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Three-Dimensional Seismic Velocity Structure under Taiwan

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ABSTRACT

Taiwan has a strong seismic activity and many disastrous earthquakes occurred in the past. In the 20th century, disastrous earthquakes in this region have caused great damage to human lives. With large number of earthquakes in and around Taiwan, it is thus important to analyze the seismic velocity structures beneath Taiwan Island for the purposes of future earthquake hazard evaluation. Seismic tomography is an imaging technique that uses seismic waves generated by earthquakes and explosions to create computer-generated, three-dimensional images of Earth's interior. Tomography images show the detail of velocity structure under Taiwan. Between January 2009 and December 2010 there are 98 events that have magnitude greater than 4.7. The data processing steps of seismic tomography are picking of P and S wave using SeisGram2K60, hypocenter relocation using Hypo71, and tomography inversion using LOTOS-12. Along the Ryukyu trench is dominated by positive anomaly of *Vp* and high structure of *Vp/Vs* that indicates the high seismicity in this region. Negative anomaly and high seismicity in the Central Range related to active fault zone, Lishan Fault. This feature might have resulted from the heat intrusion from the oceanic upper mantle of the Philippine Sea plate. Neogene sedimentary rocks in the Western Foothills are characterized by negative anomaly of *Vp* and Vs, and low structure of *Vp/Vs*.

Keywords: Earthquake; Taiwan; Tomography.

1. Introduction

Taiwan is located in the western portion of the Pacific Rim seismic belt. In the east, the Philippine Sea plate subducts northward under the Eurasian plate along the Ryukyu trench. Off the southern tip of Taiwan, the Eurasian plate, subducts eastward under the Philippine Sea plate (Wu et al., 2007). Taiwan has a high rate of crustal deformation, a strong seismic activity, and many disastrous earthquakes occurred. These damaging earthquakes can be divided into two general classes: earthquakes due to the subduction between the Philippine Sea plate and the Eurasian plate, and the ones associated with active faults on the main island.

Earthquakes are sudden rolling or shaking events caused by movement under the earth's surface. Earthquakes happen along cracks in the earth's surface, called fault lines (Web1). In the 20th century, disastrous earthquakes in Taiwan have caused great damage to human lives. These damaging earthquakes can be divided into two general classes: earthquakes due to the subduction of the Philippine Sea plate northward under the Eurasian plate and the ones associated with active faults on the main island. With large number of earthquakes in and around Taiwan, it is thus important to analyze the seismic velocity structures under Taiwan Island to recognize background seismicity in the Taiwan region for the purposes of future earthquake hazard evaluation.

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A technique to develop images of individual slices through the deep Earth called seismic tomography (Web2). Seismic tomography is one of the main techniques to constrain the three-dimensional (3-D) distribution of physical properties that affect seismic-wave propagation (Thurber and Ritsema, 2007). Seismic tomography itself is divided into two types of modeling, 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.

Inversion is accomplished using a tomographic algorithm, LOTOS (Local Tomography Software) is designed for simultaneous inversion for P and S wave velocity structures and source coordinates. By using this software, is expected to obtain the tomographic imaging of the subsurface structure of Taiwan region in detail.

2. Data and Methods

The data used in this study was downloaded from IRIS catalog (Web2). The events are from seismic station networks in Taiwan region during 1 January 2009 – 31 December 2010, which are located inside the study region of 21.29° – 25.36°N and 119.89° -125.51°E. There are 98 events which have magnitude greater than 4.7. The distribution of events and stations used in this study is shown in Fig.1 and Fig.2.

