Estimations of Shallow S-Wave Velocity Structures Using Microtremor Array Measurements and Their Applications

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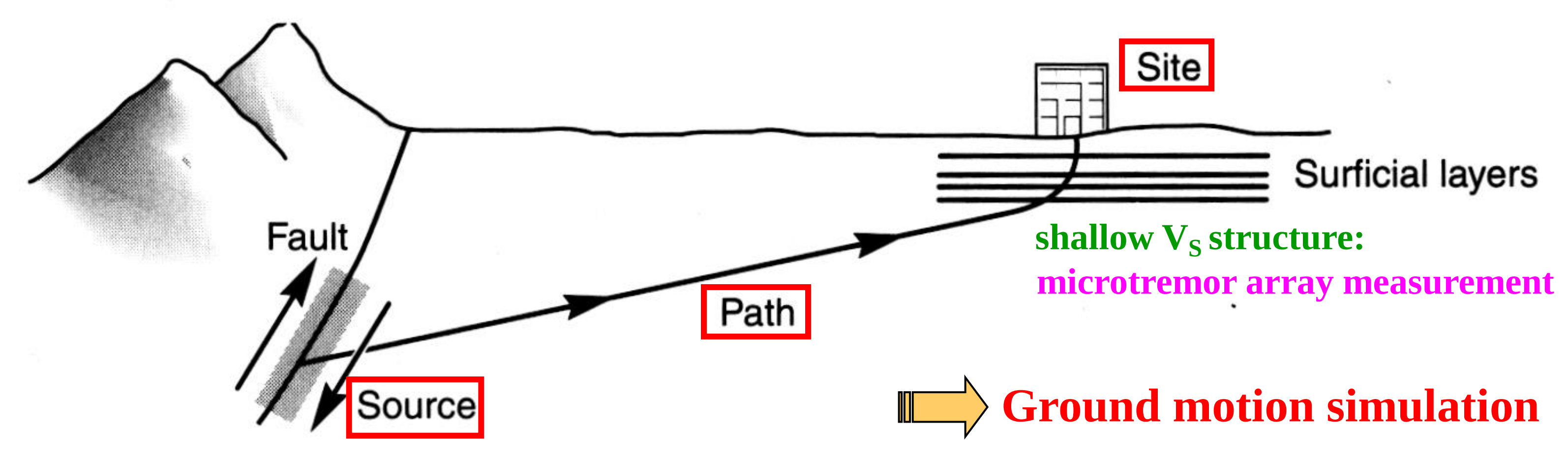
Motivations

- Factors for affecting ground motions include
  source effect, path effect and site effect.
- Shallow velocity structure is very important!
  According to damage patterns of famous large earthquakes (e.g. 1985 Mexico EQ, 1995 Kobe EQ, 1999 Chi-Chi EQ, etc.), surficial geology could affect ground motion seriously and cause heavy damage.
- Reliable shallow V_S structure is still lacking.
- Purpose: site effect study & ground motion simulation.



shallow V_S structure:
microtremor array measurement

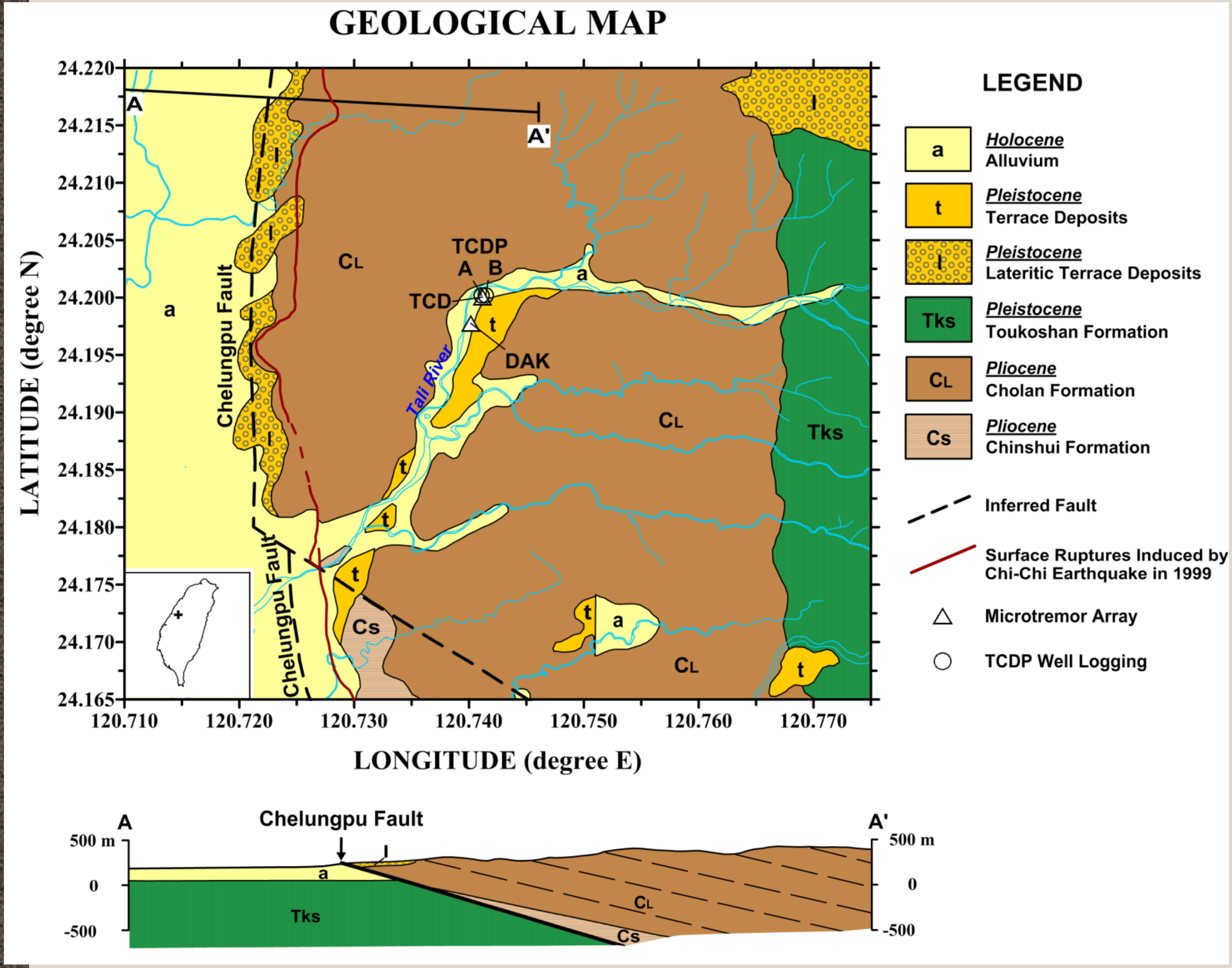
Ground motion simulation

Contents

S-wave velocity structure of the Taiwan Chelungpu Fault Drilling Project (TCDP) site using microtremor array measurements

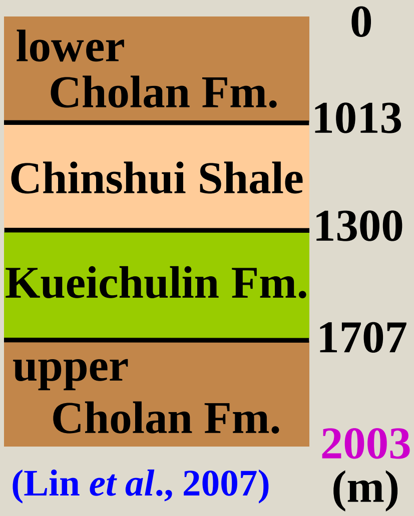
Wu, C.F. and H.C. Huang (2015). Pure Appl. Geophys., 172, 2545-2556.*

Geological map



(modified from Lo *et al.*, 1999; Ho and Chen, 2000)

Lithostratigraphy of TCDP-A:



(Lin *et al.*, 2007)

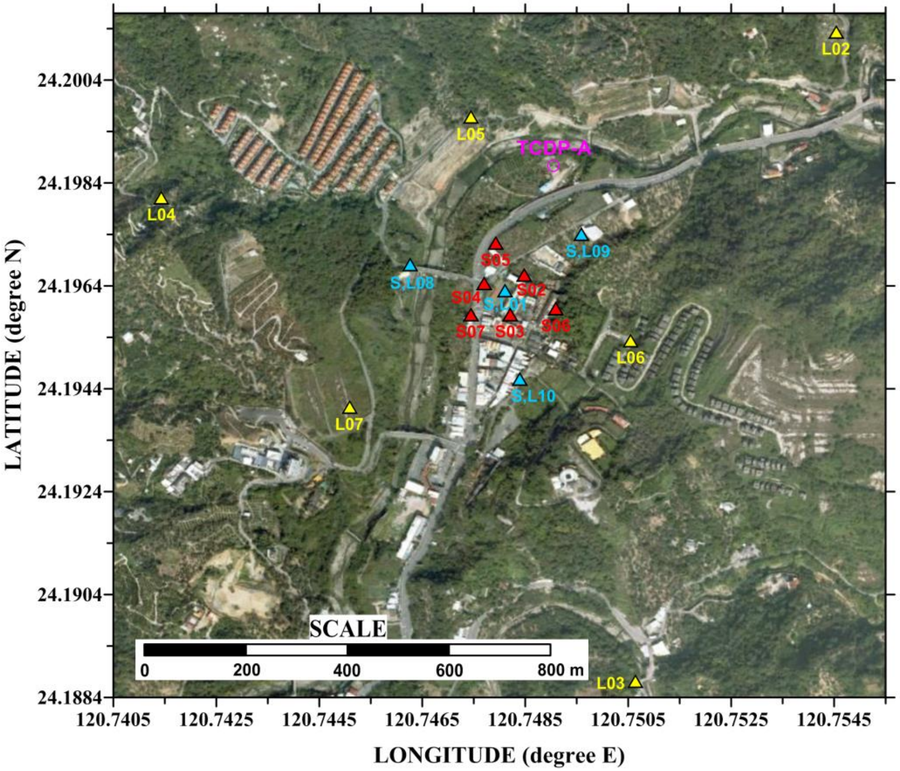
TCDP-A:

- located at Dakeng.
- depths 500-1900 m
- 2.4 km east of surface rupture.
- meets Chelungpu fault and Sanyi fault.

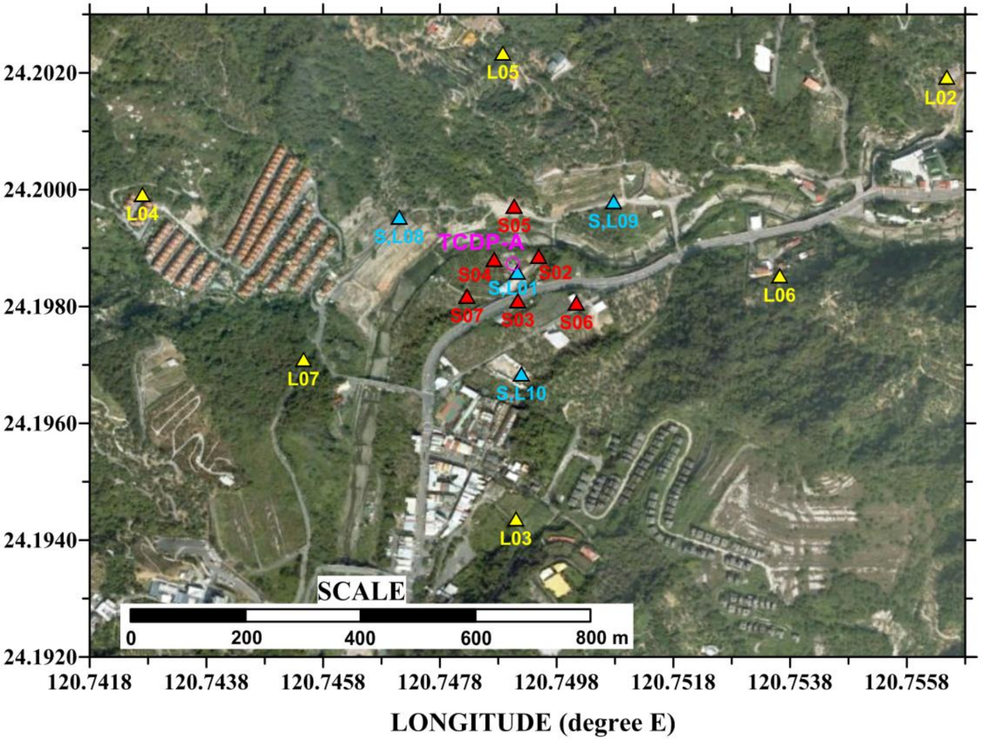
Geometries of the S- and L-arrays

- **Ten stations are in the form of three different aperture triangles around the center station at each array.**

Station Map of DAK Array



Station Map of TCD Array



▲ S array **(radii: 50-200 m)**
▲ co-stations for S- and L-arrays
▲ L array **(radii: 200-800 m)**
○ TCDP-A

sampling rate：200 Hz
gain：100
data length：582 sec
recording length：1.5-2 hr

Analysis Methods

F-K spectral analysis

The power spectrum at frequency *f* and vector wavenumber *k* for an array of N sensors by Maximum Likelihood Method (Capon, 1969) is given by：

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

- n : number of sensors.
- ψ_{lm} : cross-power spectrum between the *i*th and the *j*th sensors at frequency *f*.
- $\vec{r}_{ij}=\vec{r}_j-\vec{r}_i$: $\vec{r}_i$ and $\vec{r}_j$ are position vectors of the *i*th and the *j*th sensors.

Inversion of velocity structure

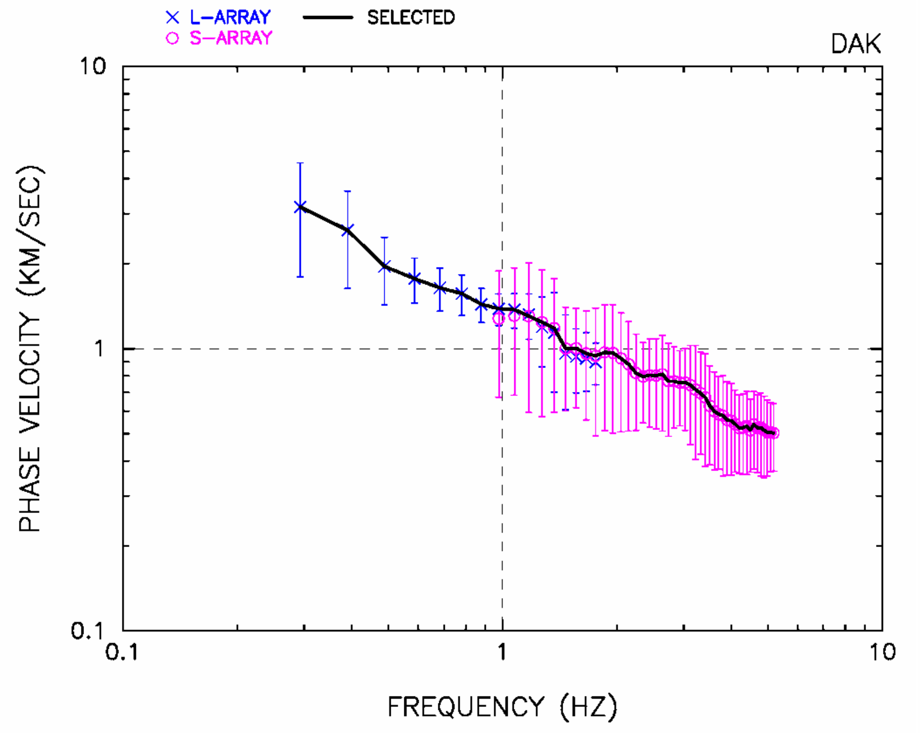
- The equation, joining the dispersion curve and velocity model parameters, can be written as follows (Hwang and Yu, 2005):

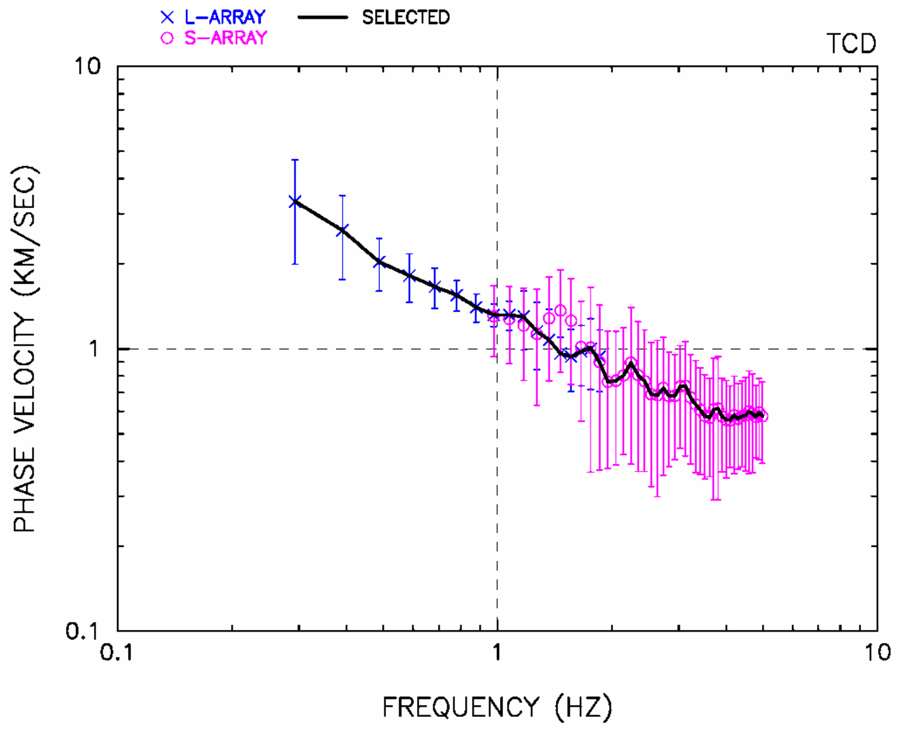
$$\Delta C(T_j)=\sum_{i=1}^{N}\left(\frac{\partial C(T_j)}{\partial \beta_i}\right)\Delta\beta_i$$

  - $\Delta C(T_j)$: difference between observed and predicted phase velocity derived from initial velocity model at the *j*th period (T_j).
  - N : number of layers.
  - $\partial C(T_j)/\partial\beta_i$: partial derivative of phase-velocity of the *j*th period with respect to V_S of the *i*th layer.
  - $\Delta\beta_i$: resulting difference in V_S of the *i*th layer between adjacent inversions.

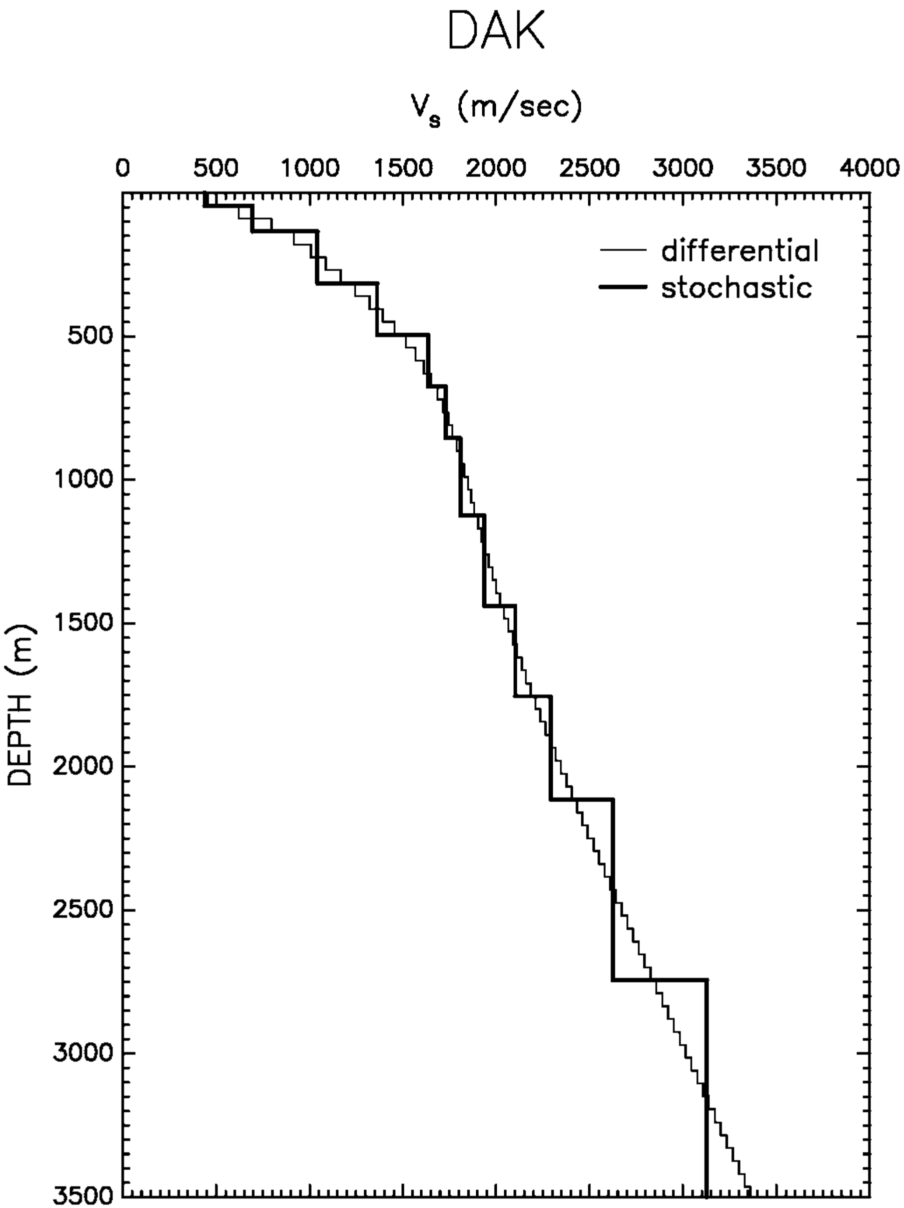
- Using surface wave inversion method– program **SURF** (Herrmann, 1991).

