Preliminary Results: Probabilistic Non-Linear Method to Determine the Hypocenter Location in the Molucca Sea Collision Zone from BMKG Networks

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Abstract. Molucca Sea collision zone is a region which has very complex geology and tectonic setting, producing high seismicity and volcanoes activities. In this study, we have determined hypocenter location around the region using local & regional network of Agency of Meteorology, Climatology, and Geophysics, Indonesia (BMKG). We used 1,647 events that recorded by 32 seismic stations. We repicked the P-and S-phase manually and have been successfully determined ~17,628 P and ~17,628 S arrival times. The P- and S-arrival times are used to determine the hypocenter location by applying NonLinLoc method which estimating the probability density function (PDF) using the oct-tree importance sampling algorithm. Our preliminary results show that the seismicity beneath the Molucca Sea collision zone forming a double subduction pattern which is dipping westward under the Sangihe Arc, reaching a depth of ~ 600 km and eastward under the Halmahera Arc, reaching a depth of ~ 250 km. The seismicity pattern under the Sangihe Arc deepens to the north and the deep earthquake events increase in number. The seismicity is related to the Molucca Sea Plate which is dipping into west and east direction beneath Sangihe-Halmahera Arc. To have a further understanding of the complex tectonic activity in this area, our future work will focus on conducting a seismic tomographic inversion to determine the 3D seismic velocities structure around the Molucca Sea collision zone.

1. Introduction
The Molucca Sea plate, a microplate flanked by three main plates: the Pacific plate, the Eurasian plate, and the Australia-Asian plate, is one of the regions with the highest seismic activity on earth [1,2,3].
The Molucca collision zone is a very complex region due to the interaction of the Halmahera Plate, the Molucca Sea Plate, and the Sangihe Plate. The interaction of the plates creates the Halmahera volcanic arc, the Sangihe volcanic arc, the double subduction, active faults, ridges, and earthquakes [1,4–7].

The Halmahera arc which is located in the eastern part and the Sangihe arc which is located in the western part converging each other at the Molucca Sea to form a collision zone [5]. This tectonic activity makes the earthquake distribution occurred in two Benioff zones, dipping away from each other. Beneath the Sangihe arc in the western part, the earthquakes distribution is deeper than beneath the Halmahera arc in the eastern part [6–8]. It is also shown in the latest research which presents a vertical cross-section of an inverted “V” seismicity pattern beneath the Molucca Sea area [9–12].

In this study, we reidentify the P- and S-phases from BMKG waveform data to determine the hypocenter location. We use a probabilistic non-linear location method with an oct-tree importance sampling approach to determine the hypocenter location [13]. We aimed to get a more accurate earthquake hypocenter location to better identify the patterns and the geometric structures beneath the Molucca Sea.

2. Data and Methods

The waveform data used is from BMKG network from period of January 1, 2010, to December 31, 2017. We used earthquake with a magnitude≥ 4. The total earthquakes recorded are 1,647 events which distributed in an area of 1.5° S - 4.25° N and 121.5° E - 129.5° E. The number of stations used is 32 stations which distributed in an area of 4.8° S - 4.25° N and 120.5° E - 134.5° E (Figure 2). The re-picking process of P- and S- waves is carried out manually and to help with quality control of the re-picking process we used Wadati diagrams.

The hypocenter determination was carried out by applying the probabilistic non-linear location method [13]. This method determine the "optimal" hypocenter by estimating the probability density function (PDF) using an oct-tree importance sampling approach. The algorithm used was developed by Moser et al., Tarantola and Valette, Wittlinger et al., [14–16], summarized in the NLLoc program [13,17]. We used a 3D seismic velocity model from high-resolution tomographic imaging results beneath Indonesia [18] which is a regional-global seismic velocity model.

3. Results and Discussions

From the re-picking process of 1,647 events, we can identified ~ 17,628 P- and ~ 17,628 S-arrival times with the Wadati diagram for all data shown in Figure 1. The Wadati diagram is a diagram that shows a linear relationship of the P-phase arrival time with the difference between the P- and S-phases arrival times which could be used to determine the origin time of the earthquake and the Vp/Vs value [19].