Figure 1. The distribution of stations

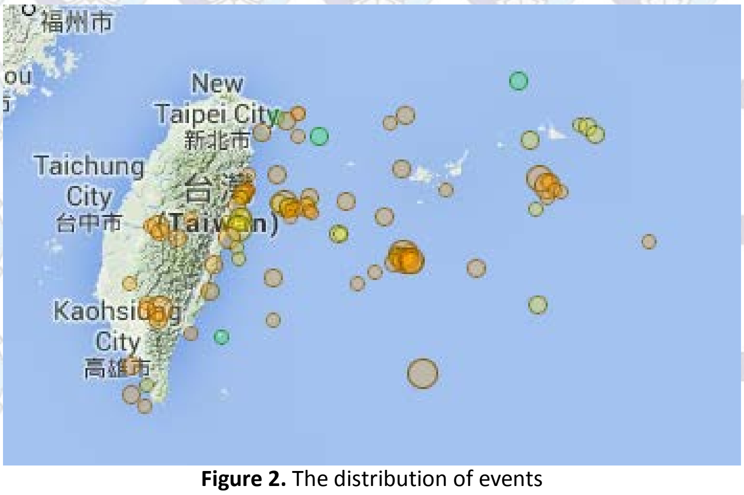

Figure 2. The distribution of events

First, pick all the arrival time of P and S wave manually using SeisGram2K60 software and re-determine locations of earthquake using HYPO71. The program is utilizes the Geiger iterative method, also known as the Single Event Determination (SED) technique. One of the input data that is needed by HYPO71 is initial 1-D velocity model. The initial 1-D velocity model that is used in this study is shown in Table 1. The initial models generally agree with the 1-D horizontally layered P and S wave velocity models that were proposed by Shin and Chen (1988) and used currently by the Central Weather Bureau for routine event locations (Wu et al., 2007).

Table 1. Initial models of *Vp* and *Vp/Vs* ratio.

Depth (km)	*Vp* (km/s)	*Vp/Vs* ratio
0	3,90	1,87
2	4,64	1,76
4	5,17	1,72
6	5,22	1,71
9	5,64	1,71
13	6,02	1,73
17	6,30	1,74
21	6,58	1,74
25	6,74	1,74
30	7,11	1,74
35	7,52	1,74
50	7,98	1,73
70	8,25	1,75
90	8,28	1,72
110	8,38	1,73
140	8,40	1,74
200	8,70	1,74
700	9,00	1,73

Source: Wu et al., 2007

The basic principle of seismic tomography is imaging subsurface area of research in the domain of velocity. Inversion is accomplished using a tomographic algorithm, is designed for simultaneous inversion for P and S wave velocity structures and source coordinates for imaging of subsurface conditions of earthquake area. LOTOS algorithm can also be easily applied to various sets of data without complicated processing parameters (Koulakov, 2009).

The general structure of LOTOS code is presented in the following flow chart:

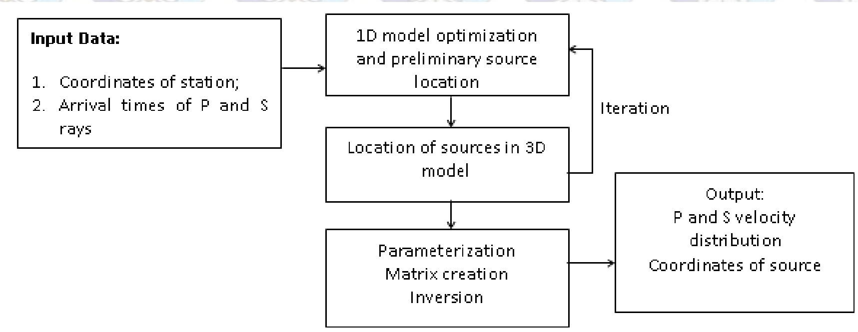

Figure 3. General Structure of LOTOS code (Koulakov, 2009)

The algorithm contains the following general steps:

1. Simultaneous optimization for the best 1D velocity model and preliminary location of sources
2. Location of sources in the 3D velocity model

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3. Simultaneous inversion for the source parameters and velocity model using several parameterization grids.

The steps for the best 1D velocity model and preliminary location of sources are data selection for optimization, calculation of a travel time table in a current 1D model, source location in the 1D model, calculation of the first derivative matrix along the rays computed in the previous iteration which the each element of the matrix A_{ij} is equal to the time deviation along the *j*-th ray caused by a unit velocity variation at the *i*-th depth level, and matrix inversion is performed simultaneously for the P and S data.

After *1D* velocity model and the preliminary location of the source is known to the optimization of *1D* model, and then do relocation with *3D* ray tracing (bending). One of the key features of the LOTOS code is a ray tracing algorithm based on the Fermat principle of travel time minimization. A similar approach is used in other algorithms (Um and Thurber (1987) and is called bending tracing. Then the next step is use a gradient method to obtain the location of the source in the *3D* model. Parameterization method using nodes and algorithms have been done by Koulakov (2009). The first derivative of the matrix A_{ij} is calculated using the ray paths computed after the location of the source has been in the *3D* model. Each element of the matrix, 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. 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.

