Focal Mechanism Analysis of the September 25th, 2019 Mw 6.5 Ambon Earthquake and Its Implication for Seismotectonics

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Abstract. On September 25th, 2019, an Mw 6.5 earthquake occurred in Ambon, Maluku Province, Indonesia, and caused casualties and infrastructures damages. The epicenter located in a tectonically active region with the potential strike-slip and thrust faulting earthquake sources, yet the responsible fault is still not well understood. Based on focal mechanism solutions from available seismological agencies, i.e. USGS, GFZ, GCMT, and BMKG, the earthquake has a similar strike-slip focal mechanism, although there are discrepancies on detailed source parameters. To provide a better understanding of the earthquake mechanism and seismotectonic, we apply the Cut-and-Paste (CAP) focal mechanism inversion method to broadband seismic waveforms from regional and teleseismic distances. The CAP inversion results on the regional data grouped in different distance ranges show a robust strike-slip solution. We then refine the earthquake focal depth by performing the CAPtele inversion and resulted in a depth of 12 km with similar fault plane solution as the regionals. The ruptured fault plane is resolved by a directivity analysis using azimuthal pattern of the apparent source durations, which indicates an obvious unilateral rupture propagation toward SSE direction. Our result suggests the NNW-SSE orientated fault is the ruptured fault plane, which is also consistent with the near N-S distributed aftershocks. This fault is located in a narrow sea between Seram, Ambon and Haruku island and was not reported yet in previous studies. The Coulomb failure stress (CFS) changes analysis of the mainshock shows that the Ambon earthquake has promoted the off-fault aftershocks which occurred to the west of the ruptured fault.

1. Introduction
A moderate-shallow earthquake hit Ambon, Indonesia with magnitude Mw 6.5 on September 25, 23:46 UTC. The earthquake caused strong shaking throughout Seram Island with the maximum intensity of VI MMI, as shown by felt reports in the Provincial Capital Ambon. Thousands of structures were damaged and dozens of fatalities were also reported in the aftermath of the earthquake. The mainshock was then followed by hundreds of aftershocks within a week. According to the Indonesian Meteorology Climatology and Geophysical Agency (BMKG) the earthquake has a strike-slip focal mechanism and the fault planes have sub-vertical dips, showing either a right-lateral N-S orientation fault or a left-lateral E-W orientation fault. The moment tensor solution from other seismological agencies (e.g. GFZ, USGS, GCMT) also present a strike-slip focal mechanism although there are detailed differences between the source parameters (Table 1).
The inconsistency of the source parameters in a tectonically active region with the potential strike-slip and thrust faulting earthquake sources requires further investigation of the earthquake source parameters, including the ruptured fault plane. The Banda Arc region including Seram Island is a product of complex ongoing collision and rotation interaction between the Eurasia and Australia plates along with Philippine Sea microplate. Due to this complex interaction, region of Seram Island and Ambon have at least three major earthquake sources (North Banda subduction, Seram Fault Thrust Belt, Kawa Fault) and numerous small faults [1]. This earthquake could occur on the east-west fault crosses Kairatu that corresponds to lineament of topography in northern and southern part of Seram, or an unknown north-south trending fault. Left-lateral Kawa strike-slip fault was first presumed to be the responsible fault because the epicenter of the earthquake is located close to its lineament. Seemingly after further analysis, despite numerous fracture zone and faults, the Ambon earthquake is more likely to have occurred on an unknown or unmapped fault. Therefore, it is important to provide more robust source mechanism solution in order to reveal the unmapped faults in the region because such faults near densely populated city could be the hosts for unexpectedly seismic events.

Here we perform the Cut-and-Paste (CAP) inversion method using regional and teleseismic data to obtain the focal mechanism and depth of the Ambon earthquake. We then conduct a directivity analysis to define the actual fault plane as well as the rupture direction propagation. We also relocate the aftershocks and calculate the Coulomb failure stress (CFS) changes of the mainshock to verify the effect on the seismicity of the surrounding area.

