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Analysis of fault patters based on erarthquake data on the land of Sumatera island

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Abstract. Geodynamics of Sumatra is interesting to study because of the unique geological setting Geodynamics of Sumatra is interesting to study because of the unique geological setting and high seismicity. This high seismicity is caused by the many faults found on land and in the surrounding waters. This paper presents the results of research that aims to determine fault patterns both on land and in the waters around Sumatra based on earthquake data from 1960-2000. The area under study is at the coordinates of 6°N - 6°S and 95°E - 109°E at an epicenter depth of <60 km with a magnitude between 4-10. The area is divided into two zones, namely the front arc and the Barisan arc. Data were obtained from ISC and Global CMT. By using the Focal Mechanism Method, the results show that the fault pattern in the Sumatran forearc Basin zone is dominated by an Reverse Fault located in the accretion zone while on the mainland of Sumatra it is dominated by Strike Slip along the Sumatran Fault System. By knowing the position and pattern of the fault, especially on the mainland of the island of Sumatra, it can be used as a reference for spatial planning. In addition, further studies will also be able to learn about the dangers or disasters caused by the fault pattern.

1. Introduction

The accumulation of natural disasters in Indonesia from the beginning of the year to the end of August 2021 was recorded as 1,805 incidents. Wet hydrometeorological disasters dominate the occurrence of this disaster. Especially for earthquakes, 23 destructive earthquakes were recorded [1]. For earthquake disasters during January to July 2021, the Meteorology, Climatology and Geophysics Agency (BMKG) recorded 4,701 earthquakes in Indonesia from which they could not be felt to those that were destructive. The results of BMKG monitoring show that the trend of earthquakes in Indonesia will increase in 2021, reaching 300 to 400 earthquakes every month [2]. The existence of the Indonesian archipelago which is located in an active tectonic plate boundary zone is the main cause of earthquakes that occur almost every day. One of the large islands in Indonesia which is located on the boundary of the world's great plates is the island of Sumatra. This geological position causes the island's seismicity to be quite high.

Sumatera geodynamics is interesting to study, especially its high level of seismicity. Earthquakes that occurred in North Sumatera and Aceh throughout the month of May 2021 alone were recorded at the Regional Earthquake Center (PGR) I Center for Meteorology, Climatology and Geophysics (BBMKG) Region 1 Medan as many as 407 events [3]. This high seismicity is due to the fact that this island is one of the traces of the Indonesian continent which is formed from broken, united and uplifted continental chunks originating from Gondwana and Cathaysian [4]. Almost all of the microscopic



continents in Indonesia are surrounded by active plate margins that form a complex plate meeting path of the world's three major plates and nine minor plates that meet each other [5]. This geological arrangement causes quite high seismicity in almost all islands in Indonesia due to the dynamics and interactions between these plates. The dynamics and interactions between these plates also cause the formation of derivative tectonic structures such as faults, local faults, folds, land subsidence in almost all of the Indonesian archipelago [6].

Earthquakes occur due to the sudden release of energy when the rock at the source location is unable to withstand the forces due to the relative motion between plates [7]. This energy propagates in the form of seismic waves that move towards the surface and cause shocks or vibrations [8]. One of the mechanisms or methods for analyzing the waveforms generated by earthquakes recorded by a number of seismographs is the Focal Mechanism Solution (FMS). The complete characterization of an earthquake's focal mechanism provides important information, including the origin time, epicenter location, focal depth, seismic moment and the magnitude and spatial orientation of the 9 components of the moment tensor. All of this information can be obtained in seconds by structural geologists who know how to interpret FMS graphic depictions, known as "beach ball" diagrams [9].

