JPPIPA 9(10) (2023)

Jurnal Penelitian Pendidikan IPA

Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

Analyzing Seismicity Pattern of the Gorontalo Region and Its Surroundings in the Form of Hypocenter Relocation Using Double Difference Method

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Received: August 24, 2023
Revised: September 19, 2023
Accepted: October 25, 2023
Published: October 31, 2023

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DOI: 10.29303/jppipa.v9i10.5400

Abstract: The level of seismic activity due to earthquake events in Gorontalo is strongly influenced by the tectonic system model of the Gorontalo region and the presence of a subduction zone in the Sulawesi Sea. These characteristics make the Gorontalo region have high seismic activity. To describe the pattern of seismicity in the Gorontalo region, it is necessary to conduct an analysis in the form of earthquake hypocenter relocation using the double difference (hypoDD) method. This method uses residual travel time data from each pair of hypocenters to the recording station. This study aims to analyze the results of hypocenter relocation and describe the subsurface model related to the seismicity pattern of Gorontalo and its surroundings. The data used are P and S waves for 7 years recorded at the Meteorology, Climatology and Geophysics Agency (BMKG) station. The earthquake hypocenters relocated in this study were 3,940 out of 4,598 earthquake events. The results of hypocenter relocation show a fairly good seismicity pattern obtained from good RMS values and distribution patterns following Gorontalo tectonic patterns. In general, the seismicity pattern of Gorontalo and its surroundings is strongly influenced by activity in the Sulawesi Sea subduction zone and the Gorontalo fault in the region. The seismicity caused by the subduction zone has a depth of 50 - 200 km, and due to the active faults in the Gorontalo region has a depth of 2 - 25 km.

Keywords: Double difference; Relocation hypocenter; Seismicity; Subduction zone

Introduction

Sulawesi Island has complex geological and tectonic conditions, indicated by its shape resembling the letter K. Three active plates are in contact with each other, causing the complexity of this region. The Australian Continental Plate is moving northward, the Pacific Continental Plate is moving westward, and the Eurasian Continental Plate is relatively south-southeastward (Audley-Charles et al., 1972; Silver, McCaffrey et al., 1983).

This condition directly causes the Sulawesi Island tectonic area to experience active plate movements in Gorontalo. The fault area also affects seismicity, such as the Palu-Koro fault affects the South-West Arm of Sulawesi and the Gorontalo fault affects the North Arm of Sulawesi (Hall, 2012; Hamim et al., 2023; Socquet et al., 2006; Tjia, 1978). In addition to several faults, there are subduction models, such as the Sulawesi Sea subduction north of the study area. This is shown by the Sulawesi Island tectonic system model in Figure 1.

How to Cite:
Meidji, I. U., Jatnika, J., Samatowa, L., Ramadani, A. I. W. S., Ramdhan, M., Efendi, H. A., & Jayadi, H. (2023). Analyzing Seismicity Pattern of the Gorontalo Region and Its Surroundings in the Form of Hypocenter Relocation Using Double Difference Method. *Jurnal Penelitian Pendidikan IPA*, *9*(10), 8581–8587. https://doi.org/10.29303/jppipa.v9i10.5400

