

Double-difference tomography of P- and S-wave velocity structure beneath the western part of Java, Indonesia*

Shindy Rosalia^{1,✉} Sri Widiyantoro¹ Andri Dian Nugraha¹ Pepen Supendi^{1,2}

¹ Faculty of Mining and Petroleum Engineering, Institute of Technology Bandung, Bandung 40132, Indonesia

² Meteorological, Climatological, and Geophysical Agency (BMKG), Bandung 40161, Indonesia

Abstract West Java in the western part of the Sunda Arc has a relatively high seismicity due to subduction activity and faults. In this study, double-difference tomography was used to obtain the 3D velocity tomograms of P and S waves beneath the western part of Java. To infer the geometry of the structure beneath the study area, precise earthquake hypocenter determination was first performed before tomographic imaging. For this, earthquake waveform data were extracted from the regional Meteorological, Climatological, Geophysical Agency (BMKG) network of Indonesia from South Sumatra to Central Java. The P and S arrival times for about 1,000 events in the period April 2009 to July 2016 were selected, the key features being events of magnitude > 3, azimuthal gap < 210° and number of phases > 8. A nonlinear method using the oct-tree sampling algorithm from the NonLinLoc program was employed to determine the earthquake hypocenters. The hypocenter locations were then relocated using double-difference tomography (tomoDD). A significant reduction of travel-time (root mean square basis) and a better clustering of earthquakes were achieved which correlated well with the geological structure in West Java. Double-difference tomography was found to give a clear velocity structure, especially beneath the volcanic arc area, i.e., under Mt Anak Krakatau, Mt Salak and the mountains complex in the southern part of West Java. Low velocity anomalies for the P and S waves as well as the v_p/v_s ratio below the volcanoes indicated possible partial melting of the upper mantle which ascended from the subducted slab beneath the volcanic arc.

Keywords: West Java; P- and S-wave velocity structures; double-difference tomography

1 Introduction

The western part of Java is a tectonically active zone between the oblique subduction of the Indo-Australian plate beneath Sumatra and the perpendicular subduction of the same plate beneath Java (Malod et al., 1995). The oceanic lithosphere is continually being subducted northward beneath the Sunda volcanic arc at a rate of 6–7 cm/year (Hamilton, 1979). The change in the subduction orientation affects the deformation, e.g., the fault structure and the seismic activity in the western part of Java. This tectonic activity is also related to the development of an active volcanic arc in the southern part of West Java which has the highest volcanic density in Java Island (Setijadji, 2010). Subduction beneath Java began in the Eocene, but an older Paleogene arc ceased activity in the Early Miocene and volcanic activity resumed in the Late Miocene producing a younger arc to the north of the older arc, which continues to the present day (Cottam et al., 2010).

The structure beneath the Sunda arc, including West Java and its surroundings, has been investigated by e.g. Widiyantoro and van der Hilst (1996) using a global data set, and Widiyantoro et al. (2011) using a non-linear approach. Other studies include hypocenter relocation and 3D seismic velocity imaging for West Java (Sakti et al., 2012), seismic tomographic inversion beneath Mt Guntur, West Java (Nugraha et al., 2013), hypocenter determination using nonlinear methods in West Java (Rosalia et al., 2017), attenuation tomography beneath the Sunda Strait between Sumatra and West Java (Anshori et al., 2017), hypocenter relocation in Central Java (Ramadhan et al., 2017b) and seismic travel-time tomography beneath Merapi Volcano and its surroundings (Ramadhan et al., 2017a). The use of a global data set cannot image shallow structures in detail because of the limited data coverage and the grid size employed, which is rather coarse for relatively small structures. Meanwhile, a previous study

* Received 23 February 2018; accepted in revised form 18 September 2018; published 2 September 2019.

✉ Corresponding author. e-mail: shindy.rosalia31@gmail.com

© The Seismological Society of China and Institute of Geophysics, China Earthquake Administration 2019

used local data but did not use the S phase arrival time data (Sakti et al., 2012).

In this study, the tomographic method was used to obtain the 3D seismic velocity structures in order to image the subsurface and to gain a better understanding of the tectonic processes and the development of the volcanic arc in the study area. For this, a different set of data and a different tomographic method were compared to previous studies. In addition, the S phase arrival times were used to improve the characterization of the velocity structures of the various tectonic regimes in the study area.

2 Data

The P- and S-wave arrival times of waveform data recorded at 33 stations of Meteorological, Climatological, Geophysical Agency network of Indonesia (BMKG) from April 2009 to July 2016 and additional P- and S- wave arrival time data from an independent study (Supendi and Nugraha, 2016) were selected. Figure 1 shows the distribution of the stations ranged from South Sumatra to Central Java with the number of dominant phases being recorded in the southern part of West Java. An example of the arrival time selection is shown in Figure 2. There were

in total 1,305 events recorded within the above period used in the hypocenter determination. In this study, we employed a nonlinear hypocenter determination method using the NonLinLoc program (Lomax et al., 2009). The events for the double difference tomography (tomoDD) were selected based on the following criteria: (i) azimuthal gap $< 210^\circ$, (ii) magnitude > 3.0 , (iii) number of phases > 8 , and (iv) shifting between BMKG and NonLinLoc locations < 50 km. Based on the selection criteria, there were 1,097 earthquake events with 16,245 P and 8,207 S phases. We also used a Wadati diagram to check the quality of selection and to obtain a v_p/v_s ratio model to be used as an initial model upon inversion (Figure 3).

3 Method

In this study, a tomoDD algorithm developed by Zhang and Thurber (2003) and based on the double-difference algorithm of Waldhauser and Ellsworth (2000) was used. The tomoDD method uses the combination of cross-correlation data, differential data and absolute data to calculate simultaneously the hypocenter relocation and velocity model. In this study, tomoDD was applied using the absolute catalog and the differential catalog data only, without using a cross-correlation waveform. The differential data were obtained from the clustering process by input of the absolute catalog data of P- and S-wave arrival times into the ph2dt program, which is part of the hypoDD algorithm (Waldhauser and Ellsworth, 2000). These differential catalog data were used to ensure the stability of the least-squares solutions and to optimize the relationship between two earthquake events. The adjacent seismic events were collected in one group. The number of seismic events that are clustered depends on the grouping parameters used. The best quality is achieved by making as many group pairs of events as possible (Boyle et al., 2007).

The initial velocity model used in this study was a 1D P-wave velocity model generated by Sakti et al. (2012) using the VELEST program (Kissling et al., 1995) to update the AK135 velocity model of Kennett et al. (1995); see Figure 4. The S-wave initial velocity model was constructed using a v_p/v_s value of 1.76 obtained from the Wadati diagram shown in Figure 3. For horizontal model parameterization, a grid node size of $30 \text{ km} \times 30 \text{ km}$ was used for the area with dense seismic rays and for the station network, and $60 \text{ km} \times 60 \text{ km}$ elsewhere. For vertical parameterization, a grid node size of 10 km was used and increasing with depth as shown in Figure 5.

In the tomoDD inversion process, there are several important parameters that need to be determined: the wei-

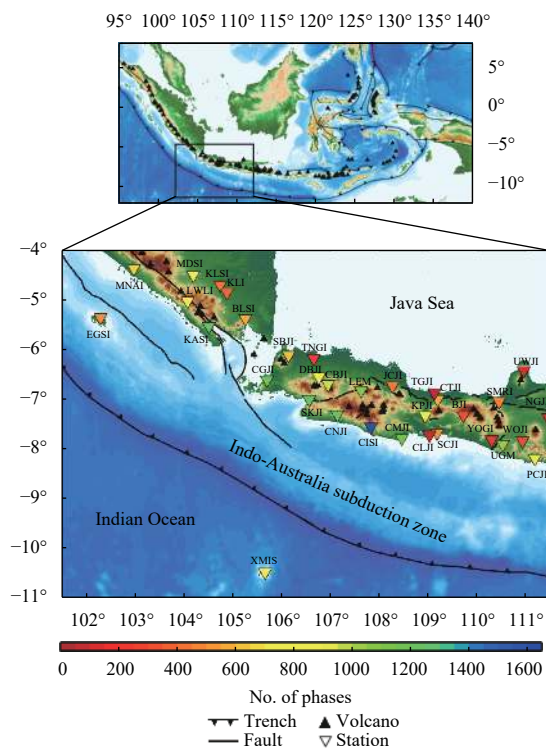


Figure 1 Location of the study area and distribution of BMKG stations (reverse triangles). The stations are color-coded to show the number of phases recorded by each station

