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Ambient Noise Tomography Around The Banda Arc Study Case: Before Earthquake of February 2nd, 2022

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Abstract - Banda Arc is one of the vulnerable areas in Indonesia. It is trapped by the slab coming from Australian-Eurasian Plate with the S–N direction and the slab coming from Pacific Plate with the E–W direction. Because of its location, it has a high seismicity, for example there was an earthquake that raised a big tsunami in 1852. On February 2nd, 2022, the newest earthquake with magnitude of 6.2 hit the Banda Arc. In many cases, earthquakes are damaging disasters, because their surface waves are shocking through anything they pass. Nowadays the surface wave is used to get the subsurface description and the variation of its velocity, and ambient noise tomography (ANT) is one way to solve it. By using some analyses like cross correlation and fast fourier transform (FFT) from the earthquake waveform three days before February 2nd, 2022, the depth and velocity group around the Banda Arc can be known. There is an indication that it was influenced by the ocean wave, which became wider and close to the main shock. Besides that, ANT result shows that the low velocity anomaly was distributed around the deepest area of the Banda Arc, because the energy absorbed more there, besides in the near location of hypocenter and resulting low velocity anomaly. It is shown that the low velocity anomaly can show how the geological condition is.

Keywords: Banda Arc, subduction zone, surface wave, ambient noise tomography

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Introduction

Background

Banda Arc is one of the vulnerable earthquake areas in Indonesia. There was a big tsunami in 1852 with the magnitude of more than 8.4 that was caused by the Tanimbar Trough activity in this place. Based on Indonesia tectonic setting, the subduction system is a product of the collision of Eurasia, Australia, and Pacific Plates elongates from the western part until the eastern part of Indonesia (Fisher and Harris, 2016). The Banda Arc itself is located in the eastern part of Indonesia, especially between the Sulawesi and Papua Islands. It is dominated by the oceanic crust, and it also has many volcanoes as part of the ring of fire (Milsom, 2000). Especially in the northern part, Banda Arc faces directly to the Bird's Head of Papua. It also consists of several through and trenches as a result of Late Cenozoic uplift that extend to Cendrawasih Bay. Another through and trenches are also appeared between Banda Arc and Bird's Head of Papua, as a source of earthquake and a result of collision process between three active plates (Saputra & Fergusson, 2023). Based on Figure 2, Banda Arc has high seismicity with huge number distribution of hypocenter located along Timor and Seram Through with the depth ranging from 50 to 600 km. Again, on February 2nd, 2022 there was an earthquake with quite high magnitude about 6.2 hit the Banda Arc as a proven that this area is included to the active plate movement as a result of collision.

Actually, the Banda Arc has a complex geological tectonic setting. It is located between the plates that have a different movement, and The Banda Arc is trapped in the centre of it (Figure 1). It is supported by a research by Titu-Eki and Hall (Titu-Eki and Hall, 2020), there are several features around Banda Sea. They are gravitational collapse, seamount and elongated ridges as a result of Shuttle Radar Topography Mission (SRTM) data. The bathymetry variation formed around Banda Sea looks like a circle as a result of complex geological setting and plate movements in this area. The ridge elongates around the south part of Banda sea can reach to 50 km length .

On Figure 1 is shown that, The Banda Arc has a bowl shape, generated by the oceanic seafloor spreading process of the Indo-Australian Plate in the Late Jurassic along the northeast Gondwana margin (Heine *et al*., 2012). The subduction then became slower and met with Australian plate resulted collision between the trench and volcanic arc and the embayment margin of Timor in 3.5 Ma. The slowing of subduction resulted from the interaction of tectonic plates, the physical properties of the lithosphere and the dynamic forces within the Earth's mantle. After that, Weber Deep presented and completed the embayment (Baillie & Milne, 2014).

