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Distribution of Seismic Wave Velocity beneath Sunda-Banda Arc Transition Zone using Local Earthquake Tomography

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Abstract. We studied the 3D seismic tomography modeling for the internal structure of the Earth beneath the Sunda-Banda arc transition zone at coordinates 114 to 125 E and 13 to 4 S with 25 recording stations and tectonic earthquakes as the source of the rays with 7,279 P data and 1,168 S data. The data processing methodology consisted of determination of source location in 3D using ray tracing algorithm and Local Earthquake Tomography Inversion of Lotos-12. The modeling has three models such as: Anomaly velocity modeling, Absolute velocity modeling, $V_p/V_s$ ratio modeling. The results obtained velocity value of $P$ increase from 5.4 km/s to 7.14 km/s of the upper crust and decrease in the eastern part of Sumbawa Island and the western part of Flores Island at 40 km depth. Whereas, the velocity value of $S$ from 2.5 km/s to 4.2 km/s and the coverage data of $V_s$ cannot be found at the depth above 40 km. The results of ratio $V_p/V_s$ has a high value at the depth from 0 to 40 km. In 3D modeling of tomography in the same location, negative anomalies were obtained in the eastern part of Sumbawa Island and the western part of Flores Island. These results are indicative of active volcanic activity under Sumbawa Island and Flores Island as part of the active magmatic arc of the Sunda-Banda region.

INTRODUCTION

The tectonic plate is the Earth's crust, which moves very slowly across the surface of the planet. [1] The movement of the tectonic plate is influenced by the motion that occurs between two plate boundaries. Indonesia is located along the "Pacific Ring of Fire", where there are several collisions of tectonic plate, volcanic eruptions, and earthquakes. One example of the result of inter-plate collisions that produces zones with the complicated tectonic conditions is the Sunda-Banda arc transition zone. This transition zone lies in the south of Sumba Island [2,3]. The plate boundary in the south of Sumba Island is characterized by changes in the tectonic regime of the subduction activities of the Indo-Australian oceanic plate in the west, which is considered as a collision activity between the Australian Continent boundary and archipelago along the Banda Arc that spread at Kala Pl ions [4]. This transition zone provides a variety of geological and geodynamic settings in this transition area. These variations cause the appearance of the faults and folds, the volcanic formation, and the increase of seismic activity [5].

The existence of tectonic variations from this transition zone is an ideal target for conducting a research to determine the crystal structures associated with deformation along plate boundaries and to determine the possibility of new subduction zones that can increase the damage at this transition zone. The method that can be used to see the tectonic state in the Sunda-Banda arc transition zone is the seismic tomography method. The tomography seismic method is a method used to model the three-dimensional underground surfaces. This method uses inversion to look for wave propagation velocities from travel time data using graphics with residual system error.

This study applied the tomographic modeling in the Sund-Banda Arc Transition Zone area using the LOTOSOS-12 program. We hope that this research can produce good modeling to study the subsurface structure variations of the
Sunda-Band arc transition zone of wave propagation velocity from travel time data by using the system with residual system error.

**METHOD**

The data used in this study comes from the ISC (International Seismological Center) catalog at coordinates 114 to 125 E and 13 to 4 S and there are 25 stations. Data were collected from January 1, 2000 to December 31, 2017. Processing data were carried out, in general, using LOTOS-12 and MATLAB R2017a software and Google Earth.

The first processing is to make the input data for LOTOS-12 using MATLAB R2017a to find the earthquake coordinates, the station coordinates, the wave phase, the depth and the travel time for each earthquake event. The input data were obtained from the ISC earthquake data catalog with 6751 \( P \) data, 2599 \( S \) data and 1,391 earthquake events. Next, we make a parameter in the MAJOR_PARAM.dat file on LOTOS-12.

In seismic tomography using LOTOS-12, there are several inversion stages to obtain the subsurface structure modeling. The first stage is the 1D Velocity Optimization. For the 1D velocity optimization, the search for the best 1D velocity model and the preliminary source location are done by the initial step of calculating the 1D model travel time list. The travel time of the 1D model is obtained from the reference velocity (TABLE 1).

