Maluku Sea Plate Faulting Regime Analysis: A Preliminary Study

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Abstract. Present day Molucca or Maluku sea plate in the eastern of Indonesia possesses a complex tectonic setting. This complex tectonic setting has been formed due to the collision of an actively moving Eurasian plate and Philippine sea plate toward the Maluku sea plate. At the west, Maluku sea plate is subducting beneath Sangihe arc, which began in the early Miocene. While at the east, Maluku sea plate is subducting under Halmahera arc, since in the middle Miocene. These subduction processes take place up to the present. Therefore, it has formed Maluku sea plate into an inverted U-shape slab under a thickening accretionary complex. Seismicity distribution has clearly shown the U-shape slab. Earthquake events take place on the subducting slab, and interestingly on the above accretionary complex as well. Maluku sea plate might pose hazards to surrounding islands: northern Sulawesi, Halmahera island, Sangihe island and Talaud island. The possible hazard, for instance, a thrusting earthquake which may generate tsunami to the nearby islands. Hence, understanding its tectonic and seismicity signature, especially at the shallow part, are indeed important in the Maluku sea region. Faulting regime could be analyzed using focal mechanism ternary diagram analysis, by categorizing the focal mechanisms’ strike, dip and rake values. Thus, in this study we aim to analyze faulting regime and hazard potential in the complex. Maluku setting using ternary diagram analysis.

Keywords: Maluku sea plate, ternary diagram, faulting regime, double subduction zone

1. Introduction

Present day Molucca or Maluku sea possesses a complex tectonic setting. Its location is at the triple junction of three major plate, i.e., Philippine-sea, Eurasian, and Australian plate [1]. It separates volcanic Sangihe arc in the west and volcanic Halmahera arc in the east, forming an arc-arc collision or double subduction in the Maluku sea plate [2]. The ongoing movement of plates and the colliding fore arcs at both sides, are surpassing the Maluku sea plate. At the present, the Maluku sea plate has been almost eradicated by these subductions [3, 4], forming an inverted U-shape beneath colliding fore arcs [2]. Though this collision complex area has low gravity [2], many earthquake events took place in this area: in the subducting slab (depth > 25 km) and above the accretionary complex/collision complex area (0 km < depth < 25 km) [2]. Indeed, the Maluku sea plate might pose earthquake or tsunami hazards to surrounding islands.

Earthquake focal mechanisms can give us a vivid representation of the faulting mechanism of an event: their type and parameter (strike, dip rake, B, P and T axis). Anderson [5] categorized the type of earthquake faulting based on the stress regime into normal fault, strike slip fault and thrust fault. By
utilizing the P/T and B axis parameter, these focal mechanism’s types could be further classified in the Ternary diagram.

As we know that dip slip mechanism, such as thrust fault and normal fault, in the offshore could displace sea columns and trigger tsunamis. Hence, analysing focal mechanisms in the Maluku region is important. In this study we aim to analyse faulting regime and signature in the complex Maluku setting using focal mechanism and Ternary diagram analysis.

2. Data and Methodology

2.1. Ternary Diagram

Ternary diagram categorized focal mechanism into their faulting mechanism, i.e., strike slips, normal or reverse. The diagram utilizes the B, T and P axis plunge of the focal mechanism for the classification. The result is plotted in the diagram using the projection concept of a point in a spherical octant over a planar surface. Frohlich and Apperson [6] represent the spherical octant as a triangle, which can classify the focal mechanism into pure strike slip, pure normal and pure reverse faulting. Kaverina et al. [7] and Kagan [8] further modified the projection and used Lambert Azimuthal Equal-Area. Álvarez-Gómez [9] adopts the modified projection in the Ternary diagram so it could also plot the oblique faulting. Hence, there are seven categories of focal mechanism in the Ternary diagram: normal, normal-strike slip, strike slip-normal, strike slip, strike slip-reverse, reverse-strike slip and reverse. In this study we used the FMC, a Python program for classifying and plotting focal mechanism data [9].

2.2. Data

We used focal mechanisms data from the Global Centroid Moment Tensor Catalog [10, 11] to analyse the earthquake event in our study area. We took events which occurred between January 1st, 1976, to September 30th, 2020, with depth between 0 km to 100 km and with minimum magnitude of Mw 4. The given criteria generate a maximum magnitude of Mw 8 in our study area. There are approximately 999 events. These events are plotted in figure 1.
3. **Result and Discussion**

We plotted all the events in figure 1 to the Ternary diagram in figure 2. The focal mechanisms are classified into pure strike slip, pure normal, pure reverse, and oblique mechanisms. In this study we focus only on the pure mechanisms which we refer as strike slip, normal and reverse faulting mechanisms.

![Figure 2. Ternary diagram of focal mechanisms in Maluku sea plate and surrounding area.](image2)

From the Ternary diagram classification, there are a few strike slip mechanisms (64 events) which are mostly clustered in the inland (0 km – 25 km) of the northern Halmahera Island (figure 3 (a)). For the reverse mechanism, there are 513 events (figure 3 (b)) which are mostly located in the 0 to 50 km. A rather shallow depth of the Maluku sea plate double subduction zone. Indeed, reverse faulting is a common mechanism in the subduction zone [12]. There are several normal mechanisms (80 events) with varied depth in the double subduction zone area. Normal mechanisms are commonly found at the deep part of the subduction system [12]. However, in the Maluku sea plate we found normal events at shallow depth. The shallow normal events might be related to complex collision; and might pose a tsunami hazard [13]. We plotted the normal mechanisms in a map view and cross-section in figure 4.

![Figure 3. (a) Map view of strike slip faulting mechanisms. (b) Map view of thrust faulting mechanisms.](image3)
Figure 4. (a) Map view of normal faulting mechanisms. Dash blue square and red line are cross section area and line. (b) Cross section of normal focal mechanisms which lie in cross section area. Gray circles are showing the non-normal faulting mechanisms event distribution.

We further assessed the stress direction in the Maluku sea plate region. We plotted the focal mechanisms P/T axes inside the area bounded by solid blue square in figure 1 to P/T axes diagram on figure 5 (a) for 0 to 25 km depth and (b) for 25 km to 50 km depth. We used the STRESSINVERSE package [14] to plot the P/T axes diagram. There are 136 and 291 focal mechanisms in the depth ranges of 0 to 25 km and 25 to 50 km, respectively. The depth division follows the interpreted complex collision and the upper double subduction boundary [15]. In the 0 to 25 km depth the P/T axes are scattered. The stress orientation is less consistent, which might be related to the complex collision process. While in the deeper depth (25 to 50 km), we found focused P/T axes which show reverse faulting regime. The reverse stress regime is related to the double subduction process in the Maluku sea plate.
4. Conclusion

Focal mechanisms distribution shows that Maluku sea region has dominantly reverse mechanism and several normal mechanisms with varied depth. The shallow normal mechanisms might be related to complex collisions. Both shallow reverse and normal mechanisms could possibly pose a tsunami hazard. At 0-25 km depth, the stress orientation is scattered due to the complex collision process. While consistent/ focused stress orientation found at 25-50 km depth, which is related to the dominant reverse mechanism in the subduction system.

In the future we will divide the depth section more detail and assess the focal mechanisms, especially the thrust mechanism, in each depth; to get the clear and detail picture of the Maluku sea plate thrusting regime.

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Figure 5. Focal mechanisms plotted in P/T axes for: (a) 0 to 25 km depth (136 events) and; (b) 25 to 50 km depth (291 events). The events are those which located inside the solid blue square in Figure 1. The P/T axes diagrams are plotted using STRESSINVERSE package [14].
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