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Determination of Hypocentre and Seismic Velocity Structure in Guntur Volcano Using Seismic Data from 2010 to 2014

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Abstract - Guntur Volcano was in a dormant state even though its seismicity had increased on April, 2013 and August, 2013. In this study, determination of hypocentre and seismic velocity structure was conducted using seismic data from 2010 to 2014 as recorded by a seismic station of the Centre for Volcanology and Geological Hazard Mitigation of Indonesia (CVGHM). Volcano-Tectonic (VT) earthquakes were identified and carefully picked for P-and S-wave arrival times. More than 600 events of VT earthquakes from 2010 - 2014 were located using maximum likelihood estimation algorithm. The initial 1-D seismic velocity was calculated using Velest method in order to get the initial velocity as the input for the tomographic inversion. The results show distribution of VT hypocentres were clustered in three regions, namely Guntur Volcano, Kamojang geothermal area, and Darajat geothermal area. At the Guntur Volcano region, the VT events were located mostly at the northern part of the crater with the depth of hypocentre ranges from 0 - 4 km. The distribution of the VT events made alignment from the southwest to the northeast with the depth of hypocentre mostly ranges from 0 - 2 km at Kamojang region. Meanwhile, at Darajat geothermal area, the VT events were located at the depth of 0 - 2 km and made alignment from the southeast to the northwest. The low velocity zone associated with hot material or fluids was located at the depth of 5 km beneath the Guntur Crater. The location of VT earthquakes at the depth of 0 - 4 km beneath Guntur Crater was coincided with the area with high Vp and Vs anomalies. The low velocity zones were also found at Kamojang Crater and Cipanas hotspring area. It was predicted that the low velocity zone at the Kamojang Crater was related to a high temperature of the vapour system, whereas the reservoir of water was preferred to be dominated at the Cipanas hotspring.

Keywords: Guntur Volcano, tomographic inversion, volcano-tectonic (VT) earthquake

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Introduction

Guntur is a volcano complex located in Garut District, West Java Province, Indonesia (Figure 1). The young volcanic complex was line up in northwest-southeast direction namely Masigit, Sangiang Buruan, Parupuyan, Kabuyutan, and Guntur. The highest peak was located at Masigit

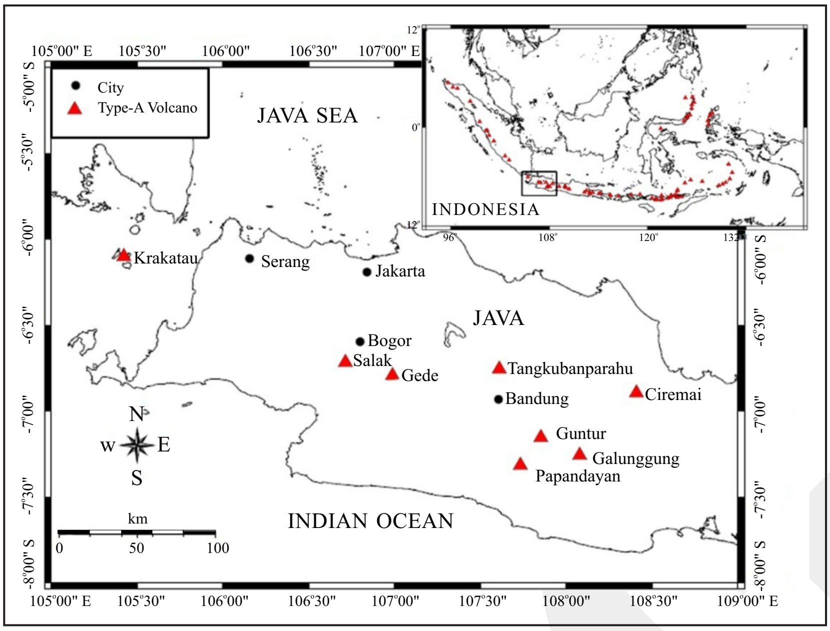

Figure 1. Location map of Guntur Volcano located in West Java Province, Indonesia.

(2,249 m) and the last eruption occurred at the Guntur Crater in 1847 (Kusumadinata, 1979).

Guntur Volcano has the repose time of more than 160 years, however increasing seismicity has been detected since 1997. The number of VT earthquakes increased on October 1997, May 1999, November 2002, and June 2005 (Sadikin, 2008). On September 2011, the number of VT earthquakes reached 277 events, and then exceeded to 300 events on September 2013. Continuous volcanic tremor was recorded on April 2013 and August 2013. The monthly number of VT earthquakes tends to increase in the last 20 years.

The previous study on VT earthquake and magmatic system at the Guntur Volcano by Sadikin (2008) mentioned the locations of VT earthquakes were distributed in three regions, between (Mount/Crater?) Masigit to Guntur Crater, between Gandapura Caldera to Gajah Crater, and at Kamojang geothermal area. The magma was estimated to be located at the depth of about 5 km. According to Nugraha (2005) low velocity zones were found beneath the Guntur Crater, Kamojang geothermal area, and Gandapura Caldera at the depths of 4.5 - 5.5 km. Meanwhile, Priyono *et al*. (2011) showed a high attenuated area at the depth of 5 - 7 km beneath the Guntur Crater, Kamojang Crater, and Gandapura Caldera. Saepuloh and Bakker (2017) conducted an identification succession of volcanic products using magnetic susceptibilty and polarimetric synthetic aperture radar (PolSAR) data that showed about fifteen successive eruption of Guntur Volcano complex. The seismicity study of Iguchi *et al*. (2012) showed VT earthquakes were frequently observed in the Guntur Volcano from the northwest to southeast along the volcanic cones and craters including Mount Masigit, Mount Parukuyan, Mount Kabuyutan, Guntur Crater, and from the Gandapura Caldera to Mount Gadja in the summit area. In order to continue the previous study on VT earthquakes and seismic velocity structure in the volcanic area, and also to understand recent activity of the Guntur Volcano, a seismic tomography study was conducted using seismicity data from 2010 - 2014 to determine the hypocenter of VT earthquakes and seismic velocity structure in the Guntur Volcano.

