P- and S-wave Velocity Structures and the Influence of Volcanic Activities in the East Java Area from Seismic Tomography

Syawaldin Ridha
Department of Physics, Universitas Brawijaya, Indonesia

Sukir Maryanto (✉ sukir@ub.ac.id)
Universitas Brawijaya  https://orcid.org/0000-0002-1882-6818

Agustya A. Martha
Meteorological, Climatological, and Geophysical Agency, Indonesia

Vanisa Syahra
Department of Physics, Universitas Brawijaya, Indonesia

Muhajir Anshori
Meteorological, Climatological, and Geophysical Agency, Indonesia

Pepen Supendi
Meteorological, Climatological, and Geophysics Agency, Indonesia

Sri Widiyantoro
Bandung Institute of Technology: Institut Teknologi Bandung

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Abstract

Indonesia is one of the most interesting targets for seismic tomographic studies due to its tectonic complexity. The subduction zone was formed when the Indian oceanic plate was subducted beneath the Eurasian continental plate. This activity caused the formation of volcanoes along the Sunda Arc, including the area of East Java. In this study, we aim to identify the influence of volcanic activities which extends from the west to the east of East Java. We used the data of 1,383 earthquakes, recorded by the 22 stations of the Indonesia Tsunami Early Warning System (InaTEWS) seismic network. We relocated the earthquakes and conducted a tomographic study using SIMULPS12. We then explored the anomalies of P- and S-wave velocities and Vp/Vs ratio. The low-velocity zone was observed in the volcanic area related to the partial melting zone or magma chamber with high Vp/Vs. This zone is observed at the depth range from 27 to 155 km and is correlated with the slab of Java subduction zone. We assume that the plumbing system of volcanoes is interlinked. If it is true, this can be helpful to carry out further detailed studies regarding the continuity of the plumbing system and the volcanic arc.

Introduction

Indonesia is a tectonically active region, as it is a meeting point of three active tectonic main plates: the Indian oceanic plate, the Eurasian continental plate, and the Pacific oceanic plate. The Indian oceanic plate sinks under the Eurasian continental plate, forming a subduction system and a volcanic arc that extends from the west of Sumatera to the south of Sumba Island. Mt. Lawu, Kelud Volcano, Semeru Volcano, Bromo Volcano, and Ijen Volcano are five of hundreds of volcanoes in Indonesia, located in East Java. Identifying the magma path orientation of these five volcanoes is a good way to better understand the volcanism as well as the predicted source of the geothermal field.

Magma forming from the partial melting of existing rock in the subsurface of the Earth (Lin et al. 2018) can be identified as either a seismic low-velocity zone (Nakamichi et al. 2009) or anisotropy (Illsley-Kemp et al. 2018) as well a high Vp/Vs ratio (Guoqing et al. 2015; Koulakov et al. 2009; Hua et al. 2019). In order to visualize the velocity structure, we performed seismic tomography using the travel time of P- and S-waves. Some tomographic studies have been published to identify slab detachment (Liu et al. 2019; Kundu & Gahalut 2011; Xu et al. 2000), partial melting zone (Nugraha et al. 2019; Indrastuti et al. 2019; Jaxylabutov & Koulakov 2011), thick sedimentary layer (Ikhsan & Yudistira 2019; Martha et al. 2017; Cipta et al. 2018), and rupture zone (Diambama et al. 2019; Koulakov et al. 2007).

In order to better understand the characteristics of the subsurface in East Java, we performed seismic tomography for the following reasons: (1) map the seismicity distribution in/from East Java by relocating the hypocenter, (2) delineate the subsurface condition from P- and S-waves modeling and Vp/Vs ratio, (3) discuss how the magma pathway influences the surrounding area.

Data & Method
We requested the dataset from the INATews (Indonesia Tsunami Early Warning System) Network developed by the Meteorological, Climatological, and Geophysical Agency of Indonesia (BMKG), which can be accessed by sending a permit letter to the agency. We used the data period from 2009 to 2017 for this study, and we noted 1,372 earthquakes were recorded from 22 broadband stations (Table 1) that generated 12,778 P- and 4,771 S-waves arrival times. We relocated 1298 earthquakes with magnitudes of more than M > 3 and modeled the earthquakes using the algorithm of SIMULPS12, which was developed by (Evan et al. 1994). SIMULPS12 can be downloaded freely by sending the authors an email. SIMULPS12 provides inversion processing to obtain the 3-D velocity model of Vp and Vp/Vs structure as well the hypocenter locations simultaneously. Using SIMULPS12, we obtained the relocated earthquakes’ parameters from the latest 3-D velocity model. During the relocation procedures, more than 74 earthquakes were discarded because of their large azimuthal gap (< 210°). Figure 1 shows the epicenter distributions according to the BMKG catalogue data from 2009–2018; it had been selected and relocated using SIMULPS12.