**TABLE 1. Reference velocity on the LOTOS-12 program [6]**

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>( V_p ) (km/s)</th>
<th>( V_s ) (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>4.30</td>
<td>2.22</td>
</tr>
<tr>
<td>6</td>
<td>5.50</td>
<td>3.26</td>
</tr>
<tr>
<td>12</td>
<td>6.70</td>
<td>3.67</td>
</tr>
<tr>
<td>15</td>
<td>6.80</td>
<td>3.96</td>
</tr>
<tr>
<td>35</td>
<td>8.10</td>
<td>4.42</td>
</tr>
<tr>
<td>74</td>
<td>8.30</td>
<td>4.54</td>
</tr>
<tr>
<td>104</td>
<td>8.40</td>
<td>4.60</td>
</tr>
<tr>
<td>124</td>
<td>8.45</td>
<td>4.62</td>
</tr>
<tr>
<td>154</td>
<td>8.50</td>
<td>4.66</td>
</tr>
<tr>
<td>400</td>
<td>9.03</td>
<td>5.00</td>
</tr>
</tbody>
</table>

The next stage is to evaluate the travel time based on bilinear interpolation of the values obtained in the reference list to calculate the source location using the grid search method. The kernel matrix, which describes the velocity variations in each depth at the time of travel of each ray, is then computed. The matrix inversion is performed for \( P \) and \( S \) wave velocity anomalies in 1D, and correction of source parameters (\( dx, dy, dz, dt \)), by doing the LSQR method [7], with damping controlled by special smoothing blocks.

Then, the bending algorithm is performed using the fermat principle to calculate the minimum travel time and the trajectory of the wave beam. The travel time is determined in the form of a line integral between source (i) and receiver (j). In the calculation process, the trajectory of the rays can be discredited using many points (number of bending points) on \( X1, X2, ..., Xn \). After passing the phase of relocation of \( Xk-1 \) and \( Xk + 1 \) positions at the new track point is obtained, namely \( Xk \). In the ray tracing process starting from the wave beam between points \( Xk-1 \) and \( Xk + 1 \) is the path of the line. Then, point \( Xk \) (on the first perturbation \( Xk = Xmid \)) is bent towards \( n \) as far as \( Rc \). Furthermore, the scheme of the three perturbation points is applied along the trajectory of the wave beam that has not reached the minimum travel time. The results in the first perturbation are used as the initial model and for the subsequent perturbation of \( Xk \neq Xmid \), the bending direction \( n \) as far as \( Rc \) is recalculated. The perturbation process is repeated until it reaches a convergence value and minimum travel time. Then relocation of the source is done to get the source location in 3D view.

The final stage is to calculate the matrix inversion using LSQR code iterations. With the addition of the parameters \( V_p \) and \( V_s \), the matrix will contain several elements related to the earthquake source (\( dx, dy, dz \) and \( dt \)) and station correction. Next, the iterations are repeated according to the steps that have been done above [8].

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RESULTS AND DISCUSSIONS

The results of 3D modeling produced three modelings at two sections (horizontal section and vertical section) for both \( P \) and \( S \) wave. The location of this study located in Sunda-Banda Arc Transition Zone at coordinates 114 to 125 E and 13 to 4 N (FIGURE 1). The location for modeling was minimized because the earthquake occurred at coordinates 117.5 to 120.2 E and 6.52 to 10.5 S. \( P \) data in this location were 7,279 and 2,616 for \( S \) data with 1,168 earthquake events and were recorded at 25 stations.

**FIGURE 1.** Study area at 114 to 125 E and 13 to 4 N. Red point shows earthquake events that occurred at 117.5 to 120.2 E and 6.52 to 10.5 S

The horizontal modeling obtained three depth sections (28 km, 38 km, 54 km and 70 km) on each modeling. The distance from the horizontal cross-section can be calculated with 1° equal to a distance of 100 km. Whereas, the vertical modeling has seven slices of sections (FIGURE 2), but three of them showed the best interpretation of the result. The first one is 2A-2B section which located at coordinates 175.5 to 120 E and 8.52 S. Then, 3A-3B located at coordinates 175.5 to 120 E and 8.48 S. And, 4A-4B section located at 175.5 to 120.2 E and 8.77 to 8.02 S. These three section lied beneath the eastern part of Sumbawa Island through the western part of Flores Island.
Anomaly Velocity Modeling of $P$ and $S$ wave