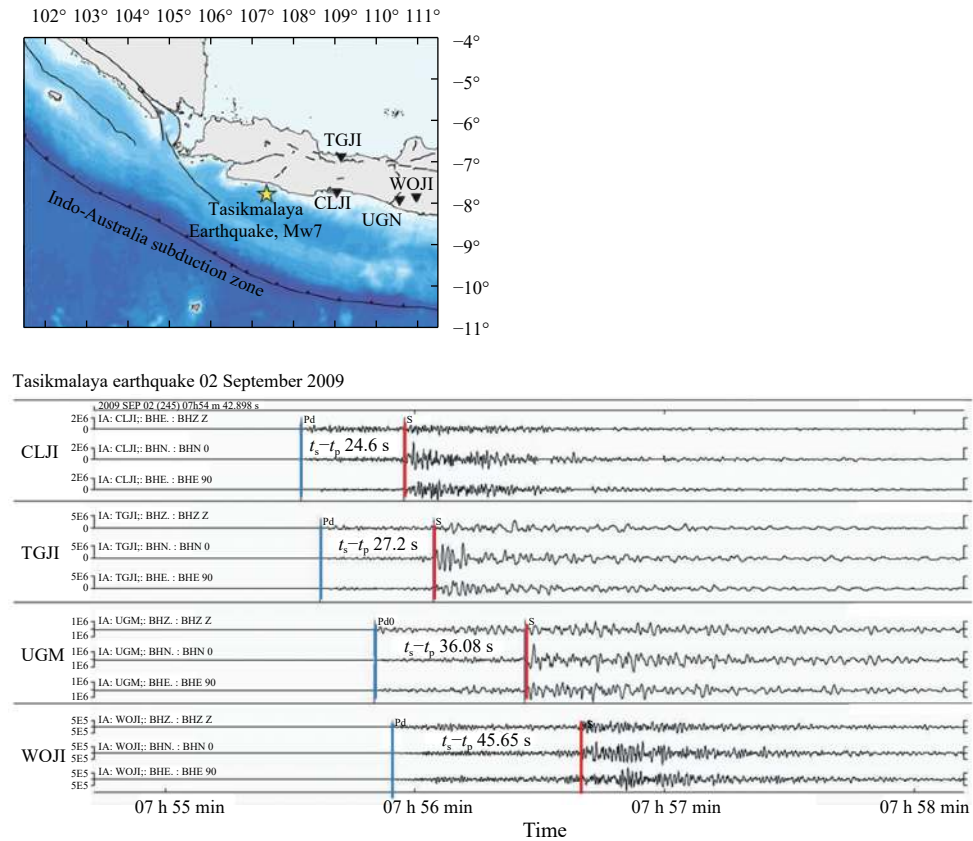


Figure 2 Example of P- and S-wave arrival time selection for 3-component waveforms of the Tasikmalaya earthquake (2009-09-02) with M_W 7 recorded by the BMKG network. The location of the earthquake and the station are shown in the top figure, blue and red lines depict P and S arrival times, respectively

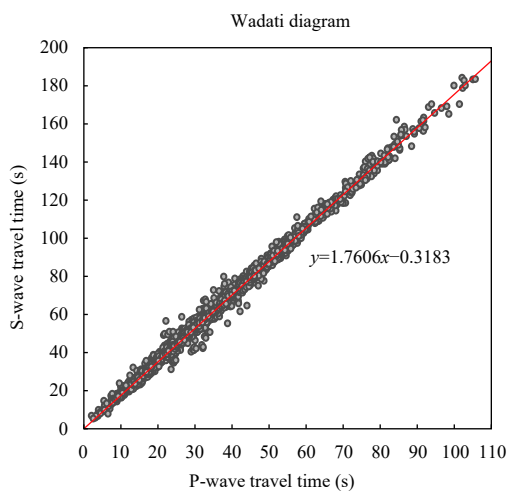


Figure 3 Wadati diagram for all P and S phases extracted from the BMKG data that gave a v_p/v_s value used as an initial velocity model in double-difference tomographic imaging

ghts for each phase, the weighting scheme for the absolute and differential catalog data, and damping. The phase weights used in this study were 1 for the P phase structures and 0.75 for the S phase structures. The weight of the P phase was greater than that of the S phase, because the

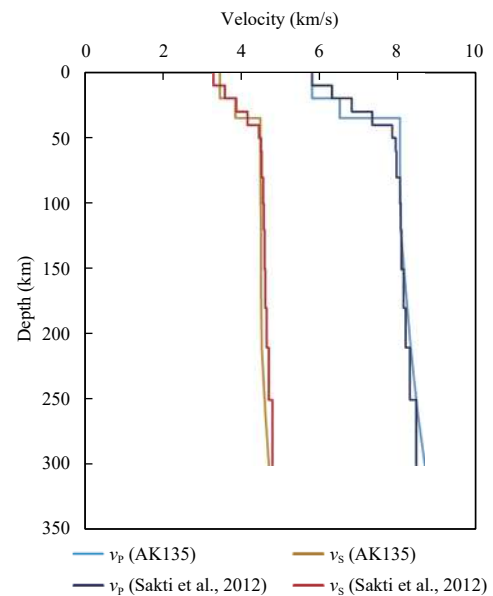


Figure 4 One-dimensional reference model of P- and S-wave velocities used in this study (taken from Sakti et al., 2012). Navy blue and red represent v_p and v_s , respectively, (from Sakti et al., 2012) and light blue and orange represent the AK135 v_p and v_s models, respectively (from Kennett et al., 1995)

