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Research Paper

Analysis of Earthquake Hypocenter Dynamics for the Period 2009-2017 in West Nusa Tenggara Using the Double-Difference Method

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Abstract: West Nusa Tenggara is an area prone to earthquakes due to the collision of tectonic plates, namely the Indo-Australian and Eurasian plates. The tectonic conditions of this region need to be known by determining the earthquake hypocenter accurately using the relocation technique. The purpose of this study was to determine the distribution of hypocenters in the NTB region and to analyze the dynamics of earthquake hypocenters after the relocation period of 2009-2017. The results of this study are the distribution of hypocenters that occurred in the NTB region at positions 7-12 LS and 115.5-119.5 BT for the period 2009-2017 on average spread and clustered in shallow earthquakes and subduction zone patterns with hypocenter depths of 0 to 300 km or shallow, medium earthquakes and several deep earthquake hypocenters. Earthquake activity continues to increase to the East from the Lombok Strait to the Sape Strait with dominant earthquake activity occurring on the Island and South of the Island. From the period of 2009 - 2017, earthquake activity continued to increase every year. This was caused by the main back arc thrust of Flores in the North and the subduction zone in the South which caused more earthquake activity in the region.

Keywords: Earthquake; Double-difference (DD); Relocation.

1. Introduction

West Nusa Tenggara is an area prone to earthquakes due to the collision of tectonic plates, namely the Indo-Australian and Eurasian plates [1]. The tectonic conditions of this region need to be known by determining the earthquake hypocenter accurately using the relocation technique [2]. Hypocenter relocation is a correction of the latitude, longitude and depth of the earthquake. Earthquake hypocenter relocation also needs to be done to correct the analysis program used by BMKG, namely SeisComP. Earthquake hypocenter relocation can be done using various methods, namely the Geiger method, the Grid search method, the Modified Joint Hypocenter Determination (MJHD) method and the Double-Difference method [3]. This study uses the Double-Difference method. The advantages of the Double-Difference method over other methods are that it can relocate the hypocenter without requiring station correction, and is able to relocate earthquakes with a large amount of data. The principle of this method is that if there are two earthquakes that have a closer distance between one earthquake and another compared to the distance of the earthquake to the recording station, then the ray path (trajectory path) of the two earthquakes is considered the same. The implementation of this method is the hypoDD software introduced by Felix Waldhauser and Ellsworth in 2000.

This study focuses on determining the distribution of hypocenters and analyzing the dynamics of earthquake activity after relocation from 2009 to 2017 [4]. This study is important to be carried out as an initial step for disaster mitigation, building design in areas adjacent to earthquake sources and is useful in further earthquake studies.

2. Literature Review

Hypocenter is the center of an earthquake located inside the earth. Sometimes the hypocenter is assumed to be a point, but in reality the hypocenter is a plane whose area depends on the amount of energy released. Wadati diagram can also be used to determine the position of the hypocenter, assuming that the earth's layers are homogeneous.

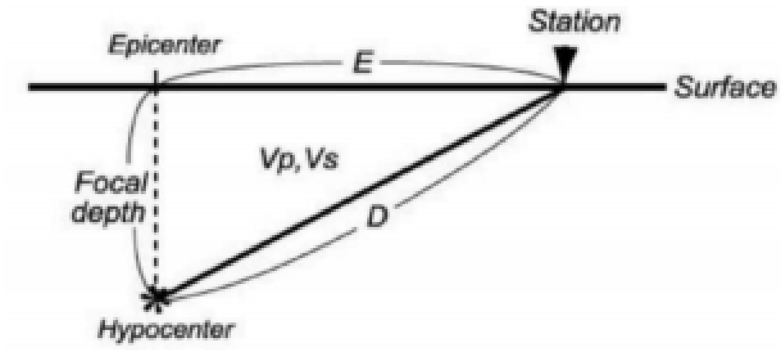


Figure 1. Hypocenter Distance

Where D is the distance of the hypocenter to the recording station, E is the distance of the epicenter to the recording station. The determination of the hypocenter was previously determined using P and S wave arrival time data from several stations [5]. Determination of the hypocenter location can experience errors, one of which is influenced by the incompatibility of the layer velocity model used. To determine the location of the earthquake hypocenter more accurately, hypocenter relocation is carried out. Hypocenter relocation is a correction of the latitude, longitude and depth of the earthquake. This study uses the Double-Difference method [6]. The advantages of the Double-Difference method over other methods are that it can relocate the hypocenter without requiring station correction, and is able to relocate earthquakes with a large amount of data [7].

The principle of this method is that if there are two earthquakes that have a close distance from the earthquake to the recording station, then the ray path (propagation path) of the two earthquakes is considered almost the same. The implementation of this method is the hypoDD software introduced by Felix Waldhauser and Ellsworth in 2000. An illustration of this method can be seen in Figure 2.