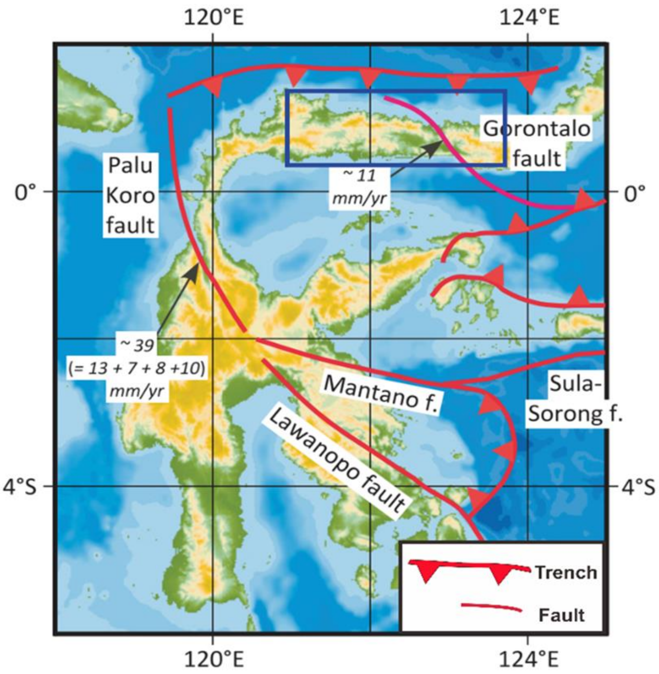

Figure 1. Tectonic setting model of Sulawesi island; the blue rectangular box is Gorontalo and the surrounding area (Molnar & Dayem, 2010)

Several areas must be watched out for, such as the intersection or intersection of one fault with another, so it is possible as a very potential location that is continuous to cause earthquake disasters (Efendi, Marliyani, & Pramumijoyo, 2021).

According to historical data collected by the Meteorology, Climatology, and Geophysics Agency (BMKG), in the Gorontalo area and its surroundings, there have been several large and destructive earthquakes with magnitudes ≥ 7, which occurred in 1990, 1991, 1997, and 2008, most of which occurred in the subduction area of the Sulawesi sea north of the Gorontalo region (Earthquake Catalog Sub-Committee, 2021). In 1939 and 1941, earthquakes also caused much damage, but the hypocenter location has not yet been obtained.

In this study area, the Gorontalo Fault, Palu Koro Fault, and Sulawesi Plate Subduction are fault segmentations that have great potential to cause earthquakes and natural disasters. Therefore, to increase the level of awareness of geological disasters in the form of earthquakes, it is necessary to conduct further research on seismicity patterns (seismicity conditions) that occur in Gorontalo and its surroundings by analyzing the results of a more detailed hypocenter relocation. The seismicity value is measured by reviewing the condition of the level of seismic activity between regions, which is also one of the most important parameters to measure a region's seismicity level.

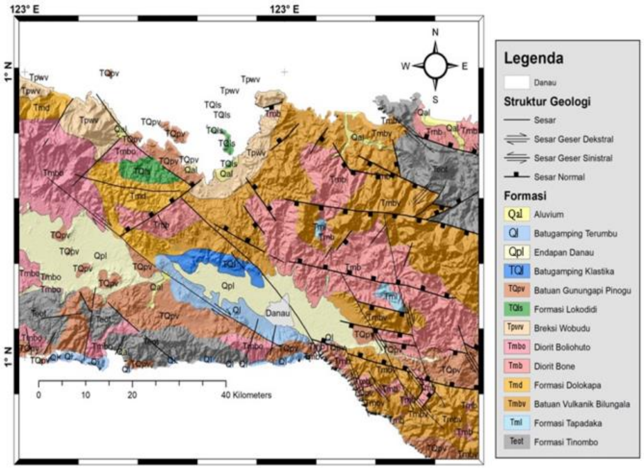

Figure 2. The geological map of the research area with DEMNAS topography is contained in the 1:250,000 Geological Map Sheet of Kotamobagu and Tilamuta (Apandi & Bachri, 1997; S Bachri et al., 1993)

Hypocenter relocation is very important in order to get the seismicity condition of an area accurately so that it can be better in analyzing its tectonic order, as has been done by (Efendi et al., 2021; Gusman et al., 2017; Jayadi et al., 2023; Syafriani et al., 2023). The purpose of this study is to analyze the level of seismicity of the Gorontalo region and its surroundings based on data from the relocation of earthquake hypocenters so that it can be used to understand better and provide more accurate information in reconstructing seismic activity and tectonic order conditions that are closely related to regional geological conditions to mitigate geological natural disasters, especially earthquakes and for development planning in the Gorontalo region and its surroundings.

