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3D SEISMIC TOMOGRAPHY ANALYSIS OF JAPAN SUBSTRUCTURE USING LOCAL EARTHQUAKE TOMOGRAPHY

Indrawati Wilujeng*, Bagus Jaya Santosa

Departement of Physics, Faculty of Mathematics and Natural Sciences
Sepuluh Nopember Institute of Technology
Jl. Arief Rahman Hakim, Surabaya 60111 Indonesia
**Email: indrawati13@mhs.physics.its.ac.id*

Abstract

Location of Japan which located in the Ring of Fire region causing Japan frequently hit by earthquakes. In these areas, there are three tectonic plates under the surface region of Japan. To determine the condition of the subsurface zone of the meeting of tectonic plates as the main source of the earthquake in Japan, we can do a seismic tomography method. This method is a development of characteristic 1D models into a 3D velocity model based on seismic wave data. The input data used are the data of tectonic earthquake that occurred in Japan in the time range from January 1st, 2010 to January 1st, 2011. Recorded 77 events occurred and 1293 seismic waves used in data processing. The steps in this study are picking P and S waves using SeisGram2K60, then relocated hypocenter using Double Difference method using HypoDD software, and for further tomographic inversion Local Earthquake Tomography using software LOTOS 12. P wave velocity (Vp) and S wave velocity (Vs) in the upper crust Vp approximately 5,961 km/s and Vs about 5,115 km/s, at the bottom crust Vp approximately 6,666 km/s and Vs about 5,961 km/s, and in the upper mantle Vp approximately 7,371 km/s and Vs is 6,666 km/s. Low anomaly of Vp/Vs indicates that the region has a tendency surrounded by the earthquake hypocenter. The area near surface has a high value of the ratio Vp/Vs when compared to the deeper area. At depth of 10 km, the value of the minimum ratio Vp/Vs is 1,6 and the value of the maximum ratio Vp/Vs is 1,899. Meanwhile, at depth of 20 km, the minimum ratio Vp/Vs is 1,646 and the value of the maximum ratio Vp/Vs is 1,865. At depth 30 km, the minimum ratio Vp/Vs is 1,680 and the value of the maximum ratio Vp/Vs is 1,761. And at depth 40 km, the minimum ratio Vp/Vs is 1,692 and the value of the maximum ratio Vp/Vs is 1,761. In the 3D image obtained by the variation of Vp and Vs anomalies around the southern part of Japan region, which tend to have a negative anomaly because in that area there are three tectonic plates such as Eurasian plate, Philippine Sea, and the western Pacific ocean plate.

Key words: seismic tomography, Local Earthquake Tomography, Japan region.

INTRODUCTION

Japan is one of the region in East Asian region which is separated from the main of Asia land. Astronomically, Japan lies on 30ºLU - 46ºLU and 128ºBT - 149ºBT. With the astronomical location, Japan is at the confluence of three major tectonic plates are moving all the time, namely the eastern part of the Eurasian plate, Philippine Sea, and the western Pacific ocean plate. When the eastern part of the Eurasian plate collides with the Pacific plate to the west, the Pacific ocean plate will infiltrates under the Eurasian plate which resulted the formation of the megathrust. As a region that is located above the megathrust and closed to the trench as plate boundaries, it is not surprising that the Japan be earthquake-prone region.

One way to determine the condition of the subsurface zone of the meeting of tectonic plates as the main source of the earthquake in Japan is using seismic tomography method. Most of the images of seismic tomography is based on the distribution of seismic wave velocity is determined by the seismic wave arrival time data [1]. Complete the definition that seismic tomography as an imaging technique that produces images of an object by using the object's response to the non-destructive external energy [4]. That external energy can be artificial or natural energy from an earthquakes. From both of these definitions, can be concluded that seismic tomography is one of geophysical methods in imaging technique that produces images of an object (in this case is the earth) based on arrival times of earthquake waves that occured on earth.

Seismic tomography itself is divided into two types of modeling, they are forward modeling and inverse modeling. In this study, seismic tomography used is inverse modeling which the model parameters have been obtained directly from seismic data. Seismic tomography method using the parameters of the P wave velocity (Vp) and the S wave (Vs) in the seismic waves. This method will be used to determine subsurface conditions Japan based on arrival times of earthquake waves that have been recorded by 62 earthquake recording stations scattered throughout the region of Japan. Then after process and analyse these parameters, we will get detailed imaging of the 3D structure of the subsurface region of Japan.