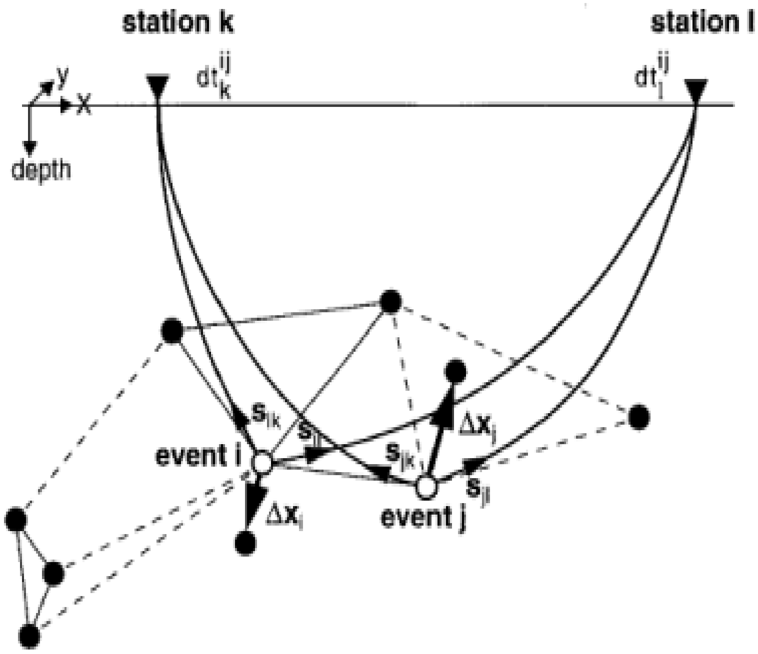


Figure 2. Illustration of the Double-Difference method

Figure 2 explains the illustration of the Double-Difference method, there are black and white circles which are the distribution points of earthquake hypocenters connected to the surrounding earthquake events by cross-correlation data (shown with thick lines) and catalogs (shown with dotted lines). Earthquakes i and j shown with white circles were recorded at the same station (station k and station l) with a travel time difference of dk^i and dl^D. Because of the close position between the two earthquakes, the raypaths of both are considered the same, namely passing through the medium at the same speed. The direction of the arrows Δ_{xi} and Δ_{xj} indicate the earthquake relocation vector that will occur [8].

The relative residual travel time between two hypocenters that are close to each other in one group (cluster) can be written as follows:

$$dr_k^{ij} = \left(t_k^i - t_k^j\right)^{obs} - \left(t_k^i - t_k^j\right)^{cal} \quad (1)$$

Where dr_k^{ij} : the difference between the arrival time of the observation wave and the calculated arrival time of earthquake i and earthquake j; t_k^i : the travel time of earthquake i recorded by station k; t_k^j : the travel time of earthquake j recorded by station k; t^{obs} : the observation travel time (recorded by the station); and t^{cal} : the calculated travel time (from the calculation).

The residual value of the travel time for a pair of events can be calculated from the difference between events I and j for each parameter (x,y,z,t).

$$\Delta d = \frac{\partial t_k^i}{\partial m}\Delta m^i - \frac{\partial t_k^j}{\partial m}\Delta m^j \quad (2)$$

The equation used in the Double-Difference method calculation, arranged in matrix form for a number of earthquakes observed by the station, can be written as follows:

$$\Delta d = \begin{pmatrix} \Delta d_1 \\ \Delta d_2 \\ \Delta d_n \\ \cdots \\ \cdots \\ \Delta d_n \end{pmatrix} = \begin{pmatrix} \frac{\partial t_1}{\partial x_1} & \frac{\partial t_1}{\partial y_1} & \frac{\partial t_1}{\partial z_1} & 1 \\ \frac{\partial t_2}{\partial x_2} & \frac{\partial t_2}{\partial y_2} & \frac{\partial t_2}{\partial z_2} & 1 \\ \vdots & \vdots & \vdots & \\ \frac{\partial t_n}{\partial x_n} & \frac{\partial t_n}{\partial y_n} & \frac{\partial t_n}{\partial z_n} & 1 \end{pmatrix} \begin{pmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \\ \Delta_t \end{pmatrix} \quad (3)$$

$$W\Delta d = WG\Delta_m \quad (4)$$

Where Δd is the residual time matrix with dimensions $M \times 1$. M and G are respectively the number of Double-Difference observation data and the Jacobi matrix with dimensions $M \times 4N$, N and Δ_m are respectively the number of earthquakes and the model change matrix with dimensions $4N \times 1$, while W is the calculation of the wave travel time [9]. Determination of the hypocenter location is continuously carried out by iterating until the results of the residual value of the observation travel time are obtained with calculations that approach the minimum value. Determination of the hypocenter is influenced by the velocity model in the research area. The velocity model used is the 1-D P-wave velocity model.

3. Method

This study uses P-wave arrival time data at coordinates 7 – 12 LS and 115.5 – 119.5 BT for the period 2009 – 2017 with a total of 7271 event data obtained from BMKG Selaparang.