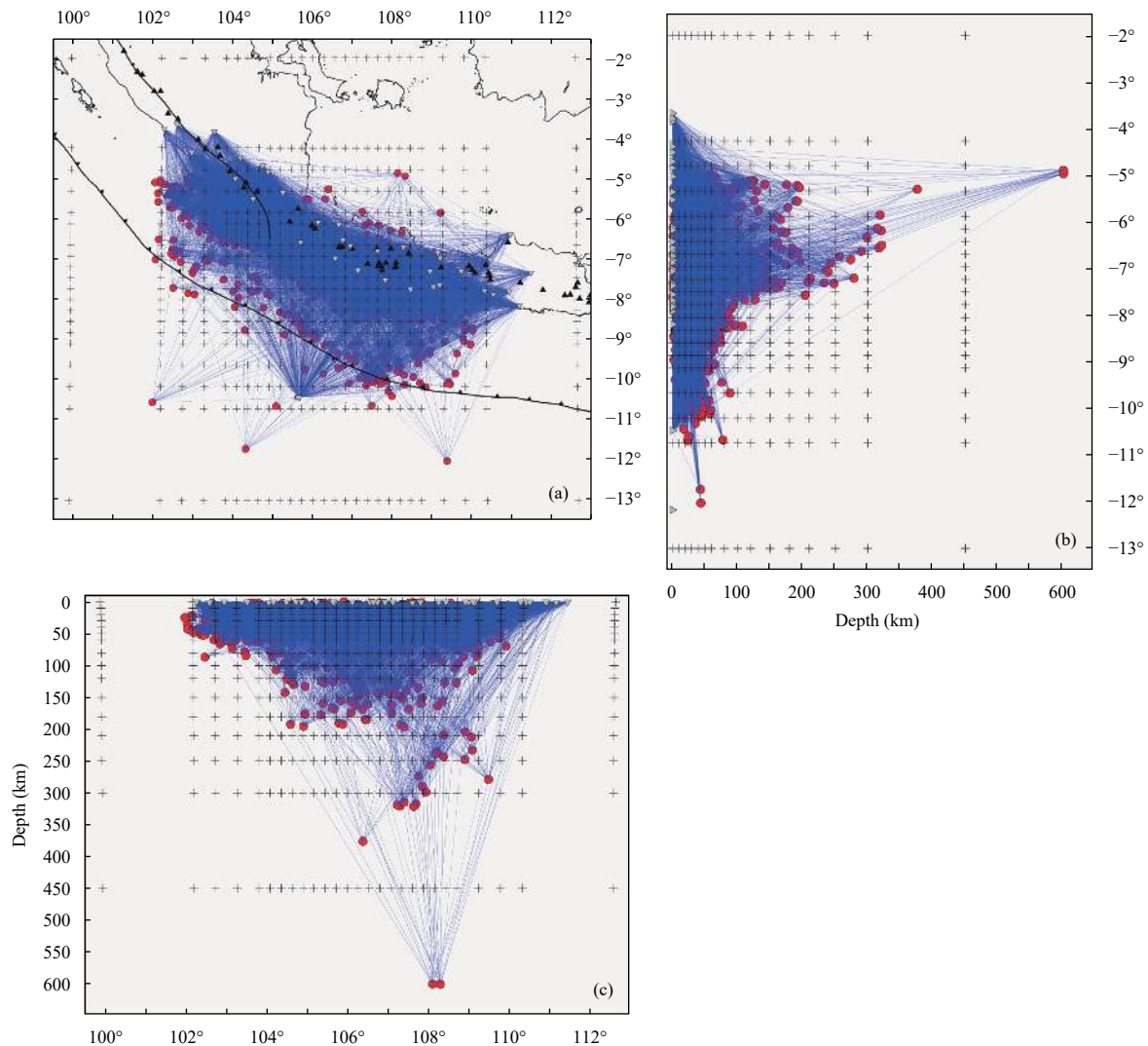


Figure 5 Grid nodes parameterization used in the tomographic processing (a). Horizontal distance between nodes is 30 km for the area within the dense station network and the dense seismic ray paths and 60 km elsewhere (b). Vertical distance between nodes increases with depth starting with a 10 km interval for the uppermost layer (c). Blue lines depict ray paths from earthquakes (red circles) to stations

determination of the S arrival time is more difficult and has a higher uncertainty than that for the P arrival times. For the weightings of the catalog and differential data, [Zhang and Thurber \(2003\)](#) proposed to give a greater weight to the absolute data at the beginning of the inversion to obtain the velocity structure globally and at the end of the inversion a greater weight for differential data should be employed to obtain the velocity structure in more detail. In this study, the following weighting schemes were used: for the 1st scheme, at the beginning of the inversion the weights of the absolute catalog and differential data were 10 and 1, respectively; for the 2nd scheme, an equal weighting of the absolute and differential data was used, i.e., 1 for the absolute and differential data; and for the 3rd iteration, the weights of the absolute and differential data

were 1 and 10, respectively. Assessment of the optimal damping parameter was made based on the condition number (CND) and the trade-off curve. The CND value was the ratio of the largest to the smallest eigenvalues. Following the study of [Waldhauser and Ellsworth \(2000\)](#), the CND should be between 40 to 80. Trade-off curves were also constructed between the data and model variance, and the model variance was computed for various damping values. A damping value of 125 was chosen for all schemes given that the CND values were between 40 and 80 and this damping corresponds to a change in the gradient of the trade-off curves ([Figure 6](#)).

The resolution of the inversion result was tested using the checkerboard resolution test along with the derivative weight sum (DWS). The result of the checkerboard reso-

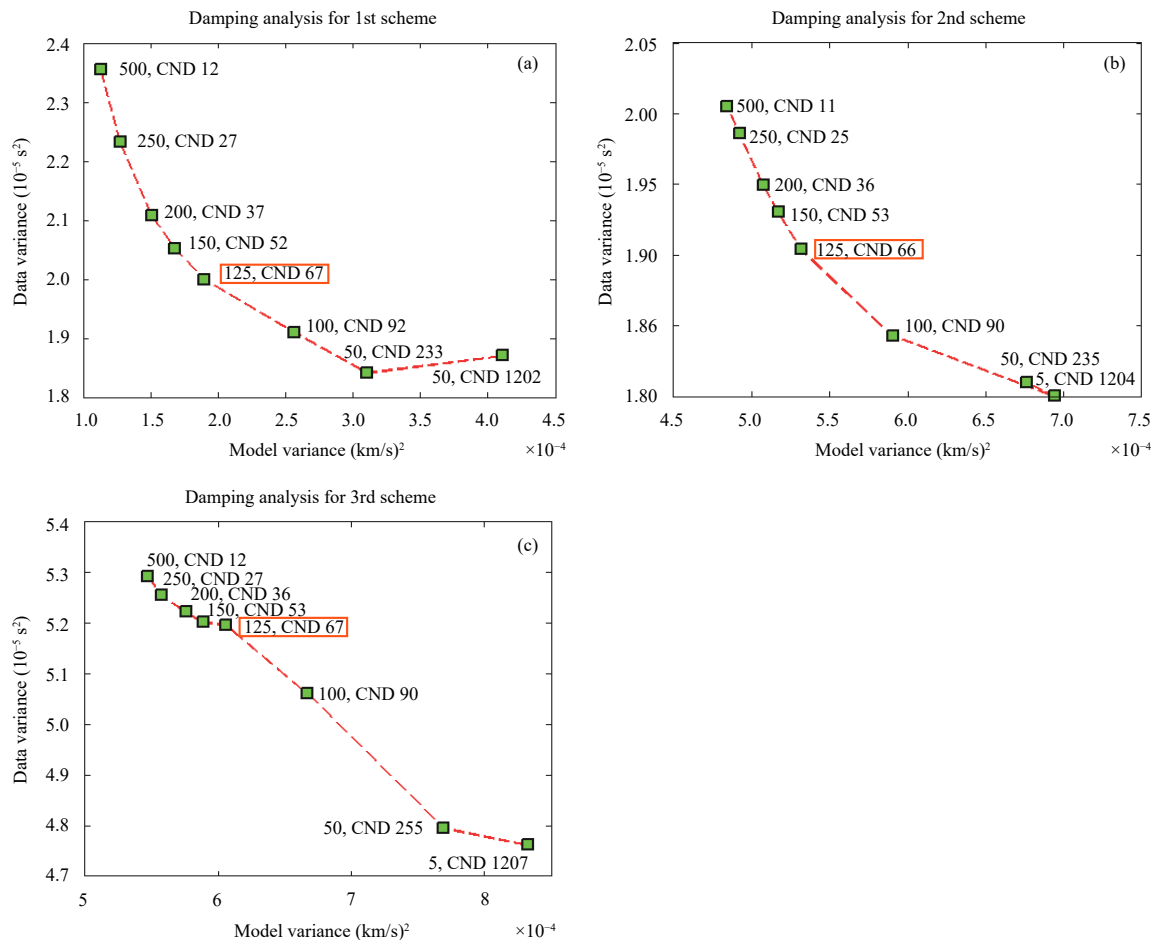


Figure 6 Damping analysis to decide the damping value used in the inversions for the 1st (a), 2nd (b) and 3rd (c) weighting schemes. The curves show the trade-offs between the various damping factors and the CNDs values. A damping factor of 125 was used for each weighting scheme

lution test is shown in Figure 7, where the horizontal sections show good resolution starting at a depth of 10 km to 80 km. In particular, good resolution was achieved in the area along Java Island, where the majority of seismic rays pass through this area. Resolution diminished toward the trench due to lack of ray path coverage as most stations were located on Java Island. The seismic rays passed mainly through the front arc region so that the slab geometry was not well resolved.

