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Identification of faults in the subsurface of Java Island using the ambient noise tomography method

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सार – **यह अध्ययन जावा द्वीप की भूमिगत भूकंपीय संरचना में दोषों की पहचान करने के लिए परिवेशी शोर टोमोग्राफी** (ANT) **पद्धति को लागू करता है, जिसकी विशेषता जटिल टेक्टोनिक स्थितियाँ हैं। शोध में** 2021 **में जावा द्वीप में वितरित** 99 BMKG **स्थिर भूकंपीय सेंसर द्वारा रिकॉर्ड किए गए तरंग डेटा का उपयोग किया गया है। डेटा प्रोसेसिंग में एकल डेटा तैयारी, क्रॉस-सहसंबंध, स्टैकिंग, फैलाव वक्र माप, समूह वेग टोमोग्राफी और परिणाम व्याख्या शामिल है। व्युत्क्रम प्रक्रिया** 1.88 **किमी/सेकंड से लेकर** 2.60 **किमी/सेकंड तक के रेले तरंग समूह वेगों की टोमोग्राफिक छवियां उत्पन्न करती है, जो वेग विसंगतियों में महत्वपूर्ण विरोधाभासों को प्रकट करती है। निम्न और उच्च वेग क्षेत्रों के बीच की सीमाओं पर स्थित ये विरोधाभास, पूरे द्वीप में दोष रेखाओं और ज्वालामुखी क्षेत्रों के साथ दृढ़ता से सहसंबद्ध हैं। परिणाम उच्च परिशुद्धता के साथ सक्रिय दोष प्रणालियों सहित भूमिगत भूवैज्ञानिक संरचनाओं को चित्रित करने के लिए** ANT **पद्धति की क्षमता को प्रदर्शित करते हैं।**

ABSTRACT. This study applies the Ambient Noise Tomography (ANT) method to identify faults in the subsurface seismic structure of Java Island, characterized by complex tectonic conditions. The research utilizes waveform data recorded in 2021 by 99 BMKG stationary seismic sensors distributed across Java Island. Data processing includes single data preparation, cross-correlation, stacking, dispersion curve measurement, group velocity tomography, and result interpretation. The inversion process generates tomographic images of Rayleigh wave group velocities ranging from 1.88 km/s to 2.60 km/s, revealing significant contrasts in velocity anomalies. These contrasts, located at the boundaries between low and high velocity zones, are strongly correlated with fault lines and volcanic zones across the island. The results demonstrate the capability of the ANT method to delineate subsurface geological structures, including active fault systems, with high precision.

Key words – Java, Fault Identification, Ambient Noise Tomography, Rayleigh Wave, Cross-Correlation.

1. Introduction

Java is the fifth largest island in Indonesia and is known for its complex tectonic conditions. These complexities arise due to its location at the convergence of two major tectonic plates, the Indo-Australian Plate and the Eurasian Plate. The movement of the Indo-Australian Plate beneath the Eurasian Plate along the southern region of Java has resulted in significant geological phenomena. This tectonic interaction is the main driver of local fault activity and the distribution of active volcanoes across the island's mainland (Soehaimi, 2008).

Historical earthquake records in Java highlight the island's vulnerability to seismic hazards. The 2006 earthquake in the Bantul region, Yogyakarta, with a magnitude of M 5.9, caused extensive casualties and damage (Nichols, 2007). In the same year, an earthquake accompanied by a tsunami with a magnitude of M 7.7 occurred in the Pangandaran region (Fujii and Satake,

