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Relocation of the Hypocenter of an Earthquake with the Double Difference Method in the Regional Study Area of Yogyakarta

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Abstract

The relocation of the earthquake hypocentre is necessary in order to determine the position of the earthquake centre with higher accuracy. An accurate hypocentre position is important for earthquake-prone areas mapping, seismicity analysis, and fault zone identification. The double difference algorithm technique using the hypoDD program can be used for hypocentre relocation. This article reports the earthquake relocation of 23 earthquakes in the Yogyakarta region recorded at four observation stations. The result shows that the hypocentre shift spreads randomly with a shift distance of less than 20 km, with the most shifting direction of the epicentre to the northeast. The Earthquake's hypocentre after relocation in the land area is estimated to be triggered by a fault under the Gamping Wungkal Formation, while the earthquake around Mount Merapi is estimated to be triggered by volcanic activity. The Relocation result in the sea area show that the hypocentre leads to the subduction line.

Keywords: double difference; fault; hypoDD; residual histogram; subduction.

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Introduction

Yogyakarta is in the collision zone of the Eurasian plate with Indo-Australian plate which makes this region prone to earthquakes (Fathani & Wilopo, 2017). Moreover, the earthquakes in Yogyakarta were caused by the activities of the local faults in this region (Wibowo & Sembri, 2017). Earthquake researches need to be carried out as disaster mitigation measure. The exact location of the hypocentre is important for mapping the earthquake-prone areas and detailed investigation of the geological subsurface.

A common problem in seismicity analysis is that hypocentres are sometimes located far from the fault where the earthquake originated. Factors affecting the accuracy of hypocentre determination include the type and number of seismic waves recorded, the geometry of the observation station, the accuracy of the reading of the time of first arrival, and knowledge of the seismic wave velocity structure. There are many ways to determine the position of the hypocentre more precisely. One technique that can be used for relocation earthquake hypocentre is double difference method (Puspita C et al., 2015; Sabtaji & Nugraha, 2015; Diaz et al., 2018; Kusmita et al., 2020). This method uses travel time data from two earthquake events to an observation station (Waldhauser & Ellsworth, 2000; Harlianti et al., 2017; Setiadi et al., 2017; Setiadi & Rohadi, 2018).

Yulianto et al. (2017) used the double difference method to relocate hypocentres around Molucca collision zone. The results show better hypocentre location according to the RMS of time residual shifting.

Waldhauser & Ellsworth (2000) used the double difference method to relocate earthquakes in the northern Haward fault zone in California. The result is a clearer picture of seismicity and shows a horizontal hypocentre line describing a small area of the fault where stress is released. In the study by Ramdhan et al. (2020), the double difference method is used to relocated the hypocentre of Central Java and surrounding areas. The result describes the Opak fault zone with dip fault plane inclined to the east and detect shallow magma activity of Merapi.

The purpose of this study is to relocate earthquakes that occurred in Yogyakarta in 2019 using earthquake data from BMKG. Result of the relocation are expected to improve the accuracy of hypocentre location. The position of the hypocentre after the displacement can then be used to analyse the tectonic features in the Yogyakarta region.

The Double Difference Method

The double difference method is one of the earthquake relocation techniques. This method was introduced by Waldhauser & Ellsworth (2000). The double difference method is the development of the Geiger method which uses travel time between the two hypocentres. The principle of the double difference method is if there are two centre earthquakes with a smaller distance between the two hypocentres compared to the distance to the observing station, then the wave beam pattern (raypath) and waveform of the two earthquakes can be considered the same (Setiadi et al., 2017; Supendi et al., 2019; Nurbaiti et al., 2019). Figure 1, describes an illustration of the double difference method. The black and white circles are earthquake events that are closed. The thick black lines show pairs of earthquakes with cross-corrected data. Dotted line shows earthquake pairs with catalogue/ bulletin data.

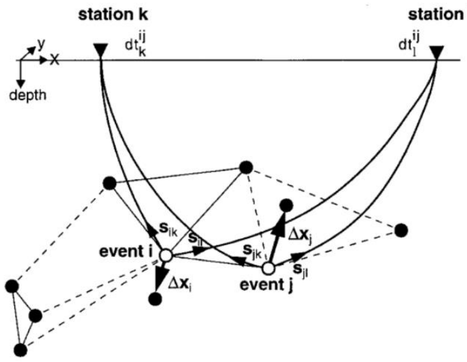

Figure 1. Illustration of the double difference method (Waldhauser & Ellsworth, 2000).