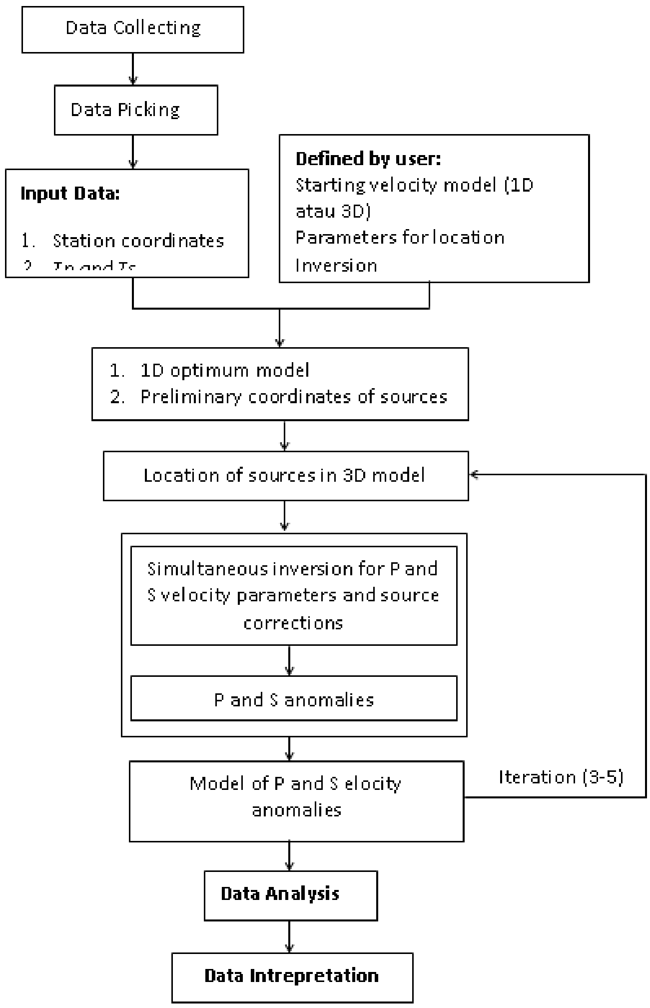

Figure 4. Flow chart of the process of tomography inversion

3. Results and Discussion

3.1 *Hypocenter Relocation*

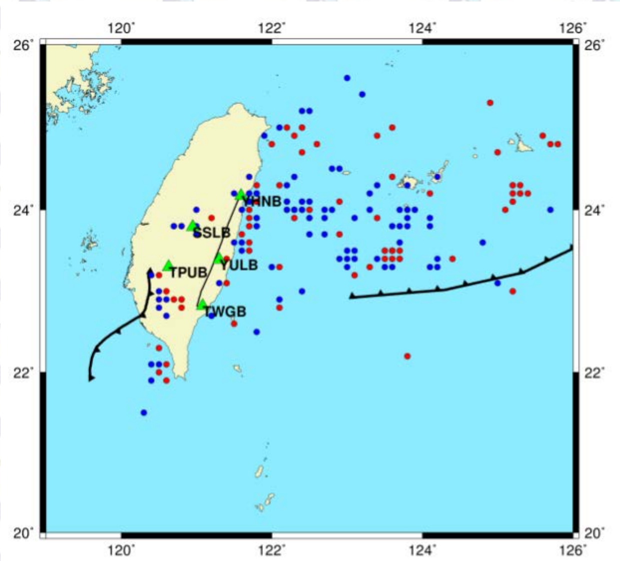

Figure 5. Hypocenter distribution, before (blue dots) and after (red dots) relocation

The relocation of hypocenter shows that the majority of recorded earthquakes are shallow earthquake that occurs at 0-70 km deep. Fig. 5 shows the high seismicity along Ryukyu Trench and Manila Trench. The seismicity along Ryukyu Trench and Manila Trench corresponds to the subduction between Eurasian Plate and Philippine Sea Plate. The high seismicity inland corresponds to the active fault zone, Lishan Fault and Lichi Melange. The Lishan Fault separates the Hsuehshan terrane from the Central Ranges and has previously been interpreted as a normal fault. The other major fault zone and source of much dispute is the Longitudinal Valley which separates the Central Range from the Coastal Range in eastern Taiwan. A recent analysis of the Lichi Melange in this valley was completed by Chang et al. (2000).

