

Seismic Hazard Assessment in Gorontalo: Subduction Zone and Earthquake Analysis

Icha Untari Meidji^{1*}, Dewa Gede Eka Setiawan¹, Irsan¹, Kartika², Harsano Jayadi²

¹ Physics Study Program, Faculty of Mathematics and Natural Sciences, Universitas Negeri Gorontalo, Gorontalo, Indonesia.

² Geophysical Engineering Study Program, Faculty of Mathematics and Natural Sciences, Universitas Tadulako, Palu, Indonesia.

Received: July 29, 2025

Revised: September 25, 2025

Accepted: October 25, 2025

Published: October 31, 2025

Corresponding Author:

Icha Untari Meidji

ichauntarimeidji10@gmail.com

DOI: [10.29303/jppipa.v11i10.12956](https://doi.org/10.29303/jppipa.v11i10.12956)

© 2025 The Authors. This open access article is distributed under a (CC-BY License)



Abstract: The Gorontalo region is one of the regions on the island of Sulawesi that is quite significant in terms of tectonic activity due to earthquakes. This is because Gorontalo is located in a tectonic environment, with a subduction zone in the Sulawesi Trench north and the Balantak Thrust and Batui Thrust south of the Gorontalo Fault. To further understand Gorontalo's seismic activity, we conducted a seismotectonic analysis in the form of identifying the number of earthquakes from 1994 to 2025, interpreting the results of the focal mechanism distribution by classifying them in the Kaverina diagram, and analyzing the results of earthquake hypocentre relocation from 2015 to 2022. The study results show that 2.317 earthquake events over 30 years spread across all areas of Gorontalo, categorised as shallow, medium, and deep earthquakes. The Gorontalo area is dominated by reverse faulting focus mechanisms, which are commonly found at shallow to intermediate depths. This is interpreted as being due to the presence of a subduction zone. A different situation occurs at deep depths, where the focal mechanism is normal faulting, indicating the presence of extensional forces due to the rollback slab process. The distribution of earthquake mechanisms also shows that a combination of strike-slip and reverse mechanisms occurs around active fault zones. In contrast, strike-slip mechanisms with standard mechanisms are more dominant in extensional zones.

Keywords: Earthquake; Focal mechanism; Gorontalo; Relocation; Subduction zone

Introduction

Indonesia is prone to earthquakes because it is located in the Pacific Ring of Fire zone (Robert Hall, 2012). Sulawesi is one of the regions in Indonesia that is vulnerable to earthquakes (Bellier et al., 1998). The island has complex geological and tectonic conditions, as seen from its K-shaped form (DeMets et al., 2010; Hamilton, 1979). This complexity arises from the interaction between three major plates: the Indo-Australian Plate moving north, the Pacific Plate moving west, and the Eurasian Plate moving south-southeast, as well as the influence of the Philippine Plate (O. Bellier et al., 1998; Robert Hall, 1996; Tjia, 1978). In the Figure 1,

these conditions make the Sulawesi Island region a tectonically active area with a high level of seismicity, so the Gorontalo region directly experiences active plate movement (Audley-Charles et al., 1972; Jayadi et al., 2025; Katili, 1971; Meidji et al., 2023). The tectonics of Sulawesi are dominated by several significant sinistral strike-slip faults, one of which is the Gorontalo Fault (Olivier Bellier et al., 2001, 2006).

Geologically, Gorontalo is located near the complex North Sulawesi subduction zone, where the Eurasian Plate collides with the Pacific Plate and the Australian Plate (Permana et al., 2025; Serhalawan & Chen, 2024). The interaction between these plates generates tectonic forces that trigger earthquakes of varying magnitudes

How to Cite:

Meidji, I. U., Setiawan, D. G. E., Irsan, Kartika, & Jayadi, H. (2025). Seismic Hazard Assessment in Gorontalo: Subduction Zone and Earthquake Analysis. *Jurnal Penelitian Pendidikan IPA*, 11(10), 893-901. <https://doi.org/10.29303/jppipa.v11i10.12956>

and depths. In addition, active faults, such as the Gorontalo Fault, contribute to the seismic hazard potential in this region (Massinai et al., 2019; Nahli & Oryzavica, 2017).

early warning systems for communities residing in earthquake-prone areas easier (Iervolino et al., 2007). Given Gorontalo's potential for rapid infrastructure expansion, seismic hazard assessment is becoming increasingly important (Ahmed & Perrone, 2019; Silalahi et al., 2023). Roads, bridges, and tall buildings are examples of rapid infrastructure development that necessitate cautious planning in the face of potential earthquakes. Therefore, the purpose of this study is to use current geological data and historical earthquake data to identify and assess Gorontalo's possible seismic dangers. It also intends to create a seismic map that the community and policymakers can use as a guide for addressing earthquake concerns. With an emphasis on examining the distribution of earthquakes in the subduction zone, including trends based on magnitude, depth, and time of occurrence, this study attempts to evaluate the seismic dangers in Gorontalo. In order to give a better picture of earthquake risk and support development planning and catastrophe risk reduction (McGuire, 1995; Souisa et al., 2023; Wells & Coppersmith, 1994).

