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Study of Seismicity Based on the Results of Hypocenter Relocation Using Double Difference (HypoDD) Method in West Sumatera and Its Surrounding

Syafriani[1*], Furqon Dawam Raharjo[1,2], Suaidi Ahadi[2], Mohamad Ramdhan[3]

[1] Department of Physics, Universitas Negeri Padang, Padang, Indonesia.
[2] Meteorological, Climatological and Geophysical Agency (BMKG), Padang Panjang, Indonesia.
[3] Research Center For Geological Disaster, National Research and Innovation Agency (BRIN), Bandung, Indonesia.

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Corresponding Author:
Syafriani
syafri@fmipa.unp.ac.id

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Abstract: The presence of the Indo-Australian plate, the Eurasian plate and the active Sumatra fault zone makes the West Sumatra region and its surroundings have very high seismic activity. To describe the seismicity pattern, it is necessary to analyze the earthquake hypocenter relocation, one of which is using the double difference (hypoDD) method. This method basically uses the data residual travel time from each hypocenter pair to the earthquake seismic station. The purpose of this research is to analyze the relocation of the hypocenter and describe the seismicity pattern in the West Sumatra and surrounding areas. The data used in this study are the time arrivals of P and S waves during the period of 2022 obtained from the earthquake catalog at the Padang Panjang Geophysical Station. The results showed that the earthquake hypocenter was relocated 888 out of 934 earthquake events and the distribution of hypocenter relocation produces a good seismicity pattern. From the results of the earthquake hypocenter relocation, the seismicity pattern in the West Sumatra region and its surroundings is generally influenced by subduction zones and some due to active fault zones. Seismicity in the subduction zone and active faults of Sumatra has a depth of about 50 - 250 km and 5 - 20 km. This indicates that during the period of 2022, subduction zones with medium to deep depths are very active as well as in Sumatra's active fault zones, especially in the Sianok segment.

Keywords: Double difference; Relocation; Seismicity; Subduction zone

Introduction

The tectonic conditions of the West Sumatra region and its surroundings are influenced by the Indo Australian plate, the Eurasian plate, the Mentawai backthrust structure and the active Sumatra fault zone. (Figure 1), so that this region has very high seismic activity. Indo-Australian plate moves northward and then subducts the relatively stationary Eurasian plate. The movement velocity of the tectonic plates is about 50-60 cm/year and the the subduction slope is about 12° (Natawidjaja, 2018). The subduction pattern of the plates moves obliquely (obligue), causing the formation of Sumatra active fault zone (Prawirodirdjo, 2000). With the existence of a very active tectonic setting in West Sumatra and its surroundings, it can trigger strong and destructive earthquake sources (Arimuko et al., 2020; Guci et al., 2020; Nurbaiti et al., 2019; Syafriani et al., 2020).

According to Pawirodikromo (2012) seismicity is a description of the relationship between spatial time, magnitude and frequency of earthquake occurrence in a particular area. Seismicity studies can used to study or describe seismotectonic patterns in a region and is also useful for disaster mitigation. Seismicity studies have a correlation to positioning of earthquake sources (Jatnika et al., 2015; Ramdhan et al., 2021; Sabtaji et al., 2015).

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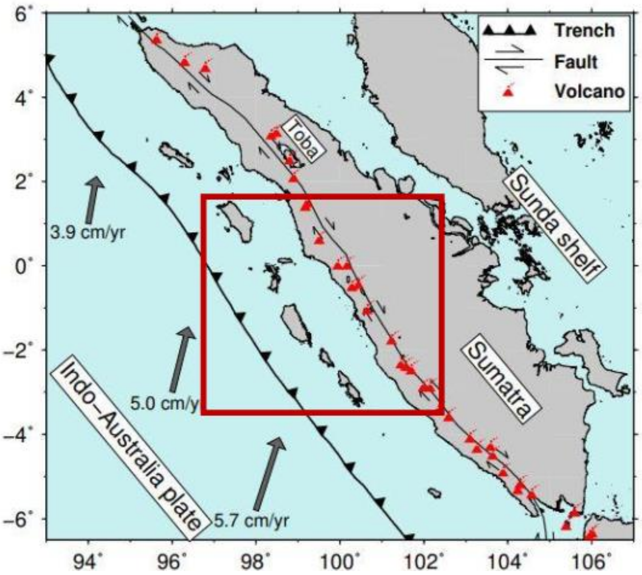