As seen on Figure 1, it is no wonder that the Banda Arc has high seismicity (Figure 2). The tomography study result shows that the Banda Arc is also surrounded by two separated subduction slabs from the south to the north (Spakman and Hall, 2010). Subduction slab is one of hypocentre areas, and it is included into the megathrust that has the potential to cause big earthquakes.

Red and blue colours of the tomography result on Figure 3 b show the low and high velocity anomalies. They are usually interpreted as the partial melting or fluid indication and the subduction slab. Generally, a low velocity anomaly is always associated to a vulnerable zone. If a low velocity becomes larger, the vulnerability zone will follow and result more seismic risks. Based on the tomography study showing on Figure 2, the red colour is also connected with the volcano locations or the subduction. The large area can be predicted by seeing the tomography pattern. However, as explained previously the Banda Arc is dominated by the oceanic crust. It is very interesting to look the description of the crustal wave velocity of the earthquake around the location (Rosalia *et al*., 2019). The ambient noise tomography (ANT) is the suitable method to solve this problem. This paper discusses the influence of the oceanic wave

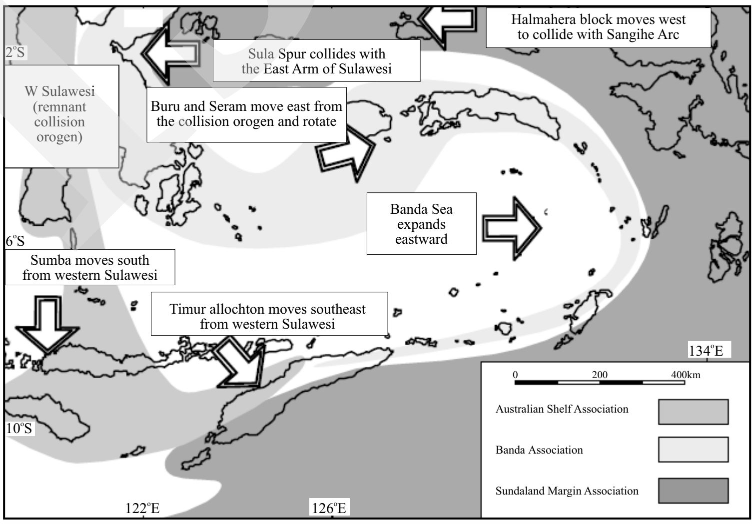

Figure 1. The movement plates around The Banda Arc (Milsom, 2000).

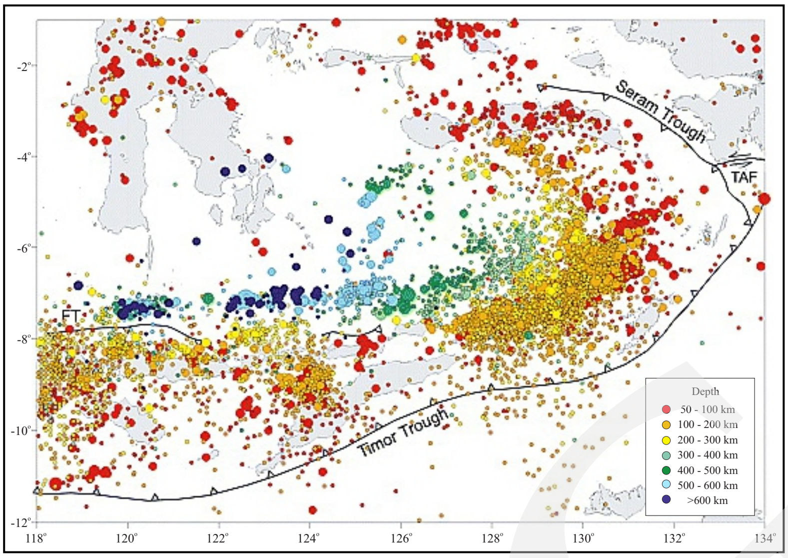

Figure 2. The high seismicity is shown by the hypocentre distribution around the Banda Arc (Das, 2004).