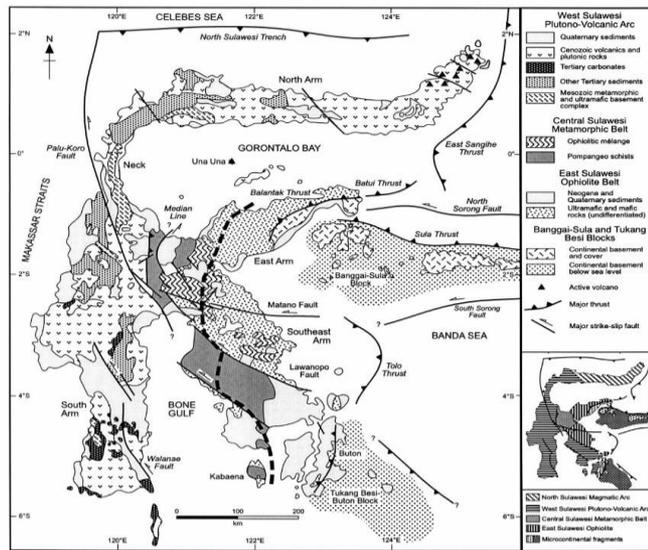


Figure 1. The geological map of Sulawesi delineates the tectonic framework and identifies several faults, trenches, and subduction zones. The thick black line indicates the approximate location of the early Miocene, which has experienced displacement and alteration during the late Miocene (R. Hall & Wilson, 2000)

Seismicity in Gorontalo shows a varied distribution pattern of earthquakes, with depths ranging from 50 to 200 km due to subduction activity and shallow earthquakes associated with active faults on land (Efendi et al., 2021; Meidji et al., 2023; Permana et al., 2025). This indicates that two main sources of seismic activity need to be analysed separately to obtain a more accurate picture of the potential earthquake hazard in this region (Chacón-Hernández, 2024; Hong et al., 2009). Analysis of earthquake distribution in Gorontalo also reveals a concentration of seismic activity along the Gorontalo Fault, indicating that this fault is still active and has the potential to cause major earthquakes in the future (Efendi et al., 2021; Meidji et al., 2023; Permana et al., 2025). Understanding the characteristics of this fault is crucial in efforts to mitigate risk and plan earthquake-resistant development in the region.

On the other hand, medium and small earthquakes occur frequently in Gorontalo, even though huge earthquakes do not always occur there. Therefore, a thorough examination of the likelihood of future earthquakes and a better understanding of the distribution of earthquakes and seismic features in this area are critically needed (Shohaya et al., 2013). A more thorough understanding of seismic distribution will make designing disaster mitigation plans and enhancing

This research is crucial as it offers an enhanced comprehension of the seismic hazards that jeopardize Gorontalo, which may have been neglected in regional development planning. The findings of this research are anticipated to assist local governments, infrastructure planners, and the community in identifying possible earthquake hazards and formulating more effective mitigation strategies. This research is anticipated to enhance understanding in geophysics, specifically the evaluation of seismic hazards in Indonesia. It employs historical data and spatial analysis to yield novel insights into the analysis and prediction of earthquakes in regions with distinctive geological conditions, such as Gorontalo.

Due to its significant seismic potential, the Gorontalo region must possess a comprehensive grasp of the hazards associated with earthquakes and the potential risks involved. This project aims to enhance public knowledge of earthquake risks and aid local governments in formulating improved policies to address the threat of natural disasters. The findings of this research will assist not only the inhabitants of Gorontalo but also other areas situated within Indonesia's subduction zone.

This research will significantly enhance disaster management in Indonesia by detecting earthquake distribution patterns and quantifying the probability of future seismic events. Thus, it will support the attainment of sustainable and secure development objectives. This discovery is a crucial advancement in alleviating the effects of earthquakes in disaster-prone regions, particularly in Gorontalo.

Geological Setting

The volcanic rocks of the Eocene to Pliocene periods and the breakthrough rocks make up the volcano-plutonic strata of North Sulawesi, which encompasses the Gorontalo region. Furthermore, it is very uncommon for volcanic rocks to be found intermingled with sedimentary rock strata, as many of these sedimentary rock units contain volcanic material. According to Bachri et al. (1993), points out that when rock units are named using either volcanic or sedimentary rock units, the supremacy of one of these two types of rocks over the other is highlighted. The Tinombo Formation is one of the formations that contains the oldest rock unit in the area. However, it continues to present stratigraphic challenges, particularly regarding younger volcanic rock units.

There is a connection between the North Sulawesi Arm and the South Sulawesi Arm, and both of these arms are included in the West Sulawesi Mandala (Sukanto, 1978), which is a geological mandala that is also known as a volcano-plutonic lane. The term "enzymatic volcanic arc" is another name for the North Sulawesi arc. The sialic volcanic arc is the name given to the neck of Sulawesi, which extends to the southern arm (Carlile et al., 1990).

Due to a collision between the Banggai-Sula continental segment and the Sulawesi Arc, the northern part of the Sulawesi Arc experienced a clockwise rotation. This collision was followed by a process of subduction in the Sulawesi Sea (Carlile et al., 1990; Kavalieris et al., 1992). The segment of Sulawesi that has undergone the most change is the northern arm, which has shifted from its initial location of north to south to its current position of west to east. It is believed that the volcanic activity that is connected with the eastward Sangihe Thrust is responsible for the formation of the Quaternary volcanic rocks that are found in the eastern half of the North Sulawesi Arc. On the other hand, the North Sulawesi Rise, which is sometimes referred to as the Sulawesi Sea Rise, is believed to have been caused by volcanic activity that resulted in the formation of Neogene volcanic rocks (Kavalieris et al., 1992; Simandjuntak, 1986).

The Gorontalo region is situated inside the North Sulawesi Arc, which was created by volcanic plutonic eruptions. Plutonic and volcanic rocks from the Paleogene to Neogene predominantly characterize this region. Moreover, sedimentary rock formations are present, typically affected by volcanic activity. The studied area exhibits a continuous production of volcanic and sedimentary rocks from the Eocene through the Early Miocene to the Quaternary, representing a regressive sequence in a deep sea-to-land environment. Intervals of sedimentary rock are typically located within volcanic rocks, while intervals of volcanic

rock are generally situated within sedimentary rock strata. This demonstrates a distinct superposition relationship between the two categories of rock units.