Dispersion Curves



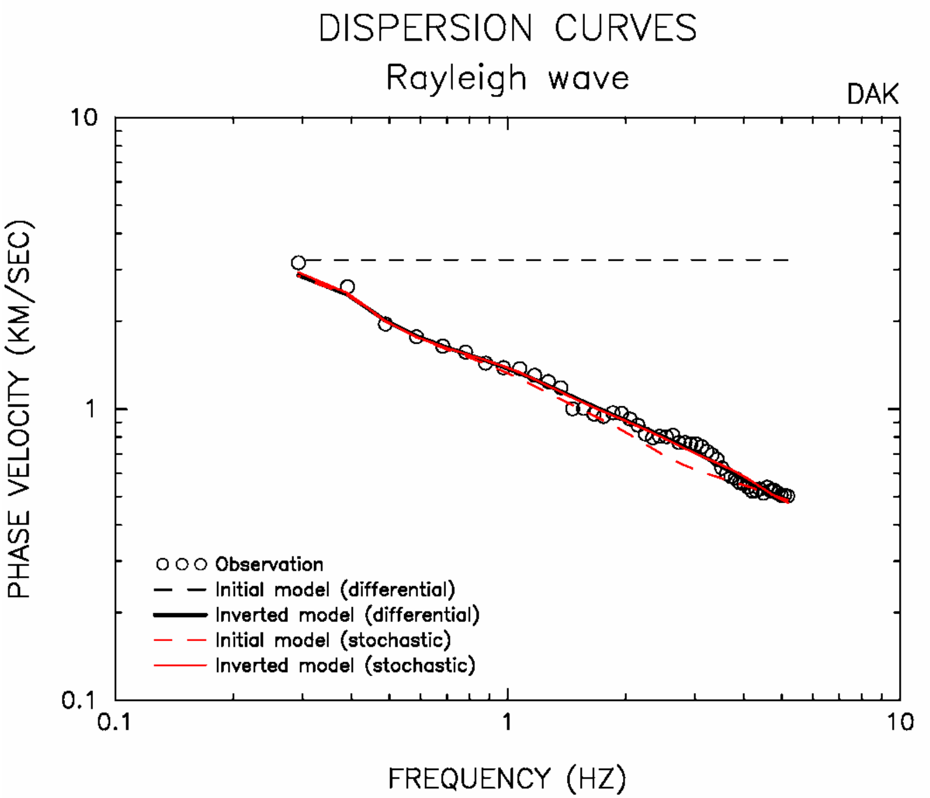


- **The results of the L-array are stable at lower frequencies, whereas those of the S-array are stable at higher frequencies.**
- **The observed phase velocities at these two sites results are similar.**

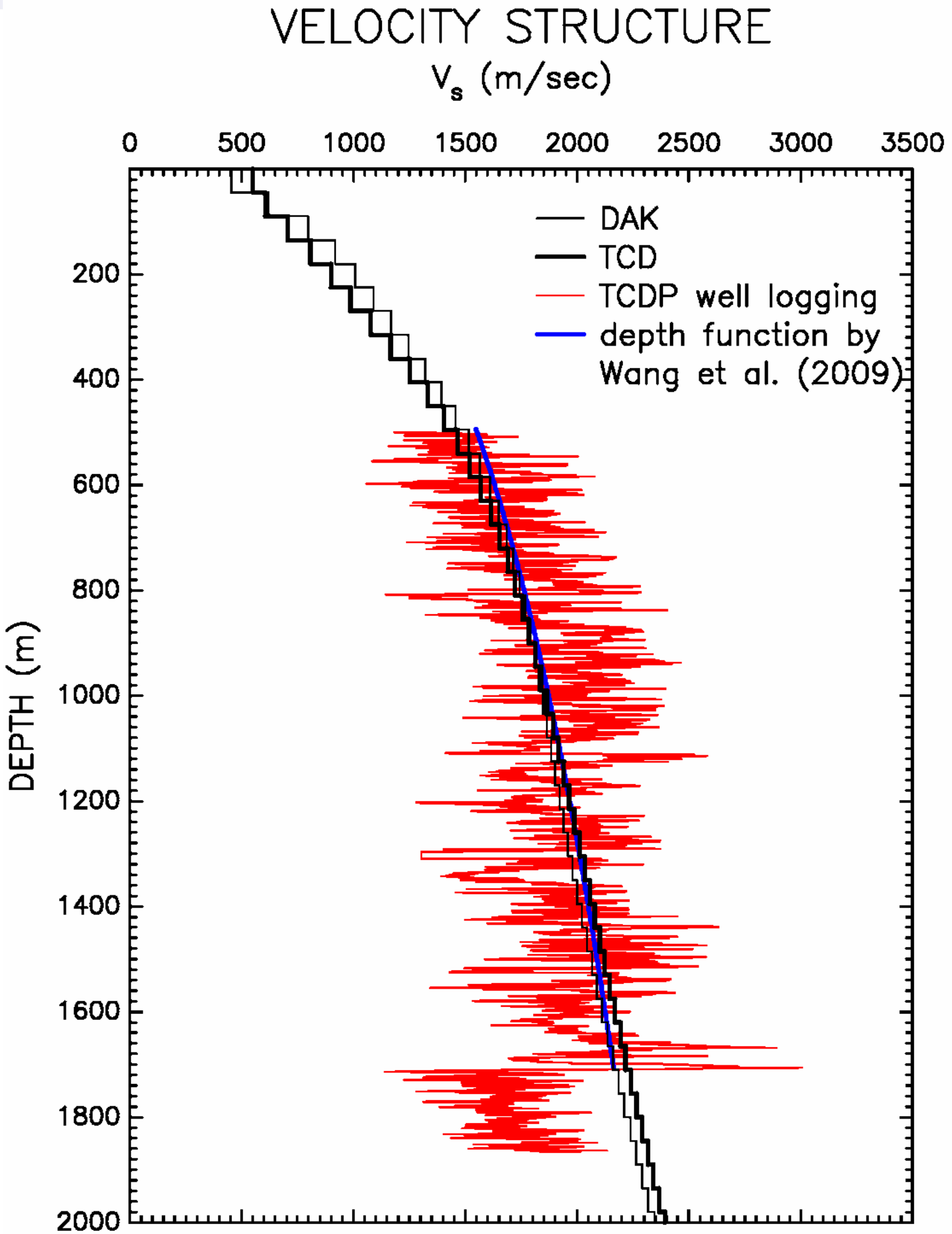


Inversion results at DAK

The initial model is a half-space structure with $V_S = C_{max}/0.92$.



The velocity structure from the surface to a depth of 3500 m can be roughly divided into 12 layers.

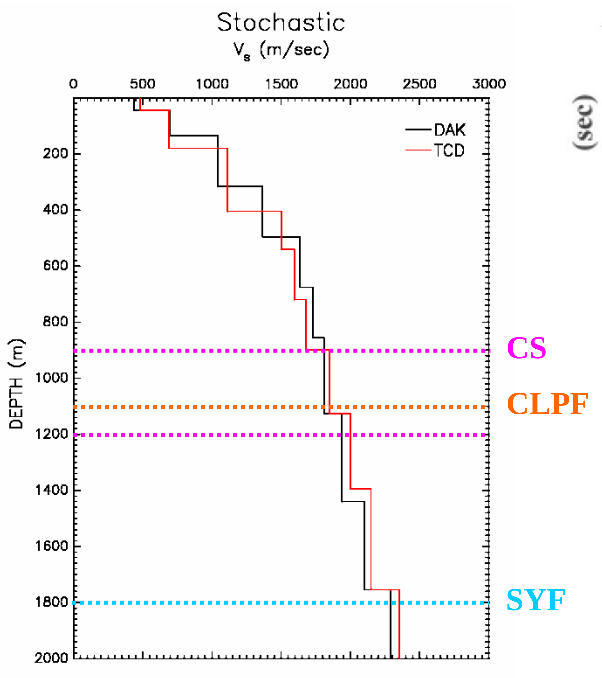


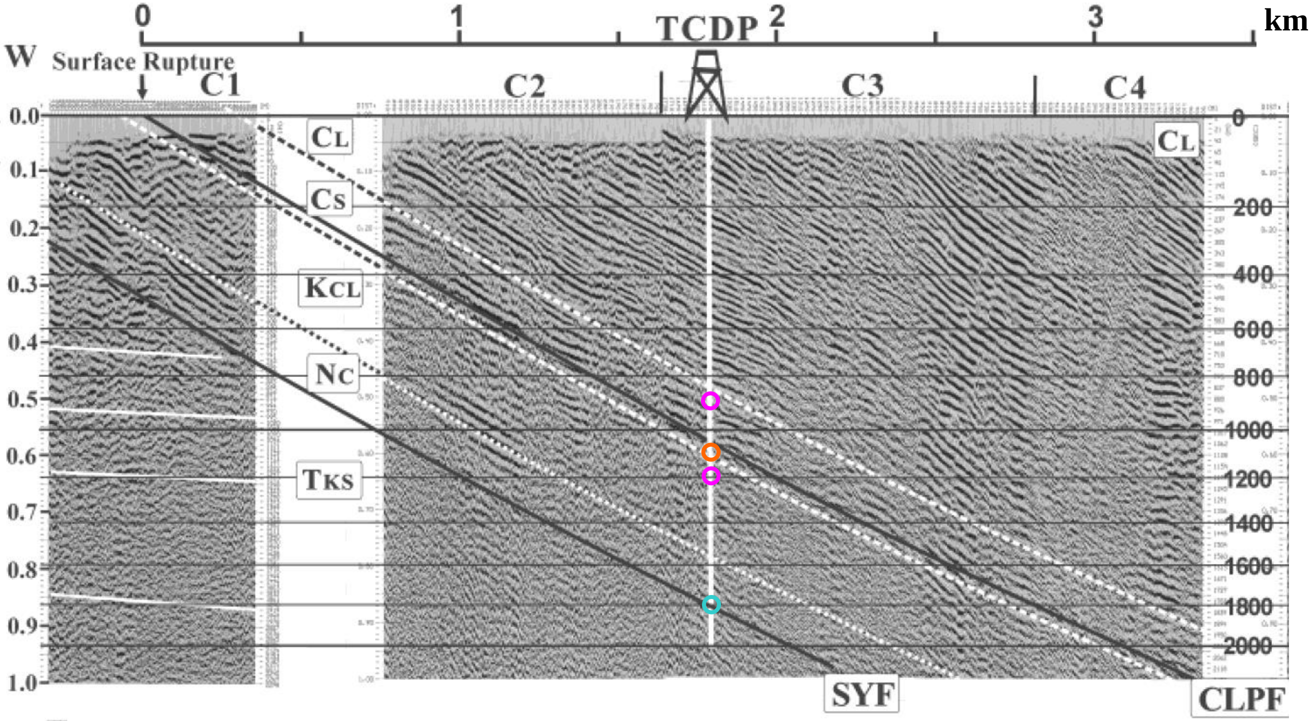
Comparisons of V_S Structures

- Geophysical logging of TCDP-A was conducted for depths between 500 and 1,900 m.
- The inverted V_S gradually increases from 1.52 to 2.22 km/s at depths between 585-1710 m, and the averaged V_S is 1.899 km/s.
- Our results are similar to those from velocity logs (1.4-2.98 km/s between 597-1705 m) and the averaged V_S is 1.860 km/s (Wu *et al.*, 2007).
- Our inversion results approximate to the regression result by Wang *et al.* (2009).

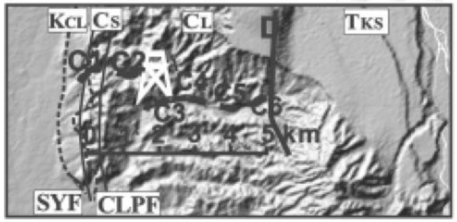
$$\boxed{V_S(z) = 0.29z^{0.27}}$$

Comparisons of V_S Structures





Formations / Methods	Chinshui Shale (CS) (depth: m)	Chelungpu fault (CLPF) (depth: m)	Sanyi fault (SYF) (depth: m)
seismic reflection method	900-1200	1100	1800
microtremor array measurements	855-1440	1125	1755



(Wang *et al*., 2007)

Comparison of Structures between Different Methods

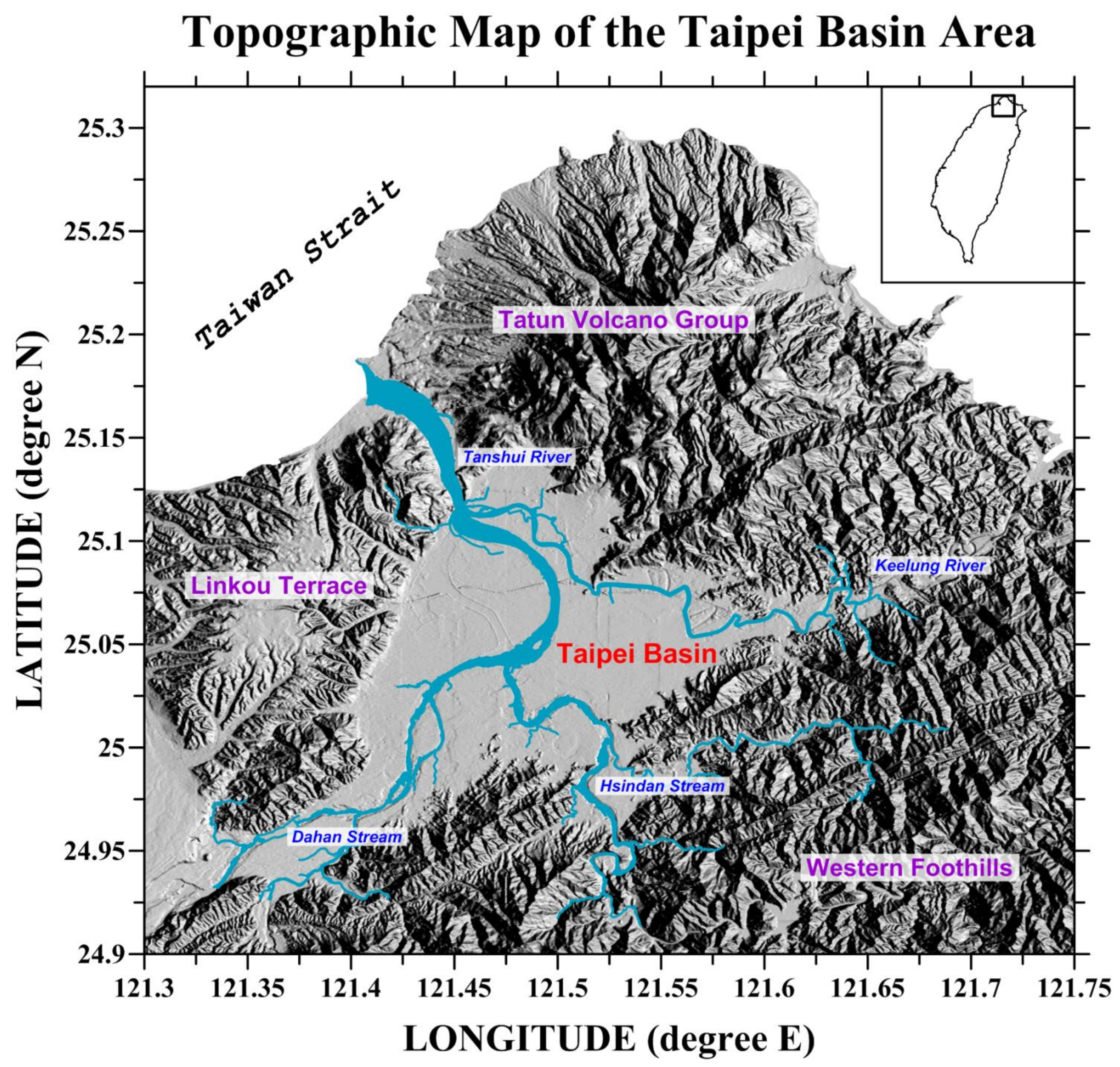
Formations Methods		Chinshui Shale (depth: m)	Chelungpu fault (depth: m)	Sanyi fault (depth: m)
microtremor array measurement	DAK	855-1440	1125	1755
	TCD	900-1395	1125	1755
seismic reflection method (Wang *et al.*, 2007)		900-1200	1100	1800
lithostratigraphy (Lin *et al.*, 2007)		1013-1300	1111	1707
physical properties (Hung *et al.*, 2007)		1013-1300	1111	1712
lithology and stratigraphy (Song *et al.*, 2007)		1029-1303	1111, 1153	1712

The stochastic inversion results are comparable to those from the geophysical methods.

CASE 1A:

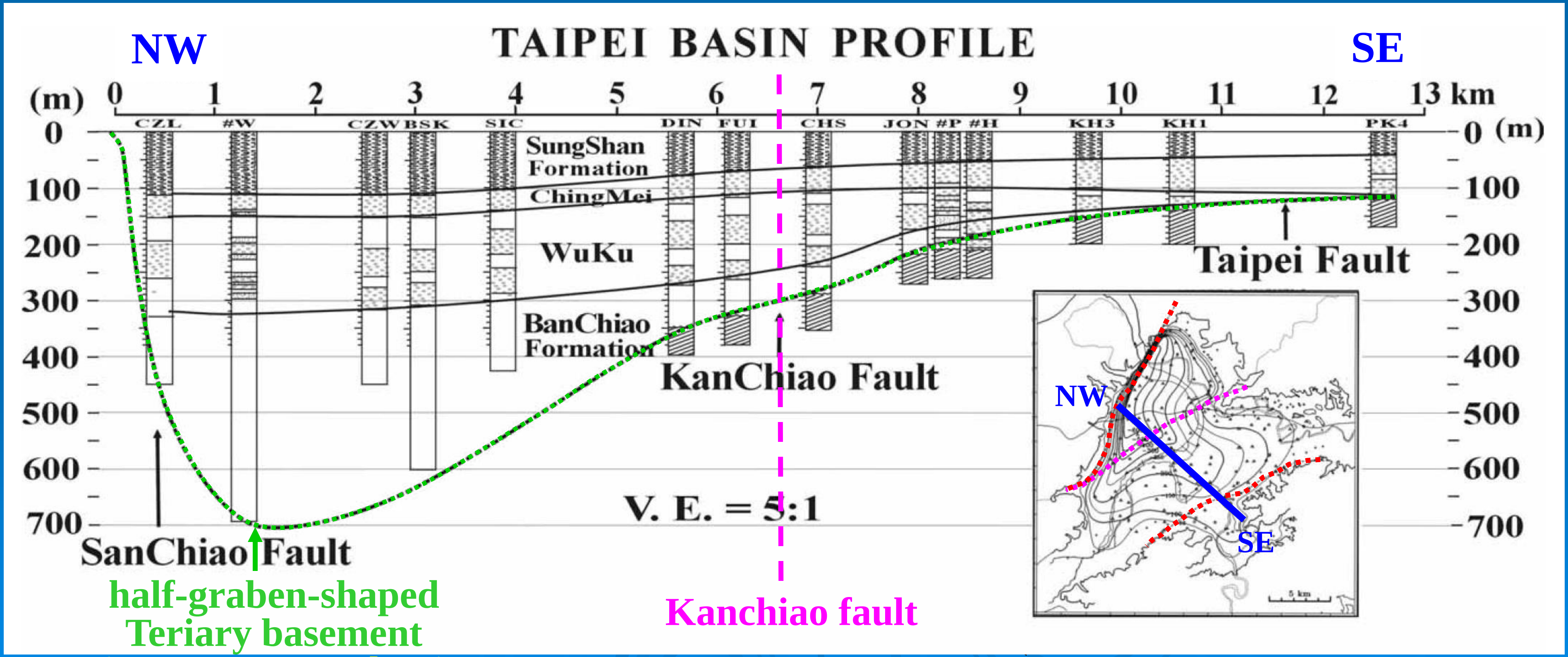
S-wave velocity structures of the Taipei basin, Taiwan, using microtremor array measurements

Huang, H.C., C.F. Wu, F.M. Lee and R.D. Hwang (2015). J. Asian Earth Sci., 101, 1-13.



- Taipei Basin is triangular in shape with an area of about 20 km × 20 km.
- The basin is formed by alluvial deposits from the Tanshui River and its three tributaries, namely Hsindian Creek, Dean Creek, and Keelung River.
- Taipei Basin is bordered by Western Foothills, Linkou Tableland and Tatun Volcanoes.