To facilitate researchers in obtaining fine imaging of subsurface conditions of a region, it is necessary to use certain software tools. There are several software that is introduced to obtain tomographic imaging an area of seismic data processing, one of them is the Local Tomography Software (LOTOS). LOTOS is designed to invert the structure of P and S wave velocity and coordinate simultaneous seismic source for imaging of subsurface conditions earthquake area. LOTOS algorithm can also be easily applied to various sets of data without complicated processing parameters [2]. By using this software, is expected to be obtained 3D imaging of the subsurface structure of Japan region in detail.

The aims of this study is to obtain tomographic imaging of subsurface regions of Japan by using Local Earthquake Tomography. Tomography is expected to allow researchers to get better understanding about the mechanism of tectonic on Japan region.

RESEARCH METHOD

In this study, the data used is secondary data that is downloaded from http://www.fnet.bosai.jp. The data is the seismic data that occurred in Japan with coordinates 30ºLU - 46ºLU and 128ºBT - 149ºBT, within one year starting January 1st, 2010 to January 1st, 2011. Recorded in 77 events with 1293 seismic waves that can be analyzed. Seismic recording station network by 62 stations scattered throughout the region of Japan. 1-D velocity model for the Japanese region as shown in Table 1.

Table 1. Reference model 1-D velocity structure of the Japan region

Depth(km)	Vp(km/s)	Vs(km/s)
0	5.50	3.14
3	6.00	3.55
18	6.70	3.83
33	7.80	4.46
100	8.00	4.57
225	8.40	4.80
325	8.60	4.91
425	9.30	5.31

Hypocenter Relocation

The method that will be used to relocate hypocenter is Double Difference (DD). Principle of Double Difference method is to use the data travel time between two earthquakes which their hypocenter lies adjacent. If the distance between two earthquake hypocenter is very small compared with the distance of the epicenter to the station, it can be considered that the raypath between the two earthquakes is similar. So it can be assumed that the difference in travel time between the two earthquakes recorded on the same station is a function of distance between the hypocenter.

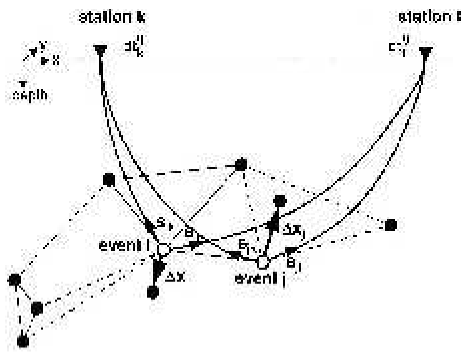


Fig. 1. Illustration of Double Difference Algorithm [6]

Fig. 1 is an illustration of the double difference earthquake relocation algorithm. Black and white circles indicate the preliminary hypocenter were associated with earthquakes around the cross correction data (straight line) or catalog (dashed line). The adjacent earthquake, *i* earthquake and *j* earthquake are indicated by white circles. Both earthquakes are recorded at station *k* and *l* with dt_k^{ij} and dt_l^{ij} time difference, and its vector slowness s [6].

Travel time observation and travel time calculation residual between the two adjacent seismic can expressed by the equation:

$$d_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal} \quad (1)$$

with d_k^{ij} is the residual value, $(t_k^i - t_k^j)^{obs}$ is the travel time of seismic waves based on observations between *i* earthquake and *j* earthquake to *k* station, and $(t_k^i - t_k^j)^{cal}$ is the travel time of seismic waves based calculations between *i* earthquake and *j* earthquake to *k* station.

To facilitate the solution it is assumed that the velocity model has represented the actual situation, and reading of travel time is right. Linearization of the problem can be written as follows:

$$\Delta d = \frac{\partial t_k^i}{\partial m}\Delta m^i - \frac{\partial t_k^j}{\partial m}\Delta m^j \qquad (2)$$

Δm is the hypocenter model changes consisting of four parameters hypocenter (x_0, y_0, z_0, t_0). If the equation (2) is arranged for all stations and formed into the matrix can be written as follows:

$$\boldsymbol{W}\Delta\boldsymbol{d} = \boldsymbol{W}\boldsymbol{G}\Delta\boldsymbol{m} \qquad (3)$$

Δd matrix containing a residual and its size is M x 1. M is the number of double difference observations.