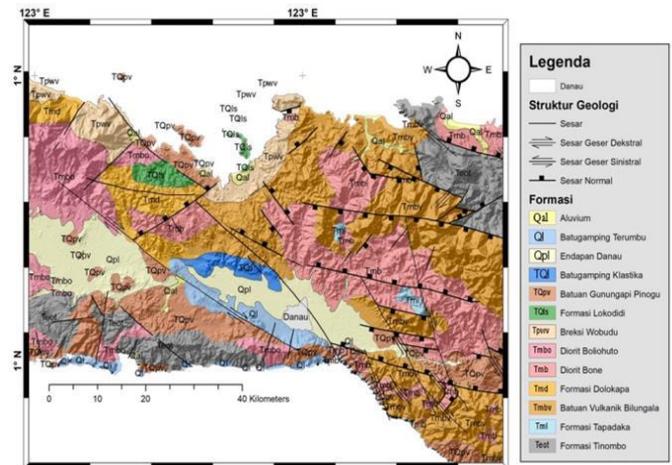


Figure 2. The geological map of the research region, featuring DEMNAS topography (Apani & Bachri, 1997; S Bachri et al., 1993; Syaiful Bachri, 2006), is included in the 1:250,000 Geological Map Sheet of Kotamobagu and Tilamuta

The younger volcanic rocks of the Tinombo Formation are classified as island arc rocks, whilst the older volcanic facies are regarded as ophiolite rocks. The two possess an incompatible relationship (Syaiful Bachri, 2006). Gorontalo has very active tectonics due to earthquake activity and ground acceleration. Folds and faults characterize Gorontalo's geology. In Gorontalo, specific active faults include normal and shear faults (Apani & Bachri, 1997; S Bachri et al., 1993; Syaiful Bachri, 2006), as illustrated in Figure 2. Because of its intricate geological structure, Gorontalo is very susceptible to earthquakes and tsunamis. The existence of subduction zones and active faults influences seismic activity, which is induced by land movement and results in both shallow and deep earthquakes.

The Gorontalo Fault, the greatest horizontal fault in the region, is one of the most significant geological features in Gorontalo. Analysis has demonstrated that this fault line can generate significant future earthquakes, as it exhibits right-lateral movement. Furthermore, several fault zones have an angle of 30 degrees, particularly in the Bilungala volcanic rocks, which is evidence that there was a time of repetitive tectonic compression and that geological folds were formed (Efendi et al., 2021; McCalpin, 2013).

According to Soehaimi (2008), asserts that investigations into regional and local active geological structures must prioritize the correlation between geological conditions and a region's seismicity. A region's geological conditions encompass rocks, geological formations, and tectonics, whereas its seismicity includes epicenter, depth, strength, and

intensity. The Gorontalo fault is an active geological fault traversing Gorontalo city with a northwest-southeast orientatio (Katili, 1970). It intersects with a secondary fault oriented northeast-southwest, creating distinct segments, specifically northern and southern. Furthermore, a right-lateral fault is located near the primary fault in the Gorontalo region.

Method

Data Sources and Description

This study utilised catalogue data sourced from the Meteorology, Climatology and Geophysics Agency (BMKG) and the International Seismological Centre (ISC), downloaded from <http://www.isc.ac.uk/>. The data covers the period from 1 January 2015 to 31 December 2022, magnitides 1.0 to 6.0 Mw with a distribution of 3.940 events (BMKG) and 1 January 1994 to 31 August 2025, magnitudes 3.0 to 9.0 Mw with a distribution of 2.317 events (ISC), spread across Gorontalo and its surrounding areas, which have shallow depths (< 70 km), medium depths (70–300 km), and deep depths (≥300 km). In addition to earthquake data, we collected geological data related to the subduction zone and its seismotectonics from the study area.

Data Analysis and Procedures

The data contains the time of occurrence, longitude, latitude, depth, and magnitude. Furthermore, we collected focal mechanism data from Global Centroid Moment Tensor (GCMT) project Catalog (Dziewonski et al., 1981; Ekström et al., 2012), which was downloaded from <https://www.globalcmt.org/>. The data includes information on earthquake parameters, such as the epicenter location, depth, moment magnitude (Mw), and focal mechanism solutions, including fault plane orientation (strike, dip, rake). The earthquake data we obtained was processed by plotting it on a seismicity map, performing a cross-section result of relocation the earthquake to see the subsurface model of the study area (Waldhauser & Ellsworth, 2000), and conducting a seismotectonic analysis using a Caverina diagram (Kaverina et al., 1996).

Using a quantitative descriptive approach and spatial and temporal analysis to describe and analyse the distribution of earthquakes in the Gorontalo region based on earthquake parameters and subduction zones, the study assessed the seismic hazard occurring in the study area. In addition, the analysis of earthquake distribution was also conducted spatially and temporally to identify earthquake patterns that could potentially endanger the study area in the future.

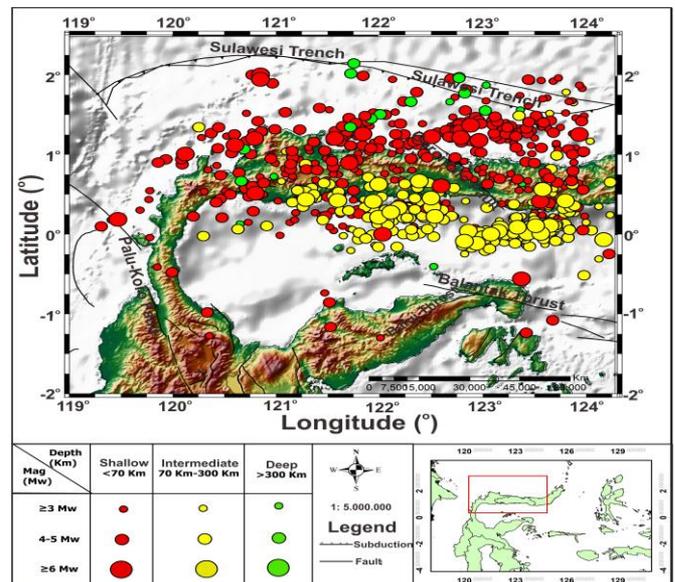


Figure 3. Seismicity in Gorontalo and surrounding areas from 1994-2025, where the coloured dots represent earthquake events. Red, yellow and green represent shallow, medium and deep earthquake events. Earthquake data was obtained from the International Seismological Centre (ISC)

