Geological structure analysis in Central Java using travel time tomography technique of S waves

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Abstract
Java is one of the islands in Indonesia that is prone to the earthquakes, in south of Java, there is the Australian Plate move to the Java island and press with perpendicular direction. This plate movement formed subduction zone and cause earthquakes.

The earthquake is the release of energy due to the sudden movement of the plates. When an earthquake occurs, the energy is released and record by seismometers in the waveform. The first wave recorded is called the P waves (primary) and the next wave is called S waves (secondary). Both of these waves have different characteristics in terms of propagation and direction of movement.

S wave is composed of waves of Rayleigh and Love waves, with each direction of movement of the vertical and horizontal, subsurface imagining by using S wave tomography technique can describe the type of the S wave through the medium. The variation of wave velocity under Central Java (research area) is ranging from -10% to 10% at the depth of 20, 30 and 40 km, the velocity decrease with the depth increase. Moho discontinuity is lies in the depth of 32 km under the crust, it is indicates there is strong heterogeneity in Moho.

1. Introduction
Earth is composed of several layers. The first layer is a lithosphere, the second is mantle that consisting of the upper and lower mantle and the last is the earth's core. The core layer is hot and heats the mantle that is liquid, causing convection currents. This then leads to convection currents make plate movement which resulted the earthquakes and subduction zones.

Subduction zones are formed because the density is different between the two plates that meet each other. Oceanic crust will infiltrate under the continental crust because the density is higher. The subduction zone's temperature is cooler than the surrounding area, then the subduction zone is lifted the continental crust around it and form a row of volcanoes, such as a series of volcanoes along the western coast of Sumatra and South of Java as the impact of the Australian plate and the Eurasian collision [1]

Widiyantoro (2003) op cit [1] hypothesized that the plates of the ocean in subduction zones have positive anomalies due to tectonic processes and compressed, while the continental plates have a negative anomaly due to decompression.
The purpose of this research is to examine the S wave tomography relationship with the character of the S wave itself of Java.
2. Tectonic Setting of Java

Java tectonic system is still a hot topic discussed by geologists. According to Hamilton (1979) op cit [2] subduction path of Java, particularly in the Cretaceous is described curved from the Ciletuh (Sukabumi, West Java) continues to the northeast in Meratus (East Kalimantan). Meanwhile, according to another researcher, subduction curved from Ciletuh continue to Karangsambung and turn to Meratus [2].

There are some faults in Java trending east-west direction and parallel to the subduction tertiary pathways, while the structure trending structural pattern with northeast - southwest direction parallel to the Cretaceous subduction path that can be seen in Figure 1 [2]

![Figure 1](image)

Figure 1. Patterns of Western Java Geologic structure. There is a similar pattern pre-Tertiary rock structure between Ciletuh and Karangsambung [2]

3. Characteristics of S Waves

S wave is a wave that the spreading direction is perpendicular with the propagation. S wave appears after the P wave, and has two directions, namely vertical and horizontal directions. In addition, the S waves cannot propagate in the liquid medium.

The negative velocity anomaly (it is means low velocity) for S waves is directed horizontally on a layer of top layer that is associated with Love wave and positive velocity anomalies (it is means high velocity) on the below layer that associated with Rayleigh waves and the arrival time is slower than the Love wave [1].

Because the S waves cannot pass through the liquid medium, then the S wave is namely ScS where waves were only able to pass through the mantle boundary.

4. Methodology

This study uses USGS earthquake data since 1952 to 2012 around Central Java, with 2783 numbers of S wave arrival time data. The data subsequently relocated using the Grid Search to get a better velocity model to get the description of S wave velocity model and it's characteristic in subsurface by tomography technique.

The concept that used in this research is tomography with ray tracing pseudo bending that is based on the principle of Fermat in which the wave propagates through a medium with the fastest travel time (Um and Thurber (1987) op cit [3]).

Wave propagation time can be defined in the following equation:
\[ T = \int_{source}^{accept} \frac{1}{V} dl \]  

(1)

Where \( T \) is the travel time, \( V \) is the velocity model in the model parameterization and \( dl \) is the length of the track. To obtain velocity model inversion time delay process is carried out by dividing the area carefully situations into blocks of a certain size to facilitate the calculation, so that the equation (1) can be written as:

\[ t = \sum S \cdot dl \]  

(2)

Where \( t \) is the travel time, \( S \) is the slowness and \( dl \) is the path length for each block [3].