The matrix G is the Jacobian matrix, containing the partial derivatives of travel time residual value of each station to the hypocenter parameters which size is M × 4N, N is the number of seismic events and 4 is the number of parameters hypocenter (x_0, y_0, z_0, t_0). Δm matrix containing position and time of the earthquake hypocenter (*x*, *y*, *z*, *t*) which size is 4N x 1. While the matrix W is a diagonal matrix containing the weighting in the calculation of the travel time of the wave equation. If the hypocenter determination has been done, but the result in minimum residual value is still great so it is necessary to do the iteration, so that the minimum residual value will be smaller and closer to zero which indicates that improvements hypocenter position has been reached.

Seismic Tomography

The basic principle of seismic tomography is imaged subsurface area of research in the domain of velocity. Tomographic inversion process in this study aided by a software called Local Tomography Software (LOTOS) version 12. LOTOS-12 is a software that can be used for tomographic imaging of an area based on seismic waves that occured in that region. LOTOS is designed to invert the structure of P and S wave velocity and coordinate simultaneous seismic source for imaging of subsurface conditions earthquake area. LOTOS algorithm can also be easily applied to various sets of data without complicated processing parameters [2].

In general, the working principle of LOTOS can be presented in the following flow chart:

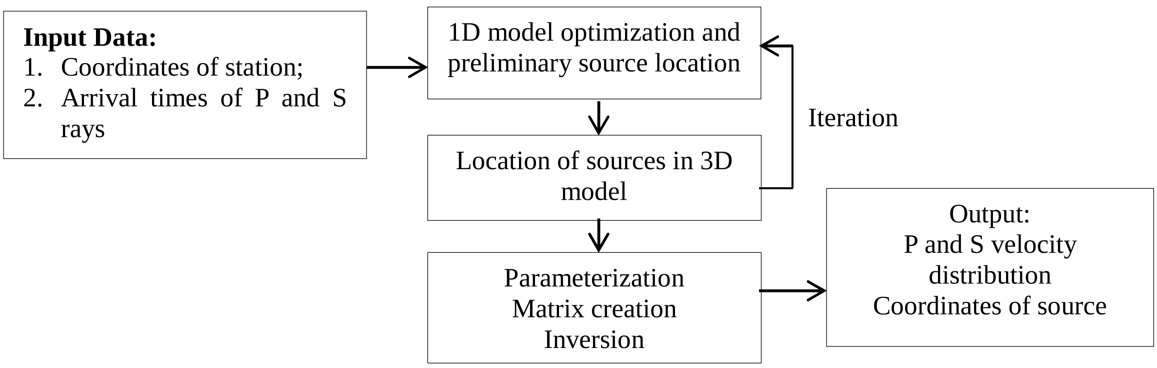


Fig. 2. The main step optimization 1D velocity and the preliminary location of the source [2]

After 1D velocity model and the preliminary location of the source is known to the optimization of 1D models, then do relocation with 3D ray tracing (bending), then the next step is use a gradient method to obtain the location of the source in the 3D model [3]. Parameterization method using nodes and algorithms have been done by Koulakov [2]. The first derivative of the matrix is calculated using the ray paths computed after the location of the source has been in the 3D model. Each element of the matrix, $A_{ij} = \partial t_i / \partial v_j$ proportional to the deviation of the time along the beam to-*i* in the *j*-th node. Overall matrix inversion to be obtained by using the iterative LSQR [5]. Iteration cycle starting from step determines the location of the source, matrix calculations, and inversion. Iteration can be repeated in order to get the best results.

