Crustal Structure of Taiwan Orogen Constrained by Ambient Seismic Noises

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Surface wave tomography

Ambient noise technique

Wavelet-based multi-scale inversion

Crustal anisotropy

Orogenic model

RESEARCH

REPORT

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GEOPHYSICS

Layered deformation in the Taiwan orogen

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The underthrusting of continental crust during mountain building is an issue of debate for orogens at convergent continental margins. We report three-dimensional seismic anisotropic tomography of Taiwan that shows a nearly 90° rotation of anisotropic fabrics across a 10- to 20-km depth, consistent with the presence of two layers of deformation. The upper crust is dominated by collision-related compressional deformation, whereas the lower crust of Taiwan, mostly the crust of the subducted Eurasian plate, is dominated by convergence-parallel shear deformation. We interpret this lower crustal shearing as driven by the continuous sinking of the Eurasian mantle lithosphere when the surface of the subducted plate is coupled with the orogen. The two-layer deformation clearly defines the role of subduction in the formation of the Taiwan mountain belt.

GEOPHYSICS

How mountains get made

Observations of crustal deformation constrain models of mountain formation

By **Maureen D. Long**

Outline

* Plate tectonics
* How mountains get made
* Why study seismic anisotropy
* Information from surface wave
* Ambient noise tomography
* Crustal structures of Taiwan
* Layered deformation in the Taiwan orogen

Plate tectonics

Wilson cycle

(Press et al. 2003)

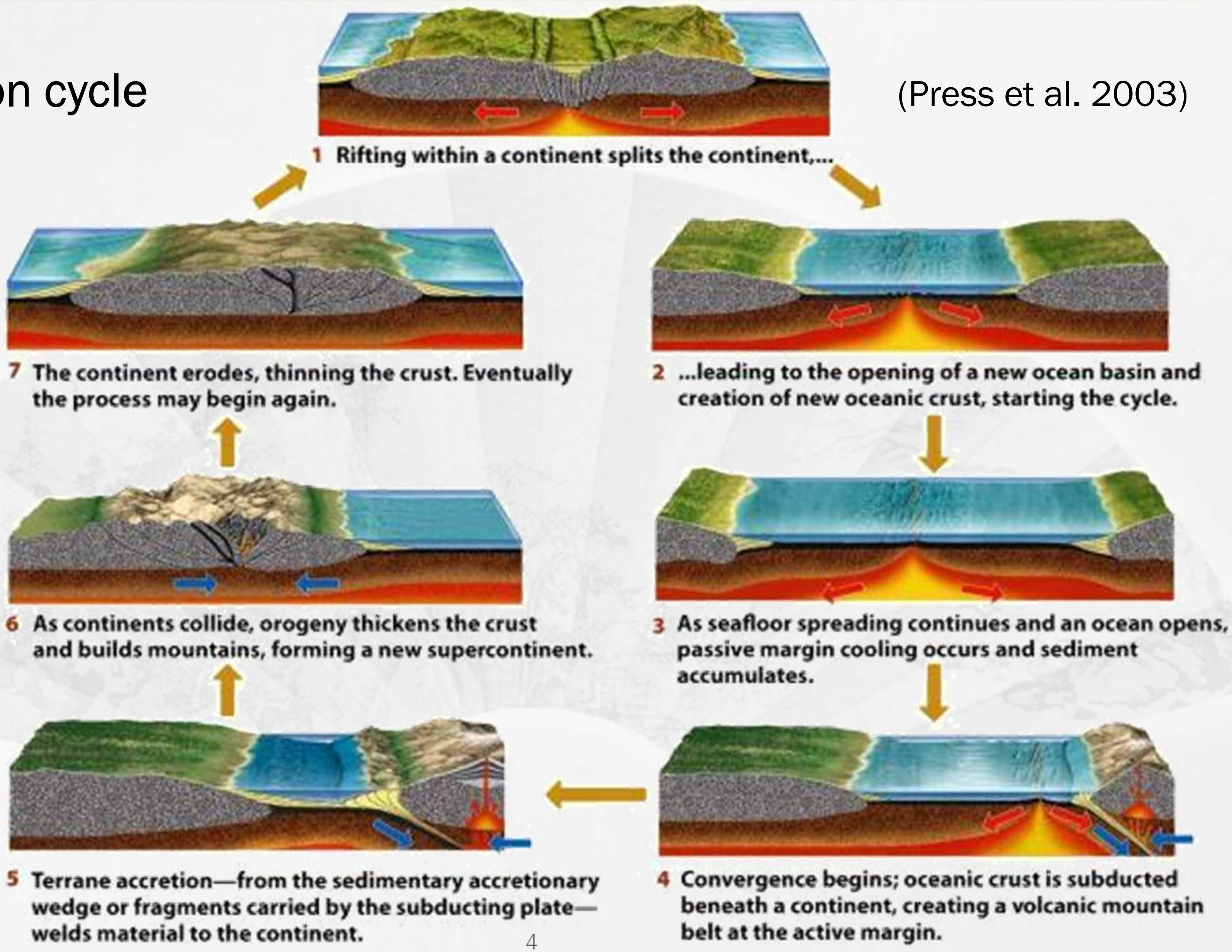
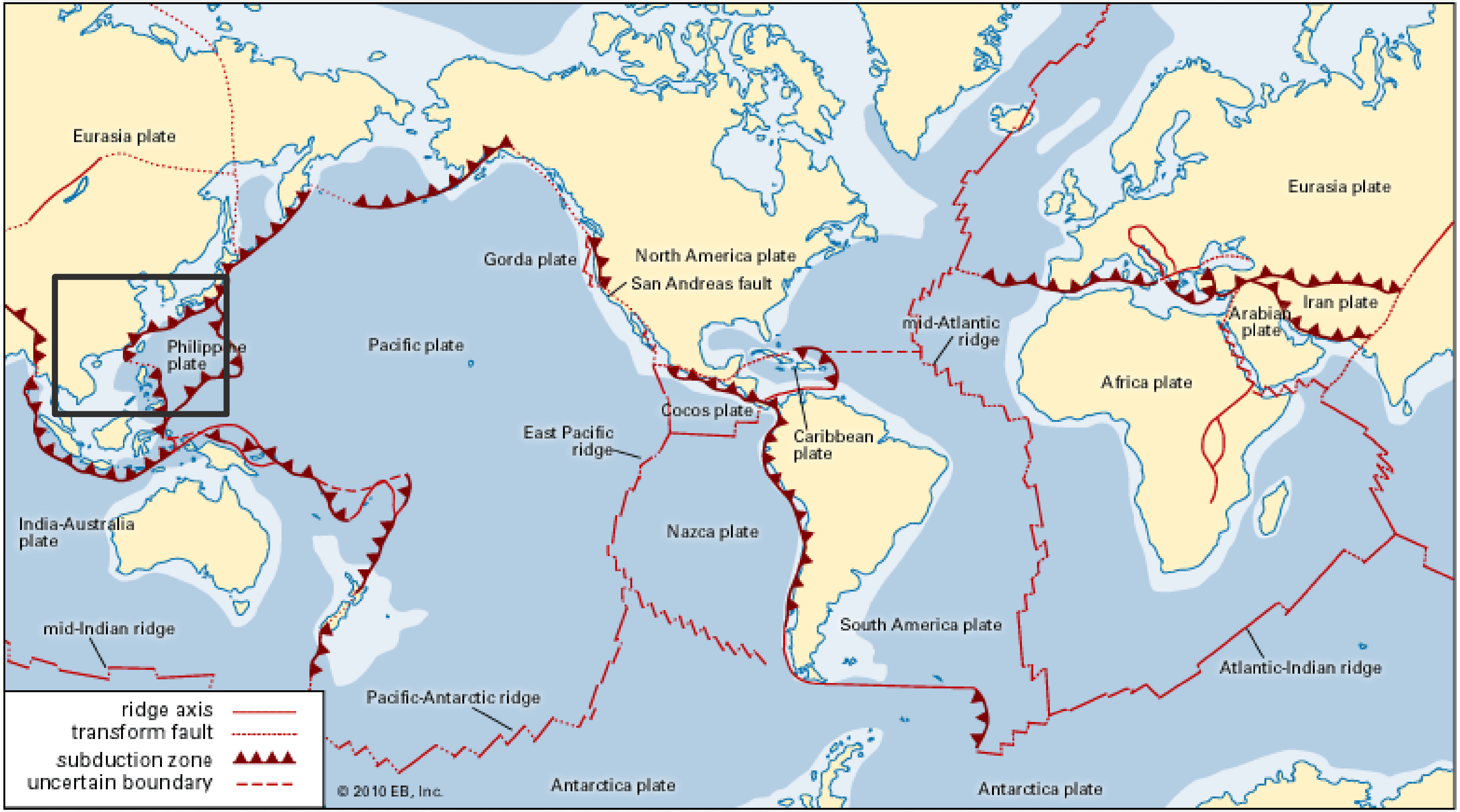
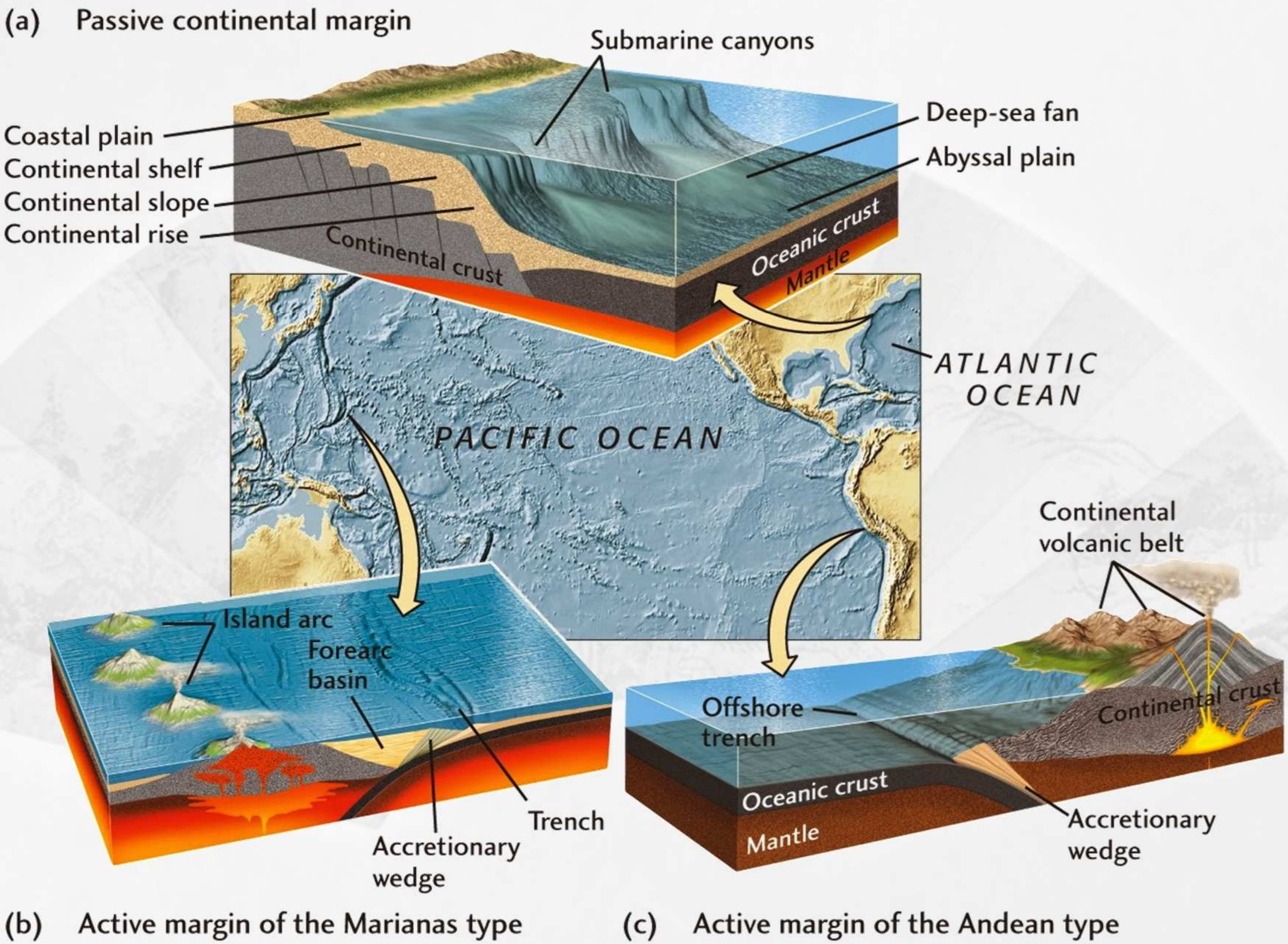


Plate tectonics



(http://media.web.britannica.com/)

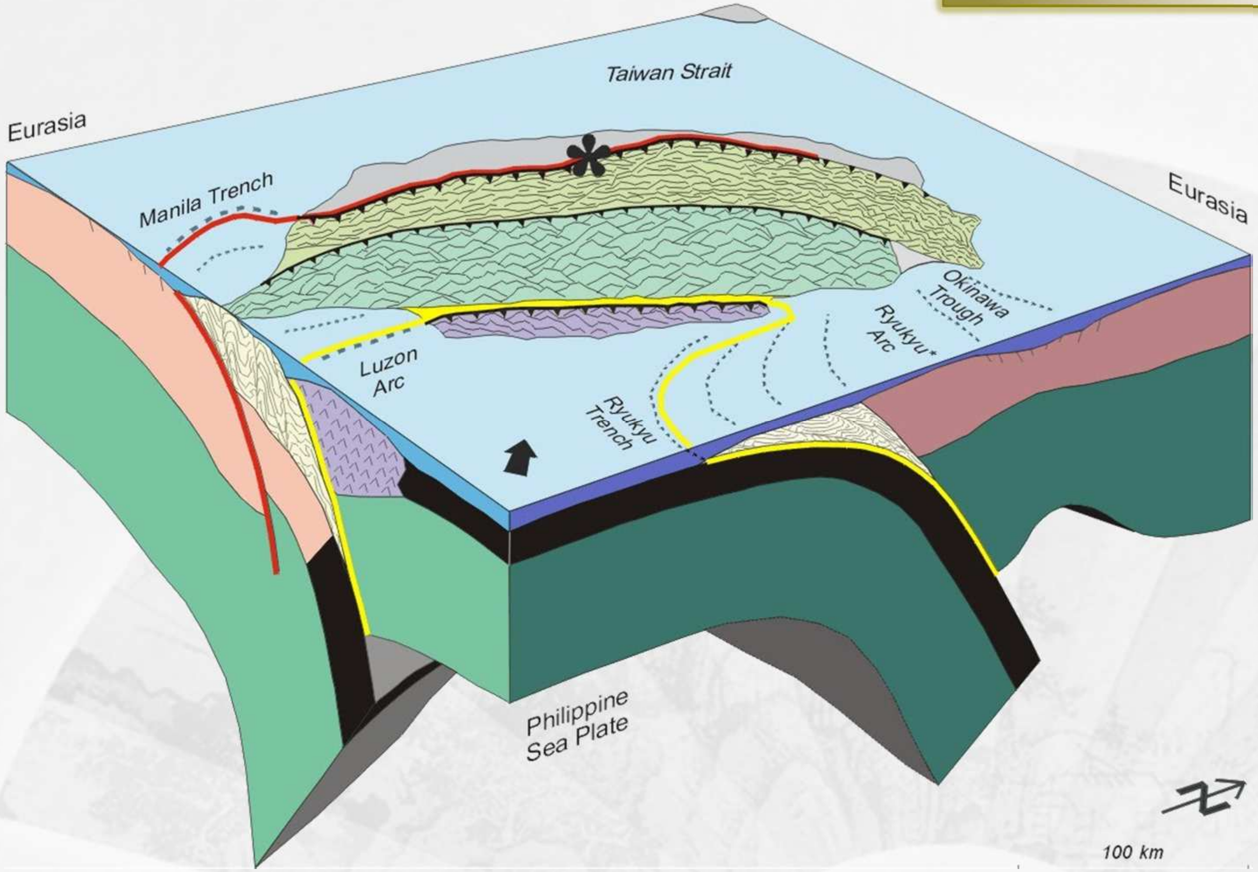
Plate tectonics



(http://www.geologyin.com)

Tectonics in Taiwan

(Angelier et al, 2001)



Northeast:
Ryukyu system
trench, trough,
volcanic arc

South:
Luzon system

The mountain building of Taiwan?

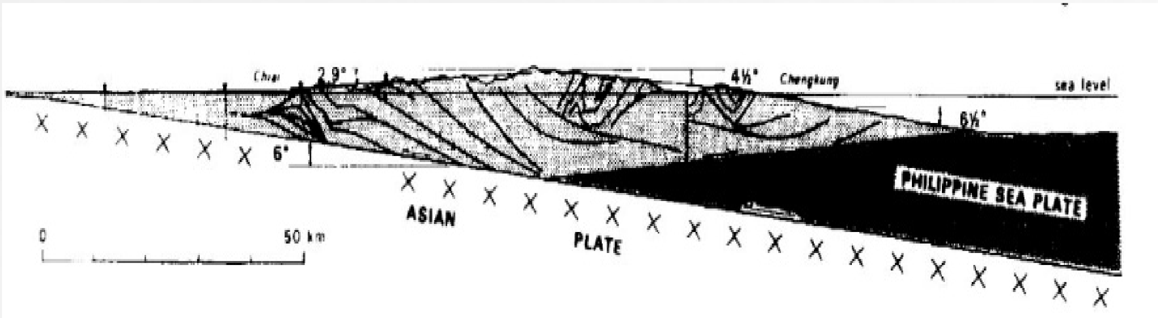
How mountains get made?