Beachball diagram or also known as Focal Ball has a three-dimensional shape and is analyzed for the direction of movement of the origin of the P wave. Visual interpretation is done by dividing the focus ball into two parts, the top and bottom. Then the lower half of the sphere is irradiated from below, so that a two-dimensional image of the sphere is obtained, which is called the focal sphere diagram [10]. From this diagram it will be possible to know the parameters of the orientation of the fault plane of the fault that caused the earthquake. The fault parameters consist of strike (ϕ), dip (slope) (δ), rake (slip) (λ). Strike is a fault plane move measured from north to east ($0^\circ - 360^\circ$). Dip is the angle formed by the fault plane with the horizontal plane, and is measured in a vertical plane whose direction is perpendicular to the fault direction ($0^\circ \leq 90^\circ$). Rake or slip, is the hanging-wall movement angle with respect to strike ($-180^\circ \leq 180^\circ$), rake is positive for ascending fault and negative for descending fault [11].

Earthquake waves propagate in all directions in the form of various wave phases with P waves as the phase with the greatest speed. This direction of motion is the first to be observed to study the source mechanism. Studying the P wave mechanism is not only to study the initial motion of the earthquake and the solution of the fault plane, it can also be used to determine the motion of tectonic plates which is used to determine the relative motion of the lithosphere [12]. Fault is a fracture that has a clear shift. The shifts range from a few millimeters to hundreds of meters while their lengths range from a few decimeters to thousands of meters. Faults can occur in all kinds of rocks with various types. Faults in rock structures can lead to topographic changes and developments, change the flow of water below and above the surface and damage rock stratigraphy and so on [13].

This study of focal mechanism is carried out in disaster mitigation efforts because earthquakes are difficult to predict when, where and how large they are accurately. This disaster must continue to be watched out for because it often causes damage to infrastructure and even casualties. Mitigation is carried out not to reduce or prevent disasters, but to reduce their impact, both on infrastructure and on casualties. Mitigation efforts can be carried out through mapping the affected area and increasing the capacity of the affected community through awareness and concern in dealing with disasters. In this study, apart from knowing the types of faults that cause earthquakes, the fault parameters will also be known. From the magnitude of the earthquake, further studies will be able to map the level of risk of damage from the earthquake. By knowing the types of faults and their parameters, it will also be possible to study the spatial arrangement around the fault and the development of its infrastructure that is adaptive to the characteristics of the fault. The most important thing from the results of this study is to know the points or locations and types of faults on the mainland of the island of Sumatra more accurately so that the impact can be known if an earthquake occurs and mitigation is carried out continuously.

2. Method

To determine the types of faults that cause earthquakes in Sumatera and its surroundings, this paper uses the Focal Mechanism Solution or Focal Mechanism method. This method is used to interpret a fault

form in the form of a focal sphere caused by the initial motion of the P wave from an earthquake. From the focus ball, information on the shape of the fault and the direction of the slip will be obtained. The parameters of the fault that can be studied from this method include strike, dip and slip.

The data processing and analysis of this study was carried out in three stages, namely processing seismicity data with Magnitude, Focal Mechanism using data from ISC and CMT global catalog and geological mapping and focal data using Arcview GIS 3.3 software. Earthquake data obtained from the ISC and the CMT global catalog in determining the faults are classified according to the desired depth, which in this study uses earthquake data with a depth of less than 60 kilometers (shallow earthquake) with geographical limitations $6^{\circ}\text{N} - 6^{\circ}\text{S}$ and $95^{\circ}\text{E} - 109^{\circ}\text{E}$ and using magnitude 4-10. The classification of the data that has been obtained is then carried out by fault analysis based on the obtained focal ball (beachball) data.

There are three zones analyzed for fault types, namely the Forearc Basin zone, Sumateran Fault zone and Backarc Basin zone. Earthquake data from these three zones is already available and the analysis and interpretation is adjusted to the geological data. Due to the less significant seismicity in the Backarc Basin zone, it was not reported in this paper.