Geological Setting

Guntur Volcano complex consists of several peaks which are divided into young and old volcanic complexes. The old volcanic complex consists of Gajah, Gandapura, Agung, Picung, and Batu, whereas the young volcanic complex comprises Masigit, Sangiang Buruan, Parupuyan, Kabuyutan, and Guntur (Purbawinata, 1990). The location of the young volcanic complex is surrounded by the old ones. Two calderas, namely Kamojang and Gandapura, are located at the western side of the young volcanic complex. The Guntur Volcano is formed by basaltic-andesite and andesite rocks with 52% to 63% of SiO_2 (Purbawinata, 1990). Lava and pyroclastic flow spread from the Guntur Crater reaching 3 km distance to the southeast direction. The fault system at Guntur Volcano complex is a normal fault striking from Gandapura Caldera to Mount Masigit (Alzwar *et al*., 1992). At the western side of the volcano, there is also a strike-slip fault and normal fault elongated from Kamojang geothermal field to Darajat Caldera.

Methods and Data

The selected seismic data used in this study is from January 2010 to January 2014. There are 10 CVGHM seismic stations installed to monitor Guntur Volcano activity as seen in Figure 2. Six seismic stations, namely Dano (DAN), Citiis (CTS), Kabuyutan (KBY), Sodong (SDN), Legokpulus (LGP), and Masigit (MSG) were located about 3 - 5 km from the Guntur Crater. Four seismic stations are Kiamis (MIS), Papandayan (PPD), Wanasuka (WNS), and Ciparay (CPR), situated about 10 - 30 km at the western side of Guntur Volcano complex. VT earthquakes that were recorded at 4 - 10 seismic stations were picked to get arrival times of P-wave and S-wave. The hypocenter distribution of Guntur Volcano is calculated using Hypomh software (Hirata and Matsura, 1987). The seismic velocity structure model was composed of three layers according to the study of velocity structure in West Java by Kartodinomo (1996). The velocity of P-wave in the first, second, and third layer are 4.3 km/s, 6.1 km/s, and 7.0 km/s with the thickness of 4 km, 12 km, and 17 km, respectively.

The 1-D initial seismic velocity was calculated using Velest method (Kissling, 1995) in order to get the initial velocity as the input for the tomographic inversion. Seismic tomographic study was carried out to determine 3-D Vp, Vs,

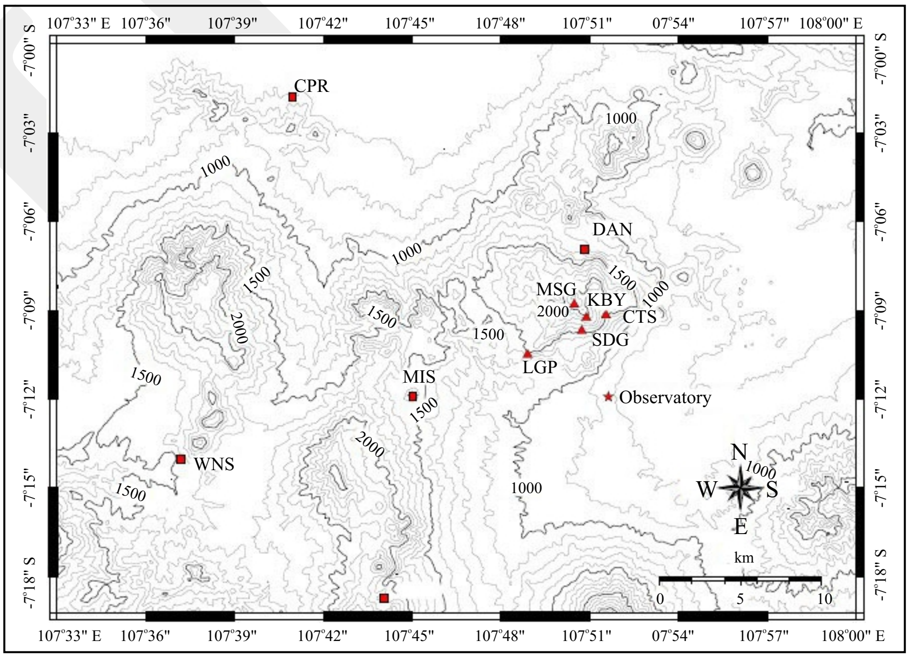

Figure 2. Location map of CVGHM seismic stations around Guntur Volcano. Red triangles, squares, and a star represent 1 component station, three component stations, and observatory station, respectively.

and Vp/Vs ratio using arrival times data of VT earthquakes by applying SIMULPS12 (Evans *et al*., 1994). The area of study was divided into certain grid nodes, consisting of short and long intervals grids (Figure 3). Short interval grid was 2 km, while the long one was 10 km. Short interval grids were located around Guntur Crater until 10 km distance from the centre. While for vertical direction, the area of study was divided into 1 km interval grid nodes.

Checkerboard

Checkerboard test was made by creating a velocity model with 10 % perturbation (Figures 4 and 5). Forward modeling is executed using the real earthquake location and P-phase and S-phase time through a checkerboard model. The synthetic travel time results were then used as an input to perform inverse modeling using the initial velocity model. The checkerboard recovery results showed well resolution areas were at a distance of 8 km to the north and west, while to south and east direction, well resolution areas were only at 4 - 5 km distance from the Guntur Crater. The resolution also looks good until 5 km depth at the western side of the Guntur Crater, meanwhile at southern and eastern side of the Guntur Crater, well resolution regions were located at the depths of 0 - 3 km.