The double difference equation for relocating the earthquake hypocentre is expressed in the equation:

$$dr k_{ij} = (Tk_i - Tk_j)_{obs} - (Tk_i - Tk_j)_{cal} \qquad (1)$$

The values of i and j indicate two adjacent hypocenters, and the values of k are recording stations for two adjacent hypocenters.

Method

In this research, the earthquake hypocentre in Yogyakarta was relocated using the double-difference method. The BMKG Yogyakarta research data includes 23 earthquake events and was recorded at four observation stations. The hypocentre was relocated using the hypoDD program, which used the double-difference method to relocate the earthquake hypocentre (Waldhauser, 2001; Utama et al., 2015; Syafriani et al., 2023).

The relocation of earthquake hypocenters using the double-difference method is done in two steps. First, the data are clustered using the program ph2dt. The second step is the relocation of the hypocenter with the calculation of the paired earthquake travel time using the program hypoDD. The complete procedure of the research flow is shown in Figure 2.

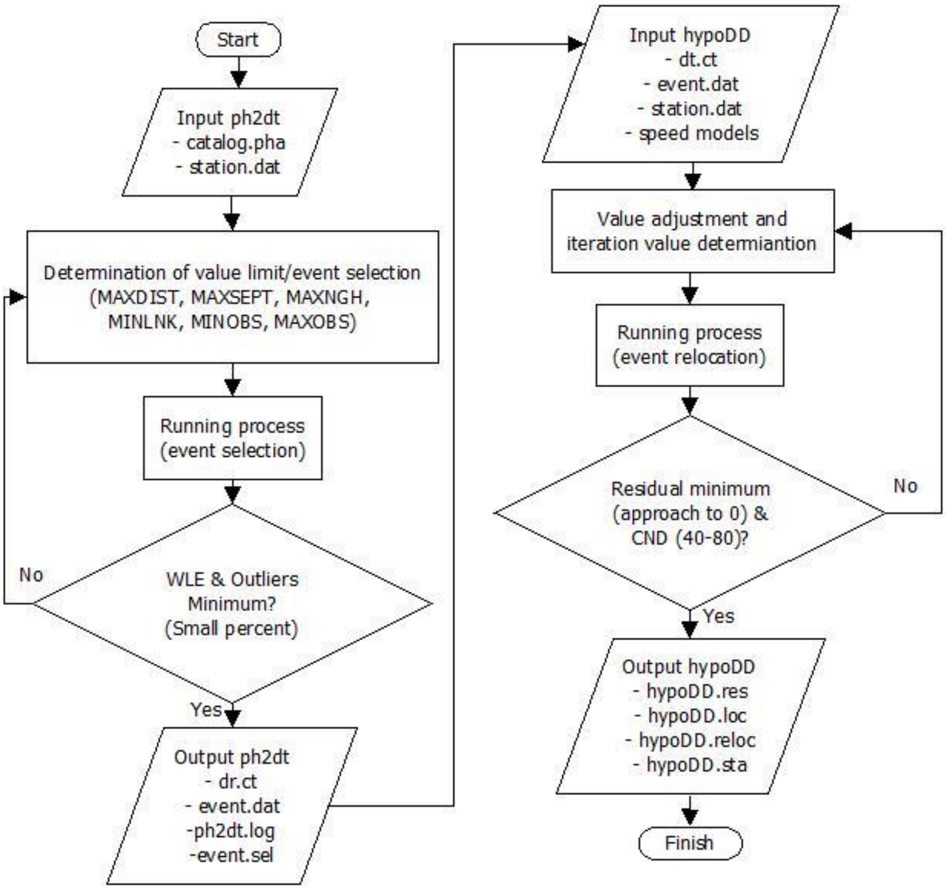

Figure 2. Research flow chart.

P wave velocity model for depths less than 20 km using Wegner wave velocity model, while for depth more than 20 km using the AK135 model. The results that need to be considered in hypoDD processing are the CND (Condition Number for the system of Double Difference equation) value and the residual value. The CND value is the ratio between the maximum and minimum values of the eigenvalues in equation used in the hypoDD program. The required CND values are between 40 and 80. The residual value is the RMS (Root Mean Square) value of the residual time generated by the hypoDD program.