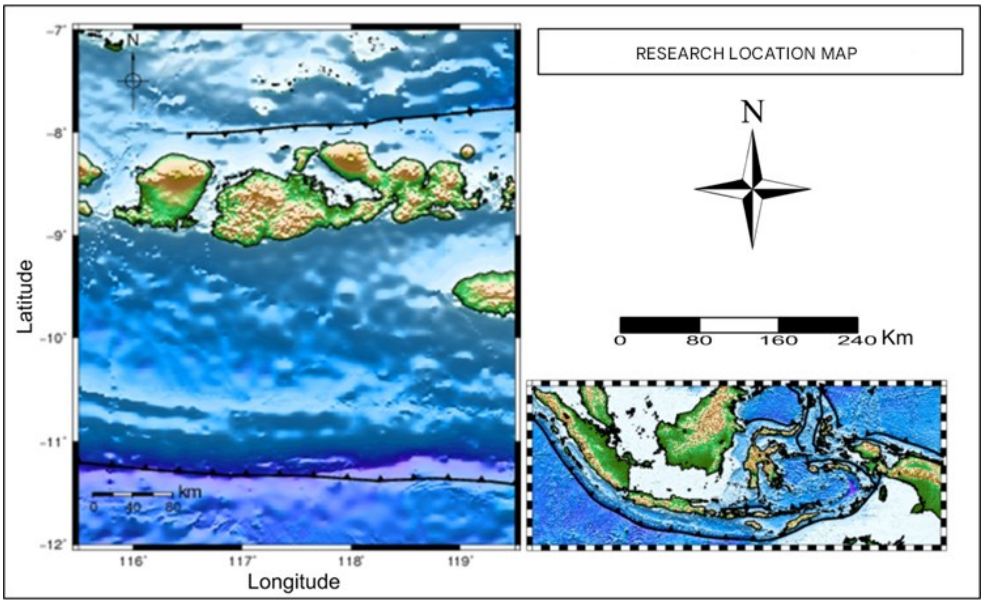


Figure 3. West Nusa Tenggara Region Map Image

The parameters used for hypocenter relocation are latitude, longitude, depth, and time of the earthquake. Furthermore, the data will be processed and analyzed. The steps for processing data to produce hypocenter relocation data are as follows:

a. Data format as input for relocation. Changing the earthquake catalog data format from BMKG (*.txt) into input data for ph2dt program processing (*.pha).
b. Earthquake relocation using the double-difference method Earthquake data is relocated using the Double-Difference method with the help of hypoDD software. The data from ph2dt processing is used as input in the hypoDD program. The results of hypoDD processing are earthquake parameters after relocation.
c. Plotting earthquake relocation data The parameters used are station coordinates, event data before relocation, event data after relocation, and topographic data. Using GMT software.
d. Making a cross-section After the relocation data results are plotted, the next step is to make a cross-section to see the distribution of hypocenters before and after the relocation using GMT software.
e. Analysis of hypocenter distribution before and after earthquake hypocenter relocation. The relocated catalog data is then analyzed for hypocenter distribution and compared with data before relocation.

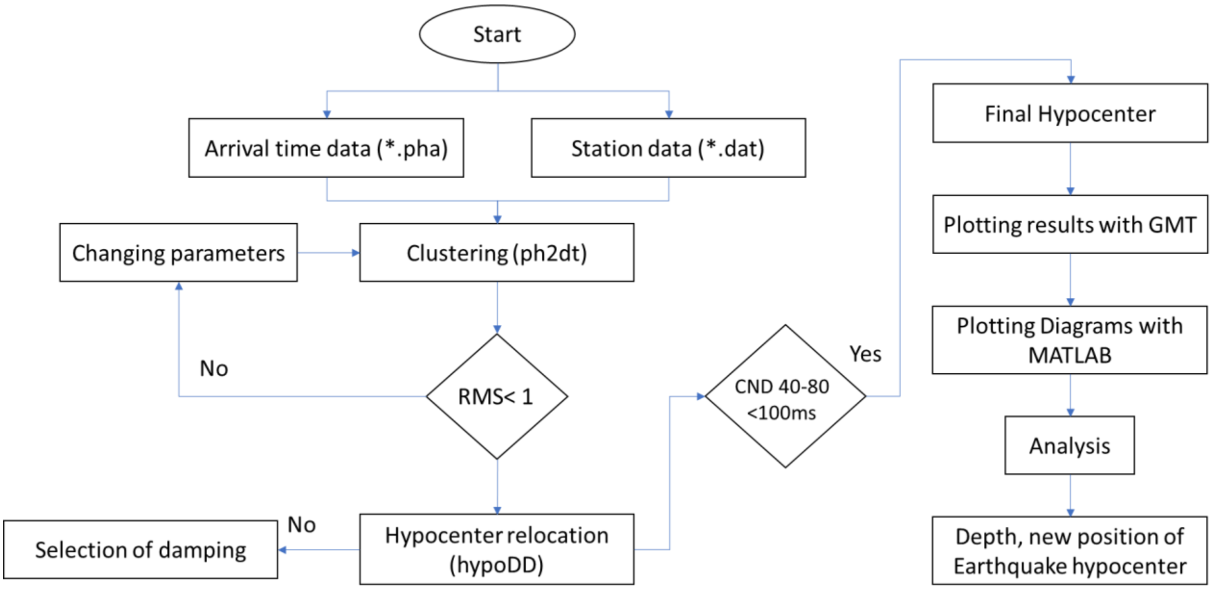


Figure 4. Data Processing Stages

4. Result and Discussion

4.1 Earthquake Hypocenter Relocation Results Data Validation Using the Double Difference Method

Validation of relocation results is done by creating a histogram before and after relocation. By doing validation it can be said to be accurate, if the residual value after relocation is relatively close to zero. The residual value is getting closer to zero, indicating that the calculation results and observation values are getting closer to the same [10].

