Analysis of Source Mechanism and Coulomb Stress Change (Case Study: Molucca Sea Earthquakes November 15th, 2014 and November 14th, 2019)

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Abstract. On November 15, 2014, and November 14, 2019, two major earthquakes occurred in the Molucca Sea with a moment magnitude of Mw 7.0 and Mw 7.1, respectively. These earthquakes were caused by the convergence activity between the Sunda Plate and the Philippine Sea Plate which form a double subduction zone in the Molucca Sea. We carried out the moment tensor inversion using Kiwi Tools to analyze the source mechanism for both of the earthquakes. The results show a thrust fault mechanism with the strike, dip, and rake of the ruptured fault planes are 187°, 63°, 85° and 196°, 43°, 83°, for the first and second events, respectively. We refine the location of the two mainshocks and their aftershocks by performing hypocenter relocation using the double difference method. This resulted in NE-SW aftershocks distribution for both events which occurred close to the Molucca Sea Plate boundaries with the mainshocks location are relatively close to each other (± 50.32 km). Finally, we calculate the Coulomb stress changes to analyze the triggering effect between the two major events and between the mainshock and its aftershocks for each event. The results show that the hypocenter of the November 14, 2019 earthquake is in the increased zone of Coulomb stress changes produced by the November 15, 2014 earthquake with the value of 1.2 bar. The aftershocks of both events also occurred in the increased Coulomb stress changes with the range value of 0.5 - 1.8 bar for the first event and 0.2 - 0.8 bar for the second event.

1. Introduction
Molucca Sea is an area with active seismicity due to the historical complex collision that include the Eurasian Plate, Indo-Australian Plate, Pacific Plate and Philippine Sea Plate [1]. The collision formed the Sangihe Arc on the west and Halmahera Arc on the east, and enforce the Molucca Sea Plate subduct beneath the Sangihe and Halmahera arc which form a double subduction. The Meteorology Climatology and Geophysical Agency of Indonesia (BMKG) has recorded 13 earthquakes with magnitude of M>6 in the Molucca Sea from 2014 to 2019. From this series of earthquakes, there was two M>7 earthquakes that occurred in a relatively close distance between each other. Based on BMKG catalog the earthquakes was occurred on November 15, 2014 02:31:41 UTC with moment magnitude of Mw 7.0 and on November 14, 2019 16:17:40 UTC with moment magnitude of Mw 7.1.

The purpose of this study is to enhance our understanding of the seismotectonic characteristics of the Molucca Sea region by identifying the source mechanism of these two large earthquakes and analyzing...
its Coulomb stress changes. A detailed analysis is carried out by relocating the mainshocks and aftershocks hypocenter using double difference method, obtaining the focal mechanism using moment tensor inversion on regional broadband waveform, and calculating the static Coulomb stress changes for both of Mw>7 earthquakes.

2. Data and method
It is necessary to an accurate parameter of the earthquakes to provide a reliable information for better analysis. Therefore, we first relocate the hypocenter of the mainshock and the aftershocks using the double difference method [2]. The method assumes that two earthquakes which has hypocentral distance smaller than its distance to the station will have a same ray path. The relocation process is done by minimizing the time residual between the observation and calculation data.

\[ dr_{ck}^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal} \]

where \( i \) and \( j \) show the index of two adjacent hypocenter and \( k \) is the index of the station. We used the arrival time data of P and S waves obtained from BMKG catalog for mainshocks and aftershocks of the November 15, 2014 event and the November 14, 2019 event. We use the aftershocks for both events in the period of 30 days after the mainshock. The range of the study area is 1.14° - 2.26°N and 126.14° - 126.75°W (Figure 1).

![Figure 1. Map view of study area](image)

Focal mechanism is estimated by performing the moment tensor inversion to the regional broadband waveform. The focal mechanism is used to determine the fault plane parameters, those are strike (\( \Phi_f \)), dip (\( \delta \)), slip along the fault plane, and rake (\( \lambda \)). Moment tensor inversion solves the equation of the moment tensor which can be represented as follows:

\[ u_n(x, t) = M_{pq}(\xi, t) \ast \frac{\partial}{\partial \xi} G_{np}(x, \xi, t)|_{\xi=0} = M_{pq}(\xi, t) \ast G_{np,0}(x, \xi, t) \]

where \( u_n \) is the component of soil displacement at a point \( x \) (station). \( M \) is the moment tensor of point source at location \( \xi \) (source), and \( G_{np} \) is the spatial derivative to \( \xi_k \) is the component of Green's function (Green's tensor) [3]. We use the Kiwi Tools that resolve not only the focal mechanism but also a simplified finite source model which is called as eikonal source model. The inversion is following the procedure in [4] which consist of 3 steps; the first step uses the amplitude spectra inversion to obtain the focal mechanism parameters (without polarity), the second step uses the waveform inversion in time domain to provide the polarity and determine the compression and dilatation quadrant, and the final step
uses the amplitude spectra inversion to obtain the eikonal source model that provide the rupture area, rupture duration, and the rupture propagation direction.