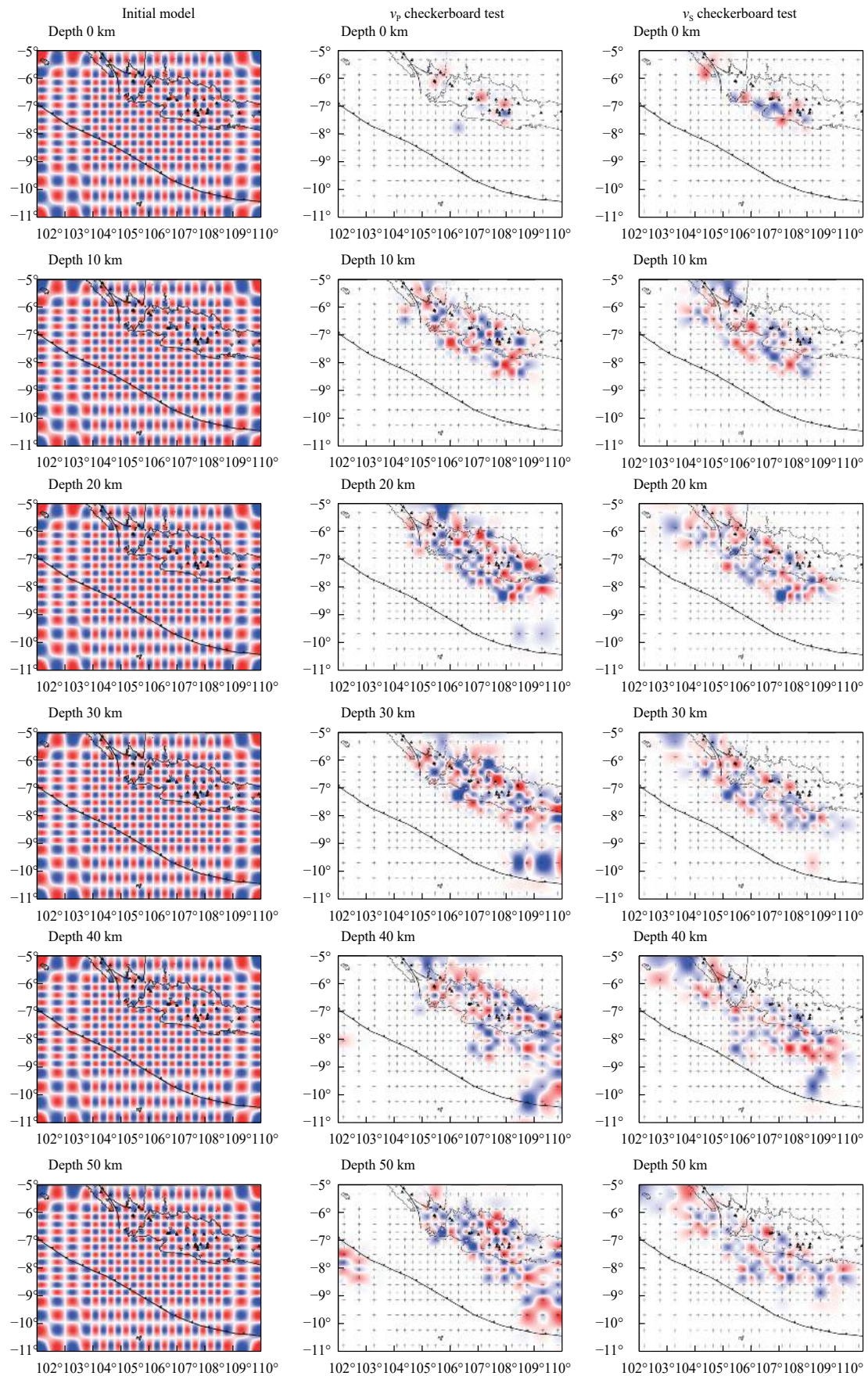
The DWS values, which were plotted on a logarithmic scale, are presented in Figure 8. High DWS values for the P- and S-wave data are indicated by the dark colors. The DWS results look reasonably good for depths from 10 km to 60 km. The inferences of the DWS results correspond well to the results of the checkerboard test, in which good recovery is indicated by $\log(DWS) > 3.25$ for the P-wave structures and > 3.00 for the S-wave structures. For the v_p/v_s tomogram the resolution test results based on the S-wave data were used, given that the number of S-

wave arrival times was less than that for the P-wave arrival times.

4 Results and discussion

The results for hypocenter determination using the NonLinLoc program show smaller travel-time residuals compared to those based on the Geiger method, which is usually used for routine hypocenter determination in Indonesia (Figure 9). The nonlinear global search methods performed for hypocenter determination allow us to calculate complete probabilistic locations, so that we can avoid hypocenter solutions trapped in local minima. The present hypocenter determination results were used as an input in the tomoDD process and this produced even smaller travel-time residuals compared to that for the NonLinLoc program (Figure 9).

In this section, the tomoDD results are presented in terms of velocity perturbations relative to the initial



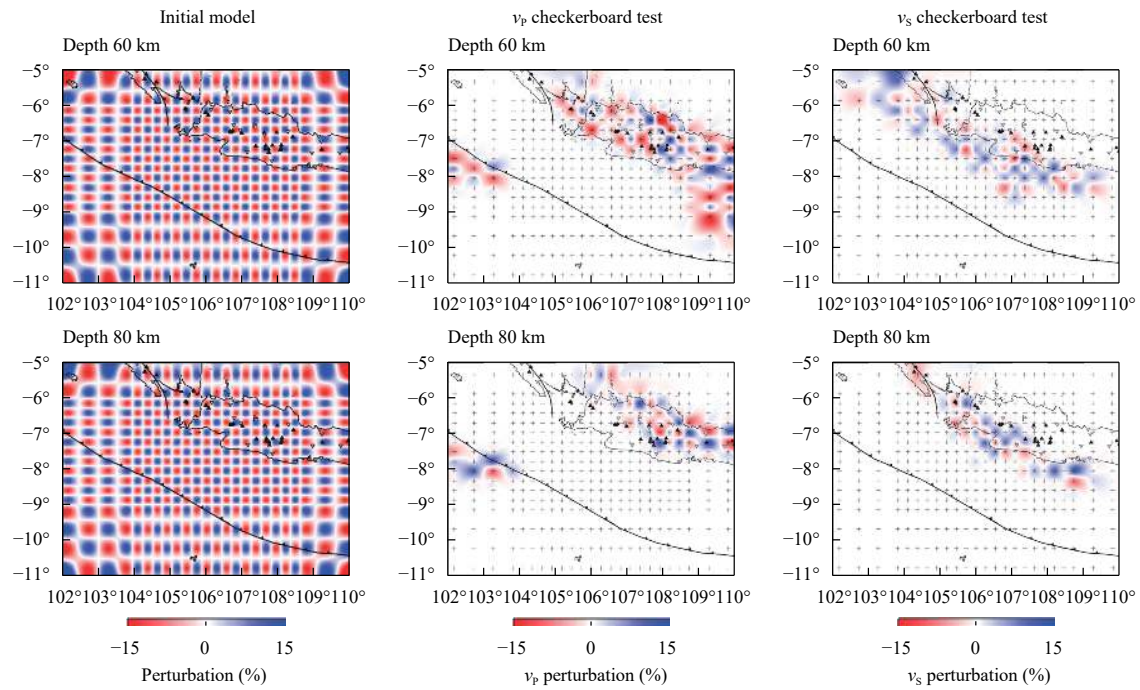
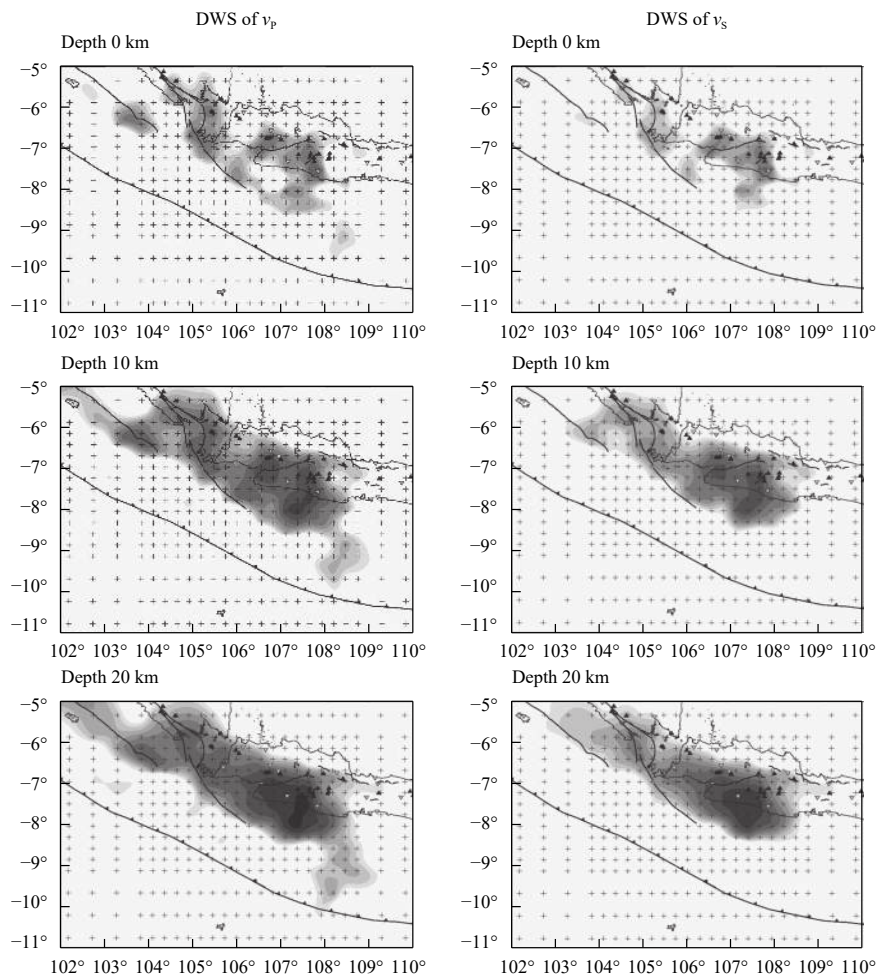