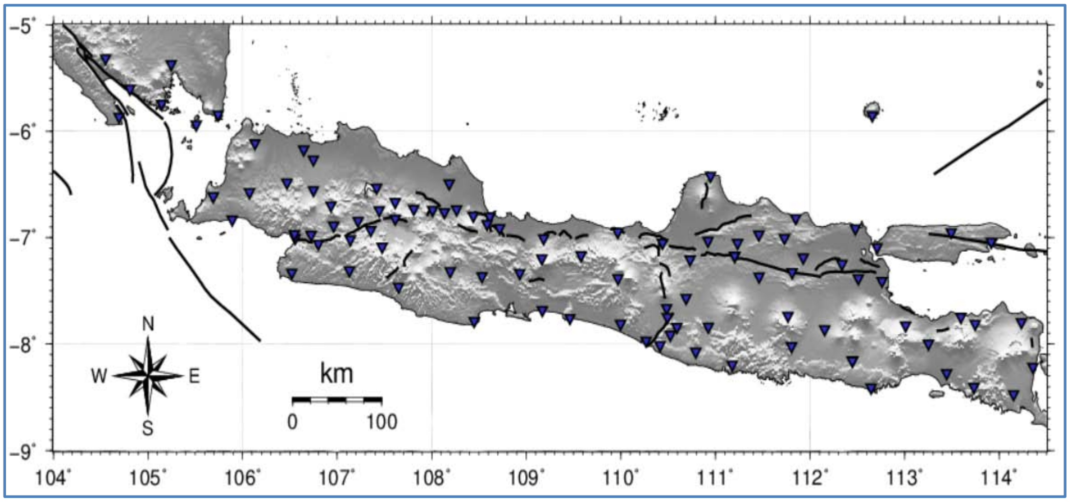

Fig. 1. Distribution of the BMKG stationary seismograph network of 99 stations on Java Island and its surroundings (blue inverted triangle)

2006). Other significant events include the 2009 Tasikmalaya earthquake with a magnitude of M 7.0 (Suardi *et al*., 2014), followed by another earthquake in the same region in 2017 with a magnitude of M 6.9. The 2018 earthquake in the Lebak area had a magnitude of M 6.1, while another earthquake in the same year, with a magnitude of M 6.9, was felt across Central Java and originated from the Banten region (Sirait *et al*., 2020). Most recently, the 2021 earthquake in Malang with a magnitude of M 6.1 caused considerable damage to infrastructure and communities (Muntafi and Nojima, 2021).

Understanding subsurface structures is crucial for evaluating seismic hazards and reducing the potential impacts of earthquakes. Accurate assessments of subsurface seismic structures are vital for identifying areas vulnerable to intense ground shaking and formulating effective earthquake mitigation strategies (Mayoral *et al*., 2019). The study of subsurface structures is effectively conducted using seismic noise recordings. The Ambient Noise Tomography (ANT) method has proven to be a reliable approach for imaging shallow subsurface structures. This method utilizes ambient seismic noise as the data source to derive key information about the Earth's layers. By calculating the cross-correlation between seismic recordings at two stations, the Green Function of the region can be extracted, revealing the elastic properties of the subsurface (Shapiro and Campillo, 2005). The dispersion curve obtained from the analysis of Rayleigh wave group velocity provides essential insights into the seismic structure, as Rayleigh waves dominate due to their resistance to attenuation over long distances (Saygin and Kennett, 2010).

Despite Java's tectonic significance, comprehensive seismic tomographic studies focusing on the entire region have not yet been fully explored. Previous studies using the ANT method have been conducted at a regional scale, including in Central Java (Zulfakriza *et al*., 2014), East Java (Martha *et al*., 2015), Jakarta (Saygin *et al*., 2016), and West Java (Rosalia *et al*., 2022). However, a detailed and high resolution investigation encompassing the whole Java region remains limited. This research employs the ANT method to provide a detailed seismic tomographic study of Java Island. The primary focus is to identify fault zones and delineate the subsurface geological structures in this tectonically active area.

2. Data

The seismic data used in this study were processed using a Python script from the Noise Py program package (Jiang *et al*., 2020). The data were collected from the BMKG stationary seismograph network, consisting of 99 stations, which recorded seismic waveforms continuously over the course of one year across Java Island and its surroundings (Fig. 1). At this stage, corrections for instrument response were applied to ensure data accuracy. The processed data were stored in the ASDF (Adaptable Seismic Data Format) format for each station and component, following established standards (Krischer *et al*., 2016). The dense spatial distribution of seismograph sensors provides sufficient resolution for detailed studies of subsurface structures through seismic tomography, particularly using the Ambient Noise Tomography (ANT) method. By leveraging this extensive dataset, the study aims to produce high resolution Rayleigh wave velocity models for Java Island, offering insights into subsurface