Results and Discussion

The residual histogram is a graph that shows the residual time of earthquake waves. Figure 3, the residual histogram after relocation, shows that the residual values are closer to zero compared to the residual values before relocation. The result shows an improvement in quality when the distribution of the residual time values is considered. The residual time of the earthquake is the difference between the observed travel time and the calculation results. The closer the residual time is to zero, the closer the hypocenter is to the actual position. The research results map in Figure 4 shows that the location of earthquakes in the sea tends to change randomly or in all directions after resettlement. The earthquakes in the marine areas may originate from subduction in the south of Yogyakarta and active faults under the sea.

The distribution of earthquakes on the map before and after land resettlement shows in Figure 5 that there are 2 earthquake events around Mount Merapi and 13 earthquake events in the Gunungkidul area. The epicentre of the earthquake around Mount Merapi is located about 10 km south of the peak of Merapi. After the displacement, the epicentre has moved closer to the summit of Mount Merapi. The earthquakes around Mount Merapi are earthquakes caused by volcanic tectonics (VT), i.e., earthquakes related to magma activity (Ramdhan et al., 2020). Data from Geological Agency of the Ministry of Energy and Mineral Resources show that the time of earthquake was close to the increase in volcanic activity Mount Merapi in October-November 2019.

Earthquakes in land areas mostly near minor faults in the Wonosari Formation. The Wonosari Formation has a layer thickness of 800 meters (Qodri & Sopamena, 2022). The earthquake hypocentre int the land are of the research results is at a depth of 3-18 km. This indicates that the earthquake is not sourced by faults in the Wonosari Formation, but may be caused by another, older formation beneath Wonosari Formation.

Figure 5 shows the geological composition of the study area. here are several formations under the Wonosari Formation, which are the Sambipitu Formation, the Nglanggran Formation, the Semilir Formation, the Oyo Formation, the Kobobutak Formation, and the Wungkal Formation. Thus, earthquakes from the land research area under the Wonosari Formation can be suspected under the Wungkal Formation (Limestone Wungkal) (Wibowo and Sembri, 2017), because the formation has the oldest age and is located at a depth of more than 1 km (Surono, 2009).

Figure 6 & 8 shows the distribution of earthquakes before and after relocation in earthquakes that occur in land areas with cross sections A-A’. Before the relocation there were many earthquake events with a depth of 10 km (fix depth) obtained from earthquake catalogue data. On the line A-A’ at a depth of less than 20 km, there is a change in the hypocentre after relocation, some are shifted and shallower, others deeper. The changes in the distribution of location and depth earthquakes after relocation tend to be more evenly distributed and dominated by shallow earthquakes less than 20 km. Earthquakes less than 20 km deep are consistent with studies showing that the maximum depth of earth’s crust in the study area has a maximum depth of 30 km (Ramdhan et al., 2020). Earthquakes in land areas with shallow depths and small magnitudes are possible due to local fault activity in the study area.