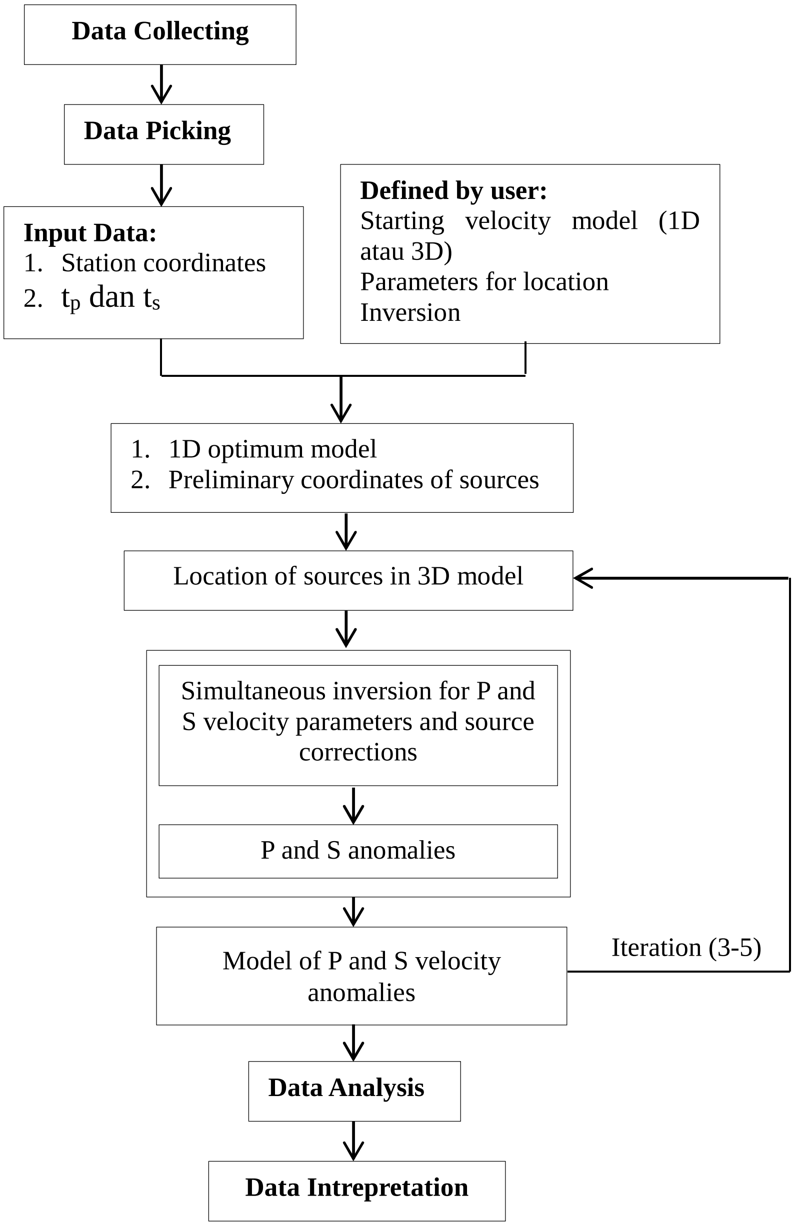


Fig. 3. Flow chart of the process of tomography inversion

RESULT AND DISCUSSION

The data used in this research is the seismic data that has been recorded in approximately 62 earthquake recording stations scattered throughout the region of Japan, in the time range starting January 1st, 2010 to January 1st, 2011. Recorded 77 events, which each event has recorded the number of stations ranging from 4 to 17 stations. So, there are 1293 seismic waves that can be analyzed, which consists of 649 P waves and 644 S waves. Then the seismic waves are picked to get their arrival time. The process of manual picking done by using Seisgram2KV6.0.0x02 (BETA) software.

Hypocenter Relocation

After passing through the process of picking, obtained arrival time of P waves and waves. Then, this data is used as input data on software HypoDD to get earthquake relocation position. In hipocenter relocate, it is also necessary 1D velocity model parameters. 1D velocity model used in this study is a velocity model as shown in Table 1. The determination of the hypocenter relocation is intended to improve the accuracy position of earthquake sources so the new hypocenter can be used as a reference to the next process, that is tomography inversion.