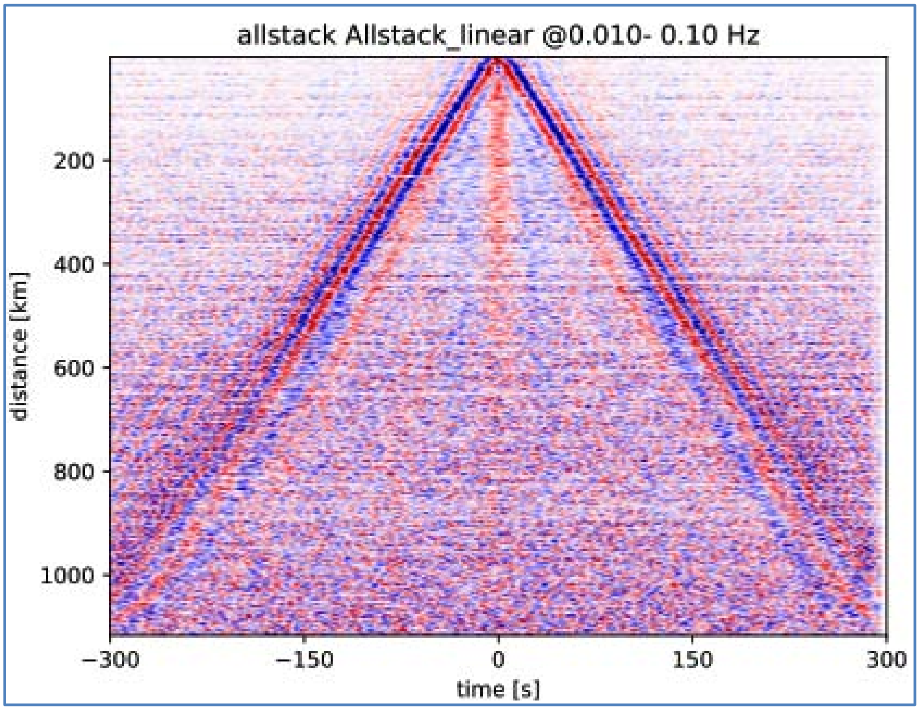

Fig. 2. Vertical cross-correlation of all station pairs computed on five-minute-long windows and stacked over twelve months, sorted according to the inter station distance in the Java Island region

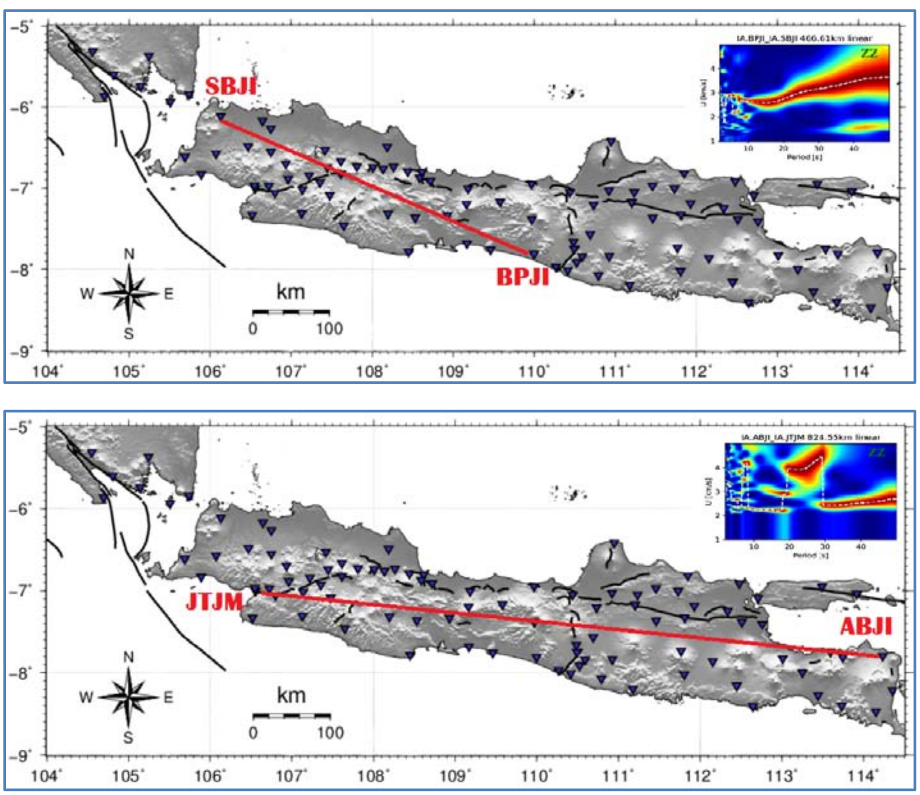

Fig. 3. The results of the dispersion curves from several station pairs are in the upper right corner of the map. The red lines are the distances between stations