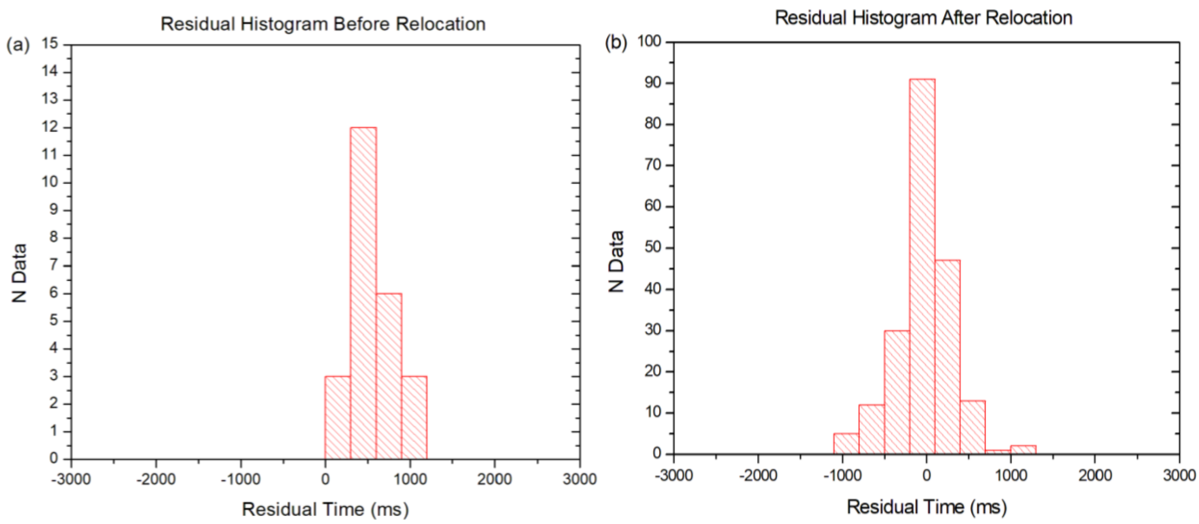

Figure 3. (a) - (b) Residual histogram before and after relocation, respectively.

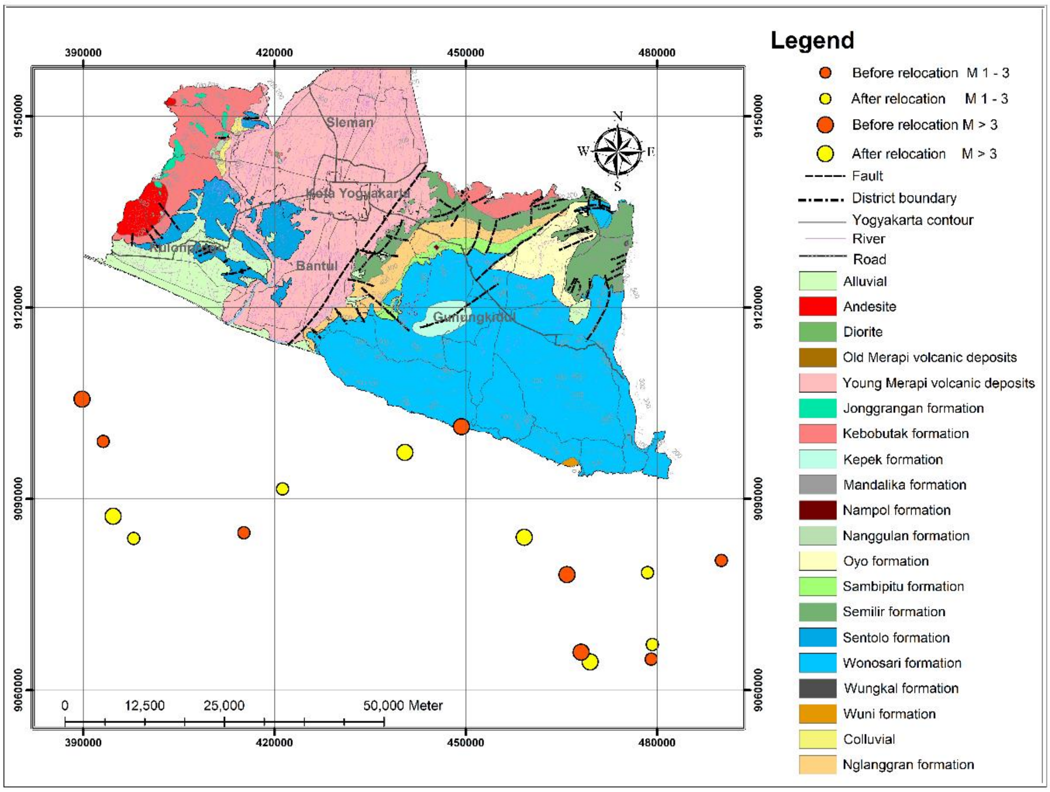

Figure 4. Distribution of sea area epicentres before and after relocation (modification from Wartono et al., 1977).

