Hypocenter Determination of Volcano-Tectonic (VT) Earthquake around Agung Volcano in Period October-December 2017 Using a Non-Linear Location Method: A Preliminary Result

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Abstract. Agung is one of active volcanoes in Indonesia, located on island of Bali. Since 1963, Agung has not had significant activity, until in September 2017 the volcano was active again which was marked by increased seismic activity and eruptions in November 2017. Therefore, to analyze the dynamics and processes of active volcanic eruptions requires an understanding of the structure of the volcano, especially the position of the magma reservoir and its path. The depiction of the structure of this volcano can be analyzed by determining the location of the earthquake due to volcanic activity, especially Volcano-Tectonic (VT) earthquake. In this study, we determined the location of the hypocenter around the Agung using the non-linear location method. VT earthquakes have similar characteristics to tectonic earthquakes so this method can be used to determine the initial hypocenter. The data used in this study came from 8 PVMBG seismographs from October to December 2017. We manually picking arrival time of P- and S-waves from the 3948 VT events found. Pair of P and S wave phases with 18741 P-wave phases and 17237 S-wave phases, plotted in a wadati diagram resulting in a vp/vs ratio of 1.7117. We use 1D velocity models derived from Koukalov with the assumption that the geology of the study area is not much different from the volcanoes in Central Java. The resulting hypocenter distribution shows a very random location and has uncertain X, Y, and Z directions from a range of 0 to 91 km. This study limits this uncertainty to 5 km resulting in a more reliable earthquakes distribution of 3050 events. The results indicate 2 clustered events, a swarm of VT events that occur every month at a depth of 8 to 15 km and there are 2 paths that lead to the top of Agung and SW of that swarm. These preliminary results will be used to update 1D velocity model and relocate the events beneath Agung region for further studies.
1. Introduction

Agung is one of active volcanoes in Indonesia, located on Bali Island, and became active in September 2017 and erupted again in November 2017 after dormant since 1963. The eruption in 1963-1964 was one of the biggest eruptions in Indonesian history after the Krakatoa eruption in 1883, especially since the eruption affected the global climate [1–5]. The explosive eruption column reached more than 20 km above the summit of Agung to penetrate the tropopause and cause injection of ash and sulfur gas in the stratosphere [5]. Influence of eruption results in this stratosphere can reduce climate temperatures around -0.3°C [4]. Agung eruption can occur as large as in 1963 if the composition of magma and eruption type is still the same [4]. However, the eruption in 1963 did not have specific data information about its eruption, due to limited tools. Therefore, Agung needs to be studied more deeply about the nature and process of its dynamics apart from the previous eruption comparison.

To understand the dynamics and eruption of active volcanoes requires an understanding of the structure of volcanoes, especially the position of the storage and the path of magma. It has been obtained several studies on this volcano such as research on tomography[6], geology[7], satellite imaginary [8], activity reports[9], as well as determining the location of the hypocenter swarm with regional network[10]. However among the previous studies did not explain in detail for the seismicity during the initial activity in 2017 on this volcano. So that in this study we want to determine the location of the hypocenter of the seismicity that occurred before and during the 2017 eruption using the local network in period October - December 2017. Determination of the initial hypocenter using the non-linear location method[11].

2. Data and Methods: Non-Linear Location Determination

The data used in this study are earthquake waveform data recorded by 8 seismometers from the Center for Volcanology and Geological Disaster Mitigation (PVMBG) in the period 18 October- 31 December 2017. The distribution of this seismometer is around Agung (Figure 1). The earthquake used in this study was volcanic earthquake type A (VTA) and B (VTB).

