

4<sup>th</sup> IASPEI / IAEE International Symposium:

## Effects of Surface Geology on Seismic Motion

August 23–26, 2011 • University of California Santa Barbara

### Shallow S-Wave Velocity Structures of the Tiehchenshan Region in Taichung-Miaoli Area, Taiwan, Using Array Records of Microtremors

#### Huey-Chu Huang

National Chung Cheng University  
168 University Road, Minhsiung  
Township, Chiayi County  
Taiwan, ROC

#### Che-Lun Yang

National Chung Cheng University  
168 University Road, Minhsiung  
Township, Chiayi County  
Taiwan, ROC

#### Cheng-Feng Wu

National Chung Cheng University  
168 University Road, Minhsiung  
Township, Chiayi County  
Taiwan, ROC

#### ABSTRACT

Shear-wave velocities have widely been used for earthquake ground-motion site characterization. Thus, the shallow S-wave velocity structures of the Tiehchenshan region in the Taichung-Miaoli area are investigated using the array records of microtremors at 19 sites. The dispersion curves at these sites are calculated using the  $f-k$  method (Capon, 1969); then, the S-wave velocity structures of the Tiehchenshan region are estimated by employing the surface wave inversion technique (Herrmann, 1991). At frequencies lower than about 3 Hz, the propagation directions are concentrated between the northwest and southwest quadrants. The generation of these may be attributed to the ocean waves of the Taiwan Strait. If the S-wave velocity of the bedrock is assumed to be 2000 m/s, the depths of the alluvium are between 1060 m and 2120 m. S-wave velocity gradually decreases from east to west at the depths less than 1200 m. At the depths between 1200m and 4000m, the higher  $V_s$  values appear at the north and the south of the region while the lower values are at the east and the west. Our results are in good agreement with the available geological and geophysical information at the Tiehchenshan region.

#### SITE AND DATA

The Tiehchenshan region in Taichung-Miaoli area, northwest part of Taiwan, covers the geological area which is located at the edge of the western foothills geological region and the coast region to the west of the foothills (Fig. 1). The basement rock of this area is mainly rocks of Toukoshan Formation, which are partly widely distributed on the surface, whereas part of this Toukoshan formation is concealed under lateritic terrace deposits and alluvial deposits. The western edge of this terrain adjoins the coastal alluvial plain. The regional structures within the area include Tunghsiao Anticline, Tiehchenshan Anticline, Tunglo Syncline, Futoukeng Fault, Tachia Fault, Tapingting fault, Tiehchenshan fault, and Sanyi fault (Chang, 1994).

In order to study the S-wave velocity structure of this area, array measurements of microtremors are carried out at 19 sites, as shown in Fig. 1. We use seven observation points in each array deployment and four array measurements of different size (M, L, X and D) at each site. Here, we take site JEP as an example. Figure 2 shows the array configurations in both the M and D sizes at the site. The central station (No. 1) is fixed for all of the arrays which are M (radius=100m), L (radius=200m), X (radius=400m) and D (radius=800m) arrays. The configuration of these seven stations is in the form of two different-aperture triangles around the central station. The vertical velocity recordings of M array at JEP are shown in Fig. 3. Clearly, waveforms are similar to each other especially among the closer stations.

#### ANALYSIS METHOD

##### Method of F-K Spectral Analysis

The power spectrum at frequency  $f$  and vector wavenumber  $k$  for an array of  $N$  sensors by MLM (Capon, 1969) is given by

$$P(f, k) = \left[ \sum_{i, j=1}^N \phi_{ij}^{-1}(f) \exp(i k \cdot \vec{r}_{ij}) \right]^{-1} \quad (1)$$

where

$N$  = number of sensors.

$\phi_{ij}(f)$  = cross-power spectrum between  $i$ th and  $j$ th sensors at frequency  $f$ .

$\vec{r}_{ij} = \vec{r}_j - \vec{r}_i$  ( $\vec{r}_i$  and  $\vec{r}_j$  are the position vectors of the  $i$ th and  $j$ th sensors).

### Inversion of Velocity Structure

The discrete generalized inversion method has been applied to determine the S-wave velocity structure. The problem is written as

$$Y = AX \quad (2)$$

The vector  $Y$  of length  $n$  corresponds to the difference between the measured phase velocities and the calculated ones for the initial model. The vector  $X$  of length  $m$ , which is the solution to be sought, corresponds to the first order correction to an initial model. Here we use the surface wave inversion method (Herrmann, 1991) to inverse the S-wave velocity structure.

## RESULTS AND DISCUSSION

### F-K Analysis of Microtremor Array Data

We estimate phase velocities by  $f$ - $k$  spectral analysis based on the Maximum Likelihood Method (Capon, 1969). Figure 4 shows examples of  $f$ - $k$  spectra for four different size arrays using the records observed at JEP. The  $f$ - $k$  spectra are calculated at  $51 \times 51$  grid points at each frequency. This figure presents the  $f$ - $k$  spectra at 2.73Hz, 1.66Hz, 0.98Hz and 0.49Hz from the records observed by the M-, L-, X- and D-arrays, respectively. The propagation direction ( $\theta$ ) is measured clockwise from the north in degrees. We estimate the phase velocity ( $V$ ) in km/sec from the maximum peak in the  $f$ - $k$  spectrum.