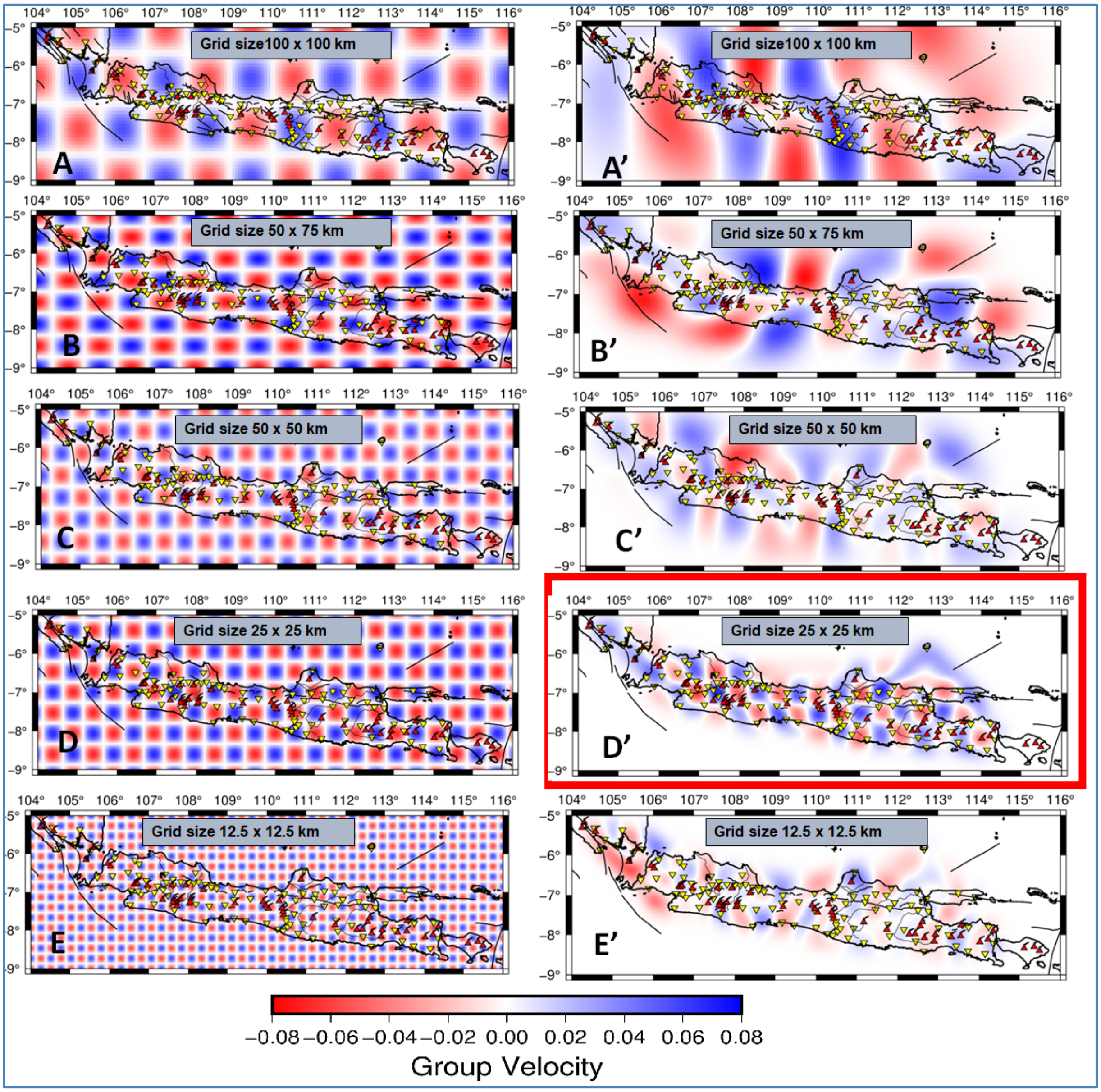

Fig. 4. The results of the model resolution test using a checkerboard test in the 10s period with various grid sizes, (A) 100 × 100 km, (B) 50 × 75 km, (C) 50 × 50 km, (D) 25 × 25 km and (E) 12.5 × 12.5 km in a 10 second period. The yellow inverted triangle is the distribution of the BMKG sensors, and the red box is the grid size used in this study

structural variations. These findings can also contribute to earthquake disaster mitigation efforts in the region.

3. Ambient Noise Cross-Correlations

Determining the Rayleigh wave group velocity dispersion curve involves the use of the Python program package Noise Py (Jiang *et al*., 2020), which implements conventional frequency-time analysis techniques (FTAN; Dziewonski *et al*., 1969; Levshin and Ritzwoller, 2001). The FTAN processing procedure consists of four main stages: data preparation, cross-correlation and temporal stacking, dispersion curve determination, and quality control. During data preparation, signal processing steps include instrument correction, mean removal, band pass filtering, temporal normalization, correction for instrument irregularities and spectral whitening.