Figure 7 The results of checkerboard tests for P and S waves at depths down to 80 km beneath the study area. Blue and red depict positive and negative velocity perturbations, respectively



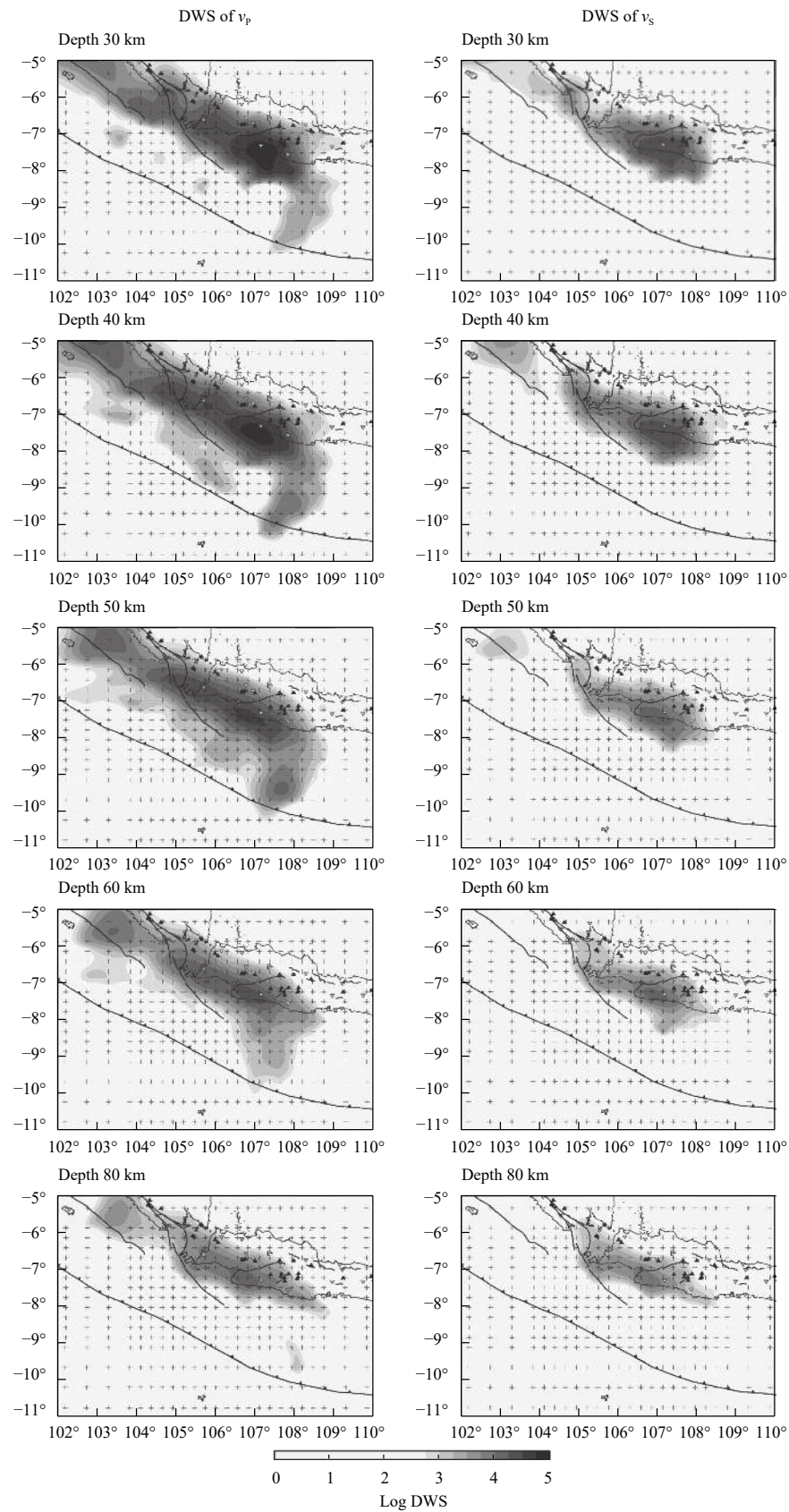


Figure 8 The derivative weight sum (DWS), i.e., a weighted measure of the total length of the seismic ray through the nodes, of the real data inversion of P and S waves at depths down to 80 km

velocity model for the P and S waves, while the v_p/v_s ratios are plotted as absolute values (Figure 10). The blue color scale shows high velocity anomalies for the P and S waves, while the red color scale shows low anomalies. For the v_p/v_s scale, the red color indicates a high v_p/v_s value while the blue color indicates a low v_p/v_s value. Horizontal sections are displayed for a depth of 0 to 80 km, while three vertical sections are displayed across West Java through $A-A'$, $B-B'$ and $C-C'$ (Figure 11). The $A-A'$ cross-section passes through Mt Anak Krakatau, $B-B'$ through the Mt Salak complex and $C-C'$ through the mountains complex in the southern part of West Java.

Interpretation of the tomograms is only conducted for areas with a good checkerboard recovery or DWS. The P- and S-wave tomograms in general agree well. Based on previous results (Koulakov et al., 2007; Nakajima et al., 2001a; Tsuji et al., 2008), a negative anomaly may indicate weak zones of a fault or thermal structures derived from partial melting of tectonic plates. In the resulting tomograms (Figure 10), a negative anomaly pattern is seen in the middle part of the area which corresponds to the volcanic arc with active volcanoes. These negative anomalies

start from the surface to a 40 km depth in the southern mountains of West Java (Mts Guntur, Papandayan, Galunggung, Malabar, Wayang Windu and Patuha) and from a 20–40 km depth below the Mt Salak complex. Meanwhile, under Mt Anak Krakatau, the negative anomaly was observed at a depth of 10 km and this is continuous to a depth of 20 km. The anomaly at a depth of 10 km is in good agreement with a local earthquake tomography study of Jaxybulatov et al. (2011) given the additional data coverage used in this study. In addition, there is also a negative anomaly found in the Sumatran fault. For the positive anomaly which occurred in the southern part, this may reflect the presence of rigid and dense rocks such as tectonic slabs or basements.

Generally, in the vertical sections of v_p , v_s and v_p/v_s (Figure 11) the subducted slab of the Indo-Australian plate is poorly imaged, although in some regions such as in the $B-B'$ vertical section of v_s , the slab is imaged as a positive anomaly in the depth interval of 80–120 km. Also, from the vertical sections of the v_p and v_s tomograms across three regions in western Java (Figure 11), there are, overall, negative anomalies for P and S wave tomograms

