Source mechanism identification using regional waveform inversion approach, case study: July 7, 2019 Molucca Sea earthquake

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Abstract. Molucca Sea is a seismically active area in eastern Indonesia. An earthquake occurred near to Ternate City, Province of North Maluku (M6.8: depth 29 km) on July 7, 2019. To investigate the detail about the mechanism of the earthquake, we analyzed the moment tensor of the earthquake by applying the regional waveform inversion. We used three components waveform broadband data from 18 station of IA-net seismic network in this study. We carried out the deviatoric mode to determine the double couple and compensated linear vector dipole (CLVD) component of the earthquake. The position and origin time of the earthquake were calculated by a space-time grid search in vertical and lateral positions. The frequency band of 0.01 – 0.023 Hz is used in the inversion process to reduce the instrument low-frequency disturbance and the effect of inaccurate velocity model for the synthetic seismogram. The moment tensor inversion result shows that the source mechanism of the earthquake is transpressional fault. This result agrees well with the tectonic setting of the study area.

1. Introduction
The triple junction of converging plate between Eurasia, Australia, and Philippines Sea plates generating the unique tectonic setting in the Molucca Sea [1]. Unique tectonic setting of the Molucca Sea plate termed as divergent double subduction, that a plate has a subduction zone in both east and west boundary [2]. Sangihe slab in the west and Halmahera slab in the east having been subducted down to the discontinuity of upper and lower mantle. Both subducting slab dip at angles approximately 45° [3,4]. The plate lies beneath the forearc basin and the accretional complex of the Molucca Sea. The accretional complex being the most seismically active region leads to the uplift of Talaud-Mayu ridge at the center of the Molucca Sea [5-7]. This area marked by the intense shallow seismicity.

Molucca Sea earthquake on July 7, 2019 occurred at 15:08:40 (UTC) near to Ternate City, Province of North Maluku. The event location was at latitude 0.54 degrees and longitude 126.15 degrees presumably in the Talaud-Mayu ridge. The earthquake had been categorized as a shallow-depth earthquake of 29 km. The moment magnitude of 6.8 made this earthquake usable to determine the earthquake mechanism. Global Centroid Moment Tensor (GCMT) determined the earthquake mechanism with strike 341°, dip 49° and rake 34 for 1st fault plane and strike 228°, dip 65° and rake 134 for 2nd fault plane.
In this study, we applied regional waveform inversion to determine the mechanism of the July 7, 2019 Molucca Sea earthquake. The purpose of this paper is to provide more accurate moment tensor and earthquake mechanisms of this seismic event. We compare the result of the regional waveform inversion using local seismic stations from IA-network with the GCMT global station. The final result determined the source of this seismic event, whether from the subduction slab or the thrust fault in the accretional complex of Talaud-Mayu ridge.

2. Methodology
The earthquake waveforms were obtained from German Research Center of Geosciences (GFZ) seismological data archive and each station chosen from IA-network. Usable waveform data controlled by the continuity of the records, noise level, station distance, and azimuthal coverage. Based on that parameter control, a total of 18 stations were used to determine the earthquake source mechanism. The distribution of the seismic station we can see in figure 1. We applied the regional waveform inversion by using ISOLA code to model the source mechanism. The retrieved waveform converted from SAC format into ASCII to conform to the needs of ISOLA code [8]. The instrumental correction had been done to remove the effect of instrument response so the record showing the corrected velocity data.

![Figure 1. The focal mechanism, that represent the source mechanism of the July 7, 2019 Molucca Sea Earthquake. The triangles are the seismic station being used in the regional waveform inversion.](image)

An essential stage in the waveform inversion is to determine the usable frequency range. We try several filters to avoid low-frequency disturbances and the effect of inaccurate velocity model. The frequency band used for the inversion stage estimate between 0.01 – 0.023 Hz. The velocity model used in the inversion adopted from the velocity model of AK135 which designated to provide a good fit to the full waveform of the seismic phase. The velocity model had been used in the inversion can be seen in figure 2(a). The velocity model was being used as the input of Green’s functions computation [9] with the maximum frequency of 0.05 Hz. Another input for the Green’s function computation is the geometries of trial source position [10]. In this study, there is two inversion stage based on geometry. The first stage was using a one-dimension vertical source position to estimate the optimum depth of the event centroid. The next stage was designing a plane on the depth determined before, to estimate the best lateral position of the event centroid.
Green’s function computation was generating the synthetic seismogram for each station which will have been used in the inversion. Regional waveform inversion finding the best fitting between the observed displacement from seismic records with the synthetic seismograms by iterative deconvolution method [11]. The moment tensor calculated at each trial source position based on the space-time grid. The calculation carried out with deviatoric mode to resolve the double couple and compensated linear vector dipole component of the earthquake. The dominant component should be the double couple because this seismological event source comes from the faulting mechanism. The quality of the inversion process quantifies by the variance reduction (misfit) between the record from the seismic station and the synthetics seismograms [12].