Hypocenter Distribution

The arrival times of P-wave and S-wave were picked from 744 VT earthquakes. The hypocenter location was calculated by using maximum likelihood estimation algorithm (Hirata and Matsura, 1987). The distribution of VT events (for the periods of January, 2010 - January, 2014) were clustered in three regions (Figure 6), namely Guntur Volcano, Kamojang Crater, and Darajat geothermal area. At the Guntur Volcano complex, the VT earthquakes were elongated from the northwestern part until the southeastern part of the Guntur Crater. The depths of VT earthquakes range from 1 - 17 km under the summit, but were mostly located at the depth of 1 - 5 km (Figure 7). It seems that VT events are controlled by local fault structure near the Guntur Crater. At Kamojang area, the

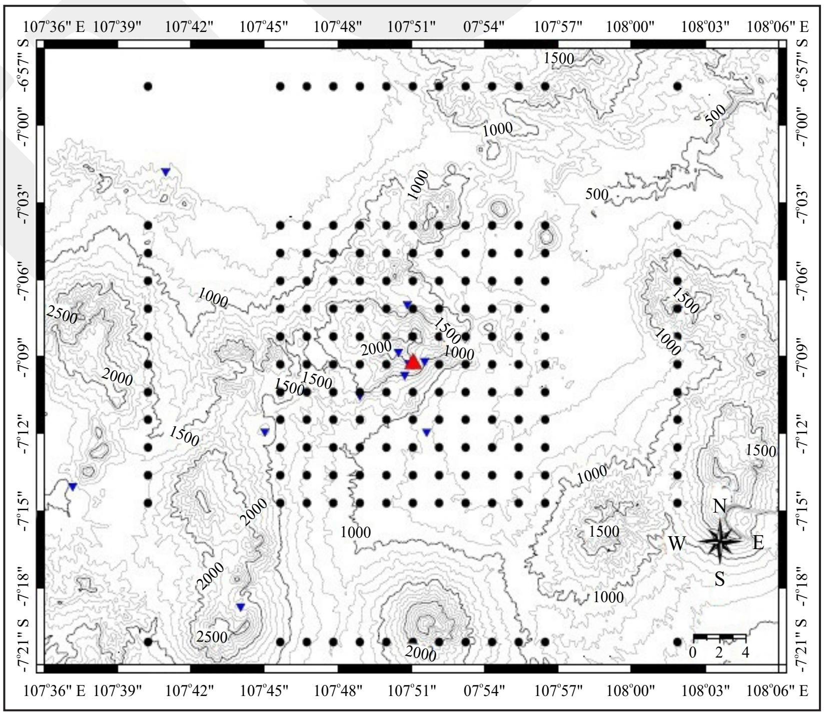

Figure 3. Parameterization model (filled black circles) of the studied area into block of (2km)(2km)(1km) with the centre of coordinate located at the Guntur Crater (red triangle). Seismic stations were denoted by blue inverse triangles.

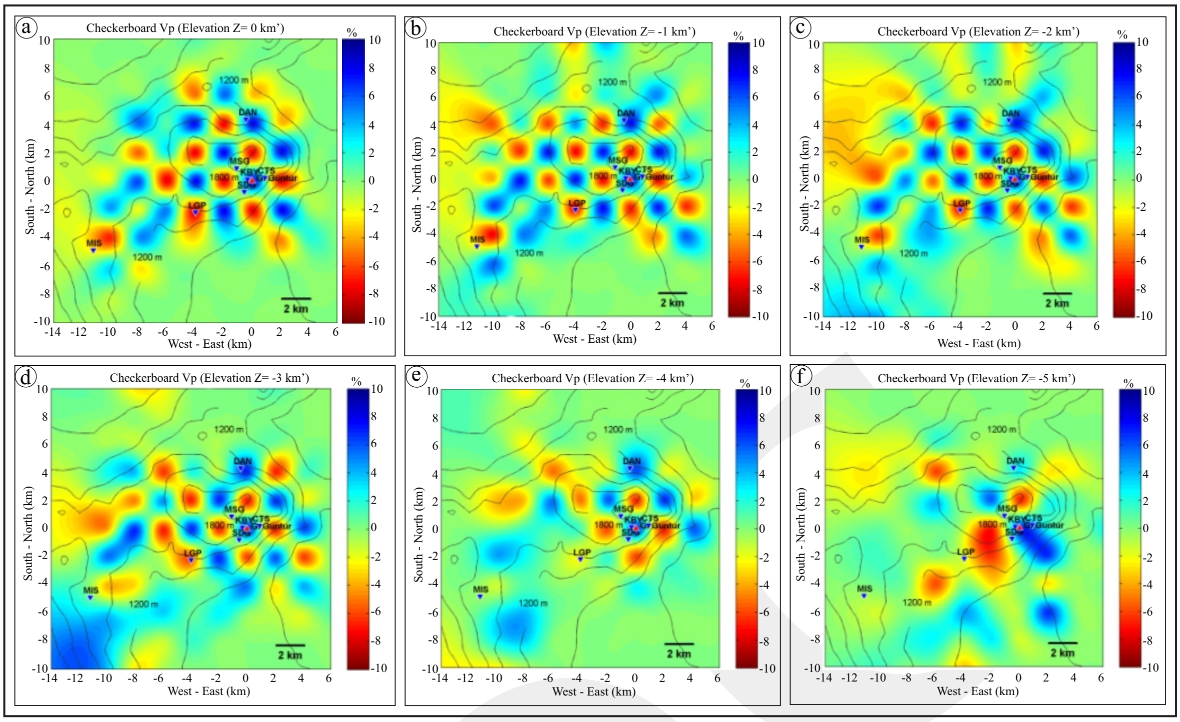

Figure 4. Recovery checkerboard test of Vp from 0 km to 5 km depth. Blue and red colours are positive and negative anomalies, respectively.