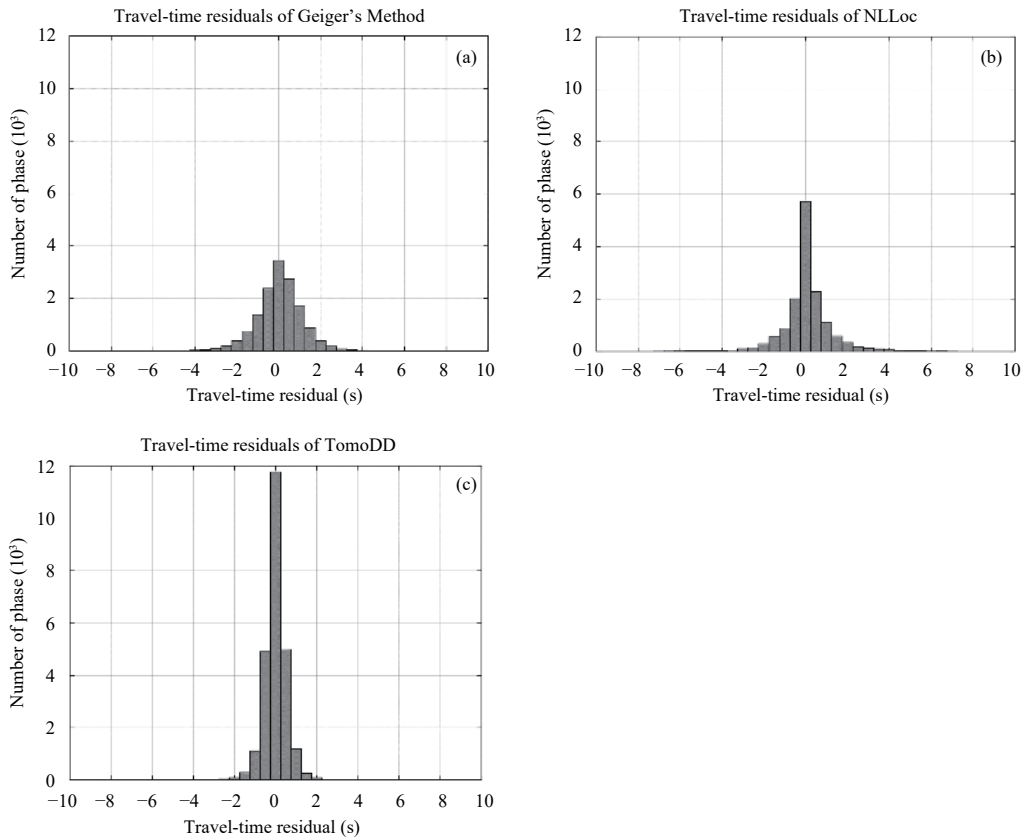
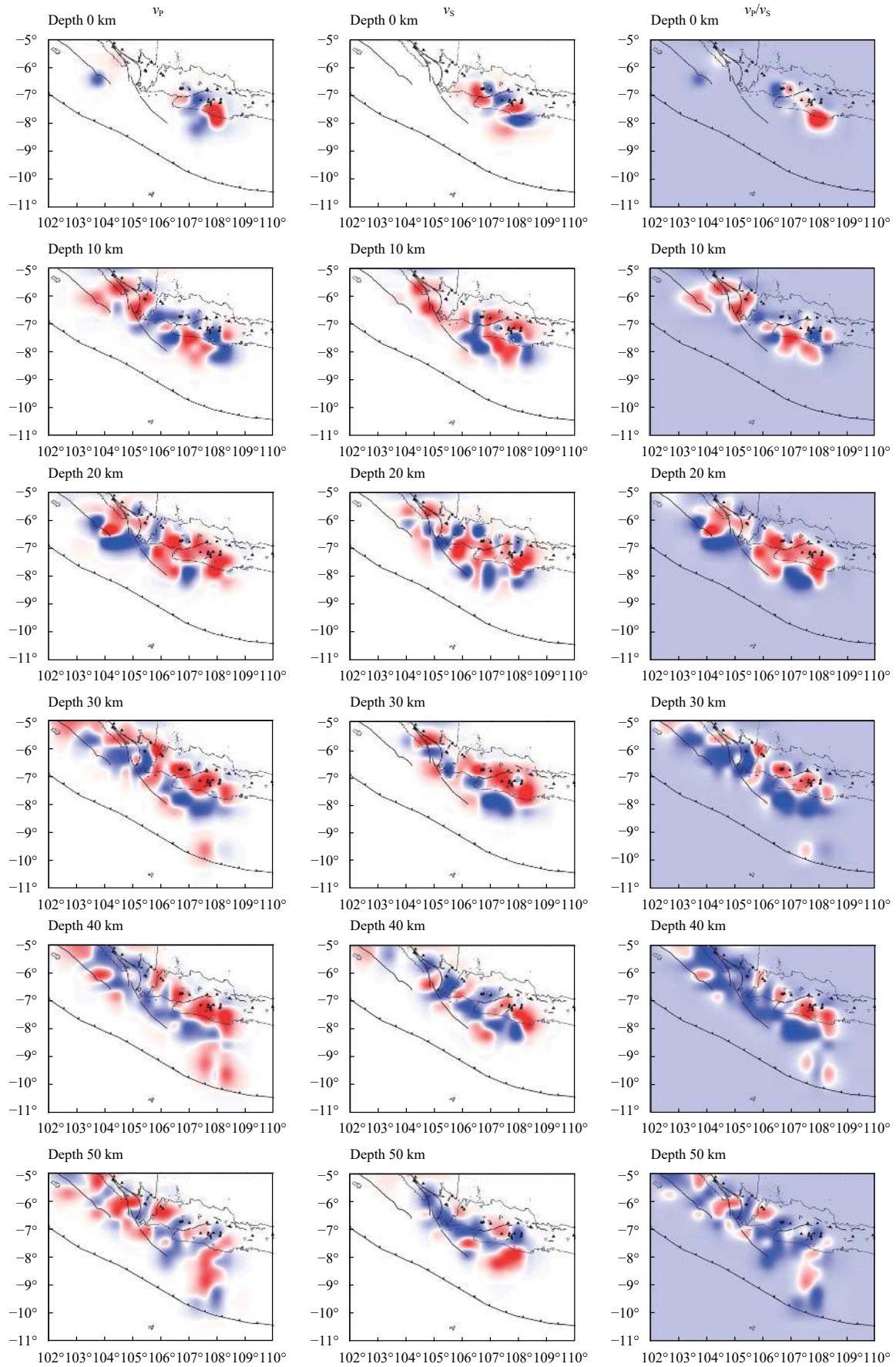


Figure 9 Histograms of the travel-time residuals for the Geiger method (a), NLLoc (b) and tomoDD (c). The NLLoc results give significantly better travel-time residuals than the Geiger method; and the tomoDD results provide better travel-time residuals than that of the NLLoc method



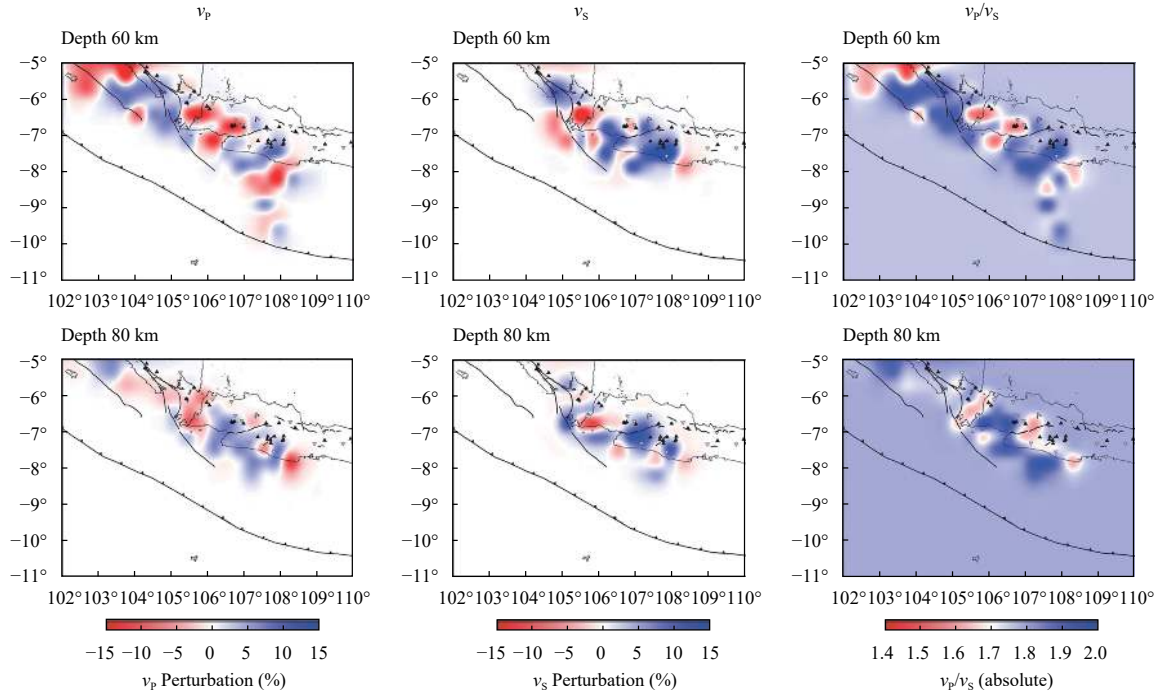


Figure 10 Horizontal slices for v_p , v_s and v_p/v_s resulting from the double-difference tomographic inversions at depths from 0 to 80 km