Figure 5 shows propagation directions estimated from the  $f$ - $k$  spectra at frequency ranges of (a) 0.2-1.0 Hz, (b) 1.0-2.0 Hz and (c) 3.0-5.0Hz at all 19 sites. At frequencies lower than about 3Hz (Fig. 5(a) and 5(b)), propagation directions are concentrated between the northwest and southwest (azimuth:  $-45^\circ \sim -135^\circ$ ), which may be attributed to the effects of the Taiwan Strait on the coast. When the frequency becomes higher (Fig. 5(c)), propagation directions are relatively scattered. Through on-site inspections, this result is consistent with traffic sources and human activity.

The phase velocity can be estimated from the frequency and the wavenumber of the maximum peak in the  $f$ - $k$  spectrum. In Fig. 6, we present phase velocities obtained from recordings observed at all the arrays. Apparently, the estimated phase velocities vary from site to site. Sites RHU and CHC have higher phase velocities while YOA site has lower phase velocities at frequencies less than 2 Hz.

### Inversion of S-Wave Velocity Structure

We invert S-wave velocity structures using the Herrmann's technique (1991). Figure 7 shows the estimated S-wave velocity structures by the differential inversion technique at all the sites. If the S-wave velocity of the bedrock is assumed to be 2000 m/sec, the alluvial thickness overlying on the bedrock of the Taichung-Miaoli area is between 1060m (RHU) and 2120m (YOA). Compared with other sites, YOA has lower S-wave velocities at depths less than 2500m and thicker alluvium.

To understand the variation of the shallow S-wave velocity at the study area, we show the contours of S-wave velocity at the depths of 300-4000m in Fig. 8, based on the results of Fig. 7. This indicates that the lateral heterogeneity exists there, and velocities change with depths. The results are stated as:

- (1) 300-1000m depth: The higher S-wave velocities appear at the eastern part of the area while the lower velocities are at the southwestern part. The S-wave velocity gradually decreases from east to west.
- (2) 1200-2000m depth: The higher velocities appear at the north and south parts of the area.

(3) 2200-3000m depth: The higher velocities (WME, PYU and CHI) appear at the north and south parts of the area while the lower ones (CHC and YOA) are at the east and west parts of the area.

(4) 3200-4000m depth: The higher velocities (ZTO) appear at the north part of the area while the lower ones (CHC) are at the east part.

The above results are consistent with their shallow geology and geological structures (Tunghsiao Anticline, Tiehchenshan Anticline and Tunglo Syncline).

#### Comparison of the S-Wave Velocity Structures

Furthermore, in order to examine the validity of the shallow velocity structures inverted from the microtremor array records, we compare our results with those from the seismic exploration method (Wu, 2010) as shown in Fig. 9. According to Wu (2010), Fig. 9(a) presents contour map of depth variations of subsurface structures at the top of Chinshui Shale of the Tiehchenshan region. Apparently, one zone with shallower depths (about 1500m) appear at the Tunghsiao Anticline while another one (about 1300m) is located at the Tiehchenshan Anticline. Based on Fig. 7, we show the contour map of the depth variations at the velocity of 2200 m/sec in Fig. 9(b). There are two zones with shallower depths located at the north and south parts of the area, respectively, while one zone with deeper depths appears at the southeast part of the area. Besides,  $V_s$  contour map at the depth of 2000 m is superimposed with Fig. 9(a) and shown in Fig. 9(c). Obviously, two zones with higher velocities in this study can match well with those with shallower depths from Wu (2010). Therefore, the microtremor array measurements can provide a good alternate to investigate subsurface structures.

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## Geology of Miaoli & Taichung

