

# 3D Tomographic Imaging of P Wave Velocity Structure Beneath Java Island using Fast Marching Tomography Method

Uswatun Chasanah<sup>1</sup>, Bagus Jaya Santosa<sup>2</sup>

**Abstract**—Java Island one of the best locations for geophysics research, as it's located near the edge of the junction of continental Eurasia Plate and the Indo-Australia Plate with the movement of the plates 6 cm/year. Its needed the accurate imaging of subsurface structure to understanding complex tectonic setting. The first arrival time from local earthquake of Java (6,360-9,150 S and 105,890-115,540 E) with magnitude greater than 4,5 Mw occurred from 2011 until 2013 recorded by local network seismograph has been inverted for three dimensional variation of the depth to the P wave velocity in the Java island. At the same time, earthquake hypocenter location has been corrected simultaneous. This research apply a new tomographic inversion scheme FMTOMO that has been developed by Rawlinson (2004). The results of inversion show that there are three layer in 100 km from the surface at continental plate side (Eurasia). The continental upper crust has P wave velocity variation about 4-5,5 km/s in the depth until 30 km from the surface. There are low velocity anomaly inclined towards the slab which probably have associated with shallow earthquake along the slab.

**Keywords**—P-wave, seismic tomography, Java Island

## I. INTRODUCTION

The subduction zones on the crust of the Earth is related with the seismic and volcanic activity. Java island, located at the junction of two major tectonic plates (Indo-Australian plate and Eurasian plate), is formed by a complex mosaic of oceanic plates, island arcs, continental shelf and crustal fragments [1]. Tectonic structure of Java island is dominated by the almost orthogonal convergence between the Australian plate and Eurasia (67-70 mm/year, today).

The Indo-Australia plate is pushing the Eurasia plate. In north of Java island, Indo-Australia plate is moving 100-200 under the Eurasian plate [2]. The deeper slab beneath Java, appearing as an inclined high-velocity feature, seems to be continuous from the Earth's surface to the lower mantle [3].

To understand the mechanisms of the process of tectonic activity, seismicity and volcanism, we need some tools. Seismic tomography is one of the most powerful tools to obtain these constraints [4]. This is a form of seismic traveltime inversion that is used to constrain 2D and 3D models of the Earth represented by a significant number of parameters [5]. Actually the earthquake cause the propagate of seismic wave that bring some information about interior structure of the earth. Seismic data in seismograph represent one of the most valuable resources and important information for investigating the internal structure and composition of the earth.

The accurate of hypocentre location is one of the main things when studying the seismicity of the area within the parameters of the earthquake because there is important information from ongoing seismotectonic process [6]. The earthquake parameters are usually magnitude, origin time, epicentre and depth. The accuracy of seismic parameter calculation is highly dependent on the structure of seismic wave velocity models used. The aim of this local scale studies on this paper is to explore the deep structure of slabs beneath Java Island by means of tomographic imaging using P wave phases.

## II. METHOD

The 431 P wave phases was picked from waveform 3 components that recorded by 35 local network seismograph. And it was inverted using FMTOMO that calculated using fast marching tomography method. This processes obtaining the value of 3D velocity to determine the real structure of tectonic settings under the Java island.

Origin time value of P waves is obtained by picking the seismic waveform from each station. In this study, picking process of arrival time of P wave is using software Seisgram2K (Figure. 1).

FMTOMO uses the fm3d package to solve the forward problem. Fm3d is based on the multi-stage Fast Marching Method (FMM), a grid based eikonal solver (1) that implicitly tracks the evolution of waveform in 3-D layered media. For more details, refer to Sethian (1996), Sethian & Popovici (1999), Sethian (1999) and Popovici & Sethian (2002) [7], [8]. The eikonal equation states that the magnitude of the traveltime gradient at any point along a wave front is equal to the inverse of the wavespeed at that point [9] and may be written as:

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$$|\nabla_x T| = s(x) \quad (1) \quad \text{slowness [10].}$$

where  $\nabla_x$  is the gradient operator,  $T$  is traveltimes and  $s(x)$  is