below active volcanoes. While for the vertical section of v_p/v_s it can be observed that there is a high v_p/v_s ratio of 1.8 to 1.98 below the volcanoes. Based on previous studies (Nakajima et al. (2001b); Koulakov et al., 2007), low v_p and v_s values with high v_p/v_s values of about 1.8–1.9 indicate the presence of material with high fluid content or thermal structures in the form of a partial melt below a volcano. The thermal structural feature is considered to originate from a tectonic slab at a depth of 80–120 km which then rose and finally resulted in an active volcano series, i.e., Mt. Anak Krakatau in the Sunda Strait, Mt. Salak in the southern part of West Java and the Southern Mountain Complex of West Java. There is a high velocity anomaly at shallower depths around Mt. Anak Krakatau (Figure 11, profile A) which may be interpreted as a granitic basement (Jaxybulatov et al., 2011). In Figure 11, profile B, we observed low v_p , low v_s and low v_p/v_s just beneath Mt. Salak. Based on the results of Nakajima et al. (2001b) and Zhang et al. (2004), these anomalies may indicate the presence of inclusions filled with water and with a large aspect ratio or may indicate an area with high water content. We could not explain the anomalies beneath the northern volcanoes such as Mts. Tangkuban, Perahu and Burangrang because the locations of these volcanoes were in regions that corresponded to the resolution limit of the tomography as indicated by lack of checkerboard recovery (Figure 7) and low DWS value (Figure 8),

respectively.

With regard to the seismicity resulting from the event relocation for profile A in Figure 11, this shows the occurrence of a few deep earthquakes compared to profiles B and C. The area in profile A is well known as a seismic gap zone. This area is the transition zone from the oblique subduction beneath Sumatra to the perpendicular subduction beneath Java. In Figure 12, it can be seen that the slab beneath West Java has a steep subduction angle with an initial subduction angle of 10°–30° close to the surface, which becomes steeper, ~70°, at a depth of 100 km. This finding is in good agreement with previous studies (Cottam et al., 2010; Widiyantoro et al., 2011). An interpretation of the tomograms in terms of the velocity structure beneath West Java is outlined in Figure 12.

5 Concluding remarks

The 3D v_p , v_s and v_p/v_s structures beneath West Java have been imaged successfully using tomoDD. Based on the results, the tomographic method is sufficiently powerful to image the subsurface structure beneath, e.g., a volcanic arc. The velocity structure below the volcanic arc of West Java is, in general, characterized by low v_p anomalies, low v_s anomalies and high v_p/v_s ratios. These anomalies are associated with areas of high fluid content due to partial melting of the upper mantle.

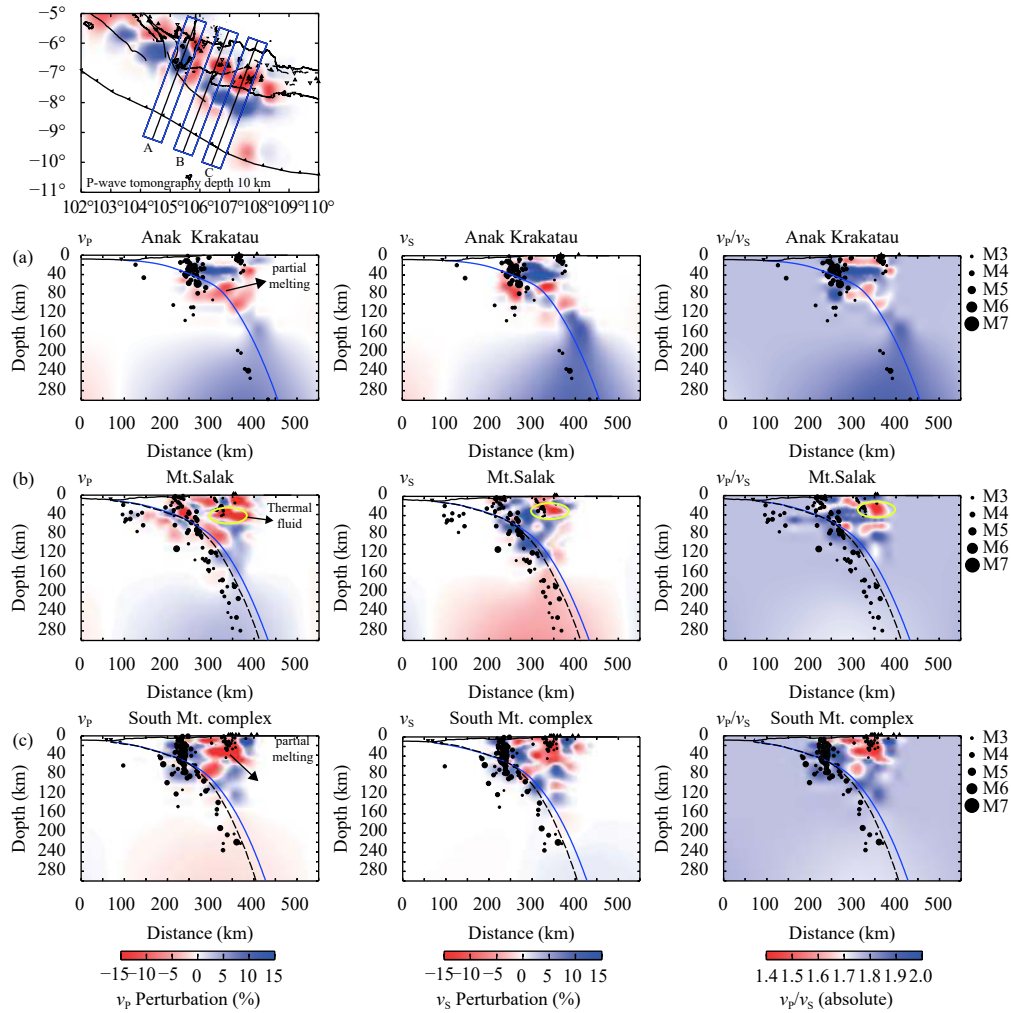


Figure 11 Top figure shows the location of the vertical slice profile and bottom figure shows its corresponding vertical slice of v_p , v_s , and v_p/v_s through A (a), B(b), and C(c)

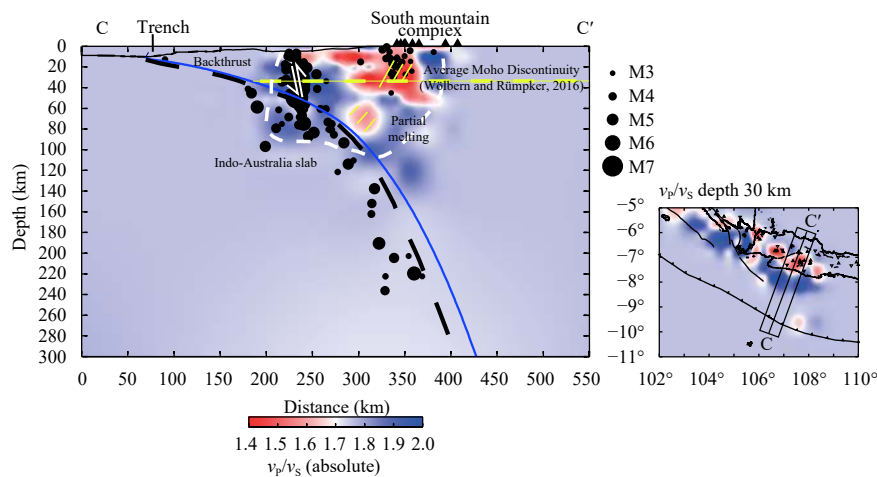


Figure 12 Interpretation of structures beneath West Java. Blue line represents slab model 1.0 (Hayes et al., 2012), white dashed line shows the good resolution area based on S-wave checkerboard results and DWS values, and black dashed line depicts our interpretation of the subducted slab based on earthquake hypocenters resulting from tomoDD (black dots). The dashed yellow line depicts the average depth of the Moho discontinuity, i.e., 34 km, taken from Wölbern and Rumpker, (2016). Note that the angle of subduction is steeper than that from the slab model 1.0

Acknowledgments

We are grateful to the Meteorology, Climatology and Geophysics Agency of Indonesia (BMKG) for the waveform and catalog data used in this study and the Directorate General of Resources for Science Technology and the Higher Education of the Republic of Indonesia for granting a PMDSU scholarship to SR. We also thank the reviewers for their constructive comments. Figures 1, 5, 6, 7, 9, 10 and 11 were produced using GMT Software (Wessel and Smith, 1998). Topography and bathymetry data were taken from SRTM 30 Plus (Becker et al., 2009). The plate boundary diagram was adapted from Bird (2003).