Geological Setting

Eocene-Pliocene volcanic rocks and breakthrough rocks form the volcano-plutonic strata of North Sulawesi, which includes the Gorontalo region. In addition, several sedimentary rock units often contain volcanic material and are interspersed with volcanic rocks. Naming rock units into volcanic or sedimentary rock units emphasizes the dominance between the two types of rocks (Syaiful Bachri, 2006). The Tinombo Formation, one of the formations in which there is the oldest rock unit in the region, still raises stratigraphic issues, especially concerning younger volcanic rock units.

The North Sulawesi Arm is connected to the South Sulawesi Arm, and both are incorporated in one geological mandala called the West Sulawesi Mendala (Sukamto, 1978), a volcano-plutonic lane. The North Sulawesi arc is also called an enzymatic volcanic arc. The neck of Sulawesi to the southern arm is called the sialic volcanic arc (Carlile et al., 1990).

The northern part of the Sulawesi Arc underwent a clockwise rotation as a result of a collision between the Sulawesi Arc and the Banggai-Sula continental section, which was also followed by subduction in the Sulawesi Sea (Carlile et al., 1990; Kavalieris et al., 1992). The northern arm of Sulawesi is the part that changed from its original north-south to west-east position. Quaternary volcanic rocks in the eastern part of the North Sulawesi Arc are thought to be the result of volcanic activity associated with the eastward Sangihe Thrust. In contrast, the Sulawesi Sea Rise, also known as the North Sulawesi Rise, is considered to be the result of volcanic activity that produced Neogene volcanic rocks (Kavalieris et al., 1992; Simandjuntak, 1986).

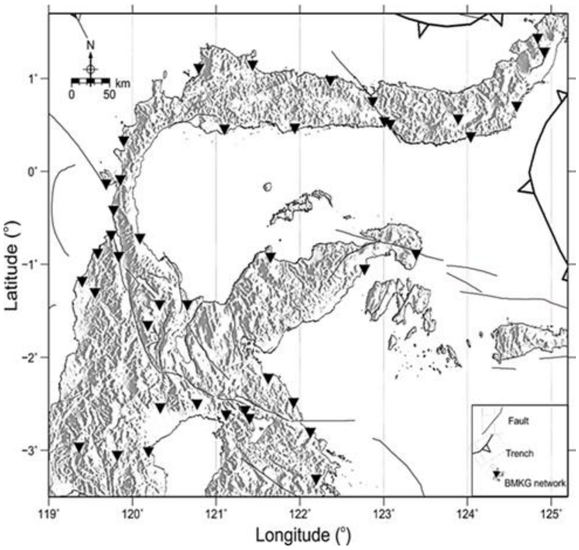

Figure 3. Distribution of BMKG recording stations located in Gorontalo and its surroundings

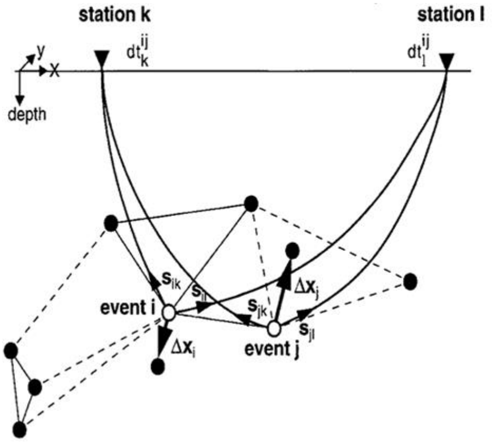

Figure 4. Illustration of the double difference method. Black and white dots represent hypocenters connected by cross correlation (solid line) or catalog data (dashed line). For two events, i and j relocated together concerning stations k and l, and their positions move to the black dots indicated by the vectors Δxi and Δxj (Waldhauser & Ellsworth, 2000)