- Subduction or collision?
- Continental crust deforms to produce shortening and uplift
- Thin-skinned and thick-skinned models:
  How the deep crust deforms
  → Décollement or mountain root ?
- Geodynamic problem
  → Seismic tomography and anisotropy

Taiwan orogen

Thin-skinned:

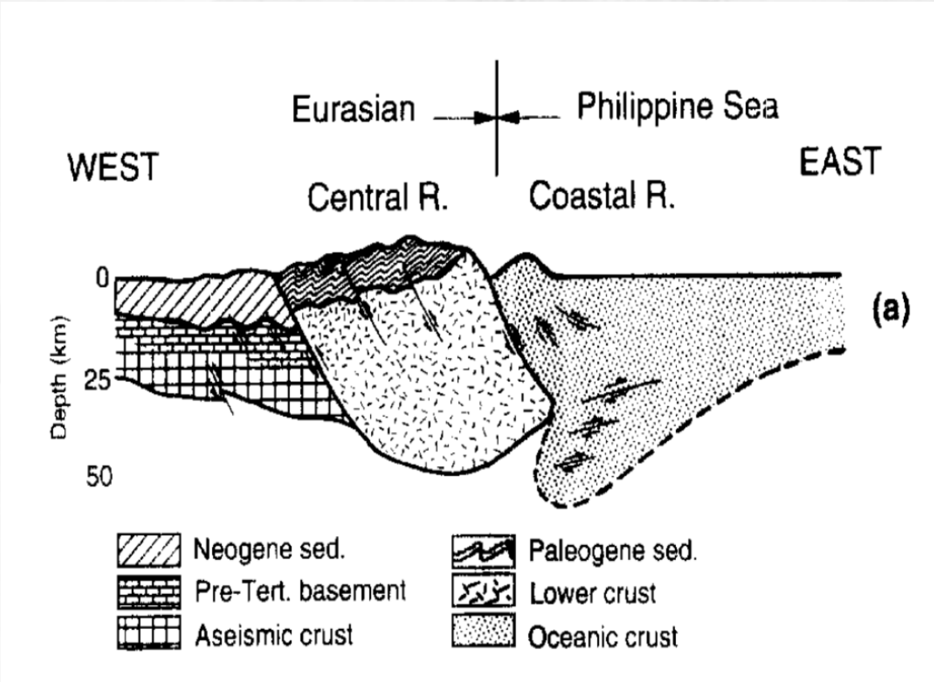
Critical tapered wedge



(Suppe, 1981)

- Thrust and fold belt
- Topography
- Main detachment

Decoupled



Thick-skinned:

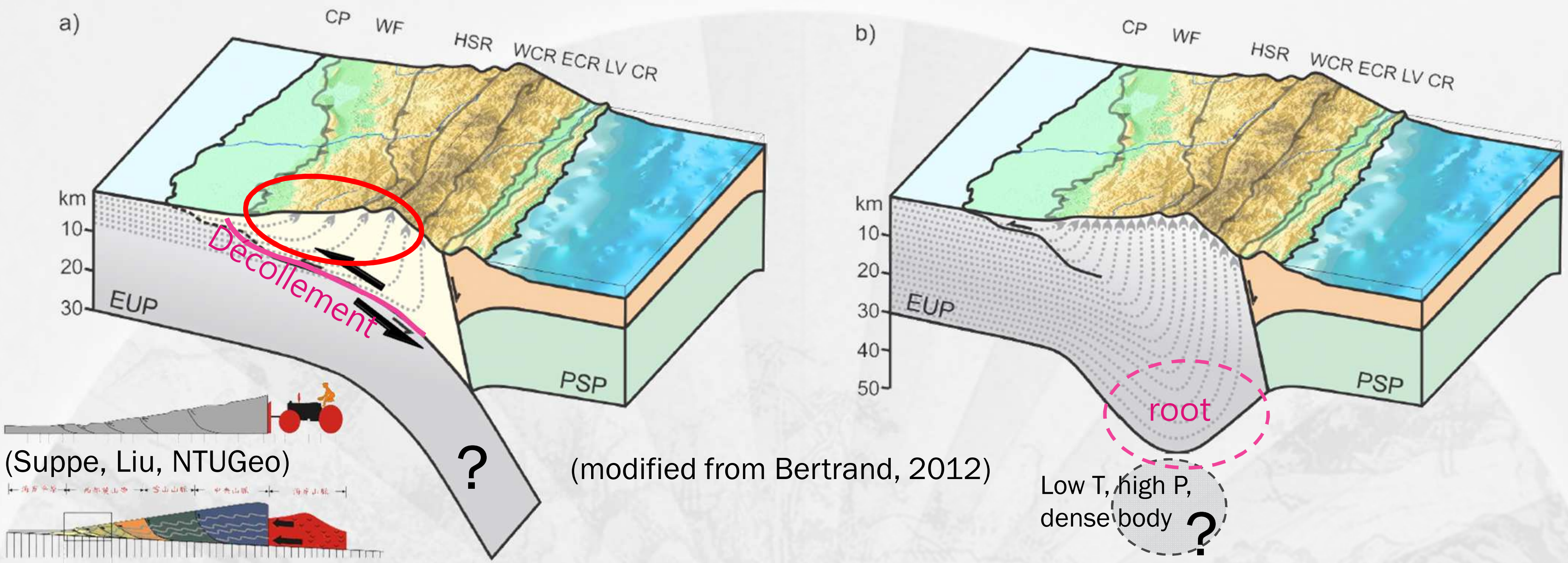
Lithospheric collision

(Wu, 1997)

- Seismicity, Moho
- Tomography, anisotropy
- Magnetotelluric results
- Mountain root

Coherent deformation

Taiwan orogen



(Suppe, Liu, NTUGeo)
(modified from Bertrand, 2012)

Key: Décollement or mountain root?
→ lower crustal deformation?
Method: seismic evidence

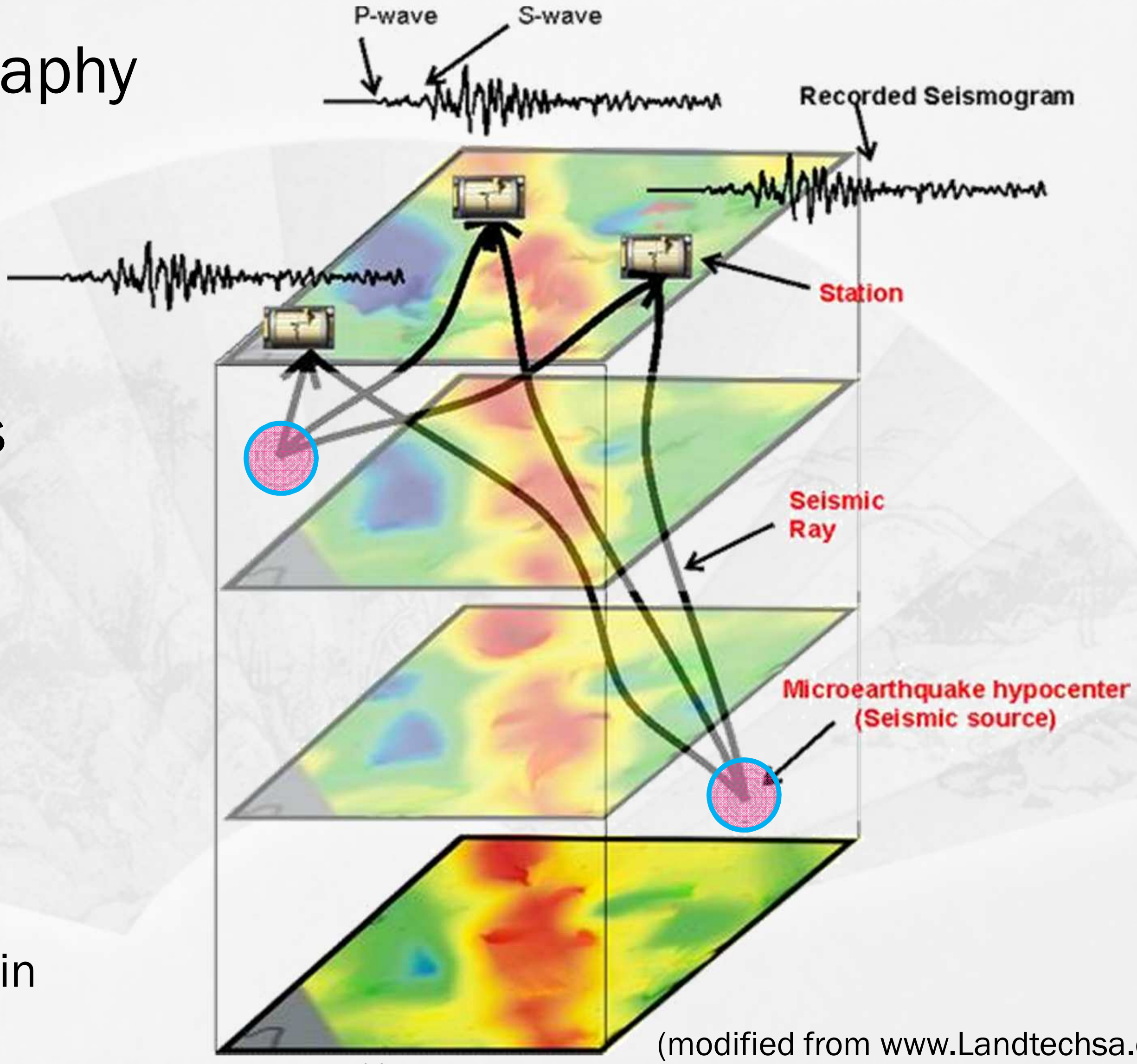
Information from seismic wave

Seismic tomography

Arrive time of P & S wave → Vp & Vs

Taiwan:
high seismicity + dense stations = 3-D isotropic velocity models

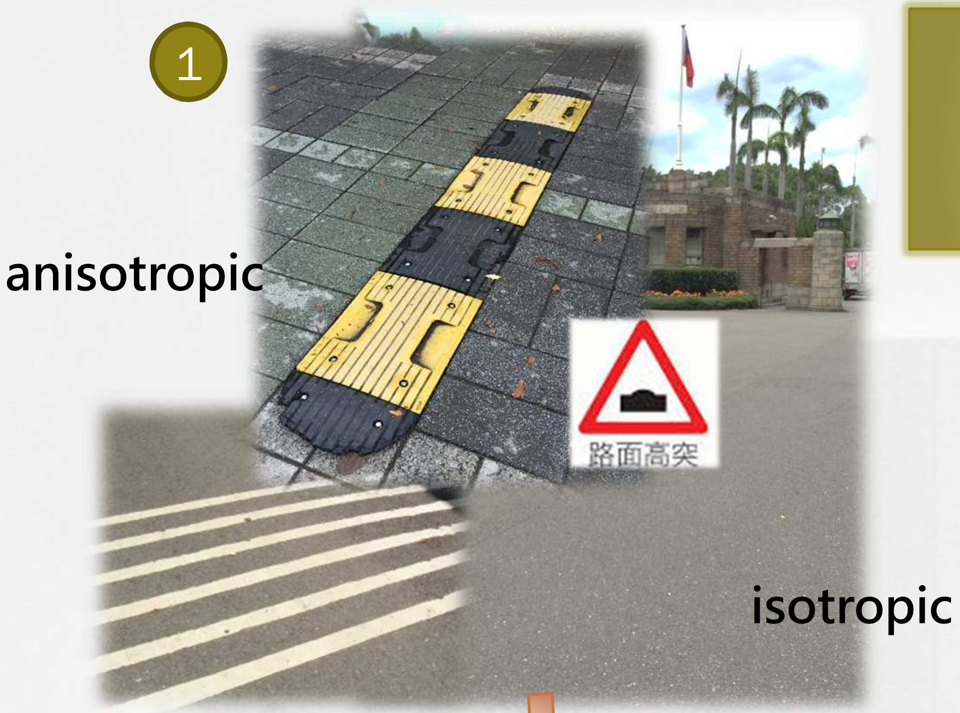
- Poor resolution in shallow crust



(modified from www.Landtechsa.com)

Why study seismic anisotropy?

1



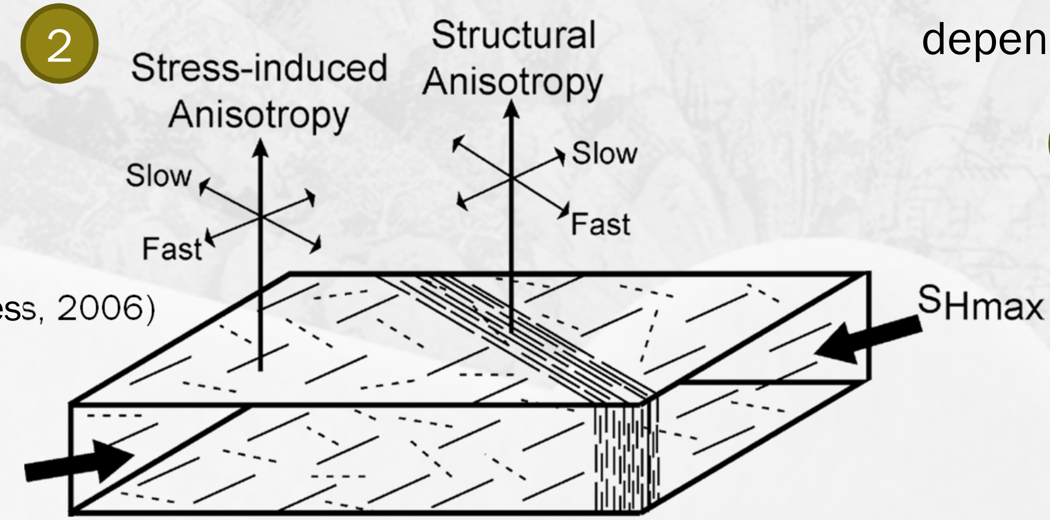
Crustal fabrics

→Deformation ?

→Anisotropic elastic property

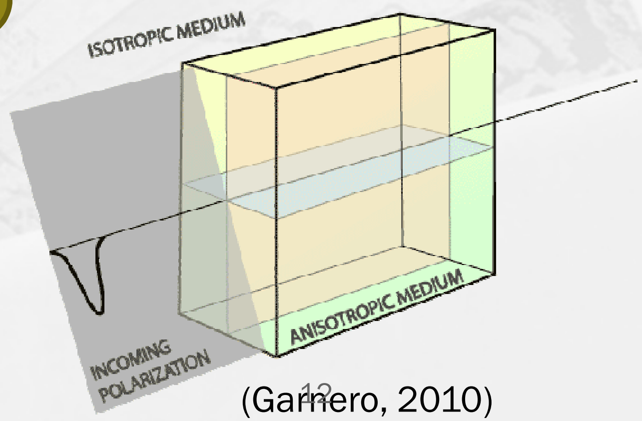
Seismic anisotropy:
dependence of velocity on direction

2



(Boness, 2006)

3

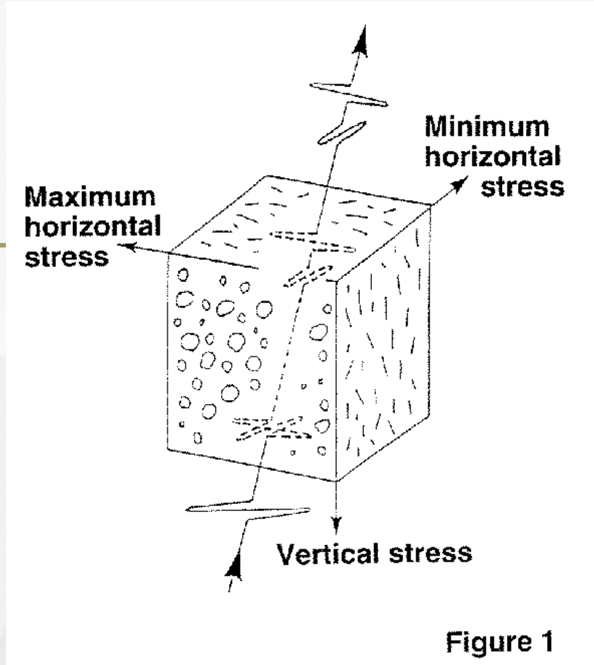


(Garnero, 2010)

Why study seismic anisotropy?

Crustal anisotropy :

- SPO (shape-preferred orientation)
  - Stress-aligned fluid-filled cracks, microcracks, and preferentially oriented pore space, lineations
  - Layering strata ($V_{SH} > V_{SV}$)
- LPO (lattice preferred orientation)
  - Mica, amphibole

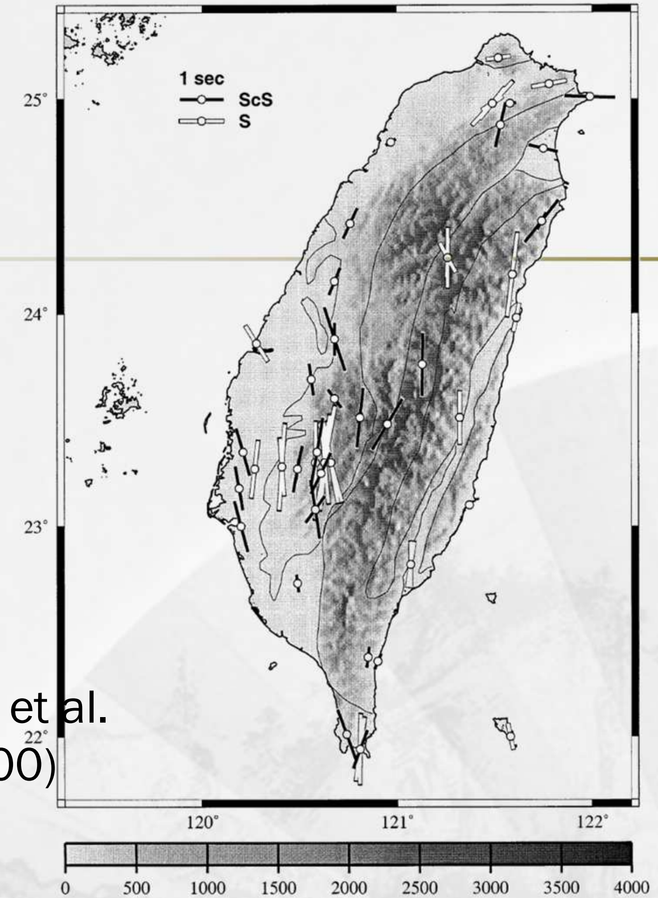


Crampin and Rowlands (1996)

Stress & strain

Tectodynamic problem in Taiwan ?

Results from shear wave splitting (SWS)

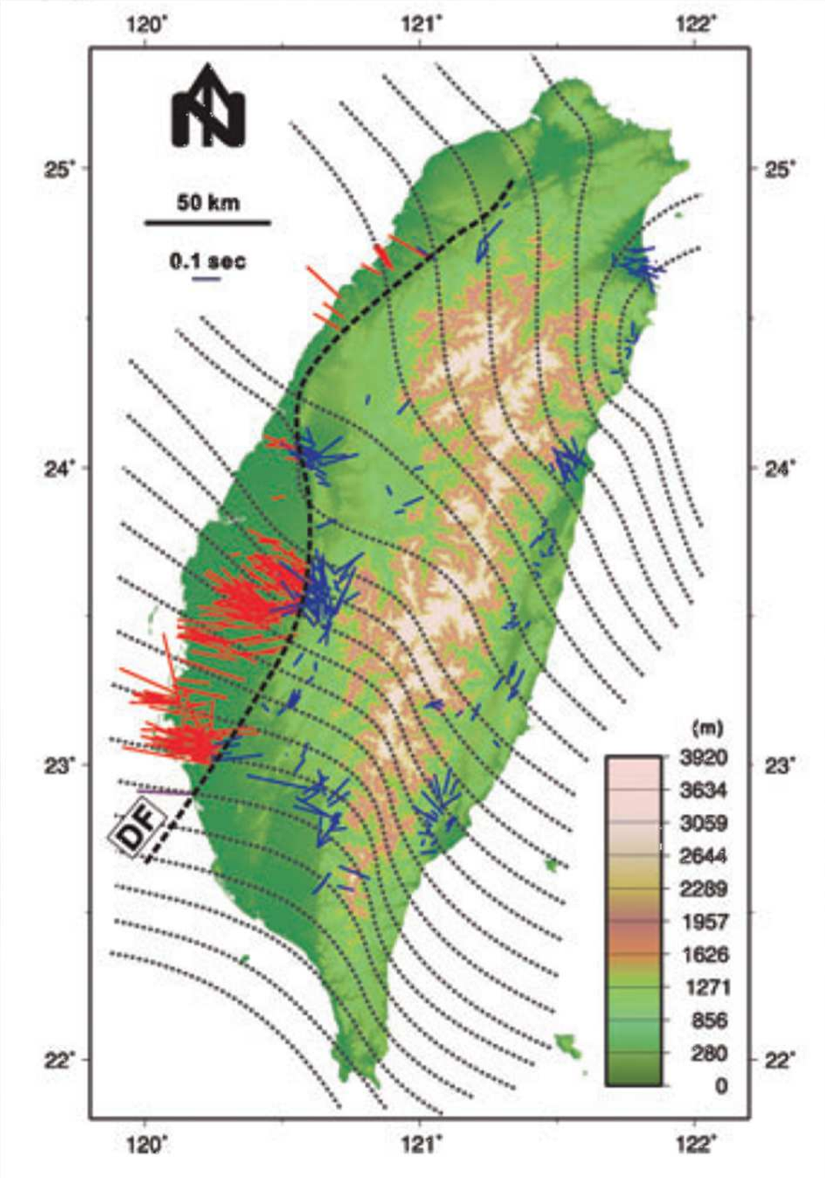


Rau et al. (2000)

Huang et al. (2006)

- Fast axis - parallel to the strike of the mountain belt(NE-SW)
- (SKS) An anisotropic layer thickness of 5–180 km in the uppermost mantle, and 115–180 km beneath mountain belt.
- (S and ScS) Main source: 25-230 km depths, upper mantle anisotropy.
- Delay time –
  1. Largest values from the SW foothills
  2. An abrupt change in south Taiwan.