2. Data and method
In this study we carried out the Cut-and-Paste (CAP) method [2, 3] to determine both depth and source mechanism of the Mw 6.5 Ambon earthquake. The idea of CAP method is to divide the seismogram into five segments including two segments of Pnl wave and three segments of surface wave and invert them independently. This approach provides the advantage due to the different sensitivity of the body and surface wave to varied parts of crustal structure. The CAP method also allows time shifting on each segment which make the inversion is less dependent to the assumed velocity model and earthquake location inaccuracy. The dominance of surface wave amplitude then can be avoided by applying different weight to the body and surface wave, while the dominance of near station records is balanced by the distance scaling factor. The best solution of the focal mechanism, source depth, and moment magnitude are obtained using grid search procedure by minimizing the misfit between the observed and synthetic seismogram. We applied the CAP inversion to both regional and teleseismic data to get better constrain for the solution. The regional data were collected from the BMKG broadband seismic network within 20 degrees from the epicenter (Figure 1b), while the teleseismic data were retrieved from the stations available at IRIS server (https://www.iris.edu) within the range of 30-90 degrees (Figure 1c).

The full waveform recorded at regional stations were used in the inversion with the intention of using the body and surface wave. We first corrected the data by removing the instrument response and rotating the two horizontal components to radial and tangential components. The Green’s functions were computed using frequency-wave number (F-K) method [4]. The modified PREM 1-D velocity model [5] with the addition of a detailed crustal model from Crust1.0 [6] was used to calculate the synthetics seismogram for both regional and teleseismic distances. We then applied the inversion on 50 s window length of Pnl wave and 180s window length of surface wave. The synthetic and observed signals were filtered using 4th order Butterworth bandpass in the frequency band of 0.01-0.07 and 0.005-0.02 for Pnl wave and surface wave, respectively. The example of waveform fit for regional distance is shown in Figure 2a.

We used only P and SH wave records for the CAPtele inversion considering the teleseismic surface waves are more distorted due to the lateral heterogeneities over long propagating distances. The tel3 program was used to compute the synthetics waveform for teleseismic distance. The teleseismic waveform inversion was conducted at the frequency band of 0.01-0.05 Hz and 0.01-0.04 Hz for P and SH wave, respectively, which fit of the waveform is shown in Figure 2b.
Figure 1. (a) Map view of the study area with moment tensor distribution of the historical Mw≥5.0 earthquakes from GCMT catalog around the 2019 Ambon earthquake (yellow star) and its aftershocks (purple circles). Colored slab contours obtained from slab2.0 [7]. Black box shows the map in Figure 4. (b) Regional stations used in the CAP inversion, different colors indicate different distance from the epicenter (blue for 5º, red for 10º, black for 20º). Red box shows the map in panel (a). (c) Teleseismic stations used in the CAPtele inversion (black inverted triangles). Red box shows the map in panel (b).

3. Result and discussion
The CAP inversion was performed to the regional data for three different station distance ranges and resulted in a strike-slip mechanism for all of the models (Table 1). We excluded three closest stations to the epicenter because the near-source ground shaking of the earthquake was much affecting the waveform. The best solution is the outcome from the inversion on all stations within 20 degrees from the epicenter (Figure 2a). The focal mechanism indicated a near-vertical dip for both nodal planes which had NNE-SSW and WSW-ENE orientation with the source parameters were 252/82/-8 and 343/82/-173 for strike, dip, and rake, respectively. The earthquake focal depth from the three inversions were obtained at 11 km and 16 km (Figure 2c), although there was local minimum at 12 km depth for 5- and 20-degrees inversions.

Table 1. Summary of the double couple point source solutions for the 2019 Ambon earthquake from this study and its comparison with the solutions from available seismological agencies.

| Model     | Fault Plane 1     | Fault Plane 2     | Depth (km) | Magnitude |
|-----------|-------------------|-------------------|------------|-----------|
| GlobalCMT | 253/84/-12        | 345/78/-174       | 12.7       | 6.5       |
| USGS      | 71/75/-12         | 164/78/-165       | 11.5       | 6.46      |
| GFZ       | 76/76/9           | 343/81/165        | 14         | 6.4       |
| BMKG      | 256/89/9          | 346/81/179        | 10         | 6.6       |
| CAP (0-5) | 252/76/-15        | 346/75/-165       | 16         | 6.5       |
| CAP (0-10)| 251/74/-17        | 346/74/-163       | 11         | 6.46      |
| CAP (0-20)| 252/82/-8         | 343/82/-173       | 16         | 6.48      |
| CAPtele  | 253/74/-7         | 345/83/-164       | 12         | 6.59      |
We carried out the CAPtele inversion at a relatively high frequency to include the depth phases to better constrain the focal depth. The inversion yielded the focal depth of the Ambon earthquake in a depth of 12 km (Figure 2d). The obtained magnitude was 6.59, slightly larger than the regional result. A strike-slip mechanism was also acquired with the parameters almost similar compared to the regional result (Figure 2b). The good agreement came from the strike and dip orientation with insignificant differences. However, an obvious difference appeared from the rake angle with the CAPtele result provided a bigger dip-slip component compared to the CAP solution. This was probably caused by the incident angle which is more evident for the teleseismic stations than the regionals.