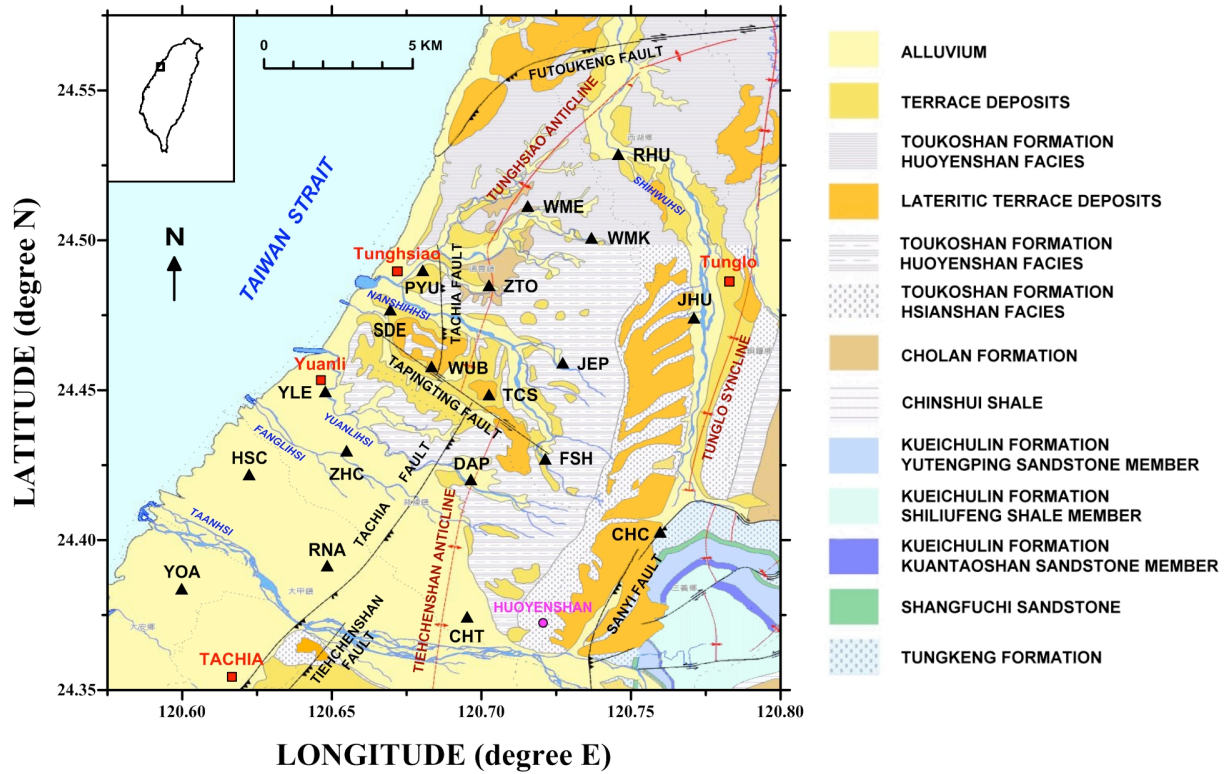


Fig. 1. Geological map of the Tiehchenshan region in the Taichung-Miaoli area superimposed with the 19 used sites. Black triangles denote the sites of the microtremor array measurements. (modified from Chang, 1994)

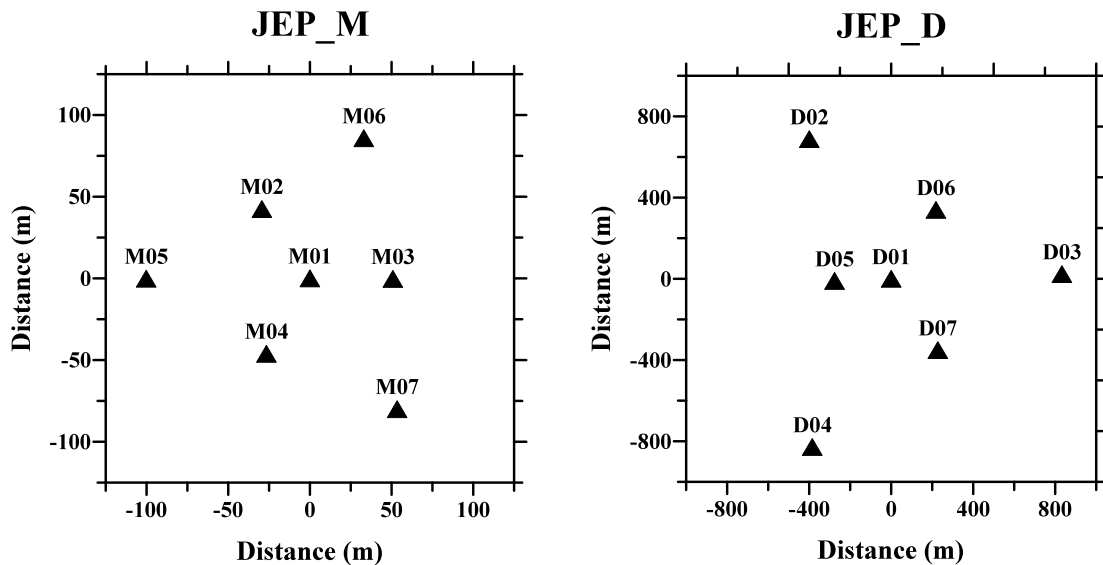


Fig. 2. Array configuration of M and D arrays at JEP site.