Chang et al.(2009)



Upper crust:

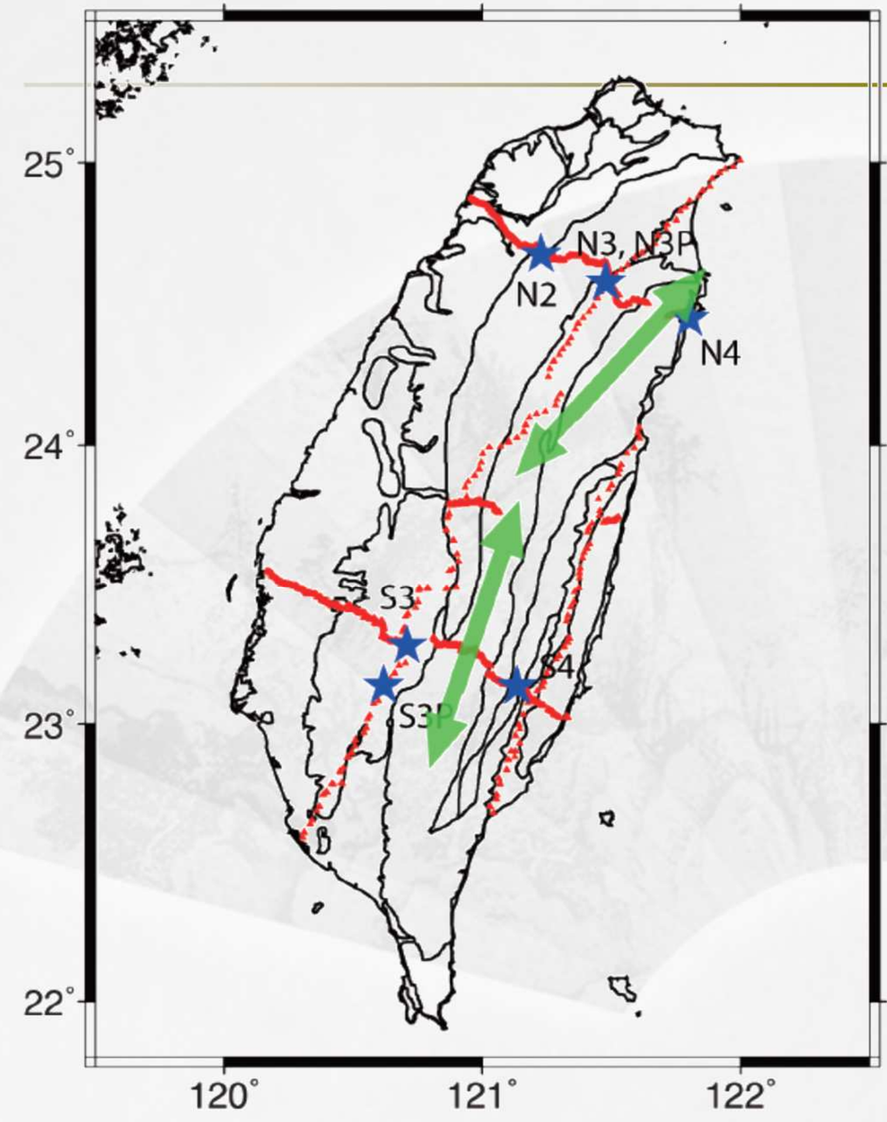
- Two domains in W/E Deformation Front:

  W: convergence-parallel laminating

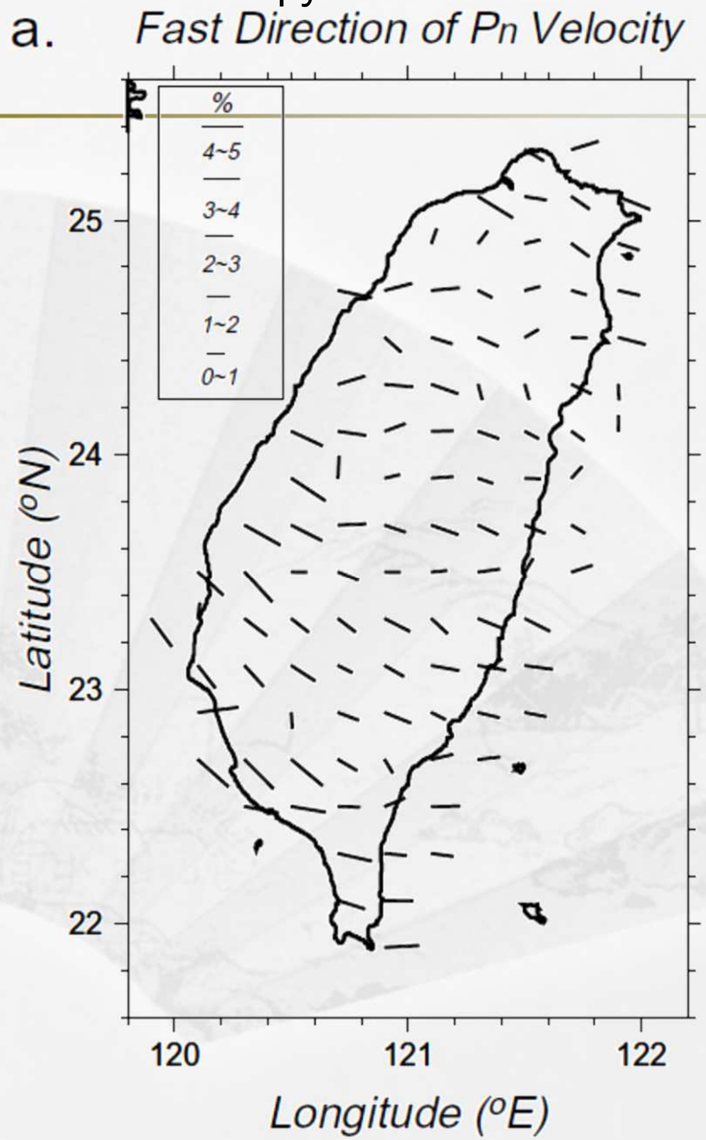
  E: convergence-perpendicular striking

- Seismic anisotropy in the upper crust may come from multiple layers, and the fabric lamination causing the anisotropy may be confined only within the shallow crust.

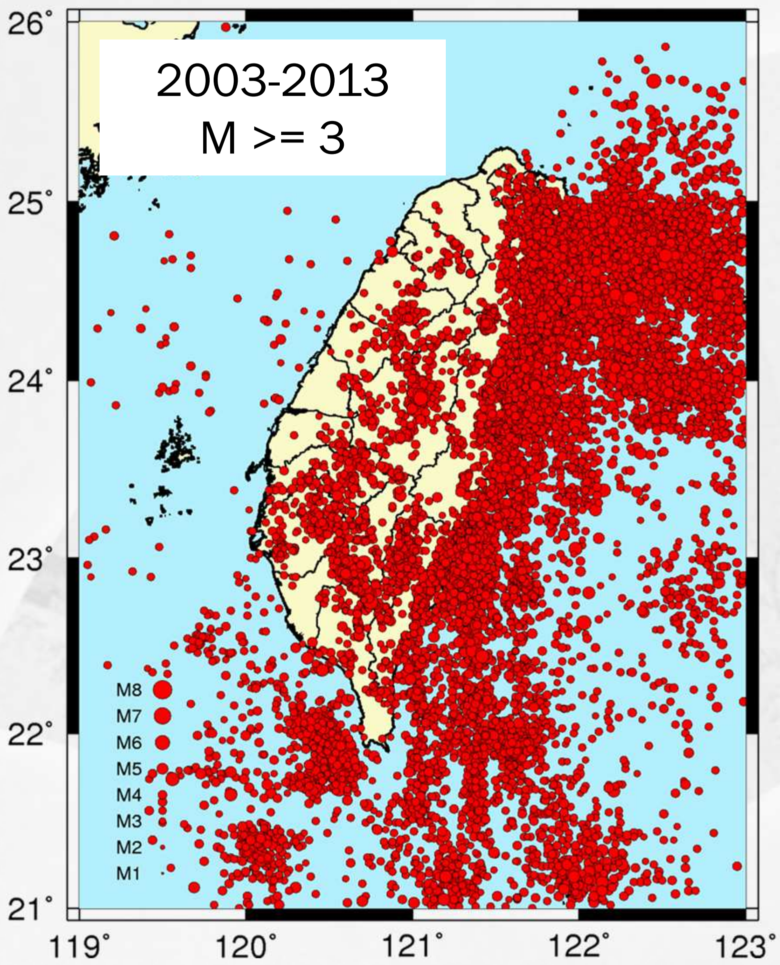
Kuo-Chen et al. (2013)
Crustal P wave anisotropy



Chen et al. (2003)
Pn anisotropy



Information from seismic wave



(catalog from CWB)

High seismicity and dense stations

→ Isotropic velocity - high resolution body wave tomography

Kim et al. (2005), Wu et al. (2007), and Kuo-Chen et al. (2012)

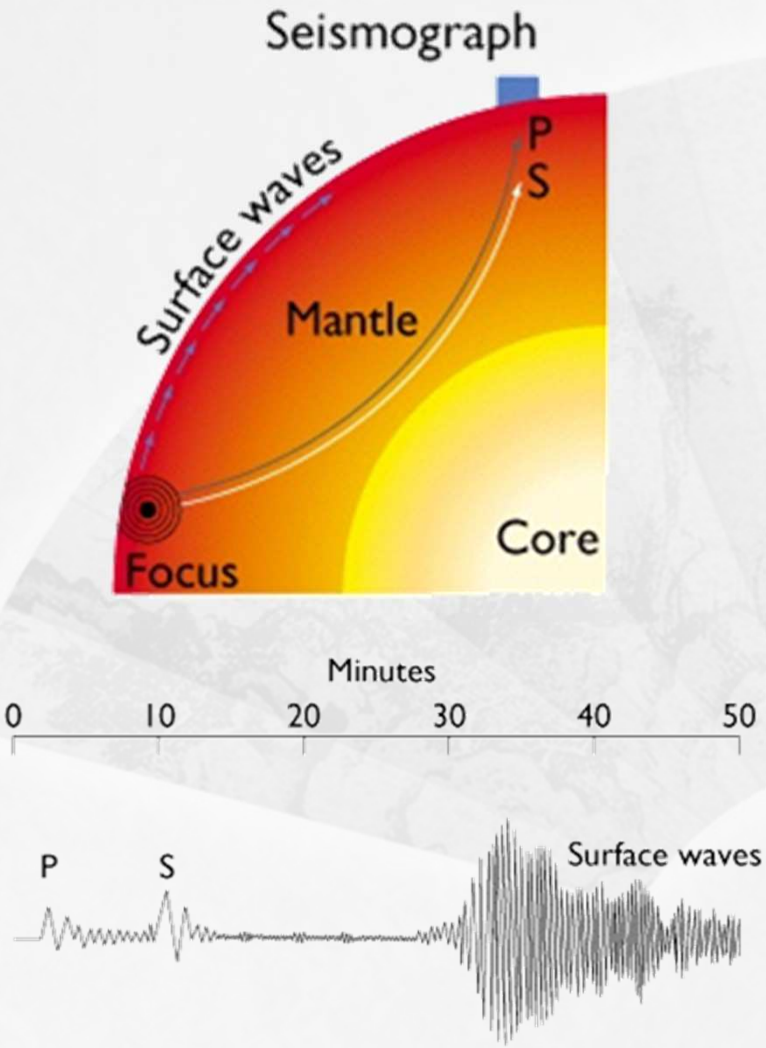
→ Anisotropy – constrained mainly by shear-wave splitting (SWS)

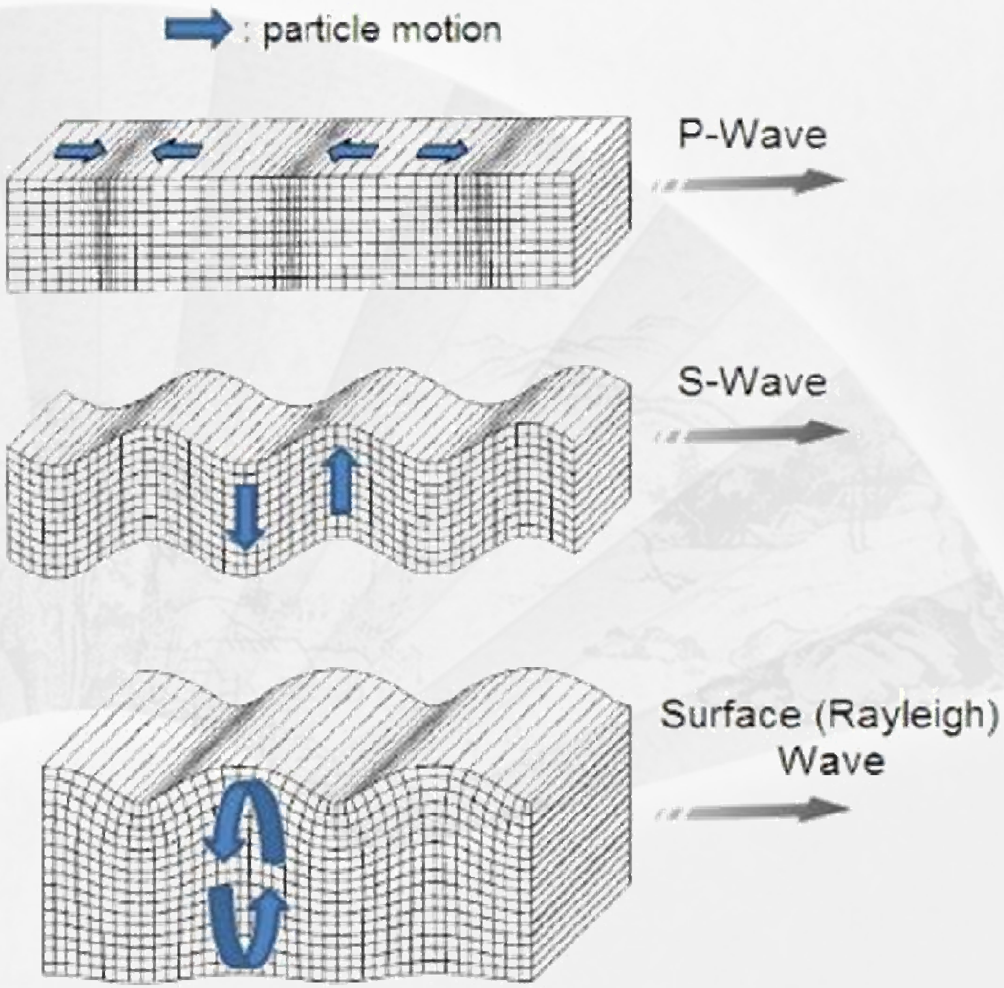
Kuo et al. (1994), Rau et al. (2000), Huang et al. (2006), and Chang et al. (2009)

- SWS - poor depth resolution
- Depth constraints can be provided by surface waves

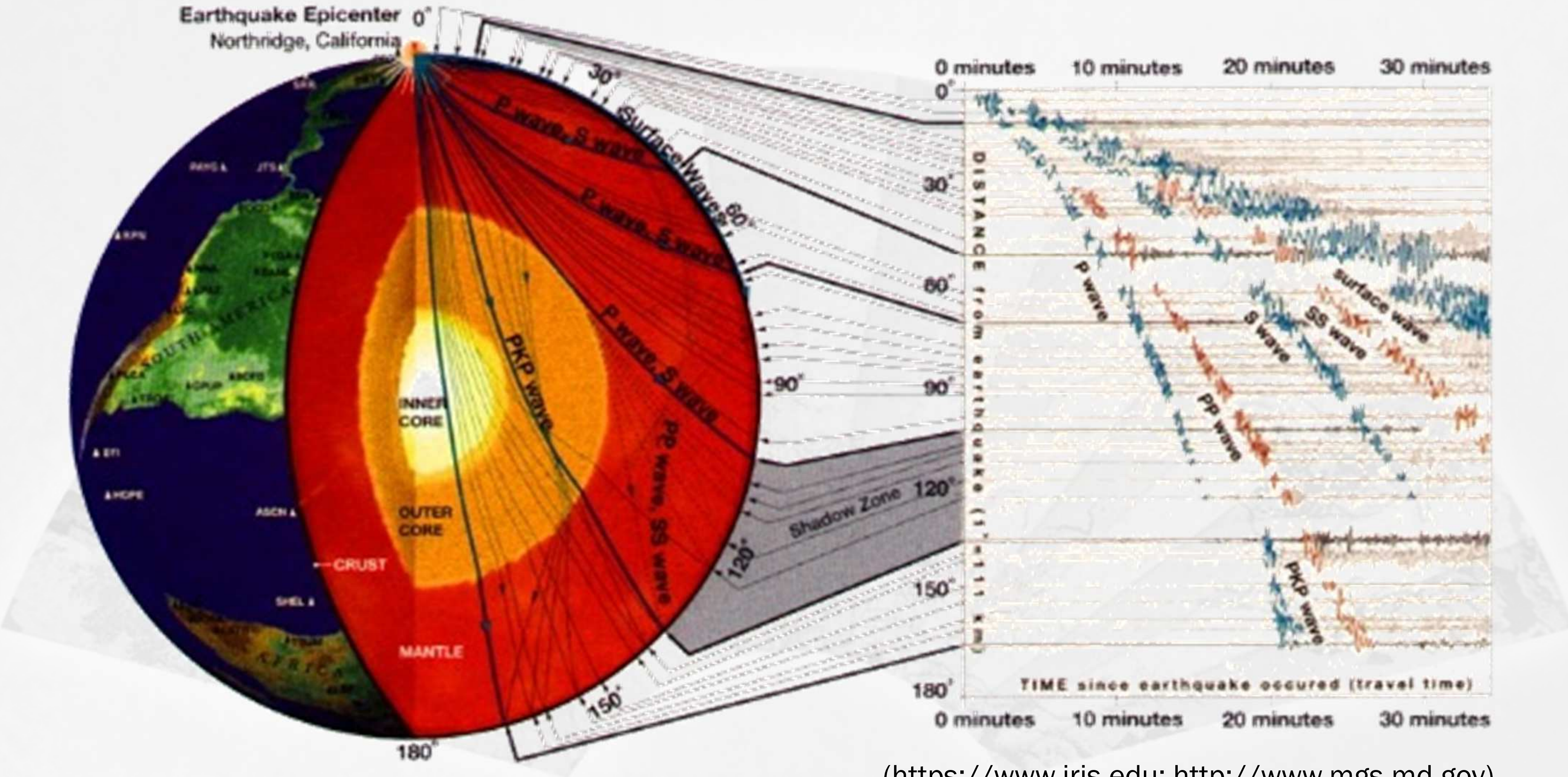
Information from surface wave

generated along any free surface in the medium



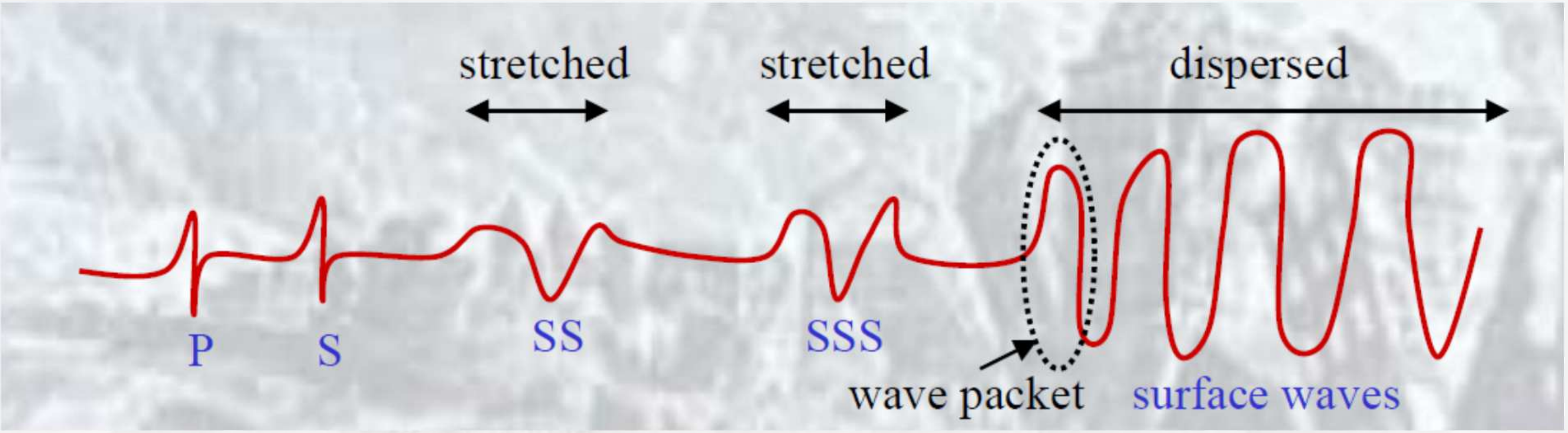


Information from surface wave

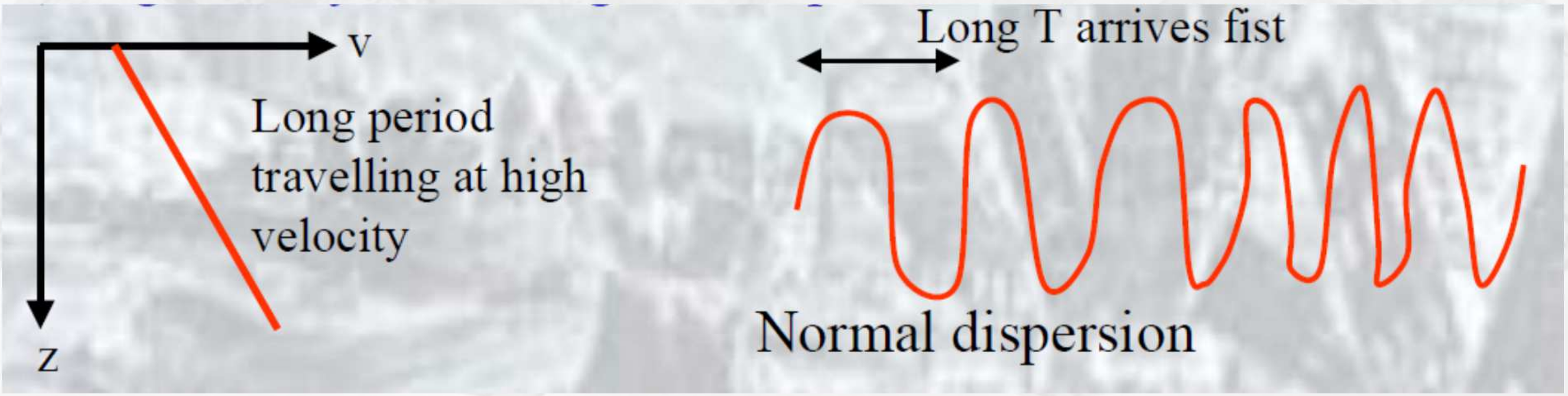


(https://www.iris.edu; http://www.mgs.md.gov)

