Bayesian Inference of Centroid Moment Tensors of the 2019 Ambon (Mw 6.5) Aftershock Earthquake Sequence, Indonesia: A Preliminary Result

Abstract. The Ambon Mw 6.5 earthquake on September 26th, 2019, had contributed to give severe damages and significantly increased seismicity around Ambon Island and surrounding areas. Mainshock was followed by aftershocks with spatial distribution added to the impact of destructions in this region. We investigated aftershocks sequences to reveal the effect of mainshock toward the change in the in-situ stress field, including the possibility of the existing faults reactivation and the generation of aftershocks. We inferred centroid moment tensor (CMT) for significant aftershock events with Mw more than 4.0 using waveform data recorded from October 18th to December 15th, 2019. The aftershock focal mechanism was determined using the Bayesian full-waveform inversion code ISOLA-Obspy. This approach provides the uncertainty of the CMT model parameters. From ten CMT solution we had inferred in three seismic clusters, we found that majority of events have a strike-slip mechanism. Four events located on the south of the N-S trendings have a dextral strike-slip fault type, reflected the rupture of the mainshocks fault plane. Three events in the cluster of Ambon Island are dextral strike-slip, confirming the presence of the fault reactivation. Meanwhile, three CMT solutions in the north show the dextral strike-slip faulting and may belong to the mainshock main fault, connected with the cluster in the south.

Keywords: Aftershocks, Ambon Mw 6.5 earthquake, Bayesian full-waveform inversion, fault reactivation

1. Introduction
The Ambon earthquake on September 26, 2019, with a magnitude of 6.5 Mw had increased the seismicity level in the surrounding area, where aftershocks with a significant amount consistently occurred over several months after the mainshock. The earthquake exhibited a strike-slip fault type of focal mechanism with N-S strike trends [1]. Most of the aftershock events are parallel with the north-south trendings from the SW of Seram to
the area between Ambon and Haruku island. We noticed that two cluster events appeared to be outside the supposed main fault area where most of the aftershock occurred. One cluster is located on Ambon Island with a North-South to NE-SW trend parallel to the surface faults in the region. On November 12, 2019, an aftershock event with a magnitude of 5.1 Mw occurred in this area. Another suspected cluster is in the north that shows a branching of the aftershock distribution. These two findings raise our consideration that the Ambon earthquake aftershock occurred in more than one sequence, and may involve the presence of fault reactivation.

The analysis of the earthquake aftershock sequence has become an interesting issue to be analyzed. Mainshock is probably followed by direct aftershock that triggered by a given primary shock and also secondary aftershock that are not related to the original mainshock [2]. Understanding the sequences of aftershock is quite essential to reveal the rupture process of an earthquake sequence. In other words, we need to clarify how the aftershock generation occurs. Many seismologists reveal the geometry of the mainshock fault plane based on the distribution of aftershocks [3]. Meanwhile, a study of the focal mechanism could give us a better understanding of the physical process of an individual seismic event as it provides information about the fault plane parameter. In the present study, we combined accurate determination of hypocenter and estimated focal mechanism to reveal these issues. However, this study focuses more on the CMT solution in which the focal mechanism will be analyzed further to interpret the generation of aftershock events.

2. Methodology

2.1. Waveform Data

We used earthquake waveform data of aftershock events on the period October 18 to December 15, 2019, which were recorded by 11 temporary local seismic networks deployed by ITB, BMKG, and BPNP and four regional BMKG seismic stations.

2.2. Estimation of focal mechanism

The Bayesian full-waveform CMT inversion approach was applied using python-based ISOLA-Obspy programming [4]. This method uses a combination of assessing the full moment tensor by linear least-squares approach and the estimation of centroid location and time by grid search [5]. The full-wavefield Green Functions are constructed by the discrete wavenumber method [6] in a 1D velocity model with homogenous layers. Then, the inverse problem is solved within the Bayesian framework [7]. The events were selected based on the seismic cluster of the hypocenter and then we inferred CMT of aftershock earthquakes with Mw magnitude more than 4.0. We also included events with magnitude below the criteria to accommodate the CMT solution in all clusters.

Waveform velocity data are corrected from the instrument responses and then filtered by a bandpass filter and integrated into displacement waveforms. We selected signals by executing Mouse Trap code [8], where station components with the high noises and disturbances are rejected. The bandpass filters cut-off were determined manually thorough evaluation based on the best waveform fitting. Filtered and integrated waveforms were downsampled to the sampling frequency of about 1.0-1.2 Hz to ease the computational process.

![Figure 1](image-url)  
**Figure 1.** Example of selected signals by executing Mouse Trap code. The output visualize steplike disturbance in the integrated (raw displacement) from AAI station on N and E component.