Table 1. List of the seismic stations that are used in this study
<table>
<thead>
<tr>
<th>No.</th>
<th>Stations Code</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>ABJI</td>
<td>-7.8</td>
<td>114.23</td>
<td>114.36</td>
</tr>
<tr>
<td>2.</td>
<td>BLJI</td>
<td>-7.75</td>
<td>113.59</td>
<td>80.85</td>
</tr>
<tr>
<td>3.</td>
<td>BWJI</td>
<td>-5.85</td>
<td>112.66</td>
<td>57.56</td>
</tr>
<tr>
<td>4.</td>
<td>BYJI</td>
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<td>114.36</td>
<td>99.5</td>
</tr>
<tr>
<td>5.</td>
<td>GMJI</td>
<td>-8.27</td>
<td>113.44</td>
<td>80.13</td>
</tr>
<tr>
<td>6.</td>
<td>GRJI</td>
<td>-6.91</td>
<td>112.48</td>
<td>97.14</td>
</tr>
<tr>
<td>7.</td>
<td>JAGI</td>
<td>-8.47</td>
<td>114.15</td>
<td>171</td>
</tr>
<tr>
<td>8.</td>
<td>KMMI</td>
<td>-7.04</td>
<td>113.92</td>
<td>49.14</td>
</tr>
<tr>
<td>9.</td>
<td>KRK</td>
<td>-8.15</td>
<td>112.45</td>
<td>330.3</td>
</tr>
<tr>
<td>10.</td>
<td>NBBI</td>
<td>-8.46</td>
<td>114.94</td>
<td>27</td>
</tr>
<tr>
<td>11.</td>
<td>NGJI</td>
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<td>111.46</td>
<td>149</td>
</tr>
<tr>
<td>12.</td>
<td>PCJI</td>
<td>-8.19</td>
<td>111.18</td>
<td>702.27</td>
</tr>
<tr>
<td>13.</td>
<td>PWJI</td>
<td>-8.02</td>
<td>111.8</td>
<td>205</td>
</tr>
<tr>
<td>14.</td>
<td>RTBI</td>
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<td>300.7</td>
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<td>15.</td>
<td>SMRI</td>
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<td>110.44</td>
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</tr>
<tr>
<td>16.</td>
<td>SNJI</td>
<td>-7.78</td>
<td>111.76</td>
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</tr>
<tr>
<td>17.</td>
<td>SWJI</td>
<td>-7.73</td>
<td>111.77</td>
<td>723.33</td>
</tr>
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<td>18.</td>
<td>TBJI</td>
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<td>54.45</td>
</tr>
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<td>19.</td>
<td>UGM</td>
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<td>110.52</td>
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<tr>
<td>20.</td>
<td>UWJI</td>
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<td>110.95</td>
<td>61.52</td>
</tr>
<tr>
<td>21.</td>
<td>WOJI</td>
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<td>110.92</td>
<td>183.62</td>
</tr>
<tr>
<td>22.</td>
<td>YOGI</td>
<td>-7.82</td>
<td>110.3</td>
<td>176</td>
</tr>
</tbody>
</table>

We performed the travel time tomography algorithm developed by Thuber and Eberhart-Philips (1999) by calculating the arrival times. Calculated arrival times are determined from the trial hypocenters, origin times, and initial model of the seismic velocity structure and the pseudo-bending ray tracing method (Um & Thurber 1987). We then obtained the residual time which is related to perturbation of the hypocenters and velocity model. We then easily obtained the ratio of Vp/Vs from the origin time and P- and S-waves arrival times. We observed the origin time (t_o), P-wave travel time (t_p – t_o), and S-wave travel time (t_s – t_o) model of Vp and Vs structures. We can easily obtain the ratio of Vp/Vs from the origin time and P- and S-
waves arrival time. We observe the origin time \( (t_o) \), P-wave travel time \( (t_p - t_o) \), and S-wave travel time \( (t_s - t_o) \). We then calculate the distance of P- and S-wave travel shown by Equation 1 as follows.