Figure 1. Tectonics of Sumatra Island, the red box is the region of West Sumatra and its surroundings (Natawidjaja, 2018)

To study seismotectonic patterns in detail and thoroughly, it is necessary to relocate the epicenter and hypocenter of an earthquake based on the seismicity of the earthquake catalog data. There are several factors that affect the accuracy of earthquake source positioning, including seismic station configuration, seismic wave arrival time (picking), wave phase and primary wave velocity model (Azizah, 2014; Jatnika et al., 2015; Naamin et al., 2018; Putra et al., 2019). Relocation of the earthquake source position is necessary to obtain more accurate and precise earthquake information parameters, such as hypocenter and epicenter, in order to understand and study the tectonic conditions in a region. Previous research on relocated seismicity studies has been conducted by (Jatnika et al., 2015; Kusmita et al., 2020; Ramdhan et al., 2020). The research has been able to study and characterize the tectonic conditions in the study area. This study uses the hypocenter double difference (hypoDD) method with the help of HYPODD software developed by (Waldhauser et al., 2000). This method uses residual travel time data from each hypocenter pair to the earthquake recording station (Serhalawan, 2018; Supendi et al., 2017). The purpose of this research is to relocate the hypocenter and epicenter based on the seismicity of the earthquake catalog, so that it is expected to describe and understand the pattern of seismotectonic conditions in the West Sumatra region and its surroundings.

Method

This study uses P and S wave arrival time data in the West Sumatra region and its surroundings for the observation period January 2022 to December 2022 obtained from the earthquake catalog at the Padang Panjang Geophysical Station (BMKG). In this study, the number of earthquake catalogs was 934 earthquakes and recorded by 42 BMKG seismic stations spread across West Sumatra and its surroundings. Then the 1D velocity model data uses AK135 (Arimuko et al., 2020). The distribution of seismic stations is shown in Figure 2 and the 1D velocity model data is shown in Table 1.

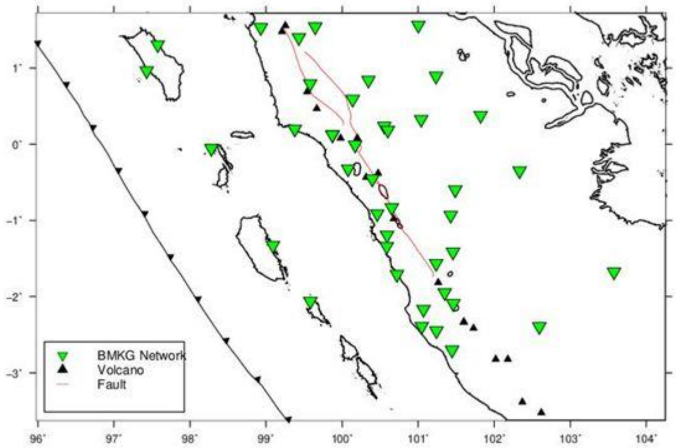


Figure 2. Distribution of seismic stations recording earthquakes owned by BMKG in West Sumatra and surrounding areas

Table 1. 1D Velocity Model of AK135

Depth (Km)	Wave velocity P	Wave velocity S
0.00	5.80	3.46
20.0	5.80	3.46
20.0	6.50	3.85
35.0	6.50	3.85
35.0	8.04	4.48
77.5	8.045	4.49
120.5	8.05	4.50
165.0	8.175	4.509
210.0	8.30	4.518

In this study, the hypocenter was relocated using the double difference (HypoDD) method. This method was introduced by Waldhauser et al. (2000) based on the Geiger method using residual travel time data from each hypocenter pair to the earthquake recording station. The principle is to compare two earthquake hypocenters that are close to the recording station, assuming that the distance between the two hypocenters must be closer than the distance between the hypocenter and the recording station (Bunaga et al., 2015; Hijriani et al., 2017; Supendi et al., 2019; Wu et al., 2009). An illustration of the basic principle of the double difference method is shown in Figure 3.