**Figure 2.** Best solution and representative waveform fit for (a) CAP inversion on regional data and (b) CAPtele on teleseismic data (black lines are observed, red lines are synthetic). Depth misfit curve for (c) CAP and (d) CAPtele inversion.
Figure 3. Azimuthal distribution of apparent durations obtained from fast directivity inversion, including the map view (left) and azimuthal distribution (right). Colored circles show the apparent durations according to the color scale, black line shows the best matching pattern for unilateral rupture.

We further clarify the source of the Ambon earthquake by performing a directivity analysis to determine the actual fault plane. The directivity analysis was carried out using the amplitude spectra inversion to derive the apparent duration at each station [8], which can reveal the direction of the rupture propagation. The idea is the stations which located toward the rupture propagation will have shorter duration, and longer duration for stations in the opposite direction [9]. We used only the P-wave recorded at seismic stations within 10 degrees from the epicenter and applied a bandpass filter in the range of 0.01-0.1 Hz to get the amplitude spectra for each station. The inversion was conducted by fitting the observed and synthetic spectra from several possible source duration using grid search procedure. The apparent durations were well distributed and resulted in a unilateral rupture propagating to southeast direction (Figure 3). This indicates that the Ambon earthquake was generated by a fault with NNW-SSE orientation. This also implies that the earthquake occurred in a northeast-dipping plane and the rupture propagated opposite to the strike direction.

Based on the focal mechanism and the focal depth, the Ambon earthquake is estimated did not take place by the subduction occurring in the region. The slab beneath the epicenter location is around 30-40 km for a subduction event with the strike orientation is NW-SE (Figure 1a). Furthermore, a shallow subduction event is commonly indicated by a thrust fault. Therefore, it is expected to be a local fault that was responsible for the earthquake. However, we cannot determine the possible existence of local faults based on the surface morphology since the epicenter and mostly of the aftershocks were distributed at the sea between the Seram, Ambon and Haruku Island. Historical seismicity with similar mechanism at the same or adjacent locations was also unavailable.

We did the aftershock relocation using the double-difference algorithm [10] and resulted in a predominantly N-S distribution with mostly occur at the depth of 2 to 10 km. This result corresponds well to the NNW-SSE orientation of the Ambon earthquake. However, a detailed study using local seismic network shows that the aftershock distribution deviates from the main rupture plane with a diffuse pattern at both ends and is therefore thought to be related to reactivation of minor faults around the fault plane [11]. The aftershocks also occurred to the west of the earthquake fault in the Ambon Island. We explain this off-fault occurrence using Coulomb failure stress analysis. Figure 4 shows the Coulomb stress changes distribution caused by the 2019 Ambon earthquake using the focal mechanism from the regional CAP inversion result with the focal depth of 12 km.
Figure 4. Coulomb stress changes of the 2019 Ambon earthquake at depth of 5 km. Dark red circles show the M>3 relocated aftershocks, yellow rectangle and green line show the map and surface projection of the fault, respectively.

The off-fault aftershocks on the western side occurred in the positive Coulomb stress changes which imply that this aftershock cluster has been triggered by the mainshock. This occurrence also indicates that there could be a potential earthquake source in the region. The results of this study are expected to be useful for increasing public awareness and assisting the earthquake disasters mitigation efforts.

4. Conclusions
We have successfully investigated the focal mechanism of the 2019 Ambon earthquake using broadband waveform inversion. The results show that the earthquake had a right-lateral strike-slip mechanism with the focal depth of 12 km. The directivity analysis provided a clear azimuthal pattern of the apparent durations which conclude that the earthquake was occurred in a northeast-dipping plane with a unilateral rupture propagate to SSE direction, as opposed to the strike direction. These results correspond well with the N-S aftershock distribution. The Ambon earthquake is expected to be generated by an N-S orientated unmapped fault at a narrow sea between Seram, Ambon, and Haruku Island. Based on the Coulomb failure stress analysis, the mainshock has generated an off-fault aftershocks cluster that occurred to the west of the ruptured fault.

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