The Gorontalo area is part of the North Sulawesi Arc, formed by volcano plutonic eruptions. Plutonic and volcanic rocks from the Paleogene to Neogene dominate this region. In addition, there are sedimentary rock units found, which are usually influenced by volcanic activity. With a deep sea-to-land environment, the formation of volcanic and sedimentary rocks in the study area is relatively continuous from the Eocene to the Early Miocene to Quaternary, or a regressive sequence. Sedimentary rock intervals are usually found in volcanic rocks, and volcanic rock intervals are usually found in sedimentary rock units. This shows a clear superposition relationship between the two types of rock units.

While the younger volcanic rocks of the Tinombo Formation are island arc rocks, the older volcanic facies are considered ophiolite rocks. The two have an incompatible relationship (Bachri, 2006).

Caused by seismic activity and ground acceleration, Gorontalo has very active tectonics. Gorontalo has a geology consisting of folds and faults. Some of the active faults in Gorontalo are normal and shear faults (Apandi & Bachri, 1997; Bachri et al., 1993), as shown in Figure 2. Gorontalo is very vulnerable to earthquakes and tsunamis due to its complex tectonics. The presence of subduction and active faults affects earthquakes. Land movement causes earthquakes, both shallow and deep.

According to Soehaimi (2008), research on regional and local active geological structures should emphasize the relationship between geological conditions and the seismicity of a region. The geological conditions of a region consist of rocks, geological structures, and tectonics, while the region's seismicity consists of epicenter, depth, strength, and intensity.

The Gorontalo fault is an active fault that cuts Gorontalo city in a northwest-to-southeast direction (Katili, 1970), which intersects with a minor fault in a northeast-southwest direction to form a segment, namely north and south. In addition, there is also a right-direction fault adjacent to the main fault in the Gorontalo area.

Method

This study uses catalog data sourced from the Meteorology, Climatology and Geophysics Agency (BMKG) with a period of January 1, 2015-December 31, 2022, magnitude 1.0 to 6.5 Mw with a distribution of 4,598 events spread across Gorontalo and surrounding areas. This earthquake was recorded by 41 stations (Figure 3) with the determination of the initial hypocenter distribution using the Geiger method (Geiger, 1912).

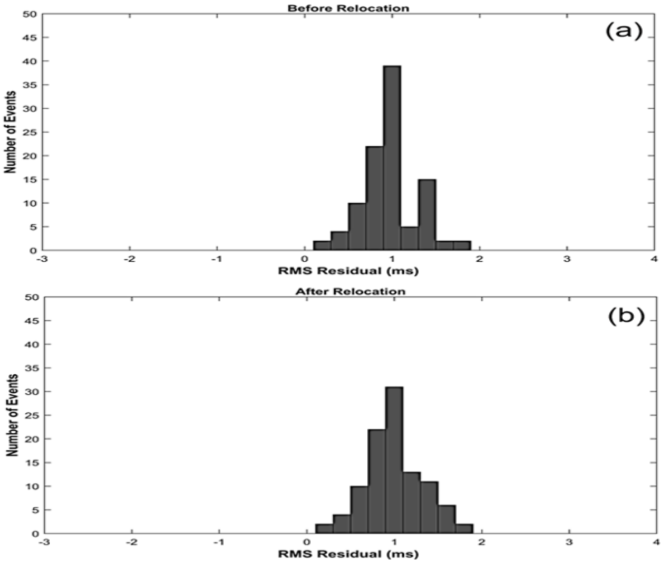

Figure 5. Histogram of root mean square (RMS) residual values: (a) BMKG earthquake catalog data that has not been relocated, and (b) BMKG earthquake catalog data that has been relocated using the Double Difference method

Using the principle of least square approximation, this method requires arrival time data, velocity model, and station location in cartesian coordinates (Nugraha et al., 2017). IASP91 is the initial velocity model used in this procedure (Kennett & Engdahl, 1991). We also used the two-difference method used by the HypoDD program to perform the hypocenter relocation process (Waldhauser, 2001). During this relocation process, we use at least six arrival phases for both P and S waves, possibly only P waves (Waldhauser, 2009).