The distribution of hypocenter from our relocation largely agrees with that obtained in previous studies. The zones of highest background seismicity rates correspond to the zones of high stress accumulation on the tectonic boundaries, such as the large transfer fault zones along the eastern part of Longitudinal Valley and the northern region of the Ryukyu trench, beneath which lies the boundary of the Eurasian plate and the subducting Philippine plate (Zhuang et al., 2005).

3.2 *Analysis of 3D Velocity Distribution*

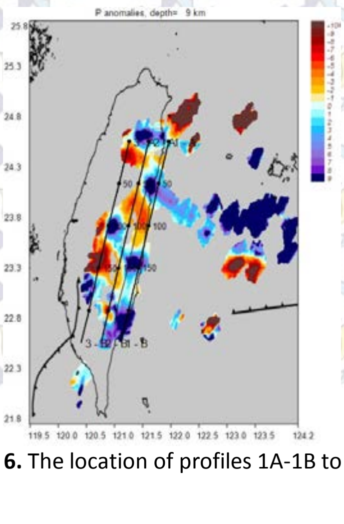

Figure 6. The location of profiles 1A-1B to 2A-2B

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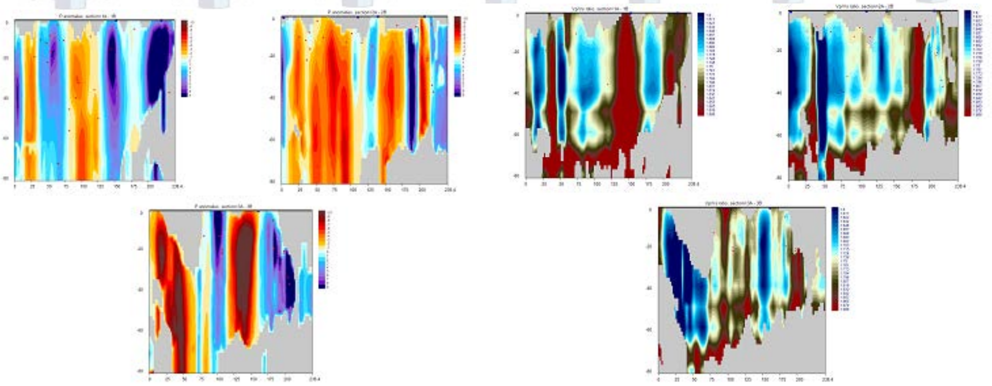
After two iteration of inversion there are 93 events with the number of P and S wave respectively 633 and 625 waves. This inversion result the images of *Vp* and *Vs/Vs* anomaly in horizontal and vertical section. Horizontal section is represented by 9 different depths, 9 km, 13 km, 17 km, 21 km, 25 km, 30 km, 35 km, 50 km, and 70 km as shown in Fig. 8 and Fig. 9. While the vertical section is represented by 3 profile of 1A-1B to 3A-3B, as shown in Fig. 6 and Fig. 7. The value of *Vp* anomaly is about -10% to 10%. The *Vp/Vs* ratio is an important parameter for analyzing the petrology and rheology of the crust and upper mantle, and could provide more constraints than *Vp* or *Vs* (Li et al., 2009).

The profile of 1A-1B is across The Coastal Range and eastern part of Taiwan. Fig. 7 (a) and (b) show there are negative *Vp* and high *Vp/Vs*. The negative *Vp* and *high Vp/Vs* corresponds to the containing rocks of Luzon arc affinity, both volcanic and young sedimentary rocks in the Coastal Range. This high *Vp/Vs* belt may indicate fluids in the crust, possibly along the major fault zones of the suture (Wu et al., 2007). The high *Vp/Vs* may indicate the material with a low shear modulus (Moos and Zoback, 1983). This profile show that the eastern part of Taiwan dominated by positive *Vp* that clearly reflects the oceanic crust of the Philippine Sea plate.

The profile of 2A-2B is across The Central Range. Negative *Vp* and high seismicity in this region is correspond to the active fault zone, the Lishan Fault. The Lishan Fault has previously been interpreted as a normal fault. The existence of this feature might be due to heat intrusion from the oceanic upper mantle of the Philippine Sea plate, which is colliding with the Eurasian plate, and to the effect of partial melting (Ma et al., 1996).