- **The Quaternary sediments overlie the half-graben-shaped Teriary basement.**
- **Kanchiao fault forms a boundary which separates the deep NW and the shallow SE parts of the basin.**
- **Quaternary stratigraphy:**
  - **Sungshan Formation** ← **plays an important role on site amplification**
  - **Chingmei Formation**
  - **Wuku Formation**
  - **Banchiao Formation**

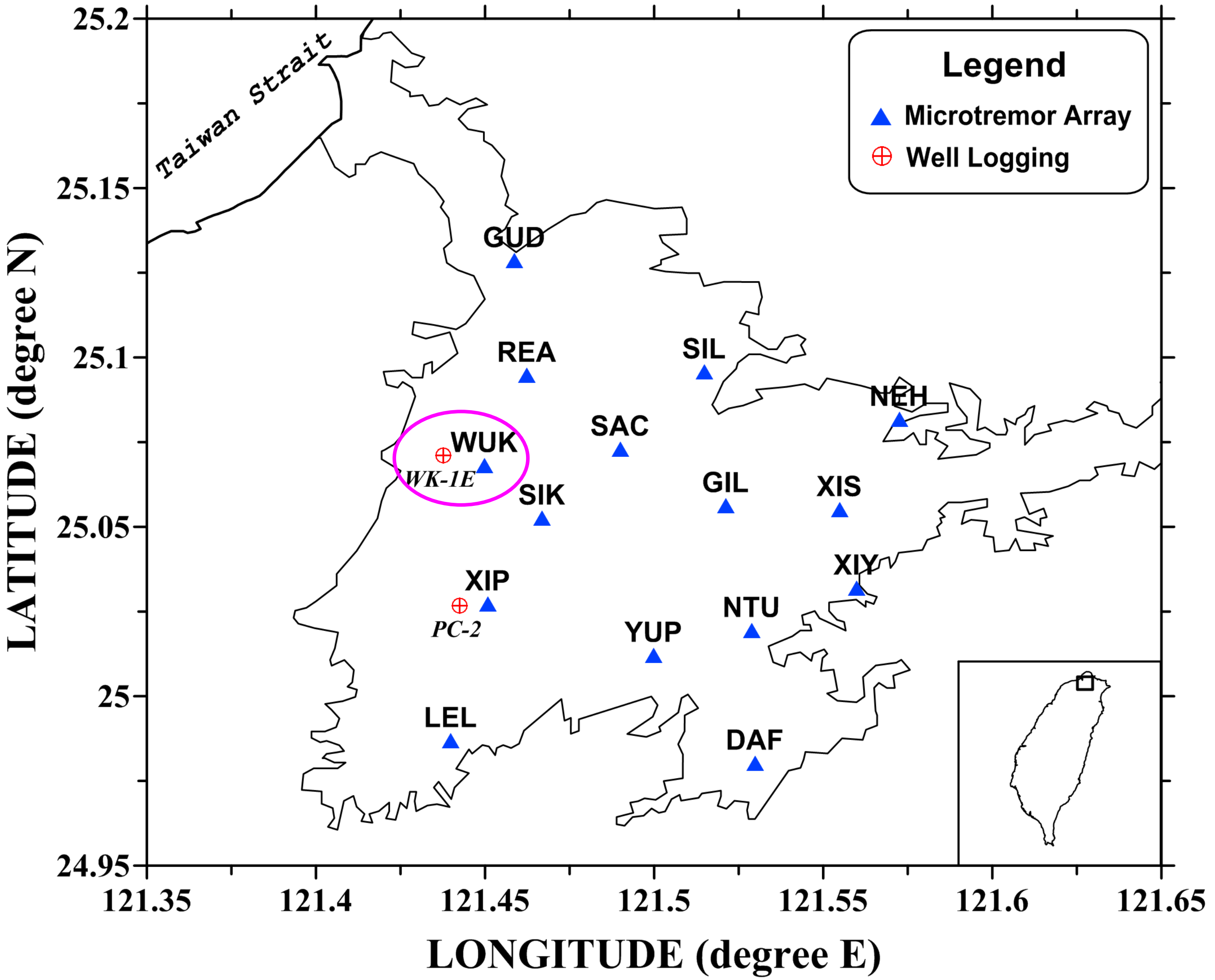


half-graben-shaped Teriary basement (at most 700 m deep)

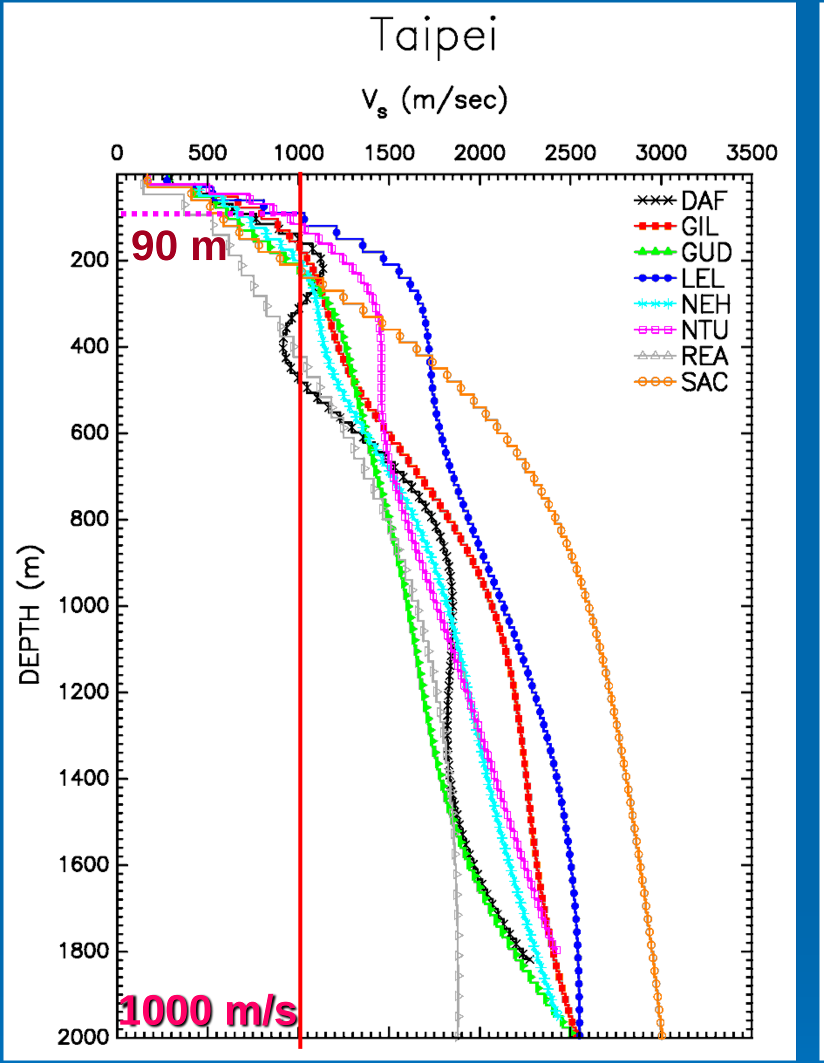
Kanchiao fault

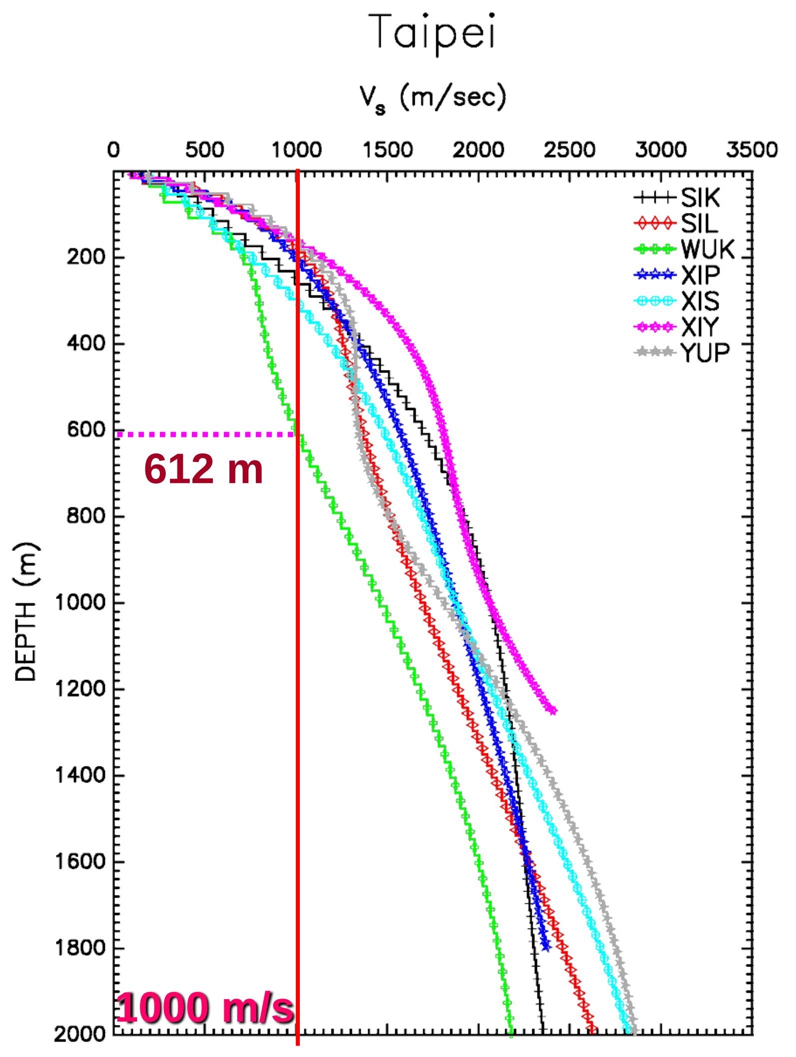
(adopted from Wang *et al.*, 2004)

Locations of the Array Sites in the Taipei Basin

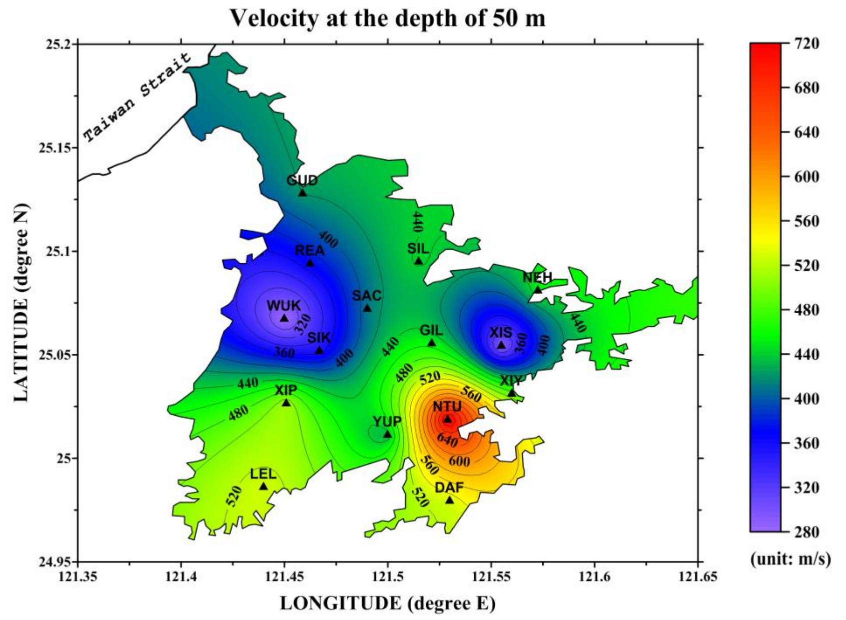


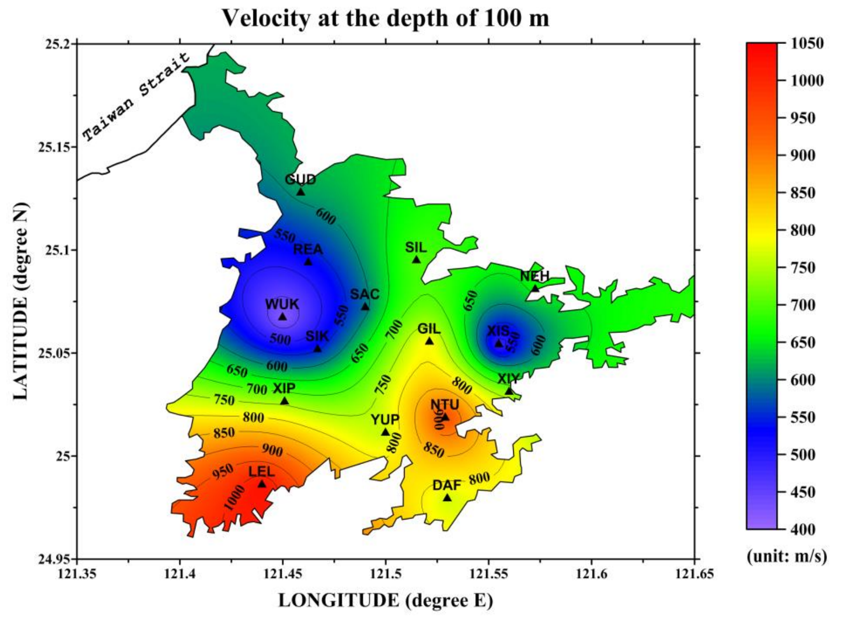
- Microtremor array measurements are conducted at **15 sites**.
- The two used well-logging sites (**WK-1E and PC-2**) are also showed here.

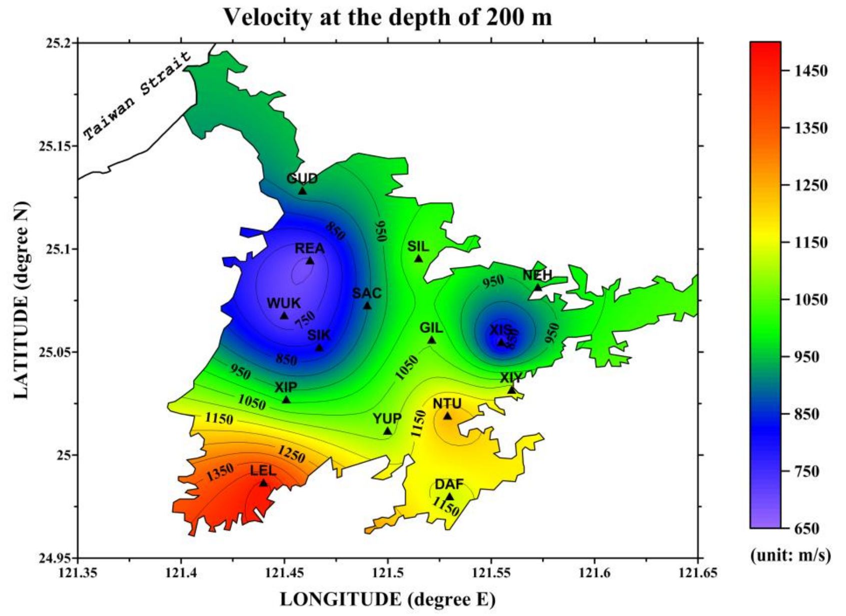


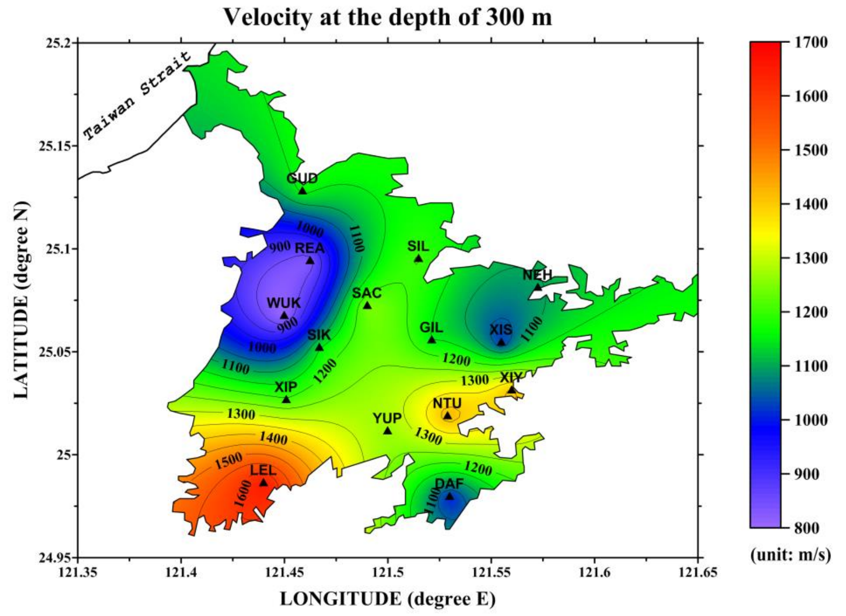


- **Estimated V_S structures by differential inversion technique at all sites.**
- **the V_S of the shallower depths (about 0-800 m) at sites REA and WUK are lower than those at other sites.**
- **If we assume that the averaged V_S of the Tertiary Basement in the Taipei Basin is about 1,000 m/s (Wang and Sung, 1999, Wang *et al.*, 2004 and Chen, 2004), the depths of the Quaternary sediments are between 90 m (LEL) and 612 m (WUK).**

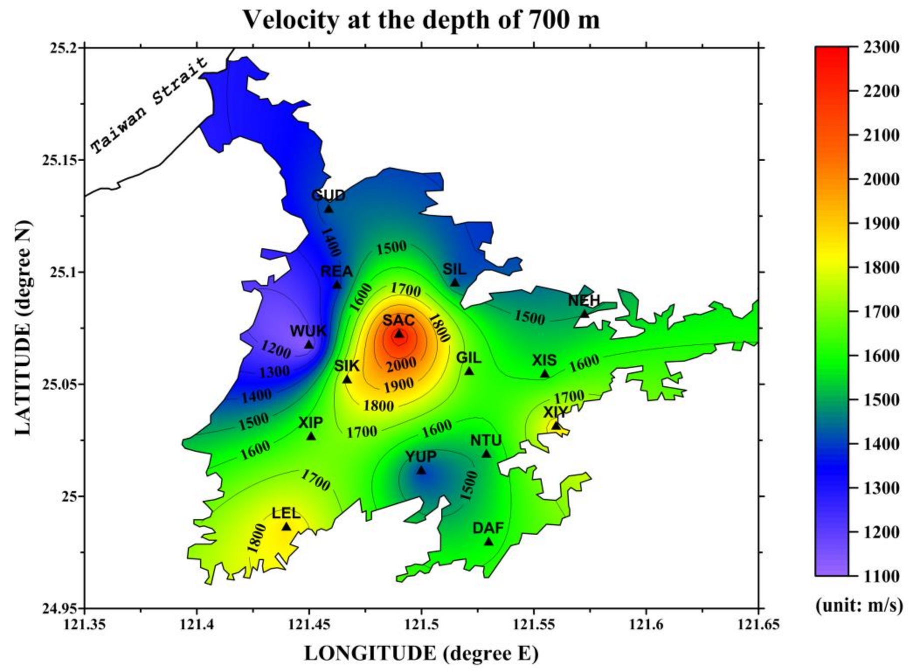

Velocity at the depth of 50 m

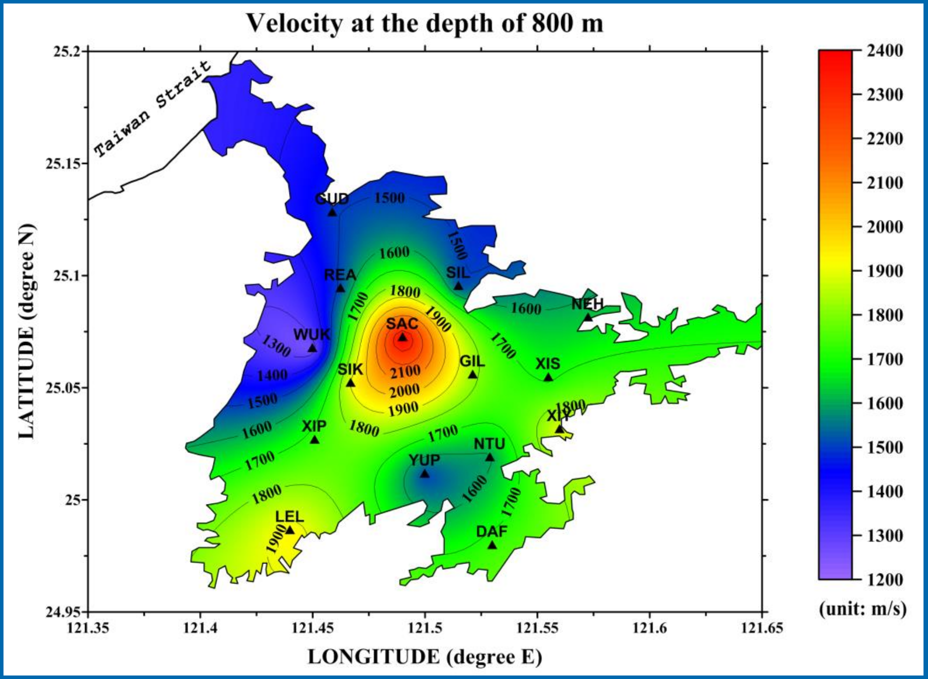

Velocity at the depth of 100 m

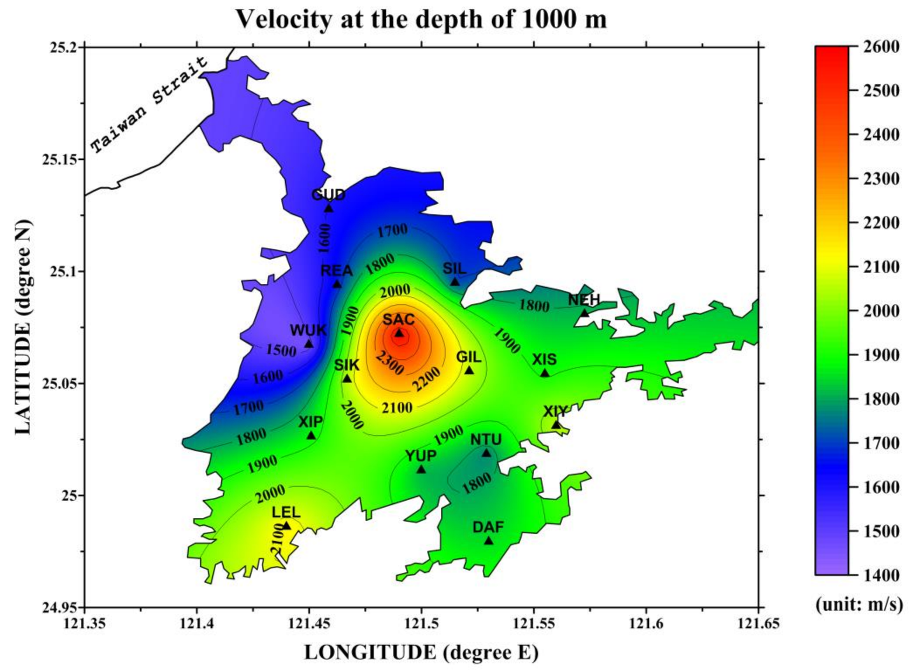

Velocity at the depth of 200 m


Velocity at the depth of 300 m

Lower velocities appear at the northwest part (**WUK**) and the northeast part (**XIS**) of the basin while the **higher velocities** are evident at the southwest part (**LEL**) and the southeast part (**NTU**) of the basin.


Velocity at the depth of 700 m


Velocity at the depth of 800 m


Velocity at the depth of 1000 m

Lower velocities appear at the northwest part (WUK) and northern part (GUD) of the basin while higher velocities prevail at the central part (SAC) of the basin.