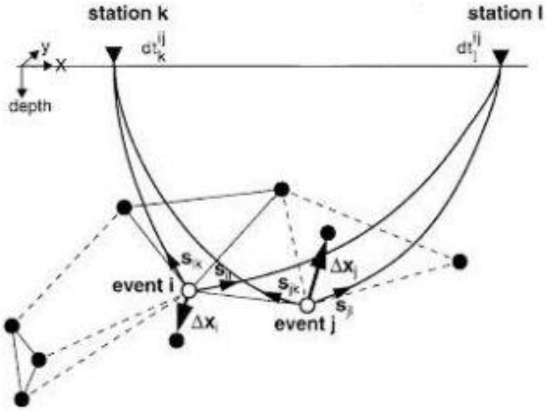


Figure 3. Illustration of the double difference method. Black and white circles are earthquake events that are related to each other. The thick black line is an earthquake pair with cross-correlation data and the dashed line with catalog data (Waldhauser et al., 2000)

The residual equation between 2 hypocenter distances that are close to each other with earthquake events 1 and 2 recorded at the recording seismic station is described as follows:

$$\frac{\partial t_k^i}{\partial m}\Delta m^i - \frac{\partial t_k^i}{\partial m}\Delta m^j = dr_k^{ij} \quad (1)$$

then translated back into the following equation:

$$\frac{\partial t_k^i}{\partial x}\Delta x^i + \frac{\partial_k^i}{\partial y}\Delta y^i + \frac{\partial_k^i}{\partial z}\partial z^i + \Delta\tau^i - \frac{\partial t_k^j}{\partial x}\Delta x^j + \frac{\partial t_k^j}{\partial y}\Delta y^j + \frac{\partial t_k^j}{\partial z}\Delta z^j + \Delta\tau^j = \Delta d \quad (2)$$

The calculation process continues until the residual value between observed and calculated travel times approaches zero. This iteration process is done efficiently using the hypoDD program (Bunaga et al., 2015; Ramdhan, 2019; Ramdhan et al., 2019; Supendi et al., 2021).

Result and Discussion

By using the double difference method, it has successfully relocated earthquake events in the West Sumatra region and its surroundings for the period of 2022 as many as 888 out of 934 earthquake events. The earthquake event relocation results in this study show better results, this is evidenced by the root mean square (RMS) residual time value close to zero (Figure 4). The RMS value is getting closer to zero, meaning that the results of the earthquake event relocation position are getting more accurate and precise. The RMS residual time values in this study are presented in the form of a histogram in Figure 4.

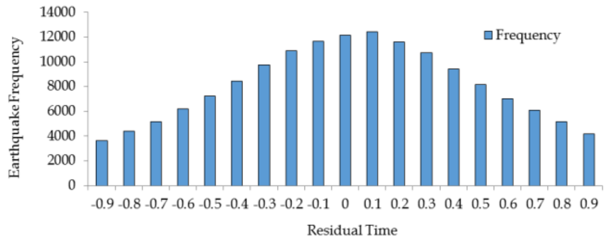
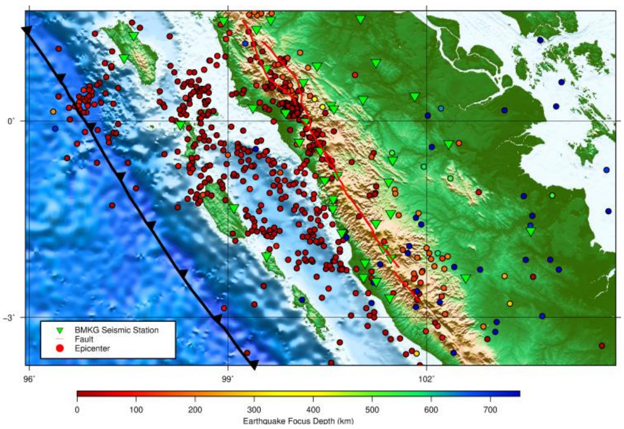
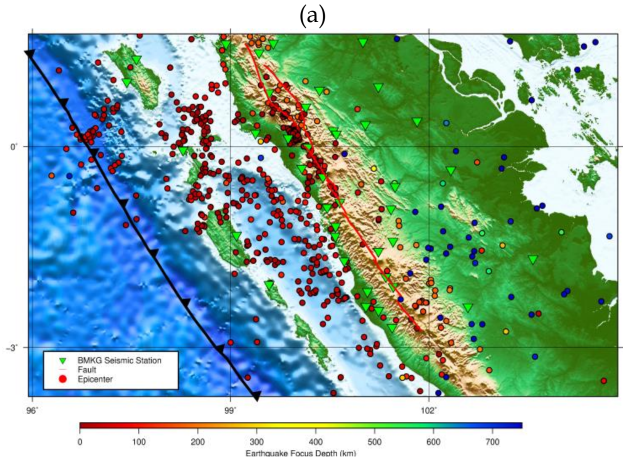