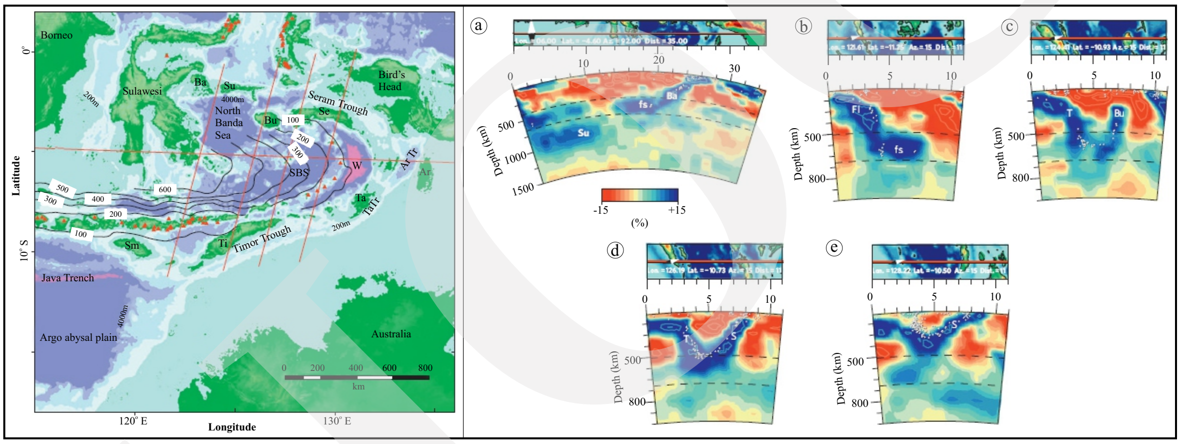

Figure 3. (a) Five tomography cross sections around Banda Arc represented by a, b, c, d and e lines. (b) P wave tomography result each cross section line (Spakman and Hall, 2010).

as a noise part of the earthquake before February 2nd, 2022, that shows the vulnerable zone based on the low velocity zone.

Actually, ANT can be applied in several cases, for example to get the description of volcanoes reservoir until the global seismic tomography. Utilizing waveform from a station to the other stations around the research area, then analyze the cross correlation of the coda wave as a noise between the interstation, the changing of the surface wave can be described well. ANT is solved by inversion method and it has limitation, but it still reliable to describe the subsurface condition of the research area. The coda wave frequency can vary from the high to the low and sometimes it is related with the ocean waves, especially in the low frequency (Nakata *et al*., 2019).

Method

Generally, ANT is started by analyzing the waveform of the stations around the researched area. It needs to make sure that there are cross correlations amongst them in a certain period of time, although just for a few minutes or seconds, then to determine the velocity model by stacking the waveform with each other, and to make the dispersion curve. While for the depth information, it can be observed from the fast fourier transform

(FFT) technique based on the waveform. The last step is to carry out the tomography study by the inversion method with the ray tracing calculated between two stations and more.

However, ANT comes from the earthquake and the other wave connection, like the ocean wave dominated by the surface wave. There are two kinds of surface waves, Rayleigh and Love waves. To find out the type of the surface wave, it is important to determine the velocity group with cross correlation of interstation around the researched area. It is assumed as the Green's function to get the differentiation between one station to another (Martha *et al*., 2017; Sarvandani *et al*., 2021). The velocity group also helps in determining the initial velocity of surface wave.

Green's function represents the wave that is recorded at Station 1 because of the impulse from Station 2 (Figure 4). In this case, the wave is the coda wave or the noise. However, the earthquake wave will be disturbed at the surface or the crust, and it increases the first earthquake energy release. Of course the noise in each station has the low energy. Thus, to get the good description of the noise, stacking process (interferometry) from the cross correlation interstation is needed (Das and Rai, 2016).