We set a dense grid in our grid search parameter where the step of the grid point was on the range of 0.1-0.4 km in all three coordinates within the distance of 2-5 km from the CMT centroid location. With standard time
grid steps of 0.6-0.8 s, the time grid covers 0-3 s after the hypocenter time. 400 possible solutions was
generated from ten-dimensional posterior PDF. We decompose the MTs solution into DC and CLVD component.

Figure 2. Example of selected CMT solution on a grid point by spatial grid search from an aftershock event
occurred on Oktober 18, 2019 11:36:37 UTC. The beachball size reflected the value of variance reduction (VR),
where the best solution is marked by red circle. The background color represents the inverted centroid time at a
specific grid point, while the contour lines represent the condition number.

3. Result and Discussion
The CMT solution parameters for all nine events are shown in Table 2, consisting of CMT location, magnitude,
Variance reduction (VR), fault parameters (strike, dip, and rake) for the two nodal planes, DC percentage, and
DC uncertainty. We checked the reliability of our results based on VR percentage, DC percentage, and DC
uncertainty. The CMTs solutions are acceptable if VR value> 40%, DC percentage> 50%, and uncertainty
<30%. we defined these criteria based on [4] where we simplify and downgrade the criteria for VR from 50%
to 40%. Based on our results, 8 out of 9 events had VR values> 40%. Then there are five events with a DC
component> 50% where events 1 and 7 have a significant percentage of DC (74 and 88%). Most of the events
have low uncertainty, except event numbers 4 and 7 with an uncertainty of more than 20%. We noticed that
these two events have a small magnitude (below 3.2 Mw) for which the inversion process in our data
processing didn’t give robust solutions.

Figure 3 below shows the focal mechanism distribution derived from The Bayesian CMT full-waveform
inversion. The majority of CMT solution showed strike-slip fault type. Four solutions in the southern cluster
were dextral strike-slip mechanism with N-S strike orientation. Similar to the solutions in the south, The
northern cluster was also characterized by dextral strike-slip faulting with N-S strike trends but the dip was not
so steep as the south. We considered that The CMT solution in the southern and northern part of the
aftershocks distribution was still correlated with the rupture of the mainshock fault plane. However, the CMT
solution in Ambon was strike-slip with N-S strike trends. These events may belong to the fault reactivation
triggered by stress change during the aftershock sequences which impacted to the surrounding areas.
Table 1. Parameters of the inferred CMT solutions

| Event ID | CMT Location | Depth (km) | Mw  | VR(%)  | DC Component (1) | DC Component (2) | DC (%) | Unc. (%) |
|----------|--------------|------------|-----|--------|------------------|------------------|--------|----------|
| 1        | -3.642       | 128.388    | 5.3 | 4.2    | 58               |                  |        |          |
| 2        | -3.61        | 128.230    | 7.0 | 4.2    | 47               |                  |        |          |
| 3        | -3.636       | 128.348    | 7.4 | 4.0    | 40               |                  |        |          |
| 4        | -3.399       | 128.345    | 4.0 | 3.2    | 50               |                  |        |          |
| 5        | -3.635       | 128.345    | 6.5 | 3.8    | 53               |                  |        |          |
| 6        | -3.609       | 128.377    | 5.0 | 3.8    | 44               |                  |        |          |
| 7        | -3.396       | 128.313    | 9.0 | 3.0    | 9                |                  |        |          |
| 8        | -3.579       | 128.243    | 10.7| 3.6    | 44               |                  |        |          |
| 9        | -3.564       | 128.255    | 6.6 | 4.2    | 68               |                  |        |          |

Figure 3. Map of Focal mechanism distribution derived from Bayesian CMT full-waveform inversion for nine aftershock events. The solution is shown by blue beachball with event numbers correspond to data in Table 1. A green star symbol depicts the mainshock event. The cyan and yellow reverse triangles depict the BMKG stations and local stations respectively.

4. Conclusions

CMT solutions of nine aftershocks had been inferred using CMT inversion with a Bayesian framework. In general, the parameter of the CMT solution followed the criteria we had set before in which 90% of data give VR values more than 0.40. Most CMT solutions give a high percentage of DC components with low
uncertainties for events with a magnitude greater than Mw 4.0 and show a higher value of uncertainties for events with a small magnitude with the order below 3.5 Mw. From the focal mechanism solution, we concluded that the event cluster located on the north and the south which have a dextral strike-slip mechanism reflect the reupture of the mainshock fault plane. While three solutions in Ambon Island with dextral strike-slip faulting proved the presence of fault reactivation.

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