\[
(t_s - t_p) = \left( \frac{v_p}{v_s} - 1 \right) (t_p - t_o)
\]  

(1)

Then we substitute Eq. (1) to linear equation \( y = mx \), where \( y \) is \( (t_s - t_p) \), \( m \) is \( \left( \frac{v_p}{v_s} - 1 \right) \), and \( x \) is \( (t_p - t_o) \), then the ratio \( \frac{V_p}{V_s} \) can be expressed as the form of gradient \( m+1 \).

Checkerboard test is commonly used in seismic tomography studies for minimalizing errors and assessing a reliable result. In order to obtain the closest image to the actual structure, Lévêque et al. (1993) assumed a uniform velocity structure in the whole medium so that the source-to-receiver paths are straight lines. Checkerboard test will use an arbitrary model, first, as a regular pattern of high and low attenuation zones. The synthetic data will be computed and inverted using the Lanczos’s (1961) method to obtain the inverted (true) model. We then differentiate the model into horizontal and vertical profiles to ease the interpretation. We used the longitude range of \( 110^\circ - 115^\circ \) E, the latitude range of \( 5^\circ - 12^\circ \) S, and the depth range of \( 0 - 300 \) km. We discretized the model space by grid to represent the 3-D velocity structure model. We used both the horizontal & vertical grid of \( 17 \times 17 \) with interval \( 50 \times 50 \) km.

**Results**

We show the results for \( V_p \) and \( V_s \) structures as well the values of \( \frac{V_p}{V_s} \) ratio in Figs. 5 – 11, which plot the percentage perturbation from the P-wave 1-D velocity model of Koulakov et al. (2007) (Table 2) as the initial model. In order to obtain the \( \frac{V_p}{V_s} \) ratio, we referred to the Eq. (1), using the linear regression, then we obtained the average ratio of \( \frac{V_p}{V_s} \) of \( 1.75 \pm 0.038 \) as shown in Fig. 2.

Table 2. The interpolated average value of minimum 1-D velocity model of Koulakov et al. (2007). Depth in negative value means that the average value is above the mean sea level.
<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>P-wave velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>4.3</td>
</tr>
<tr>
<td>0</td>
<td>4.9</td>
</tr>
<tr>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>40</td>
<td>7.31</td>
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<tr>
<td>60</td>
<td>7.57</td>
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<tr>
<td>90</td>
<td>7.87</td>
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<tr>
<td>120</td>
<td>8.05</td>
</tr>
<tr>
<td>160</td>
<td>8.16</td>
</tr>
<tr>
<td>200</td>
<td>8.27</td>
</tr>
<tr>
<td>300</td>
<td>8.62</td>
</tr>
</tbody>
</table>

We presented the tests in eight horizontal profiles at depth of 0, 20, 40, 60, 90, 120, 160, and 200 km. We reconstructed the results to assess the resolution and the reliability of the structures. In order to know the raypath based on the same source-receiver pairs, here, we show the ray tracing of the actual dataset (Fig. 3).

Viewed in horizontal cross section, the velocity anomalies in the study area are well defined as shown in Fig. 4. The decrease of P- and S-waves anomalies is shown by low-velocity rocks, with the lowest anomalies at the depth of 20 km, appearing along the volcanic arc of the study area (black dashed line in Fig 4a-h), where the young volcanic rocks formed. In contrast, we figured out the high anomalies, appearing along the fore-arc, which suggested as the slab material due to the subduction zone. At the depth of 40 km, the velocity patterns begin to increase. A relatively high-velocity zone appears beneath the volcanic arc to basin (north of the island) between the depth of 40 – 60 km. At the depth of 90 km, positive dVp zone appears to shift eastward (Fig. S1) and disappear at the depth of 120 km (Fig. S1). However, this high-velocity zone appears again at the depth of 160 km, which may represent the slab material down deep to that depth.

