The north arm of Sulawesi has a fairly high level of seismicity. The North Sulawesi arm is bounded in the south by the Palu-Koro Fault, the northern part is bounded by the North Sulawesi Trench and the Molluca Sea Thrust in the east. Therefore, this study aims to analyze the characteristic of the 2010-2020 earthquakes in the north arm of Sulawesi by analyzing the earthquake's focal mechanism and mapping the b-value using the maximum likelihood method. From this study, we obtained the focal mechanism consist of thrust and strike-slip, this is due to the activity of faults and subduction zones in the North arm of Sulawesi such as the Palu-koro fault, the Gorontalo Fault, North Sulawesi Trench, Molucca Sea Collision, and several other faults that affect the seismicity of this region. The variation of the b-value ranging from 0.5-1.1. These studies indicate that thrust fault regions have lower b-values, while strike-slip fault regions have intermediate b-values. Meanwhile, areas with active volcanoes tend to have high b-values. The results of this research can be used as a basis for decision making related to earthquake mitigation in this area in the future.

1. Introduction

Sulawesi Island and its surroundings, especially northern Sulawesi, are one of the most complex active margins in terms of geology, structure, and tectonics. This region is the center of the meeting of three convergent plates due to the interaction of the three main earth plates in the Neogene era. This convergence has led to the development of all types of structures at all scales, including subduction and collision, fault, and thrust zones. Currently, most of the Neogene structures and some praneogene structures are still active or reactive [1].

The geological structures identified in Sulawesi are still actively moving at different shifting speeds and often produce earthquakes [2]. According to [3], the North Sulawesi Arm is bounded to the south by Palu-Koro Fault, to the north it is bordered by North Sulawesi Trench and Molluca Sea Thrust in the east. This is indicated by the presence of a crust that has a high shear strain due to the movement of the Sula Block around the Palu-Koro Fault. In this zone, there are also some strike-slip fault activities, including the Poso fault and the Gorontalo fault. On the western side of the Molluca Sea there is a Sangihe plate with a west-dipping direction. And there is also a plate under the North Sulawesi Arm called the Celebes plate. This plate subducts the Sulawesi Sea lithosphere to the south from the North Sulawesi trench [4].
One of the parameters that can be used in studying the characteristics of an earthquake that occurs is the focal mechanism. Seismograms record various distances and azimuths which are used to study fault geometry due to earthquakes [5]. The focal mechanism is a term used to describe the propagation properties of the hypocenter of earthquake energy. When an earthquake occurs, the seismic waves caused by the earthquake will be emitted in all directions in the form of wave phases. The initial phase recorded first is the P wave because it has the greatest speed compared to other waves. The direction of the first P wave motion recorded by the seismogram is then used to study the focal mechanism. This is because the P waves are the clearest to read and easy to spot. Besides, the polarity and amplitude of the S wave and the moment tensor inversion are also used in determining the focal mechanism [6].

The figure below is an example of the focal mechanism of a beach ball earthquake and its fault geometry.

![Focal Mechanism Example](image)

**Figure 1** Some examples of focal planes and their fault geometries [7].

Physically, the value of b can be said to be the seismotectonic parameter of a region. Meanwhile, regionally, a change in the b-value is believed to have an inverse relationship with changes in stress levels. The method commonly used in determining the b-value is the classical frequency distribution (FMD) [8]. From FMD, information about the number of earthquakes is obtained as a function of magnitude (M) that has occurred in an area, with the following formula:

\[
\log N = a - bM
\]  

(1)

where \(N\) is the total number of earthquakes that have occurred, \(M\) is the magnitude of the earthquake, constant \(a\) characterizes the general seismic activity in an area, the higher the number, the higher the seismic level. Constant \(b\) is believed to depend on the stress level and tectonic character of the area. This study seeks to analyze the fault characteristics that caused earthquakes in the North arm of Sulawesi based on the focal mechanisms and possible implications for future earthquakes using b-value. The results of this research can also be used as a reference for mitigating natural disasters.

2. Data and Method

The research location focused on the North Arm of Sulawesi. The data used in this research is the earthquake data online catalog belonging to the International Seismological Center (ISC) [9]. The data used in this research include information about origin time, magnitude, hypocenter, and fault parameters such as strike, dip, rake, etc. The total earthquakes data used are 10,094 events that occurred from January 2010 to August 2020 with a variation of the magnitude ranging from 1.1 to 6.9. The research is focused on the coordinate 119° – 127° E dan -1° - 3° N. The research began with hypocenter mapping to see the distribution of earthquake depths and the focal mechanisms using the Generic Mapping Tools (GMT) [10]. To study variations of the b-value, we use the maximum likelihood method and it was done using Zmap code [11].
3. Results and Discussion

3.1 Analysis of the focal mechanism

The distribution of the hypocenter (figure 2) in the North Arm of Sulawesi, both on land and coast, shows high seismicity in this decade. We analyze the earthquake focal mechanisms by dividing it into 3 regions, namely western North Arm, central North Arm, and Eastern North Arm. This is because there are significant differences in earthquake focal mechanisms in these three areas, so that analysis is needed to determine the characteristics of the earthquake causes.