The initial description of the group velocity can be calculated from the cross correlation by using the gradient between the distance of the interstation and the time from the waveform itself, then 1-D velocity profile is observed. Because the noise is a random condition, it is important to notice the interstation distance. If the distance is close, it is better to carry out the ANT in a short period (3, 5, 10 seconds, *etc*.) While if the distance is far (hundreds kilometers) it is better to get a long period (40 to 150 periods) (Bensen *et al*., 2007; Wang *et al*., 2017).

In this paper, the station and waveform data from "GEOFON and EIDA Data Archives" by GEOFON Data Centre (1993) was used from January 28th, 2022, to February 1st, 2022. There are five stations with each interstation distance reaching 300 km, and the signal analysis of the long period is chosen (150 seconds). To calculate the velocity group, the cross correlation analysis, the depth information of FFT calculation based on the waveform, and the initial velocity from 1-D (Vp and Vs) velocity PREM Model by (Bormann, 2012) as the global velocity model were used. This velocity group information was then used to calculate the synthetic travel time in interstation model as the travel time calculated.

Besides travel time, the ray tracing is important to do in the tomography process. The ray tracing was calculated based on the station that had cross correlation between one and another. Based on

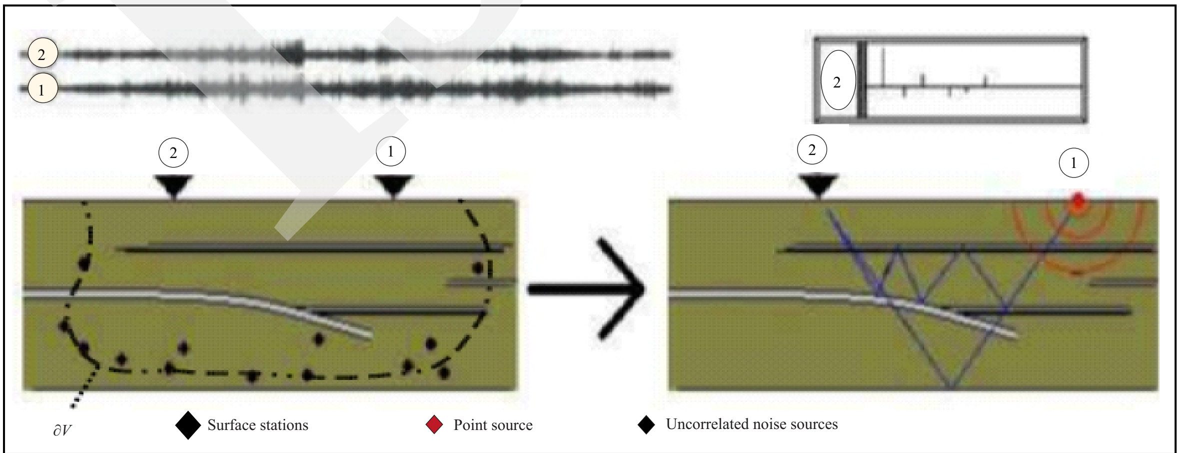

Figure 4. The illustration of Green's function interpretation in ANT (Das and Rai, 2016). It connects impulse relation between two stations represented in coda wave or noise. Then it is stacked together to find the cross correlation in finding the initial velocity of surface wave.

the station locations 9x9 size grid model was used. In tomography, this step is called the parameterization model. To get the tomography model, the linier inversion was used based on the equation (1):

$$d = Gm \quad (1)$$

where d, G, and m are the differences between the travel time calculated and the travel time observed, Kernell matrix or the forward modelling equation and velocity model that were searched for. However, the forward modeling in this case is generated from the Equation 2:

$$t = s/v \quad (2)$$

where t, s, and v are the time, distance on each grid, and the velocity. By submitting the Equation 2 to Equation 1, it is found Equation 3:

$$\begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_N \end{bmatrix} = \begin{bmatrix} r_{11} & r_2 & 0 & \cdots & 0 \\ 0 & r_{21} & r_{22} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{N-1M} & r_{NM} \end{bmatrix} \begin{bmatrix} 1/v_1 \\ 1/v2 \\ \vdots \\ 1/v_{NM} \end{bmatrix} \quad (3)$$

Based on Equation 3, N and M are the total number of data and grid. The Kernel matrix in Equation 3 is included into the singular matrix. To solve the inversion the Equation 4 was used

$$m = G^T \left(GG^T + I\alpha\right)^{-1} d \quad (4)$$

where I and α are the identity matrix and damping factor (Fichtner, 2021).