To analyze how the distribution of the velocity structures based on the depth, we divided the study area into 6 cross section profiles; each profile sliced the volcanic area (Fig. 1). The resulting distribution of seismic velocities obtained from this study can depict the structure well. Since we have lack of earthquake data at the depth of 100 km down, we analyze those depths according to the 1-D average velocity model of Koulakov (2007).

a. Profile A – A'
We observed the low anomaly beneath Mt. Lawu to 100 km northward are due to the volcanic activity of Young Lawu shown by the negative value of Vp and Vs perturbations. Some low anomalies of Vp and Vs perturbations are observed around the slab of the subducting plate. We interpreted that these low anomalies are the partial melting of the slab. High anomaly appears along the slab (black line, Fig 5). We interpreted that these high anomaly represents the material of the slab, which are shown by the positive values of the Vp and Vs perturbations.

b. Profile B – B’ (Mt. Wilis)

We observed high-velocity anomaly exhibits from the depth of 25 – 150 km (Fig. 6). We first observed the high-velocity zone at the slab down to depth of 150 km, which indicates the slab material. Then, these high-velocity patterns, forming a path 200 km northward with ~50 km thick. However, the anomaly of the low velocities appears at 60 km northward of Mt. Wilis, which may relate to the activity of Mt. Pandan or Kendeng fault zone (Vp/Vs ~1.88) at the depth of less than 20 km. Another anomaly of low-velocity zone is observed at approximately 70 km to the southward of Mt. Wilis with dVp and dVs decrease into -9.5%. We suggest that this negative values represent the old Southern Mountain Range activities in the past.

c. Profile C – C’

Our profile C – C’ is depicted well in Fig. 7. This profile uniquely sliced three neighbourhood volcanoes (Mt. Arjuno, Mt. Welirang, and Mt. Kelud). We observed negative values beneath these volcanoes with dVp and dVs ~ -10% and down to the depth of 100 – 150 km, which may represent the partial melting of the slab. This partial melting then may supply the negative body in the upper part (Vp/Vs ~ 1.88). We also observed a low-velocity pattern in the fore-arc which may represent as the partial melting at that part. Some low anomalies of Vp and Vs are observed at the north part of the profile, is related to the sediment of the basin at the north of East Java. High anomaly appears along the slab (black line), is interpreted as the material of the slab. These positive bodies form a lateral pattern towards the north, which may represent the Moho.

d. Profile D – D’ (Mt. Semeru)

In Profile D – D’ (Fig. 8), low-velocity patterns exhibit from the depth of 0 – 200 km. We observed a lateral negative body right beneath Mt. Semeru at the depth of 20 – 30 km, which may relate to the magmatic activity of the volcano (Vp/Vs ~1.86). Down to the depth of 150 km represents the partial melting of the slab. This partial melting then feeds the magmatic system at the upper part. Then, these low-velocity patterns form a path 200 km northward with ~30 km thick, which may relate to the sediment in basin. We also observe a negative body at the fore-arc and down to the depth of 50 – 150 km (Vp/Vs ~1.87). We observe high-velocity bodies at the fore arc and basin at the depth of ~50 km. This positive body may indicate the slab of subducting plate (black line) then elongated a lateral body to the northward, which may represent the Moho.

e. Profile E – E’ (Mt. Argopuro)
In profile E – E’ (Fig. 9), high-velocity zones exhibit from the depth of 0 – 250 km. High-velocity zone at the slab down to depth of 250 km indicates the slab material. However, these high-velocity zones exhibit high Vp/Vs at the slab material, which we are still questioning and this might be a good indication to conduct the next tomographic studies. These high-velocity patterns are likely due to the continuity of another positive body at the depth 100 – 150 km in the southern part which elongates up to the depth of 50 km northward, being ~50 km thick. Meanwhile, the anomaly of the low velocities appears right beneath Mt. Argopuro which may relate to the magmatic activity. Another anomaly of a low-velocity zone is observed at approximately 80 km to the northward of Mt. Argopuro with dVp and dVs decreasing to -10%. We suggest that this negative value represents the sediment basin of north East Java.

f. Profile F – F’ (Mt. Ijen)

In profile F – F’ (Fig. 10), high-velocity patterns exhibit from the depth of 0 – 150 km shown by the positive anomaly. We suggest that this positive body represents the slab material. Right beneath Mt. Ijen, a negative body exhibits at the depth 0 – 30 km, which is likely related to the magmatic system of Mt. Ijen and Mt. Raung (Vp/Vs ~ 1.87). However, this negative body is likely forming a path to the continuity of another positive body 100 km away toward the south. We interpret that this continuity of the negative body relates to the sediment at the basin. At the depth of 100 – 200 km right beneath the volcanoes, we figure out a vertical high Vp/Vs (~1.89) body, which may represent as the partial melting feeds the magmatic system at the upper part.