Seismic data cross-correlation begins by converting the time-domain signals into the frequency domain using

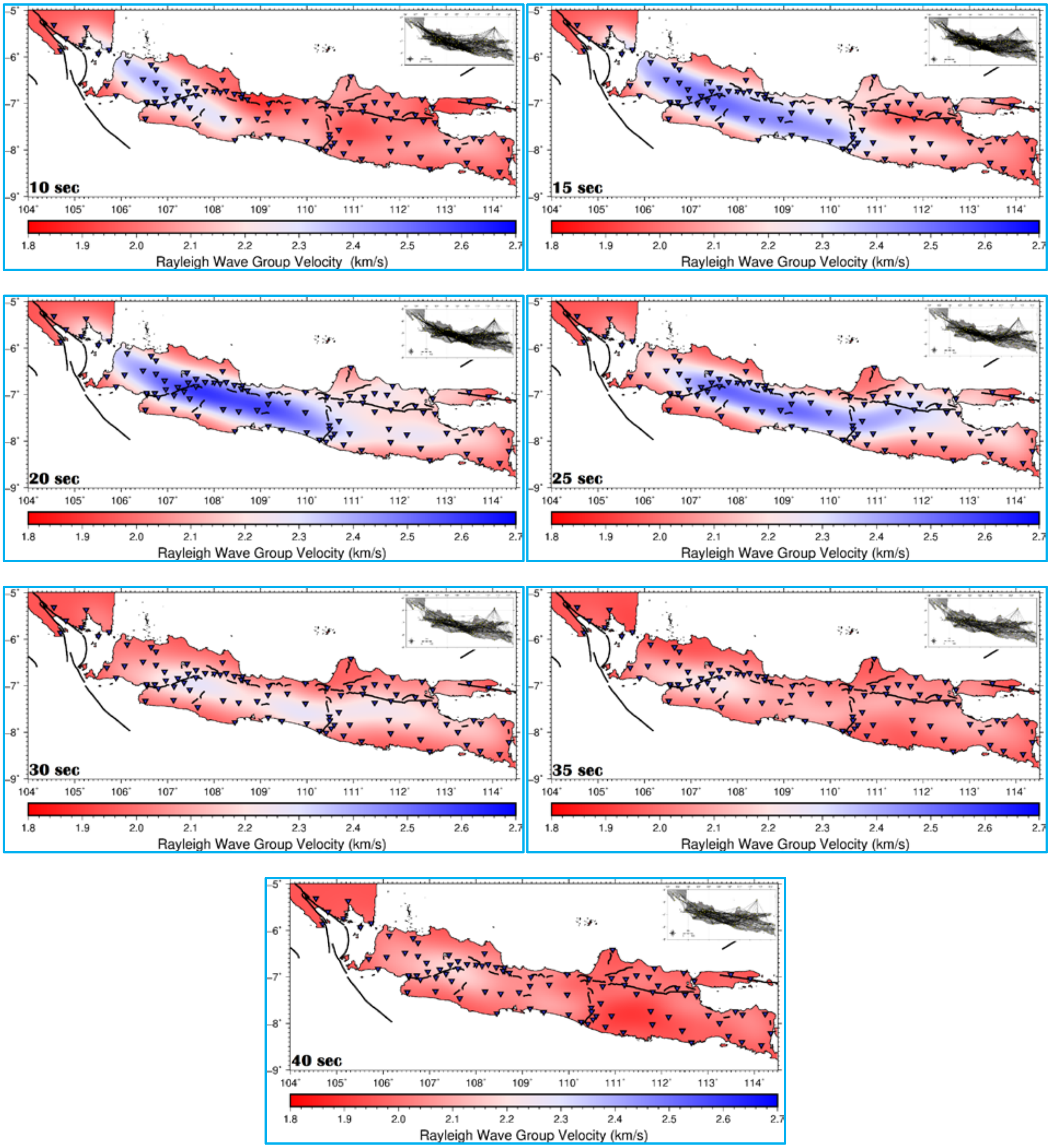

Fig. 5. Group velocity map of Rayleigh waves for the Java region and its surroundings, showing variations in velocity for periods of 10, 15, 20, 25, 30, 35 and 40 seconds. The map uses a color scale where blue represents high velocity values (typically associated with hard rock or dense materials) and red indicates low velocity values (commonly linked to soft rock, sediments, or high fluid content). The maps highlight significant geological features, including fault zones and volcanic regions, as reflected in the contrasting velocity anomalies

the Fourier transform. Cross-correlation is then performed in the frequency domain within a frequency range of 0.01–0.10 Hz, with a sampling frequency of 10 Hz. The quality of the cross-correlation results depends on factors such as the duration of the waveform, subsurface conditions affecting surface wave propagation, interstation distance and the quality and quantity of waveform data (Brenguier *et al*., 2008; Prieto *et al*., 2009).