Figure 4. Residual time RMS value after relocation

In Figure 4 the histogram of RMS residual time produces values ranging from -0.9 s to 0.9 s, then the residual time value is getting closer to zero with the dominant values of 0 s and 0.1 s. The accuracy of the earthquake event relocation results is influenced by the local velocity model Vp in the study area and the results of primary and secondary wave picking. The results before and after seismicity relocation in West Sumatra and surrounding areas are shown in Figure 5.

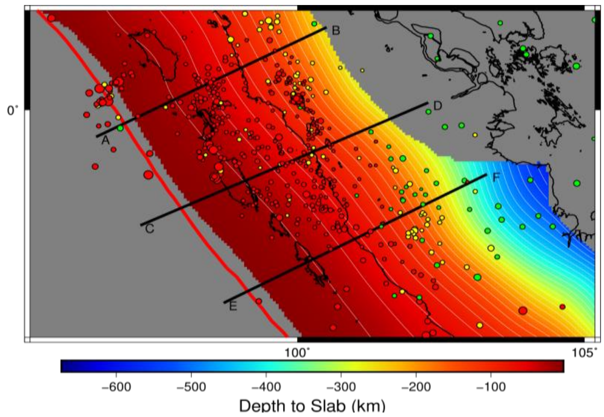


(a)

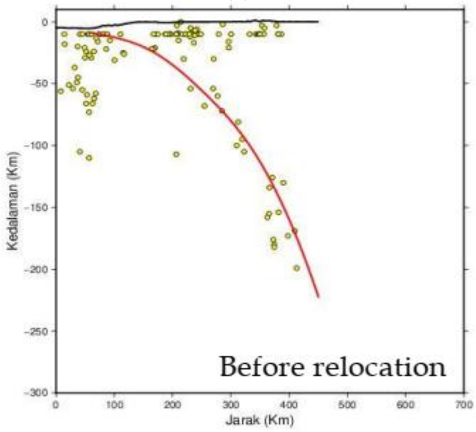


(b)

Figure 5. Seismicity results (a) Before, (b) After relocation in West Sumatra and surrounding areas for the period of 2022 using the double difference method



(a)