Result and Discussion

The hypocentre of the earthquake on February 2nd, 2022, had the magnitude of 6.2, located at 7.75°S and 128.64°E in 131 km depth. It occurred at 02.25.10 AM of Indonesia Time. It is assumed that the event is the main earthquake. The earthquake did not cause the tsunami. According to the GEOFON Data Centre (1993) there were six earthquakes from January 28th, 2022, to January 31th, 2022. Unfortunately, there were no information about the earthquake on February 1st and February 2nd, 2022. Based on the waveform signal analysis, there is a similar waveform characterization in each station at 9.30 PM with the duration of 12.5 seconds, used as the input data. The epicenter location can be seen in Figure 7. Each earthquake from 28th to 31st January has 518 km, 538 km , 345 km, 10km, 128 km and 134 km depth.

We do some cross correlations and FFT of the waveform to get the group velocity that ranging from 1.05 km/s to 3.9 km/s with low frequency about (0.08 Hz) and it is ranging from 13.2 to 34 km depth. Group velocity represent velocity profile through its depth (it is different with earthquake depth or hypocenter). The depth in group velocity represents the medium location with certain velocity value and it is calculated

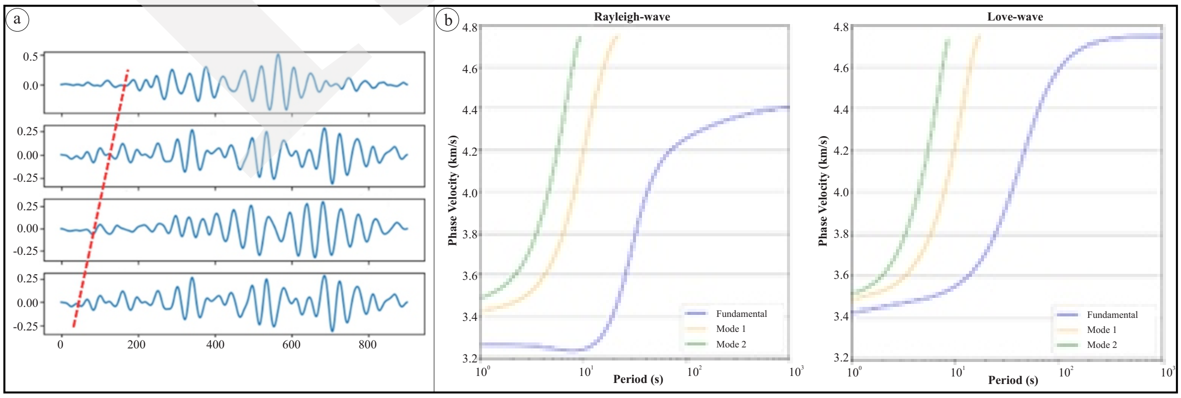

Figure 5. (a) Example of stacking and cross correlation on January 28th – 29th, 2022, x and y axis are the time and the distance interstation. It is used to get initial velocity of surface wave; (b) Phase Velocity vs time of the surface wave based on dispersion curve visualization.

from FFT data. To make sure that the velocity group was included into the surface wave, some calculation were done to get the velocity group dispersion of the Phase Velocity based on Bormann (2012) and Luu (2021), and the result can be seen on Figure 5.