The double difference (DD) method assumes that the ray paths and waveforms of two earthquakes can be considered the same if the two epicenters are paired at a distance smaller than the distance between the two epicenters to the recording station. Therefore, the travel time between two earthquakes recorded at the same station is a function of the distance between the two epicenters (Figure 4). Thus, this method can avoid velocity model errors without analyzing the station correction (Waldhauser & Ellsworth, 2000).

We used 8 iterations in this process to avoid wasting data not included in the cluster. Therefore, we used Least-squared inversion to dampen the different data in each iteration (Waldhauser, 2001). Unlike the initial data, we changed the input parameters of the 1-D velocity model for each depth and changed Vp (P-wave velocity) to AK135 (Kennett et al., 1995).

Result and Discussion

In this hypocenter relocation process, we only relocate data around the Gorontalo region. Therefore, using the double difference method, we have relocated earthquake events in the Gorontalo region and its surroundings during the 2015 to 2022 timeframe, as many as 3,940 events out of 4,598 earthquake events. The earthquake events that were not successfully relocated were because the data needed to match the criteria and were scattered, so they did not have other pairs of events in making a cluster. However, the results of this relocation are good, as evidenced by the root mean square (RMS) residual time values that are increasingly heading towards zero and forming a normal distribution curve (Figure 5).

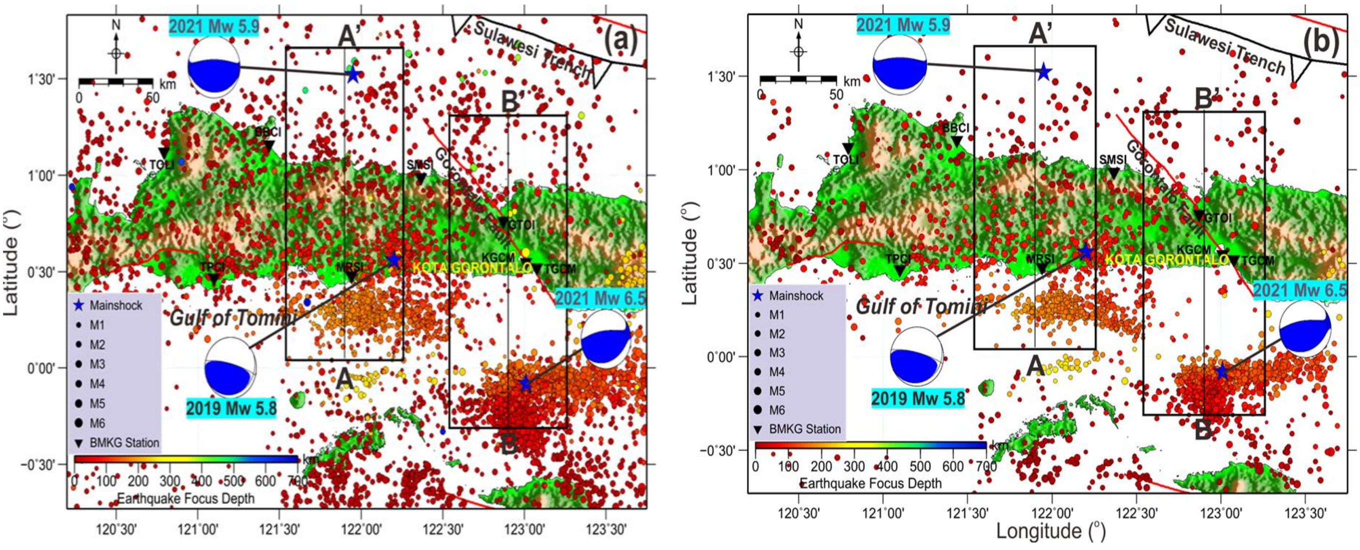

Figure 6. Distribution of earthquake events in the study area with some of the BMKG recording station networks used in this study, (a) Distribution of earthquake epicenters from the BMKG catalog that have not been hypocenter relocated, and (b) Distribution of earthquake epicenters that have been hypocenter relocated. The black boxes A-A' and B-B' are south-north oriented cross-sections with a distance of 200 km each.