Information from surface wave

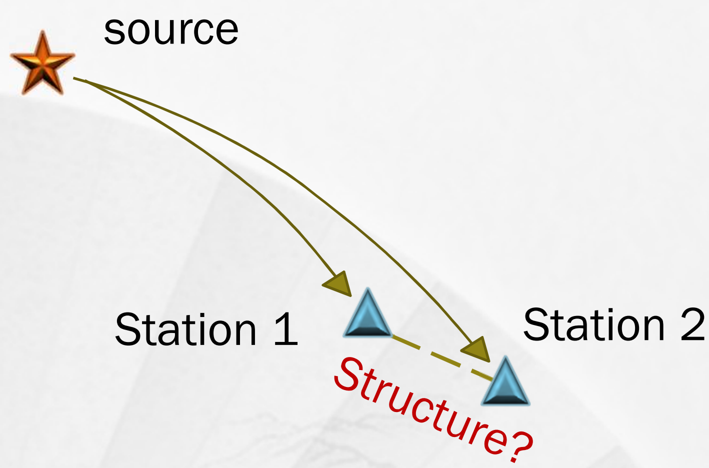


Dispersed, arrive in wave packets ➔ group & phase velocity



longer wavelength surface waves (higher velocities with depth) will travel faster than those with shorter wavelengths ➔ Depth resolution

Information from surface wave



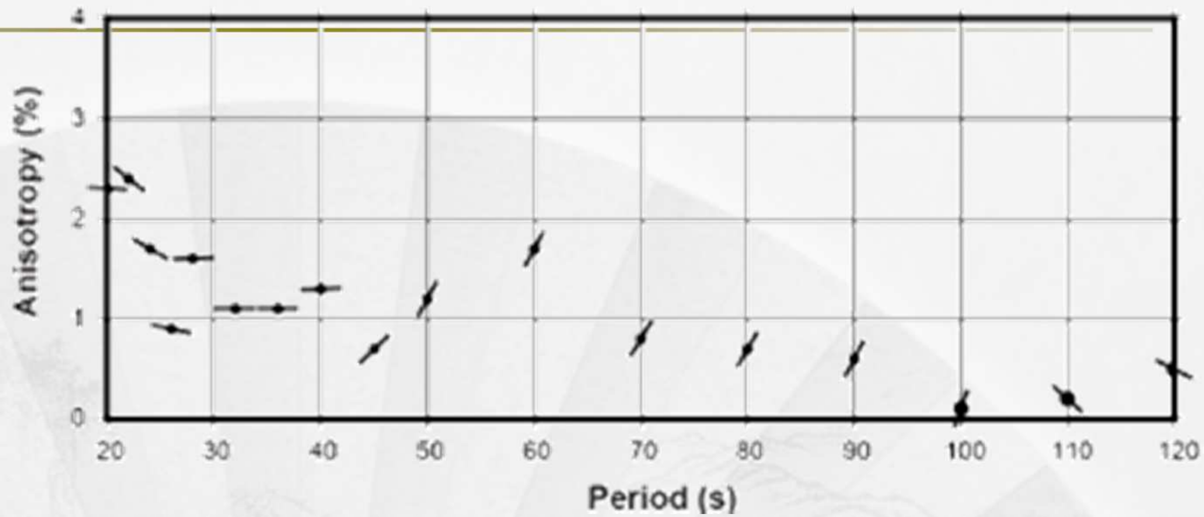
- Single-station method
  - Source effects?
  - Velocity structure?
- Two-station method
  - Eliminate the uncertainty from source
  - Response function between two stations

- Surface wave velocity models of Taiwan are mainly limited by
1. Sparse distribution of moderate earthquakes
2. Short epicenter distances

Poor resolution in short-period surface-wave tomography

Information from surface wave

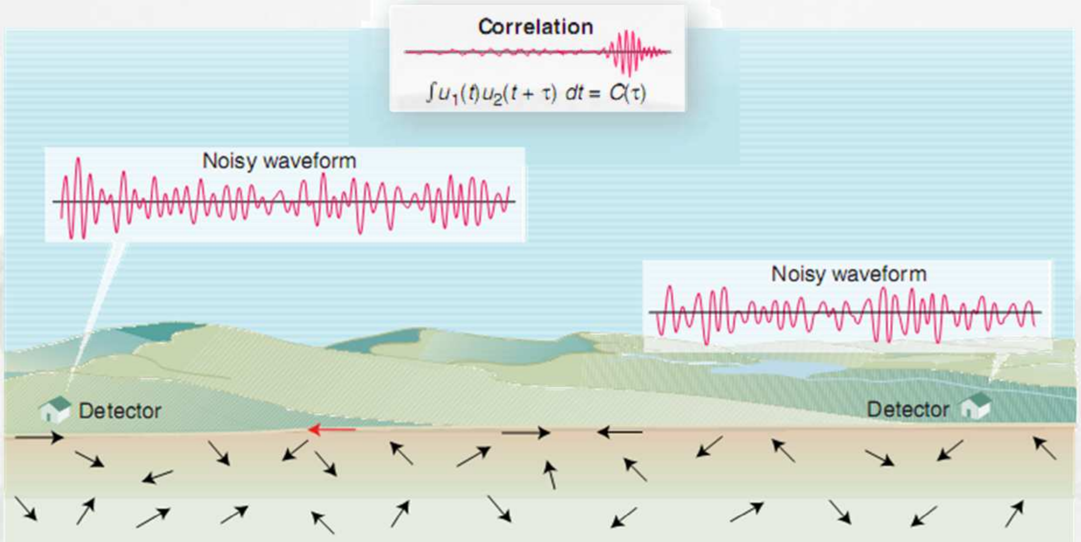
Lai (two-station method, 20-120 sec)(2009 PhD thesis)



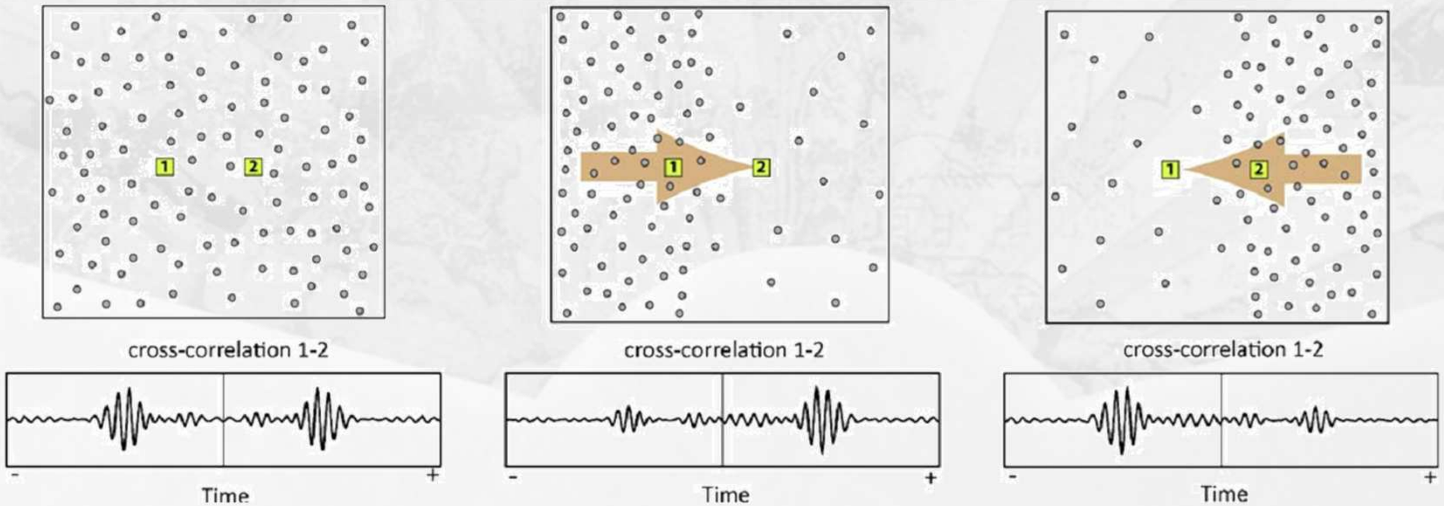
- The azimuthal anisotropy beneath CR varies with period.
  - Upper layer → fast in E-W.
  - Lower layer → fast in NE-SW (LPO of olivine alignments, from compression or transcurrent motion during plate collision).

Ambient noise tomography

In a diffuse wave field

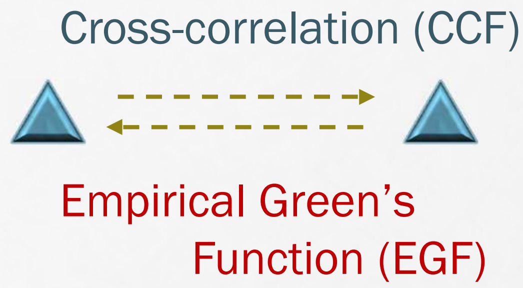


(Weaver, 2005)



(Stehly et al., 2006)

Ambient noise tomography



- Ambient noise tomography

1. Seismic tomography without earthquakes
2. Robust Green's functions of short-period surface-wave
3. Resolution depends on the inter-station paths

- Taiwan: High noise level + dense seismic networks

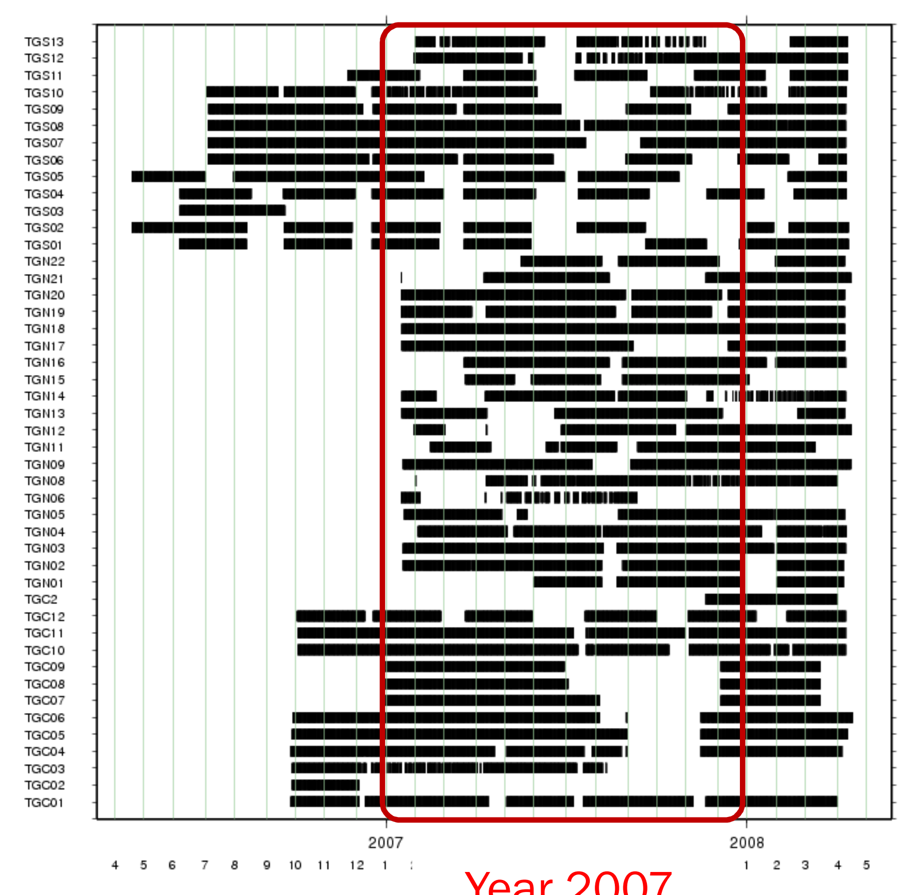
Broad-band Rayleigh wave tomography of Taiwan and Its Implications on the Regional Gravity Anomalies
(Huang et al., 2012)