On Figure 5a there is a dash black line which shows calculation of initial velocity of surface wave by the gradient method. Figure 5b is the dispersion curve of the Rayleigh and Love waves based on 1-D of Vp and Vs global velocity model. It can be known that the velocity group as the result of the cross correlation is included into both of them. The velocity group was then used to make the travel time synthesis by dividing the ray trace length to the velocity group. In this paper, Sarvandani *et al*. (2021) statement was referred to, that the ray tracing was made between one and another station that had cross correlation to each other.

In this paper, focal mechanism was also used as the additional information, but unfortunately there was only one data. This information is important to know the type of the earthquake source, and to make sure that it is suitable with slab condition around The Banda Arc. Based on the International Seismological Centre (ISC), Online Bulletin, there were two earthquakes on January, 31st, 2022. The first hypocentre was located at 6.7°S and 129.35°E with strike slip fault of focal mechanism, and the other was located at 2.4°S and 129.35°E with no information (International Seismological Centre, 2022). After that, the next step to do was to use the inversion method.

Before doing the inversion, it was important to make the checkerboard design to get the validation result of the tomography. The checkerboard design can be seen on Figure 6.

Velocity distribution is represented by colours. The red and blue colours are representing the low and high velocity around the researched area. If the tomography model has the similar pattern to the checkerboard design, it represents low velocity zone or the high seismicity area, and it is also a sign that the tomography model is good enough. Figure 7 shows the tomography model and its checkerboard test.

When the time was close to the main shock (February 2nd, 2022), the distribution of low velocity anomaly became wider (Figure 7). It indicates that the activity of the ocean wave became closer to the main shock. However, these phenomena could be caused by the seafloor activity. The low velocity was distributed along the boundary, especially in the Seram and Timor through the centre of the bowl shape of the Banda Arc from the first to the last day of the research time. These low velocity distributions were located close to the slab (Figure 8).

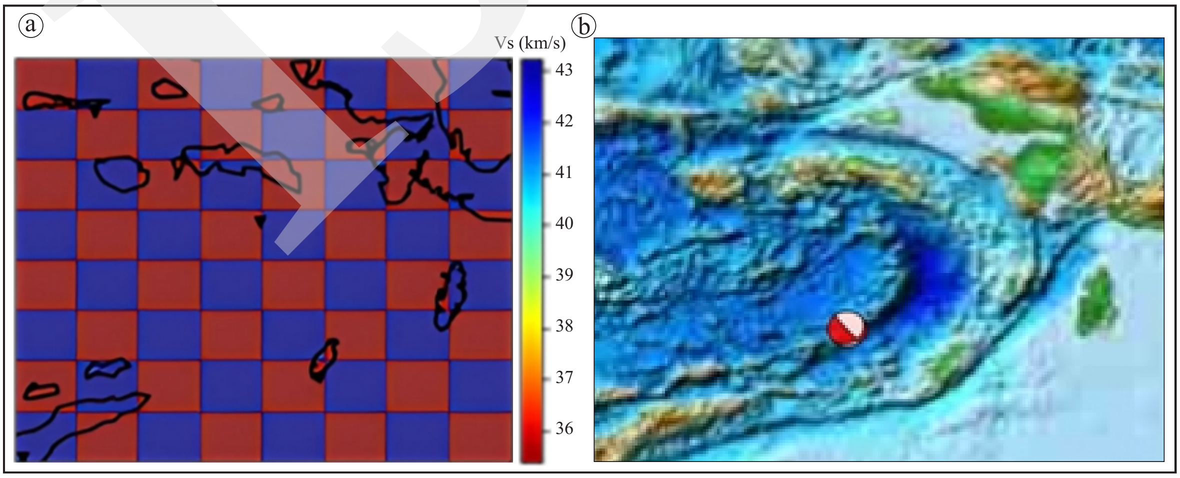

Figure 6. (a) Illustration of checkerboard pattern around the research area (interlude color, high and low velocity) the scale bar represents surface wave velocity (Vs) in km /s, while black triangles represent the stations; (b) Focal mechanism (represented by beach ball) of the earthquake in January, 31st, 2022.