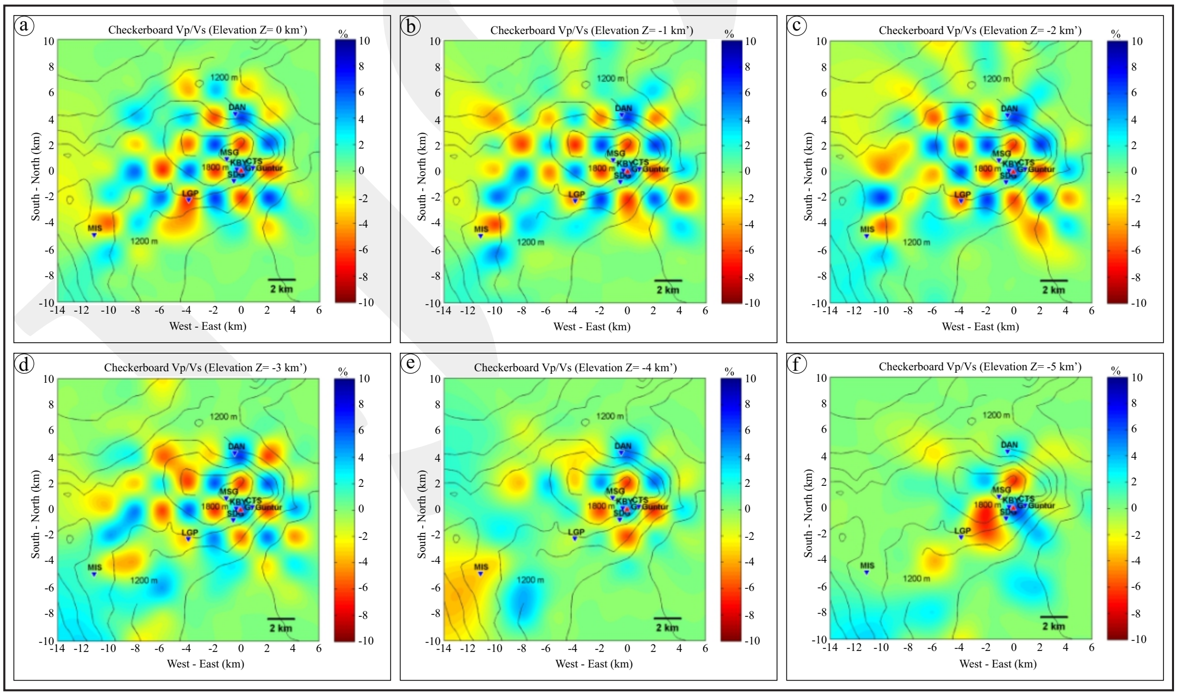

Figure 5. Recovery checkerboard test of Vp/Vs ratios from 0 km to 5 km depth. Blue and red colours are positive and negative anomalies, respectively.

focus depth of the VT events ranges from 0 - 8 km, but mostly located at the depth of 0 - 4.5 km. The focus depth of VT events became shallower at Darajat geothermal area. The VT events at Darajat geothermal area mostly had shallow depths of about 0 - 2 km.

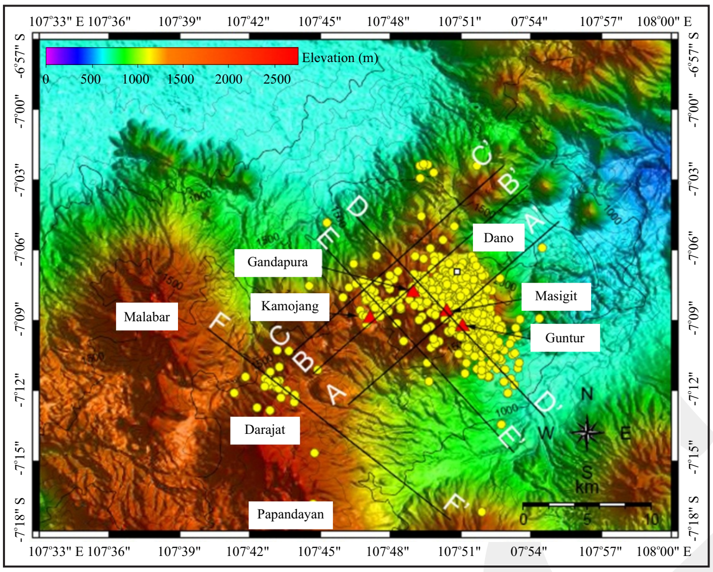

Figure 6. Distribution of VT earthquakes (filled yellow circles) from January 2010 until January 2014 recorded by CVGHM stations around Guntur Volcano, Kamojang, and Darajat areas. Red triangles represent the volcanoes.