Software

All maps produced in this study were created using Generic Mapping Tools (GMT) software versions 4 and 6 (P. Wessel et al., 2019; Paul Wessel et al., 2013). The cross-section results of the hypocentre relocation (Syafriani et al., 2023) were compared with the slab 2.0 (Hayes et al., 2018). Geometric model and the tectonic and fault models occurring in the study area. Similarly, the seismotectonic analysis, in the form of earthquake focus mechanisms (Ekström et al., 2012), was compared with the geological conditions of the study area.

Result and Discussion

From the research we have conducted using catalogue data from International Seismological Centre (ISC) and Meteorology, Climatology and Geophysics Agency (BMKG), we have obtained three results, namely a seismicity map from 1994 to 2025 (Figure 3), cross-section results to determine the subsurface model of the Gorontalo area (Figure 4) from 2015 to 2022, and a classification of the focus mechanism of the research area. In addition, we also produced a graph of earthquake occurrence frequency from 1994 to 2025.

Seismicity Rates

The level of seismicity occurring in the study area varies greatly depending on location, both in terms of magnitude and depth. In the Figure 3 shows shallow earthquakes (<70 km) are widespread across the entire Gorontalo region in the south and north. However, most of them are concentrated in the northern part of

Gorontalo. In contrast, earthquakes of intermediate depth (70–300 km) predominantly occur in the southern part of Gorontalo. Conversely, earthquakes of deep depth (>300 km) are concentrated or occur frequently in the northern part of Gorontalo. This seismic activity trend can be observed more closely by measuring the level of seismicity by depth. The level of seismicity provides an overview of the most seismically active areas and how activity changes with depth, and is compared across the entire study area.

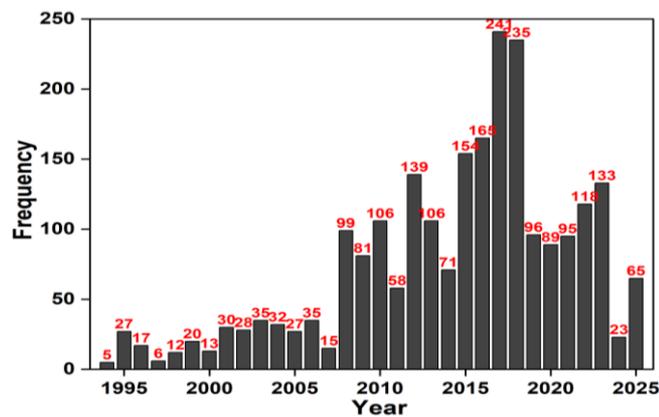


Figure 4. Frequency graph of earthquakes in Gorontalo and surrounding areas from 1994 to 2025 with a magnitude ≥ 3 Mw. There are varying earthquakes, both shallow, intermediate and deep

From the graph data of earthquakes that occurred in the study area using the ISC data catalogue covering

the last 30 years, 2317 earthquakes had a magnitude ≥ 3 Mw. The highest number of earthquakes occurred in 2017, with 241 events, and the lowest number occurred in 1994, with 5 events. For more details on the frequency of earthquake events in Gorontalo and its surrounding areas, see Figure 4.

Relocation Hypocenter

Earthquake hypocentre relocation data in the study area shows a more accurate subsurface model. Data from 2015 to 2022 reveal two clusters located south of Gorontalo. In addition, several earthquake events are scattered throughout the Gorontalo region, but do not form a cluster. The cluster that occurred in southern Gorontalo, precisely south of the Gorontalo Fault, is interpreted as a result of the seismicity pattern of the subduction slab that plunges from north to south to the Banggai-Sula region due to the deflection of the slab movement in the Sangie Arc (Weston et al., 2018).

The activities taking place in the northwest of the Gorontalo Fault are due to the subduction activity of the Sulawesi Sea Trench, which is a result of the movement of the Eurasian Plate as it plunges into the Indo-Australian Plate (Hamilton, 1979; Katili, 1970). However, activities to the southwest of the Gorontalo Fault are understood to be the result of the Kwandang Fault, a component of the Gorontalo Fault segment (Hutchings & Mooney, 2021; Meidji et al., 2023).