3. Result and Discussions

3.1. Distribution of seismicity on the island of Sumatera

Figure 1 shows the distribution of seismicity and its magnitude between 1960 and 2000 in Sumatera at the geographical boundary between $6^{\circ}\text{N} - 6^{\circ}\text{S}$ and $95^{\circ}\text{E} - 109^{\circ}\text{E}$. From this distribution, it can be seen that the earthquakes in Sumatera mostly occurred in the west of the island and along the Sumatera fault area. The seismicity in the western region of Sumatera is along the acceleration zone or in the subduction zone where one plate is subducting under the other. In this zone the Indian Ocean plate is subducting under the Eurasian plate and this strip is called the Benioff Strip. On the mainland of the island of Sumatera, many earthquakes occur along the Sumatera Fault where this fault is one of the land faults in Indonesia which is very dynamic so earthquakes often occur along this fault.

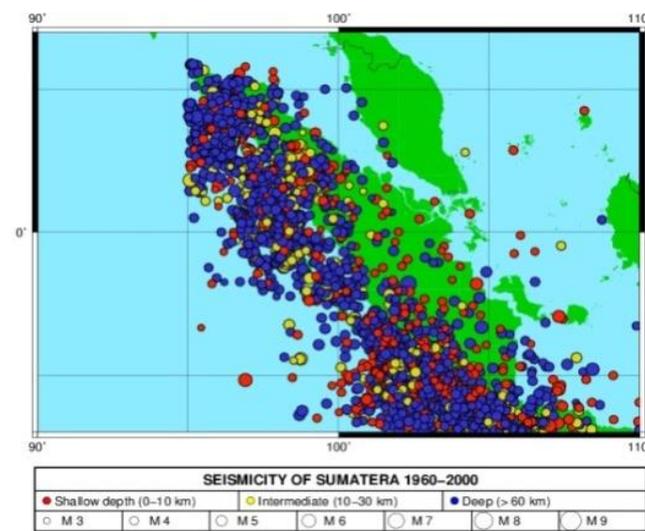


Figure 1. Distribution of seismicity of Sumatera.

If a transverse incision is made as shown in Figure 2, it will show the distribution of seismicity in the vertical plane under the incision as shown in Figure 3. From Figure 3, it can be seen that in one plane in the vertical direction there have been many earthquakes with varying depths and magnitudes. In Figure 3 at a depth between 30-50 km there is an earthquake phenomenon with a relatively the same depth as

if forming a boundary pattern. It is therefore necessary to further study whether this is a weak zone that might show plate boundaries, or whether the Sunda Microplate is shifting over the Eurasian Plate.

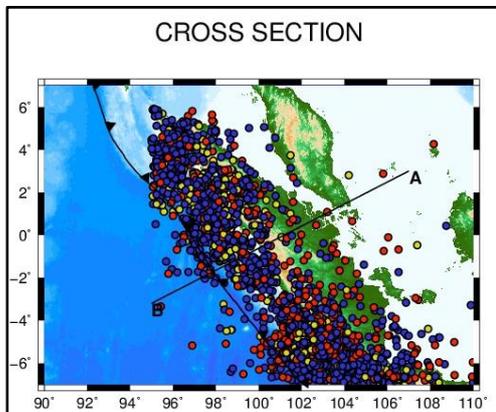


Figure 2. Cross section on seismicity

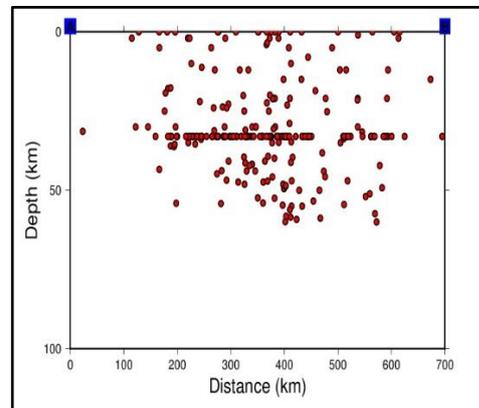


Figure 3. Distribution of seismicity in the vertical plane under the cross section

3.2. Types of faults on the island of Sumatera and its surroundings

By using the focal mechanism method to analyze the types of faults on the Sumatran fault island and its surroundings, four types of faults were obtained, namely strike slip, reverse fault, normal fault and oblique. Table 1 shows the types of the 24 faults that exist along the Barisan Zone. In this zone, it can be seen that the strike slip type or shear fault dominates in this zone.