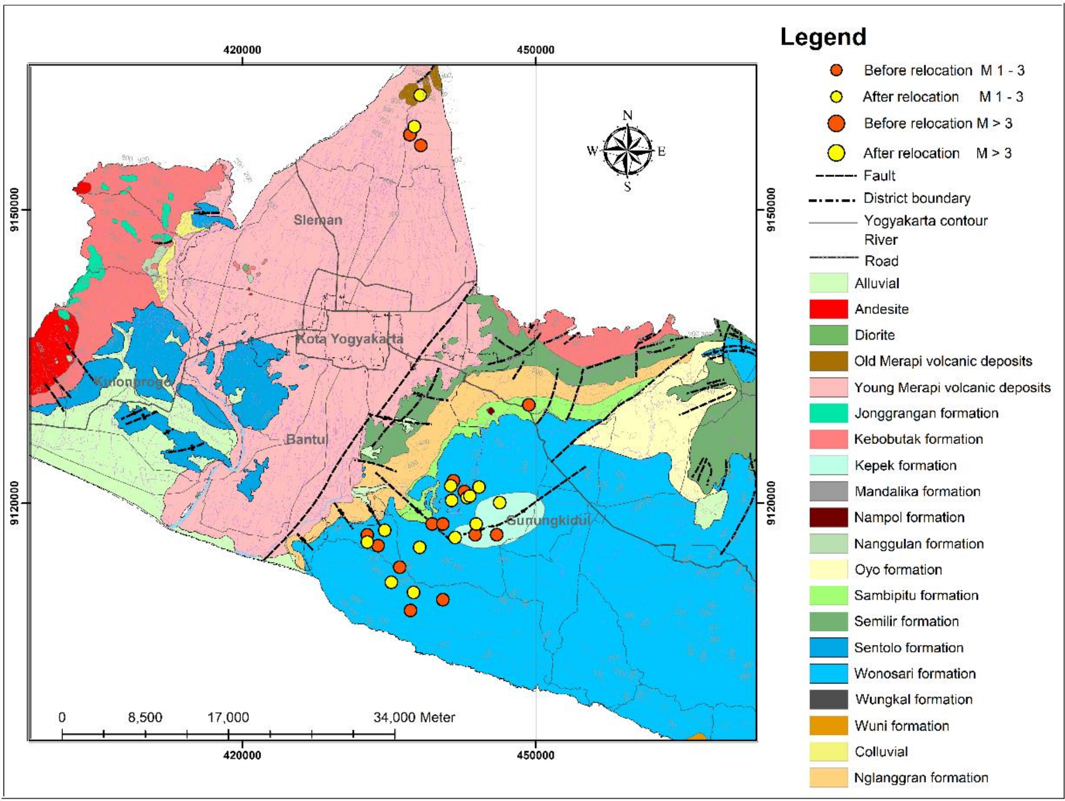

Figure 5. Distribution of land area epicenters before and after relocation (modification from Wartono et al., 1977).

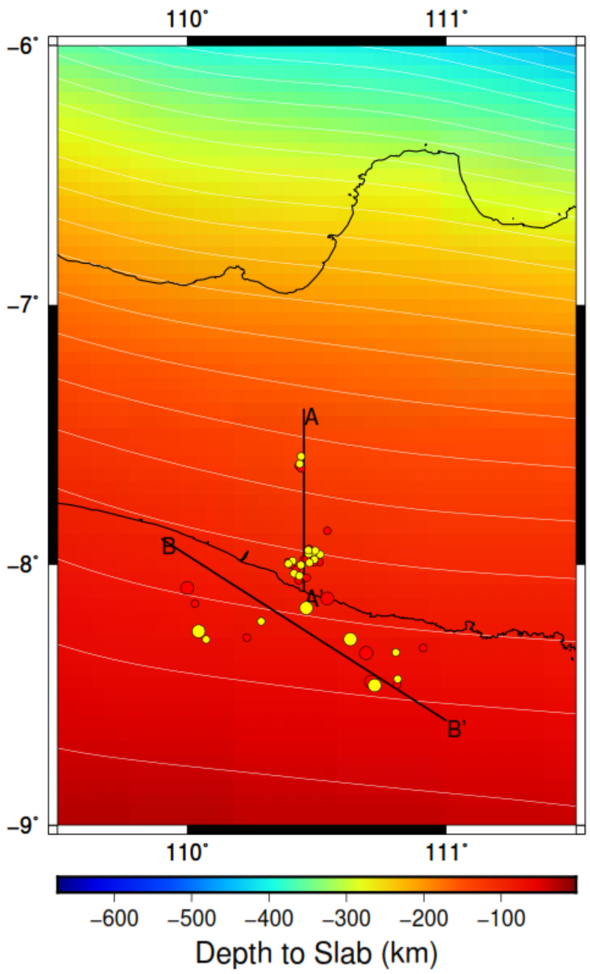

Figure 6. Distribution of earthquake hypocentres before and after relocation, line A-A' on land and line B-B' on sea.