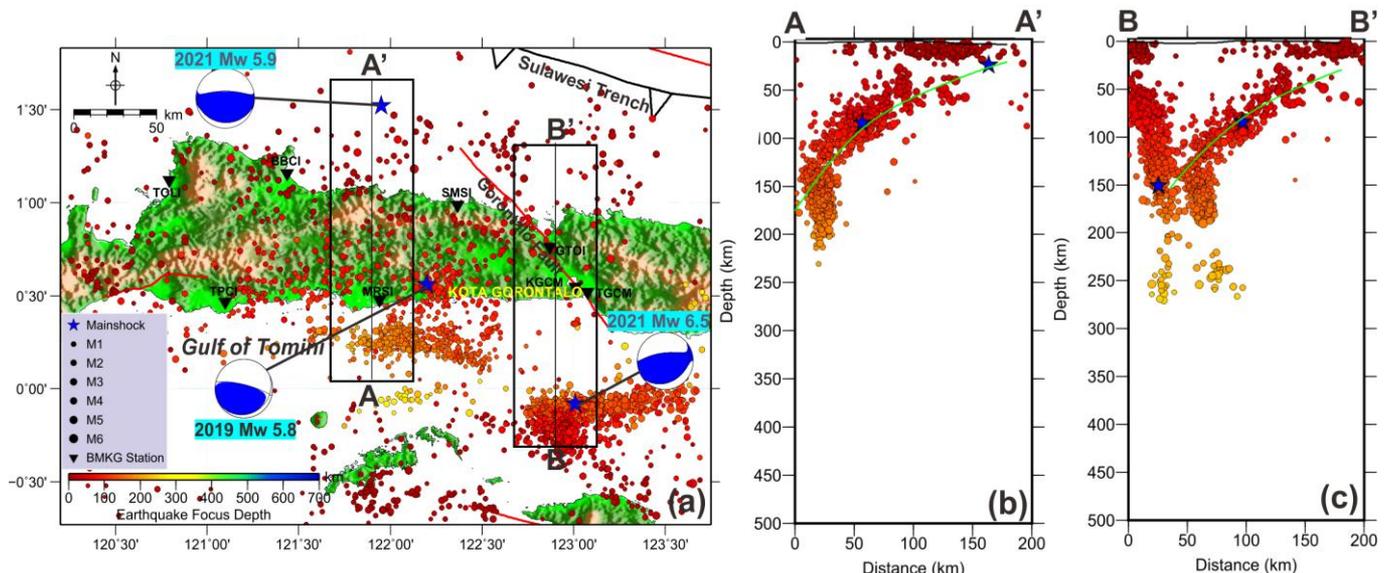


Figure 5. Distribution of earthquake occurrences and subsurface models in the Gorontalo region based on cross-section results of earthquake occurrences from 2015 to 2025 with magnitudes of 1 to 6 Mw

To determine the characteristics of the subsurface model in the study area, we conducted cross-section analyses in a south-north direction for both A-A' and B-

B'. Seismic activity occurring beneath the Gorontalo region is largely caused by the presence of a subduction

zone and a tectonic system in the form of faults, see figure 5 (a) and (b).

The slab geometry model has good consistency, and two clusters appear south of the Gorontalo Fault. The slab geometry model in the Gorontalo area shows a subduction zone that plunges southwards into the Gorontalo region, which is located west of the Gorontalo Fault and below the Gorontalo Fault. This plunge has a depth of up to 200 km. This is likely the result of the activity of the northern arm of Sulawesi in the form of the Sea Trench, combined with the activity of the Gorontalo Fault (Hutchings & Mooney, 2021).

Classification of Focus Mechanisms

From the GCMT data obtained, information regarding the type of earthquake focus mechanism based on the orientation of the principal stress axes (P-axis, B-axis, and T-axis) can be analysed, which is then classified into three main categories, namely strike-slip, reverse, and normal. Identifying these mechanisms is important because it can describe the tectonic forces at work in the region and help to understand the tectonic dynamics in Gorontalo and its surroundings. To better understand the characteristics of earthquake focus mechanisms in the Gorontalo region, we used the Kaverina diagram (Figure 6). This diagram shows a diagram (P-T-B axes plunge diagram) of earthquake focus mechanisms in the Gorontalo region. This Kaverina diagram shows the distribution pattern of

various types of earthquake focus mechanisms based on the P axis (minimum pressure), T axis (maximum pressure), and B axis (neutral pressure). This diagram is divided into three main categories: strike-slip faulting, normal faulting, and reverse faulting.

From the analysis of the Kaverina diagram at a shallow depth of < 70 km (Figure 6.a), it can be seen that the Gorontalo area is dominated by reverse faulting and strike-slip focus mechanisms. This indicates the presence of a compressional zone. This condition is commonly found in subduction zones, as the northern part of Gorontalo has a subduction zone in the form of the Sulawesi Trench, which plunges southwards towards Gorontalo. This zone is usually classified as a convergent zone or transpresional with a very high level of seismic activity. This is caused by the accumulation of stress, which is released in the form of earthquakes. Therefore, the earthquakes are shallow, causing significant impacts, such as tsunamis, crustal deformation, and infrastructure damage. There are also influences from the Balantak Thrust and Batui Thrust, located south of the Gorontalo fault. Regarding strike-slip, the Gorontalo area is interpreted as having relatively horizontal movement on the fault plane. This is suspected to be due to the movement of the Gorontalo fault, which divides the city in a northwest-southeast direction. This pattern indicates that there are rock blocks that move laterally, rather than vertically, when an earthquake occurs in the study area.

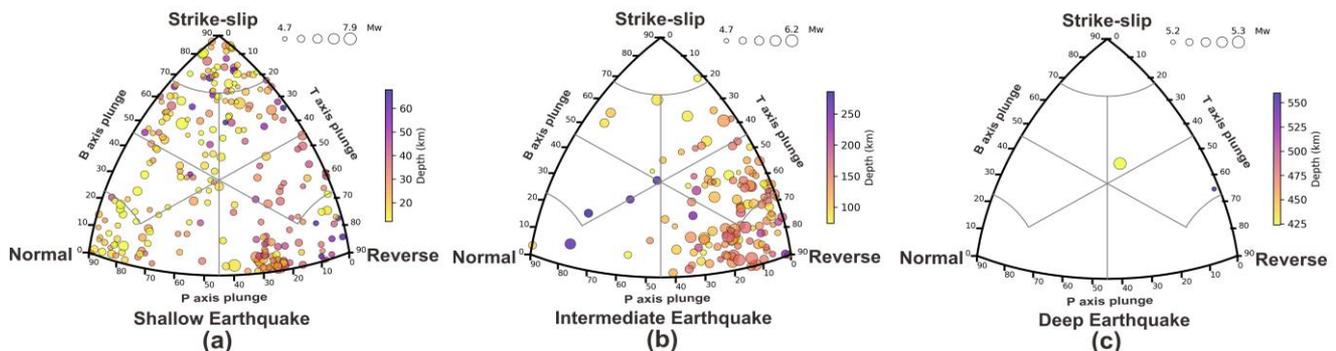


Figure 6. Classification model of the focus mechanism from Kaverina's diagram in the Gorontalo region. The colourful circles relate to the vertical distribution of earthquake sources for the tectonic structure model of the study area, and their size reflects the magnitude of the earthquakes that occurred