Anomaly velocity modeling derived from the travel time of $P$ waves and $S$ waves which displayed by percentage of $V_p$ and $V_s$. Anomaly values obtained from the differences of absolute velocity $P$ and $S$ waves with the reference velocity (TABLE 1). Coverage data in the anomaly velocity modeling can be seen from the large of areas in the image that are covered by colorful scales. This colorful scale shows the anomaly value starting from the deep red value of -10% to the dark blue value of +9%. The positive anomaly value explains that the absolute speed of the modeling results is greater than the reference speed. On the other hand, the negative anomaly value explains that the absolute speed of the modeling results is smaller than the reference velocity. The X-axis in the anomaly velocity modeling results in FIGURE 3 are longitude and the Y axis is latitude.

The results of anomaly velocity modeling show the increment of coverage data at 28 km depth to 54 km depth and tend to decrease gradually at depth below 54 km. This is because the object of research uses a local earthquake, an earthquake that occurs at a depth deep enough to the mantle layer as a source of waves. So the average depth of the earthquake detected ranged in depth from 40 to 50 km. The results of this horizontal modeling show the existence of negative anomaly values at the range of -3% to -10% in the north and west of Sumbawa Island. Negative anomaly values are seen in the ocean to the west of Sumbawa Island with the same range of values. Komodo Island is located between Sumbawa and Flores Island, has positive anomaly value in the range from 0 to 3%. The western part of Komodo Island is Flores Island, it has positive anomaly value which coverage increased as the value of depth increased. While on Sumba Island, it has a slight positive anomaly coverage above 9% and on the North side, it has an anomaly value of 3% which spreads from Flores Island. The results of other negative anomalies are also seen in waters that extend from latitude 6.52 to 8.02 S into that area, which shows an increase in anomaly values from negative anomalies to positive anomalies that indicate the differences structure in the area.

Horizontal anomaly modeling of the $S$ wave has less coverage than the $P$ wave (Fig. 4). This because there are significant differences in the amount of $S$ and $P$ data. The coverage on horizontal $S$ has increased little by little until it reaches a depth of 50 km as though as $P$ data. The biggest cover located from the north of Sumbawa Island and Flores Island spreads to the eastern part of Sumbawa Island with negative anomaly values. While the anomaly values surrounding Sumba Island are the same as in the $P$ anomaly model which is with a positive value.
FIGURE 3. Horizontal anomaly velocity modeling of P wave at each depth, a) 28 km, b) 38 km, c) 54 km, d) 70 km with color scale shows the values of anomalies.
FIGURE 4. Horizontal anomaly velocity modeling of S wave at each depth, a) 28 km, b) 38 km, c) 54 km, d) 70 km with color scale shows the values of anomalies

Coverage data in vertical modeling as through as horizontal modeling. The results of anomaly value are equal, from the negative anomaly value (-10%) to the positive anomaly (+ 9%). The X-axis in the modeling results illustrates
the distance (km) at which the incision extends. While the Y axis in the modeling results shows a negative value that illustrates the subsurface depth. Vertical modeling in this study was carried out to a depth of 100 km with different distances depending on the parameters of the coordinates.

Sections 2, 3 and 4 of the $P$ (Fig. 5) waves originating from Sumbawa Island stretching to the west of Flores Island with a distance of 274 km and 300 km. Coverage in these three sections has a similar pattern, namely there are areas that have positive and negative anomalies. Positive anomalies are seen at distances of more than 75 km. This positive anomaly is on Komodo Island, which in horizontal modeling and at the same location has the same anomaly value.

The cross section on the $S$ (Fig. 6) wave has a negative anomaly value in the western part of Sumbawa Island and shows a change to a positive anomaly in the eastern part of Sumbawa Island. This negative anomaly has a vulnerable depth from 0 to 60 km.

The results of anomaly velocity modeling of the $P$ wave and $S$ wave from both the vertical and horizontal sections show the same area in the negative anomaly and the positive anomaly. Most of the anomalies seen in this study area are negative anomalies.