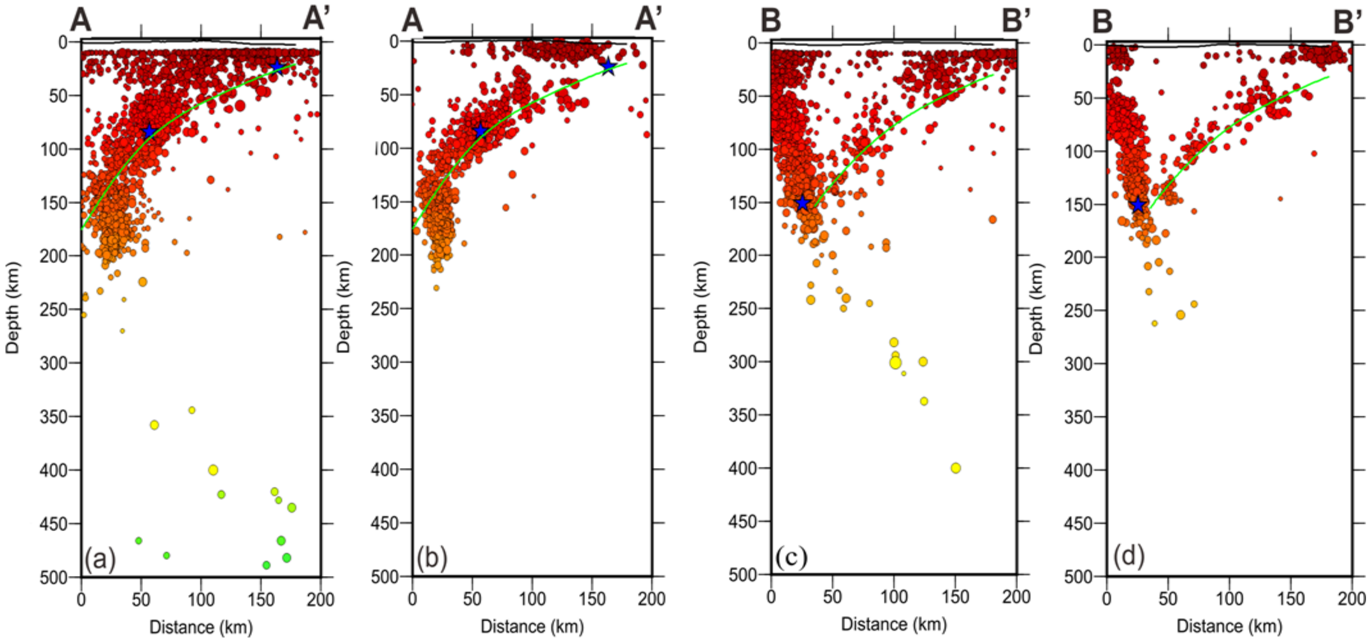

Figure 7. Cross-section results of the distribution of earthquake activity in the study area: (a) cross-section for data before relocation, (b) cross-section for earthquake distribution after relocation, (c) cross-section for earthquake distribution before relocation, and (d) cross-section for earthquake distribution after relocation. The curved yellow line is the geometry model of the subduction slab in the study area (Hayes et al., 2018)

The distribution of earthquake events in Gorontalo is quite varied. Several clusters are formed in three zones, namely to the south, southwest, and north-northwest of the Gorontalo Fault. This is evidenced by the three large earthquakes in 2019 and 2021, magnitudes of 5.8 Mw to 6.5 Mw (Figure 6). The clathrate model is still clearly visible from the distribution of the relocated hypocenters, so the local velocity model of Vp waves used in the relocation is quite good.