Table 1. Types of faults along the Barisan zone

Longitude (°)	Beachball	Fault Type	The amount
95-105 EL		Strike Slip	15
		Reverse Fault	3
		Normal Fault	1
		Oblique	5

In the Forearc Basin Zone, the types of faults that caused 153 earthquakes occurred in this zone were studied. Table 2 shows the types of faults that caused 153 earthquakes in the Forward Arc zone. From this table, it can be seen that the reverse fault type dominates in this zone with 68 occurrences. This shows that the dynamics in the subduction zone are the cause of most of the earthquakes in this zone.

Table 2. Types of faults along the Forearch Basin zone

Longitude (°)	Beachball	Fault Type	The amount
		Strike Slip	32

95 ⁰ -105 ⁰ EL		Reverse Fault	68
		Normal Fault	20
		Oblique	33

3.3 Geology and Tectonic Studies

The geodynamics and tectonics of the island of Sumatera in particular and the entire archipelago in Indonesia in general are strongly influenced by the dynamics of the three major world plates. The three major plates are the Indian-Australian Ocean Plate moves from south to north, the Pacific Plate from east to west and the Asian Plate moves from north to south southeast [14]. Based on the data on the types of faults that cause earthquakes in Sumatera as stated above, it can be said that the seismicity on this island is strongly influenced by the dynamics of the subduction zone in the western zone of the island. This zone is a convergent plate boundary that extends from north to south and extends to the south of the island of Java. The most intense tectonic plate interactions occur in the western and southern parts of the Indonesian archipelago and form the Sunda Arc [15]. This Sunda arc is the meeting between the Indian-Australian plate and the Eurasian Plate. The movement of plates in this zone also causes the formation of faults, folds, land subsidence and so on. Other secondary processes due to activity in this subduction zone have also led to the formation of troughs, non-volcanic outer arcs, forearcs, volcanic arcs, and back arc basins [16].

The dynamics of this zone also causes the formation of regional geological structures on the Sumatera mainland, among which the best known is the Sumatera Fault System. Based on the results of mapping the types of faults as in table 1 shows that in the Sumatra Fault System with a reverse fault. The results of mapping the types of faults also showed that earthquakes in the path of the Sumatra fault system were less than in the forearc basin. Bellier et al in this case also said that earthquakes with magnitudes of 5 or more or less occurred on the Sumatran mainland and most earthquakes occur in the forearc basin [17]. Due to subduction in the forearc basin zone also causes the formation of a line volcanoes known as Bukit Barisan.

As stated in the previous section, the geological and geodynamic structure of Sumatra is indeed quite unique. In terms of seismicity, the fairly high seismicity on this island (figure 1) shows that the source of the earthquake on this island is caused by two causes, namely the forearc basin and the Sumatran Fault System. Of course, mitigation must be different because the location of the epicenter is different. Mitigation carried out for earthquakes whose epicenter is on land must be more careful and accurate because the source of the earthquake can be directly located in residential areas. The damage to infrastructure and the resulting loss of life will be more than that of an earthquake whose epicenter is in the water, even though the magnitude is smaller. Mitigation for the type of fault must also be different according to the type of fault and the parameters of the fault. For this reason, further studies on the appropriate mitigation for each fault are needed.

3. Conclusions

From the analysis of 177 earthquake data with a depth of <60 km that occurred in Sumatra and surrounding areas it can be concluded that the types of faults are strike slip, reverse fault, normal fault and obliques. In the forearc basin zone the type of fault is dominated by an reverse fault. From this type of fault shows that in this zone is an accretion zone that is tectonically a subduction zone between the Indian-Australian Plate and the Eurasian Plate. In the zone along the Sumatra Fault System type of fault is dominated by a strike slip. The dominance of this type indicates that the land of the central part of

Sumatra fault is controlled by the Oblique Collision of the two plates proposed earlier. On the backarc basin there is no significant earthquake data so it is not studied in this paper.

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