**FIGURE 5.** Vertical anomaly velocity modeling of $P$ wave at each section, a)2A-2B, b)3A-3B, c)4A-4B with color scale shows the values of anomalies
FIGURE 6. Vertical anomaly velocity modeling of $S$ wave at each section, a)2A-2B, b)3A-3B, c)4A-4B with color scale shows the values of anomalies

**Absolute velocity modeling of $P$ and $S$ wave**

Absolute velocity modeling derived from the relative velocity of the $P$ wave and $S$ wave which displayed in units of km/s. The magnitude of the $P$ wave velocity ranges from 4 km/s to 8.5 km/s (from left to right on a color scale). While the $S$ wave velocity ranges from 2.5 km/s to 5 km/s (from left to right on a color scale). The location of the vertical section at the absolute velocity of the $P$ wave and the $S$ wave is the same as the location of the vertical section at the anomaly velocity modeling above. The X and Y axes in this model each describe the depth and distance at which the slices extend.

Based on Fig. 7, the three sections have a similarity when reach on a depth of 40 km to 100 km, the color in image modeling is yellow. The yellow color from the color scale shows a $V_p$ value of ± 8.3 km/s. While at a depth of 0 to 40 km, from these three sections above seen variations in speed values from 5.3 km/s to 7.14 km/s. Similar to the results of the Anomaly vertical modeling, at a depth of 40 km to 100 km and a distance of 0-150 km (beneath Sumbawa Island), 250-275 km (beneath Flores Island) has a $V_p$ value of 4.4 km/s to 4.6 km/s. The velocity of the three sections has increased at a distance of 150 km to 230 km to ± 8.3 km/s. The increment of velocity lied in the southern part of...
Sangeang Island to the northern part of Komodo Island. At the depth of 0 to 100 km in the above modeling can be seen an increment of velocity as deep as the depth.

In contrast to the results of absolute velocity modeling of the $P$ wave, the results of the $S$ wave modeling (Fig. 8) have less coverage. The coverage merely reaches the depth of ± 60 km similar to the vertical anomaly modeling on the $S$ wave. There are variations in absolute speed in the $S$ wave vertical modeling seen at depths of 0-60 km. The absolute speed of the $S$ wave ranges from 2.5 km/s to 4.2 km/s. The deeper the value of the absolute velocity of the $S$ wave the greater the depth interval is 0 to 60 km.

FIGURE 7. Vertical absolute velocity modeling of $P$ wave at each section, a)2A-2B, b)3A-3B, c)4A-4B with color scale shows the values of velocity (km/s)
FIGURE 8. Vertical absolute velocity modeling of S wave at each section, a)2A-2B, b)3A-3B, c)4A-4B with color scale shows the values of velocity (km/s)

$Vp/Vs$ ratio

$Vp/Vs$ ratio modeling derived from the comparison between the absolute value of $Vp$ and the absolute value of $Vs$. The results of the $Vp/Vs$ coverage less than the coverage in the $Vp$ modeling because it is affected by the results of $Vs$. Coverage data in the $Vp/Vs$ ratio modeling can be seen from the areas in the image that covered by colorful scales. This colorful scale shows the value of the ratio $Vp/Vs$ starting from dark blue, 1.66 to red, 1.88. The X-axis in the result of $Vp/Vs$ ratio modeling in Fig. 9 is longitude and the Y axis is latitude. The largest $Vp/Vs$ ratio value when viewed from horizontal modeling, is seen at 28 km and 38 km depth. Ratio value of 1.88 is around the coordinates of 118.5, 8.52. This ratio value stretches for ± 25 km distances. The remainder of the most dominant ratio value of 1.6, seen in the eastern of Sumba Island, eastern of Flores Island to the northern waters of Sumba Island and southern of Flores Island.
The vertical modeling results (FIGURE.10) shows the highest $V_p / V_s$ ratio at range of depth 0 to 40 km, seen in sections 2, 3 and 4 which are beneath Flores Island as far as 25 km. Ratio values with a magnitude of 1.6 are seen in sections 2 and 3 as deep as 80 km with a distance of 80 km under the eastern island of Flores.