![Figure 2. (a) velocity model used for the regional waveform inversion to calculate the Green’s function and the synthetic seismograms. (b) the grid search for the inversion and white line showing the subduction of Moluca Sea plate on both west and east side (white line).](image)

### 3. Result and Discussion

The first stage of inversion, a vertical search had been done for depth between 10-40 km, in the interval of 2 km. The event’s best vertical location had been calculated in depth of 22 km and used as a depth reference of lateral location. The lateral search geometry has a 15 km interval in the grid of 7 × 7 with origin location in the center. The distribution of grid search for inversion can be seen in figure 2(b). The final time-space search showing the centroid time-shifted 3 seconds before the origin time, the location shifted 0.13° to the north and 0.13° to the east. The moment tensor was calculated for Mrr, Mtt, Mpp, Mrt, Mrp, and Mtp component with a value of 1.332, 0.588, -1.920, -0.737, 0.160, and -0.877 with the scalar moment of 2.059e19.

The deviatoric dominated by the double couple component with 71.6% and confirmed the event caused by the tectonic activity. The overall variance reduction is 0.75 that means the synthetic seismograms highly match the observed waveform data. The variance reduction calculated for each component in every station and showed in figure 3. There are two waveforms not being used for the inversion, from the MPSI station EW component and BKSI station NS component. The fit of the synthetic of that two components very poor, so it is not included in the inversion to enhance the quality of the inversion result.
Figure 3. Waveform comparison between observed and synthetic. The number in end of each waveform showing the variant reduction for each station components represent the fit of inversion result. The grey waveform means it was not included in the inversion process.

Table 1. Comparison of the July 7, 2019 Molucca Sea earthquake source mechanism.

| Catalogue | NP1 Strike | NP1 Dip | NP1 Rake | NP2 Strike | NP2 Dip | NP2 Rake | T axis azimuth | P axis azimuth | T axis plunge | P axis plunge |
|-----------|------------|---------|----------|------------|---------|----------|----------------|----------------|---------------|---------------|
| Calculated| 228        | 56      | 135      | 347        | 54      | 43       | 196            | 288            | 54            | 1             |
| GFZ       | 224        | 53      | 126      | 353        | 50      | 52       | 196            | 289            | 62            | 2             |
| GCMT      | 228        | 65      | 134      | 341        | 49      | 34       | 187            | 288            | 50            | 9             |

The source mechanism from regional waveform inversion result compared with the source mechanism from GFZ and GCMT catalogue in table 1. Our inversion results similar with the other source mechanism but with slight difference caused by the different inversion method, velocity model, and station usage. The source mechanism plotted into focal mechanism to more intuitively interpreted
and showing the fault mechanism categorized as a thrust fault with slight component of lateral movement. The mechanism of this type of fault caused by compressional force in the earth crust related to the divergent double subduction of the Molucca Sea plate. This type of fault commonly known as transpressional fault.

The event occurred in the shallow depth so it might be not caused by the subduction activity. Crustal in the shallow level consist of the forearc basin and the accretional complex. The accretional complex being the most active structure which generating an uplift of the Talaud-Mayu ridge in the center of the Molucca Sea. This seismic activity

4. Conclusion
Regional waveform inversion has been successfully applied to July 7, 2019 Molucca Sea earthquake to estimate the source mechanism. The result shows that the earthquake mechanism is a transpressional fault in the depth of 22 km. This event agrees well with the tectonic setting of the study area and related to the fault activity in the accretional complex of Talaud-Mayu ridge based on the shallow depth of the earthquake and the mechanism of the fault.

Acknowledgments
This study was supported by Indonesian Ministry of Research Technology and Higher Education INSINAS Grant 042/P/RPL-LIPI/INSINAS-1/II/2019. Seismic data were obtained from GEOFON data center of the GFZ German Research Center for Geoscience.

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