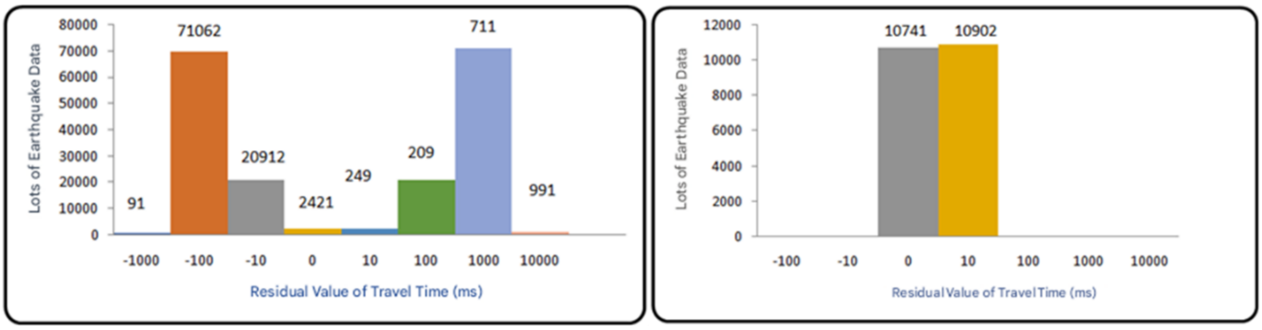


Figure 5. Histogram (a) before relocation and (b) after relocation.

Figure 3(a) is the earthquake data before relocation which shows the residual travel time value that is close to zero only 2421 compared to Figure 3(b) which is the earthquake data after relocation which has a residual travel time value of zero as many as 10,741 and a value of more than five as many as 10,903 earthquakes. Based on the results of the study using the Double-Difference method, it provides a more accurate residual travel time value for the earthquake. Thus, it shows that the calculation results and observation values are close to the same.

4.2 *Seismicity Distribution Map of Earthquake Latitude and Longitude Position Before and After Relocation*

The distribution of earthquake hypocenters before and after relocation in NTB for the period 2009-2017 is shown in Figure 6, namely the distribution map before and after relocation.

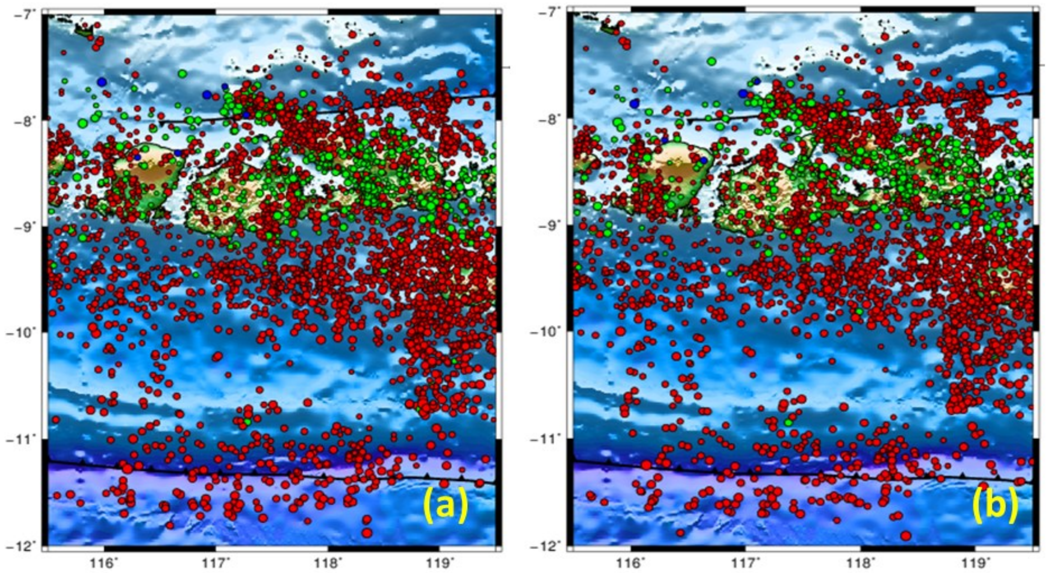


Figure 6. Map of the distribution of earthquake hypocenters in NTB in 2009-2017 (a) before relocation, (b) after relocation

Figure 6 shows the distribution of earthquakes before the major earthquake in 2018. Based on Figure 6, there is a shift in latitude and longitude after relocation, which is dominated by shifts that appear to be clusters in certain areas. The red dots in Figure 4 are shallow earthquakes with a depth of (0-70) km, the green dots indicate intermediate earthquakes with a depth of (70-300) km and the blue dots are deep earthquakes with a depth of >300 km.