Discussion

We figured out the low-velocity zones in this profile right beneath the Mt. Lawu, Quaternary volcano, as we can see in Fig. 6. We suggested that this low-velocity zone might associate with the past volcanic activity, which feeds the current geothermal heat source, composed by most basaltic andesite (Hartono 1994). The intrusion of lava in the southeastern part of Mt. Lawu is thought to be the heat source of the hydrothermal system (Koesuma et al. 2020), which then flows the heat through cracks or microcracks surrounding the observed fault zone. High Vp/Vs body at the north of Mt. Wilis, an extinct Quaternary volcano, is suggested as the hydrothermal zone (Profile B-B’, Fig. 7), which is possibly the heat source of the geothermal system of Lake Ngebel. Further to the north, a low density anomaly was observed beneath Mt. Pandan (Santoso et al. 2018), suggested as the presence of hot material because of the hot springs and warm ground. Small earthquakes were observed (M < 4), which are concentrated beneath Mt. Pandan at the depth of less than 10 km dipping to the southward. Santoso et al. (2018) suggested that the small earthquakes, which occurred in 2016, may lead to the Kendeng fault activity located northward of Mt. Pandan.

Fallahi et al. (2017) studied an ambient noise tomography along the Mt. Arjuno to Lusi mud volcano and found that beneath the Mt. Arjuno and Mt. Penanggunan, low velocity body was observed at the depth of 4 – 6 km, indicates the magmatic bodies of both volcanoes. The composed rocks of Mt. Arjuno, formed as the result of the eruptions of the Old Arjuno, the Young Arjuno, and Mt. Welirang might influence the
velocity structure beneath Mt. Arjuno itself. A high Vp/Vs body is observed, which might indicate as partial melting due to the subduction activity. Another possibility of high Vp/Vs zone might be due to the hydrothermal activity of geothermal system of Arjuno-Welirang. High velocity zone is associated with the slab material due to the subduction zone, in agreement with the study of Widiyantoro and Van der Hilst (1997), which investigated high P-wave velocity anomaly as the image of the slab in the upper mantle. We also observe a lateral high-velocity body in the northern part of the profile (Fig. 7), indicates to be either the ocean floor, crustal structures, or Moho. Moho's discontinuity, itself, is imaged as an anomaly body which depths down to 39 km (Wölbern & Rümpker 2016).

We observed both the perturbations of P- and S-waves decrease at the fore-arc, interpreted as the partial melting zone due to the collision between the oceanic and continental lithospheres. Furthermore to the north, a high-velocity zone is observed, which may represent as either the slab material or the Southern Mountain Range. Southern Mountain Range itself is composed by old volcanic rocks which were formed in the Tertiary period (Kurnianto et al. 2019; Van Bemmelen 1949). Ayu et al. (2013) imaged the seismic attenuation analysis of Mt. Semeru and found a high attenuation zone which was interpreted as the magma chamber of Semeru Volcano. According to the study of Ayu et al. (2013), we interpreted their high attenuation zone as our low-velocity zone (Fig. 8) as right beneath the Mt. Semeru, a low-velocity zone is observed at the depth of approximately 10 – 30 km.

The existence of a geothermal system in Mt. Argopuro is consisted of altered rock, reservoir, and hot rock (heat source) Singarimbun et al. (2017), strongly influenced by the volcanic activity. We interpret the geothermal system as the low-velocity zone right beneath the volcano (Fig. 9). Descatoire (2020) depicted a block diagram of the subduction zone beneath the Island of Java. Partial melting is observed as the Indo-Australian plate reaches a depth greater than 100 km, then it creates magma. We observed a vertical high Vp/Vs body at the depth of approximately 100 – 250 km (Fig. 10). We suggested this high Vp/Vs zone is due to the partial melting of the slab. This partial melting then feeds the magma chamber of Ijen and Raung volcanoes at the depth of approximately 0 – 20 km. We also observed a high-velocity zone elongated down at the depth of 50 – 200 km. Here, we interpreted the high-velocity body as the slab material of the subduction zone.