Figure 7 & 8 shows the distribution of earthquakes before and after relocation for earthquakes that occur in marine areas with cross section B-B'. On the B-B' line with a depth 60 to 125 km indicates an earthquake that has shifted in the direction of subduction (red line). On the B-B' line with a depth of less than 20 km, 2 shallow earthquake events in the ocean with small shifts are shown. Shallow earthquakes in the marine area are expected because active faults are present under the sea.

Figure 9 is a compass diagram of earthquake relocation showing the direction and distance of earthquake displacement. The diagram shows that the earthquake shifted in all directions with a distance less than 20 km. Figure 9 shows that the most distant earthquake shifted 19.0644 km from 0^o to the southeast, where 0^o is the north direction according to the compass. Figure 10 is a rose diagram of earthquakes relocation results, showing the number of earthquakes and the shift angle. From the diagram, earthquake displacement after relocation has shifted in all direction with the smallest azimuth of 4,729^o to the largest azimuth of 359,4892^o. However, there are some earthquakes that tend to a particular direction, and that is toward the northeast and northwest. The result of the shift can be influenced by the location of the stations around the study area.

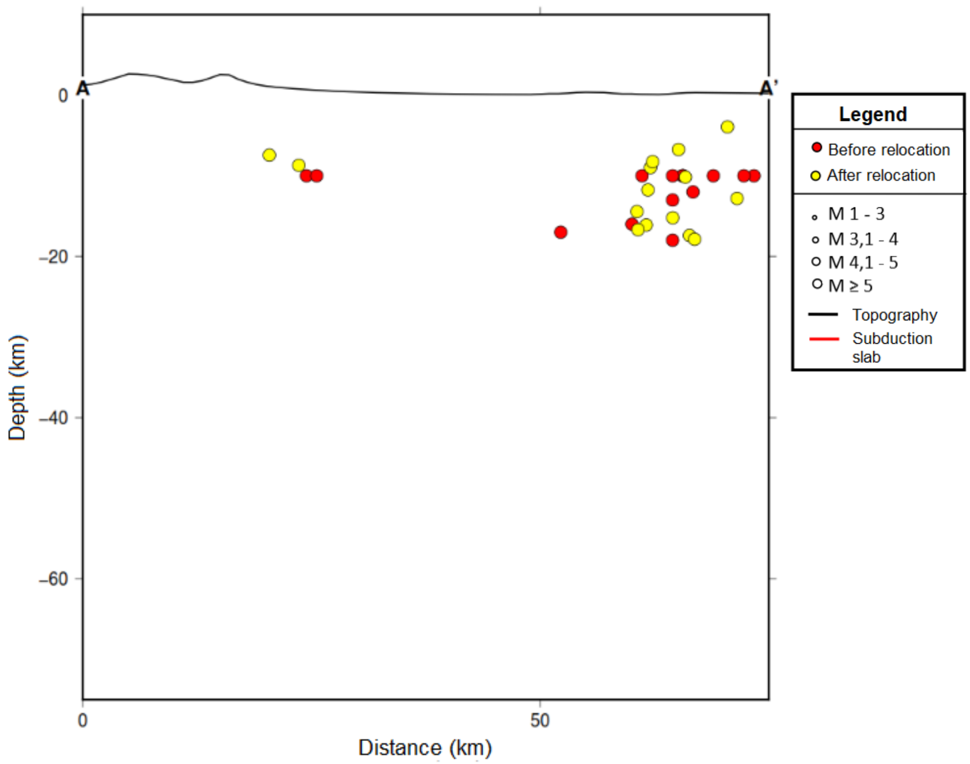

Figure 7. Distribution of hypocentre depths in the land area (line A-A' is virtually the same as line A-A' in figure 5).