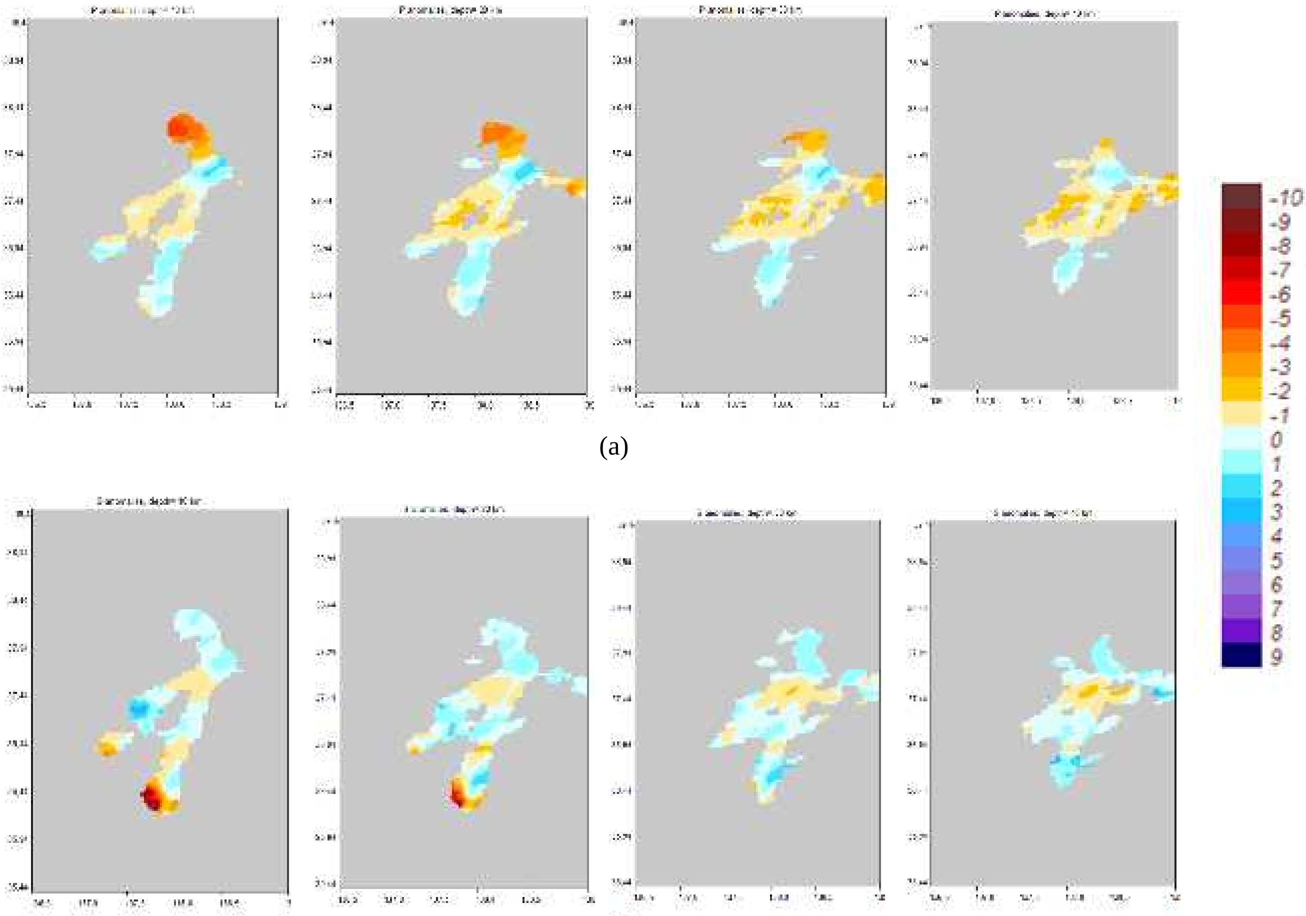
Based on the results of the relocation was found that the majority of recorded earthquakes are middle earthquakes occur at depths more than 60 km and less than 300 km. While the shallow earthquake is only 26 events which occur at depth less than 60 km.

Analysis of 3D Velocity Distribution

3D velocity distribution is obtained by several steps. First step is determination of the location in 3D models using ray tracing algorithm on minimizing travel time obtained. Second is starting location of the earthquake and relocated back that have been obtained using 3D ray tracing method (bending tracing) and third step is grid parameterization and anomaly velocity distribution between nodes are interpolated linearly to become tetrahedral blocks [2].

Furthermore, after the third steps have been done, it will obtained subsurface cross section of the Japan region, which is represented by a figure of the distribution of P wave velocity (Vp), a figure of the distribution of S wave velocity (Vs), and the ratio Vp/Vs in the vertical plane incision and horizontal plane incision.

Image anomalies obtained by travel time P and S are displayed in the percentage deviation of Vp and Vs the magnitude deviation units are km/s. Value of anomalies deviation of the distribution of P wave and wave-S velocity model lies between -10 to + 10 as shown in **Fig. 5(a)** and **Fig. 5(b)**. In the horizontal plane shown 4 depth that 10 km, 20 km, 30 km, and 40 km. While in the vertical plane shown at the incision area represents the number of earthquakes on the Japan region in the case of this study is to slice 1 and 2 are shown in **Fig. 6** and **Fig. 7**. In **Fig. 8** and **Fig. 9** are also shown for the absolute velocity of P wave and S wave.



(a)

(b)

Fig. 5. Distribution of (a) P wave velocity (b) S wave velocity anomalies in the horizontal incision tomogram. From the top and from left to right respectively at a depth of 10 km, 20 km, 30 km, and 40 km.

