3d seismic velocity structure imaging beneath Flores region using local earthquake tomography

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Abstract. Flores is one of the seismically high activity zones of Indonesia region as a consequence of Indo-Australian plate subduction under the Eurasian plate. We investigate 3D seismic velocity structure beneath Flores region and the surrounding area as an effort to understand earthquake source mechanisms and subsurface geometry for the purpose of earthquake disaster mitigation. The study based on travel-time tomography using 223 earthquakes provided by webdc.eu catalog data which is recorded by up to 4 stations during period from January 2010 to March 2018. In the early data processing stages, a total of 1763 P-wave arrivals and 1763 S-wave arrivals were manually picked from 15 seismic stations around the Flores region using SeisGram2k70. 170 events with minimum error in VELEST used to derive a minimum 1D velocity model. The combination of Santos & Haslinger and AK135 velocity model used as a reference velocity model to Flores region. Furthermore we applied Local Earthquake Tomography (LOTOS 12) to investigated 3D seismic velocity in order to describe anomalous distribution of P and S wave velocities beneath Flores Region. The results showed that Flores region is dominated by a negative seismic velocity anomaly and a high Vp / Vs ratio that is thought to be related to the fault area due to the Flores Thrust Zone in the north and west of Flores and the upward fault in east Flores. The southern part of Flores is dominated by positive anomalies and a low Vp / Vs ratio which is thought to be igneous and metamorphic layers with a low liquid saturation level. Insufficient data causes the resulting tomographic resolution to be poor.

1. Introduction
Flores lies in the junction of three major tectonic plates Indonesia i.e the Eurasian Plate which is relatively moving to south, the Indo-Australian Plate which is relatively moving to north, and the Pacific Plate which is relatively moving toward the southwest [1]. It is a typical island arc structure with its characteristic physiographic features, such as a deep oceanic trench, a geanticline belt and a volcanic inner arc, marginal basins, etc [2]. The Flores region historically is potentially a tectonic earthquake and characterized by most depth earthquake (>100 km), as gathered from BMKG data.

Tectonic studies are needed to describe subsurface structures so that it can be obtained to get tectonic patterns as data support in an effort to properly map earthquake and tsunami-prone areas. This study aims to obtain accurate velocity models at Flores region and to describe subsurface structures using BMKG observation data. The accuracy of earthquake hypocenter determined by several factors including wave arrival time, wave phase, network geometry and velocity model. In order to achieve
the precision results, in the first page, we re-picked P and S wave arrival time and then we calculated new velocity model from travel time. In the last stage, we applied the LOTOS 12 algorithm which includes source location, optimization of the starting 1-D velocity model, and iterative tomographic inversion for 3-D seismic velocity P and S wave, Vp/Vs ratio and source parameters.

2. Data and algorithms
This research uses 223 earthquake events downloaded from the catalog data at http://www.webdc.eu/webdc3. The selected earthquake data were the earthquakes occurring in Flores region and its surroundings at the latitude position coordinates between -5.15 to 10.09 and longitude between 118.72 to 124.99 with a magnitude larger than 4.0 SR for about 8 years (January 2010 and October 2018). We use 15 stations that record earthquake events in Flores. A total of 1763 P-wave arrivals and 1763 S-wave arrivals were manually picked from 15 seismic stations around the Flores region using SeisGram2k70. We only get the data because not all earthquake stations around Flores can record earthquake data properly and we choose earthquake wave recordings with a clear phase P and S. The distribution of stations and earthquake used in this study presented in Figure 1.

![Figure 1](image-url) Distribution of earthquake events (colored dots) in Flores region and the surrounding area occurred during period January 2010-March 2018 and recorded stations (red star) used for the inversion. The polygon indicates the investigated area.

2.1 Minimum 1D velocity model
The result of local earthquake tomography depends on the initial reference model. An initial model for local earthquake tomography should be close to the true model. Kissling introduced the concept of the minimum 1D model in local earthquake tomography to find the best initial model named Velest which is designed to simultaneously produce hypocenter relocation, calculate 1D velocity models and station correction [3]. In this study, the results used are only 1D velocity models. The VELEST process in finding solutions begin with the input parameters and data followed by iterations of inversion problem solving to obtain the appropriate output which is marked by minimal RMS. The input used to model 1D velocity is 170 events which have RMS <0.5. The minimum RMS presents a well-defined problem that would only have one solution for a possible combination of hypocenters, a velocity model, and station corrections. In our study, the Santos & Haslinger combination and velocity global model AK135 model with 13 layer models were used as the initial model and updated using VELEST.
to obtain a new 1D velocity model closer to the Flores region. The computed 1D model compared to the starting model is given in Figure 2. Furthermore, the final velocity model determined by VELEST will be used as a reference 1D model for tomography inversion.