CASE 1B:

Site-Effect Estimations for Taipei Basin Based on the Shallow V_S Structures

Chen, Y.C., H.C. Huang and C.F. Wu (2016). J. Asian Earth Sci., 117, 135-145.*

1D Haskell method (Haskell, 1960)

- **Purpose**: to simulate ground motions of the horizontally layered structure at different depths. (suppose it consists of n homogeneous layers)

- **The m^{th} layered propagating matrix is**

$$a_m = \begin{bmatrix} \cos Q_m & i\mu_m \gamma_{\beta m}^{-1} \sin Q_m \\ i\mu_m \gamma_{\beta m} \sin Q_m & \cos Q_m \end{bmatrix}$$

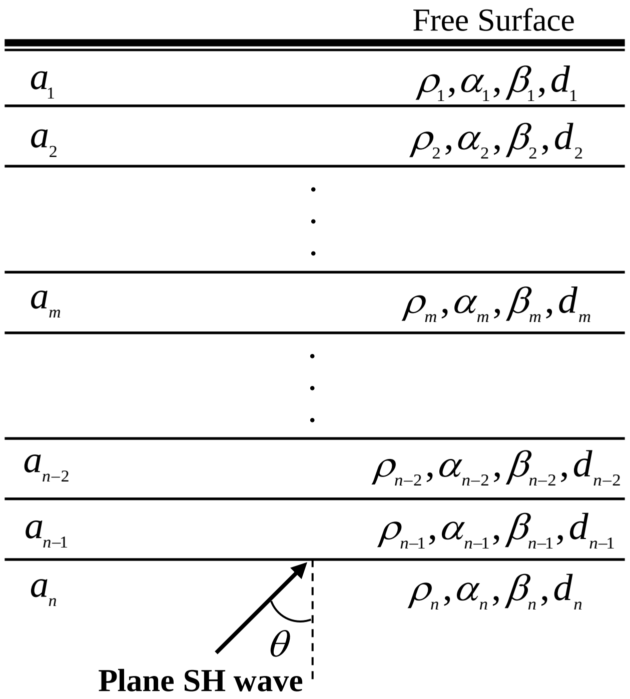
θ: incident angle of plane SH wave
(in this study, θ=0°)
β_m: shear wave velocity of m^th layer
d_m : thickness of m^th layer
μ_m: shear modulus

$$Q_m = kd_m \gamma_{\beta m}$$

$$\gamma_{\beta m} = [(c/\beta_m)^2 - 1]^{1/2}$$

$$c = \beta_m / \sin\theta$$

$$k = \omega / c$$



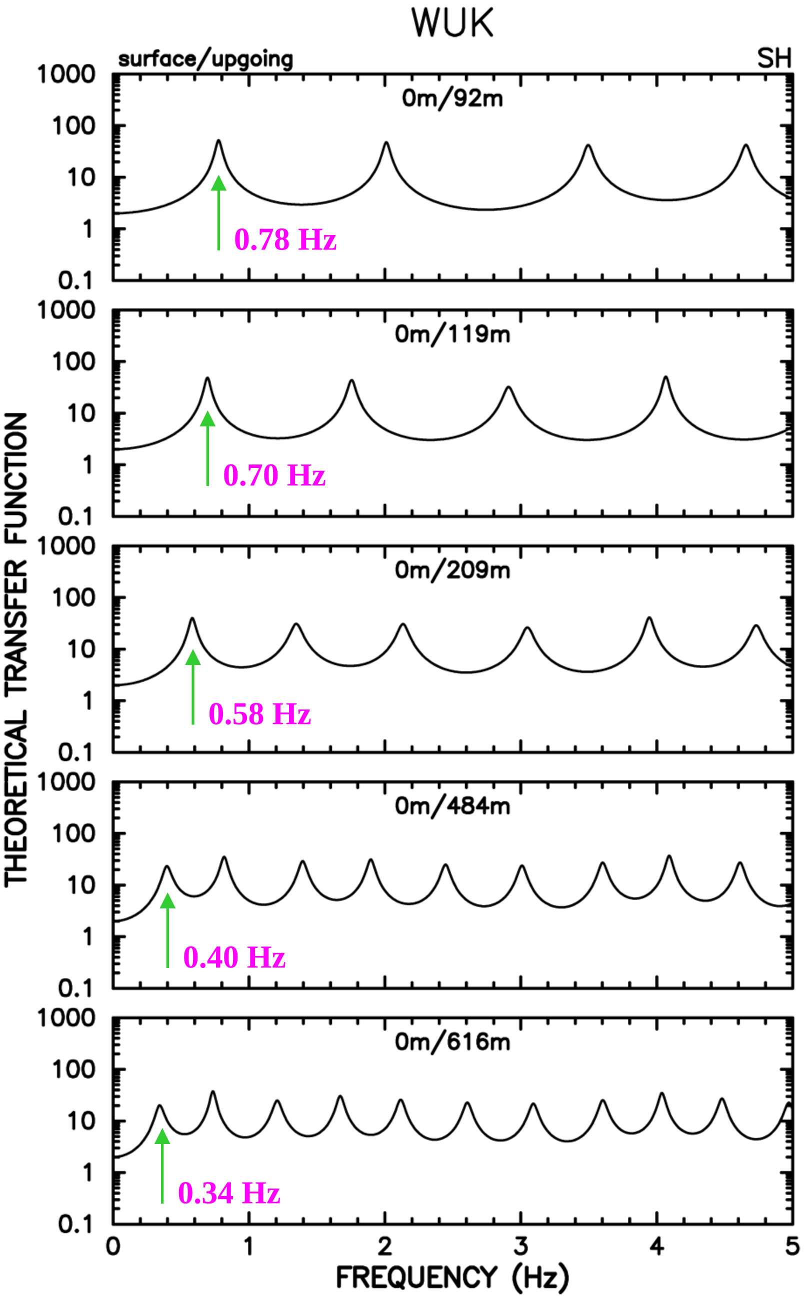
- **The transfer function is**

$$[A] = a_{n-1} a_{n-2} \cdots a_2 a_1$$

※ **Considering the vertically incident plane SH wave**

※ **Ignoring attenuation parameter Q**

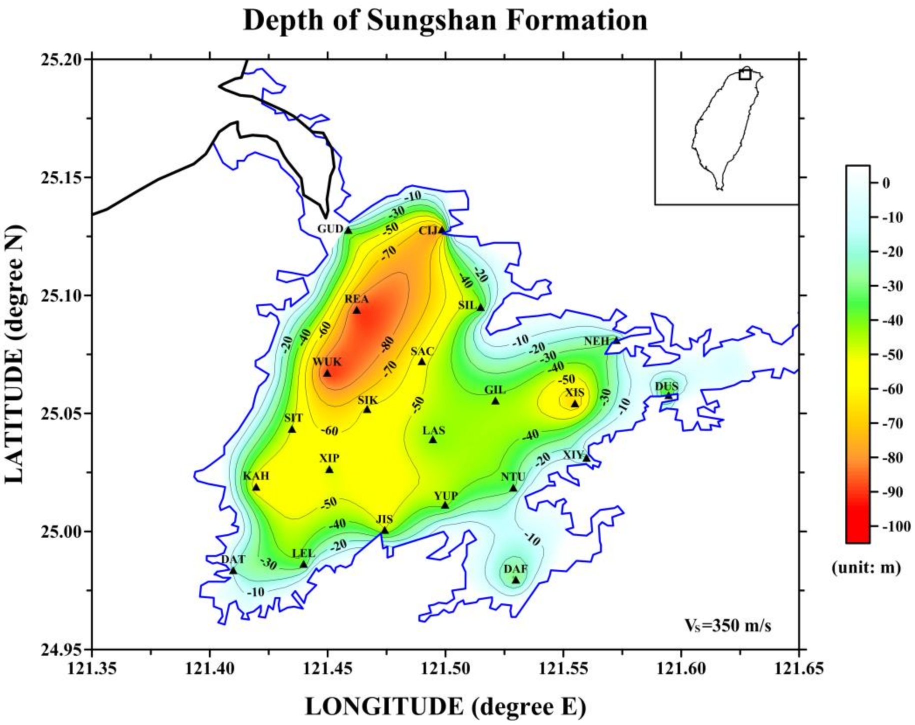
※ **Using the ground motion at the surface to simulate those at different depths**



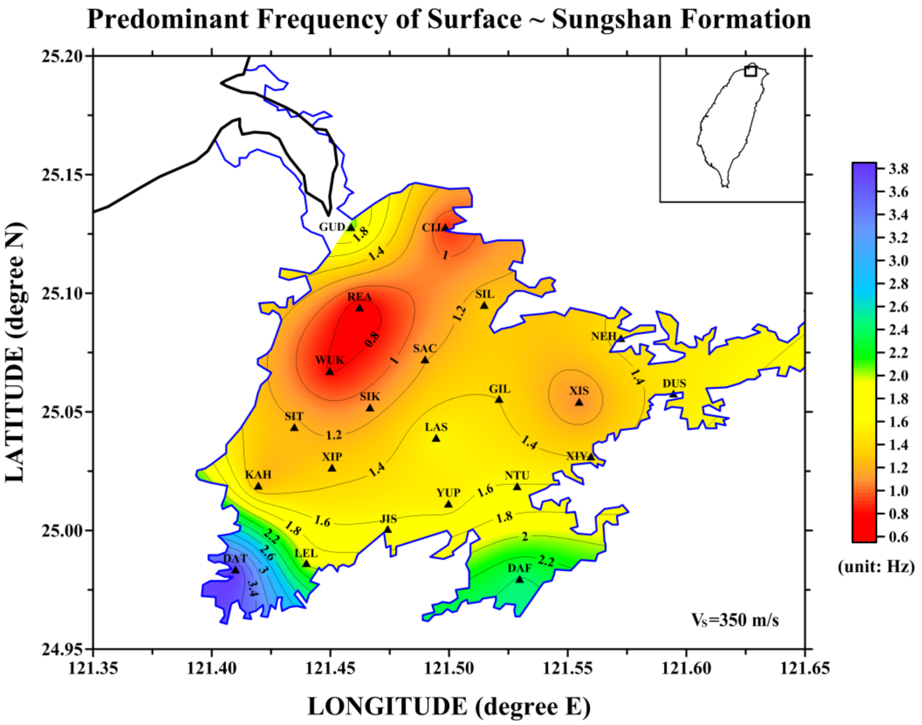
- **V_S assumption in Taipei Basin:**
  - **Bottom of Sungshan Formation: V_S = 350 m/s**
  - **Chingmei Formation: V_S = 450 m/s**
  - **Wuku Formation: V_S = 700 m/s**
  - **Banchiao Formation: V_S = 880 m/s**
  - **Tertiary Basement: V_S = 1,000 m/s**
- **At WUK array site, the depths of these five formations are about 92, 119, 209, 484 and 616 m, respectively.**
- **The predominant frequencies at these five depths are about 0.78, 0.70, 0.58, 0.40 and 0.34 Hz, respectively.**

Estimations of Site Characteristics

■ Sungshan Formation (V_S = 350 m/s)



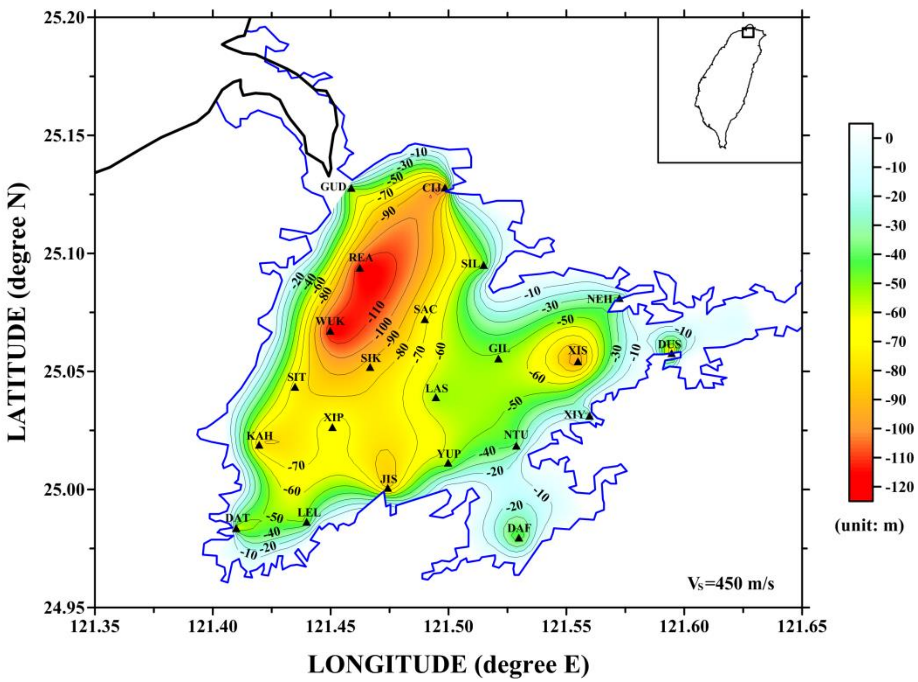
Depth of Sungshan Formation

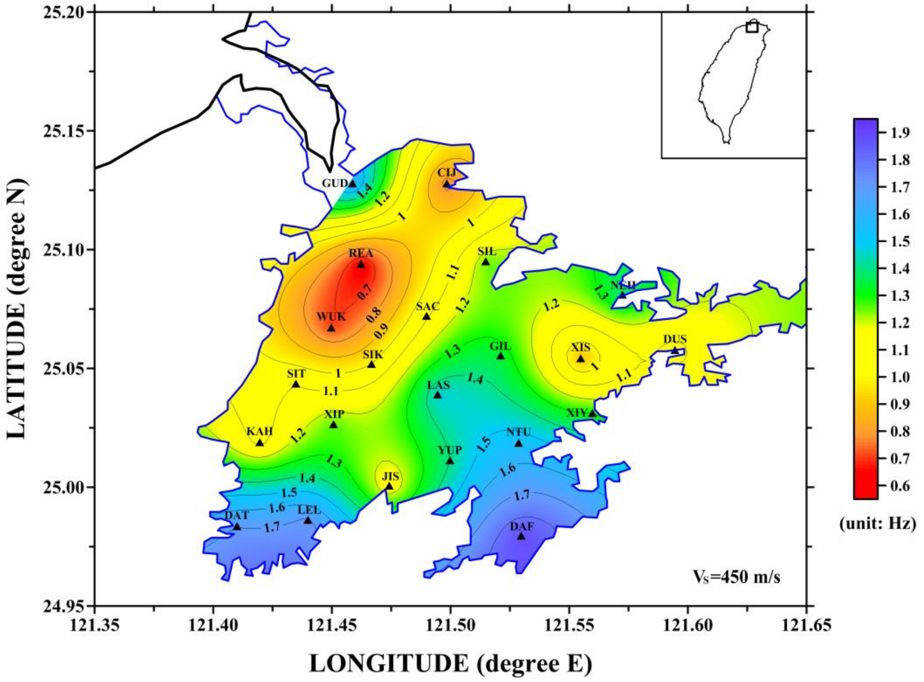


Predominant Frequency of Surface ~ Sungshan Formation

- Depth: 0 m (edge) ~ 92 m (REA and WUK)
- Predominant frequency: 0.6 ~ 3.8 Hz
- Northwestern part has deeper sediments and smaller predominant frequency while the sites at the southwestern and southeastern parts have opposite results.

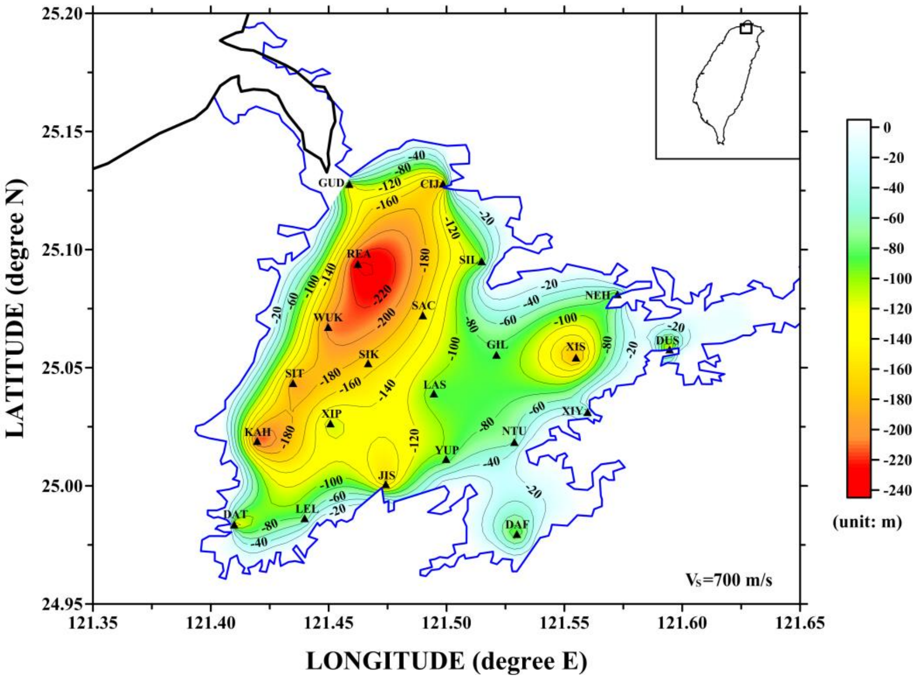
Chingmei Formation (V_S = 450 m/s)


Depth of Chingmei Formation

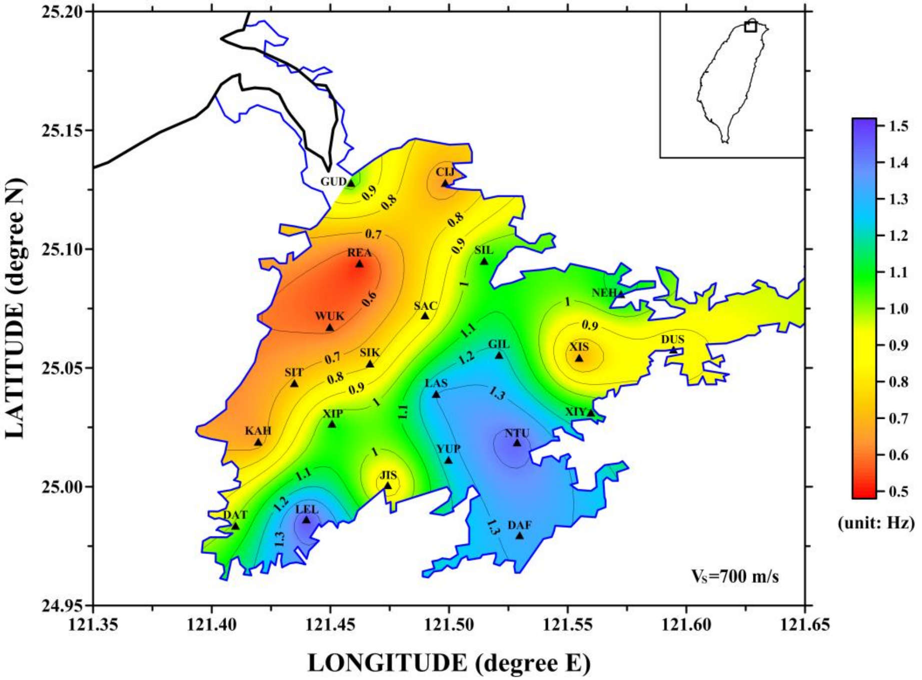

Predominant Frequency of Surface ~ Chingmei Formation

- **Depth: 0 m (edge) ~ 119 m (REA and WUK)**
- **Predominant frequency: 0.6 ~ 1.9 Hz**
- **The lower predominant frequencies appear at the northwestern part of the basin while the higher ones are at the southwestern and southeastern parts of the basin.**

■ Wuku Formation (V_S = 700 m/s)



Depth of Wuku Formation

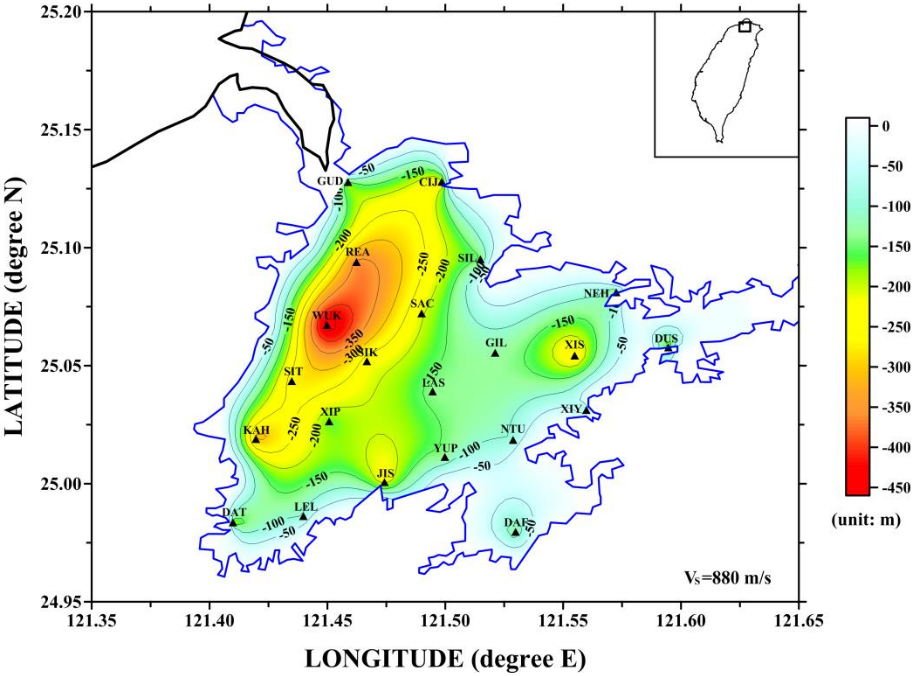


Predominant Frequency of Surface ~ Wuku Formation

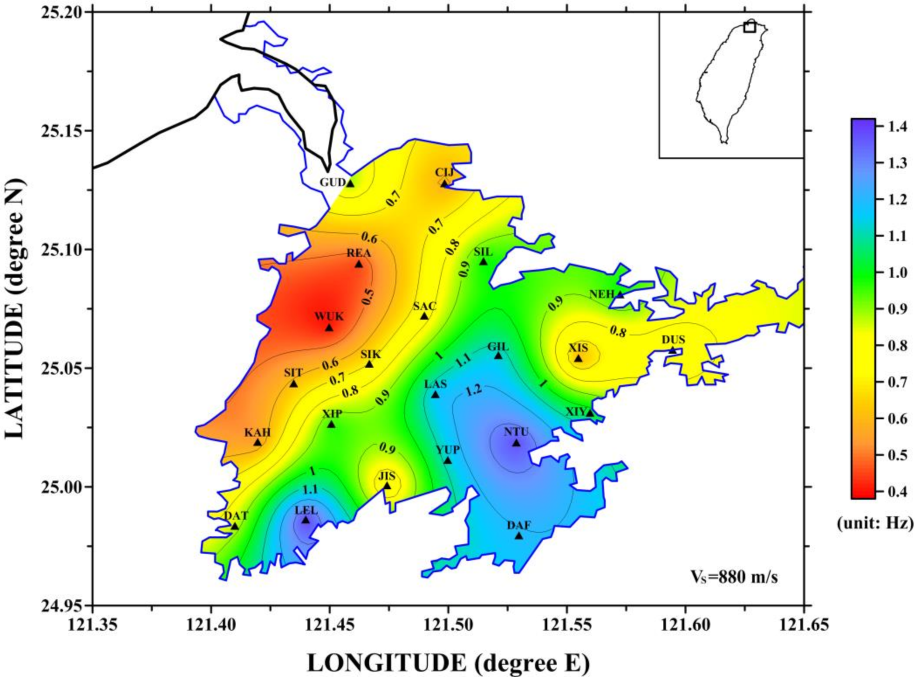
- **Depth: 0 m (edge) ~ 245 m (REA)**
- **Predominant frequency: 0.5 ~ 1.5 Hz**
- **The distribution patterns of depths and predominant frequencies are similar to those at the Chingmei Formation.**