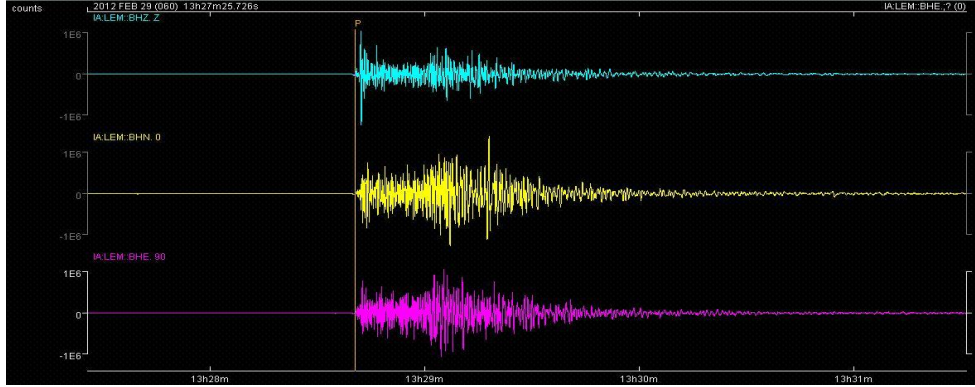


Figure 1. Picking process the arrival time of P wave using software Seisgram2K

If we represent some elastic property of the subsurface (e.g. velocity) by a set of model parameters  $m$ , then a set of data (e.g. traveltimes)  $d$  can be predicted for a given source-receiver array by line integration through the model. The inversion step, which involves the adjustment of the model parameters  $m$  to better satisfy the observed data  $d_{obs}$  through the known relationship.

$$d = Gm \quad (2)$$

In travel time tomography, the functional  $G$  is non-linear because the ray path depends on the velocity structure [11]. For an initial estimate  $m_0$  of the model parameters, comparing this equation (3)

$$d = Gm_0 \quad (3)$$

with the observed travel time  $d_{obs}$  gives an indication of the accuracy of the model. The misfit can be quantified by constructing an objective function  $S(m)$ (4), consisting of a weighted sum of data misfit and regularization terms, that is to be minimized. The objective function is given (4).

$$S(m) = \frac{1}{2}(G(m) - d_{obs})^T C_d^{-1}(G(m) - d_{obs}) + \epsilon(m - m_0)^T C_m^{-1}(m - m_0) + \eta m^T D^T D m \quad (4)$$

The steps required to produce a tomographic image from seismic data can thus be defined as follows (adapted from Nick Rawlinson et al.):

1. Model parameterization: The seismic structure of the region being mapped is defined in terms of a set of unknown model parameters.

2. Forward calculation: A procedure is defined for the calculation of model data (traveltimes) given a set of values for the model parameters.

Inversion: Automated adjustment of the model parameter values with the object of better matching the model data to the observed data.

### III. RESULT AND ANALYSIS

The tomographic solution model, obtained after six iterations of the non-linear scheme, is shown in Figure 2, Figure 3, Figure 4 and Figure 5. In horizontal cross section and vertical cross sections. The rms values of the residuals in six iterations are presented in Table 3. The ak135 velocity model was used for the reference, or starting, velocity model. Damping ( $\epsilon$ ) and smoothing ( $\eta$ ) values were chosen to solve variations in deep mantle and crustal structure may account for some of the data misfit. We used a 20-dimensional subspace scheme on six iterations to solve both P inversions. However, in some cases the subspace was reduced by Singular Value Decomposition (SVD) orthogonalization to remove unnecessary basis vectors during the inversion step. Iterations are repeated until the contribution of the next cycle becomes negligible. In case of our study, six iterations were enough to achieve sufficient convergence [12].