4.3 Analysis of Earthquake Depth and Position Dynamics After Relocation

Analysis of earthquake depth dynamics before and after relocation, was done by making cross-sections against latitude, longitude and depth. In this study, four cross-sections were made from West to East as in Figure 6, namely cross-sections A-A' to D-D'. The results of the cross-sections before and after relocation. Based on the cross-section results of Figure 6, it can be seen that the shift in earthquake depth before and after the relocation of the three periods shows a shift in depth. Based on the analysis results obtained, it can be seen that the depth before the relocation still has a fixed depth of 10 km which forms a pattern resembling a straight line. While after the relocation shows varying depths. This is obtained from the earthquake parameters of position, depth and magnitude. The red curved line is the subduction model line [11].

Figure 7 cross-section A is made around the Lombok Strait. The results of the study from the three periods of 2009-2011 to 2015-2017 show that before the relocation it tends to gather around the shallow earthquake depth and spread in the subduction zone, while after the relocation there is a shift in position that spreads in clusters between hypocenters that tend to have relatively close distances at shallow earthquake depths and subduction zone patterns. From the three periods in the cross-section in the Lombok Strait there was an increase in earthquake activity and the increase also increased every year in the subduction zone pattern at depths of 300 to more than 300 km [12].

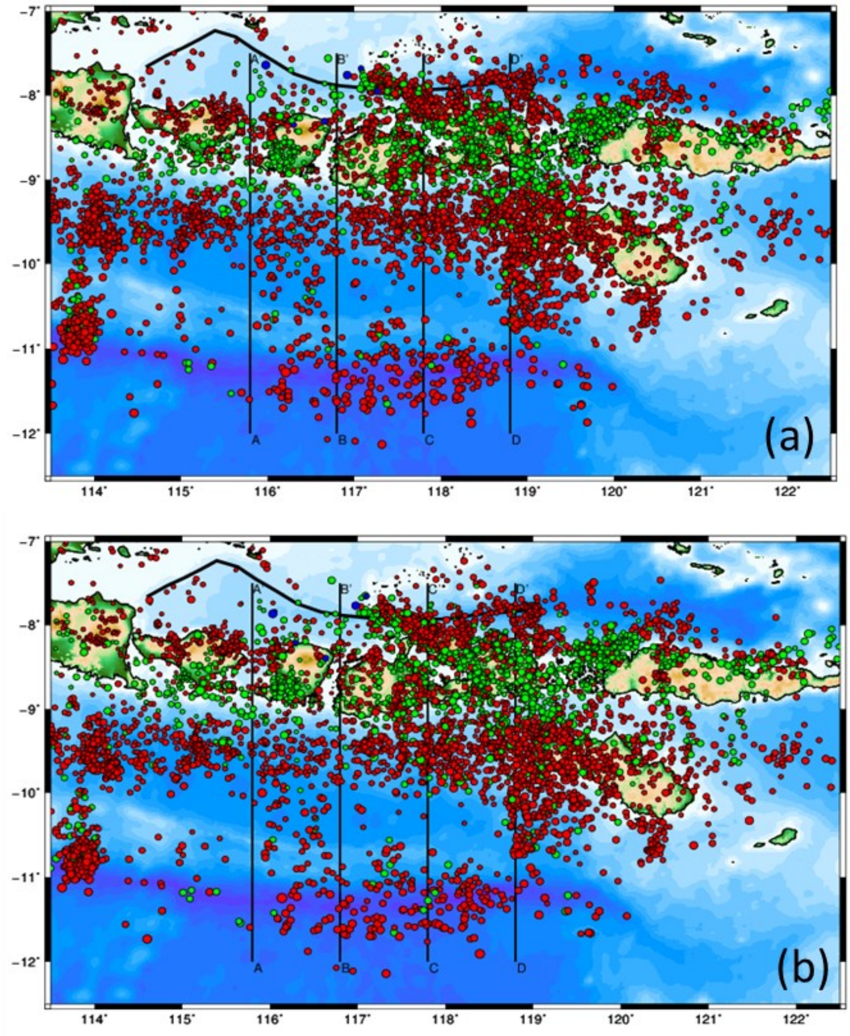


Figure 7. cross-section

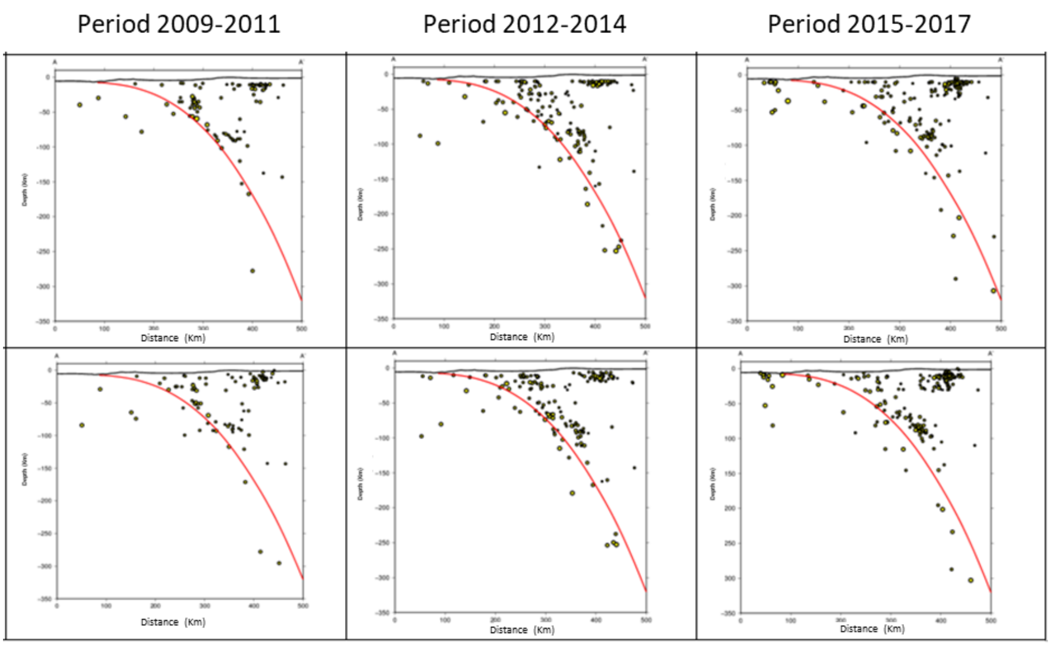


Figure 8. Cross-Section of the Alas Strait (A1) before relocation (A2) after relocation

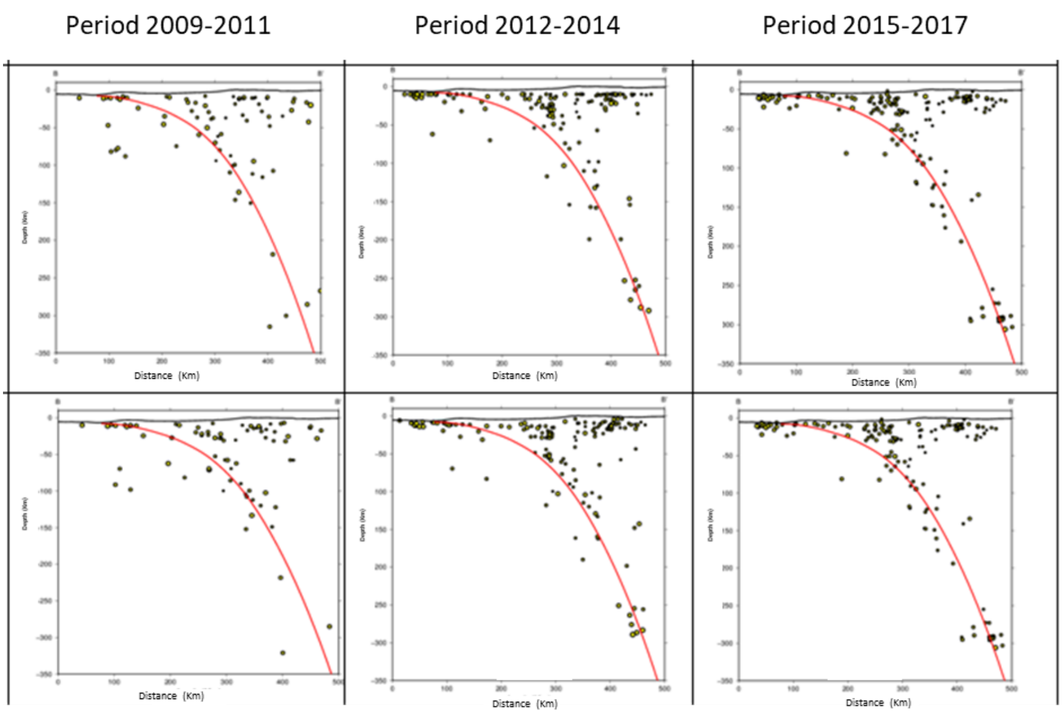


Figure 9. Cross-Section of the Alas Strait (B1) before relocation (B2) after relocation

The B1 B2 cross section was made around the Alas Strait. Based on the results of the study for the period 2009-2011 to 2015-2017, it can be seen that before the relocation it spread around the subduction zone and spread at shallow earthquake depths, while after the relocation the earthquakes tended to group into the subduction zone. In the hypocenter with a deep depth (>300) km, the dominant shift was seen, namely after the relocation there was an earthquake hypocenter that disappeared. From the three periods in the Alas Strait, there was an increase in activity every year [13].