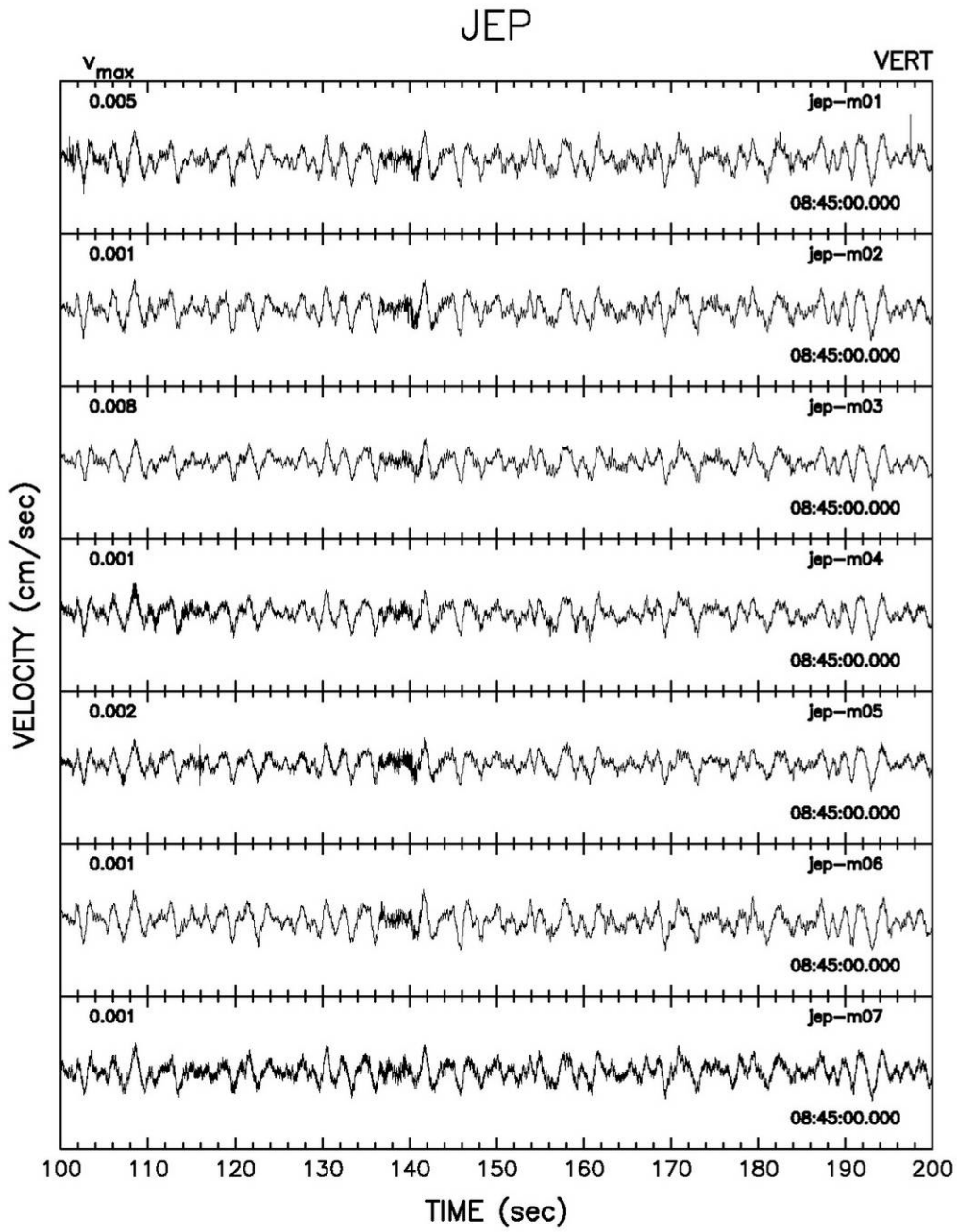


Fig. 3. Vertical component of velocity recordings of one time segment for M array at JEP site.