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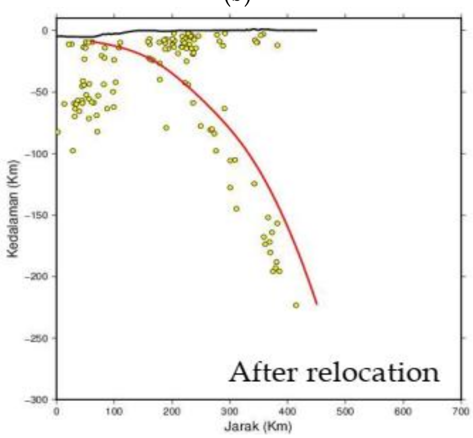
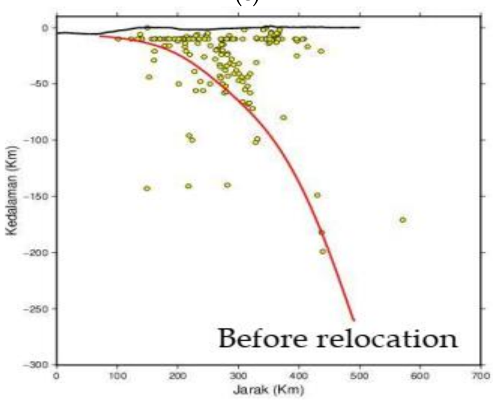
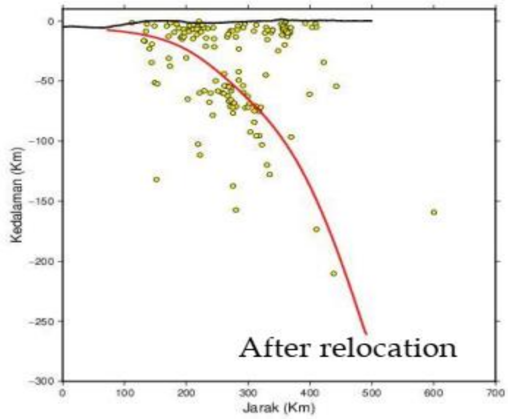


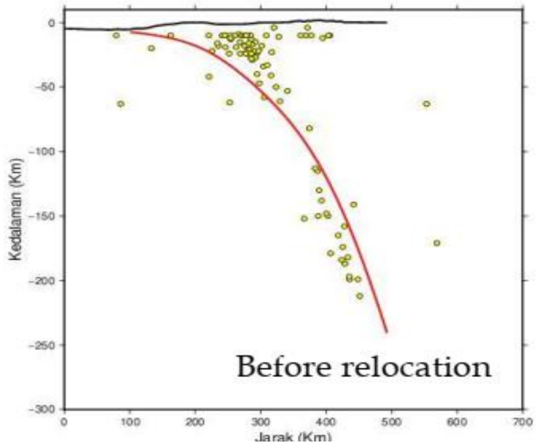
(c)



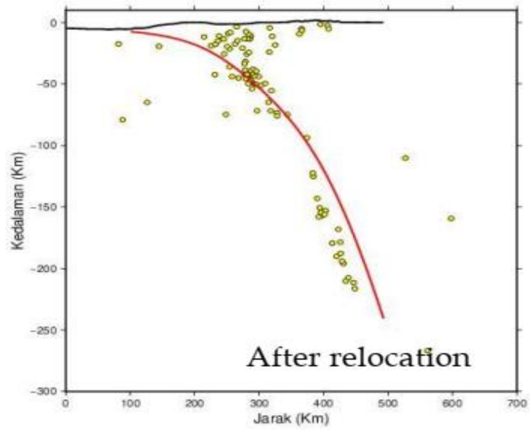
(d)



(e)



(f)



(g)

Figure 6. (a) Cross-section lines, A-B, C-D and E-F, (b) Cross-section A-B before relocation, (c) after relocation, (d) Cross-section C-D before relocation, (e) after relocation, (f) Cross-section E-F before relocation, (g) after relocation

In Figure 5, the results of seismicity distribution before relocation look spread and random, it is difficult to describe the seismicity pattern, then after relocation, the seismicity distribution is very tight and forms a grouping. In Figure 5, the distribution of seismicity after relocation shows that seismic activity is concentrated in the southwest of Nias Island, in the Mentawai Strait and on the mainland of West Sumatra and its surroundings.

This seismic activity is likely caused by the subduction zone and Sumatra fault system. The distribution of seismicity based on the depth of the earthquake hypocenter in this study is shown in Figure 6a.