After processing, cross-correlation results for all station pairs, based on twelve months of signal data, are stacked to enhance the signal-to-noise ratio using Linear

Stacking. This method amplifies coherent signals while suppressing incoherent noise. The stacked results provide an average velocity for the study area, offering insights into the subsurface seismic structure over a twelve-month period (Fig. 2).

Building on the cross-correlation results, the process of measuring the dispersion curve is carried out to extract the dispersion of group velocity and phase velocity from the ambient noise cross-correlation function (Herrmann, 2013). Dispersion analysis employs an imaging technique that automatically identifies dispersion curves in group and phase velocity images over a given period, focusing on the highest energy regions (red color) (Yao *et al*., 2006). The group velocity range is defined as 1-4 km/s, while the periods analyzed span from 1 to 50 seconds in 10-second increments (Fig. 3). The choice of wavelength values influences the periods resolvable by the observational data, which in turn affects the tomographic resolution and depends on the number of ray paths. Inter-station dispersion curves serve as the foundation for performing surface wave tomography to generate a velocity map of Rayleigh wave groups.

4. Tomographic inversion

The determination of the group velocity of Rayleigh surface waves over the spatial distribution was conducted using the Fast-Marching Surface Tomography (FMST) program (Rawlinson, 2005). FMST implements a grid-based scheme that models inverted seismic wave propagation to derive velocity variations relative to a reference velocity model. To estimate the group velocity of Rayleigh waves for various periods, the Fast-Marching Method is employed in the forward modeling process (Rawlinson and Sambridge, 2005). Before performing the group velocity inversion, a resolution test must be conducted to ensure the reliability of the results.

The resolution test in this study was designed to evaluate the resolution capabilities of the region to be interpreted. This test was performed using the checkerboard test method, which involves creating a synthetic data model with alternating high and low velocity values arranged in a chessboard pattern. The distance between recording stations, which are relatively far apart, limits the available seismic ray paths. To evaluate the effectiveness of ray paths in the study area, the checkerboard (CKB) method was applied. This approach uses synthetic models with alternating high and low speeds, and the initial velocity model employed in this study had an average velocity of 1.95 km/s. Additionally, the resolution test is influenced by the size of the grid, which determines the spatial resolution of the tomography. The grid sizes used in this study included (A) 100 × 100 km, (B) 50 × 75 km, (C) 50 × 50 km, (D) 25 × 25 km and (E) 12.5 × 12.5 km for the 10-second period (Fig. 4).

The results of the resolution test indicate that the entire area of Java Island can be effectively resolved using a recovery model with a grid size of 25 × 25 km. This grid size provides optimal resolution for the given velocity model compared to other grid sizes. The classification of resolution quality is based on model parameter values that closely approximate the initial values and are accurately resolved by seismic waves. Areas with dense seismic wave ray paths exhibit higher resolution and are therefore suitable for interpretation.

5. Results and discussion

5.1. *Subsurface Structure Analysis in the Java Island Region*

The ANT tomogram results reveal significant variations in the velocity of the Rayleigh wave group across Java Island, with values ranging from 1.8 to 2.7 km/s over periods of 10 to 40 seconds. The tomogram's color scale represents the velocity values, where red indicates low velocity anomalies, typically associated with soft or unconsolidated materials, and blue represents high velocity anomalies, linked to hard and dense rock structures.

In the 10-second period, the southern region of western Java shows a consistent high velocity anomaly (2.2-2.7 km/s). This anomaly correlates with areas of high topography and the presence of igneous rocks, which are associated with volcanic activity and the accumulation of sedimentary materials from ancient eruptions. These findings are consistent with previous studies highlighting the dominance of igneous formations in this region Pranata *et al*. (2020). Conversely, low velocity anomalies in western Java indicate the presence of quaternary deposits and volcanic materials, as suggested by Van Bemmelen (1949). Boundaries between low and high velocity anomalies coincide with major geological features, including the Baribis Fault, Muria Fault, Lasem Fault, Semarang Fault, Rawapening Fault, Opak Fault, Kendang Zone and Rembang Zone (Fig. 5). These zones highlight the interplay between fault activity and volcanic processes.