Data

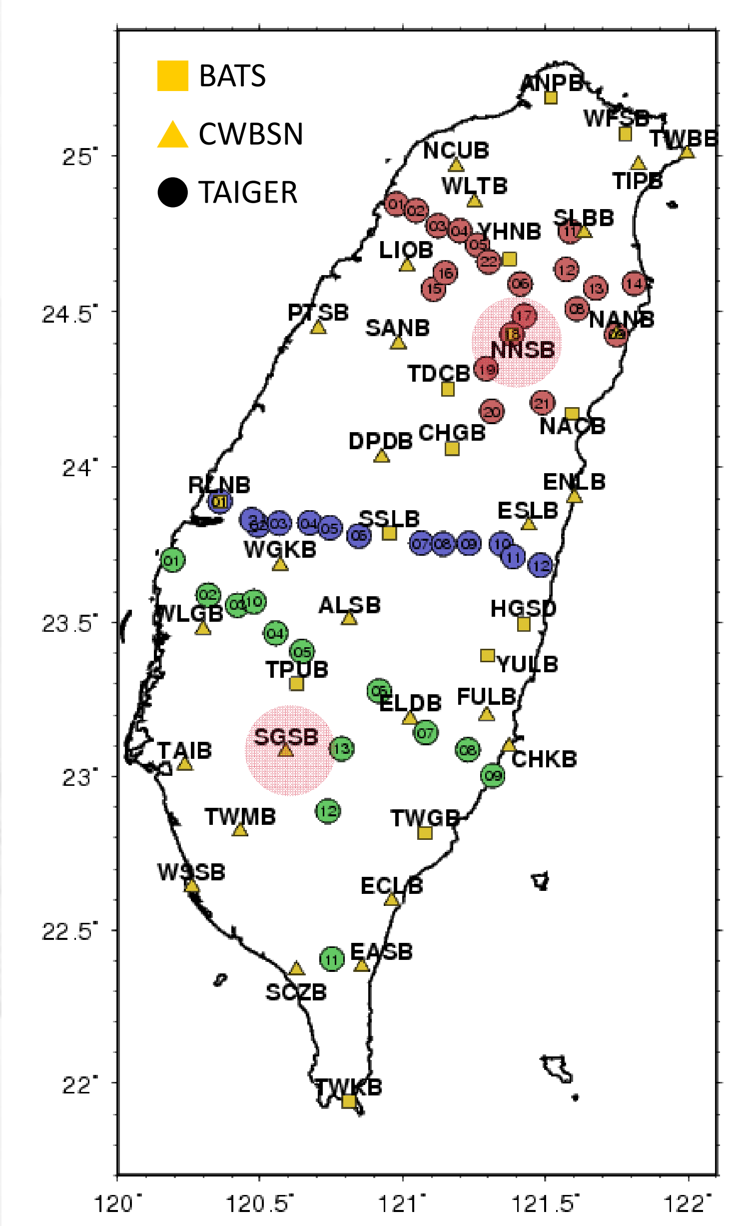
BATS (IES), CWBBB, TAIGER

85 stations in 2007

Z-component



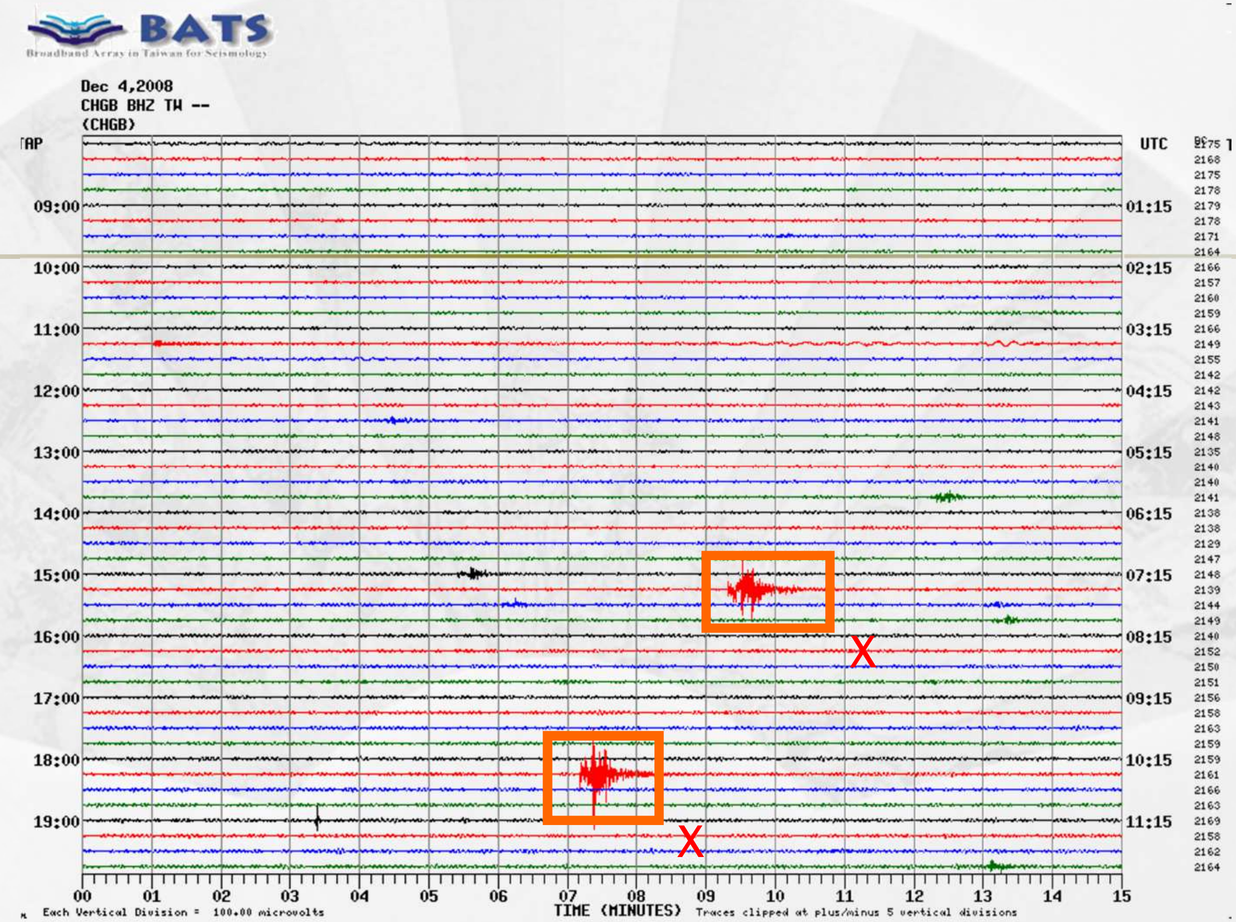
Year 2007



TAIGER: (red) TGN, (blue) TGC, (green) TGS

Ambient noise tomography

ambient noise & seismic signal

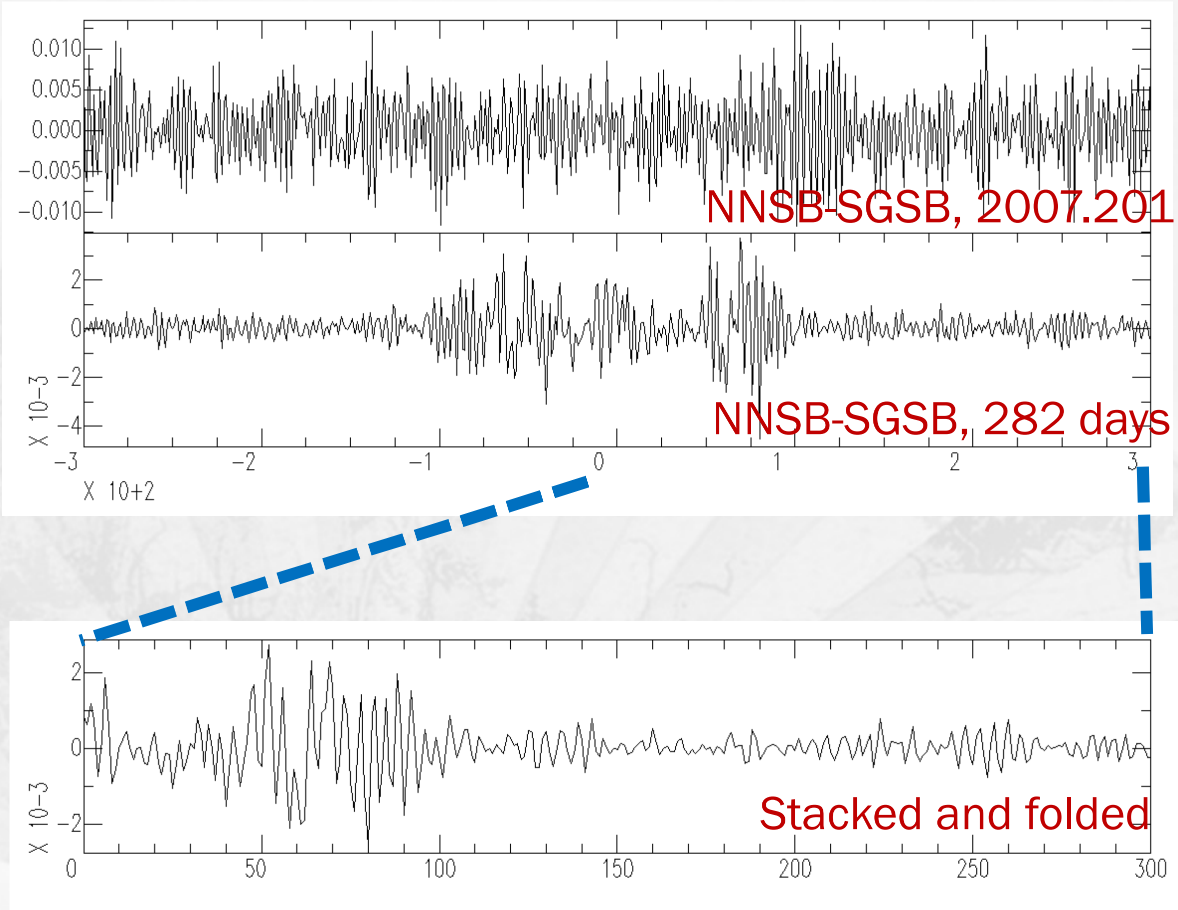


Ambient noise tomography

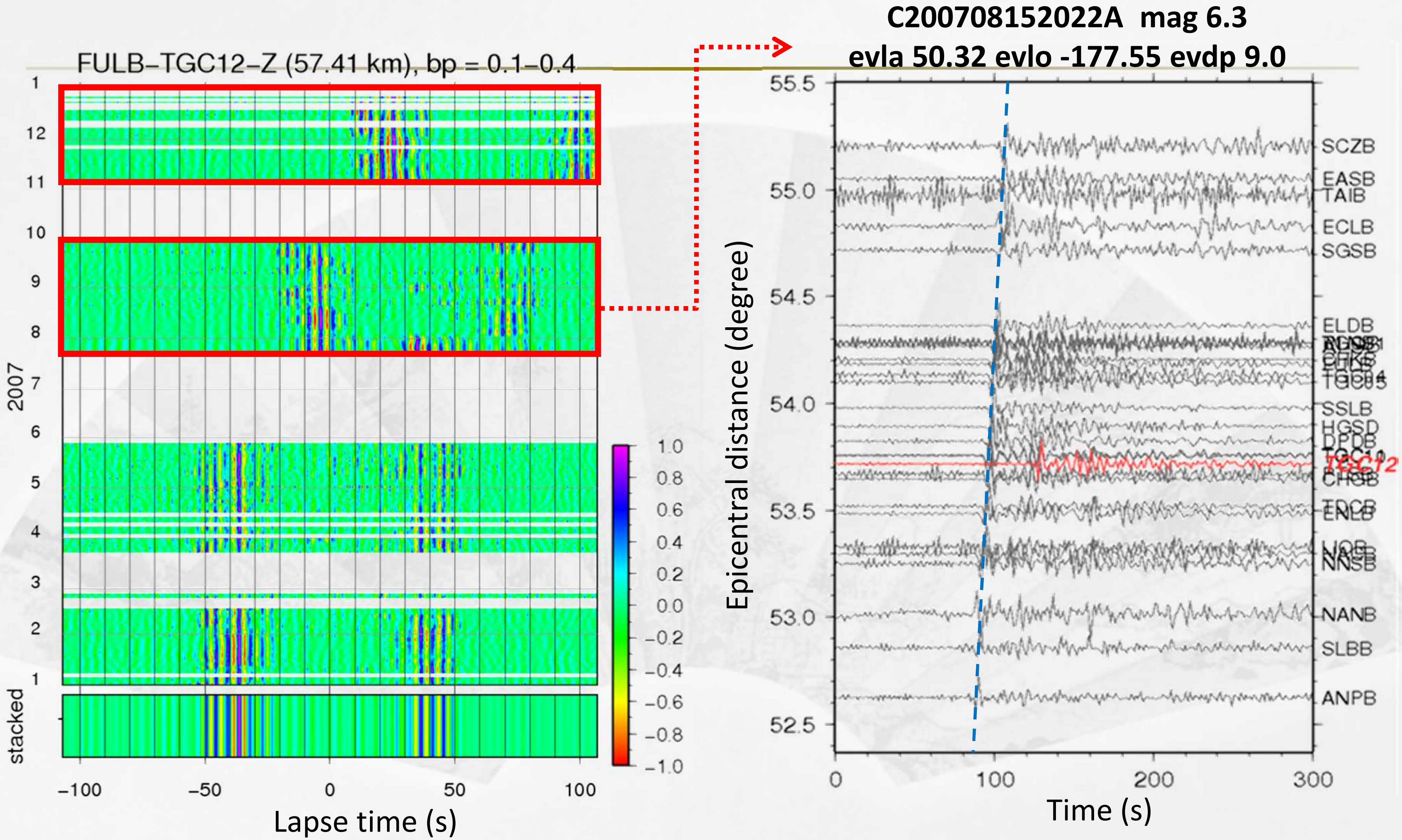
Daily cross-correlation function (CCF)

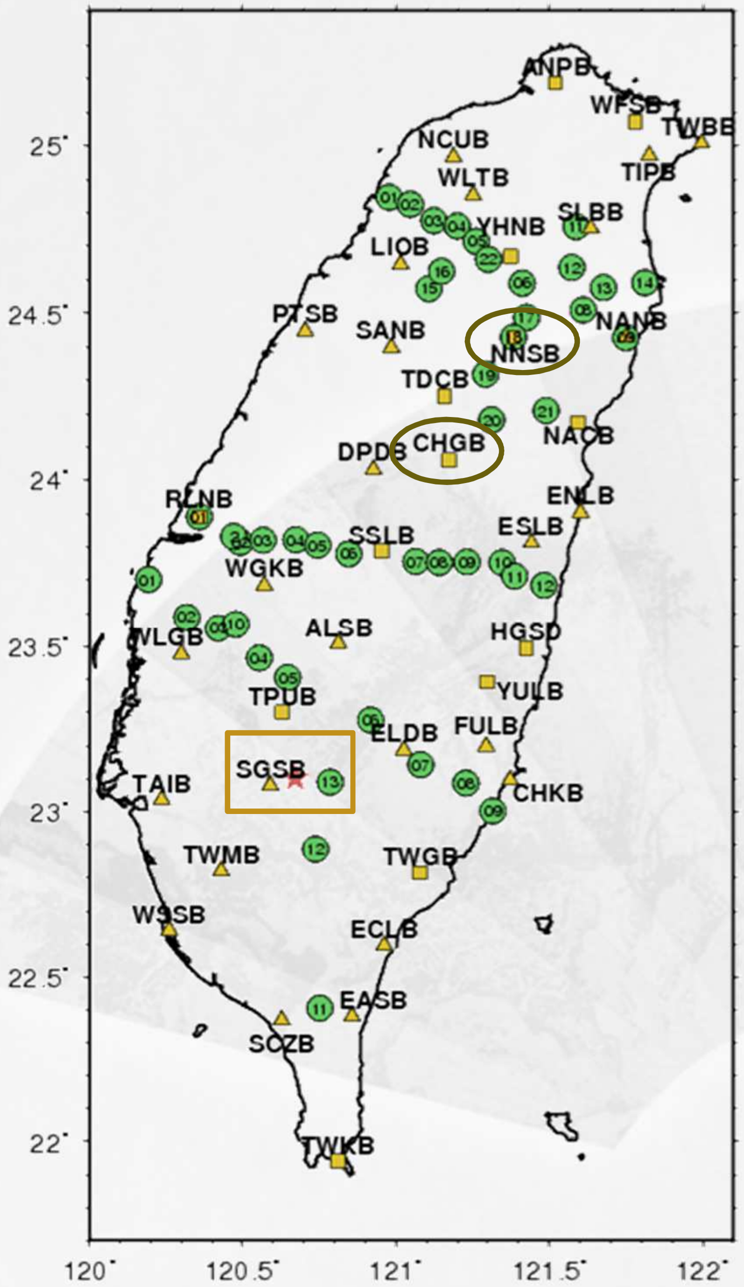
Stacked CCF

Empirical Green's function (EGF)