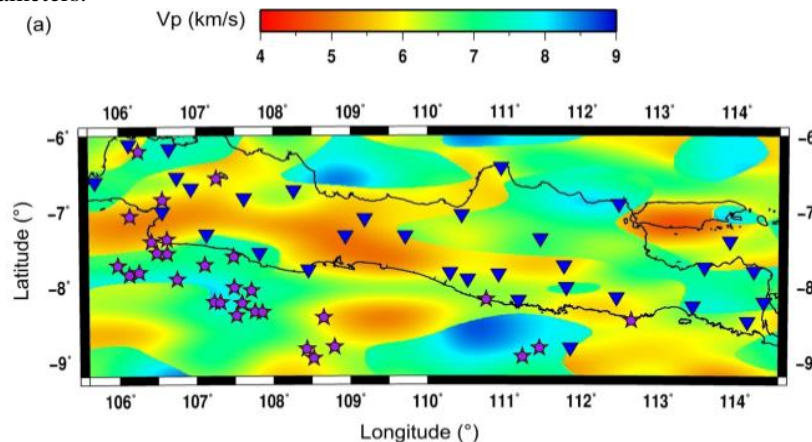


Figure 2. The resulting distribution of P-velocity anomalies after the inversion of six iterations is shown in this picture. Purple stars mark sources earthquake (epicenter) of the BMKG-IA catalogue, and blue triangles in profile marks the station that recorded the earthquake signals.

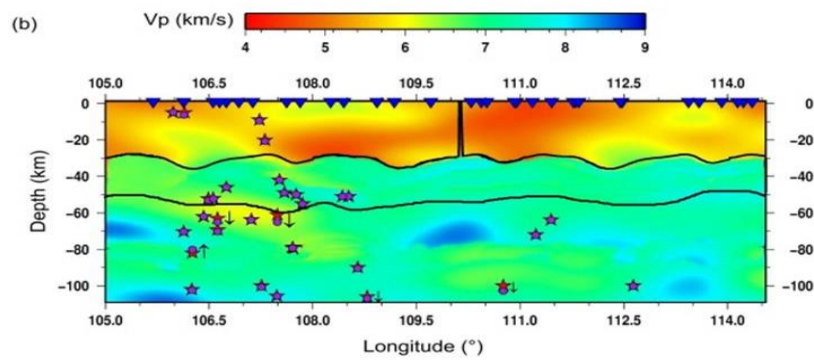


Figure 3. P-velocity model presented in vertical cross sections. Profile locations are shown in the map on slide before. Purple dots mark hypocentres of the BMKG-IA catalogue before relocation of hypocenter, red stars in profile marks the hypocentre of the Java earthquake after relocation, and the vector marks the preposition of location hypocenter before and after relocation.

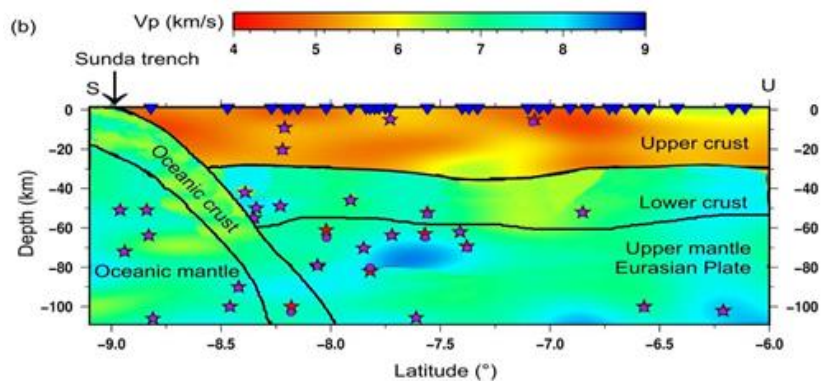


Figure 4. A large low-velocity anomaly in the upper crust northward of the oceanic crust. There are three layer in 100 km from the surface at continental plate side (Eurasia). The upper crust, lower crust and upper mantle. The oceanic plate (Indo Australia) have two layer in 100 km from the surface. The oceanic crust and the oceanic mantle.