During the 15- to 20-second period, the velocity of the Rayleigh wave group increases significantly, with blue zones (high velocity) expanding from western Java to central Java. In eastern Java, however, the Kendeng Zone remains dominated by low velocity anomalies (1.8-2.2 km/s). The persistence of low velocity in this zone

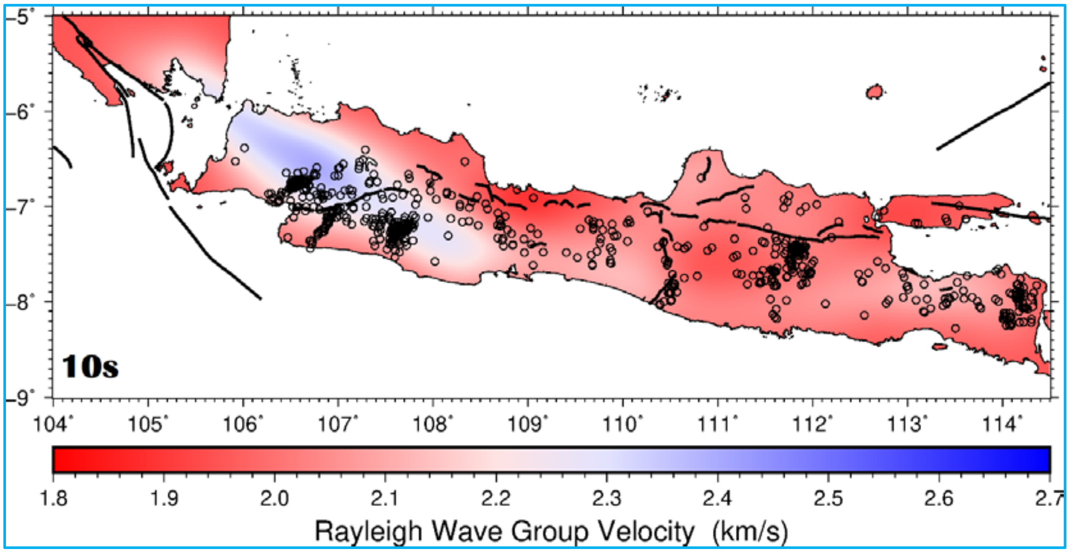

Fig. 6. Group velocity map of Rayleigh waves for the Java region and its surroundings during the 10-second period. Overlaid earthquake epicenters from relocated data (depth < 50 km) highlight the alignment of seismicity with the boundaries of low and high velocity zones, which correspond to active fault zones. This map provides insights into the subsurface geological structure and the distribution of fault zones across Java Island

suggests thick sedimentary deposits and deep sedimentation layers. These anomalies are likely influenced by hydrocarbon-related parameters, including porosity, density, Poisson's ratio, rigidity, lithology and fracture systems (Yao *et al*., 2006). Such characteristics are consistent with the Kendeng Zone's role as a hydrocarbon-rich region.

In periods of 25 to 40 seconds, high velocity anomalies dominate across Java, while the previously suggests thick sedimentary deposits and deep sedimentation layers. These anomalies are likely influenced by hydrocarbon-related parameters, including porosity, density, Poisson's ratio, rigidity, lithology and fracture systems (Yao *et al*., 2006). Such characteristics are consistent with the Kendeng Zone's role as a hydrocarbon-rich region.

In periods of 25 to 40 seconds, high velocity anomalies dominate across Java, while the previously observed low velocity anomalies in periods under 20 seconds begin to dissipate. This suggests that low velocity zones are primarily confined to shallow depths, representing sedimentary deposits or rocks with high porosity. The velocity increase to 2.70 km/s at greater depths indicates the presence of denser, harder rock formations. Additionally, a reduction in ray path density is observed, particularly in eastern Java, which may affect the resolution of deeper tomographic imaging in this region.

The boundaries between low- and high velocity zones across Java can be attributed to several factors, including variations in rock composition, density, fluid content, and temperature. Low velocity zones are typically associated with soft, low-density materials such as sediments and fluids, as well as high temperatures. In contrast, high velocity zones are linked to hard, dense rock formations, including intrusive and extrusive igneous rocks. Tertiary to quaternary volcanic rocks, known for their loose but well-structured properties, are commonly found at the boundaries of these anomalies, reflecting the volcanic sequences in Java.

The findings underscore that high velocity anomaly zones are predominantly associated with hard rock structures, such as intrusive and extrusive igneous rocks, which exhibit high density, solid structure and low temperatures. On the other hand, low velocity anomalies correspond to thick sedimentary structures or basins characterized by soft, low-density materials with high fluid content and temperature (Parolai, 2001). These characteristics provide valuable insights into the subsurface geological framework of Java and its tectonic and volcanic activity.

Fig. 5. Group velocity map of Rayleigh waves for the Java region and its surroundings, showing variations in velocity for periods of 10, 15, 20, 25, 30, 35 and 40 seconds. The map uses a color scale where blue represents high velocity values (typically associated with hard rock

or dense materials) and red indicates low velocity values (commonly linked to soft rock, sediments, or high fluid content). The maps highlight significant geological features, including fault zones and volcanic regions, as reflected in the contrasting velocity anomalies.