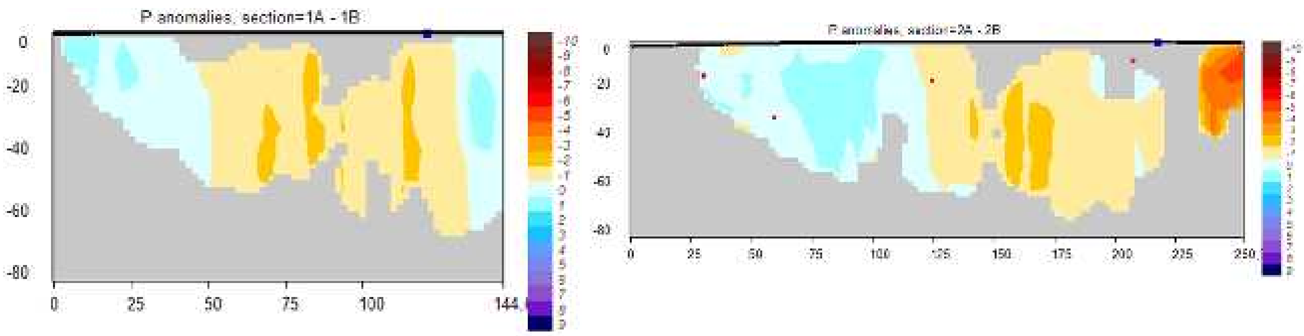


Fig. 6. Anomaly P wave velocity in the vertical incision

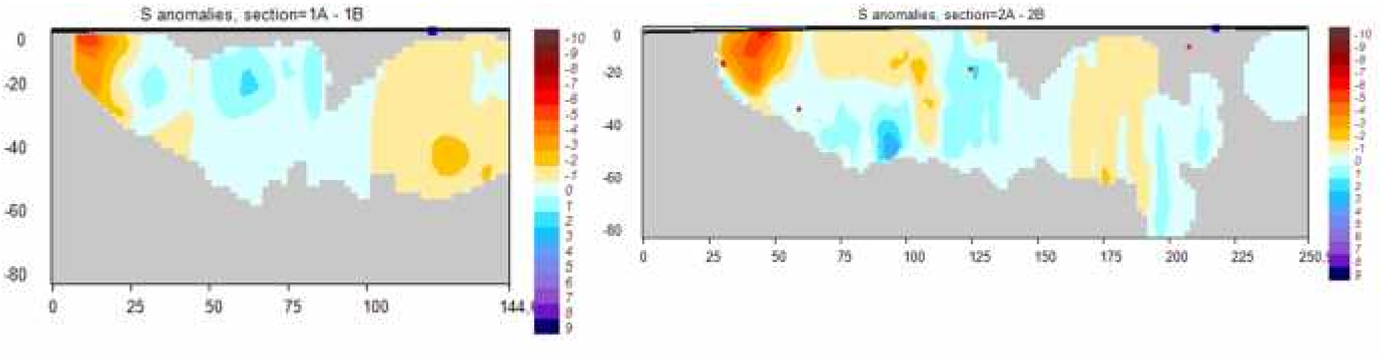


Fig. 7. Anomaly S wave velocity in the vertical incision

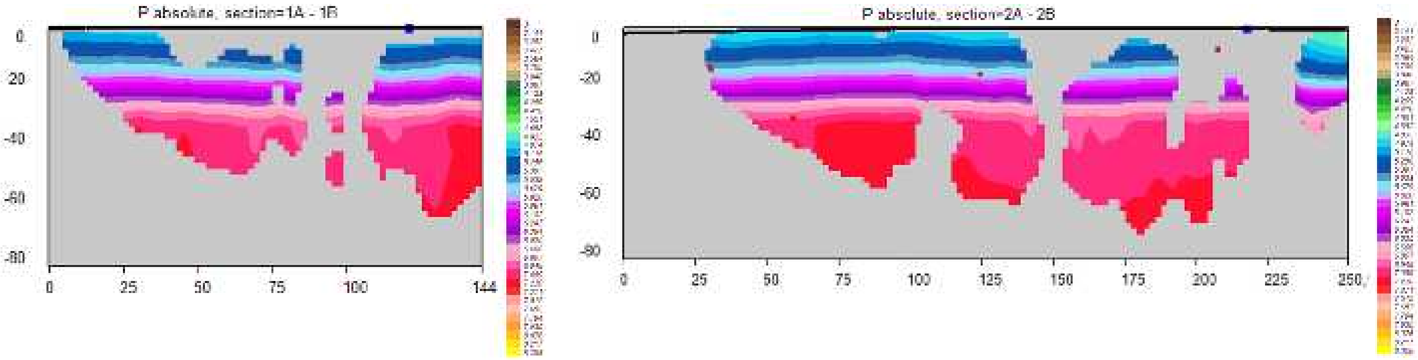


Fig. 8. Absolute anomaly P wave velocity in the vertical incision

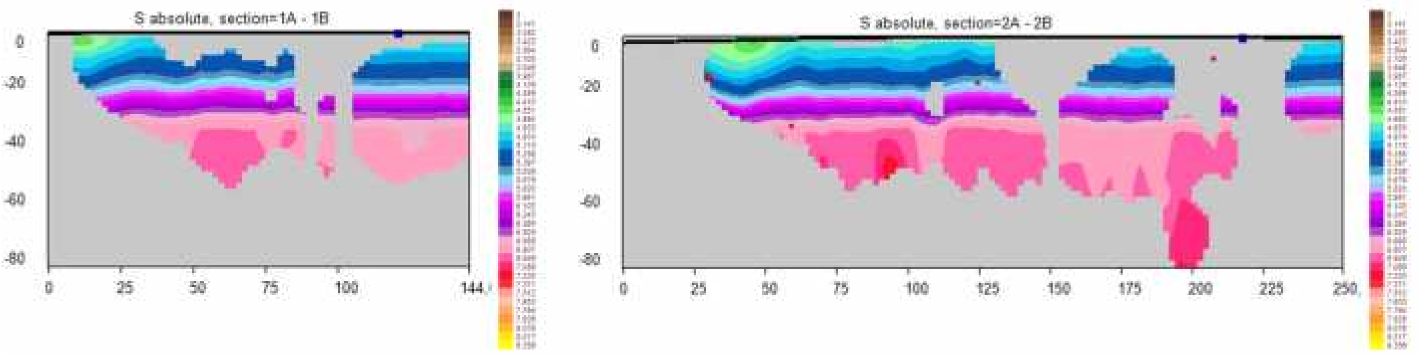


Fig. 9. Absolute anomaly S wave velocity in the vertical incision

Vp/Vs Structure Analysis

Tomogram image based on the model of the ratio Vp/Vs shown without units, the value of the ratio Vp/Vs depends on the estimation of P wave and S wave velocity. This measurement has a range between 1.4 to 1,976. Dark blue color represents the minimum Vp/ Vs ratio and dark red color represents the maximum Vp/Vs ratio, this applies to both areas of incision, the horizontal plane and the vertical plane. High value of Vp/Vs often associated with cracks in rocks containing fluid and high levels of water saturation. While the low Vp/Vs ratio associated with dry rocks are filled by gas. Rock which contain a lot of fluid will cause pore pressure changes that will lead to cracks and further contribute to earthquakes.