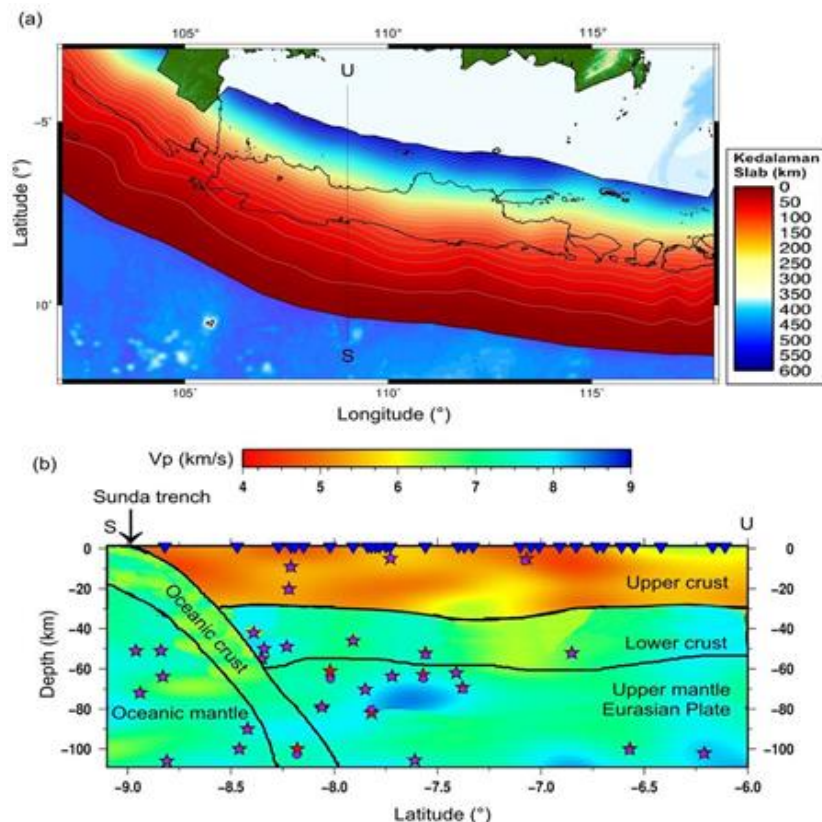


Figure 5. (a) Sketch of slab subduction of Java island, (b) Sketch and interpretation of the velocity structure in Java island. The oceanic plate pushes northward and subduct under Java. Stresses accumulate in the near of slab of oceanic crust region where fractures occur. The earthquake hypocentre is located just below this level (~60 km depth). This implies that it is located in the rigid crust that is the most probable location for stress accumulation.

TABLE 1.  
SUMMARY OF RESULT INTERPRETATION VERTICAL LONGITUDE CROSS-SECTION

Layer Number	Interpretation		
	Layer Name	Estimation Depth (km)	Estimation Vp (km/)
1	Continental Upper Crust	0-30	4-5,5
2	Continental Lower Crust	30-50	6,5-7
3	Continental Upper Mantle	50-100	6,5-8,5

TABLE 2.  
SUMMARY OF RESULT INTERPRETATION VERTICAL LATITUDE CROSS-SECTION

Layer Kind	Layer Number	Interpretation		
		Layer Name	Estimation Depth (km)	Estimation Vp (km/)
Continental plate	1	Continental Upper Crust	0-30	4-5,5
	2	Continental Lower Crust	30-50	6,5-7
	3	Continental Upper Mantle	50-100	6,5-8,5
Oceanic plate	1	Oceanic Crust	0-18	6,5-7
	2	Oceanic Mantle	18-100	6,5-8,2

TABLE 3.  
SUMMARY OF RESULTS FROM THE EARTHQUAKE HYPOCENTRE RELOCATION. THE INITIAL AND RECOVERED SOURCE LOCATIONS ARE SHOWN IN FIGURE 2, 3 AND 4.