5.2. *Fault Identification in Java Island*

The Rayleigh wave group velocity results for the 10-second period were overlaid with earthquake distributions obtained from relocated hypocenters on Java Island. Short periods are typically associated with relatively shallow depths, making them suitable for imaging near-surface structures. The earthquake dataset used in this study comprises 720 events with depths of less than 50 km, recorded from 2009 to 2020, and relocated using the Hypo DD method (Setiadi, 2022). The distribution of earthquake epicenters, as shown in Fig. 6, reveals a clear relationship between seismicity and the boundary zones of low and high velocity anomalies. These boundaries correspond to active fault zones, as previously mapped by PuSGen for the Java region.

In the eastern part of Java, the distribution of earthquake epicenters appears more dispersed compared to the western part, where events are more concentrated and form linear patterns. This observation suggests that the rock formations in northern Java are relatively compact, while those in southern Java are more fractured and influenced by fault activity.

In western Java, four out of ten faults mapped by PuSGen were identified in this study (Fig. 6). The northern region of western Java exhibits strong velocity contrasts, indicating the presence of the Subang Fault, Ciremai Fault, Cirebon Fault, and Cirebon-2 Fault, supported by the distribution of earthquake epicenters in these areas. In contrast, the southern region is dominated by high velocity anomalies during the 10-second period, which obscures the identification of faults such as the Cimandiri Fault, Cimandiri Nyalindung Cibeber Fault, Cimandiri Rajamandala Fault, Lembang Fault, Garsela Kencana Fault and Garsela Rakutai Fault. Previous studies by Pranata *et al*. (2020) and Rosalia *et al*. (2022) identified these faults at periods shorter than 5 seconds, indicating their shallow depth and association with uniform rock density. According to Bourbie *et al*. (1987), high velocity zones are linked to hard, dense rocks such as intrusive formations, andesite and breccias, while Sunardi and Koesoemadinata (1999) attribute the rock hardness in western Java to the uplift of the Southern Mountains and the presence of intrusive rocks, reflecting volcanic arc products from earlier subduction episodes.

In Central Java, 14 faults confirmed by PuSGen in 2017 were identified. These include the Brebes Fault, Ajibarang Fault, Tegal Fault, Pemalang Fault, Pekalongan Fault, Semarang Fault, Ungaran Fault, Ungaran-2 Fault, RawaPening Fault, Muria Fault, Pati Fault, Purwodadi Fault, and Merapi-Merbabu Fault, as well as the Opak Fault in Yogyakarta. The contrast between high and low velocity anomalies in this region supports the existence of the Pamanukan-Cilacap dextral fault, oriented northwest-southeast (Sumatra pattern) and northeast-southwest (Meratus pattern), as reported by Satyana and Purwaningsih (2002). These fault patterns are evident in Fig. 6.

In eastern Java, nine faults confirmed by PuSGen were identified, including the Cepu Fault, Blumbang Fault, Waru Fault, Surabaya Fault, Pasuruan Fault, Probolinggo Fault and Wonorejo Fault. The Kendeng Zone in this region is characterized by a clear north-south anomaly pattern, consistent with findings by Martha *et al*. (2017). This zone is notable for its numerous mud volcanoes, which have lower density than surrounding sediments. The Watukosek Fault, associated with hot mud eruptions, is identified in this region by its lower velocity anomaly compared to surrounding sediments (Fig. 6).

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Fig. 6. Group velocity map of Rayleigh waves for the Java region and its surroundings during the 10-second period. Overlaid earthquake epicenters from relocated data (depth < 50 km) highlight the alignment of seismicity with the boundaries of low and high velocity zones, which correspond to active fault zones. This map provides insights into the subsurface geological structure and the distribution of fault zones across Java Island.

6. Conclusion

The tomographic results from the Ambient Noise Tomography (ANT) method reveal significant variations in Rayleigh wave group velocity, ranging from 1.8 km/s to 2.7 km/s. The increase in velocity with longer measurement periods indicates a transition from shallow sedimentary layers to deeper, more consolidated subsurface structures. The study successfully delineates geological boundaries and fault zones across Java Island, where low-velocity anomalies correlate with sedimentary deposits and high fluid content, while high-velocity zones correspond to dense, rigid rock formations. The strong correlation between these velocity anomalies and major fault structures, such as the Kendeng Zone and Cimandiri Fault, reinforces the reliability of the ANT method in imaging subsurface structures. These findings highlight ANT's potential as a robust tool for tectonic studies and underscore its significance in earthquake hazard assessment and mitigation in this seismically active region.

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