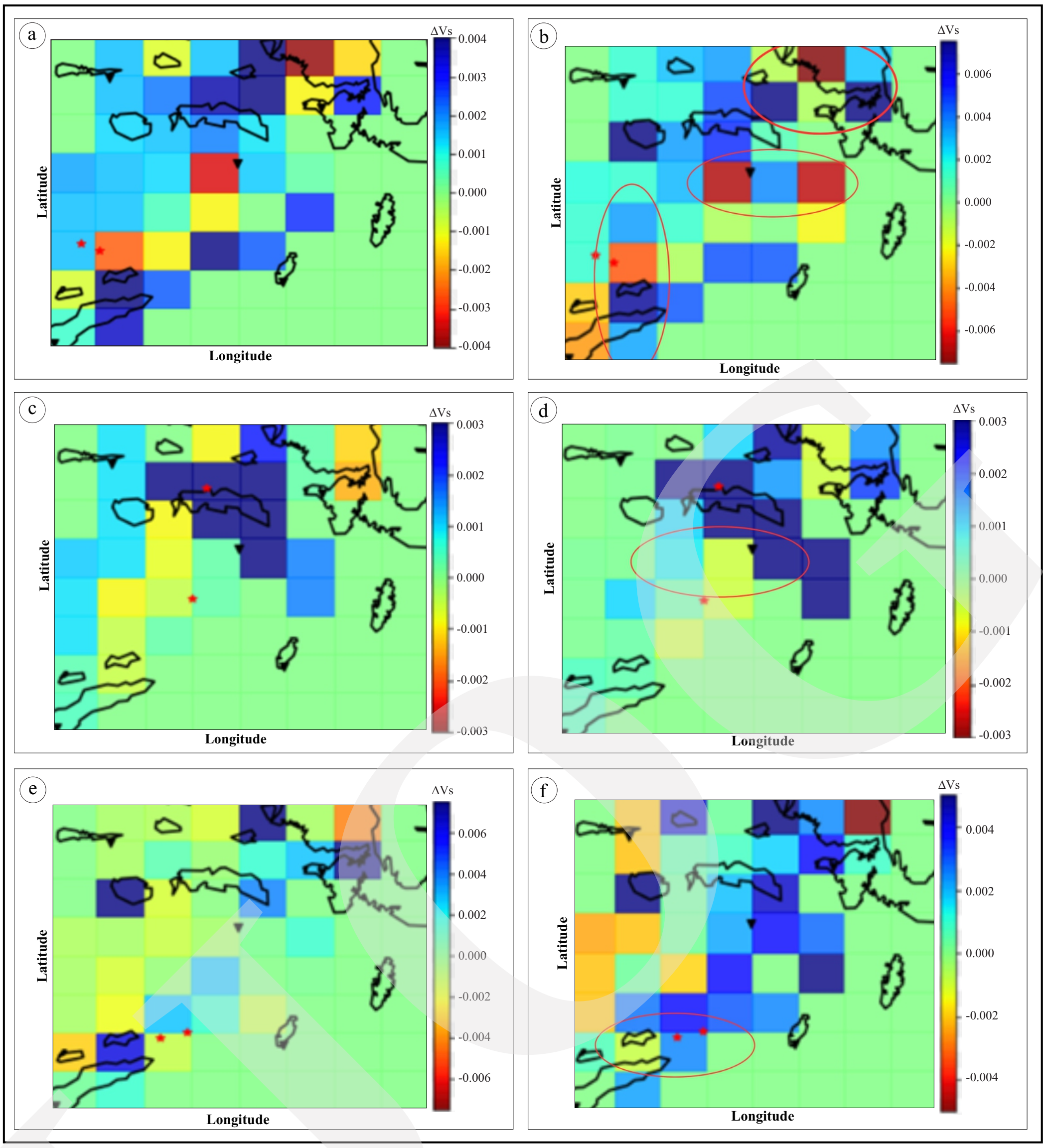

Figure 7. (a), (c), and (e) are tomography model in 28th-29th, 29th-30th, and January 30th-31st, 2022, while (b), (d) and (f) are checkerboard test model. The red stars represent the epicenters location and the dash circles in (b), (d) and (f) represent the areas that similar to the checkerboard pattern (interlude color, high and low velocity) to validate that the tomography model are good enough. The scale bar (ΔVs), means that the real value is lower than its initial velocity for negative sign and vice versa for positive sign.