■ Banchiao Formation (V_S = 880 m/s)

Depth of Banchiao Formation

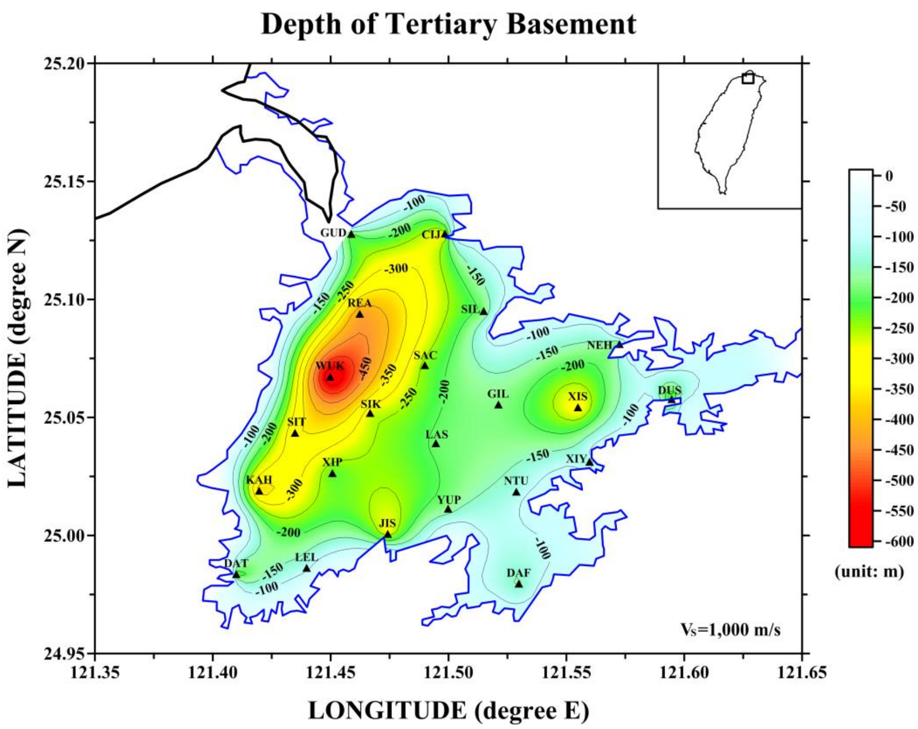


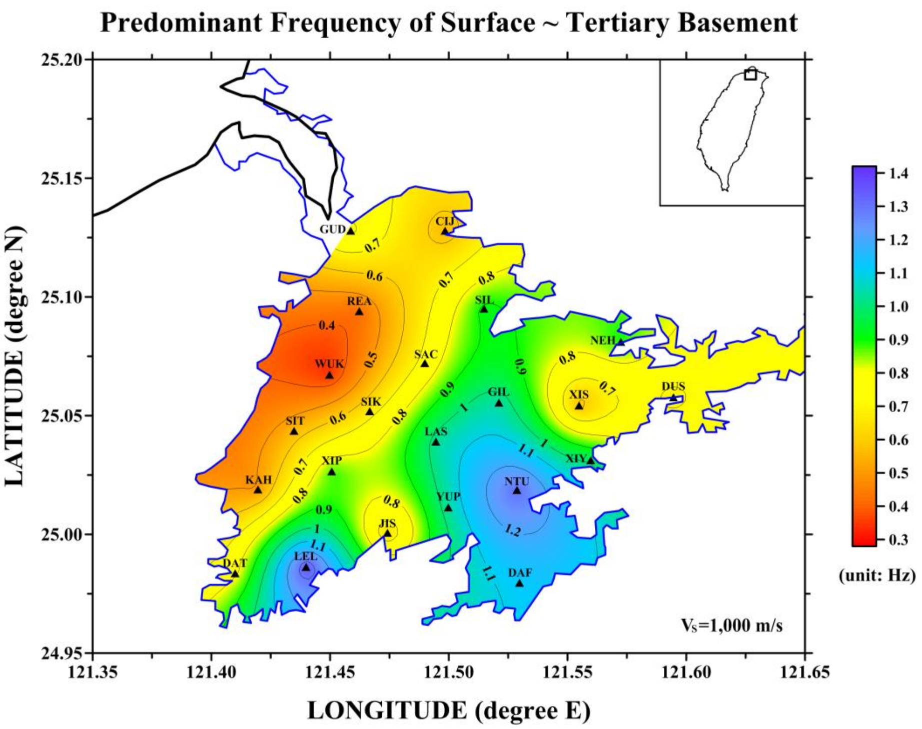
Predominant Frequency of Surface ~ Banchiao Formation



- Depth: 0 m (edge) ~ 484 m (WUK)
- Predominant frequency: 0.4 ~ 1.4 Hz
- The thicknesses of this Formation are apparently deeper than those at other formations.
- The distribution patterns of depths and predominant frequencies are similar to those at the Chingmei Formation.

Tertiary Basement (V_S = 1,000 m/s)


Depth of Tertiary Basement

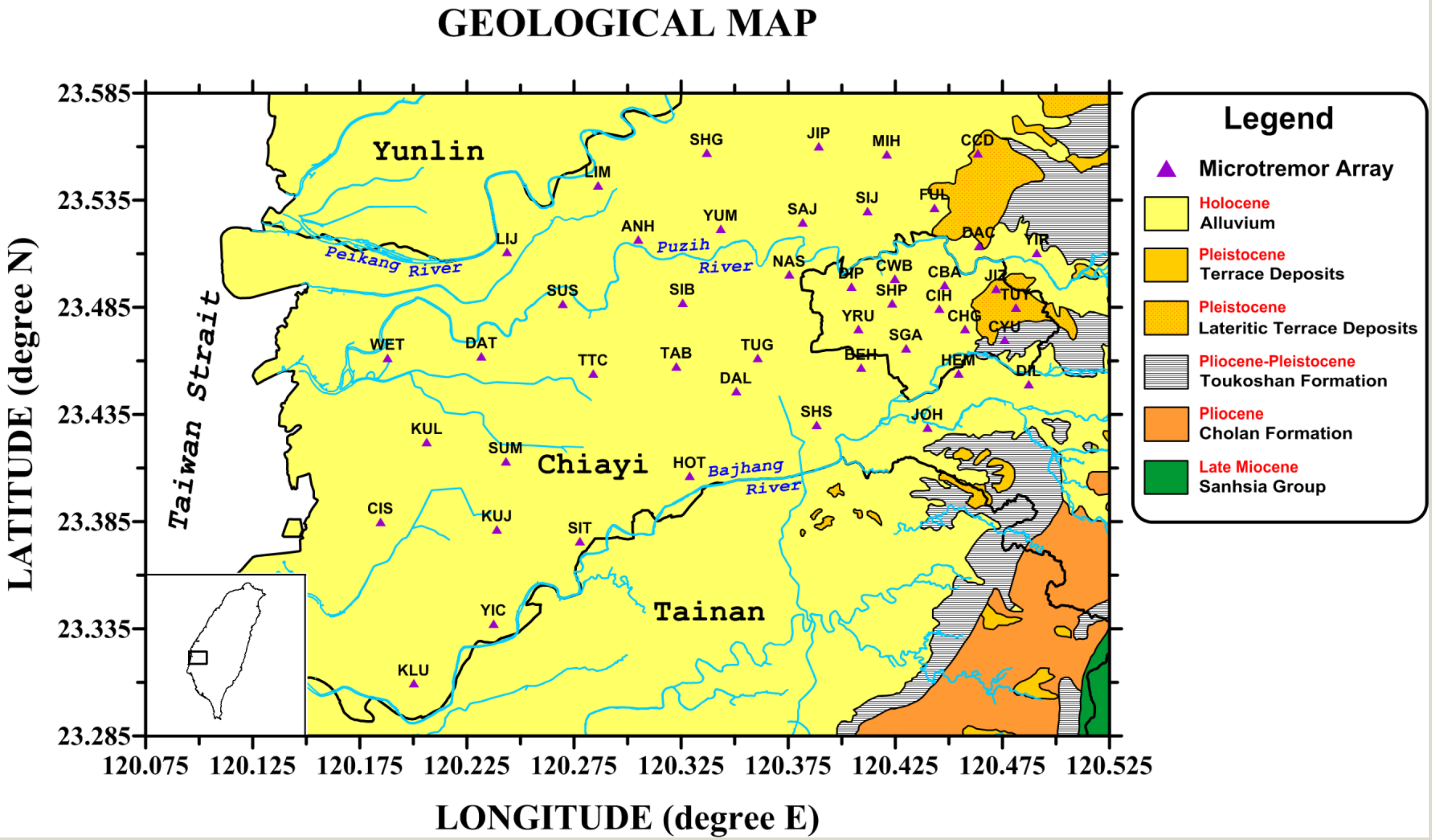

Predominant Frequency of Surface ~ Tertiary Basement

- **Depth: 0 m (edge) ~ 616 m (WUK)**
- **Predominant frequency: 0.3 ~ 1.4 Hz**

CASE 2A:

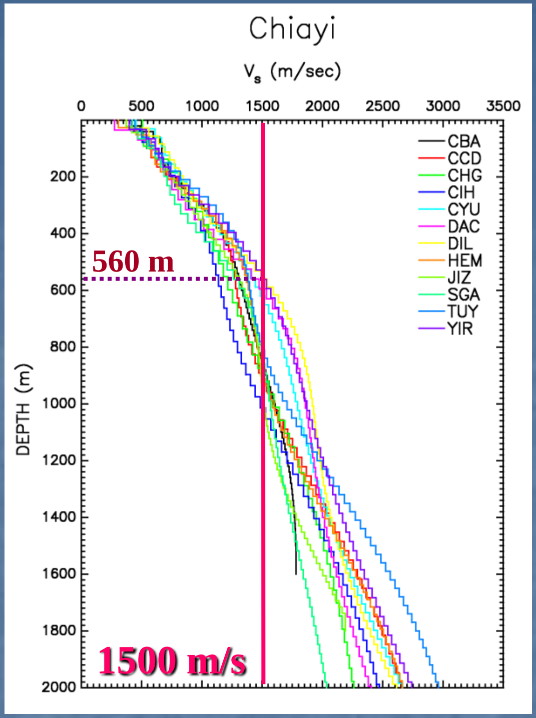
Near-surface shear-wave velocity structure of the Chiayi area, Taiwan

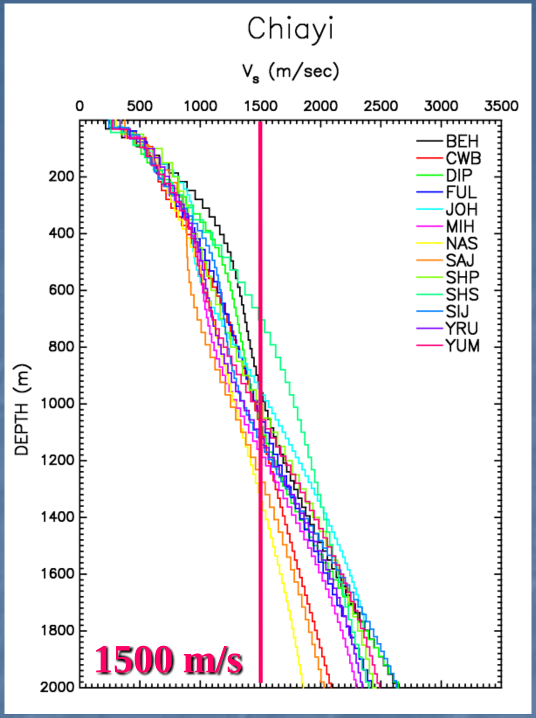
Wu, C.F. and H.C. Huang* (2013), Bull. Seism. Soc. Am., 103(2A), 1154-1164.



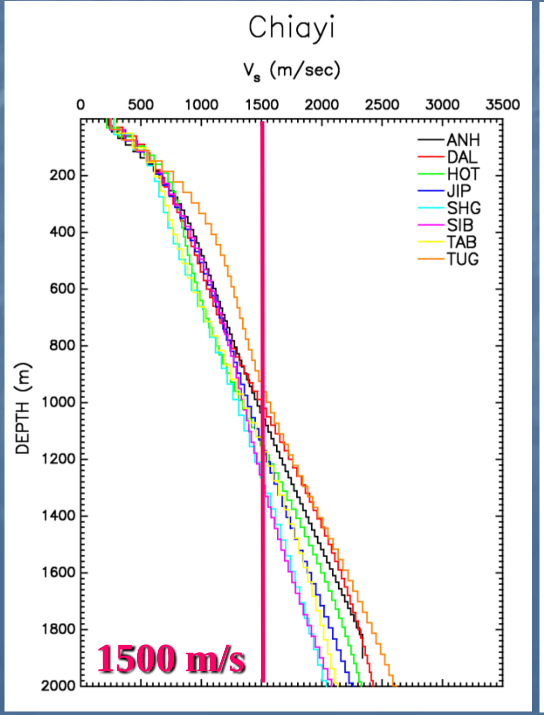
(modified from the Central Geology Survey, 2010)

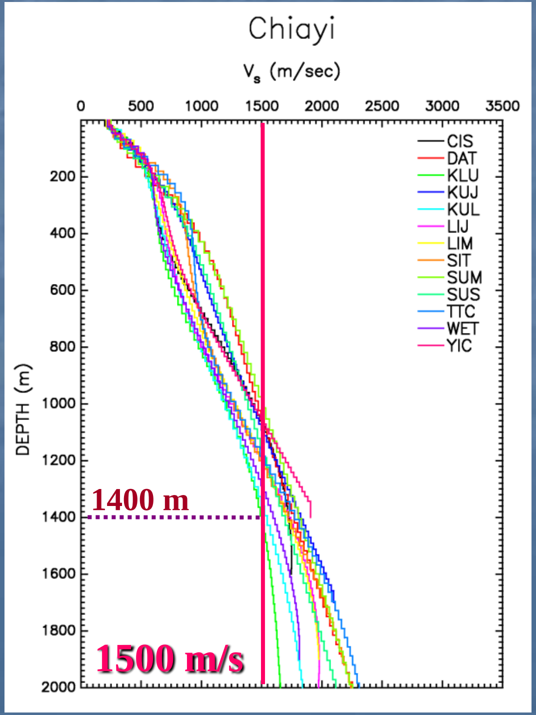
- The area’s drainage system from top to bottom is composed of the Peikang, Puzih, and Bajhang Rivers, and they predominantly flow from east to west.
- It continuously expands westward through the rapid deposition of sediments and regional uplift.

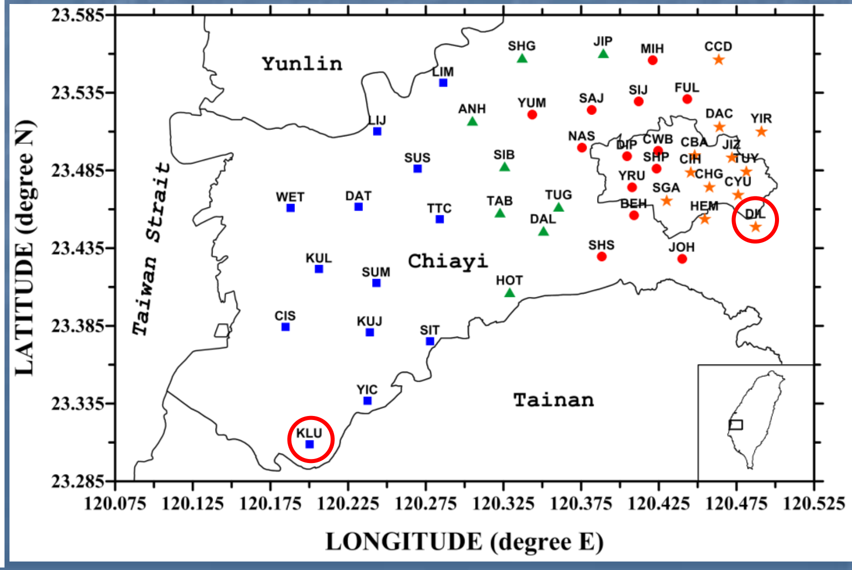




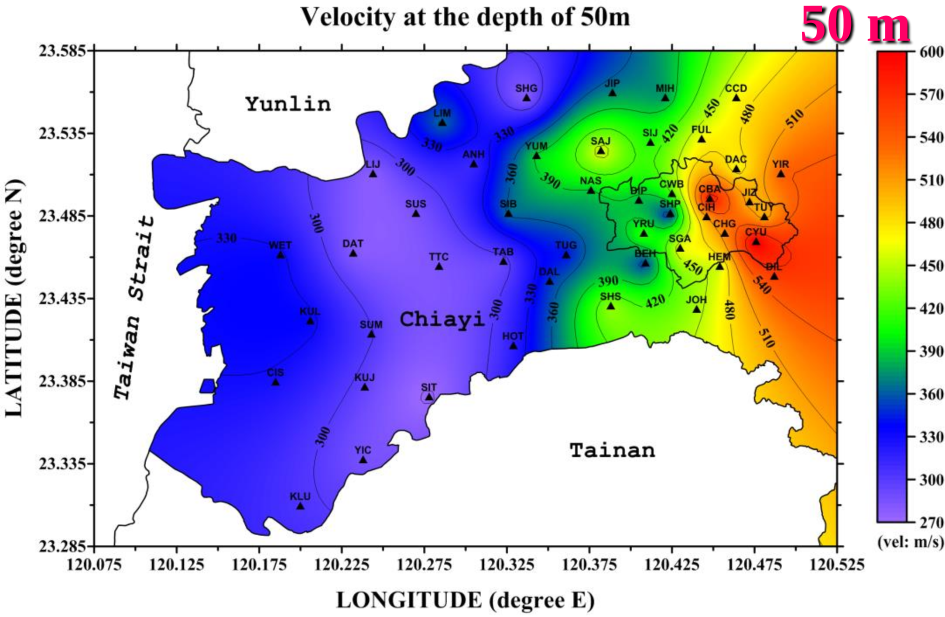
- **Estimated S-wave velocity structures by differential inversion at all 46 sites.**
- **We assume that the Pliocene formation is regarded as bedrock and then the averaged V_S of the basement is about 1500 m/s (Lin *et al.*, 2009).**
- **The depths of the Quaternary sediments are between 560 m (DIL) and 1400 m (KLU).**