In this study, the cross-section lines were overlaid with USGS subduction slab model data (Figure 6a) and divided into 3 (three) cross-section zones namely, A-B, C-D and E-F, this was done to be able to describe seismicity patterns based on depth and tectonics in detail. These three (3) cross-section zones following the pattern of subduction direction and the Sumatra fault system. Cross-sections A-B, C-D and E-F before relocation (figure 6b, 6d, 6f) It is seen that the hypocenter depth is always 10 Km (fixed depth) and aligned, then after relocating the hypocenter, the earthquake event looks spread and follows the pattern of the subduction zone slab model. In cross-section A-B after relocation (figure 6c) shows the existence of 2 (two) seismic zones, the first occurs in the Southwest of Nias island with a hypocenter depth of 5 - 60 Km, and the second occurs around the Batu-Nias South islands with a hypocenter depth of 5 - 30 Km. A zone of seismicity in the Southwest of Nias island, associated with event outerrise earthquake because the event hypocenter appears to be outerise the subduction zone.

The zone of seismicity around the Batu Islands-South Nias is thought to becaused by an active fault zone that is not yet known. Several earthquake events with deep hypocenter depth so far around 60 - 240 Km are also seen, and the hypocenter position covers the subduction slab model. This earthquake event can be interpreted as an intraslab earthquake, meaning that earthquakes that occur in deep subduction zones, and in according with the subduction pattern of Sumatra, the more east ward the subduction slab pattern will be deeper.

The results of the hypocenter relocation on the C-D cross-section (figure 6f), there are 3 (three) zones of seismicity, the first and second are seismic activity at depths of 5 - 20 Km which occurs around the Mentawai Strait and on the mainland of Sumatra. The shallow earthquakes in the Mentawai Strait may be related to the Mentawai backthrust and the on shore earthquakes are associated with the Sumatera Fault System (SFS) especially on the active Sianok segment fault. Then the third is seismic activity located at a depth of 50 - 80 Km which occurs around the Padang sea. Judging from the depth of the hypocenter, these earthquakes were located in the rupture zone of the Mw7.6 Padang earthquake in 2009. The seismic activity is likely to occur in the medium depth Wadati-Benioff subduction zone. Then the earthquakes that are located at this depth, produce a good hypocenter position, because it covers the subduction slab model. Shallow earthquake activity in the Sumatra megathurst zone is not visible in the C-D cross section.

Cross sections E-F after relocation (Figure 6g) show seismic activity at depths of 10 - 30 km, 40 - 80 km and 140 - 230 km. Earthquakes at depths of h<30 Km may still be related to the Mentawai backthrust. The backthrust fault structure has a dip or slope of the fault plane that is opposite to the slope of the main thrust plane and is formed on a thrust (Ramdhan et al., 2020, 2021). At a depth of 40-80 km there is seismic activity that follows the slab pattern of the subduction model. This seismic activity occurs in the Wadati-Benioff zone. The Wadati-Benioff Zone is an intraslab earthquake that occurred due to be ending plate and compression (Kusmita et al., 2020). Then at a depth of 140 - 230 Km, this seismic activity is categorized as an intraslab earthquake. The distribution of these earthquakes forms a sloping line with a dip parallel to the subduction dip but deeper (Ramdhan et al., 2020). These earthquakes are caused by slab pull due to its own weight (Pawirodikromo, 2012). According to these findings, the foundation zones plate bending and compression will occur at depth so between 100 and 300 km, leading to shallow intraslab earthquakes.

Conclusion

After relocation using the double difference method, the position of the epicenter and hypocenter is very good, this is characterized by the root mean square (RMS) residual time value close to zero**.** The number of earthquake events that were successfully relocated was 888 out of 934. After being relocated, the seismicity in West Sumatra and surrounding areas is dominated by medium depth subduction zones and partly due to the tectonic activity of the Sumatran fault system, especially in the segment Sianok fault. The seismicity distribution pattern after relocationc an already be described as an initial study of the seismotectonic conditions in West Sumatra and its surroundings.

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Author Contributions
The main author, Syafriani contributed to provide research ideas, provide an overview and knowledge of the double difference method, proof reading this research journal, The second author, Furqon Dawam Raharjo, role in analyzing data, creating mapping maps, and writing journals, The third author, Suaidi Ahadi, providing travel time data, directing and supporting this research, The fourth author, Mohamad Ramdhan, provide an understanding of the double difference method.

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Conflicts of Interest
The authors declare no conflict of interest.

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