2.2 Seismic tomography inversion using Lotos 12
LOTOS-12 (Local Tomography Software) code, developed by Koulaev, is a tomographic algorithm designed to inverse simultaneously the structure of P and S wave velocities (VP, VS, and VP/VS) and earthquake source coordinates (hypocenter) [4]. The calculations start with input data files including coordinates of the stations, travel times of P and S seismic rays from local earthquakes to these stations, starting velocity model (VELEST result), and the parameter of grid and inversion. The ratio value Vp/ Vs = 1.78 determined by Linear Least Square fitting for P-wave versus S-wave travel times is used as an input for tomographic inversion. Preliminary location provided by webdc.eu also used although this information not strictly required, the software start searching for hypocentre used the center of the network or based on station with minimal travel times [3]. Tomography inversion using LOTOS 12 containing follows step:

a. Searching simultaneously for optimization 1D velocity model and initial source location. It has done iteratively through the stages: travel time calculation, describing the source location in model 1D, matrix calculation and finally inversion for velocity in 1D and source parameters.

b. Iterative tomographic inversion. The inversion tomographic formulation begins from the initial hypocenter parameters of each earthquake event. The observation equation for each wave arrival time at the recording station is written as follows:

\[
T_{ij}^{obs} = T_{ij}^{cal} + \left( \frac{\partial T}{\partial \Phi} \right)_{ij} \Delta \Phi_i + \left( \frac{\partial T}{\partial \lambda} \right)_{ij} \Delta \lambda_i + \left( \frac{\partial T}{\partial h} \right)_{ij} \Delta h_i \Delta T_{oi} + \sum_{n=1}^{N} \frac{\partial T}{\partial V_n} \Delta V_n + e_{ij}
\]  

(1)

where \(T_{ij}^{obs}\) is the travel time of observation from the source -i to the –j station, \(T_{ij}^{cal}\) is the travel time calculation from the source -i to the –j station, \((\Phi_i, \lambda_i, h_i)\) is the position of latitude, longitude, and hypocenter depth, respectively; \(T_{oi}\) is the time of the earthquake to –i event; \((\Delta \Phi_i, \Delta \lambda_i, \Delta h_i)\) is a disturbance for the four hypocenter parameters, \(\left( \frac{\partial T}{\partial \Phi} \right)_{ij}, \left( \frac{\partial T}{\partial \lambda} \right)_{ij}, \left( \frac{\partial T}{\partial h} \right)_{ij}\) : expresses a partial derivative travel time for hypocenter parameters; \(V_n\) is a seismic velocity at -n node grid in the 3D model space, \(\frac{\partial T}{\partial V_n}\) states that the partial derivative of travel time to the seismic velocity parameter and \(e_{ij}\) is a calculation error.

![Figure 2. 13-Layer 1-D models of Vp and Vs determined by VELEST and the starting model (combination velocity global Santosa & Haslinger model and AK135 model).](image-url)
The travel time calculation above produces a residual value of travel time for each wave propagation from the source to the recording station. All travel time residual values are written in vectors and resolved using the LSQR iterative inversion method.

Parameterization is a taken step to determine the physical parameter values of the research area by dividing the research area into a number of blocks or nodes with a certain size. The minimum spacing between the nodes in this study is 5 km and 8 km for the vertical and the horizontal direction, respectively. We use the inversion by using several grids orientations 0°, 22°, 45° and 67°.

2.3 Checkerboard (CKB) test
Resolution test needs to be done to find out the resolution of the tomography results before data interpretation is carried out. The resolution results are affected by the distribution of the earthquake events and the recording station. The tomographic inversion results are good if the resolution test results same or close to the synthetic model. One of the resolution tests commonly used is the checkboard test or board model which is using forward modeling method. Checkboard testing is done by determining the grid size based on earthquake distribution, station position, and velocity model reference.

3. Tomography results and testing
The P, S velocity anomalies and Vp/Vs ratio in two horizontal slices at 60 and 125km depth are shown in Figure 3 and Figure 4, respectively.