Clock errors detected by phase asymmetry



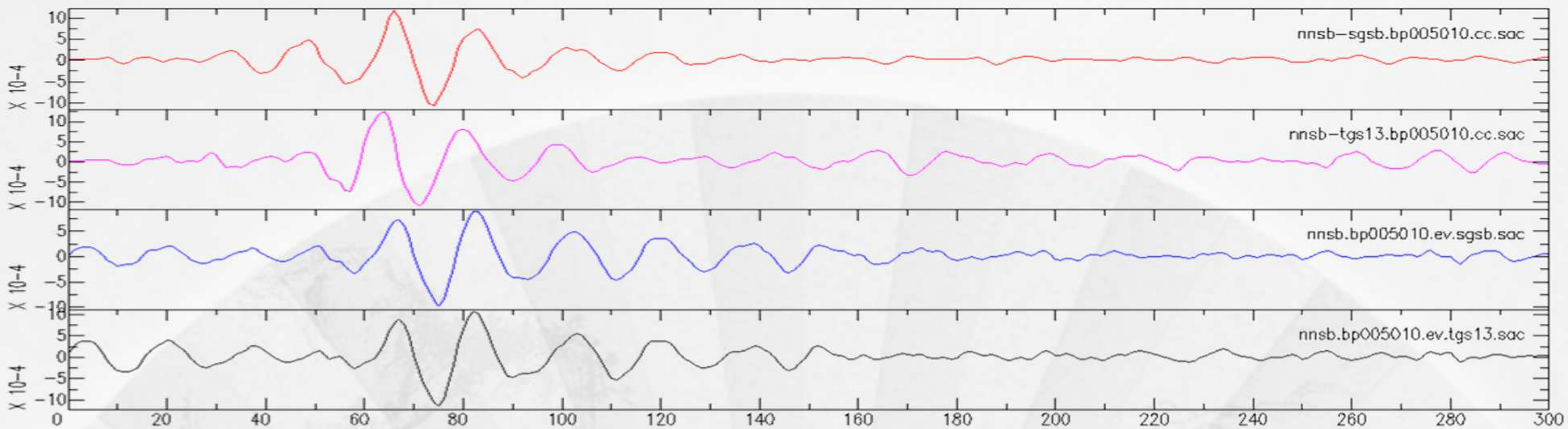


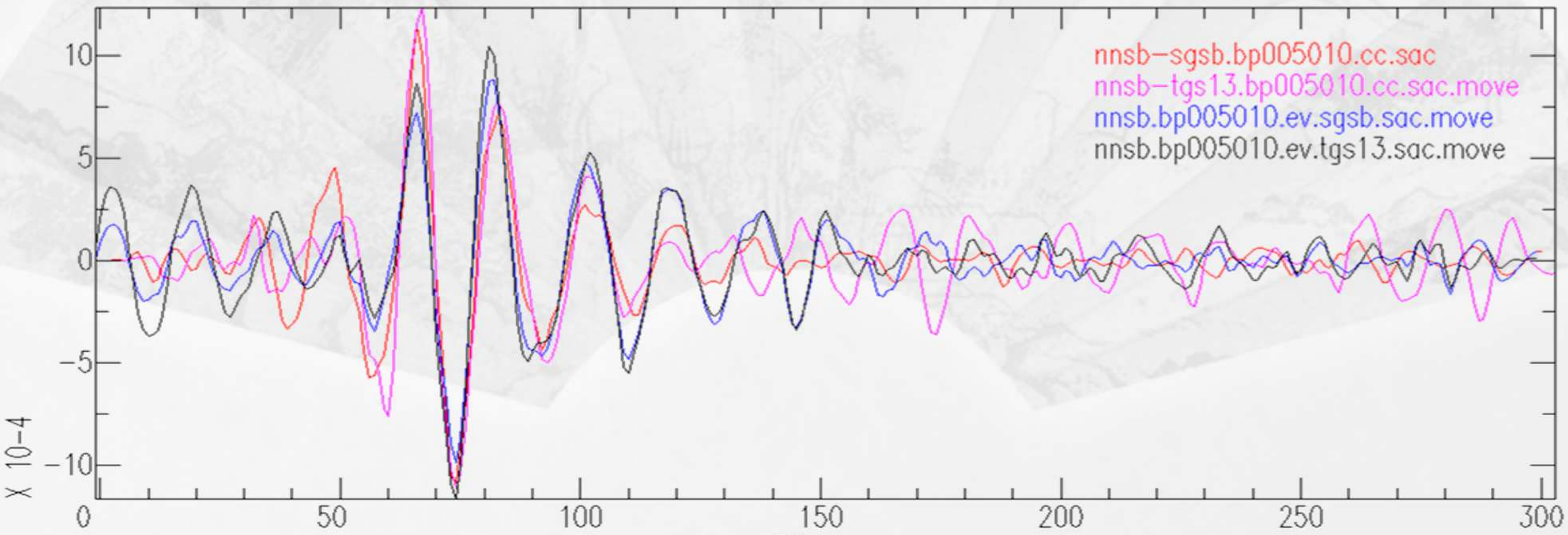
Seismic signal & Noise-derived EGF

- Event: 20073571150
- Mb = 4.2
- Depth = 7.62 km

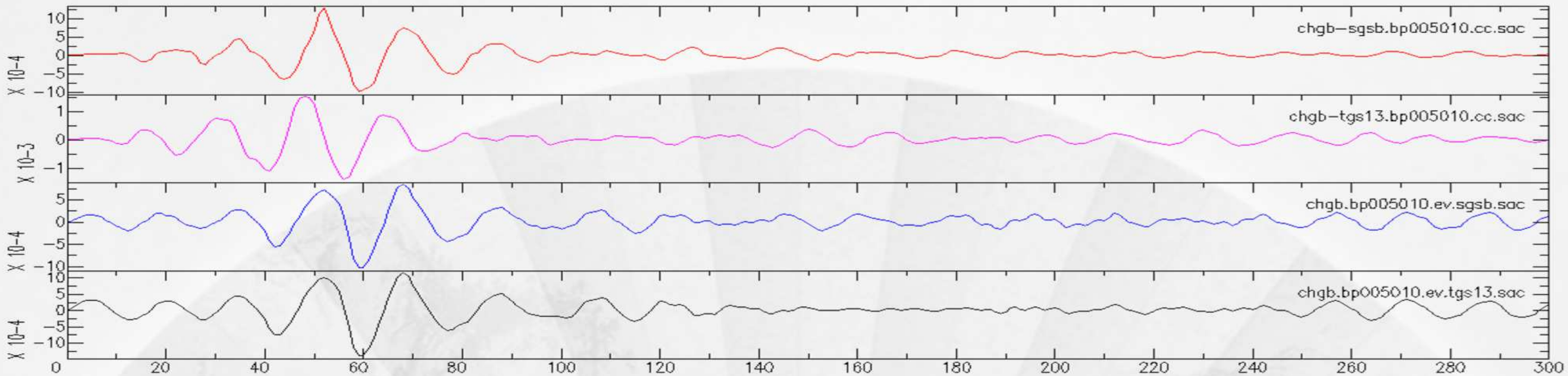
Fundamental mode Rayleigh wave

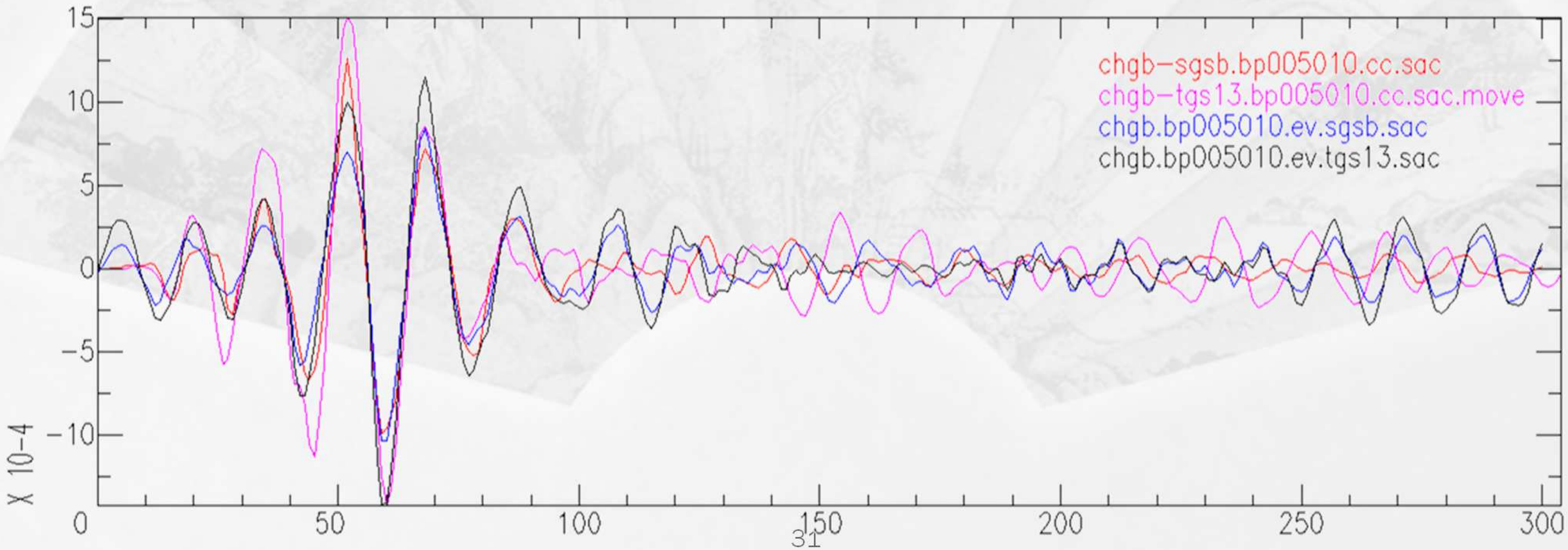
Station: NNSB, 10-20 sec





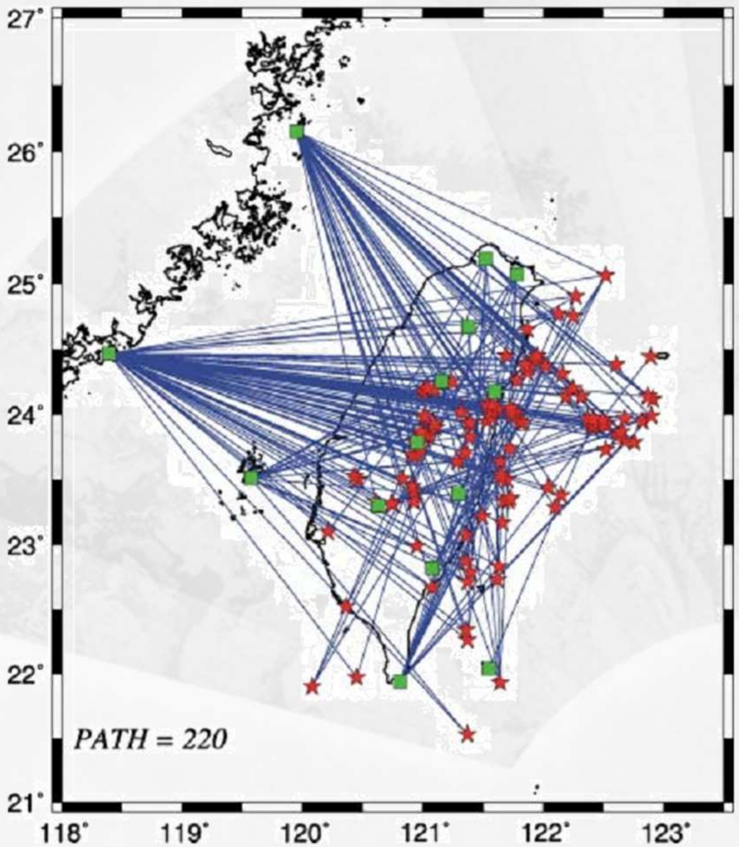
Station: CHGB, 10-20 sec



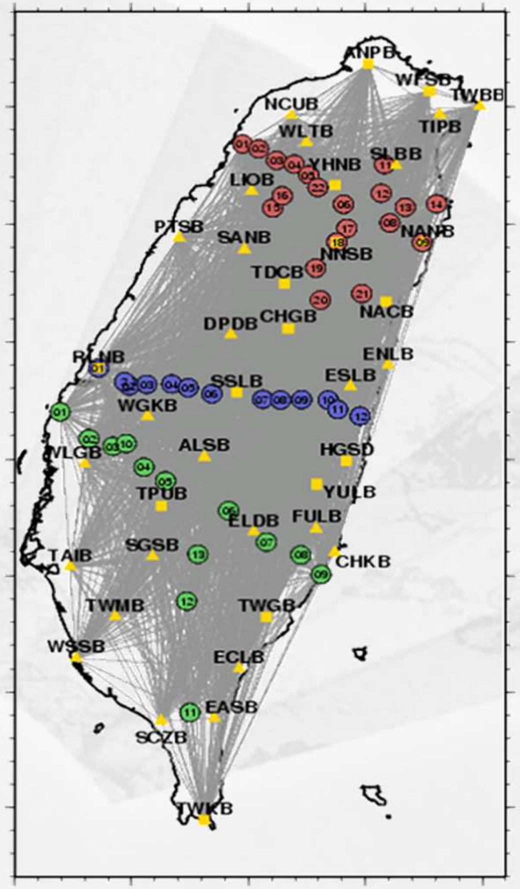


Path coverage

Traditional surface wave study

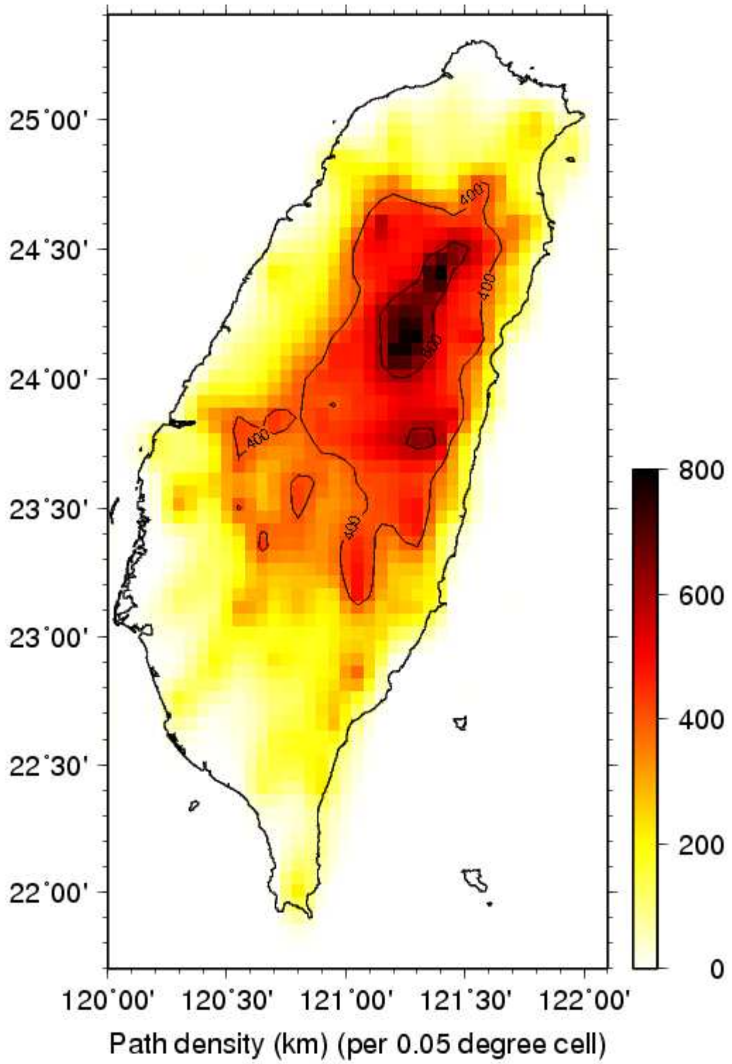


翁(2006)

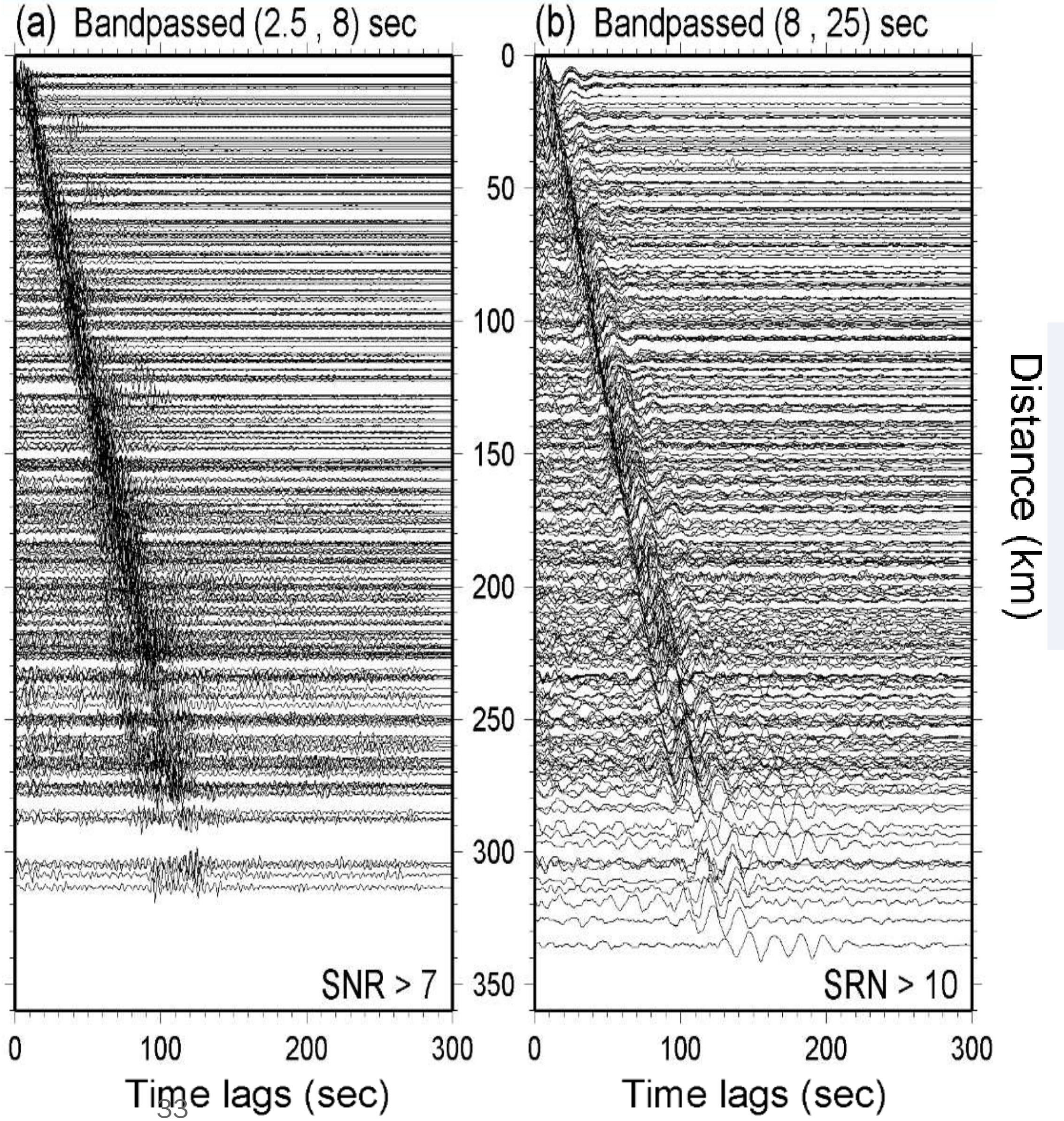


(This study)

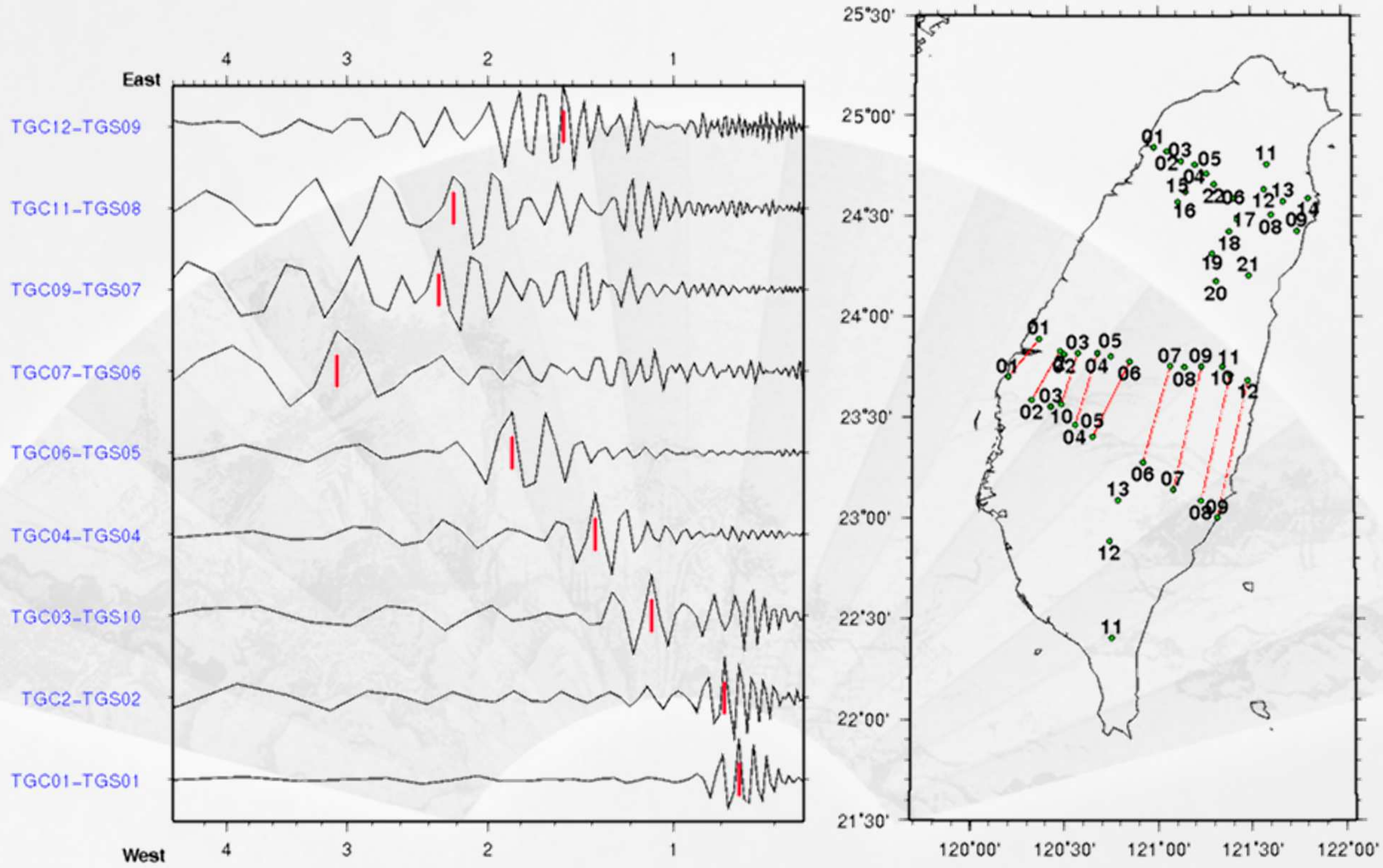
Path coverage density
(2157 paths used in 0.25 Hz)



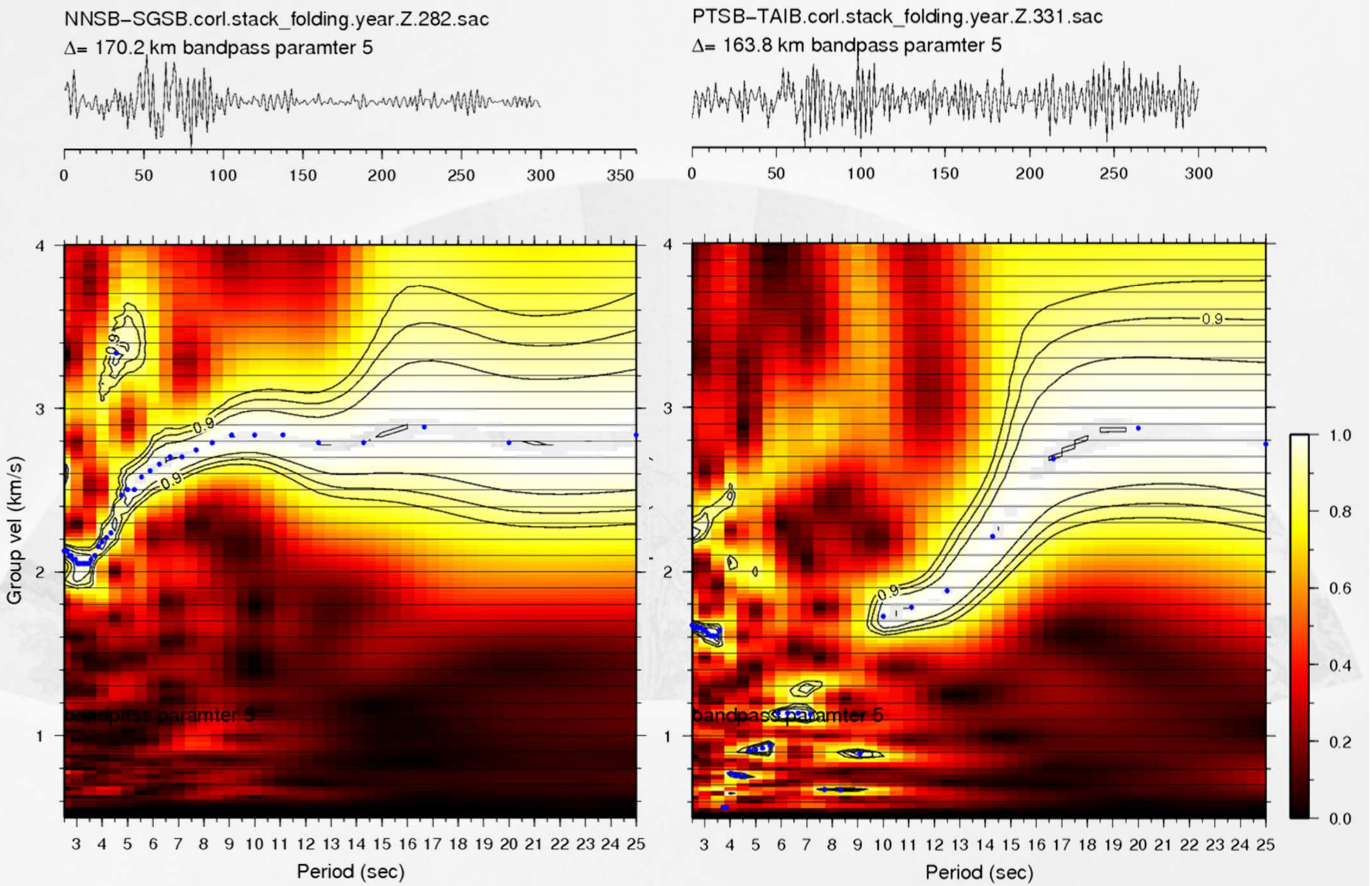
Stacked vertical component CCF



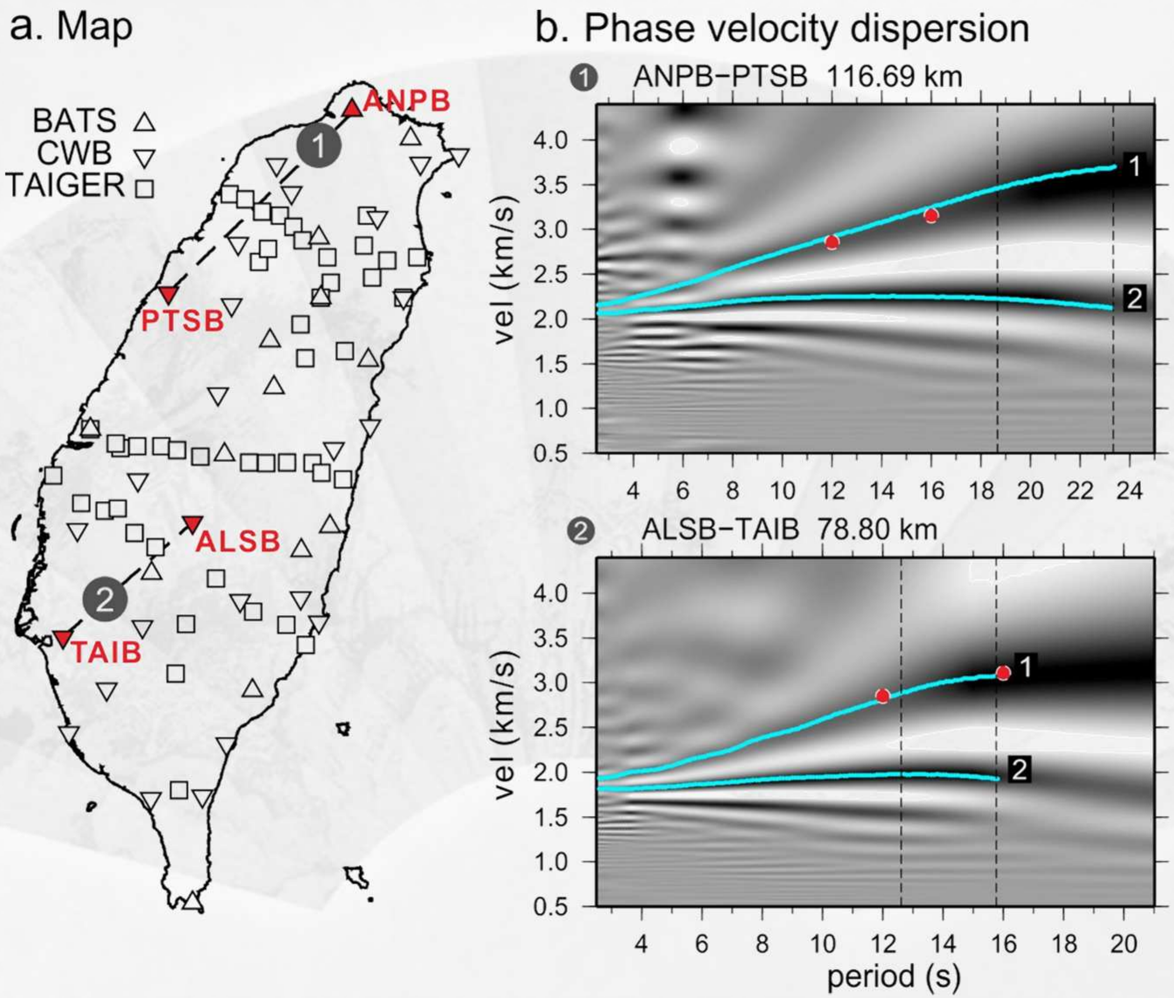
Group velocity and Phase velocity



Velocity (km/s)


NNSB-SGSB.corl.stack_folding.year.Z.282.sac
Δ= 170.2 km bandpass paramter 5
PTSB-TAIB.corl.stack_folding.year.Z.331.sac
Δ= 163.8 km bandpass paramter 5
Group vel (km/s)
Period (sec)
bandpass paramter 5
bandpass paramter 5
0.9

Phase velocity measurements



Red dots: Reference from the 3D model by Wu et al.(2007).

