Hypocenter relocation analysis of 7.5 Mw Palu and its aftershocks: A preliminary result

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Abstract. The earthquake that occurred in the Palu city and its surroundings on September 28, 2018, with a magnitude of 7.5 Mw caused a lot of casualties and infrastructure damages. Tsunami and liquefaction are secondary effects that contribute significantly to these two losses. The earthquake occurred at the Palu Koro Fault with a strike-slip mechanism. The BMKG seismic network successfully recorded aftershocks caused by the earthquake. Hypocenter relocation using the double-difference method is applied in this study to analyze the mainshock and its aftershocks so that the fault geometry of the earthquake can be known clearly. This study used the BMKG earthquake catalog at coordinates 4°S-1°N and 118°-122°E until the end of December 2018. The results show an improvement in the hypocenter position with loss of fix depth at a depth of 10 km so that the area can be interpreted tectonically. The results also show that the majority of the earthquakes beneath the fault are at a depth of less than 25 km. The relocated hypocenter parameters are very useful as a database for further tectonic studies that are useful for earthquake disaster mitigation in the area.

1. Introduction
Sulawesi Island is an area prone to natural disasters because of many earthquake sources on the island both in the land and the sea. One source of the earthquake at sea comes from North Sulawesi Subduction which moves at 42-50 mm/year [1]. Palu Koro fault is one of the sources of land earthquakes on Sulawesi Island. The fault is the longest land earthquake source that crosses the central part of Sulawesi Island with a geodetic slip rate 41-45 mm/year [1].

The high seismic activity in the Palu Koro Fault causing many earth scientists around the world from various disciplines has been attracted to investigate its characteristics [2–5]. The big earthquake that struck on September 28, 2018, occurred on this fault with a magnitude of 7.5 Mw. The earthquake caused so many fatalities and massive infrastructure damages. These two losses are generally caused by tsunami and liquefaction.

The earthquake released so many aftershocks that were still recorded by the BMKG seismic network until the end of 2018. An aftershock distribution is very useful to understand the geometry of an earthquake plane. A Segment length, a depth, a strike and dip directions from the earthquake plane can be analyzed clearly based on the distribution of the aftershocks [6,7]. The mainshock and aftershocks from the earthquake catalog BMKG were relocated firstly to obtain more precise parameters so that the tectonic condition in the area could be interpreted in more detail. An Analysis of tectonic condition in an area using a precise distribution of hypocenter parameters is one of the methods applied to understand an earthquake segment geometry. Combining of geophysical, geological and geodesy methods in tectonic studies will provide a more comprehensive understanding.
2. Data and Methods
The hypocenter parameters of the earthquake released by BMKG have been reliable in disseminating earthquake information and tsunami early warnings needed by communities and various institutions for emergency response. Both information is sent by BMKG to the public and related institutions in less than 5 minutes [8]. As for research purposes, the hypocenter parameters must be reprocessed to obtain more precise parameters. This study uses a double-difference method with a hypoDD program [9,10]. The earthquake data catalog used is in the range 118°-122°E and 4°S-1°N as shown in Figure 1. The maximum distance from the earthquake source to the seismic station is 500 km. A wide area range is used to see the Palu earthquake effect on the surrounding fault segments. The number of phases of each earthquake event uses at least 6 phases of seismic waves both P and S phases or P phase only. Each phase used in the BMKG catalog has a residual time range of -3 to 3 seconds for the P wave and -5 to 5 seconds for the S wave. The S phase wave uses a lower residual time because the S wave phase has an onset that is not as clear as the wave P. S waves also generally have a lower Signal to Noise Ratio (SNR) compared to P waves. The minimum number of wave phases used is six seismic phases so that inversion calculations are over-determined where the number of data is more than the number of models. The velocity model used is derived from the Vp 1-D model from the previous study in the fault area [3] with a ratio of Vp/Vs 1.73 [11].