A similar situation occurs in Kaverina's diagram for earthquakes with depths between 70 and 300 km (Figure 6.b). However, this section shows a dominant distribution by reverse/thrust mechanisms faulting focus mechanisms. As with shallow depths, the Gorontalo region still experiences a lot of earthquake activity caused by subduction zones, especially in northern and southern Gorontalo. This is related to the dehydration process in the subduction plate, where increased temperature and pressure cause the release of

fluids from hydrated minerals. This process weakens the plate structure and triggers earthquakes with a combination of thrust and shear, following the Wadati-Benioff zone pattern, a seismic zone reflecting the path of plate subduction into the Earth's mantle. Seismic activity at depths greater than 300 km (Figure 6.c), shows a distribution of normal faulting (downward) focus mechanisms. This indicates the dominance of tensile forces in this zone. At this depth, the main structure at

work is the subduction plate, which continues to move into the Earth's mantle due to gravitational forces.

The difference in the distribution of focus mechanisms at each depth indicates that variations in earthquake mechanisms occur in the mantle transition zone, particularly at depths greater than 300 km, where olivine minerals undergo phase changes to wadsleyite and ringwoodite. This mineral transformation can trigger transform faults (Kirby et al., 1996), which cause shifts in the stress pattern within the subducted plate. As a result of these changes, the mantle transition zone has different structural characteristics compared to the layers above it, thereby influencing the mechanism of earthquake occurrence.

Conclusion

The Gorontalo region has fairly complex tectonic activity due to the interaction of subduction zones and fault zone that intersect each other, namely the Sulawesi Trench in the north and the Balantak Thrust and Batui Thrust in the south. In addition, there is also the Gorontalo fault that divides the Gorontalo region in a west-northeast direction (Efendi et al., 2021; Mardiyah & Pohan, 2024; Nurfitriani, Pasau, & Raharjo, 2014). Analysis of the focal mechanism shows various types of plate movement, with a predominance of reverse thrust mechanisms at shallow to intermediate depths, indicating high pressure in the subduction zone. Meanwhile, at more than 300 km depths, the dominant mechanism is normal faulting, suggesting tensile forces due to the rollback slab process. In addition, strike-slip mechanisms in several areas indicate the role of strike-slip faults in accommodating horizontal movement between plates. The distribution of earthquakes observed also shows a pattern that follows the subduction zone, where shallow earthquakes occur frequently around the subduction zone in northern Gorontalo. In contrast, medium to deep earthquakes follow the path of the plate that plunges into the Earth's mantle and are located in southern Gorontalo. A seismic gap at a depth of 200 km indicates a change in rock characteristics from brittle to ductile, which affects the energy release pattern in that zone.

Acknowledgments

We want to thank the institutions that supported this research, namely Gorontalo State University through a PNBPN grant, the Meteorology, Climatology and Geophysics Agency (BMKG), and the International Seismological Centre (ISC), so that we may obtain the earthquake catalogue data for Gorontalo and neighbouring places.

Author Contributions

Conceptualization and methodology, Icha Untari Meidji (M.S), and Harsano Jayadi (H.J); formal analysis, Dewa Gede Eka

Setiawan (D.G.E.S), and Irsan (I); investigation, I.U.M, D.G.E.S, I and HJ; writing – original draft preparation, I.U.M, D.G.E.S, I, and H.J.; writing – review and editing, I.U.M, H.J, D.G.E.S, and I; Visualization. H.J and Kartika (K). All authors have agreed to the published version of the manuscript.

Funding

This research was supported by Universitas Negeri Gorontalo, through PNBPN grand 2025 with SK contract number: 575/UN.47.D1/PT.01.03/2025 and research number: 981/UN47/HK.02/2025.

Conflicts of Interest

The authors declare no conflict of interest.

References

- Ahmed, S., & Perrone, D. (2019). Large-scale simplified seismic risk mapping of residential buildings through rapid visual screening. *COMPdyn Proceedings*, 1, 1707–1718. National Technical University of Athens. <https://doi.org/10.7712/120119.7030.19230>
- Apandi, T., & Bachri, S. (1997). *Peta geologi lembar Kotamobagu, Sulawesi*. Bandung: Penelitian Dan Pengembangan Geologi.
- Audley-Charles, M. G., Carter, D. J., & Milsom, J. S. (1972). Tectonic Development of Eastern Indonesia in Relation to Gondwanaland Dispersal. *Nature Physical Science*, 239(90), 35–39. <https://doi.org/10.1038/physci239035a0>
- Bachri, S, Sukido, & Ratman, N. (1993). *Peta Geologi Lembar Tilamuta, Sulawesi*. Bandung: Pusat Penelitian dan Pengembangan Geologi.
- Bachri, S. (2006). Stratigrafi lajur volkano-plutonik daerah gorontalo, sulawesi. *Jurnal Geologi Dan Sumberdaya Mineral*, 16(2), 94-106. <https://doi.org/10.33332/jgsm.geologi.v16i2.356>
- Bellier, O., Beaudouin, T., Sebrier, M., Villeneuve, M., Bahar, I., Putranto, E., & Wilson, P. (1998). Active faulting in central Sulawesi (eastern Indonesia). *The Geodynamics of S and SE Asia (GEODYSSSEA Project)*, 276–312. <https://doi.org/10.1046/j.1365-3121.2001.00382.x>
- Bellier, Olivier, Sebrier, M., Beaudouin, T., Villeneuve, M., Braucher, R., Bourles, D., & Pratomo, I. (2001). High slip rate for a low seismicity along the Palu-Koro active fault in central Sulawesi (Indonesia). *Terra Nova*, 13(6), 463–470. <https://doi.org/10.1046/j.1365-3121.2001.00382.x>
- Bellier, Olivier, Sébrier, M., Seward, D., Beaudouin, T., Villeneuve, M., & Putranto, E. (2006). Fission track and fault kinematics analyses for new insight into the Late Cenozoic tectonic regime changes in West-Central Sulawesi (Indonesia). *Tectonophysics*,