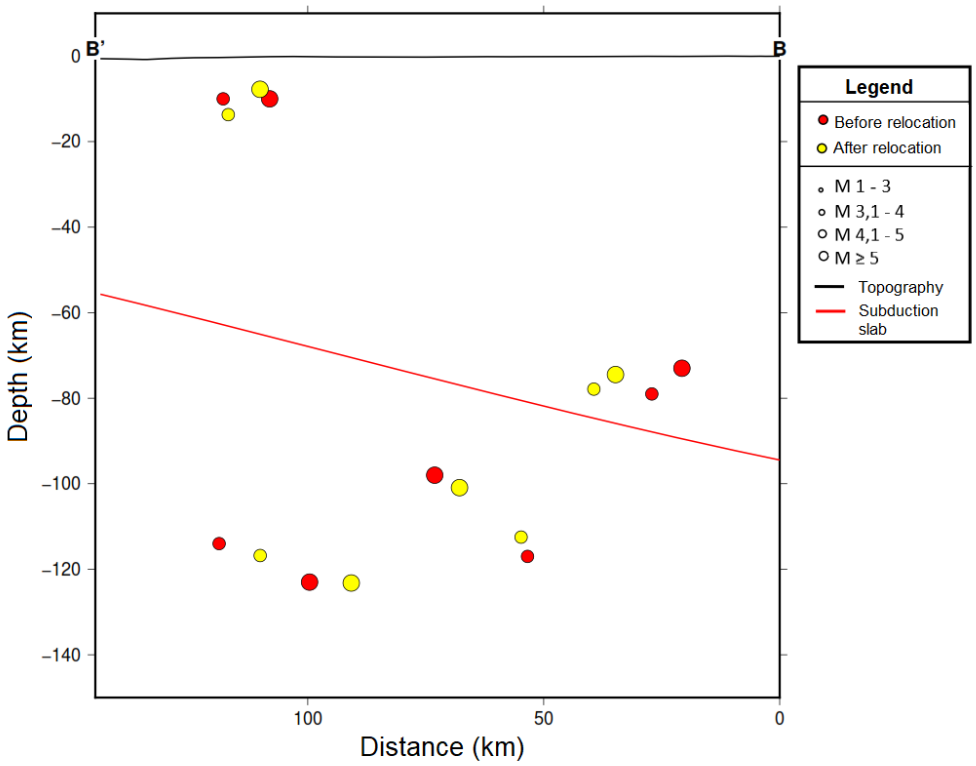

Figure 8. Distribution of hypocentre depths in the sea area (line B-B' is virtually the same as line B-B' in figure 5).

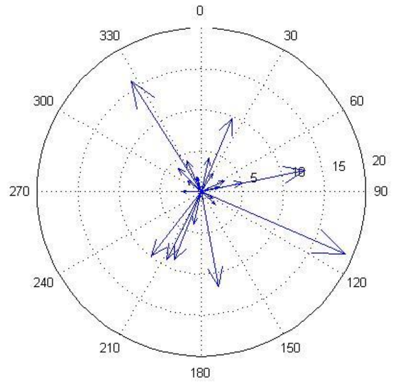

Figure 9. Compass diagram show the distance and direction hypocentre shift after relocation.

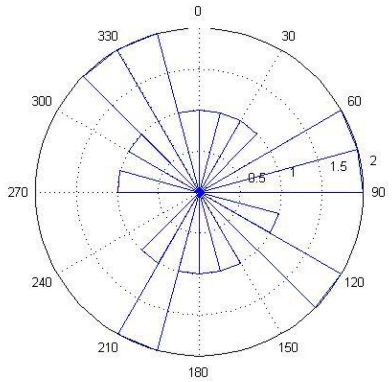

Figure 10. Rose diagram show the number and angle hypocentre shift after relocation.

Conclusion

The hypocentre relocation results can relocate the entire earthquake data by generating a residual value close to zero, which indicates position of hypocentre after relocation close to the actual position. Based on the relocation result, the source of earthquake can be analysed, i.e., the earthquakes on land caused by faults and the earthquakes in the ocean caused by subduction. The relocation results show that the source of the land earthquake in the Wonosari area is under the Wungkal Formation, while the land earthquake in the Merapi area was probably caused by a tectonic volcanic earthquake. The hypocentre of the earthquake has shifted after relocation in all directions and less than 20 km, dominated by the direction to the northeast and northwest.

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Author Contribution

Fani Rohmiasih: Conceptualization, Investigation, Visualization, Writing-original draft, Formal analysis. Andi: Investigation, Visualization, Writing-review & editing, Formal analysis, Validation. Nugroho Budi Wibowo: Investigation, Formal analysis, Writing-review & editing, Validation.

Conflict of Interest

The authors declare no conflict of interest.

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