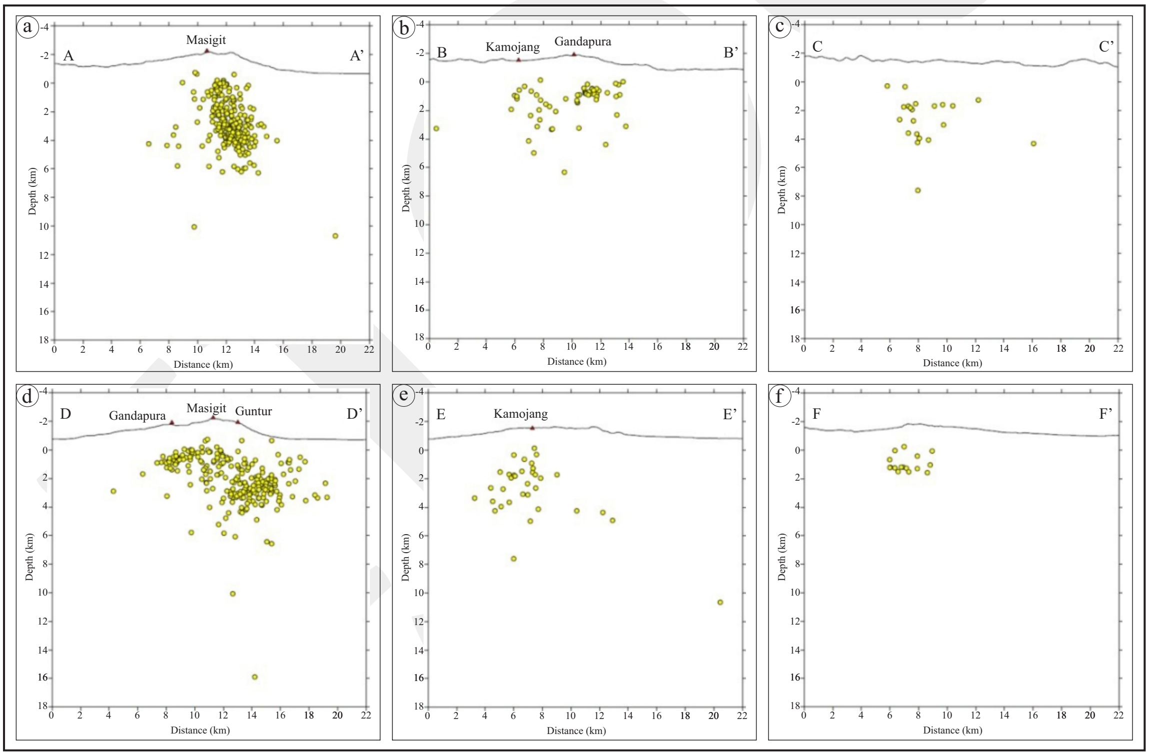

Figure 7. Hypocentre distribution from (a) vertical section of AA' (NE - SW) through Masigit Crater, (b) vertical section of BB' (NE - SW) through Kamojang and Gandapura Calderas, (c) vertical section of CC' (NE - SW), (d) vertical section of DD' (NW - SE) through Gandapura Caldera, Masigit, and Guntur Craters, (e) vertical section of EE' (NW - SE) through Kamojang Caldera, and (f) vertical section of FF' (NE - SW) as shown in Figure 6.

Discussion

Seismic velocity structures are ploted in the percent perturbation relative to initial 1D seismic velocity model as shown in Figures 8 and 9. Negative (low) and positive (high) anomalies are depicted in red and blue colours, respectively. Horizontal slices of Vp and Vs structures

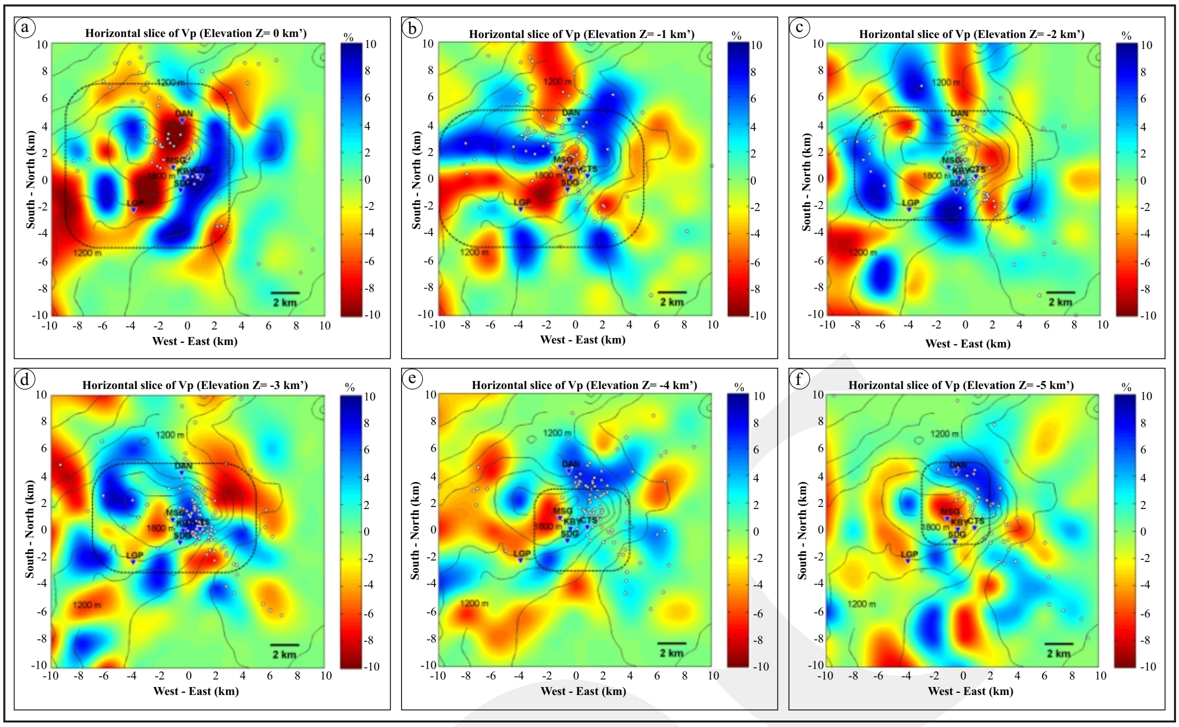

Figure 8. Horizontal slices of Vp at the depth of 0 km until 5 km. Dashed black lines represent well recovery checkerboard test. Blue and red colours are positive and negative anomalies, respectively.