- 413(3-4), 201-220.
<https://doi.org/10.1016/j.tecto.2005.10.036>
- Carlile, J. C., Digdowirogo, S., & Darius, K. (1990). Geological setting, characteristics and regional exploration for gold in the volcanic arcs of North Sulawesi, Indonesia. *Journal of Geochemical Exploration*, 35(1), 105-140.
[https://doi.org/10.1016/0375-6742\(90\)90037-B](https://doi.org/10.1016/0375-6742(90)90037-B)
- Chacón-Hernández, F. (2024). The shear wave splitting technique as a methodology to retrieve temporary variations of induced stress. *Journal of Volcanology and Geothermal Research*, 446.
<https://doi.org/10.1016/j.jvolgeores.2024.108009>
- DeMets, C., Gordon, R. G., & Argus, D. F. (2010). Geologically current plate motions. *Geophysical Journal International*, 181(1), 1-80.
<https://doi.org/10.1111/j.1365-246X.2009.04491.x>
- Dziewonski, A. M., Chou, T.-A., & Woodhouse, J. H. (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *Journal of Geophysical Research: Solid Earth*, 86(B4), 2825-2852.
<https://doi.org/10.1029/JB086iB04p02825>
- Efendi, H. A., Marliyani, G. I., & Pramumijoyo, S. (2021). Recent faulting along Gorontalo fault based on seismicity data analysis and lineament mapping. *E3S Web of Conferences*, 325, 01013.
<https://doi.org/10.1051/e3sconf/202132501013>
- Ekström, G., Nettles, M., & Dziewoński, A. M. (2012). The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors*, 200-201, 1-9.
<https://doi.org/10.1016/j.pepi.2012.04.002>
- Hall, R., & Wilson, M. E. J. (2000). Neogene sutures in eastern Indonesia. *Journal of Asian Earth Sciences*, 18(6), 781-808. [https://doi.org/10.1016/S1367-9120\(00\)00040-7](https://doi.org/10.1016/S1367-9120(00)00040-7)
- Hall, R. (1996). Reconstructing Cenozoic SE Asia. *Geological Society, London, Special Publications*, 106(1), 153-184.
<https://doi.org/10.1144/GSL.SP.1996.106.01.11>
- Hall, R. (2012). Late Jurassic-Cenozoic reconstructions of the Indonesian region and the Indian Ocean. *Tectonophysics*, 570-571, 1-41.
<https://doi.org/10.1016/j.tecto.2012.04.021>
- Hamilton, W. B. (1979). *Tectonics of the Indonesian region*. US Government Printing Office.
- Hayes, G. P., Moore, G. L., Portner, D. E., Hearne, M., Flamme, H., Furtney, M., & Smoczyk, G. M. (2018). Slab2, a comprehensive subduction zone geometry model. *Science*, 362(6410), 58-61.
<https://doi.org/10.1126/science.aat4723>
- Hong, H.-J., Chen, H.-X., Zhao, Y., & Hu, J.-C. (2009). Global earthquakes and volcanoes: Distribution and variations. *Dizhen Dizhi*, 31(4), 573-583.
<https://doi.org/10.3969/j.issn.0253-4967.2009.04.001>
- Hutchings, S. J., & Mooney, W. D. (2021). The Seismicity of Indonesia and Tectonic Implications. *Geochemistry, Geophysics, Geosystems*, 22(9), e2021GC009812.
<https://doi.org/10.1029/2021GC009812>
- Iervolino, I., Manfredi, G., & Cosenza, E. (2007). Earthquake early warning and engineering application prospects. In P. Gasparini, G. Manfredi, & J. Zschau (Eds.), *Earthquake Early Warning Systems* (pp. 233-247). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-72241-0_12
- Jayadi, H., Th. Musa, M. D., Rachman, G., Meidji, I. U., Massinai, M. F. I., & Warnana, D. D. (2025). A Non-Linear Hypocenter Localization Along The Active Palu-Koro Fault: A Case Study Central Sulawesi. *Indonesian Physical Review*, 8(2), 400-416.
<https://doi.org/10.29303/ipr.v8i2.418>
- Katili, J. A. (1970). Large transcurrent faults in Southeast Asia with special reference to Indonesia. *Geologische Rundschau*, 59(2), 581-600.
<https://doi.org/10.1007/BF01823809>
- Katili, J. A. (1971). A review of the geotectonic theories and tectonic maps of Indonesia. *Earth-Science Reviews*, 7(3), 143-163.
[https://doi.org/10.1016/0012-8252\(71\)90006-7](https://doi.org/10.1016/0012-8252(71)90006-7)
- Kavalieris, I., van Leeuwen, Th. M., & Wilson, M. (1992). Geological setting and styles of mineralization, north arm of Sulawesi, Indonesia. *Journal of Southeast Asian Earth Sciences*, 7(2), 113-129.
[https://doi.org/10.1016/0743-9547\(92\)90046-E](https://doi.org/10.1016/0743-9547(92)90046-E)
- Kaverina, A. N., Lander, A. V., & Prozorov, A. G. (1996). Global Creep Distribution and Its Relation to Earthquake-Source Geometry and Tectonic Origin. *Geophysical Journal International*, 125(1), 249-265.
<https://doi.org/10.1111/j.1365-246X.1996.tb06549.x>
- Kirby, S. H., Stein, S., Okal, E. A., & Rubie, D. C. (1996). Metastable mantle phase transformations and deep earthquakes in subducting oceanic lithosphere. *Reviews of Geophysics*, 34(2), 261-306.
<https://doi.org/10.1029/96RG01050>
- Mardiyah, A., & Pohan, A. F. (2024). Identifikasi Sesar Gorontalo Dengan Memanfaatkan Data Gravitasi Satelit Resolusi Tinggi. *Jurnal Fisika Unand*, 13(5), 658-664. <https://doi.org/10.25077/jfu.13.5.658-664.2024>
- Massinai, M. A., Harimei, B., Agustawati, A., & Massinai, M. F. I. (2019). Seismicity analysis Sulawesi North Arm based on B-Values. *Journal of Physics: Conference Series*, 1341, 082032.
<https://doi.org/10.1088/1742-6596/1341/8/082032>