The profile of 3A-3B is across Western Foothills. Fig. 7 (a) and (b) show there are negative anomaly of *Vp* and low *Vp/Vs* that show Western Foothills is consist of Neogen sedimentary rock. The seismicity in this profile is lower than the seismicity in the profile of 1A-1B and 2A-2B. It is agree with the previous study by Rau et al (1995) that find the number of earthquake in Western part of Taiwan is less than the others.



(a) (b)

Figure 7. (a) *Vp* profiles **(b)** *Vp/Vs* profiles

In the horizontal section, in shallow depth (<10 km deep) was found the negative anomaly of *Vp* and low *Vp/Vs* that indicates the existing of Neogene sedimentary rock in Western Foothills.

Negative anomaly of *Vp* also found in the northern part of Taiwan at the depth of 9 km to 35 km. It is agree with Ma et al. (1996) that show the negative anomaly is probably related to the Tatun and Chilungshan volcanic groups. Hasegawa et al. (1993) showed that the active volcanic regions are generally underlain by low-velocity zones. A low-velocity zone in the northern part of Taiwan is probably related to this geothermal effect, which reduces the P wave velocity.

High *Vp/Vs* was found in Coastal Range at the depth of 13 km to 30 km that indicate fluids in the crust at depth, possibly along the major fault zones of the suture, Longitudinal Valley.

Longitudinal Valley is suture zone between Central Range and Coastal Range. A very sharp boundary between high and low Vp coincides with the Longitudinal Valley in eastern Taiwan. High

Vp to the east of this boundary clearly reflects the oceanic crust of the Philippine Sea plate. The Central Ranges west of this boundary, however, has much lower *Vp*. This indicates clearly that a fundamental material difference exists between the oceanic Philippine Sea plate and the basement of the Central Ranges. The significant difference in *Vp* across the Longitudinal Valley supports the notion that the valley is a major suture zone (Wu et al., 2007).