The focal mechanism solution obtained from the last step is then used to calculate the Coulomb stress changes. Characterization using the Coulomb failure criteria [5] has been used to explain the occurrence of failure at the rocks. When earthquake is generated by a fault, this fracture will encourage the changes in stress on the fracture around the fault. In the Coulomb criteria, a fault occurs in a plane when the Coulomb stress exceeds a certain value.

$$\Delta CFF = \tau_\beta - \mu (\sigma_\beta - p)$$

where $\tau_\beta$ is the shear stress in the fault plane, $\sigma_\beta$ is the normal stress, $p$ is the pore pressure of the fluid, and $\mu$ is coefficient of friction. The value of $\tau_\beta$ in this equation must be positive, but the process of calculating the voltages in an area can be positive or negative depending on the potential slip. By assuming simple Coulomb friction models for the earthquake, slip potential will increase or decrease in Coulomb failure stress [6].

3. Result and discussion

3.1. Hypocenter relocation

We have successfully relocated 166 and 284 aftershocks for the first and second event, respectively. The relocation results for two earthquakes are shown in Figure 2. The mainshock of two earthquakes are located in relatively close distance ($\pm$ 50.32 km). The aftershocks are mostly distributed at the shallow depth (< 35 km). The aftershocks distribution shows an SSW-NNE oriented trend which indicate that the strike orientation of the fault. In the vertical distribution also indicate a thrust fault trend with the dip is facing to the west direction for both events. This result corresponds well with previous study [7] about the existence of a splay fault that generated the coseismic of November 15, 2014 earthquake.

![The Earthquake of 15th November 2014](image1.png)  ![The Earthquake of 14th November 2019](image2.png)

**Figure 2.** Map view (upper) and vertical cross section (lower) of relocated hypocenter for November 15, 2014 (left) and November 14, 2019 (right). Yellow stars represent the mainshock, red circles show the aftershocks. Curved red lines show the Molucca Sea plate that subducted beneath Sangihe arc (west) and Halmahera arc (east). Black dashed rectangles indicate the suggested rupture plane.
3.2. Focal mechanism

We use unrotated data of the three-component seismogram from the broadband seismic stations with a distances 10 degrees within the epicenter. The inversion is conducted in the frequency range of 0.01-0.04 Hz with a time window of 60 s for the first and second step, refer to [8] for focal mechanism inversion. The amplitude spectra and displacement waveform fit are shown in Figure 3.

The final step is conducted in the frequency domain with a higher frequency range (0.01 – 0.09 Hz) to obtain the earthquake rupture parameters. The inversion result for both Mw>7 mainshocks are presented in Figure 4. The results show that the rupture for both earthquakes were occurred in the west-dipping fault plane with the strike, dip, rake are 187°, 63°, 85° and 196°, 43°, 83° for the first and second event, respectively. Both events also have similar rupture area (30 × 30 km) with the centroid depth is relatively close (39.9 km and 37.4 km). A slight difference for both events is on the rupture propagation. The rupture for the first event propagates predominantly downward along the fault plane or to the west direction, while the second event has an oblique rupture propagation toward the southwest direction. Based on the source mechanism solution and the relocated hypocenter distribution, the November 15, 2014 and the November 14, 2019 events were originated from the same fault with a similar thrust fault mechanism.
3.3. **Coulomb stress changes**

The Coulomb stress change for the November 15, 2014 and November 14, 2019 events was calculated by using Coulomb3.3 program. In its processing, we used the equation by input magnitude and orientation of the fault (strike, dip, and rake) [9], so the result shows the fault area is $48.37 \times 22.32$ Km. Then, the coefficient of friction area of subduction (thrust faults) has high coefficient, that is 0.8 [10]. From the results showing that change of stress in aftershocks that occurred on November 15, 2014, we know that the range of Coulomb stress is from 0.5 to 1.8 bar and on November 14, 2019 the range of Coulomb stress is from 0.2 to 0.8 bar (Figure 5). The result of calculation, we also know the Coulomb stress change during coseismic on November 15, 2014 affected the location of the hypocenter on November 14, 2019, which Coulomb stress is 1.2 bar (Figure 6). That means we can conclude that the earthquake on November 15, 2014 gave the increase in stress at the hypocenter location of the earthquake on November 14, 2019.

**Figure 5.** The distribution of Coulomb stress changes on November 15, 2014 (left) and on November 14, 2019 (right) which is seen horizontally at the depth of the fault plane. The red dots are the distribution of the aftershocks, the green line is the projection of the fault trail horizontally on the surface, and the red box in the middle of the blue zone is the area of fault rupture.

**Figure 6.** The figure on right side is result of slice from line AB in the figure on left. East-West slice Coulomb stress changes from the event on November 15, 2014 for the event on November 14, 2019. Red area is positive stress and blue area is negative stress.
4. Conclusions
Based on the analysis that we have discussed, aftershocks from the two mainshocks have a similar pattern which shows a SW-NE orientation. The two mainshocks hypocenter also obtained in relatively close distance between each other (± 50.32 km). The November 15, 2014 and November 14, 2019 earthquakes were originated from the same fault and with a similar thrust fault source mechanism. The rupture area for both events are 30 × 30 km with a predominantly downward rupture propagation for the first event and an oblique downward rupture propagation for the second event. The Coulomb failure stress (CFS) changes analysis shows that the aftershocks of both events were occurred in the positive CFS area and the November 14, 2019 event has been triggered by the November 15, 2014 event with a Coulomb stress changes value about 1.2 bar.

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