- McCalpin, J. P. (2013). Tectonic and tectono-seismic hazards. In *Encyclopedia of Earth Sciences Series* (pp. 994–1004). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_48
- McGuire, R. K. (1995). Probabilistic seismic hazard analysis and design earthquakes: Closing the loop. *Bulletin - Seismological Society of America*, 85(5), 1275–1284. <https://doi.org/10.1785/BSSA0850051275>
- 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>
- Nahli, K., & Oryzavica, V. (2017). Study of earthquake potential between two major faults in Buoi area Sulawesi. *AIP Conf. Proc.*, 1857. American Institute of Physics Inc. <https://doi.org/10.1063/1.4987064>
- Nurfitriani, Pasau, G., & Raharjo, S. S. (2014). Identifikasi Sesar di Wilayah Gorontalo dengan Analisis Mekanisme Bola Fokus. *Jurnal MIPA*, 3(1), 40. <https://doi.org/10.35799/jm.3.1.2014.3905>
- Permana, D., Widiyantoro, S., Persada, Y. D., & Habibah, N. (2025). Soil Classification Mapping by Vs30 MASW Measurements in Gorontalo City. *IOP Conference Series: Earth and Environmental Science*, 1458(1), 012031. <https://doi.org/10.1088/1755-1315/1458/1/012031>
- Serhalawan, Y., & Chen, P.-F. (2024). Seismotectonics of Sulawesi, Indonesia. *Tectonophysics*, 883. <https://doi.org/10.1016/j.tecto.2024.230366>
- Shohaya, J. N., Chasanah, U., Mutiarani, A., P, L. W., & Madlazim, M. (2013). Survey Dan Analisis Seismisitas Wilayah Jawa Timur Berdasarkan Data Gempa Bumi Periode 1999-2013 Sebagai Upaya Mitigasi Bencana Gempa Bumi. *Jurnal Penelitian Fisika Dan Aplikasinya (JPFA)*, 3(2), 18–27. <https://doi.org/10.26740/jpfa.v3n2.p18-27>
- Silalahi, M. T., Dahrin, D., Abdurrahman, D., & Tohari, A. (2023). Identification Of Liquefaction-Potential Zones Using The Gravity Method In Lolu Village, Central Sulawesi. *Jurnal Penelitian Pendidikan IPA*, 9(8), 6206–6212. <https://doi.org/10.29303/jppipa.v9i8.4830>
- Simandjuntak, T. O. (1986). Struktur Duplek (Dwi Unsur) Sesar Sungkup Jurus Mendatar di Lengan Timur Sulawesi. *Prosiding PIT XV IAGI*.
- Souisa, M., Sapulete, S. M., & Siahaya, L. A. (2023). Earthquake Disaster Risk Analysis for Mitigation Efforts in Seram and Buru Islands, Maluku. *Jurnal Penelitian Pendidikan IPA*, 9(7), 5310–5316. <https://doi.org/10.29303/jppipa.v9i7.3762>
- Sukanto, R. (1978). The structure of Sulawesi in the light of plate tectonics. *Proceedings of Regional Conference on Geology and Mineral Resources of Southeast Asia*, 121–141. Retrieved from <https://www.iagi.or.id/web/digital/32/PIT-IAGI-1975-Paper-13.pdf>
- Syafriani, Raharjo, F. D., Ahadi, S., & Ramdhan, M. (2023). Study of Seismicity Based on the Results of Hypocenter Relocation Using Double Difference (HypoDD) Method in West Sumatera and Its Surrounding. *Jurnal Penelitian Pendidikan IPA*, 9(7), 5150–5156. <https://doi.org/10.29303/jppipa.v9i7.3792>
- Tjia, H. D. (1978). Active faults in Indonesia. *Bulletin of the Geological Society of Malaysia*, 10, 73–92. Retrieved from https://gsm.org.my/wp-content/uploads/gsm_file_2/702001-101282-PDF.pdf
- Waldhauser, F., & Ellsworth, W. L. (2000). A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California. *Bulletin of the Seismological Society of America*, 90(6), 1353–1368. <https://doi.org/10.1785/0120000006>
- Wells, D. L., & Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin - Seismological Society of America*, 84(4), 974–1002. <https://doi.org/10.1785/BSSA0840040974>
- Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., & Tian, D. (2019). The Generic Mapping Tools Version 6. *Geochemistry, Geophysics, Geosystems*, 20(11), 5556–5564. <https://doi.org/10.1029/2019GC008515>
- Wessel, Paul, Smith, W. H. F., Scharroo, R., Luis, J., & Wobbe, F. (2013). Generic Mapping Tools: Improved Version Released. *Eos, Transactions American Geophysical Union*, 94(45), 409–410. <https://doi.org/10.1002/2013EO450001>
- Weston, J., Engdahl, E. R., Harris, J., Di Giacomo, D., & Storchak, D. A. (2018). ISC-EHB: Reconstruction of a robust earthquake data set. *Geophysical Journal International*, 214(1), 474–484. <https://doi.org/10.1093/gji/ggy155>