The concept of ray tracing pseudo bending is assume the three points through which the seismic wave, which is denoted by \( P_{k-1}, P_k \) and \( P_{k+1} \). \( P_k \) is the mid point of \( P_{k+1} \) and \( P_{k-1} \). Then look for a new central point \( P_k \) 'criteria latency is smaller than the \( P_k \) [4].

\[ \text{Figure 2. Illustration of three points on the pseudo bending method [4]} \]

5. Discussion

The results of the S wave tomography was made with two cross-section models that cut the Java with Mount Slamet as a central location such as shown in \text{Figure 3}:

\[ \text{Figure 3. The cross section models} \]

The incision in the form of A - A 'with X = 106.503707 and Y = -6.751412 until X = Y = -7.650037 111.697802 and then the incision B-B' with coordinates X = 109 205 and Y = -5.23 to X = 109 205 and Y = -9.23.
On incision A-A there is a large negative velocity anomalies from West Java to some regions in Central Java precisely on Dieng mountain, then the positive velocity anomaly from Mount Dieng until East Java. The anomaly arises because the amount of tectonic activity of Java, giving rise to a row of volcanoes. There are two big differences anomalies that indicate differences in the character of the S wave propagation in this region. Referring to the research by [1], in West Java and some region in Central Java was dominated by Love waves associated with negative velocity anomaly while in some areas of Central Java to the East Java, precisely dominated by Rayleigh wave.

In the incision B-B there are positive velocity anomalies on the Ocean plate, exactly in front of subduction zones and negative velocity anomaly on the continental plate that accordance with the hypothesis by Widiyantoro (2003) op cit [1].

Contrast Differences of the velocity anomaly in the Dieng area prove theories about the tectonic structure in Java as proposed by [2] that there is a continuity of the subduction zone of Ciletuh - Karangsambung then turn to Meratus.

In addition, variations of the S wave associated with the danger and exploration zones [5], since the S wave is a shear wave and it is associated with a Poisson's ratio. Distribution of the S wave which is a shear wave at shallow depths of around a few hundred meters which is usually the sediments and bedrock, is a matter that needs to be considered in making infrastructure or buildings.

While tomography models for the Central Java can be seen in Figure 6:
In Figure 6 the positive velocity anomaly is bigger with increasing depth. It is accordance with research by [1]. Beside that there are negative velocity anomalies on the continental shelf. In Figure 6 there are also differences of positive and negative velocity anomaly at a depth of 40 km which the direction is corresponding with the fault direction. It can be interpreted that there are differences in the geological structure of the area and the dominance of the earthquake that occurred in West Java and some parts of Central Java which is indicated by a large negative velocity anomaly in the area.

Moho depth beneath the continental crust is about 32 km. Figure 6 show tomogram of S wave velocity in the depth of 20, 30 and 40 km. At a depth of 20 km, variation of the S wave velocity anomalies ranging from -10% to 10%, it is show that the area is very heterogeneous, as research by [6] stating that the variation of the S wave velocity anomaly which reached 6% indicated great heterogeneity in the research area, which reached a depth of Moho, exactly at middle and lower crust.

Research by [6] also showed the depth of 40 km decrease the velocity and increase in attenuation function. Figure 6 also shows the same thing, at the depth of 30 and 40 km negative velocity anomalies is wider.

Meanwhile, research conducted by Zhao et al (1996); Tape et al (2010) op cit [7] show a very strong heterogeneity in the crust and upper mantle beneath California indicated by the wave velocity description using tomographic techniques. Low wave velocity is usually associated with the fluid. Lin et al (2007); Zhao and Kanamori (1993) and Zhao et al (2005); Lees and Nicholson (1993); Tian et al (2007a) with their own researchs op it [7] show a correlation between seismic activity and heterogeneity of the crust which refers to the conclusion that the presence of fluid in the earth's crust lies in a weak zone that resulting earthquakes, in this research is the Landers earthquake.

Thus, by examining the earthquake through the wave velocity tomography, a description of the subsurface can be known.

**CONCLUSION**

The results of the S wave velocity tomography under Java island there are positive and negative velocity anomaly in the area around Dieng-Central Java, where the predominantly negative velocity anomaly is in the western part of Java island. This suggests that in the western part of Java, earthquake occurred more dominant and dominated by Love waves and prove the theories about there is a continuity of the subduction zone in Ciletuh to Karangsambung then turn to Meratus.

At a depth of 20, 30 and 40 km, there is a boundary between the the velocities in the direction of the fault which the low velocity is became wider with the depth increase. Tomographic results also showed that part of the ocean plate on the area in front of the subduction zone has a positive velocity anomaly and on the continental shelf has a negative velocity anomaly.

The variation of the velocity is ranging from -10% to 10%, it is indicates that there is strong heterogeneity in the depth of 20, 30 and 40 km, which is the Moho discontinuity.
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