Preliminary Model of P-Wave Tomography Beneath Central Java using FMTOMO

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Abstract. The tectonic setting of Java Island is mainly controlled by the collision of Indo-Australian plate subducting the Eurasian plate. The high collision activity of Eurasian and Indo-Australian plates often causes megathrust earthquakes and the rise of arc magmatism that includes volcanic eruption. This study aims to determine the tectonic pattern beneath Central Java based on P-wave tomography inversion. We used the fast-marching method as ray tracing and subspace inversion to image subsurface velocity model to a depth of 150 km. The data used in this study are catalogue events data derived from a temporary seismometer network MERAMEX installed around central Java and DOMERAPI installed surround Mt. Merapi and Mt. Merbabu. We also include events collected from the International Seismological Centre. In total, we processed 563 earthquake events to illustrate velocity structures under central Java. The checkerboard model shows that good resolutions can be identified at shallow depth, including offshore south Java contributed from Ocean Bottom Seismometer data. In vertical axis, good resolution models can be expected down to a depth 150 km following rich events from the Benioff zone. Current P wave model show a distinct low velocity zone under Mt Merapi that can be seen down to a depth of 40 km, suggesting a possible separated deep magma reservoir. To the south of Mt Merapi area also shows a low-velocity band that may be related with the southern mountain arc. Additionally, the northern part of Mt. Merapi displays a band of strong low-velocity anomaly to the East and West with the anomaly in the Eastern Part seems to have a deeper extension to a depth of ~50 km. We related this anomaly with Merapi Lawu Anomaly and Kendeng basin. Our results show a similar result with the previous tomography models in this region.
1. Introduction

Indonesia is an archipelago that its tectonic setting is affected by the interaction between 3 large tectonic plates, namely the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. The high activity of the movement of these three plates has resulted in many volcanoes forming along the island of Java to Sumatra so Indonesia is called the ring of the fire area. [1] stated that the high collision activity of the Eurasian and Indo-Australian plates often causes megathrust earthquakes which result in the high activity of many volcanoes in the Java Island region, especially Central Java. One of the most active volcanoes today is Merapi. In this study, we conducted a tomographic study in the area of Merapi volcano by using the fast-marching ray tracing method and sub-space inversion. Previous local tomography studies [2] show a region of lower Vp and high Vp/Vs ratios inside the Merapi Lawu Anomaly (MLA) region, located to the north of Mt. Merapi. They suggested that this may be related to the presence of elevated fluids and partial melts. [3] performed local earthquake tomography and found lower velocity anomaly in the back-arc crust north of the active volcano, down to upper mantle area. [4] applied Receiver Function method to estimate crust thickness in this area and proposed that the Moho is shallower beneath Mt. Merapi with higher Vp/Vs ratio. The objective of this study is to image the subsurface structure beneath central Java using alternative fast marching ray tracing method and inversion method.

Data and method

In this study, we used the same data set as in [5], [2]. The data comes from several networks: 53 stations from DOMERAPI network, 17 from local BMKG network and 134 from MERAMEX network covering a region of 150 x 200 km (Figure 1). The total duration of data is from 2004-2016 although most stations are installed in short duration time. We collected 563 events with a maximum depth of 160 km. This depth limit was chosen based on previous research regarding the depth of subduction seen at a depth of 50-100 km [2].

Events distribution is dominated by less than 100 km depth located offshore at southern part of the island of Java (Figure 1). Most event show a down-going dip to the north and most likely are tectonic event from the subduction slab between the Indo-Australian plate and the Eurasian plate. We used the fast-marching method to reconstruct ray path between source and receivers. The 3-D ray tracing is a grid based eikonal solver that uses a modified finite difference method.

![Figure 1. The distribution of earthquakes and stations in the Merapi Volcano area](image)
The inversion problem is determined by the subspace inversion method with the ak135 velocity model [6] as the initial and reference model. We used a package named tomo3d [7] to reproduce a 3-D velocity model of crust and upper mantle beneath Central Java, Indonesia. For the parameterization, we set 30 layers in depth direction with 5 km thick, 50 grids in latitude direction with 10 km length and 50 grids in longitude direction with 11 km length. The damping parameter and smoothing parameter is set to be 10 and 15 to resolve underdetermined problem in the inversion.