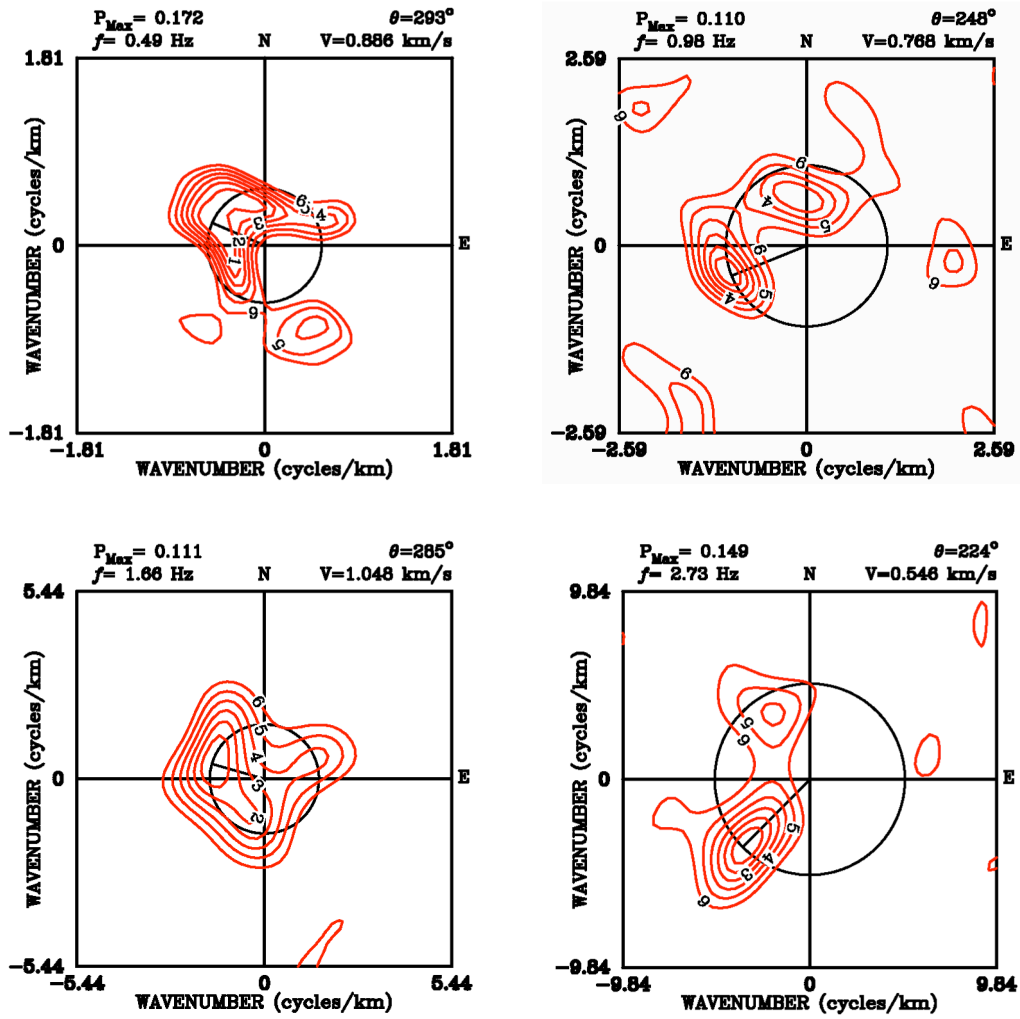
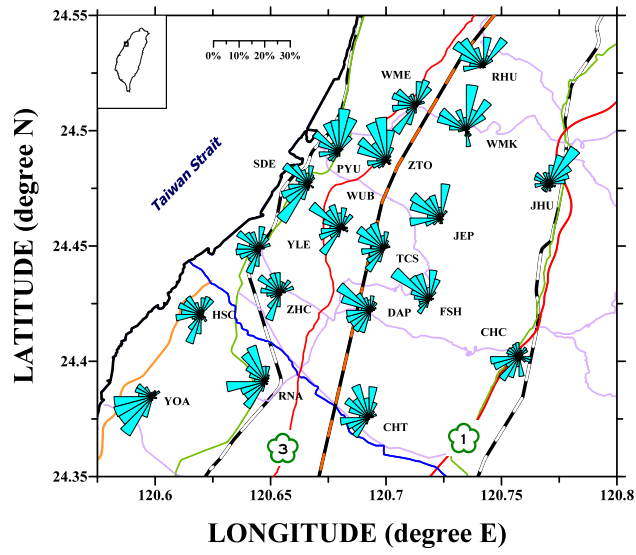
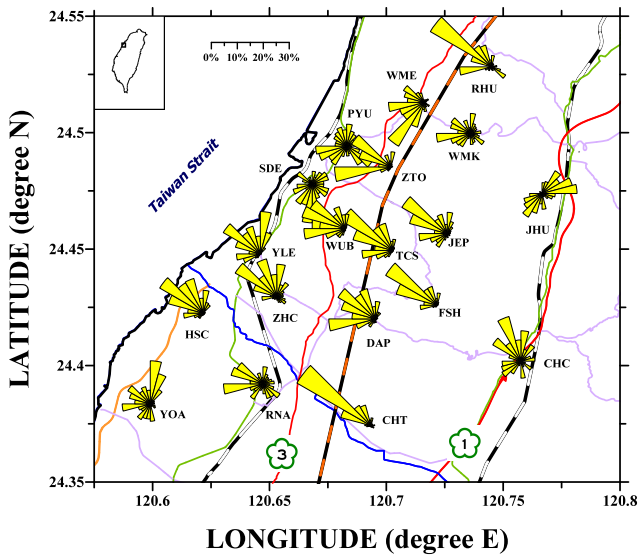


Fig. 4. The  $f$ - $k$  spectra plots of four different frequencies: 0.49, 0.98, 1.66, and 2.73 Hz are calculated from microtremors records observed by D, X, L, and M arrays, respectively, at site JEP.

(a) **Propagation Directions**  
**0.2~1.0 Hz**



(b) **Propagation Directions**  
**1.0~3.0 Hz**



(c) **Propagation Directions**  
**3.0~5.0 Hz**

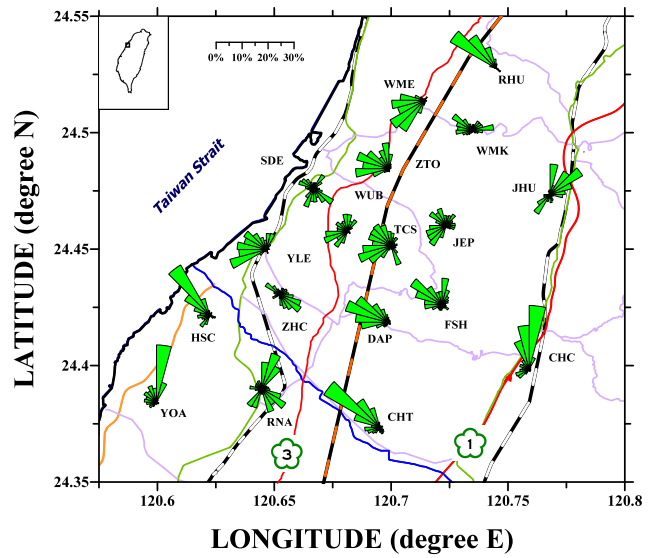


Fig. 5. Propagation directions estimated from the  $f$ - $k$  spectra at frequency ranges of (a) 0.2-1.0 Hz, (b) 1.0-2.0 Hz and (c) 3.0-5.0 Hz at all 19 sites.