![Figure 1. Distribution of seismic stations around Agung](image)

In this study, we manually picked arrival time of P and S-waves uses Seisgram2k [12] and determination of the hypocenter location uses the non-linear location method with the NonLinLoc (NLLoc) program [11,12] and uses a 1D Koulakov seismic velocity model [13]. NLLoc implements a probabilistic inversion from Tarantola and Valette [14] and produce Posterior Density Function (PDF) using Oct-Tree sampling algorithm to estimates for hypocenter locations [11]. Oct-Tree works by dividing the data area in several three-dimensional (3D) cells recursively, then the hypocenter position
is determined by calculating the PDF value of each cell\[12\]. The largest PDF value of the cells is then taken, and then divided again into several small cells, until finally obtained the greatest probability at a hypocenter location solution. We use a grid size of 1520 x 1520 x 420 with the node for each grid of 0.25.

3. Results, Discussions and Conclusions
The initial step of this study is to look for VT events that occurred during the period 18 October to 31 December 2017. VT events have the same type as tectonic earthquakes so that P- and S- waves can be determined. From the determination of this event, manual picking will be carried out to obtain 3948 VT events with a VTA that has 17,064 pairs of P and S that can be plotted in the Wadati diagram (Figure 2). This diagram is used to examine the linear relationship and time quality P and S, the mean Vp/Vs of the earth's crust is $\sqrt{3}$ or close to 1.73. Based on the Wadati diagram obtained, 1.71, it shows that the arrival times that we observed are good enough to locate the hypocenters.

Figure 2. Wadati diagram of the picked phase of each event that has been obtained. The black line indicates Vp/Vs ratio.

The results of determining the location of the hypocenter with NLLoc provide a location with various kinds of errors and uncertainty based on the probability used. The results of the uncertainty show a far range, from 0.1058 to 91.39891 km (Figure 3). This uncertainty can be caused because the search for grid locations is still very far away so that the PDF will be very low and the uncertainty will be very high. Therefore, in order to reduce the error in determining the location, we will select data with uncertainty below 5 km to get the distribution of the number of VT events over time in Figure 4.

Figure 3. Uncertainty histogram for determining Nonlinloc locations based on X (green), Y (yellow), and Z (blue) directions.
Apart from uncertainty, this 3050 events errors in determining the location can also be based on the residual travel time (Figure 5). It can be seen in the figure that all events have a very large travel-time residual range, and reduced in events with uncertainty below 5 km. The travel-time residual above 0.2 s and below 0.2 s the amount is reduced. So that errors in determining the location are also reduced.

Figure 4. Distribution of the number of VT events in a time function. All VTs in blue, for VTs under 5 km it is yellow. P is a phreatic eruption and M is a magmatic eruption.

Figure 5. Travel-time residual from hypocenter determination with NLLoc for all VT events (a) and VT events with uncertainty below 5 km (b).

Figure 6 shows the distribution of VT events in Agung during the period 18 October to 31 December 2017. These events are grouped by month, which is clear in October, it can be seen that swarm in the west of Agung. This month is the month before the eruption, which is the opening of the way for magma to rise to the surface. But this month not only happen to the top of Agung, but also located on the west side of Agung, which has a direction of SW (Figure 7).

The results of this study obtained a hypocenter distribution which adequately describes the displacement of magma from October to December 2017 (Figure 7). It is seen that there is a swarm of VT earthquakes at a depth of 8 to 15 km which every month always occurs in that area. And there are 2 different paths, the first one that goes to the top and the next one that goes to the SW direction of that swarm.
Based on our study, we identified the hypocenter location of 3050 events around Agung by applying a non-linear method with uncertainty under 5 km that distributed in 2 clustered, a swarm of VT events that occur every month at a depth of 8 to 15 km and there are 2 paths lead to the top of Agung and SW of that swarm. However, this result is still a lot of earthquakes that scatter, especially in November and December. So that further research is needed to get a more definite hypocenter. This preliminary result will be used to update 1D velocity model and relocate the events beneath Agung region for further studies.

**Figure 6.** Distribution of VT events during the period 18 October to 31 December 2017. Red dots are VT events in October, yellow dots are events in November and blue dots are events in December. Red triangles are volcanoes and black inverted triangles are PVMBG stations.

**Figure 7.** VT events distribution around Agung on the A-B cross line. Red dots are VT events in October, yellow dots are events in November and blue dots are events in December. Red triangles are volcanoes.
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