2. Result
One way to check if the perturbation velocity model is reliable, is by observing the difference between calculated travel time and observation time. A good model can be achieved by observing less number in residuals data between observed arrival time and model arrival time. Figure 2 shows the histogram of travel time between initial model and final model. Before inversion, most residuals data are negative with means about -0.4s and residual data after inversion show a more centered histogram on 0.1s, suggesting the velocity model has been optimized and move closer to real velocity number. Note that in this study, to optimize our model, we performed trade off analysis in the damping and smooth parameters. The optimal damping and smooth parameters are 15 and 20 consequently.

![Figure 2. Comparison of residual values](image-url)
To test the robustness of our model, we perform checker-board resolution test. One challenge in tomography inversion is un-balanced condition between unknown parameters and the available arrival data set that can give a non-unique solution in the inversion process. The checker-board simply arrange velocity model into alternating regions of high and low velocity. Then, we tried to invert the velocity using the same source and receiver configuration in the observation data set. The inconsistency between the input checker board model and the recovered structures reveal which regions of the model can be retrieved. Figure 3 shows the results of the checker-board test in this region. Most areas show good recovering down to a depth of 60 km although some smearing start to appear from a depth of 25 km. Resolution quality started to decrease from a depth of 80 km with less area recovered and reach maximum depth of 100 km. Figure 4 and 5 display all recovered P wave tomograms in this region in horizontal and vertical slices. Most shallow depths model show a domination of low velocity zone and deeper than 40 km show high velocity patterns.

Figure 3. Checker-Board model for horizontal and vertical slices. The vertical slices are taken on latitude 109.5, 110, 110.5 and 111 degree.
Figure 4. Horizontal tomography model

Figure 5. Cross section tomography model

Figure 5 shows a series of cross section from west to east with interesting results. A band of slow velocity can be seen at some areas such as between latitude -9\(^\circ\) to -8\(^\circ\) from a depth of 5 to 30 km at line B, C and D. Another region of low velocity can also be seen on latitude -7\(^\circ\) at shallow depth at line B, C, and D. A band of fast velocity is also seen dipping to the north although not that clear. Plot of seismicity on top of tomogram seems to show a pattern of dipping to the north.
3. Discussion
The high velocity region that dips to north may represent the subducting oceanic plate underneath the Eurasian plate. We see a pattern of steep subduction that increase its angle to the east. Steep angle of subduction may be related to the subduction rollback from north to south which resulted in a change in the subduction path which affected volcanic activity in Central Java.

In line A there is a negative anomaly in the southern part of Java Island from a depth of 5-15 km, which is associated with a marine forearc anomaly which is associated with marine sediment [1]. In line B and C, there is a negative anomaly to the north of Mount Merapi at a shallow depth of 20 km which is interpreted as a partial melting zone [2] while for a shallow depth it is associated with the Kendeng basin zone which is filled with sedimentary material.

In line C, just below and the northern part of Mount Merapi also shows a low anomaly zone to a depth of 30 km associated with a partial melting zone [2] as well as a layer of sediment originating from the Kendeng basin. Besides, there is also a negative anomaly in the southern part of Mount Merapi at a shallow depth of up to 15 km which is associated with the southern mountain arc zone where this zone is associated with volcanic rock and igneous intrusion [5].

4. Conclusion
Tomography model show Vp perturbation anomaly results showing MLA zone / partial melting zone beneath Merapi volcano, Kendeng Basin in northern part of Merapi which contains sedimentary material, igneous intrusion in southern mountain arc, and marine fore arc anomaly in southern Java island. High velocity anomaly and distribution of earthquake events at a depth of more than ± 40 km may represent down-going oceanic plate and increase its angle to the east.

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