Figure 3. The distribution of P and S wave velocity anomaly and Vp/Vs ratio at depth 60 km.
Figure 4. The distribution of P and S wave velocity anomaly and Vp/Vs ratio at depth 125 km.

The structure of the velocity anomaly is obtained based on the P and S waves travel times. The anomaly value is expressed in the presentation deviation which is between -10% to 10% of the P and S wave velocity model. Figure 3 and 4 shows that the anomalies of P and S wave velocities are correlated to each other, which is dominated by negative anomalies (red and yellow), and high Vp/Vs ratios.

It is necessary to make a resolution test to determine the tomogram resolution before we make an interpretation. The checkerboard test has been carried out and the results obtained as shown in Figure 5. CKB test results show poor resolution for P anomalies that is influenced by insufficient data that can describe the entire subsurface of the target area. We see that there are empty areas because there is no trajectory of waves through it.

For the purpose of tomography, a number of local stations in Flores need to be able to record all earthquake events or the addition of earthquake data that can be obtained directly from BMKG because the data available at webdc.eu is relatively limited so that evenly distributed wave rays are distributed to describe complete tomography with better resolution.
Figure 5. Checkerboard Tests for Vp and Vs-anomalies at several depth. a-f were synthetic model for P anomalies, S anomalies, reconstruction P and S model at 75 km and reconstruction P and S model at 125 km.
Based on the tomographic resolution obtained we made cross sections on the Flores tomogram that shown in Figure 6.

![Cross sections on the Flores tomogram](image)

(a) (b) (c)

**Figure 6.** Velocity anomalies distribution in section 3A-3B, (a) Vp, (b) Vs, (c) Vp / Vs

The results of horizontal and vertical incisions show the distribution of seismic velocity anomalies and Vp / Vs ratios which are then interpreted by comparing them with previous studies.

Negative anomalies which are marked by red, indicate the existence of an area that has a weaker or lower wave velocity value. Negative anomalies indicate areas which have weak rock density, destruction zones and melt zones, or magma zone in active mountainous regions. Negative anomalies (low zones) are generally associated with fault areas or fractures that may be filled with fluids which cause the P and S wave velocities to low. This anomaly is related to areas where earthquakes occur frequently. Zones with high stress accumulation will experience deformation which then leads to earthquakes, faults, or underwater avalanches. The accumulation of weak zones is in the north, east and west of Flores Island.

Cross section along the south of Flores shows that the southern part of the Flores Region is dominated by positive seismic anomalies and a low Vp / Vs ratio. This confirms the results of the previous study that positive velocity anomalies are found in the southern part of Flores while the central and northern parts of Flores have negative anomalies [5].

In general, the distribution of seismic velocity anomalies at all depths is dominated by negative anomalies in accordance with previous studies that the inner arc area including Flores is characterized by high-velocity in upper crust, low velocity in middle crust, high velocity along surface crust, and low velocity in upper and lower mantle [5].

The study area is dominated by negative velocity anomaly regions and high Vp / Vs ratios associated with fault areas and high liquid / gas saturation levels. In the western part of Flores, the low velocity anomaly zone is associated with Ruteng Fault, Ulumbu Fault and Pocodedeng Fault and Bajawa Fault [6]. In the central part of Flores (Maumere) the anomaly zone is thought to be a sedimentary basin due to underwater avalanches and in the east it is thought to be a rising fault in Flores. The dominant high anomaly zone in the southern part of Flores is related to rock or metamorphic layers.
4. Conclusion

In this study, we collected data from BMKG in order to investigate the P and S wave velocity structure beneath the Flores region and the surrounding. We have analyzed local earthquakes from 2010 to 2018. After picking P and S wave arrival time of each event, we derived 3526 arrival times, consisting of 1763 P wave and 1763 S wave arrival times for inputting to the LOTOS12. We derived a 1D velocity model for the Flores area by using VELEST where the velocity obtained is used as an initial to investigate 3D seismic velocity models for Flores region using Lotos 12. Insufficient data has a large influence on the results of the obtained tomography. A number of local stations in Flores need to be able to record all earthquake events or the addition of earthquake data that can be obtained directly from BMKG because the data available at webdc.eu is relatively limited so that evenly distributed wave rays are distributed to describe complete tomography with better resolution. The study area is dominated by negative seismic velocity anomalous area and high Vp / Vs ratios which is related to fault area or earthquake-prone areas and associated with fault areas and high liquid / gas saturation levels.

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