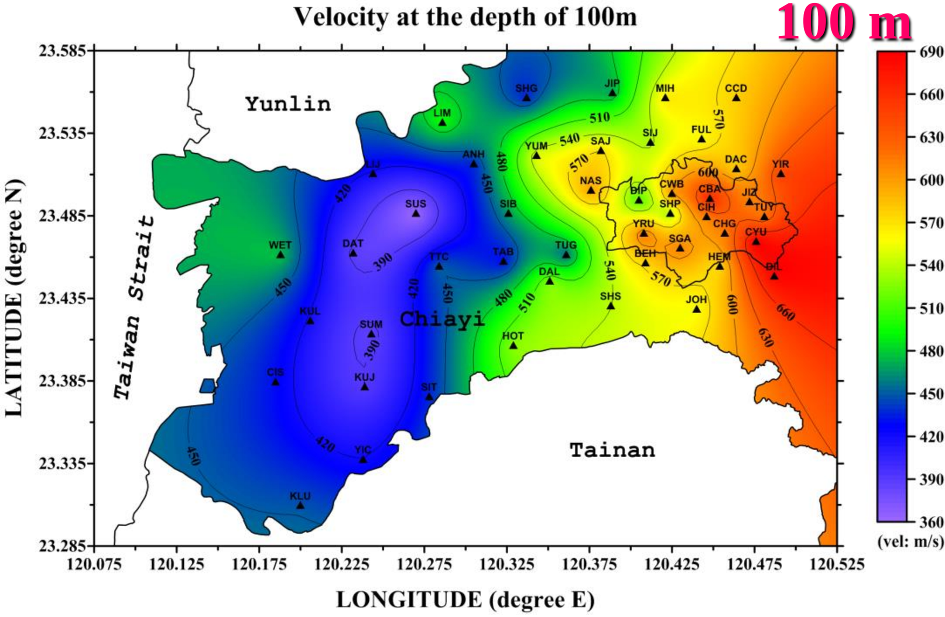


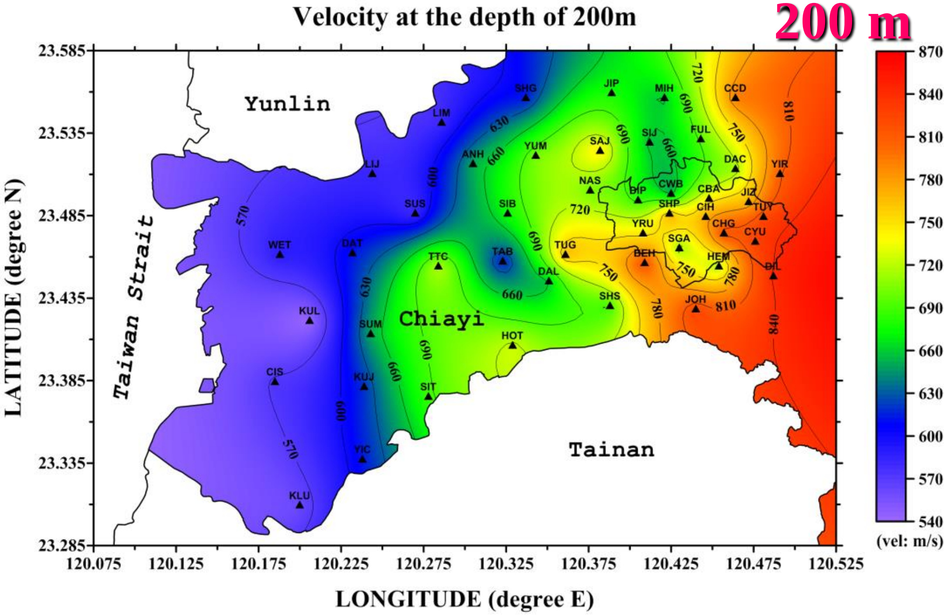


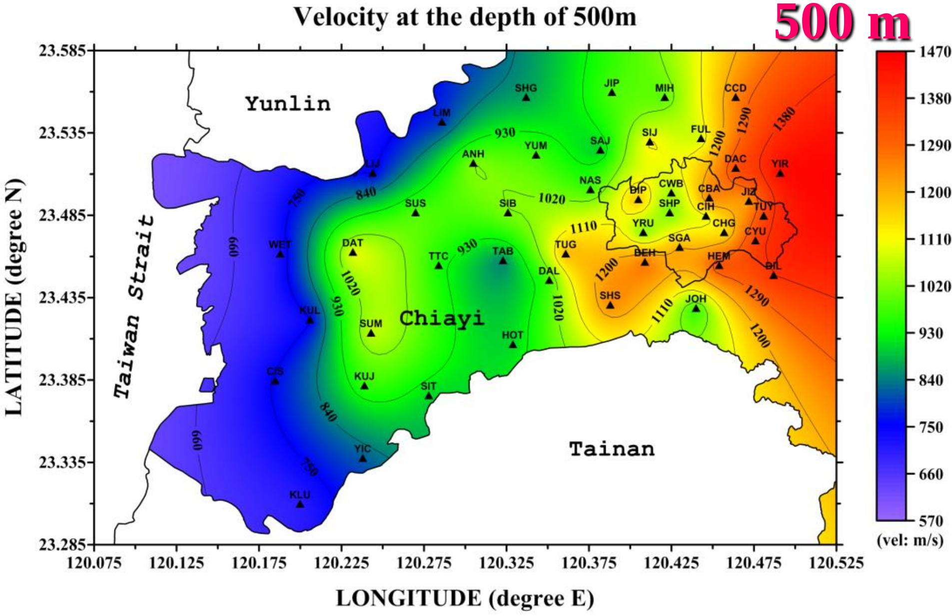


V_S contour maps at depths between 50 m and 500 m



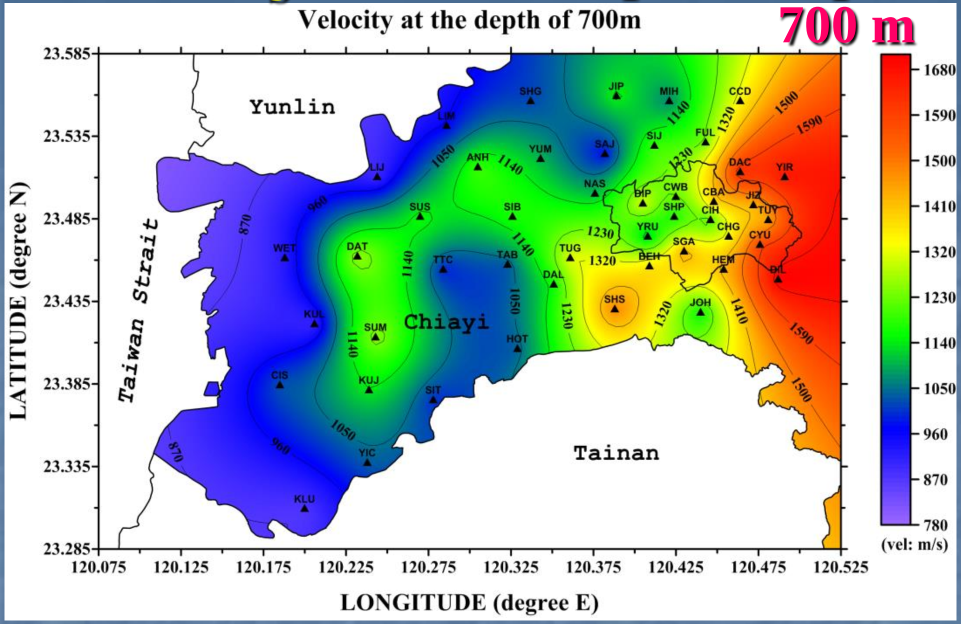


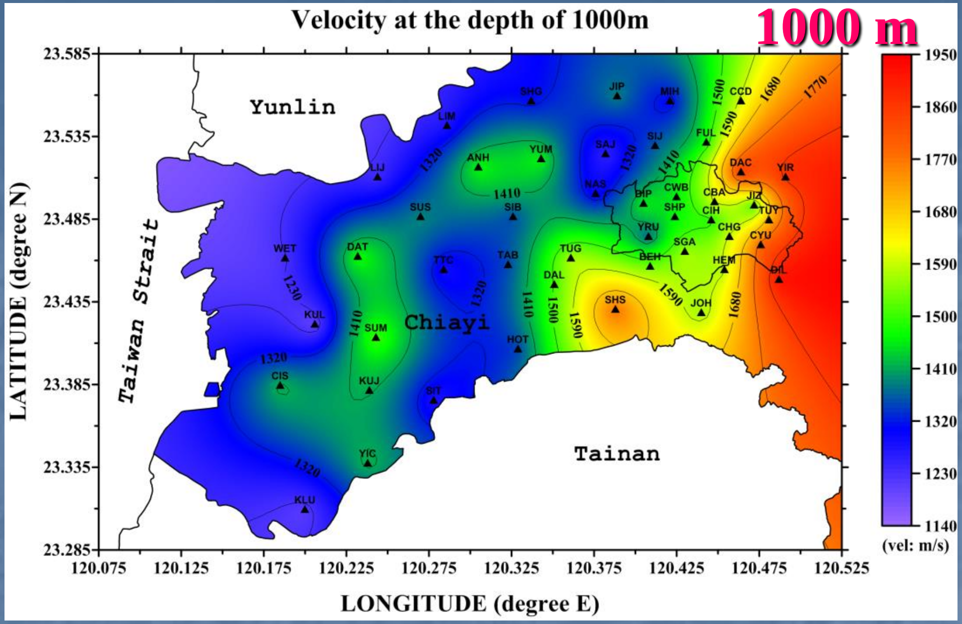


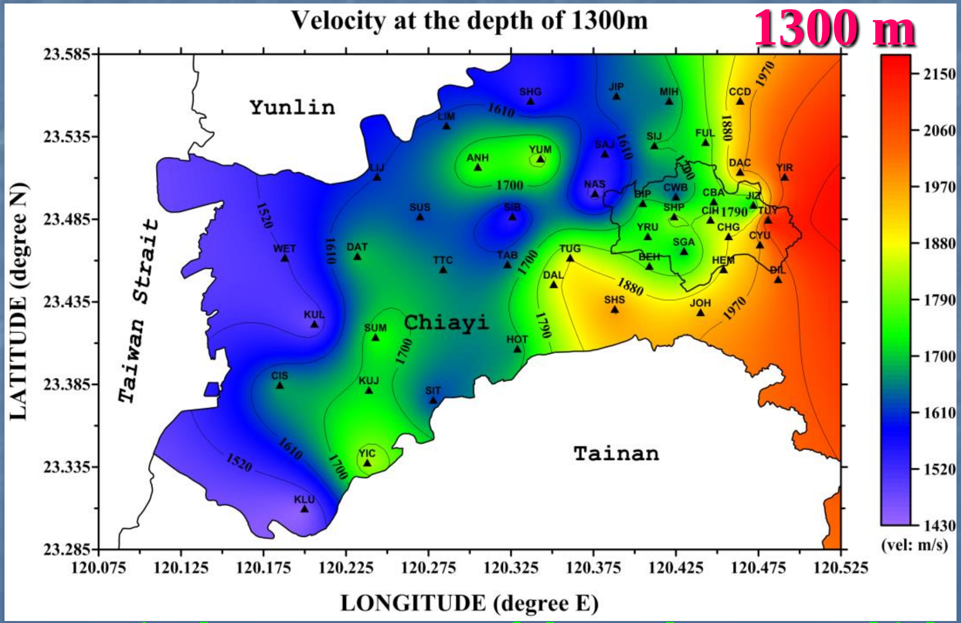


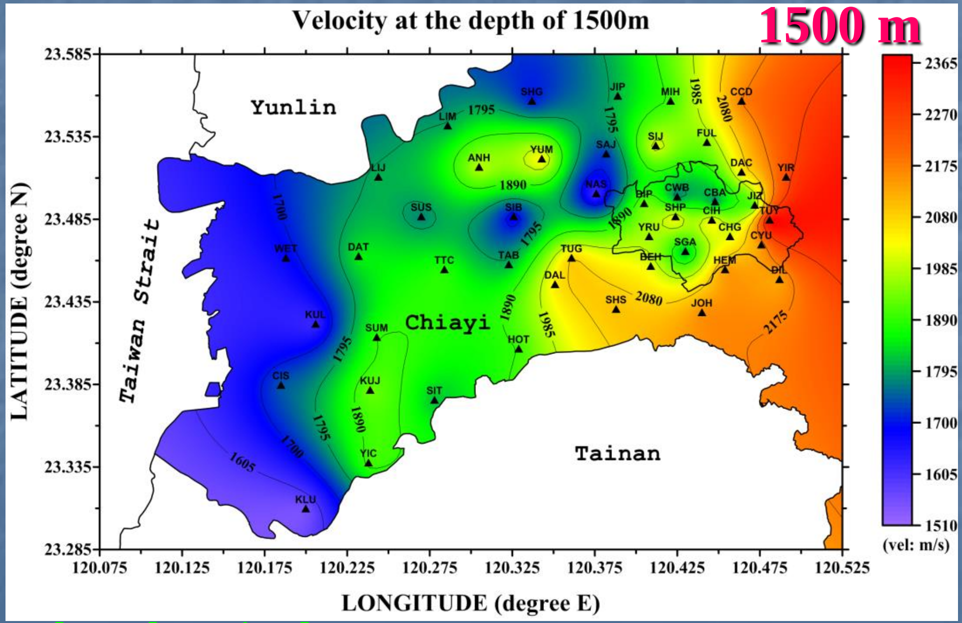
- V_S in the whole area do not exceed 1500 m/s.
- V_S in the eastern part of the study area are higher than those in the western part.

V_S contour maps at depths between 700 m and 1500 m



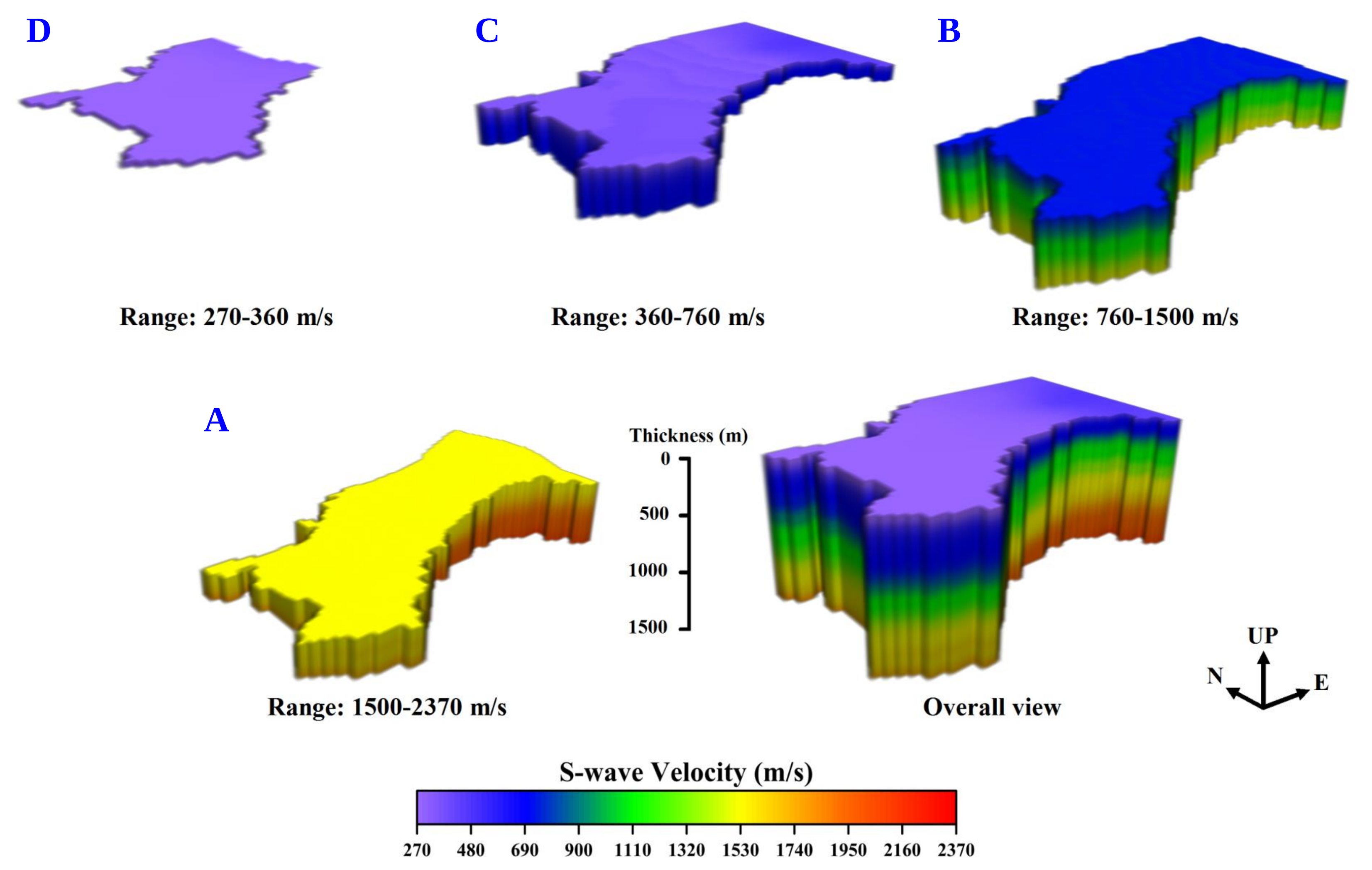






- V_S in the eastern part of the study area are higher than those in the western part.
- The relatively high V_S appear at some localized areas (e.g., DAT, SUM, ANH, and SHS) in the central and western parts.

3D Images of V_S structures



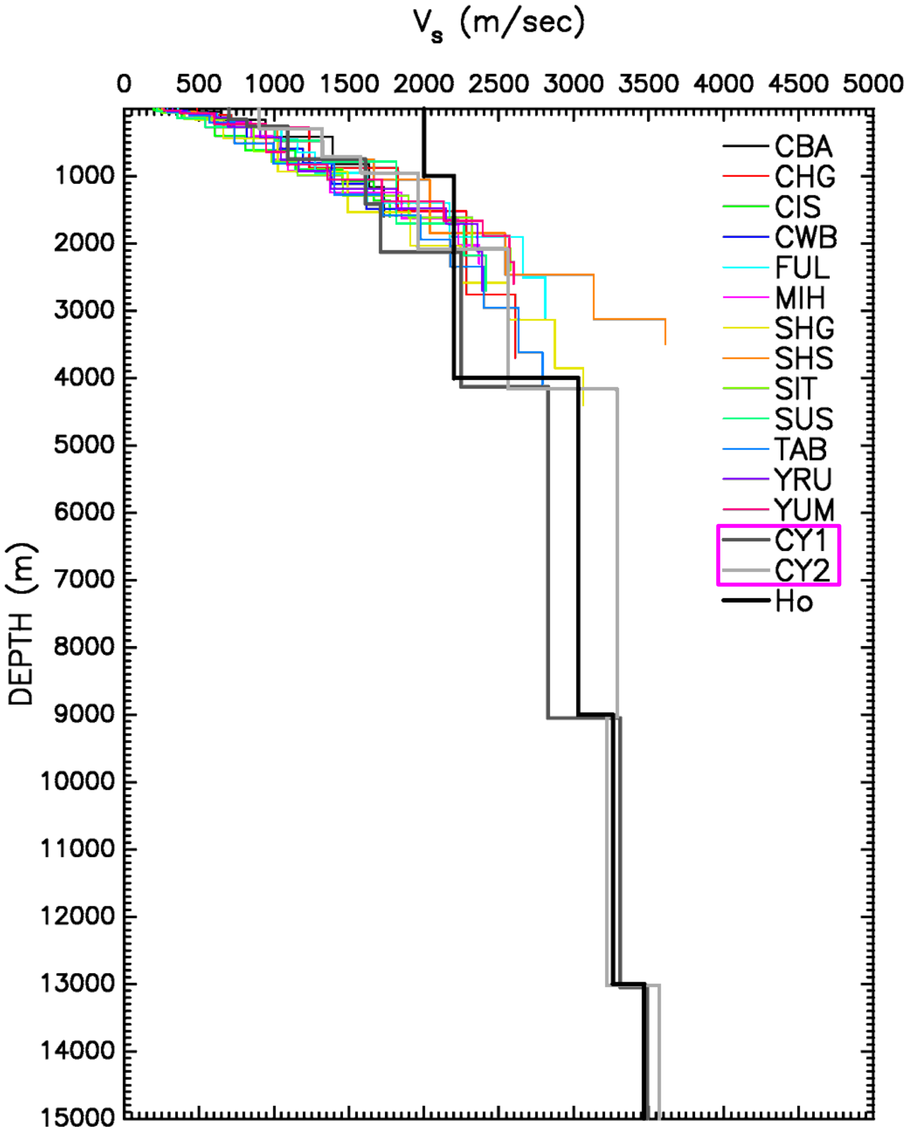
- Based on the Uniform Building Code (ICBO, 1997) and National Earthquake Hazard Reduction Program (BSSC, 1998), site class descriptions can be divided into six categories (A–F).
- V_S < 1500 m/s: the thicknesses of these velocity intervals decrease from west to east, which may be related to the depositional environment of this area.
- V_S > 1500 m/s: variation in thickness decreases from east to west.

CASE 2B:

1-D Broadband Strong Motion Simulation of the October 22, 1999 Chiayi, Taiwan Earthquake Using Stochastic Green's Function Method

Wu, C.F. and H.C. Huang (2016), to be submitted to GJI.*

Velocity models & Q values



We integrate shallow velocity structures (Wu and Huang, 2013) with the crustal velocity structures (Chung and Yeh, 1997; Ho, 1994).