Seismic activity occurring in the southern part of the Gorontalo Fault is interpreted as a result of the seismicity pattern of the north-south trending subducting slab originating from Banggai Sula. This is thought to result from a deflection from slab movement in the Sangihe Arc (Weston et al., 2018). The activity in the north-northwest of the Gorontalo Fault is caused by the subduction activity of the Sulawesi Sea Trough, resulting from the movement of the Eurasian plate subducting the Indo-Australian plate (Hamilton, 1979; Katili, 1971). Meanwhile, the activity in the southwest of the Gorontalo Fault is interpreted as a result of the Kwandang Fault, which is part of the Gorontalo Fault segment (Katili, 1970).

To find out the characteristic shape of the subsurface model in the study area, we analyzed the cross-section in the south-north direction for both A-A' and B-B'. Seismic activity that occurs in the subsurface of the Gorontalo region is mostly caused by the presence of subduction zones and tectonic systems in the form of faults in the Gorontalo region (Figure 7).

The relocation results we obtained show a significant improvement in analyzing the distribution of earthquake events in the study area. This can be seen from the fact that many earthquakes that originally had a fixed depth of 10 km (Figures 7a and 7c) have improved in-depth, as well as the earthquake's location (Figures 7b and 7d). Therefore, the relocation results show more clearly the model of the geological structure formed under the surface of the Gorontalo region.

As shown in Figure 7, the cross-section before relocation has a scattered hypocenter distribution up to 500 km depth, and there is no consistency with the subduction slab geometry model. However, after relocating the hypocenters, there is good consistency with the slab geometry model, and two clusters appear to the south of the Gorontalo Fault.

The slab geometry model in the Gorontalo area shows a subduction zone that subducts to the south of the Gorontalo region west of the Gorontalo Fault and below the Gorontalo Fault. This subduction has a depth of up to 200 km. This is probably a result of the activity of the northern arm of Sulawesi in the form of the Sea Trough combined with the activity of the Gorontalo Fault.

Conclusion

The process of relocating the hypocenter using the difference method can show clarity in showing the structural model under the surface of the research area. This can be seen from the consistency between the distribution of earthquake events and the slab geometry model in the Gorontalo region. In addition, this method can also improve the epicenter and hypocenter's position, which is characterized by a histogram of root mean square (RMS) much closer to zero. The subsurface structure model of the research area shows the seismic activity of earthquake events to the south of Gorontalo, where this activity is made possible by the subduction zone of the Sulawesi Trough to the north. This is evidenced by the subduction slab to a depth of 200 km from the cross-section results in the northwest-southeast direction.

Acknowledgments
The authors thank the Meteorology, Climatology, and Geophysics Agency (BMKG) for permission to use earthquake catalog data for Gorontalo and surrounding areas.

Author Contributions
Conceptualization and methodology, Icha Untari Meidji (M.S), and Harsano Jayadi (H.J); formal analysis, Lukman Samatowa (L.S), A Indra Wulan Sari Ramadani (A.I.W.S.R), and H.J; investigation, I.U.M, H.J, Jajat Jatnika (J.J), Hasan Arif Efendi (H.A.E) and Mohamad Ramdhan (M.R); writing— original draft preparation, I.U.M, L.S, A.I.W.S.R, and H.J.; writing—review and editing, I.U.M, H.J, J.J, H.A.E, and M.R.; Visualization. H.J and M.R. All authors have agreed to the published version of the manuscript.

Funding
This research was supported by Universitas Negeri Gorontalo, with SK number: 495/UN47/HK.02/2023

Conflicts of Interest
The authors declare no conflict of interest.

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