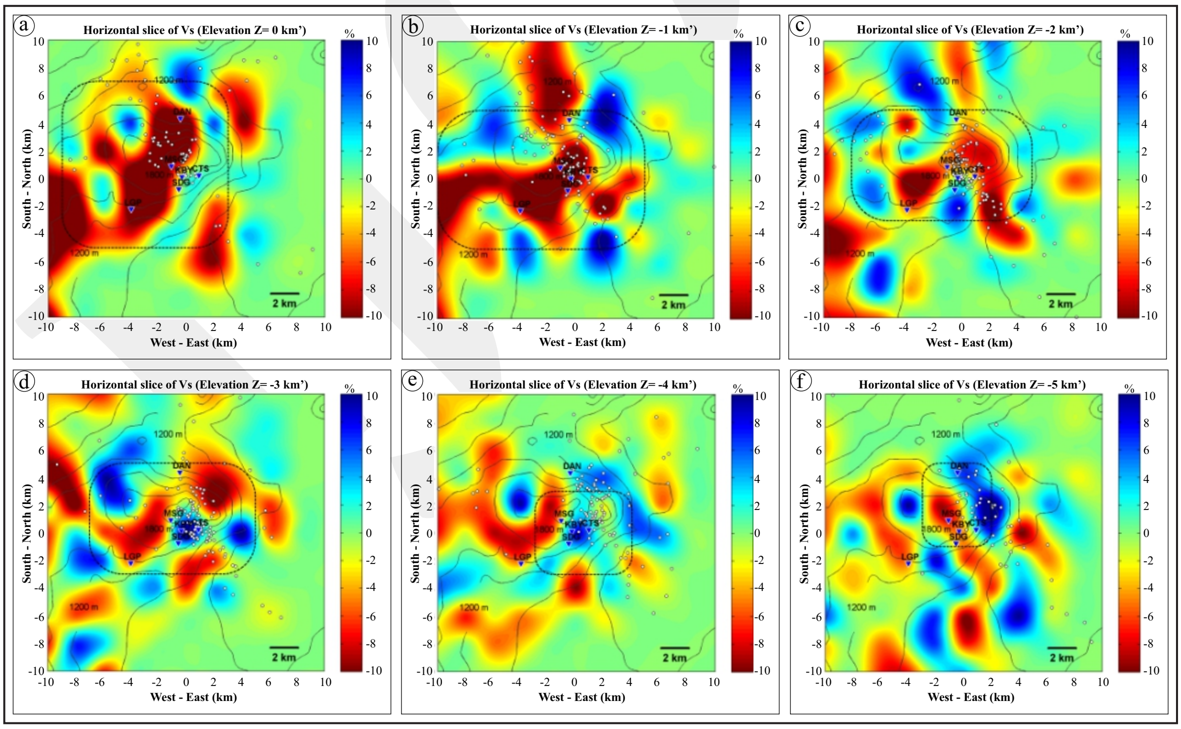

Figure 9. Horizontal slices of Vs at the depth of 0 km until 5 km. Dashed black lines represent well recovery checkerboard test. Blue and red colours are positive and negative anomalies, respectively.

are illustrated in 200 m of contour interval. At the depth of 0 km, low Vp/Vs ratio was found with low Vp anomaly at the southeastern area of the Guntur Crater. At the depth of 1 km, low anomaly zones of Vp and Vs stretch from Darajat geothermal area, passed through Kamojang and Guntur Craters. The ratio Vp/Vs in these areas are generally higher than in Cipanas area showing a low Vp/Vs ratio.

Figure 10 showing at a depth of 3 km, low Vp/Vs ratio was also located at the northeastern part of the Guntur Crater, while high Vp/Vs rasio was located beneath the Guntur Crater until Kamojang Crater. This high Vp/Vs rasio continued until 4 km depth at the western side of the Guntur Volcano. Low velocity zone was also clearly visible at 5 km depth beneath the Guntur Crater.

Vertical cross section passing through Guntur Crater shows low velocity zone (Vp and Vs) at the depth of 1-2 km with high Vp/Vs ratio (Figure11). This low velocity zone is extending from the Guntur Crater through Kamojang and Darajat areas. Low velocity zone also exhibits at the depth of 4 - 5 km, just below the location of VT earthquakes. This low velocity zone is also connected from Guntur to Darajat goethermal area. At the depth of below 5 km, a low velocity zone is found with high Vp/Vs, dipping from 5 km depth beneath the Guntur Crater down to depth of about 15 km. Vertical cross section below the Kamojang Crater shows low velocity zone of Vp and Vs, while the ratio of Vp/Vs tends to have high values, extending from surface to depth of about 5 km (Figure 12).

Based on tomographic inversion result in this study, the Guntur Volcano is surrounded by low Vp anomaly at the surface (Figure 13a). According to the geological map, the location of the low velocity zone at the western side of Guntur Crater is coincided with the location of Pangkalan Caldera formed during the Quaternary time. While at the southeastern part of the Guntur Crater, the low velocity zone is coincided with the location of Cipanas hotspring. Both regions show a difference in the Vp/Vs ratio value. At Kamojang area, Vp/Vs ratio is high and then becomes low at Cipanas hotspring (Figure 13b). Previous volcano tomographic studies by Indrastuti *et al*. (2019), Widiyantoro *et al*. (2018), Nugraha *et al*. (2017), Nakajima and Hasegawa (2003) showed a high