No	Date and time earthquake occurs	Latitude ( $^{\circ}$ )		Longitude ( $^{\circ}$ )		Depth (km)		RMS (ms)
		Initial	Recovered	Initial	Recovered	Initial	Recovered	
1	2011-02-10T23:19:30	-8,4600	-8,4613	112,6400	112,6401	140,00	140,29	2,384
2	2011-03-19T01:16:14	-8,9400	-8,9427	111,2300	111,2300	72,00	72,26	3,321
3	2011-03-20T01:20:16	-7,9100	-7,9089	106,7500	106,7485	46,00	45,95	3,153
4	2011-03-22T00:37:17	-7,7300	-7,7264	105,9800	105,9823	5,00	4,91	2,056
5	2011-04-10T04:14:23	-8,8100	-8,8113	108,7900	108,7884	139,00	137,05	2,561
6	2011-05-28T20:28:56	-8,9600	-8,9615	108,5200	108,5179	51,00	50,96	2,384
7	2011-06-11T20:23:09	-7,0700	-7,0778	106,1400	106,1381	5,00	6,27	3,651
8	2011-06-13T15:46:35	-8,1800	-8,1808	110,7600	110,7594	147,00	149,89	3,094
9	2011-06-21T22:43:11	-6,5700	-6,5717	107,2600	107,2594	180,00	180,63	3,552
10	2011-07-01T14:33:25	-8,4200	-8,4207	108,6500	108,6485	90,00	90,53	2,851
11	2011-07-09T13:27:02	-8,8400	-8,8392	108,4300	108,4285	51,00	50,95	2,105
12	2011-07-24T08:23:37	-7,4100	-7,4111	106,4200	106,4190	62,00	62,13	2,384
13	2011-08-21T16:54:21	-7,5700	-7,5690	106,6200	106,6203	63,00	65,08	4,670
14	2011-08-29T08:56:57	-8,2100	-8,2126	107,2300	107,2256	9,00	9,59	4,032
15	2011-10-23T17:45:25	-8,2300	-8,2288	107,5900	107,5883	49,00	49,02	3,270
16	2011-11-06T04:41:56	-6,2100	-6,2131	106,2500	106,2527	162,00	162,51	2,105
17	2011-12-11T06:34:18	-8,2200	-8,2206	107,3100	107,3068	20,00	20,71	3,032
18	2012-01-31T04:18:51	-8,3400	-8,3406	107,7600	107,7610	50,00	50,03	2,441
19	2012-02-03T04:01:49	-8,8300	-8,8291	111,4500	111,4504	63,80	63,94	2,384
20	2012-02-15T21:59:30	-7,8500	-7,8493	106,1300	106,1298	70,30	70,27	2,264
21	2012-02-29T13:28:15	-7,5600	-7,5582	106,4900	106,4895	52,20	53,18	2,871
22	2012-03-07T15:33:53	-7,3800	-7,3774	106,6200	106,6210	69,30	70,35	2,411
23	2012-04-12T15:01:20	-7,7200	-7,7231	107,1100	107,1094	63,70	64,02	2,005
24	2012-05-20T12:37:42	-8,3900	-8,3926	107,5200	107,5193	42,00	42,00	2,791
25	2012-05-30T04:43:17	-8,3500	-8,3496	107,8500	107,8500	55,00	55,12	2,067
26	2012-06-04T11:18:15	-7,8200	-7,8200	106,2600	106,2600	82,00	80,00	2,384
27	2012-08-03T00:57:20	-8,0600	-8,0602	107,7100	107,7118	79,00	79,26	2,017
28	2012-11-01T14:12:02	-7,6100	-7,6102	107,4800	107,4840	147,00	145,72	2,473
29	2012-11-10T06:05:27	-6,8500	-6,8524	106,5600	106,5618	52,00	52,39	2,556
30	2012-12-26T16:12:43	-8,0200	-8,0197	107,4900	107,4912	61,00	63,19	2,439

#### IV. CONCLUSION

We have used a new iterative non-linear tomography scheme to simultaneously invert seismic source datasets for the 3-D seismic structure of the Java island lithosphere.

The deployment of a exceptionally dense temporary seismic network allowed the determination of the crustal structure of Java island at high resolution.

The result of inversion show that there are three layer in 100 km from the surface at continental plate side (Eurasia).

The upper crust have  $V_p$  about 4-5,5 km/s. The lower crust have  $V_p$  6,5-7 km/s. Upper mantle have  $V_p$  higher value, about 6,5-8,5 km/s. The oceanic plate (Indo-Australia) have two layer in 100 km from the surface. The oceanic crust have  $V_p$  about 6,5-7 km/s. The oceanic mantle have  $V_p$  6,5-8,2 km/s as describe in Table 1 and Table 2. There are low velocity anomaly inclined towards the slab which probably have associated with shallow earthquake along the slab.

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