References

- Anshori M, Nugraha AD and Puspito NT (2017) Preliminary result of 3-D attenuation tomography beneath Sunda Strait and western part of Java. In: AIP Conference Proceedings, 1857(1): 020004. AIP Publishing. <https://doi.org/10.1063/1.4987046>
- Becker J J, Sandwell D T, Smith W H F, Braud J, Binder B, Depner J, Fabre D, Factor J, Ingalls S, Kim S -H, Ladner R, Marks K, Nelson S, Pharaoh A, Trimmer R, Von Rosenberg J, Wallace G, and Weatherall P (2009) *Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS* Mar Geod **32**: 355–371
- Bird P (2003) An updated digital model of plate boundaries. *Geochemistry Geophys Geosystems* 4, <https://doi.org/10.1029/2001GC000252>
- Boyle K, Hutchings L, Bonner B, Foxall B and Kasameyer P (2007) Double difference earthquake locations at the Salton sea geothermal reservoir. In: Transactions - Geothermal Resources Council. (No. UCRL-TR-233538). Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States)
- Cottam M, Hall R, Cross L, Clements B and Spakman W (2010) Neogene subduction beneath Java, Indonesia: Slab tearing and changes in magmatism. *EGU Gen. Assem. Geophys. Res. Abstr.* 12.
- Hamilton WB (1979) *Tectonics of the Indonesian region*. US Govt. Print. Off.
- Hayes GP, Wald DJ and Johnson R L (2012) *Slab1. 0: A three-dimensional model of global subduction zone geometries* J Geophys Res **117**: 1–15
- Jaxybulatov K, Koulakov I, Seht MIV, Klinge K, Reichert C, Dahren B and Troll VR (2011) *Evidence for high fluid/melt content beneath Krakatau volcano (Indonesia) from local earthquake tomography* J Volcanol Geotherm Res **206**: 96–105
- Kennett BLN, Engdahl ER and Buland R (1995) *Constraints on seismic velocities in the Earth from travel times*. *Geophys J Int* **122**(1): 108–124
- Kissling E, Kradolfer U and Maurer H (1995) Program VELEST user's guide-Short Introduction. Inst. Geophys. ETH Zurich. in review
- Koulakov I, Bohm M, Asch G, Lühr B-G, Manzanares A, Brotopuspito KS, Fauzi P, Purbawinata Ma, Puspito NT, Ratdomopurbo A, Kopp H, Rabbel W and Shevkunova E (2007) *P and S Velocity structure of the crust and the upper mantle beneath central Java from local tomography inversion*. *J Geophys Res* **112**(B8): 1–19
- Lomax A, Michelini A and Curtis A (2009) *Earthquake location, direct, global-search methods*. In: Meyers R (eds) *Encyclopedia of Complexity and Systems Science*. Springer, New York
- Malod JA, Karta K, Beslier OM and Zen Jr MT (1995) *From normal to oblique subduction: Tectonic relationships between Java and Sumatra* J Southeast Asian Earth Sci **12**: 85–93
- Nakajima J, Matsuzawa T, Hasegawa A and Zhao D (2001a) Three-dimensional structure of v_p , v_s and v_p/v_s beneath northeastern Japan: Implications for arc magmatism and fluids. *J Geophys Res Solid Earth* 106 <https://doi.org/10.1029/2000JB000008>
- Nakajima J, Matsuzawa T, Hasegawa A, Zhao D (2001b) Seismic imaging of arc magma and fluids under the central part of northeastern Japan. *Tectonophysics* 341 [https://doi.org/10.1016/S0040-1951\(01\)00181-0](https://doi.org/10.1016/S0040-1951(01)00181-0)
- Nugraha AD, Widiyantoro S, Gunawan A and Suantika G (2013) Seismic velocity structures beneath the Guntur volcano complex, West Java, derived from simultaneous tomographic inversion and hypocenter relocation. *J Math Fundam Sci* **45**(1): 17–28. <http://dx.doi.org/10.5614/2Fj.math.fund.sci.2013.45.1.2>
- Ramadhan M, Widiyantoro S, Dian Nugraha A, Saepuloh A, Métaxian J-P, Kristyawan S, Syaly Sembiring A and Budi Santoso A (2017a) Seismic travel-time tomography beneath merapi volcano and its surroundings: A preliminary result from DOMERAPI Project. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing Ltd. **62**(1), <https://doi.org/10.1088/1755-1315/62/1/012039>
- Ramadhan M, Widiyantoro S, Nugraha AD, Métaxian J-P, Saepuloh A, Kristyawan S, Sembiring AS, Santoso AB, Laurin A and Fahmi AA (2017b) Relocation of hypocenters from DOMERAPI and BMKG networks: A preliminary result from DOMERAPI project. *Earthq Sci* **30**(2):67–79, <https://doi.org/10.1007/s11589-017-0178-3>
- Rosalia S, Widiyantoro S, Dian Nugraha A, Ash Shiddiqi H, Supendi P and Wandono, (2017) Hypocenter determination using a non-linear method for events in West Java, Indonesia: A preliminary result. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing Ltd. **62**(1), <https://doi.org/10.1088/1755-1315/62/1/012052>
- Sakti AP, Nugraha AD and Rohadi S (2012) *Kajian Seismisitas Wilayah Selat Sunda dan Jawa bagian Barat Menggunakan Data Hasil Relokasi Simultan Terhadap Struktur Kecepatan Tiga Dimensi Gelombang P.JJTM XIX*(2)
- Setijadji LD (2010) Segmented volcanic arc and its association with geothermal fields in Java Island, Indonesia. In: *Proceedings World Geothermal Congress, 2010, Bali, Indonesia*
- Supendi P and Nugraha AD (2016) Preliminary result of earthquake hypocenter determination using hypoellipse around western Java region. In: AIP Conference Proceedings. <https://doi.org/10.1063/>

- 1.494 7370
- Tsuji Y, Nakajima J and Hasegawa A(2008) Tomographic evidence for hydrated oceanic crust of the Pacific slab beneath northeastern Japan: Implications for water transportation in subduction zones. *Geophys Res Lett* **35**(14), <https://doi.org/10.1029/2008GL034461>
- Waldhauser F and Ellsworth WL (2000) A double-difference earthquake location algorithm: Method and application to the Northern Hayward Fault. *Bull Seismol Soc Am* **90**(6): 1 353–1 368
- Wessel P and Smith WHF (1998) New, improved version of generic mapping tools released *Eos Trans Am Geophys Union* **79**: 579–579
- Widiyantoro S, Pesicek JD, Thurber CH and Wi M (2011) Subducting slab structure below the eastern Sunda arc inferred from non-linear seismic tomographic imaging *SE Asian Gatew Hist Tectonics Aust Collis* 139–155
- Widiyantoro S and van der Hilst RD (1996) Structure and evolution of lithospheric slab beneath the Sunda Arc, Indonesia. *Science* **271**(5255): 1 566–1 570
- Wölbern I and Rumpker G (2016) Crustal thickness beneath Central and East Java (Indonesia) inferred from P receiver functions *J Asian Earth Sci* **115**: 69–79
- Zhang H and Thurber CH (2003) Double-difference tomography: The method and its application to the Hayward Fault, California *Bull Seismol Soc Am* **93**: 1 875–1 889
- Zhang H, Thurber CH, Shelly D, I de S, Beroza GC and Hasegawa A (2004) High-resolution subducting-slab structure beneath northern Honshu, Japan, revealed by double-difference tomography *Geology* **32**: 361–364