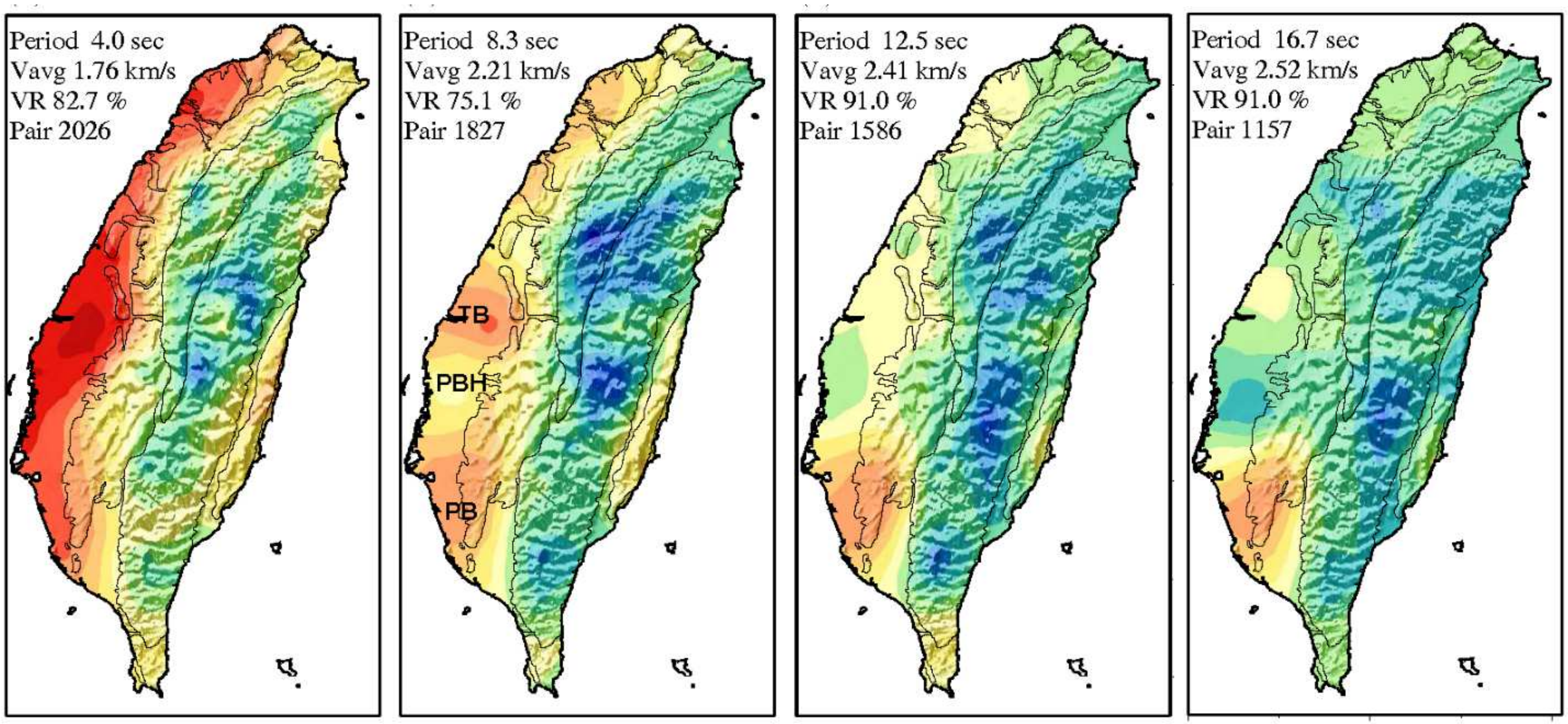
Data selection & Inversion

Period		4 s	8 s	10 s	12 s	16 s	20 s
Number of paths (3 λ criterion)		3822	3418	3321	3012	2565	2259
Qualified paths	Group velocity (Z)	2157	1950	1646	1448	1165	1074
	Phase velocity (Z)	3018	2802	2671	2452	2045	1658
	Phase velocity (T)	2397	2221	2108	1927	1601	1292

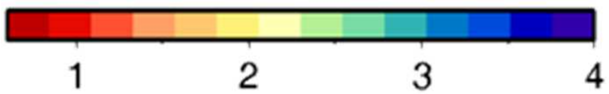
- Wavelet-based multi-scale tomography for Group & Phase velocity maps from 4-20 seconds.

Crustal structure of Taiwan (1)
Group velocity

4 sec 8.3 sec 12.5 sec 16.7 sec

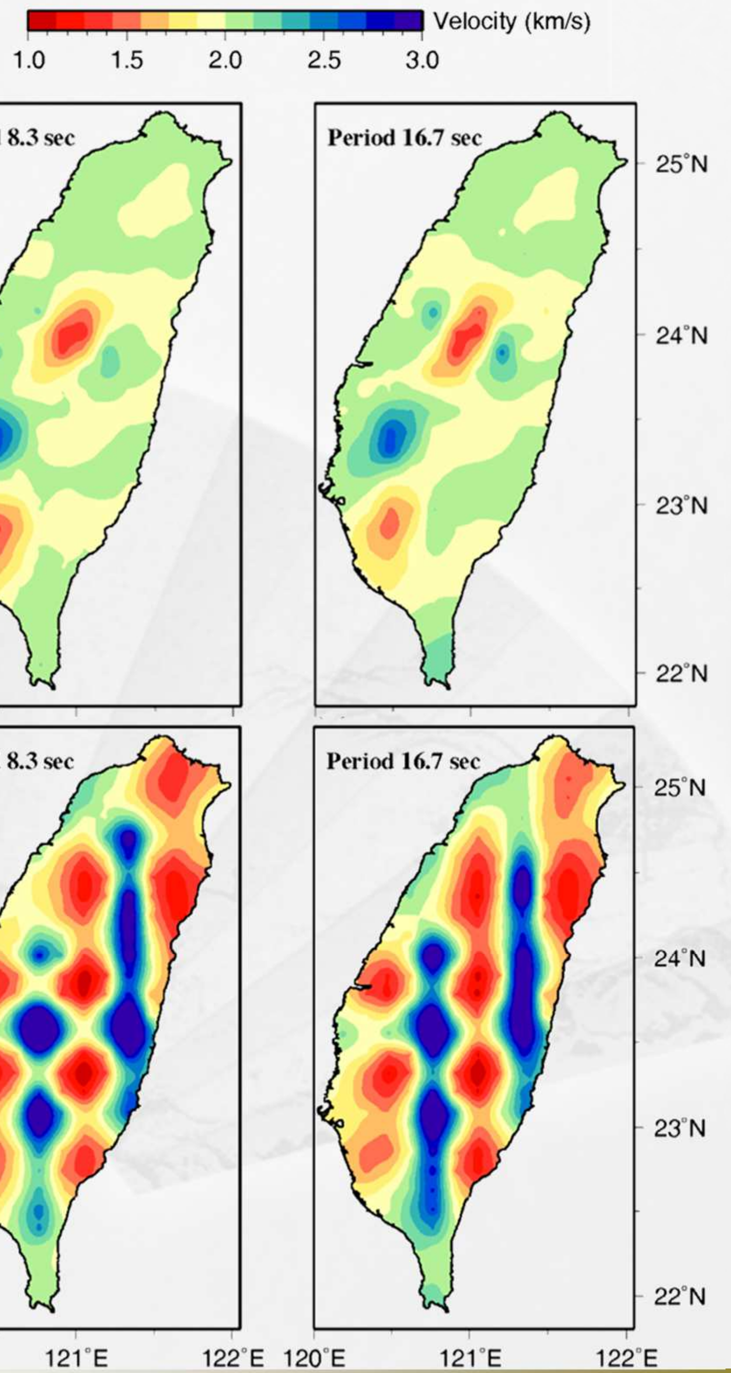


Group velocity



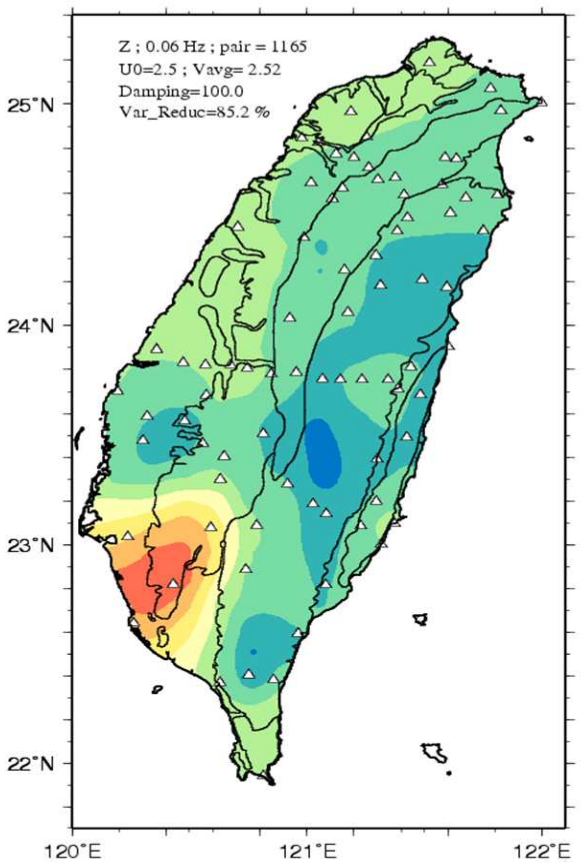
1. Variation pattern changes gradually.
2. Good correlation to surface geology at short period.
3. Low-velocity anomaly in south–western Taiwan.

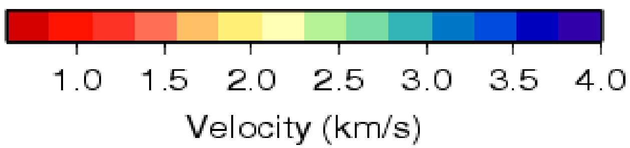
Recovery and Resolution



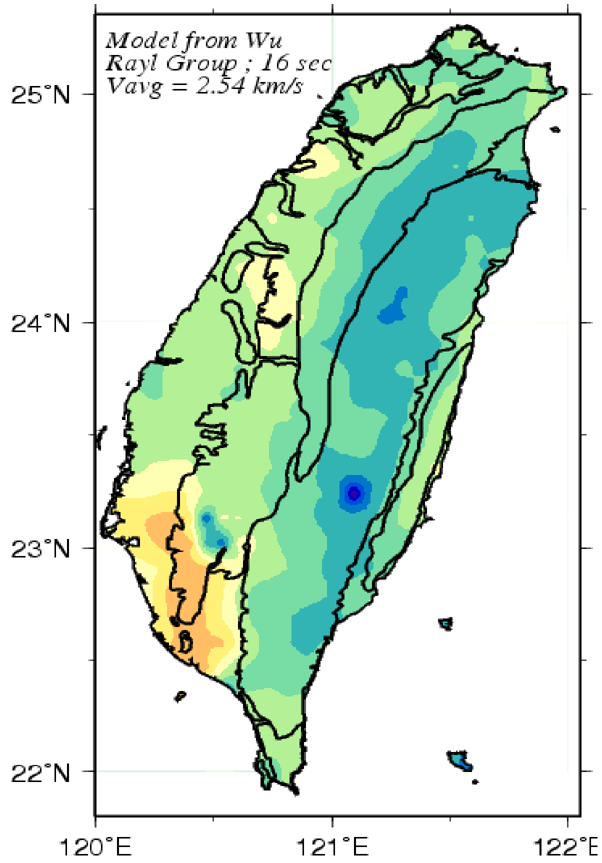
Comparison with models derived from body-wave (longer period)

Group velocity of Rayleigh waves at Period 16 sec

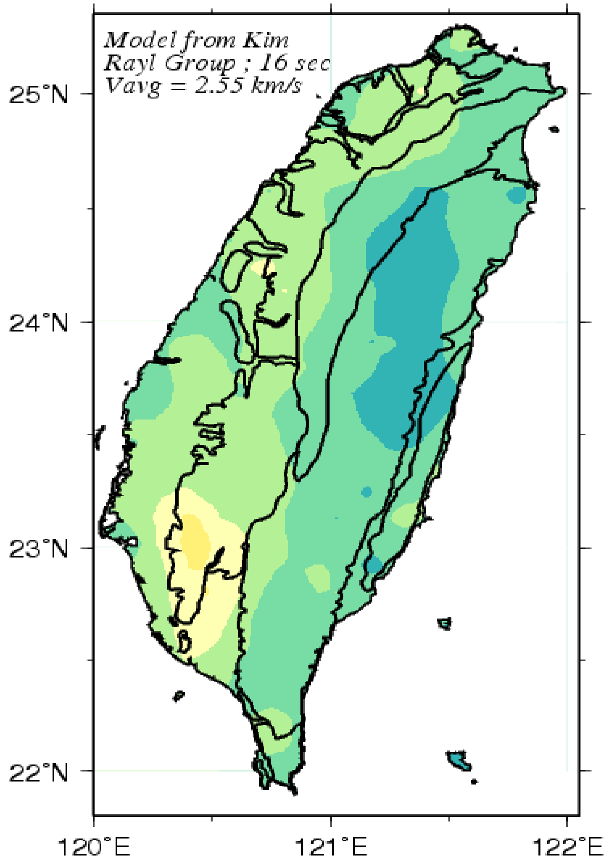




Wu *et al.*(2007)



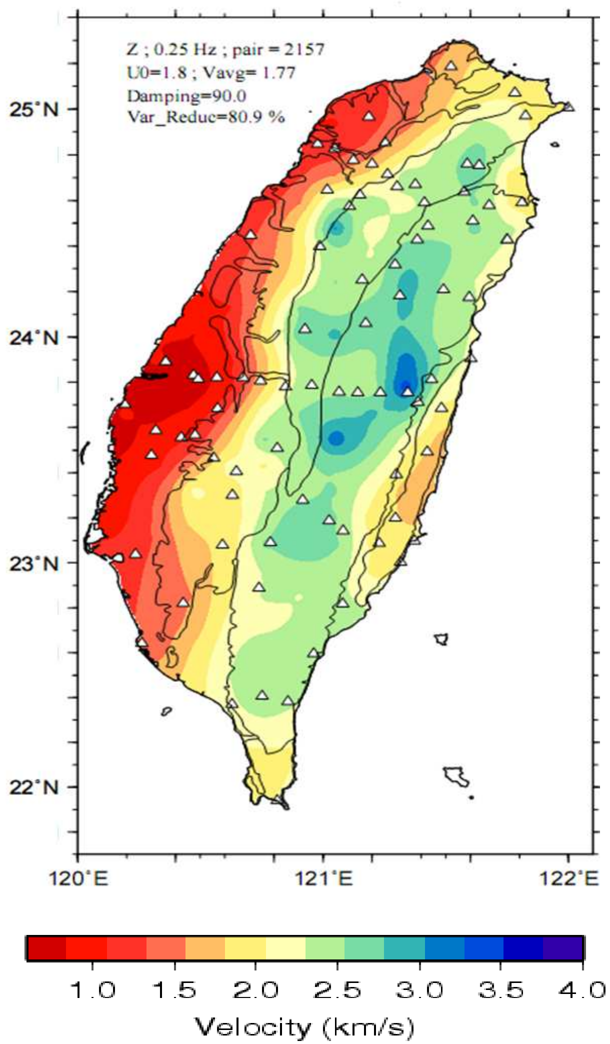
Kim *et al.*(2005)



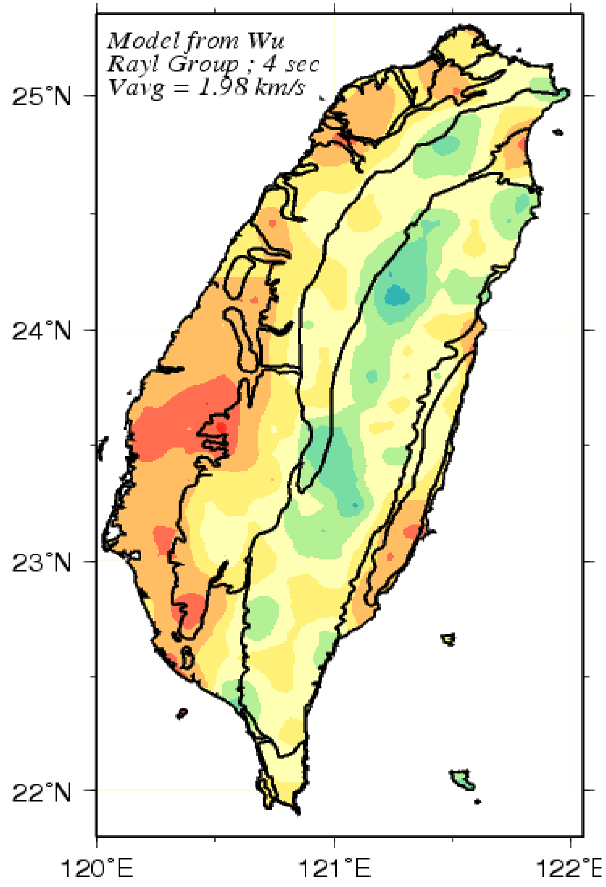
- Variation pattern and amplitude are more consistent
- The lower velocity anomaly in SW Taiwan is also visible in body-wave derived models.