Figure 2 Cross-section results of the hypocenter and earthquake focal mechanisms.
Figure 2 shows the seismic activity that occurred in the western, center (especially land and coast) and in the eastern part of the north arm of Sulawesi. In the area traversed by the A-B line, the results obtained show that the earthquake that occurred around the area was dominated by strike-slip, so it is interpreted that the earthquake that occurred were influenced by the Palu-Koro Fault. The Palu-Koro fault is one of the longest and active faults in Sulawesi. According to [3], several segments of the Palu-Koro Fault cover an area with a width of 50 km around Palu. Research by [12] states that the focal mechanism of the Palu-Koro fault is the left lateral strike-slip. The Palu-Koro fault is connected to the Matano fault and the Lawanopo fault, while the northern end of the fault passes through the Makassar Strait and is connected to the North Sulawesi subduction zone at the western end [13].

In the area traversed by the C-D line, the analysis result of the focal mechanism show the northern part of Sulawesi North Arm is dominated by thrust faults, on land by several strike-slip faults. We interpreted that the earthquakes that occurred were caused by North Sulawesi Trench on the coast and on the land caused by Gorontalo Fault. North Sulawesi Trench or better known as Minahasa Trench is the longest and largest thrust in Sulawesi. North Sulawesi Trench is a subduction zone between the Philippine Plate and the North Sulawesi microblock [2]. The North Sulawesi Trench belongs to a relatively old subduction zone whose rips develop eastward along the northern edge of Sulawesi. North Sulawesi subduction infiltrates with a slope angle of about 14° and the Benioff zone dips to a depth of 170-180 km, with an angle of about 45° [14]. Then, [15] in their analysis state that the Gorontalo Fault has a displacement speed of 11 mm/year, with a focal mechanism of right-lateral strike-slip [2], while [16] state that this fault is a type of oblique fault.

In the area traversed by the E-F line, we found that the focal mechanism of the earthquakes show thrust fault, so we interpreted that the earthquakes that occurred were caused by the Molucca Sea Collision. This zone consists of West Sangihe Thrust and East Halmahera Thrust. According to [17], the Sangihe plate with a movement towards the west has carried out deeper subduction than the Halmahera plate which points to the east. Analysis by [4,17] states that the Sangihe plate has undergone subduction of up to 660 km, while the Halmahera plate has reached a depth of 350–400 km.

3.2 Analysis of b-value

![Image](image_url)

**Figure 3** Frequency–magnitude distribution of earthquakes from January 2010-August 2020. The slope of the line represents the Gutenberg-Richter relationship.

This Mc value is the lower limit of the magnitude or magnitude that most often occurs when an earthquake occurs. According to [18], the prediction of the Mc value is based on the magnitude of the cumulative frequency. In earthquake studies, one of the parameters often used in studying the seismotectonic parameters of a region is the b-value, which varies from 0.2 to 2.0. Generally, very low b-values are found in the case of direct aftershocks and higher values are found in the case of earthquake swarms [19]. The decrease in the value of b can be affected by the increase in shear stress or the effective stress that occurs. A smaller b-value can indicate that the stress in the area is high, and vice versa.
Figure 4 Distribution of b-value in the North Arm of Sulawesi. Stars mark the large earthquakes M 6.9. Higher b-value is indicated in red and lower b-value is indicated in blue.

Based on figure 4, it is obtained that the b-value in the North Arm of Sulawesi ranges from 0.5-1.1. A high b-value means an earthquake is dominated by a small earthquake. Conversely, a low b-value indicates that earthquakes of greater magnitude predominate in the region [20]. In the area around the Palu-Koro fault, the b-value ranges from 0.7-0.8. Research by [18] state that the area around the strike-slip fault has a b-value of 0.5-1.0, while [21] mention that the temporal b-value for Palu region was in the range of 0.55-0.961. According to [22], this b-value depends on stress conditions, such as spatial and temporal changes in applied shear stress. In the central part of the north Sulawesi arm affected by the North Sulawesi Trench, there is a contrasting difference in b-values, which is around 0.5-0.6, this low b-value indicates that the stress level in the region is high. According to [3], lower b-values indicate higher seismic activity while high b-values indicate low and medium seismic activity. In the area around the Gorontalo Fault, the b-value ranges from 0.7-0.8. Meanwhile, at the eastern end of the North Sulawesi Arm, the b-value tends to be high, ranging from 0.9-1.1. From the volcanic side, this value can be influenced by magmatic activity. This is supported by the number of active volcanoes in this region. Research by [22] mentioned that high b-values are found in volcanic areas. Meanwhile, in the area around the Molucca Sea Collision, the b-value ranges from 0.8-1.1. From a tectonic perspective, areas such as the Molucca Sea Collision will have a high b-value. Research by [3] state that the b-value in West Molucca Sea and East Molucca Sea is 0.95.

4. Conclusions
Based on the analysis of the focal mechanism, the earthquakes that occurred around the North arm of Sulawesi consisted of thrust fault and strike-slip mechanisms. This was caused by the activity of faults and subduction zones existing in the North arm of Sulawesi such as the Palu-Koro fault, Gorontalo Fault, North Sulawesi Trench, Molucca Sea Collision, and several other faults that affect the seismicity of this area. These studies indicate that thrust fault regions have lower b-values, while strike-slip fault regions have intermediate b-values. Meanwhile, areas with active volcanoes tend to have high b-values. The b-value in the North Arm of Sulawesi ranges from 0.5-1.1, this indicates that the North Arm of Sulawesi region is affected by tectonic activity and volcanism.

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