![Figure 1. Wadati diagram from all of the re-picked P- and S- arrival times with the Vp/Vs ratio is 1.76.](image-url)
The horizontal results of hypocenter location from the probabilistic non-linear method using the NLLoc program are shown in Figure 2, and vertical cross-section results in Figures 3 and 4. Based on Figure 3 (profiles A-A', B-B', C-C'), seismicity in the Molucca Sea Collision Zone is mostly occurred in the subduction area. In the profile A-A' of Figure 3, seismicity clusters around the slab of Sulawesi (blue line) are at a depth of ≤ 100 km and are above the Molucca Sea Plate which is subducting to the west. Seismicity clusters around the Molucca Sea Plate (green line), forms a double subduction pattern. In the western part, beneath the Sangihe arc, the earthquakes reach depths of ~600 km and in the eastern part, beneath the Halmahera arc reach depths of ~ 250 km, this result is in good agreement with the previous research [6,7,21]. We also can see that from south to the north, the earthquakes are getting deeper which shown as green and blue circles in Figure 3. Seismicity cluster around the slab of Philippine (brown line) dips to the west at a depth of ~100 km and is above the Molucca Sea Plate which is subducting to the east.

![Figure 2](image1.png)

**Figure 2.** Seismicity maps from the NLLoc results around the Molucca Sea collision zone. Colored dots indicate the earthquakes. Inverted black triangles are BMKG station. The black boxes A-A', B-B', C-C', D-D', E-E', F-F' are the areas of the cross-section in Figure 3.

![Figure 3](image2.png)

**Figure 3.** The West-East vertical cross-section of A-A', B-B', C-C' that show the seismicity pattern beneath Molucca Sea and forms a double subduction pattern. Red triangles are the volcanoes, colored dots are earthquakes, the green line describes the Molucca Sea Plate, the blue line describes the slab2 model of Sulawesi, and the brown line describes the slab2 model of Philippine [22].
Figure 4. The North-South vertical cross-section of D-D’, E-E’, and F-F’ (beneath the Sangihe arc) and G-G’ (beneath Halmahera arc). Red triangles are volcanoes, colored dots are earthquakes, the green and blue lines describe the Molucca Sea Plate and slab2 model of Sulawesi, respectively [22].

Based on Figure 4, Profile D-D’ shows a deep earthquakes around 300-600 km which indicate the Molucca Sea Plate (green line), meanwhile a south dipping shallower earthquake from ~0-200 km indicate the subduction zone in the north of Sulawesi Island (blue line). The E-E’ profile shows the N-S earthquakes pattern in the subduction zone of Molucca Sea Plate, and the slab of Sulawesi shows the same pattern as Profile D-D’ only the depth is shallower. Profile F-F’ beneath the Sangihe volcanic arc shows the shallow and medium earthquake distribution which shows the earthquake pattern near the top of western flank of double subduction of Molucca Sea Plate. Profile G-G’ beneath the Halmahera volcanic arc shows the earthquake distribution in the eastern flank of Molucca Sea Plate.

Figure 5. Seismicity in the Molucca Sea collision zone using 3-D plots viewed from South with azimuth 180° (H) and from North with azimuth 0° (I).

Seismicity in the Molucca Sea collision zone using 3-D plots are shown in Figure 5. Based on Figure 5, the seismicity pattern beneath the Sangihe arc forms westward dipping plane associated with Molucca Sea Plate.
4. Conclusions

We have determined the hypocenter location in the Molucca Sea collision zone using a probabilistic non-linear method. We observed that the seismicity follows the pattern of the double subduction of the Molucca Sea Plate, to westward beneath the Sangihe arc which the earthquake could reach a depth of ~600 km and to eastward beneath the Halmahera arc which the earthquake reach a depth of ~250 km, from south to north, the number of deep earthquake beneath the Sangihe Arc is increasing. We also observed that the seismicity following the zone pattern of subduction of Sulawesi and Philippine. This preliminary result will be used for further research of hypocenter relocation and travel time tomographic inversion beneath the Molucca Sea collision zone.

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