**FIGURE 9.** Horizontal $V_p/V_s$ modeling at each depth, a)28 km, b)38 km, c)54 km, d)70 km with color scale shows the values of ratio
FIGURE 10. Vertical $V_p/V_s$ ratio at each section, a) 2A-2B, b) 3A-3B, c) 4A-4B with color scale shows the values of ratio.
INTERPRETATION

The tomographic modeling results of the $P$ wave and $S$ wave anomaly velocity shows negative anomalies in the eastern part of Sumbawa and Flores Island, positive anomalies around Komodo Island and a tendency for positive anomalies in parts of Sumba Island. Negative anomalies velocity according to previous studies is closely related to heat sources below the surface [9,10]. It shows an indication of a weak region which is thought to be due to increased fluid and partial melting in the subduction area [11].

Based on the geological structure, the Sumbawa and Flores Islands are part of the active magma arc in the Sunda-Banda transition zone [12]. Volcanic activity on Sumbawa Island is in the northern part of the islands, such as: Mount Tambora and Sangeang Api, respectively located 250 km to 300 km at the back of the trench and around 180 km above the Benioff Zone [13], while active volcanism on Flores is found mainly on the southern coast of the island.

![Map of Sumbawa Island](image)

**FIGURE 11.** Map of Sumbawa Island. The active volcano shows in the red triangle; the red lines triangle indicates the location of the volcano that is no longer active. The dashed line shows the Benioff Zone.

Based on the geological data, the negative anomaly position from the anomalous velocity modeling lied beneath the inactive areas of the volcanic and active areas in the eastern Sumbawa Islands and the western part of Flores Island [14]. In the $V_p/V_s$ ratio modeling located on the Sumbawa Islands, seen that there is a high $V_p/V_s$ ratio with value 1.88 at a depth of 20 km to 40 km. According to Nakajima et al, the large $V_p/V_s$ ratio indicates the presence of magma arcs and fluid regions. According to the study, $V_p/V_s$ values are caused by variations in lithology with depth. Under the active volcanic region, the value of the $V_p/V_s$ ratio is relatively small in the upper crust, but has a large ratio value in the lower crust area and the upper mantle. The difference is caused by differences in composition in the area. If the $V_p$ value is low and the value of the $V_p/V_s$ ratio is high, it can be implied that the area is a partial melting region. Partial melting is the process by which minerals with low melting points melt in the rock body due to temperature increases or pressure drops, or both, while other minerals remain solid. While areas that have a low $V_p$ value and a low $V_p/V_s$ ratio value can be considered the presence of a large enough H$_2$O [15]. If you see from the results of the absolute velocity $V_p$ at the same location as the $V_p/V_s$ ratio, the value of $V_p$ has a low velocity and the value of $V_p/V_s$ has a high ratio value. It can be concluded that the Sumbawa Islands are in active volcanic activity in accordance with the geological data mentioned above.

CONCLUSIONS

Based on the results of tomographic modeling research beneath the Sunda-Banda Arc Transition Zone, we conclude that:

- The results obtained three models, such as: Anomaly velocity modeling of $P$ and $S$ waves in the horizontal and vertical section, Absolute velocity modeling of $P$ and $S$ waves in the vertical section, $V_p/V_s$ ratio in the
horizontal and vertical section. The results of the modeling show the coverage of the waves P is better than the S wave because the amount of data from the P wave phase is greater than the S wave.

- The anomaly velocity modeling results of P wave and S wave generated negative anomaly values on the western of Sumbawa island and the eastern of Flores island. While positive anomaly values are around Sumba Island. The highest Vp value is 8.3 km / s while the highest Vs value is 4.76 km / s. The highest Vp / Vs ratio is 1.88 located in Sumbawa Island with a distance of 25 km at a depth interval of 0 to 60 km. While a ratio value of 1.6 has been found in the western of Flores Island at 80 km depth.
- The negative anomaly results in the eastern of Sumbawa Island and the western of Flores Island indicated the existence of volcanic arcs and partial melting areas. These results are reinforced by the small value of Vp with a high Vp/Vs ratio.

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