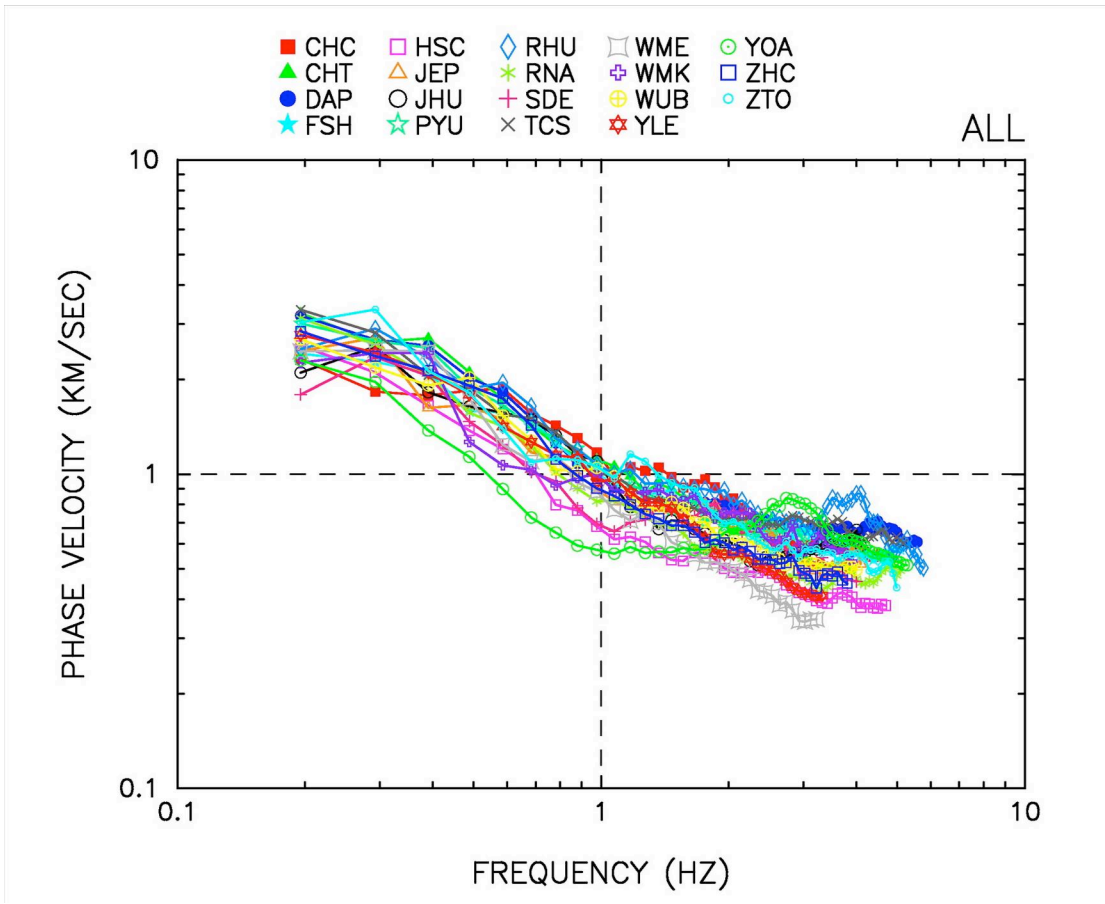


Fig. 6. Phase velocities obtained from the records observed at all 19 arrays. The estimated phase velocities vary from site to site.