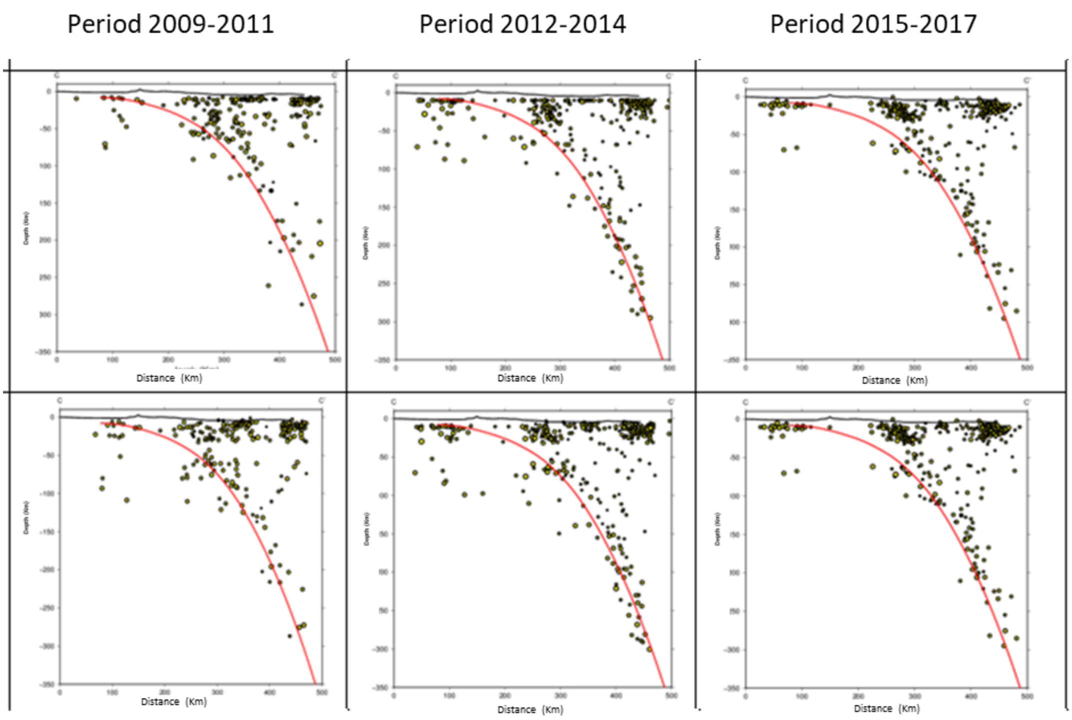


Figure 10. Cross-Section of Sumbawa Island (C1) before relocation (C2) after relocation

The C1C2 cross section was made around Sumbawa Island. Based on the research results obtained, in the period 2009 - 2011 to 2015 - 2017 it was seen that earthquakes before relocation were mostly close to the subduction zone and spread on the surface of shallow earthquakes, while after relocation they formed clusters in the subduction zone and on the surface. Of the three periods, the more towards the South, it shows a seismic gap in the period 2015 - 2017.

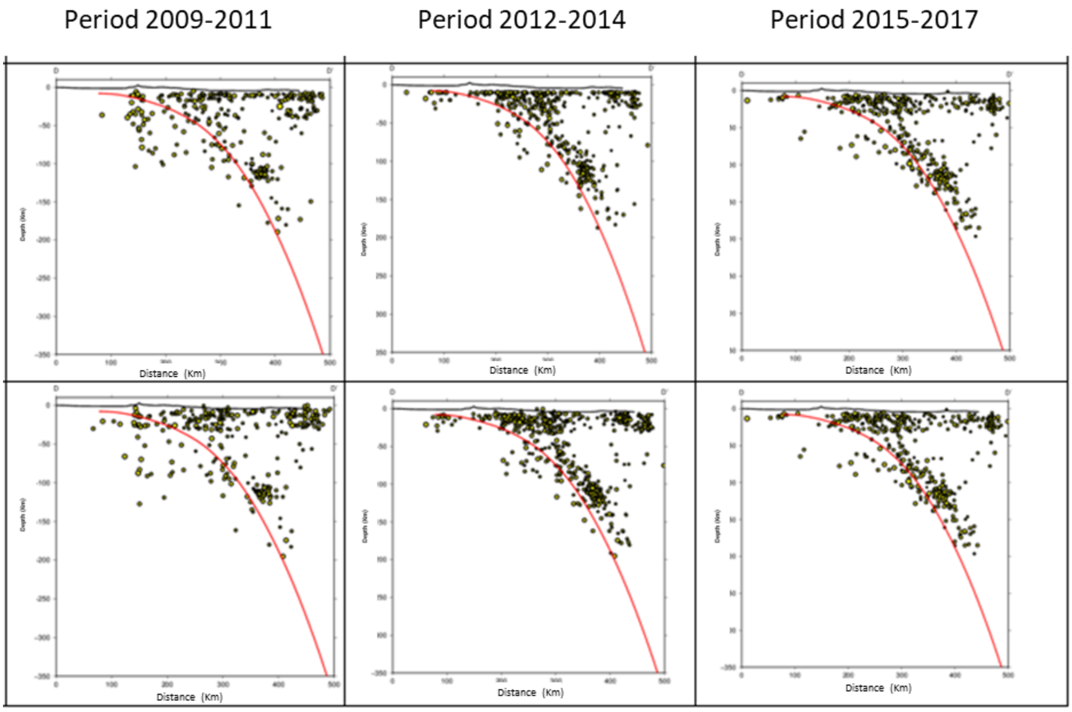
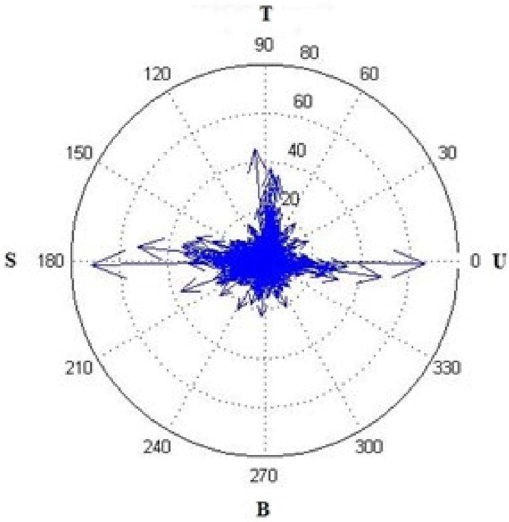