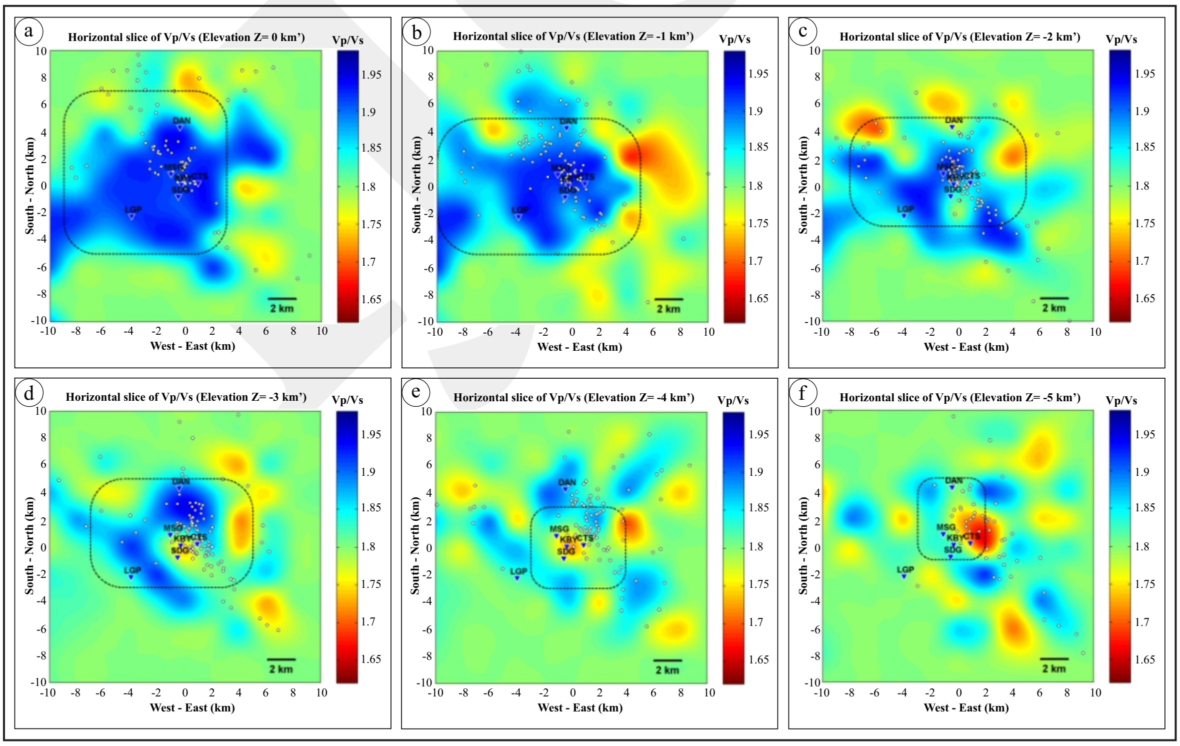

Figure 10. Horizontal slices of Vp/Vs ratio at the depth of 0 until 5 km. Dashed black lines represent well recovery checkerboard test. Blue and red colours are positive and negative anomalies, respectively.

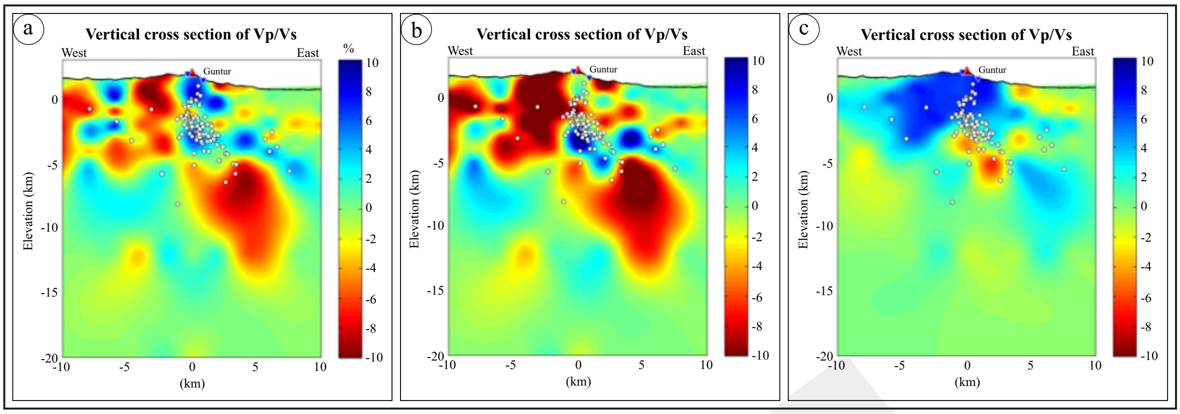

Figure 11. Vertical sections (W - E) of (a) Vp; (b) Vs; (c) Vp/Vs ratio beneath the Guntur Volcano. Filled circles represent VT events. Blue and red colours are positive and negative anomalies, respectively.

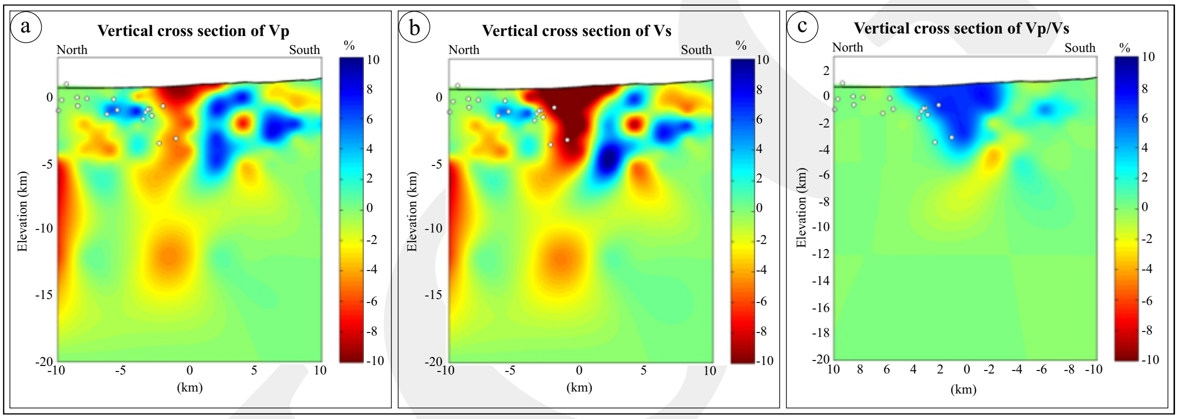

Figure 12. Vertical sections (N - S) of (a) Vp; (b) Vs; (c) Vp/Vs ratio beneath Kamojang Caldera. Filled circles represent VT events. Blue and red colours are positive and negative anomalies, respectively.