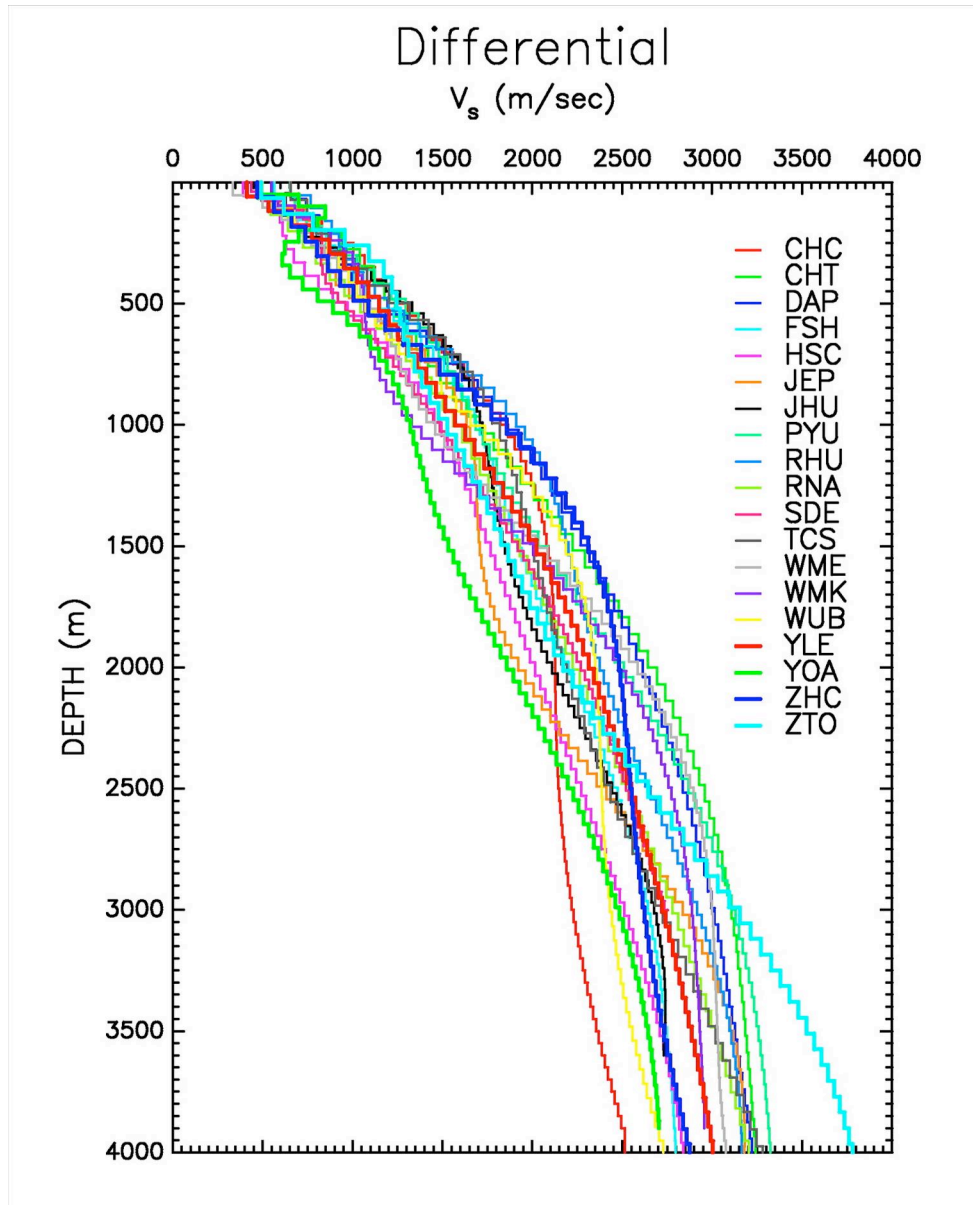


Fig. 7. Estimated S-wave velocity structures by the inversion technique (Herrmann, 1991) at 19 sites.

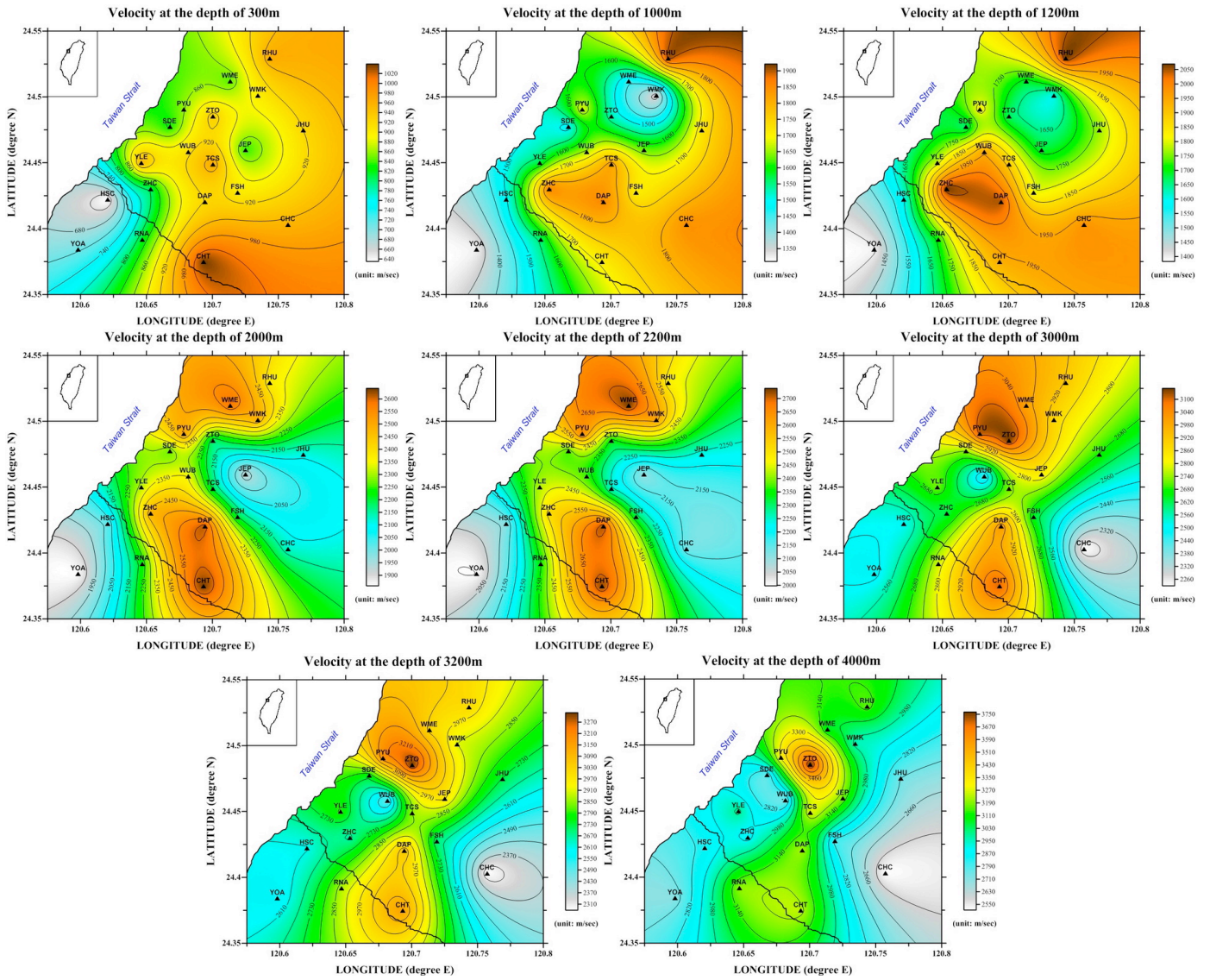


Fig. 8. Contour maps of the S-wave velocity variations of the Tiehchenshan region at the depths between 300 m and 4000 m.