Figure 12. Cross-Section of the Sape Strait (D1) before relocation (D2) after relocation

The D1 D2 cross section was made around the Sape Strait. Based on the research results obtained in the period 2009 - 2011 to 2015 - 2017, it can be seen that the earthquake hypocenters are collected at shallow depths and spread at intermediate depths, namely in the subduction zone, while after the relocation it can be seen that there is a shift in the earthquake point which tends to spread in the subduction zone by forming clusters in the depth range (70 - 180) km.

The results of the relocation using the Double-Difference method validated using a residual histogram, show that the number of earthquakes after the relocation that have a zero value is greater than before the relocation [14]. If the residual value is getting closer to zero, it indicates that the inversion of the calculation results and the observation results are getting closer to the same, thus indicating that the position of the earthquake after the relocation is more accurate than before the relocation. The shift in the hypocenter position after the relocation is dominated by an average distance of less than 10 km as shown by the compass diagram in Figure. The hypocenter shift spreads in all directions with a dominant shift towards the Southwest Southeast and towards the North [15]. In 2009-2017, earthquake activity increased every year and from West to East earthquake activity also continued to increase. This was caused by tectonic energy in the East, accumulated from the more active Flores back arc fault in the North and the subduction zone in the South, resulting in more earthquake activity in the region. In the period 2015-2017, there was an area that experienced an earthquake emptiness which was suspected to be a seismic gap on Sumbawa Island.

The depth range of earthquakes before relocation was (5 - 315 km, while the depth range after relocation was 0.025 - 320 km. This shows that the earthquakes that occurred in NTB in the period 2009 - 2017 were shallow, intermediate and deep earthquakes. With the range of shifts in the depth position of the earthquake being 0 - 56.412 km. The distribution of shallow earthquakes after relocation looks more focused or clustered which may be associated with the pattern of active faults, while deep earthquakes tend to follow the pattern of subduction zones.



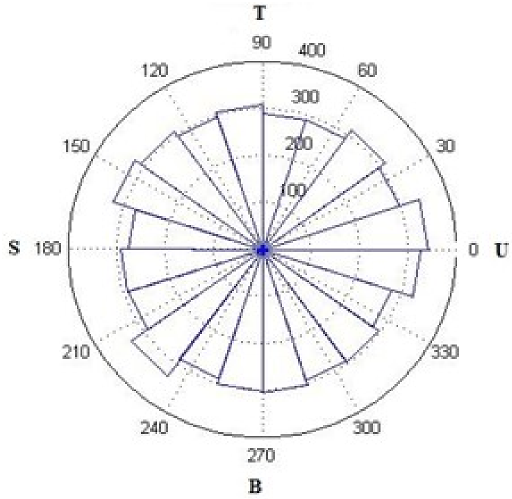


Figure 13. Compass Diagram

The compass diagram in Figure 13 shows the large shift in the angle of the initial position of the earthquake event until the change in the angular position after relocation [16]. In the compass diagram, the scale 0 - 330° shows the large angle of the hypocenter shift after relocation. The circle on the compass diagram shows the distance of the shift with a layer scale, namely 0 - 80 km. The diagram in Figure 5.4 shows the shift in the distance of the earthquake position after relocation is dominated by a distance of less than 20 km. Earthquake shifts of more than 20 km are more dominant in the North and South directions.

The rose diagram in Figure 13 shows the number of earthquakes and the frequency of the dominant direction and the interval of the angle of change of the hypocenter direction [17]. In the rose diagram, the scale 0 - 330° shows the magnitude of the angle of the earthquake hypocenter shift after relocation [18]. The circle in the rose diagram shows the number of earthquake events with a scale of 100 - 400. From the rose diagram, it can be seen that after relocation, the earthquakes that occurred spread in all directions. However, it does not have a dominant tendency in a particular direction. The largest hypocenter shifts are towards the Southwest, Southeast and North.

5. Conclusions

Based on the research that has been conducted, the following conclusions can be drawn: (1) The distribution of hypocenters that occurred in the NTB region in the period 2009-2017 at positions 7-12 LS and 115.5-119.5 BT were on average spread and grouped in shallow earthquakes and subduction zone patterns with hypocenter depths of 0 to 300 km or shallow, medium earthquakes and several deep earthquake hypocenters. (2) Earthquake activity continues to increase towards the East from the Lombok Strait to the Sape Strait with dominant earthquake activity occurring on the Island and South of the Island. From the period 2009 - 2017 earthquake activity continues to increase every year. The large range of earthquake depth shifts is 0 - 56.412 km. This is caused by the Flores back arc thrust in the North and the subduction zone in the South which causes more earthquake activity in the region.

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