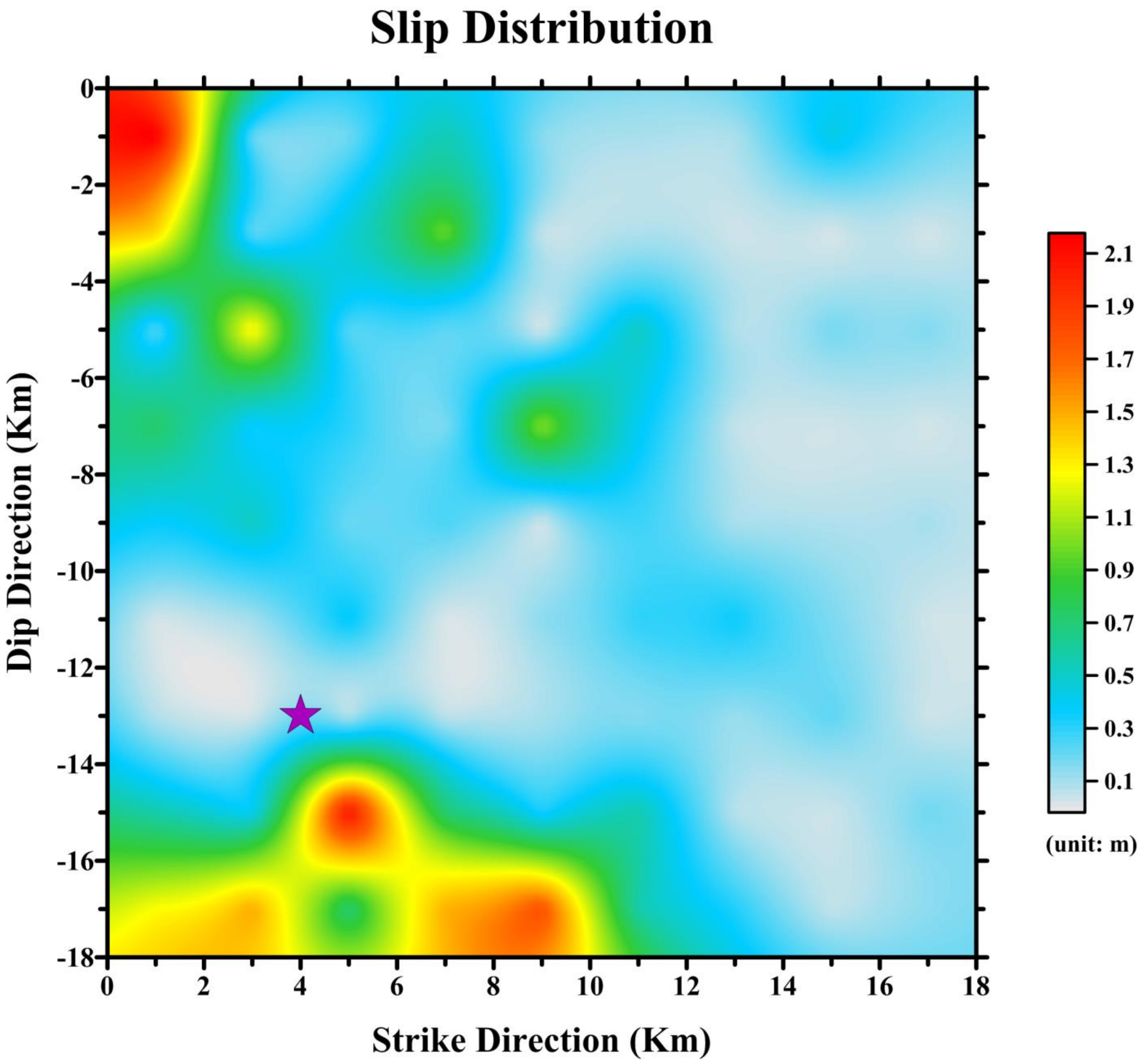
$$V_P = 1.29 + 1.11 V_S$$ **(Kitsunezaki *et al.*, 1990)**

$$\rho = 0.23(3081.5413 V_P)^{0.25}$$ **(Gregory, 1977)**

$Q(f) = Q_P f^{0.8}$ $Q(f) = Q_S f^{0.8}$

Depth (km)	**Q_P**	**Q_S (Q_P/2)**
0-5	**123**	**62**
5-10	**141**	**71**
10-30	**245**	**123**

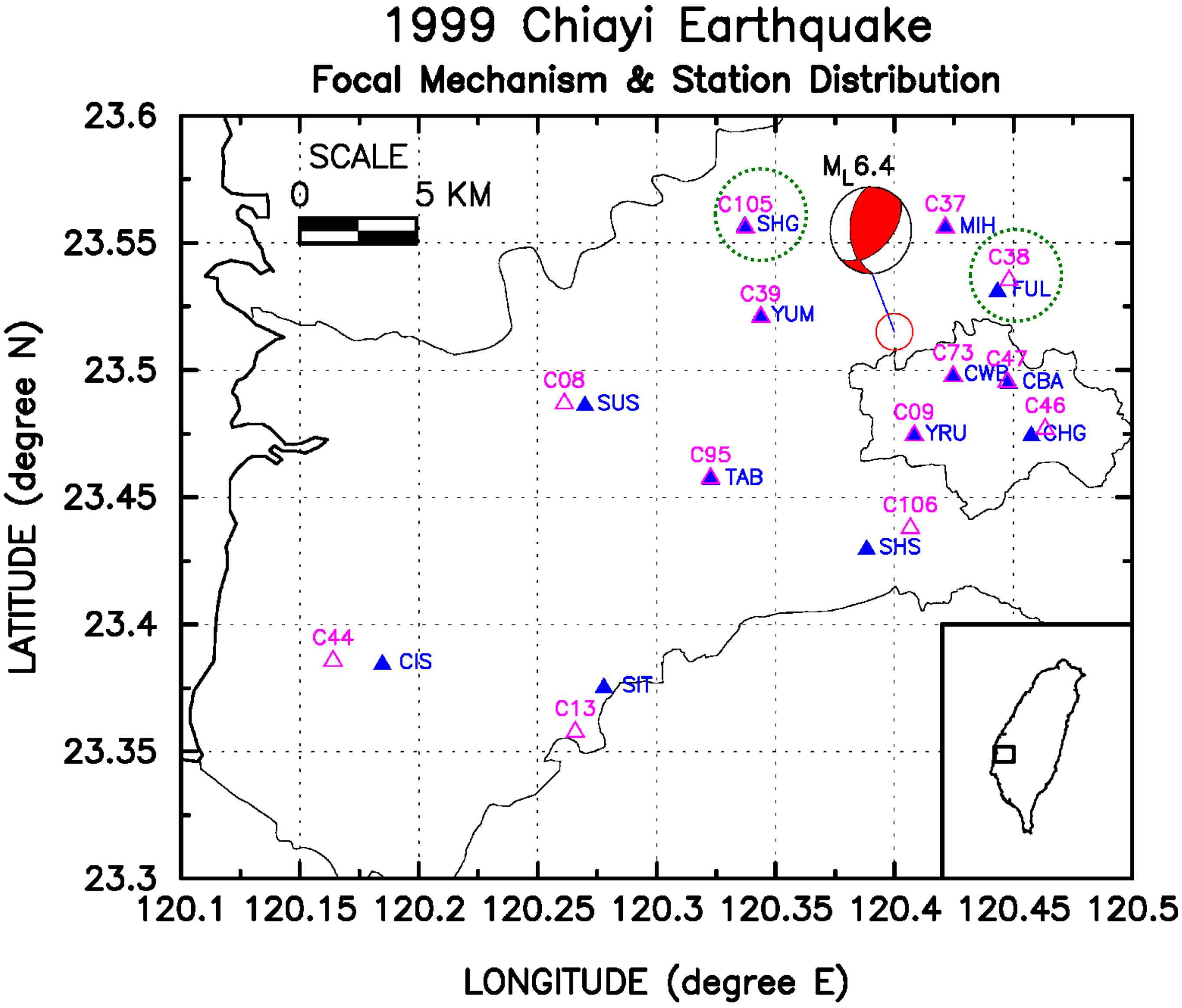
(Ji, 2006)



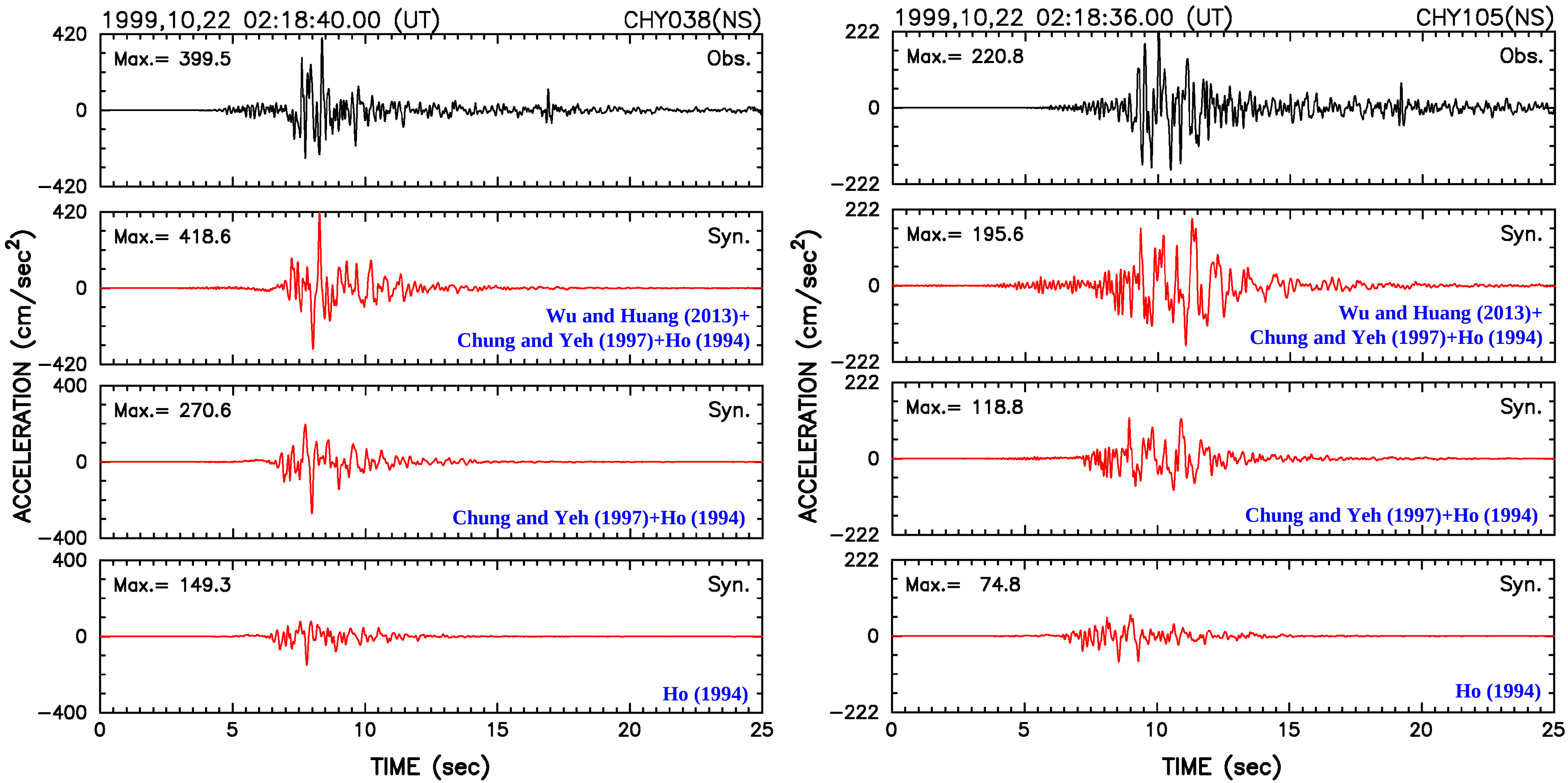
- **Using hybrid blind deconvolution method and genetic algorithm**
- **Fault dimention: 18 km × 18 km**
- **No. of Subfualts: 9 × 9**
- **Slip variations: 0.004-2.2 m**

(modified from Liao, 2006)

Influence of shallow velocity structures

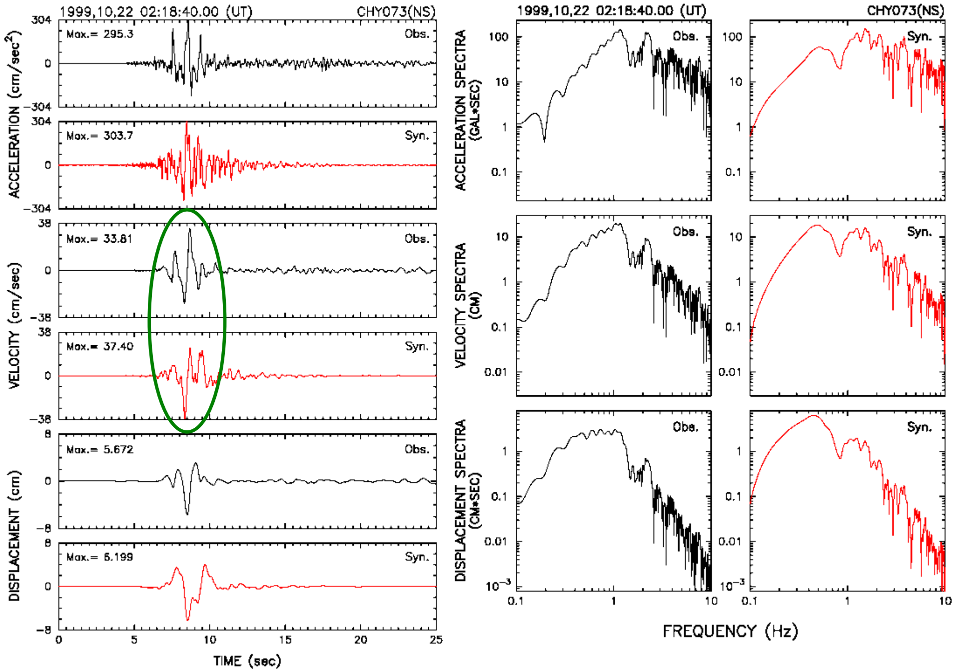


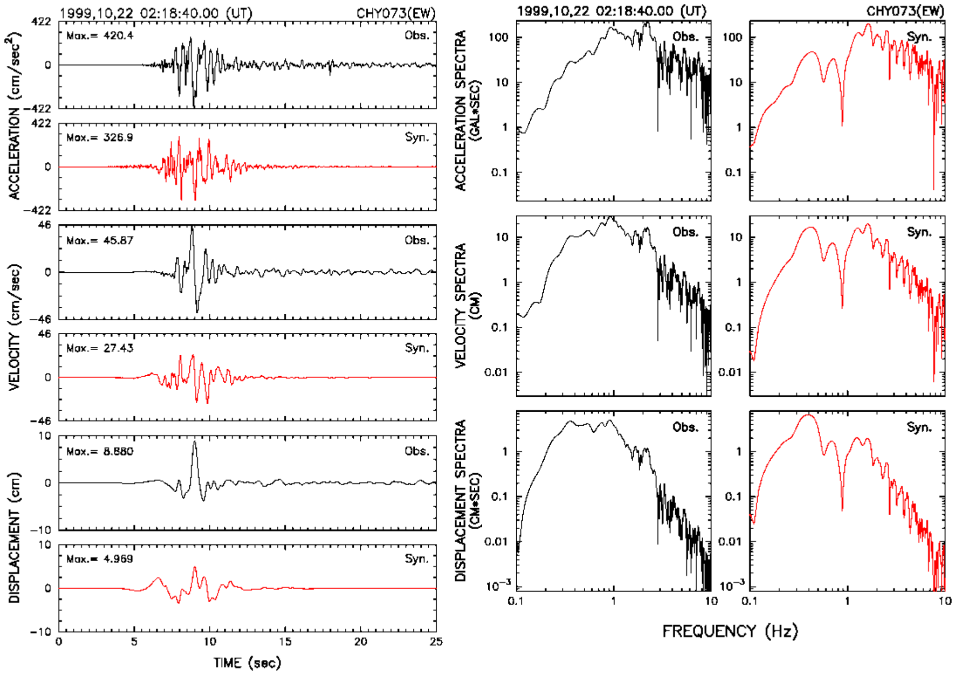
Influence of shallow velocity structures



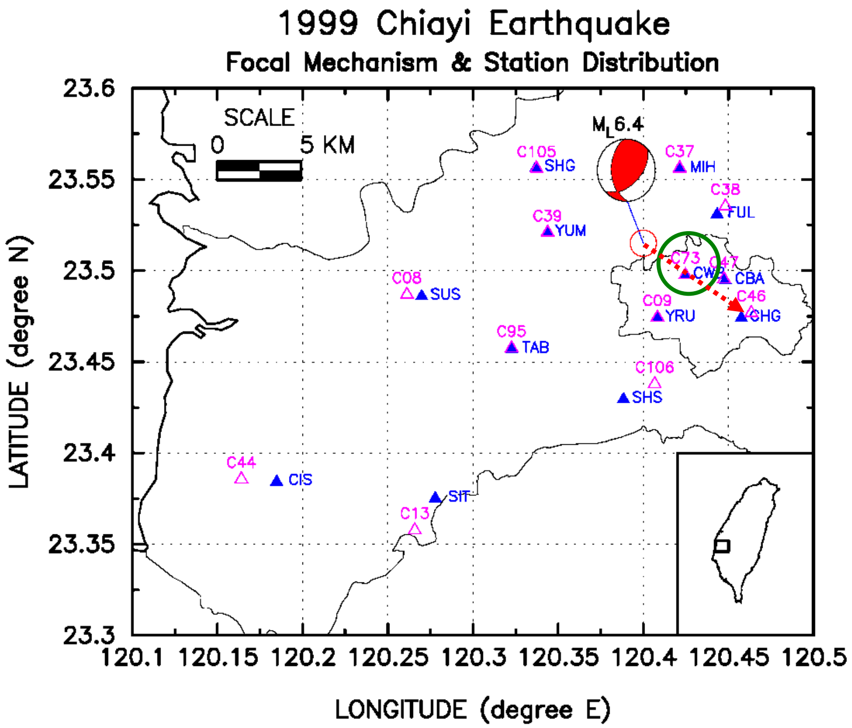
- If we integrate the shallow velocity structures with the crustal velocity structures, the synthetic results are well improved in amplitude and phase and similar to the observed data.
- It indicates that the shallow velocity structures not only play a very important role in the site amplification but also improve the simulation results.

CHY073

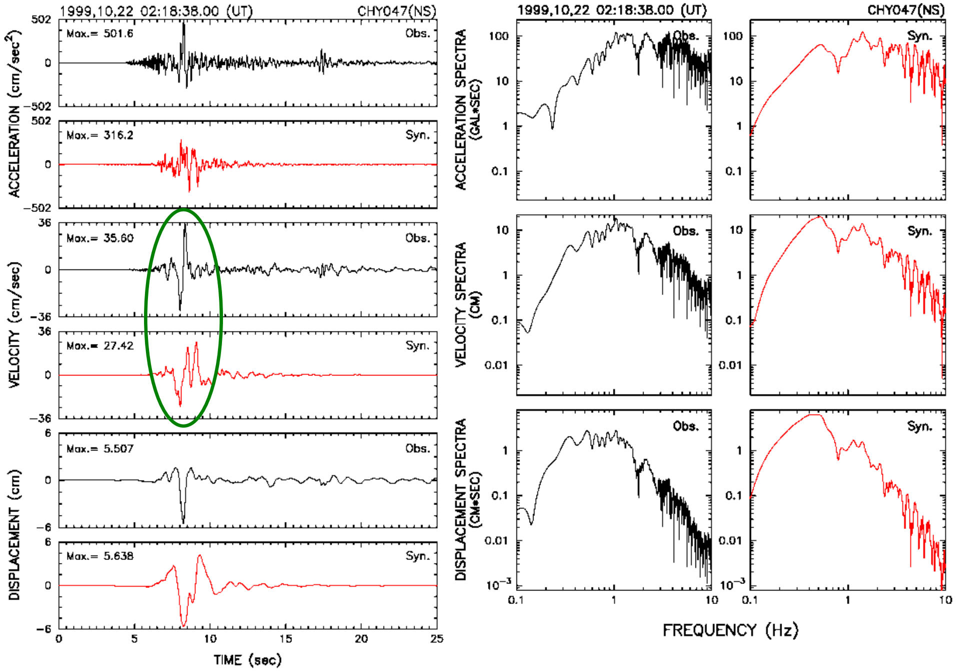


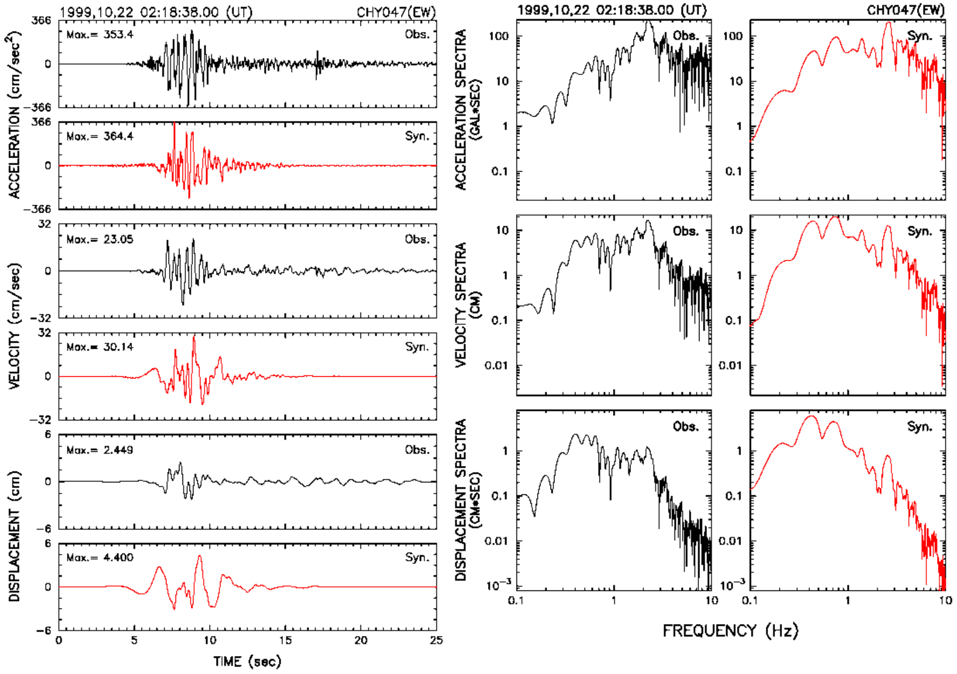


- Synthetic waveforms are similar to observed data.
- Velocity waveform shows the forward directivity pulses, namely, large amplitudes and short durations.

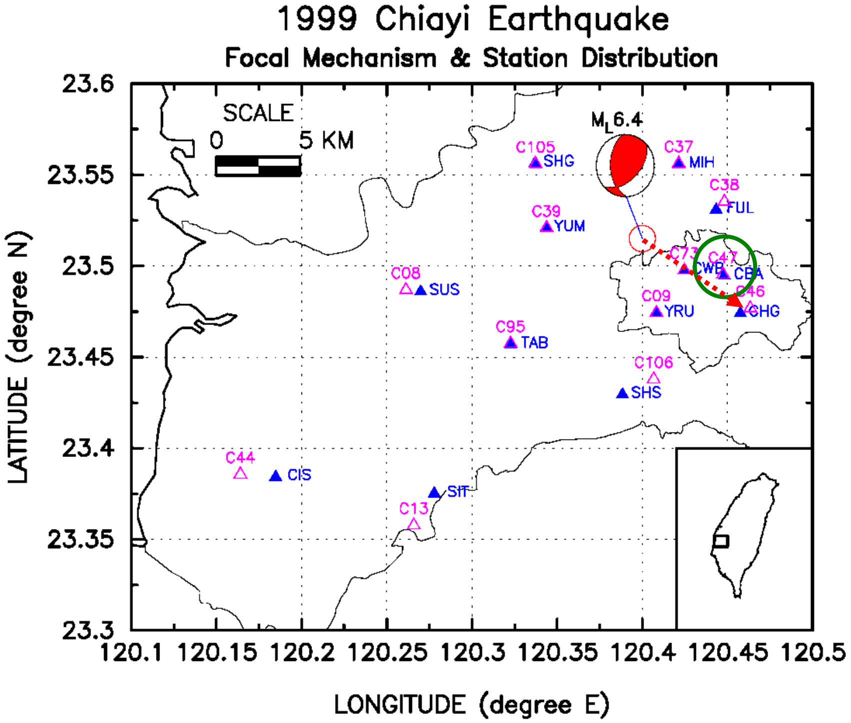


CHY047





- The coherent waves (directivity pulses) are also successfully reproduced at CHY047.
- They both (CHY047 & 073) are located in the rupture direction.