![Figure 1. Seismic station of The Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) for the hypocenter relocation study (blue reverse triangles).](image)

3. Results and Discussions
The number of earthquakes that were successfully relocated was 1457 from 1556 events. 99 earthquakes were not successfully relocated because the data were not fit with the criteria. The distribution of seismicity shows that the 7.5 Mw earthquake affected the fault system which was outside the Palu Koro Fault. This can be demonstrated by the increasing seismic activity in the southeast and southwest of the aftershock zone as shown in Figure 2. Seismic activity in the southeast is related to the Matano Fault and in the southwest part is most likely related to the Sadang Fault passing through Mamasa District [5,12]. The relationship between the 7.5 Mw earthquake and the seismic activity in the Matano Fault and Swarm earthquake in Mamasa District needs to be further investigated with a coloumb stress study [13]. The study will show clearly whether the earthquake 7.5 Mw affected or not seismic activities at the two fault systems ?.
aftershock activity that propagates to the south part is most likely caused by more faults or weak zones in the area compared to the area north of the mainshock.

**Figure 2.** a). Seismicity before hypocenter relocation from the BMKG network. b). The same as (a) but after hypocenter relocation. The fault map was taken from *Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017* [14]. The line A-A’ and B-B’ are the cross section line along strike and dip direction of Palu Koro fault plane. The maximum hypocenter distance to line A-A’ is 20 km and to line B-B’ is 5 km.

Vertical cross-sections along strike direction (A-A’) and dip direction (B-B’) are shown in figure 3. Both cross-sections show a number of fix depth at 10 km can be improved to the more proper position so that the hypocenter distribution depths are more fit with the tectonic condition in the area. The mainshock depth after hypocenter relocation is at a depth of 11 km (Figure 3(b) and 3 (d)). The results shows that the earthquake depth majority is mostly at a depth of less than 25 km. It can be assumed that the Moho depth benath the fault is at a depth of more than 25 km because it is in the aseismic zone associated with the mantle structure. Although to get the Moho depth which is more precise, we need to do a receiver function study. The vertical cross section of the dip direction (B-B’) shows a declivous slope to the west and a sharp slope to the east. The strike-slip earthquake mechanism has a sharp dip angle so that the dip angle is fit to eastward. This is consistent with the results of a focal mechanism study which has a dip angle of 57° [15].
Figure 3. a) Vertical cross section A-A’ before hypocenter relocation. b) The same as (a) but after hypocenter relocation. c) Vertical cross-section B-B’ before hypocenter relocation. d) The same as (c) but after hypocenter relocation.

The vertical cross-section A-A’ after hypocenter relocation in figure 3(b) shows some dense seismicity zones and no seismicity zones. The no seismic zones is most likely related to the asperity location. This occurred due to those zones have released their energy during the mainshock. Those zones located at a depth of 0-10 km and at a distance 180-210 km. The dense seismicity zone is most likely related to asperity edge. This is due to the stress transfer from the asperities to its surrounding zone causing some smaller earthquakes. The aftershock distributions from Donggala to the north (distance 0-70 km) occurred at a depth of more than 5 km. This is probably related to the interface zone of the Palu Koro fault which is deeper to the north following the bathymetry of the Makassar Strait which is also deeper to the north as shown by the schematic model in figure 4.
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Figure 4. The schematic model of the west block and east block in the Palu Koro Fault based on hypocenter relocation of this study. The fault plane interface is deeper into Donggala follows the Makasar strait bathymetry.

4. Concluding Remarks
This study successfully improves hypocenter parameters so that the geometry Palu Koro fault can be interpreted in more detail. The resulting study also can be used to estimate roughly Moho depth beneath Palu Koro Fault. The depth is more than 25 km. The schematic model from Palu to Donggala shows the earthquake depth to northward is deeper than the earthquake depth to southward. It is caused by the interface zone follows Makasar strait bathymetry. The dense seismicity zones are most likely related to asperity edge which received stress transfer from the asperities. The no seismic zone is most likely related to the location of asperity itself which has released their energy during the mainshock.

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