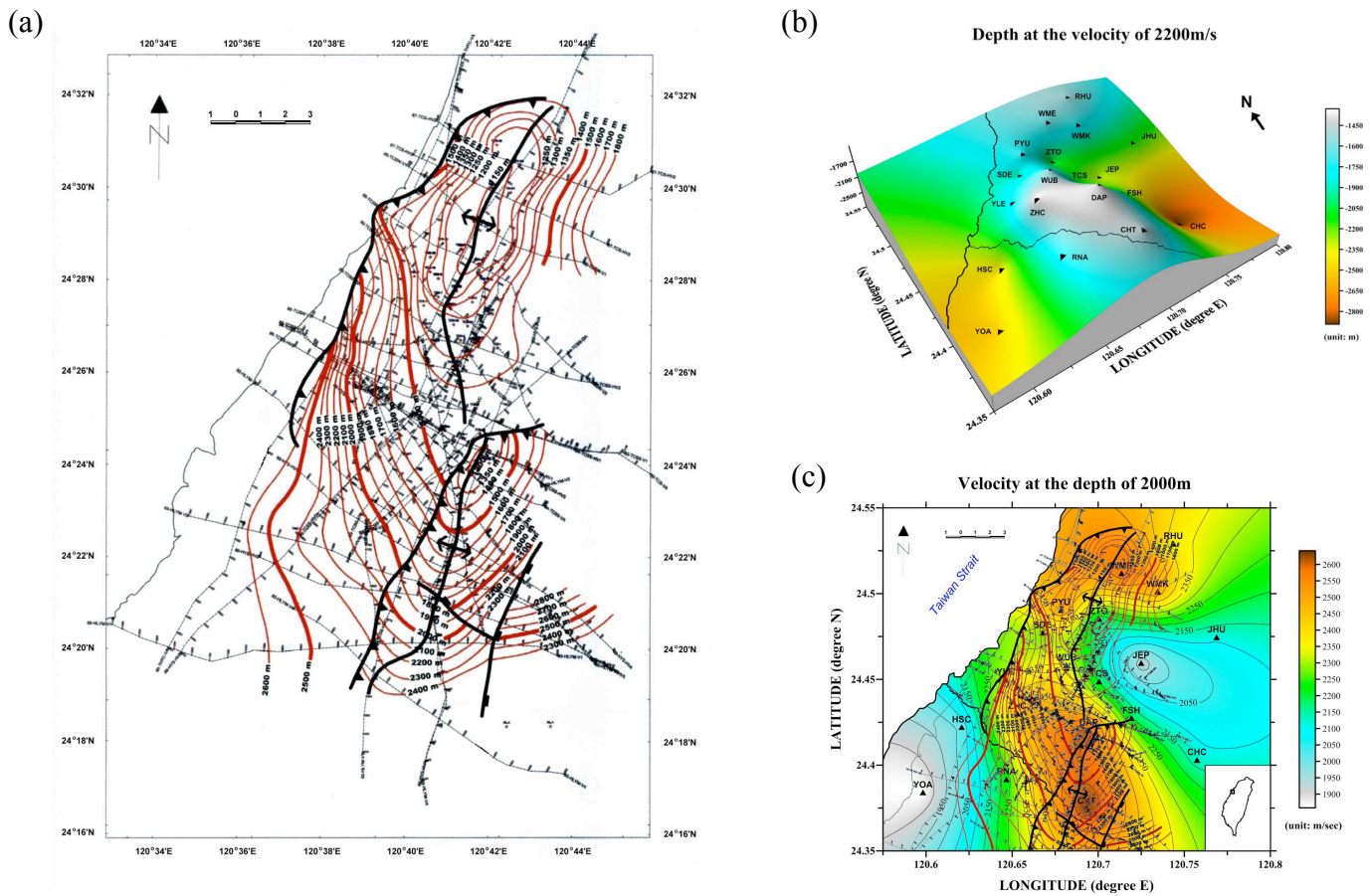


Fig. 9 Comparison of the velocity structures between this study and Wu (2010). (a) Contour map at the top of Chinshui Shale of the Tiehchenshan region (Wu, 2010); (b) Contour map of the depth variations at the velocity of 2200 m/sec; (c)  $V_s$  contour map at the depth of 2000 m is superimposed with (a).

**For additional information or clarification, please contact:**

Huey-Chu Huang  
 Department of Earth and Environmental Sciences  
 National Chung Cheng University  
 168 University Road, Minhsiung Township, Chiayi County Taiwan, ROC  
 Phone: 886-5-272-0411#66207  
 FAX: 886-5-272-0807  
 E-mail: seihuey@eq.ccu.edu.tw