Figure 8 describes two parts of the subduction zone around the Banda Arc based on the hypocentre distribution. The first slab comes from the Australian-Eurasian Plates with the S -N direction, and another one comes from the Pasific Plates with the E-W direction. The E-W slab is steeper than the S-N slab. The explanation of this phenomenon is related to the geological setting of the Banda Arc. Anyway, the subduction model is resulted from the triple junction from three plates tectonic. The Pacific Plate with

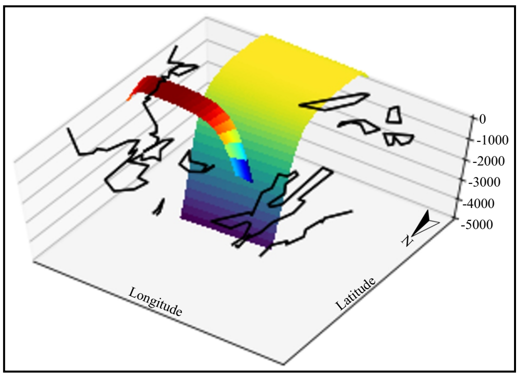

Figure 8. The slab or subduction zones around The Banda Arc.

E-W direction pressed the Indo-Australian Plate (S-N direction), making the Indo-Australian Plate was pushed to the northwest direction. In another part, the interaction between the two plates resulting some faults in the Bird Head of Papua, the stable continent. Based on this condition, the ANT result also has a similar form, the hypocentre location was dominated in the south, while the surface wave was distributed along the boundary first, and then moved to the northwest as long as the research time. However, the centre of the Banda Arc is deeper than the boundary, dominated with the ocean. As the consequence, the earthquakes that came from the boundary were shallow and middle earthquakes (based on the hypocentre depth). Thus, when the earthquake wave was spreading far away from the hypocentre (source), it would be absorbed more in the deepest area in The Banda Arc, resulting the low velocity besides in the near location of hypocentre as the source. It means that, low velocity anomaly can good enough describe the geological condition.

Conclussions

The Banda Arc as one of vulnerable zones in Indonesia with high seismicity and historical tsunami evidence was attacked by an earthquake on February, 2022. There were six foreshocks before the main earthquake with 6.2 magnitude on February, 2nd, 2022. As the main damaging actor, it is important to get the distribution of the surface wave, especially its low velocity zone. To know the variation of the surface wave, the ambient noise tomography (ANT) method was applied. By using some signal analyses like cross correlation and the fast fourier transform (FFT), it is known that the ocean wave has the big influence to the seismicity. This is indicated by low frequency around the researched area based on the data. However, the ocean wave can generate the seismic signal caused by seafloor activity or movement, resulting push and pull forces. While for the low velocity distribution, it is showed by the low velocity anomaly that became wider following the deepest slab around the Banda Arc. Besides near the hypocentre, it is in accordance with the Indo-Australian Plate movement direction (northwest). Dominated by the ocean, the earthquake energy would more be absorbed, following the deepest area or the geological condition and resulting low velocity anomaly.

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We are pleasure to give high appreciation to all of our team that involved in this research both of Geophysical Engineering UPN "Veteran" Yogyakarta and BMKG. Starting by collecting the data, processing until visualizing the model. Hopefully, this article can be a new insight in hazard mitigation of earthquake, especially in the eastern part of Indonesia.

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