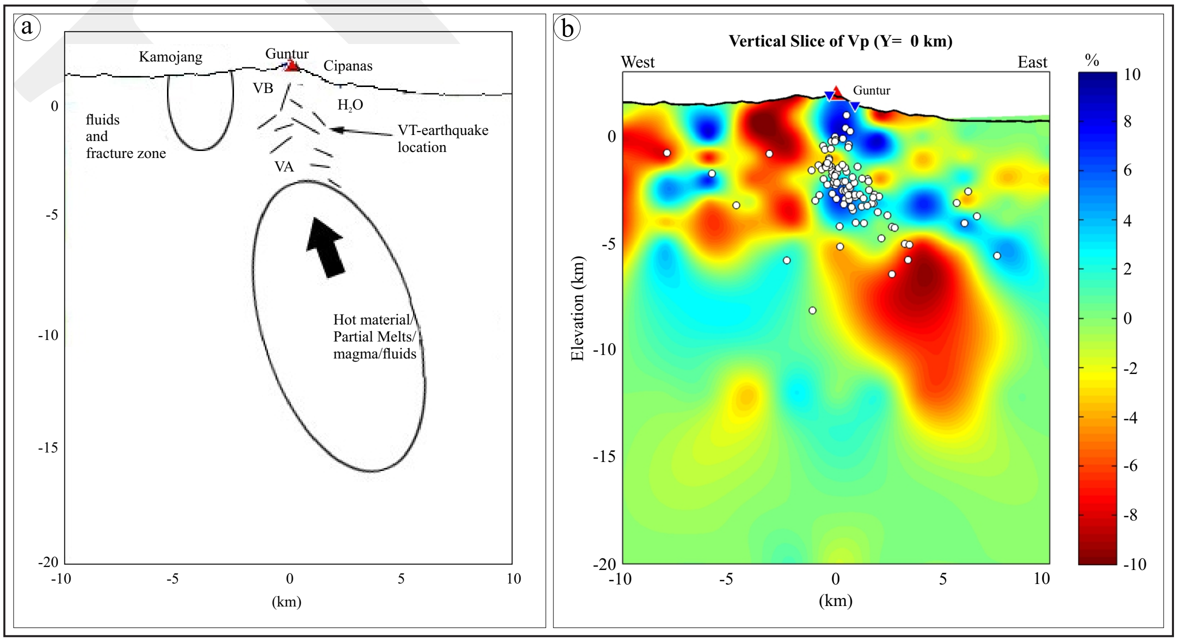

Figure 13. (a) Schematic model beneath the Guntur Volcano derived from; (b) Vp structure in this study.

Vp/Vs value was associated with the location of partial melting or magma, while low Vp/ Vs ratio was related to a rich water zone. Nugraha (2005) also mentioned that the Vp/Vs ratio was associated with the location of fluid zone or hot material zone. Futhermore, Nugraha *et al*. (2013) interpreted high Vp/Vs regions in Guntur Volcano as a melt-filled pore rock structure. A recent study in Sinabung Volcano interpreted high Vp/Vs anomaly to be caused by the presence of partial melt (Indrastuti *et al*., 2019; Nugraha *et al*., 2017; Indrastuti, 2014).

A resistivity-structure study in Kamojang area was conducted by Raharjo (2011). The results showed that the subsurface structure consisted of conductor layer associated with 1 km-thick layer with the temperature of about 150°C. Meanwhile, the moderate resistivity layer is found in 0 - 2 km depths with the temperature of more than 200°C. Thus, it is suggested that the low seismic velocity zone in Kamojang area is associated with the presence of fluid in the form of high temperature vapour. However, the low velocity zone in the southeastern part of the Guntur Volcano is related to the presence of hot springs in Cipanas area. A low velocity zone at 5 km depth beneath the Guntur Crater is predicted as a partial melting zone or magma pocket of the Guntur Volcano. It is also inferred by the location of VT earthquakes lying just above the low velocity zone, as we know that VT earthquakes occured due to magmatic activity (Zobin, 2012).

Conclusions

Tomographic inversion conducted to determine Vp, Vs, and Vp/Vs ratio structures around Guntur Volcano system by using local seismic stations operated by CVGHM for the period of January 2010 to January 2014, can be concluded as follows:

- The VT events are distributed along NW-SE direction. The foci are distinguished into three groups: (a) at the depths of 0 - 5 km beneath the Guntur Crater, (b) at the depths of 0 - 4.5 beneath the Kamojang area, and (c) at the depths of 0 - 2 km beneath the Darajat area.
- The low Vp and Vs zones appear connecting Guntur to Darajat areas through the Kamojang area at the depths of 1 - 2 km and 4 - 5 km.
- The low velocity zone probably associated with partial melting/hot material zone is found at the depth of around 5 km beneath the Guntur Crater elongated until beneath the Cipanas hotspring area. High Vp/Vs zone was also found at 5 km western side of the Guntur Crater, coincided with the location of the Kamojang Crater. It is intrepreted as regions of a high temperature of vapour. Low Vp/Vs is found near the surface at the Cipanas hotspring that is correlated with a rich-water zone.

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