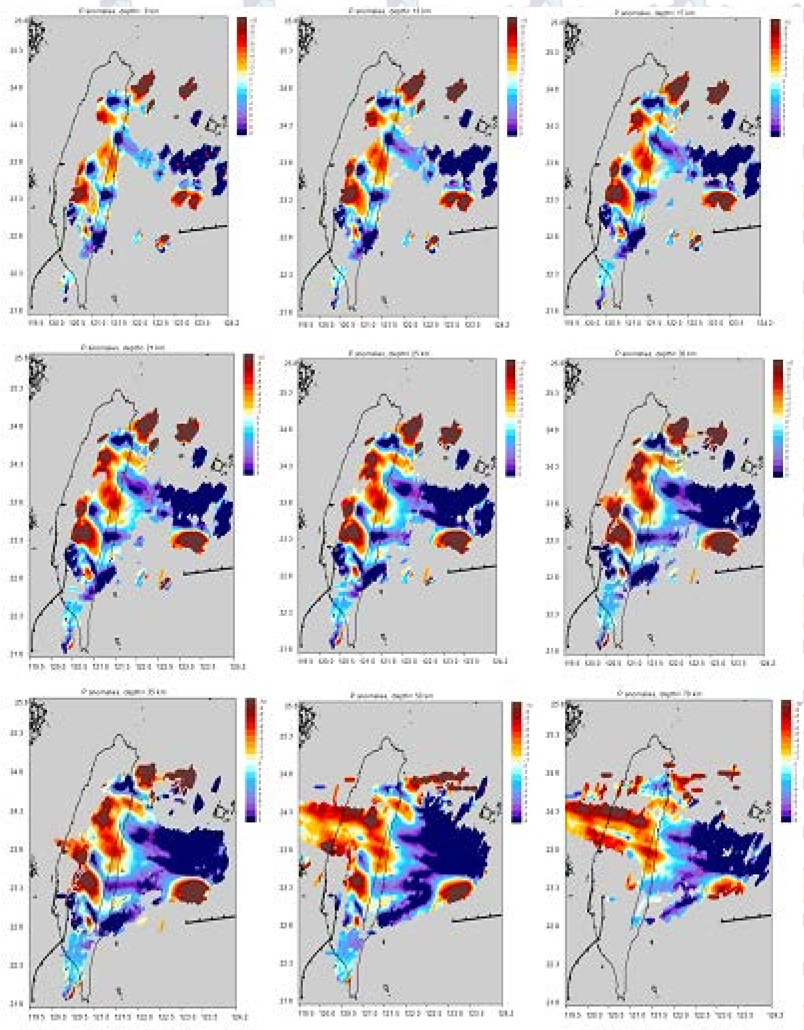


Figure 8. *Vp* perturbation maps at nine different depths; 9 km, 13 km, 17 km, 21 km, 25 km, 30 km, 35 km, 50 km, and 70 km. Blue and red show high and low velocity, respectively.

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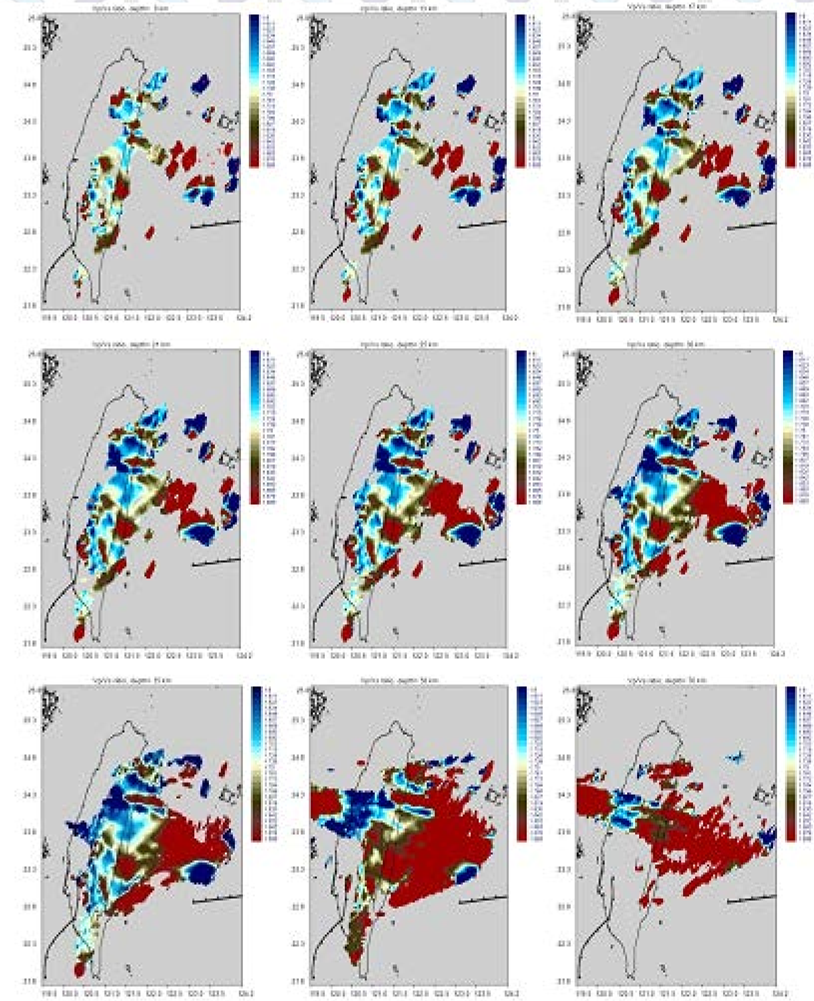

Figure 9. *Vp/Vs* perturbation maps at nine different depths; 9 km, 13 km, 17 km, 21 km, 25 km, 30 km, 35 km, 50 km, and 70 km. Blue and red show high and low velocity, respectively.

4. Conclusion and Remarks

The eastern part of Taiwan was dominated by positive anomaly of *Vp* reflect the west boundary of Philippine Sea Plate with Longitudinal valley as a suture zone. The negative anomaly of *Vp* and high seismicity in Central Range was correspond to active fault zone, Lishan Fault. This anomaly may indicate heat intrusion from the Philippine Sea plate. Negative anomaly of Vp and low *Vp/Vs* that show Western Foothills is consist of Neogen sedimentary rock. High *Vp/Vs* in Central Range correspond to large amount of young sediments, active fault zone, and may indicate fluids there.

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