996, 1997, 2007, 2008, and 2009 are in the Sumatran Fault. The 1967 and 2003 are off Sumatran Fault.

We also relocated M $\geq$ 6.8 earthquakes from 1900 to 2011. We found that seven earthquakes with magnitude M $\geq$ 7.0 have occured along the Sumatran Fault and rupture the following fault segments. On 1933, 1935, 1936, first event of 1943 doublet earthquakes occured along the Kumering, northmost of Tripa, southmost of Tripa, Ketaun segment, respectively and the second event of 1943 doublet occured at the Sumani and Suliti segment. The 1900 and the 1909 earthquake occurred along the Dikit and Siulak segments, respectively. In addition, the 1892 earthquake occurred along the Angkola segment.

The result of M $\geq$ 7.0 earthquake locations for period 1892 to 2011 and expected fault length of M $\geq$ 7.0 earthquakes, we obtain earthquake history and possible seismic gaps along the Sumatran fault in Sunda, Semangko, Manna, Mussi, Sianok, Sumpur, Barumun, Toru, Renun, center part of the Tripa, Aceh and Seulimeum segments.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Dr. Tatsuhiko Hara and Dr. Bunichiro Shibazaki for their valuable suggestion for my individual study.

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