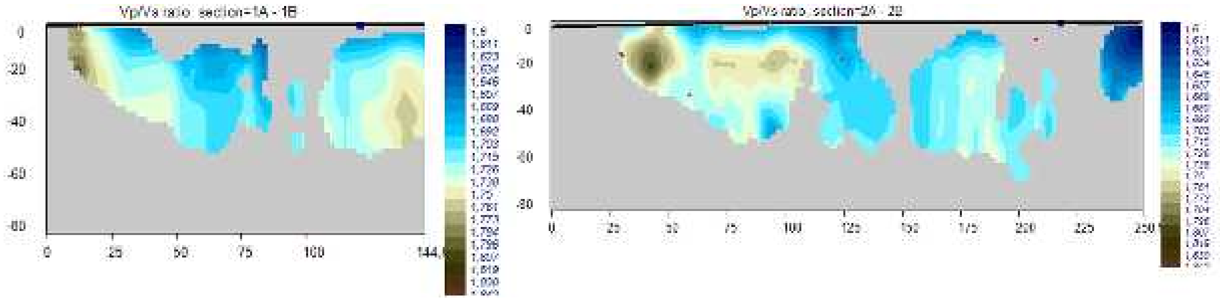


Fig. 10. Anomaly distribution of the ratio Vp/Vs in the vertical incision

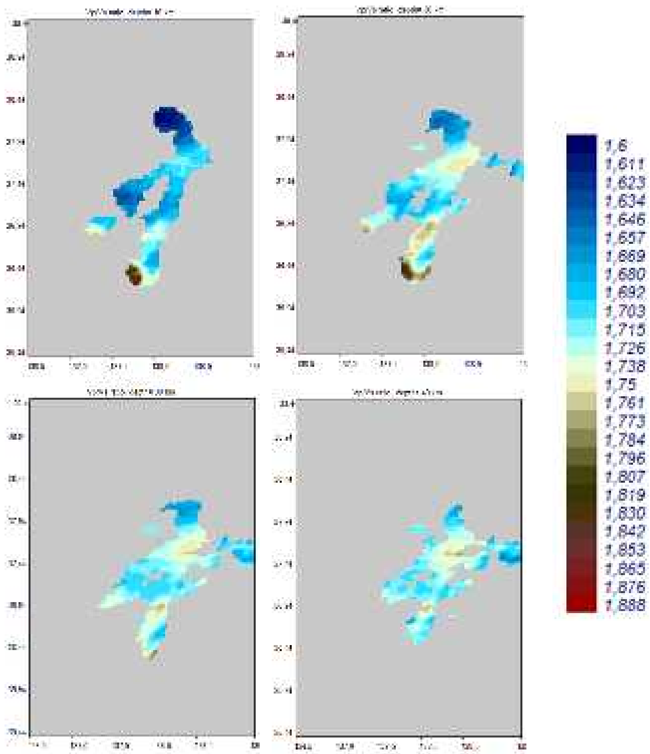


Fig.11. Anomaly distribution of the ratio Vp/Vs in the horizontal incision

Based on the tomogram image generated on the horizontal plane, in the area near the surface has a high value of the ratio Vp/Vs when compared to the deeper areas. At a depth of 10 km, the value of the minimum ratio Vp/Vs is 1,6 and the value of the maximum ratio Vp/Vs is 1,899. Meanwhile, at depth of 20 km, the minimum ratio Vp/Vs is 1,646 and the value of the maximum ratio Vp/Vs is 1,865. At depth 30 km, the minimum ratio Vp/Vs is 1,680 and the value of the maximum ratio Vp/Vs is 1,761. And at depth 40 km, the minimum ratio Vp/Vs is 1,692 and the value of the maximum ratio Vp/Vs is 1,761. The existence of weak areas such as faults or subsurface structures result of tectonic activity. Low anomaly shows a tendency surrounded by the earthquake hypocenter.

CONCLUSION AND SUGGESTION

Based on the discussion in the previous chapters of this research tomography in Japan region can be drawn some conclusions as follows:

1. There are 77 earthquakes in Japan with a magnitude above 4.7 and the number of picking waves as much as 1293 waves.
2. P wave velocity (Vp) and S wave velocity (Vs) in some parts of the Earth are as follows:
   - In the upper crust Vp approximately 5,961 km/s and Vs of about 5,115 km/s,
   - At the bottom crust Vp approximately 6,666 km/s danVs about 5,961 km/s, and
   - In the upper mantle Vp approximately 7,371 km/s and Vs 6,666 km/s.
3. Anomaly Vp/Vs Low indicates a tendency surrounded by the earthquake hypocenter indicated by the area near the surface has a high value of the ratio Vp/Vs when compared to the deeper areas. At a depth of 10 km, the value of the minimum ratio Vp/Vs is 1,6 and the value of the maximum ratio Vp/Vs is 1,899. Meanwhile, at depth of 20 km, the minimum ratio Vp/Vs is 1,646 and the value of the maximum ratio Vp/Vs is 1,865. At depth 30 km, the minimum ratio Vp/Vs is 1,680 and the value of the maximum ratio Vp/Vs is 1,761. And at depth 40 km, the minimum ratio Vp/Vs is 1,692 and the value of the maximum ratio Vp/Vs is 1,761.
4. In the 3D image obtained by the variation of Vp and Vs anomalies around the southern part of Japan region, which tend to have a negative anomaly because in that area there are three plates such as Eurasian plate, Philippine Sea, and the western Pacific ocean plate.

REFERENCES

[1] Iyer, H.M. dan Hirahara, K.. 1993. *Seismic Tomography: Theory and Practice.* Cambridge: Cambridge University Press.

[2] Koulakov I.. 2009. “LOTOS Code for Local Earthquake Tomographic Inversion. Benchmarks for testing tomographic algorithms”. *Bulletin of the Seismological Society of America*, Vol. 99, No. 1, pp. 194-214.

[3] Koulakov I, dan S.V. Sobolev. 2006. “A Tomographic Image of Indian Lithosphere Break-off beneath the Pamir Hindukush Region”. *Geophys.Journ.Int.*,164, p.425-440.

[4] Lo, Tien-when dan Inderwiesen, Philip L.. 1994. *Fundamentals of Seismic Tomography*. Society of Exploration Geophysicists.

[5] Paige, C.C., dan M.A. Saunders. 1982. “LSQR: An Algoritm for Sparse Linear Equations and Sparse Least Squares”. *ACM Trans. Math. Soft.*, 8, 43-71.

[6] Waldhauser, F. & Ellsworth, W.L. 2000. *A Double Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California*. Bull. Seism. Soc. Am., 90(6), 1353-1368.