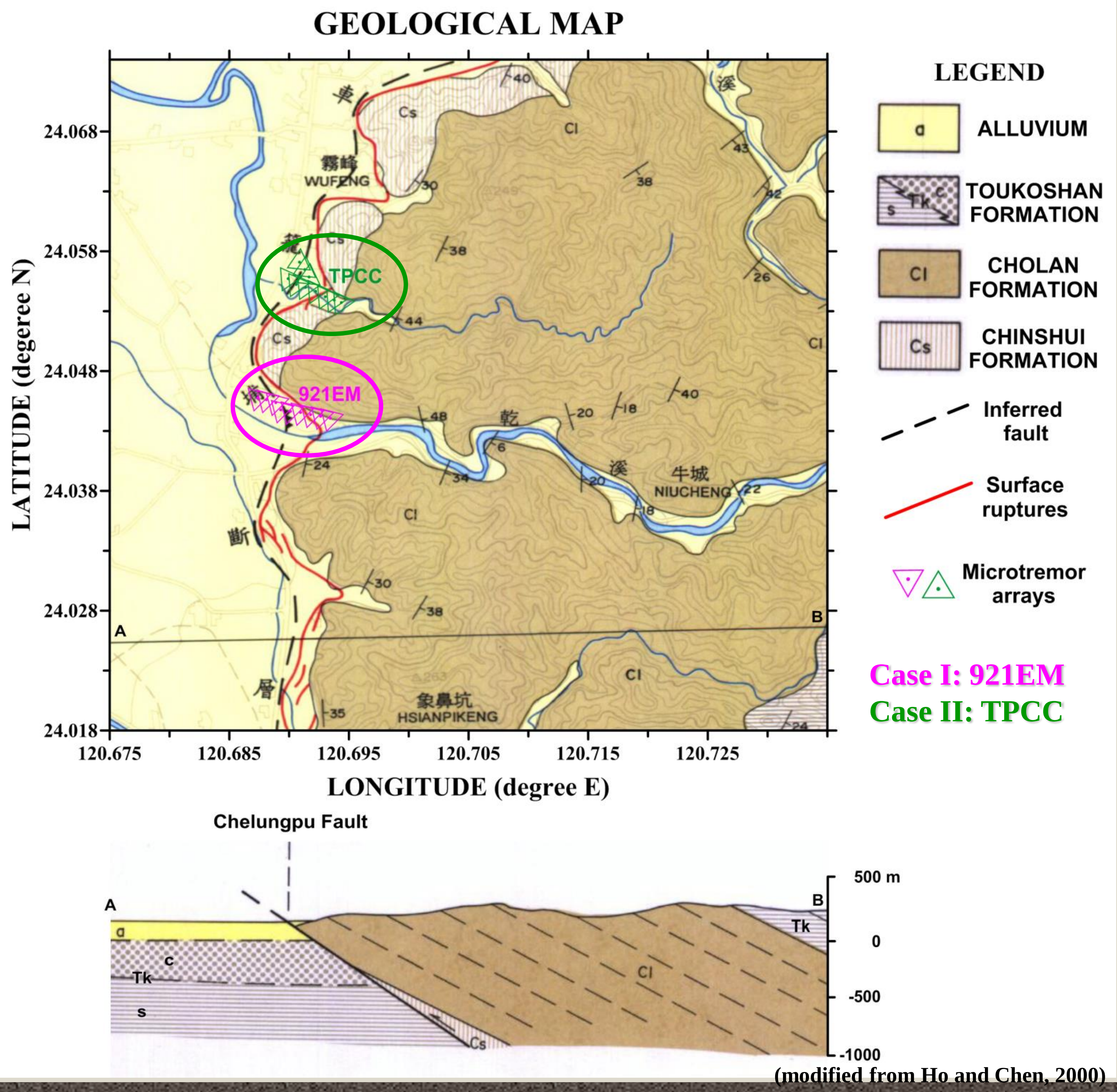


CASE 3:

Detection of Fracture Zones of Chelungpu Fault Using Microtremor Array Measurement

Poster: P108B

Wu, C.F. and H.C. Huang (2016). To be submitted GRL.



Case I: 921EM

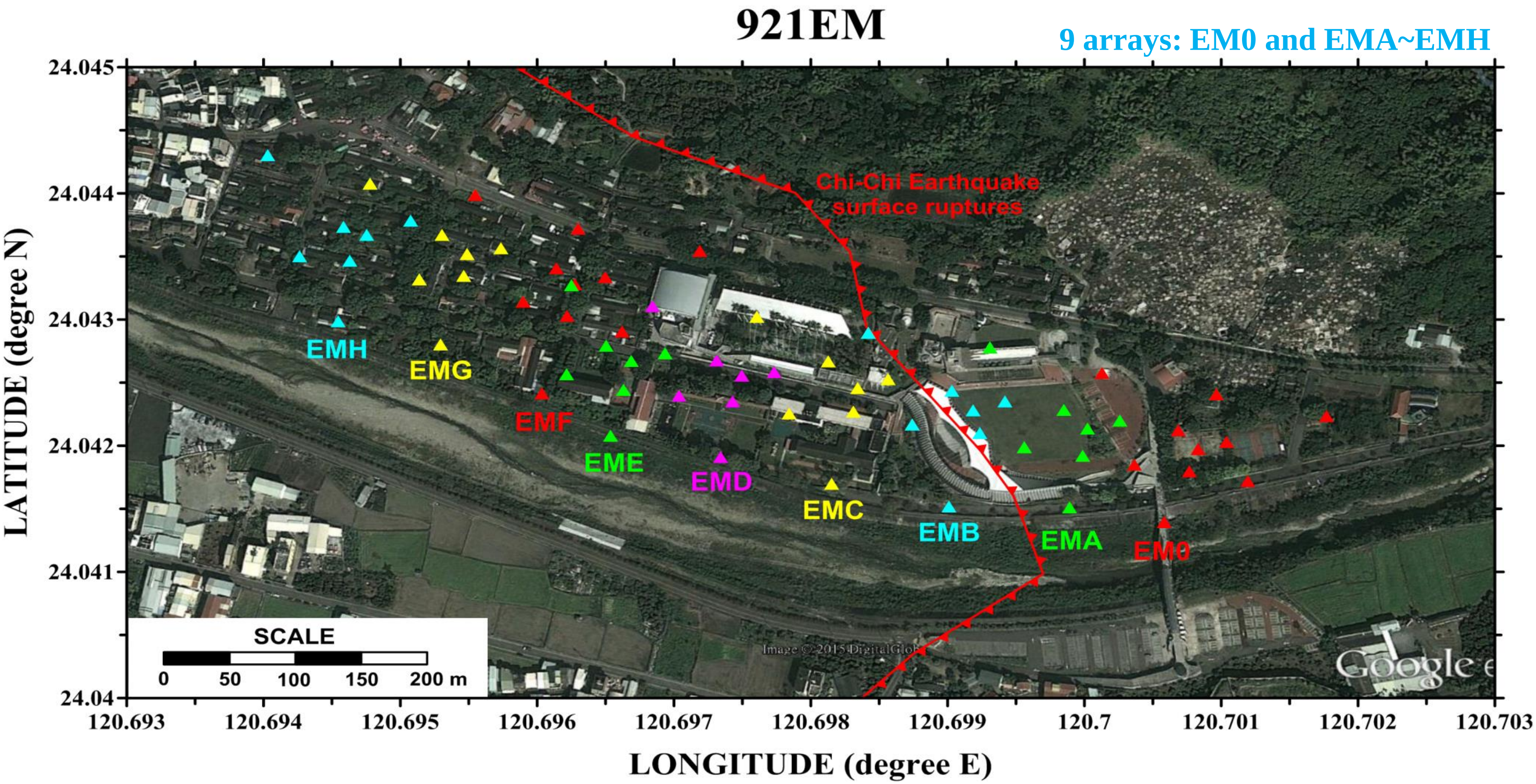
Case II: TPCC

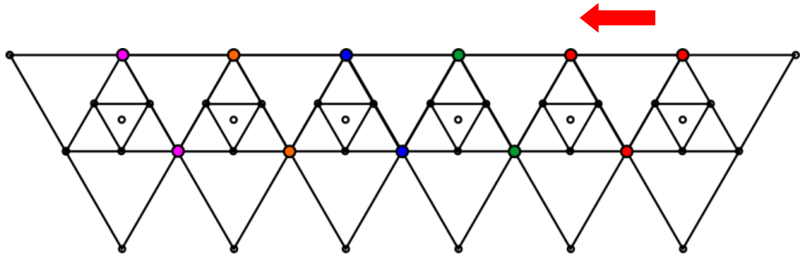
(modified from Ho and Chen, 2000)

Lithostratigraphy of TCDP-A:

(Lin *et al.*, 2007)

Geometries of the arrays (921EM)

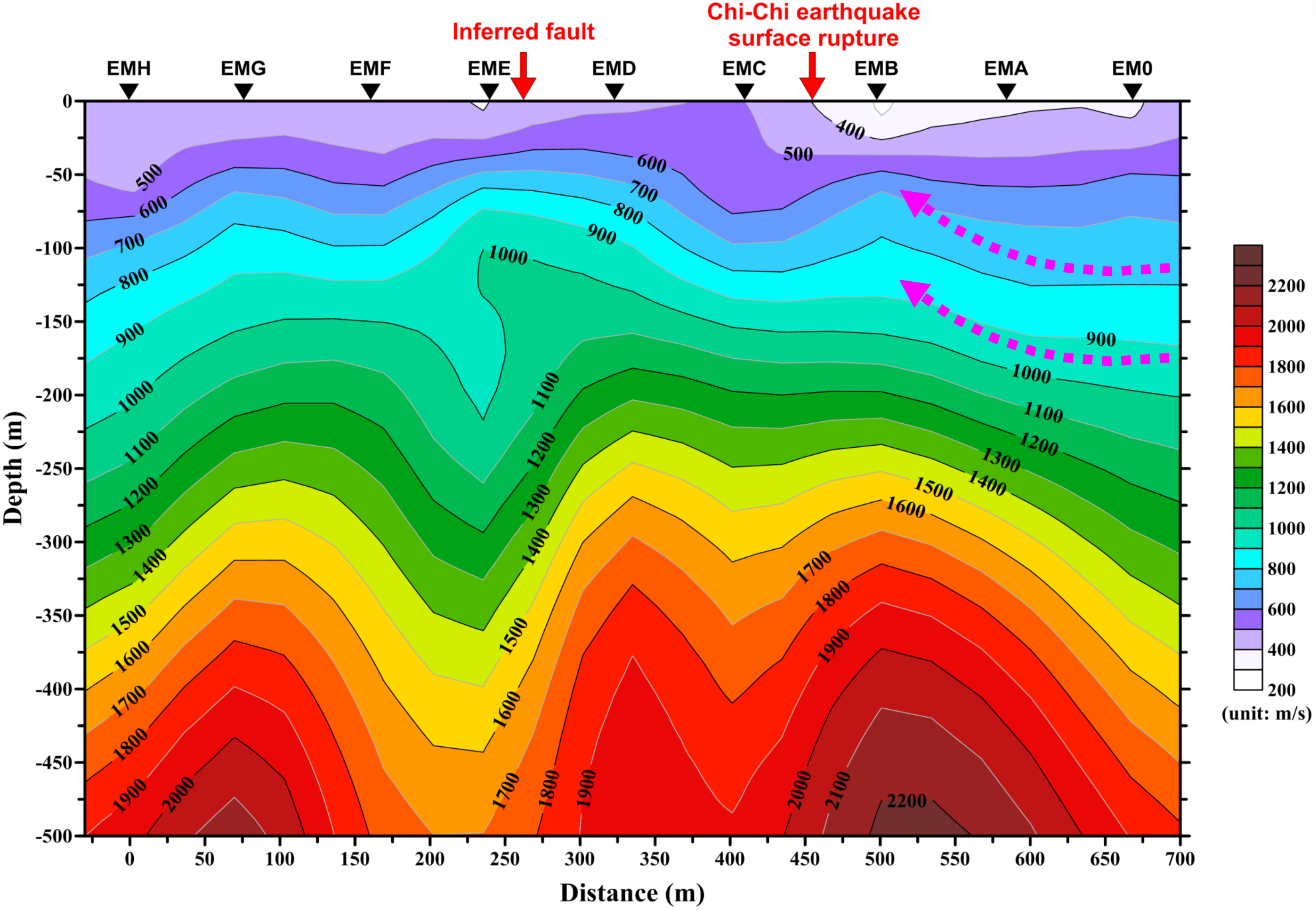




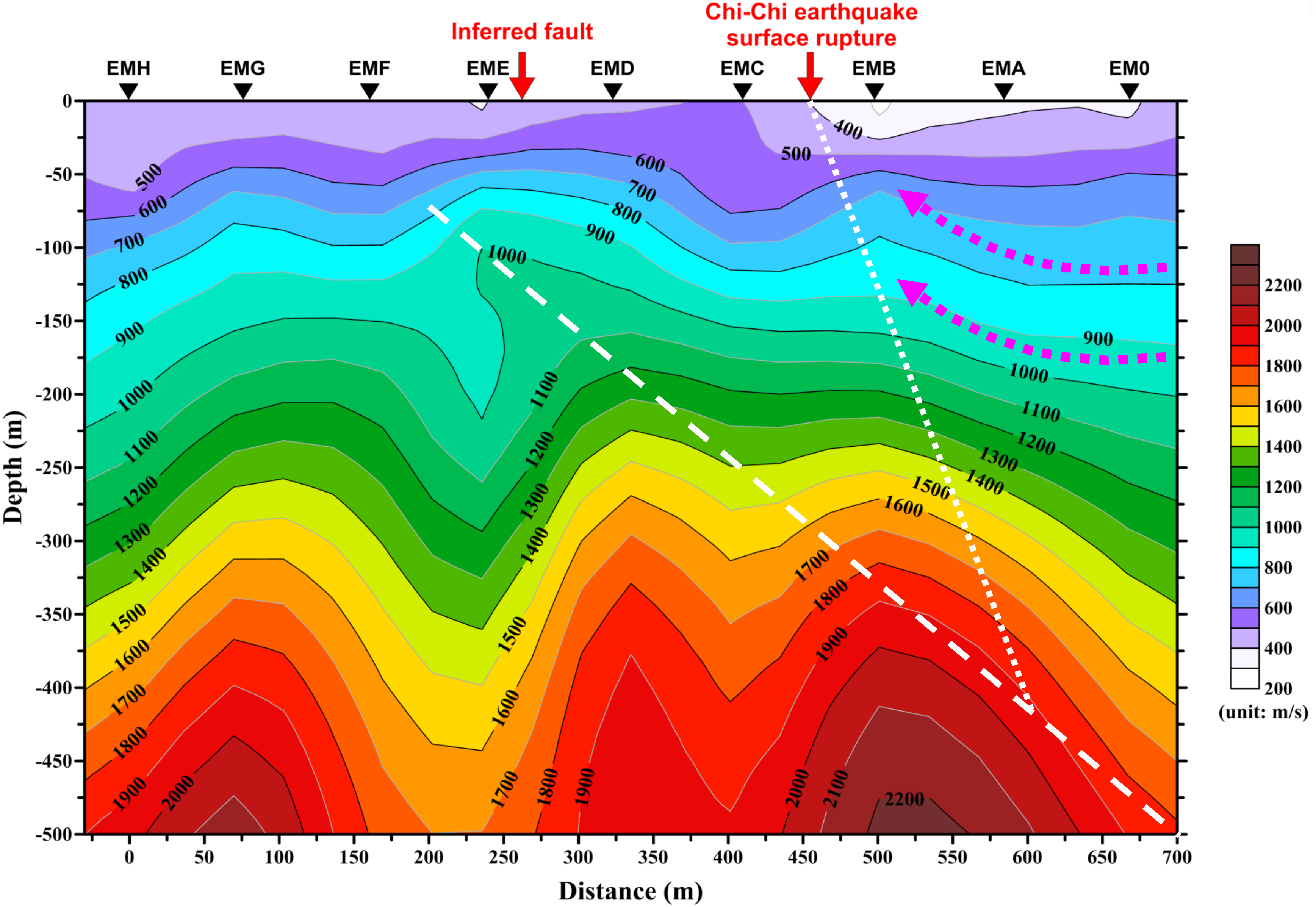
- 10 stations.
- 3 different-aperture triangles.
- Radii: 25, 50, 100 m.

- Sampling rate: 200 Hz
- Gain: 100
- Data length: 600 sec
- Recording length: 1-2 hr

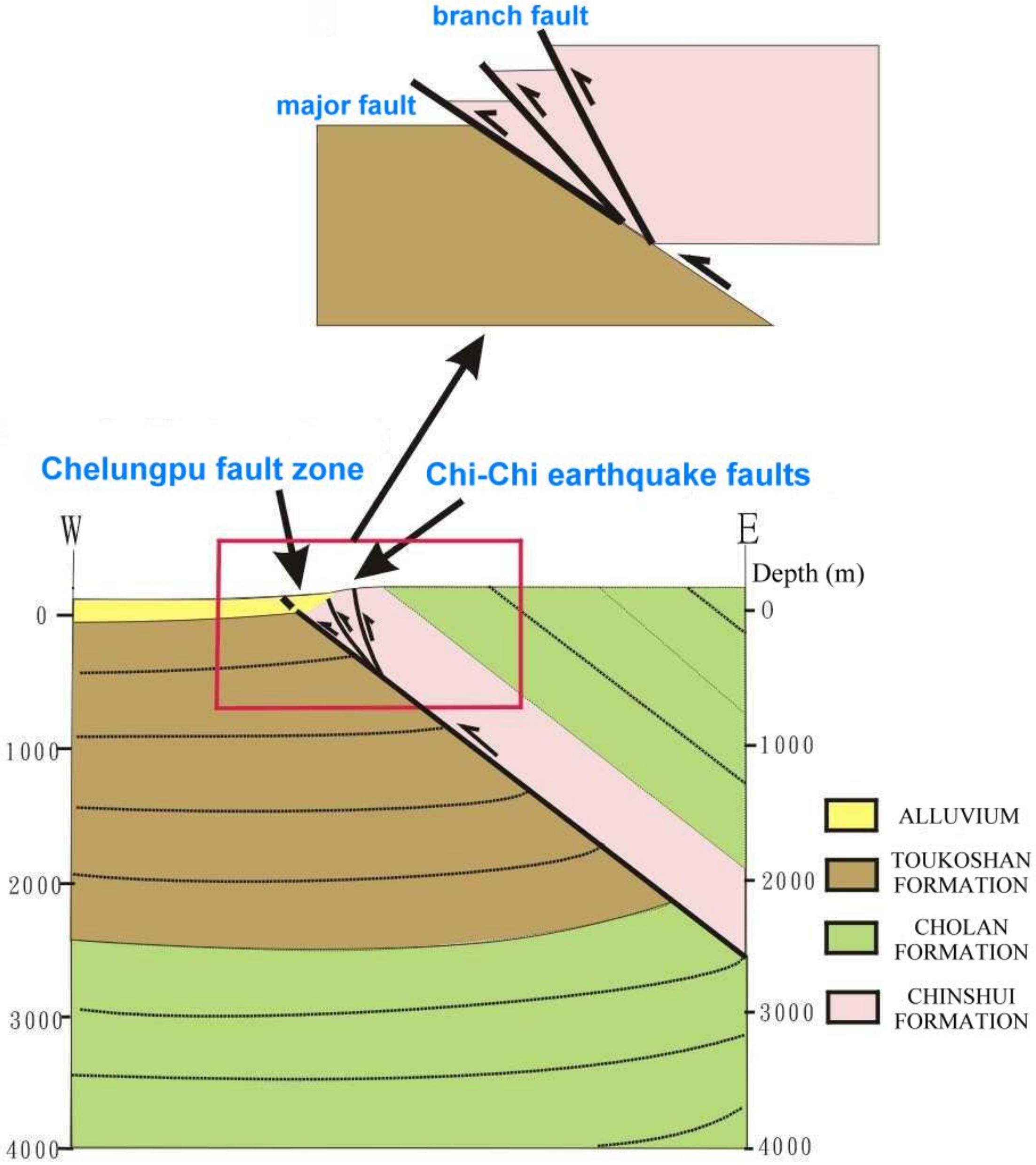
921EM



- The compressive and flexural deformation structures are shown obviously.
- Surface ruptures are located at the relatively weak (low V_S) zone (near EMB).
- These co-seismic flexural-slip folding structures commonly occurred in or near the surface rupture zone, which have an orientation in fold axes parallel or oblique to the surface rupture zone (Lin *et al*., 2001).



- **We can find a leading edge of fault plane under EME at depths of 100-150 m.**
- **We draw a major fault plane (dashed line) with an angle ~ 40˚ (Wang *et al*., 2002) and let it pass through the leading edge.**
- **A branch fault (dotted line) caused by the Chi-Chi earthquake with dip angle ~ 70˚(Chen, 2002; Wang, 2002).**



The surface deformation of the Chi-Chi earthquake was believed to be closely related to the imbricate splay faults at shallow depths, which were usually associated with a thrust fault zone on the surface (Huang *et al*., 2000).

(modified from Huang *et al*., 2000)

Thank you for your attentions!