Our interpretation in all profiles is in agreement with the study of Nugraha et al. (2019), which found that a high Vp/Vs was observed at Sinabung Volcano. They interpreted the anomalies is associated with the plumbing system of the volcano itself. Martha et al. (2017) did the ambient noise tomography study along the volcanoes which included Mt. Semeru, Mt. Argopuro, Mt. Raung, and Mt. Ijen, found low-velocity structures; might be caused by the age of the volcanic rocks, which is relatively young and might still be producing magma.

**Conclusions**

We studied seismic tomography in the East Java area using the data of 1,372 earthquakes, which were recorded by the 22 seismic stations of InaTEWS network during 2009 – 2018. The main conclusions of
this study are summarized as follows:

1. We obtained the P-wave velocity in the range of 3.37 – 9.61 km/s from the depth of 0 – 300 km. Meanwhile, the S-wave velocity is in the velocity range of 1.91 – 5.59 km/s. Ratio of Vp/Vs of the study area in the range of 1.45 – 2.05.

2. Low-velocity zone and high ratio of Vp/Vs are observed in the volcanic complex, which is expected to act as a partial melting zone or magma chamber due to the existence of volcanic activities. A low-velocity zone at the depth of 27 – 155 km suggested as the partial melting of the slab.

3. Due to the existence of volcanic activities in the East Java area, we suggested that there is an influence of magma chamber, which forms a pathway, continually extending from the Mt. Lawu to the Ijen-Raung Volcano Complex.

Declarations

Availability of data and materials

We used the catalogue of seismic data provided by Meteorological, Climatological, and Geophysical Agency of Indonesia. Data can be accessed directly by sending a permit letter to the agency.

Competing Interests

The authors declare no conflict of interest with any research. The funding sponsor had no role with all the data, materials, analysis, or data interpretation in writing the manuscript or decision to publish the study.

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Author’s contributions

Syawaldin Ridha: Investigations, Formal Analysis, Software; Sukir Maryanto: Conceptualizations, Supervision, Writing – review & editing, Validation; Agustya A. Martha: Validation; Vanisa Syahra: Writing – original draft, review & editing, Visualization; Muhajir Anshori: Data Curation, Software, Resources, Validation; Pepen Supendi: Supervision, Writing – review & editing; Sri Widiyantoro: Supervision, Writing – review & editing.

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References


Figures
Figure 1

Distribution of earthquake locations in the East Java area based on the catalogue of BMKG and InaTEWS seismic network using the 1-D velocity model of Koulakov (2007): a) before relocated, b) after relocated. The red triangles represent the 22 stations used in the study area. The black lines across the study area show the vertical profiles used for depicting the P- and S-waves velocity anomalies.
The obtained Wadati diagram of Vp/Vs in our study area.
Figure 3

Raypaths in the study area with different source locations. (a) Raypath coverage and station locations. (b) West-east cross section with raypaths. (c) South-north cross section with raypaths. Raypaths represent as blue lines and yellow inverted triangles represent as the seismic station.
Figure 4

Map of tomography study at different depths. (a – c) Perturbation of P-wave velocity. (d – f) Perturbation of S-wave velocity. (g – i) Ratio of Vp/Vs in the study area. Black dashed lines depict the volcanic arc of the island.
Figure 5

South-north tomographic sections of the Profile A – A’ in the study area. The upper part shows the perturbation of P- and S-waves (right and left, respectively). The middle part shows the absolute velocities of P- and S-waves (right and left, respectively) of the study area. The last bottom part is the ratio of Vp/Vs of the study area. The red triangles depict where the volcano lies on the profile. The black lines deep down depict the slab of the subducting plate.
Figure 6

South-north tomographic sections of the Profile B – B’ in the study area.
Figure 7

South-north tomographic sections of the Profile C – C’ in the study area.
Figure 8

South-north tomographic sections of the Profile D – D’ in the study area.
**Figure 9**

South-north tomographic sections of the Profile E – E’ in the study area.
Figure 10

South-north tomographic sections of the Profile E – E' in the study area.

Supplementary Files

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• TableSupplementary1.xlsx
• FigureSupplementary1.tiff