Comparison with models derived from body-wave (shorter period)

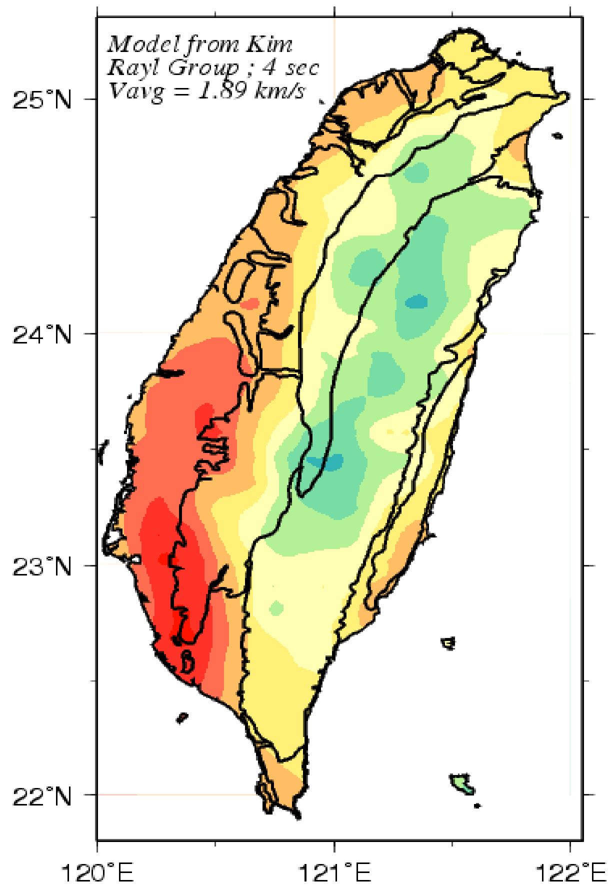
Group velocity of Rayleigh waves at Period 4 sec



Wu *et al*.(2007)



Kim *et al*.(2005)



Lateral variations are generally consistent, but weaker in body-wave derived models.

Ambient noise tomography

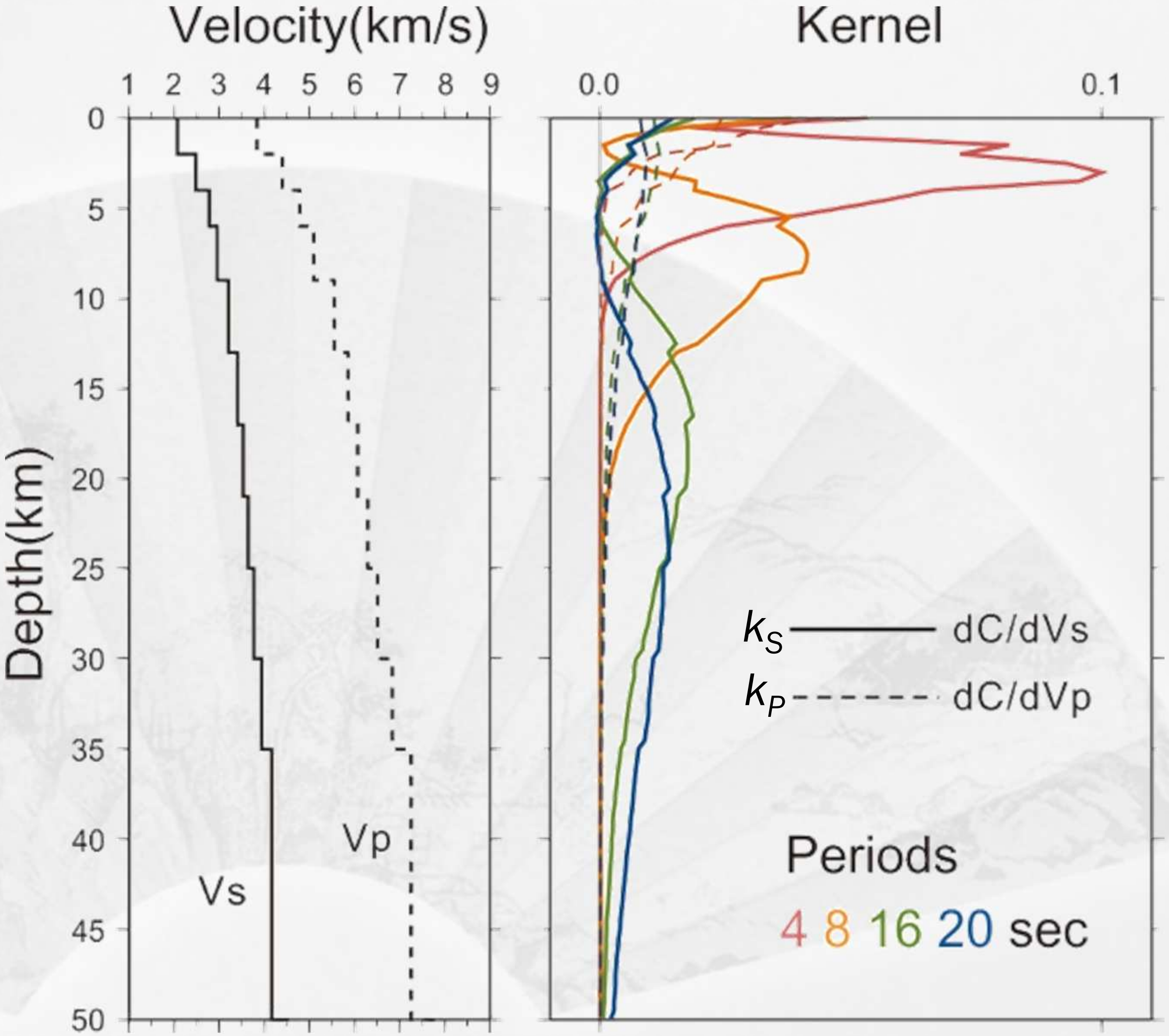
- Inversion method
  - wavelet-based multi-scale tomography with anisotropic components
  - + iterated updated location-dependent kernels
  - = 3-D models
- 12 layers from surface to 50 km depth
- Starting model: Isotropic 1-D model averaged from Wu et al. (2007) → smoothed 3-D model
- 5 iterations, with anisotropic components involved in the final iteration

Depth sensitivity kernels for surface waves

When reference 1D velocity model is given:

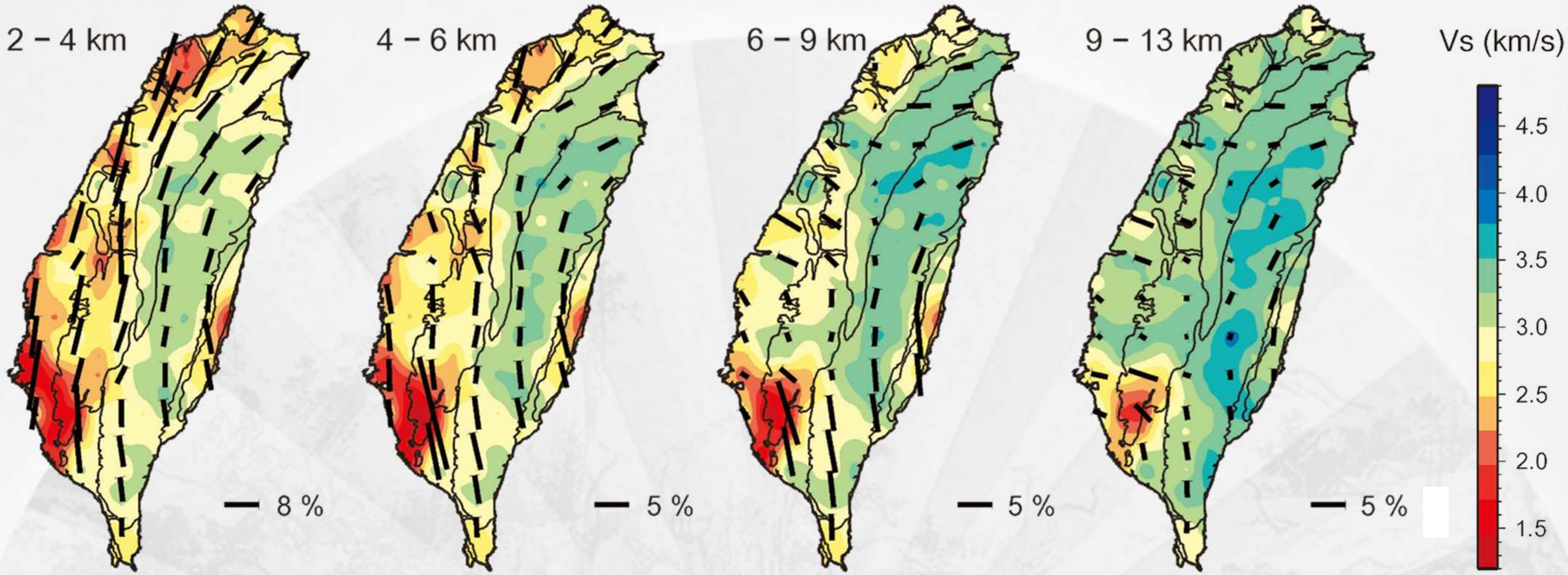
$$
\begin{aligned}
\partial C
&= \frac{\partial C}{\partial Vs}\,\delta Vs + \frac{\partial C}{\partial Vp}\,\delta Vp \\
&= k_s \delta Vs + k_p \delta Vp \\
&= k_s \delta Vs + k_p \left(\frac{\delta Vp}{\delta Vs}\right) \delta Vs \\
&\approx k_s \delta Vs + k_p \left(\frac{Vp}{Vs}\right) \delta Vs
\end{aligned}
$$

(scaled to 1.75)



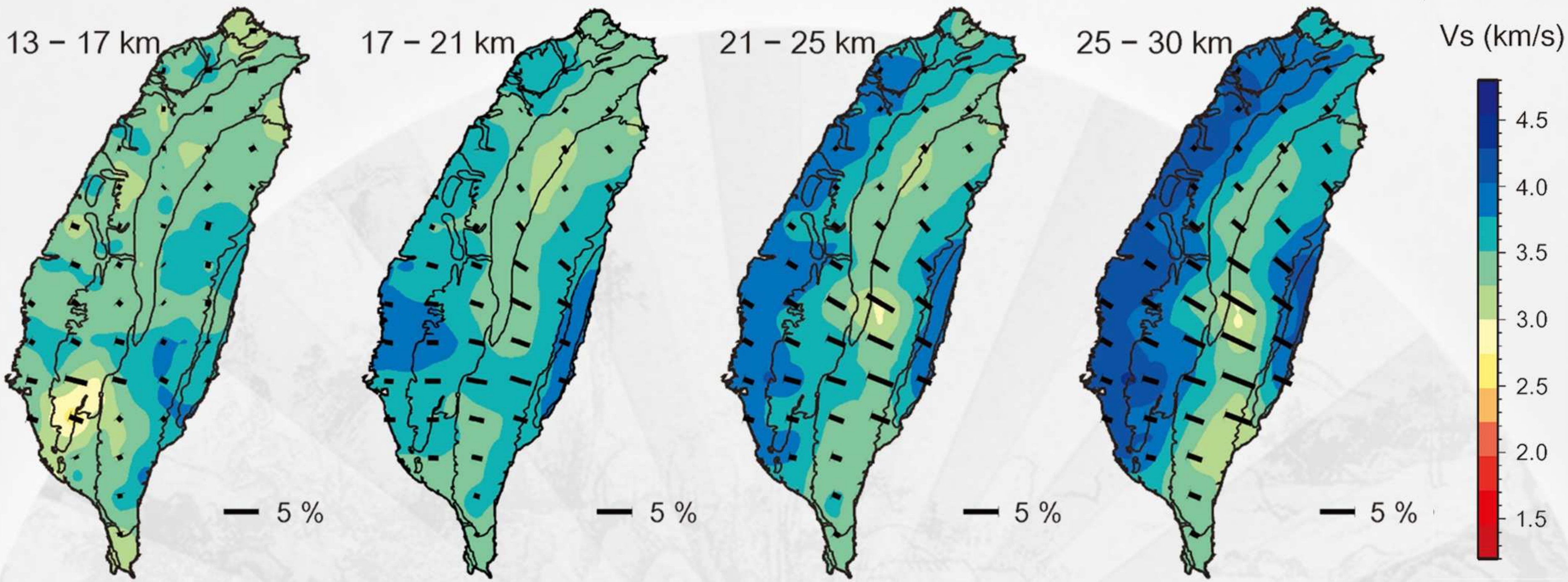
Reference 1D model – averaged model from Wu et al.(2007).

Layered deformation in the Taiwan orogen (2 - 13 km)



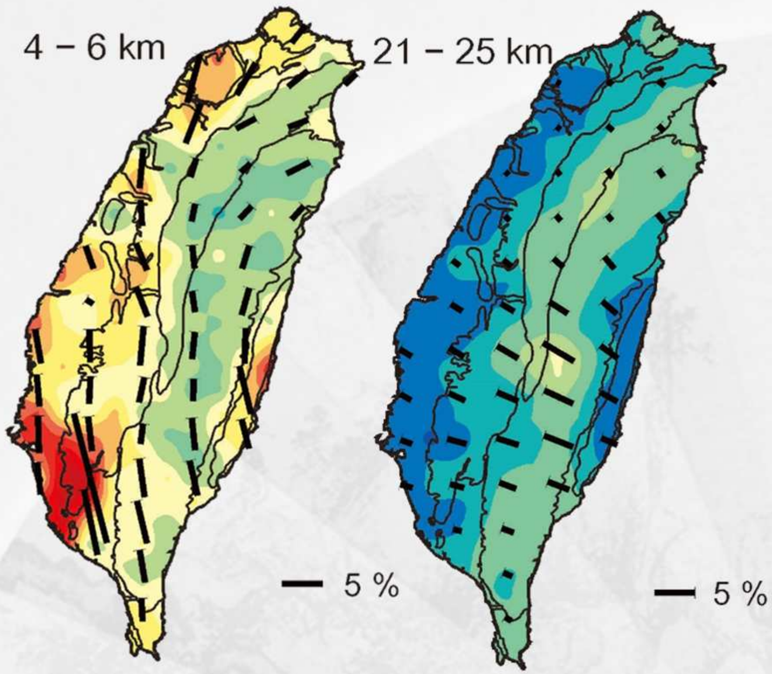
- Great correlation to surface tectonics at shallow depths
- Characteristics of anisotropy at upper crust – convergence-perpendicular striking anisotropy → strong foliation in mountain range.

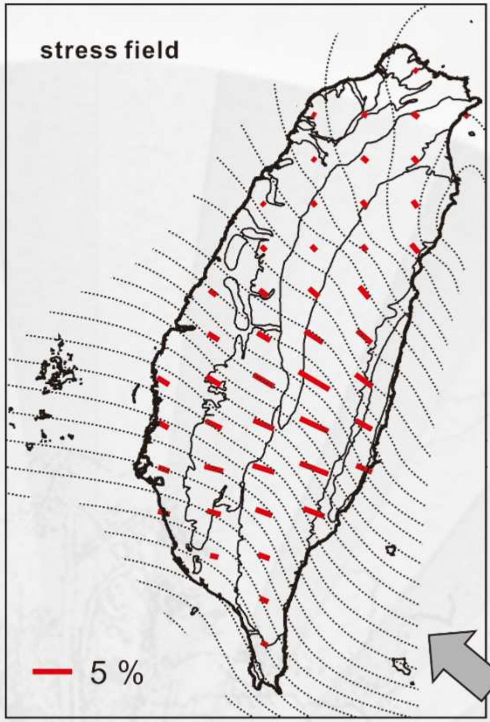
Layered deformation in the Taiwan orogen (13 – 30 km)



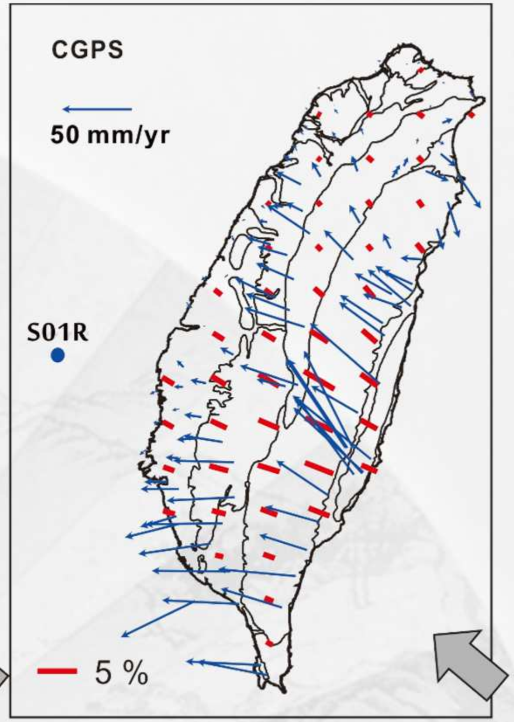
- More homogeneous isotropic velocity
- Convergence-parallel E-W anisotropy in middle to lower crust

Orthogonal patterns of crustal anisotropy at different depths v.s. strain field in Taiwan





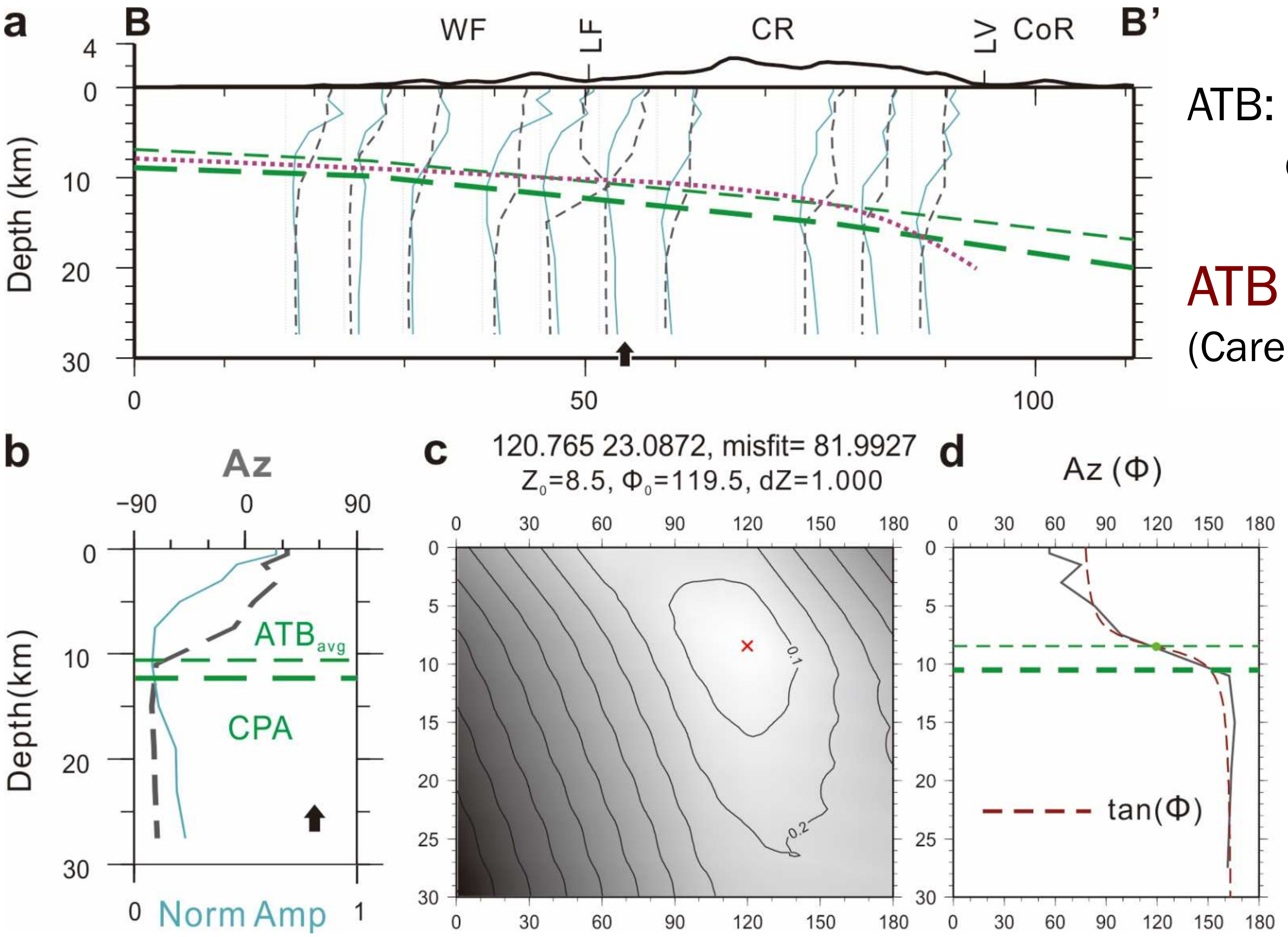
(Chang et al., 2003)



(Lin et al., 2012)

1. Foliation-dominated anisotropy at shallow crust (brittle) – Orogen-parallel anisotropy (OPA)
2. Lineation-dominated anisotropy at middle crust (weak rheology) – Convergence-parallel anisotropy (CPA)

Anisotropy Transition Boundary (ATB)



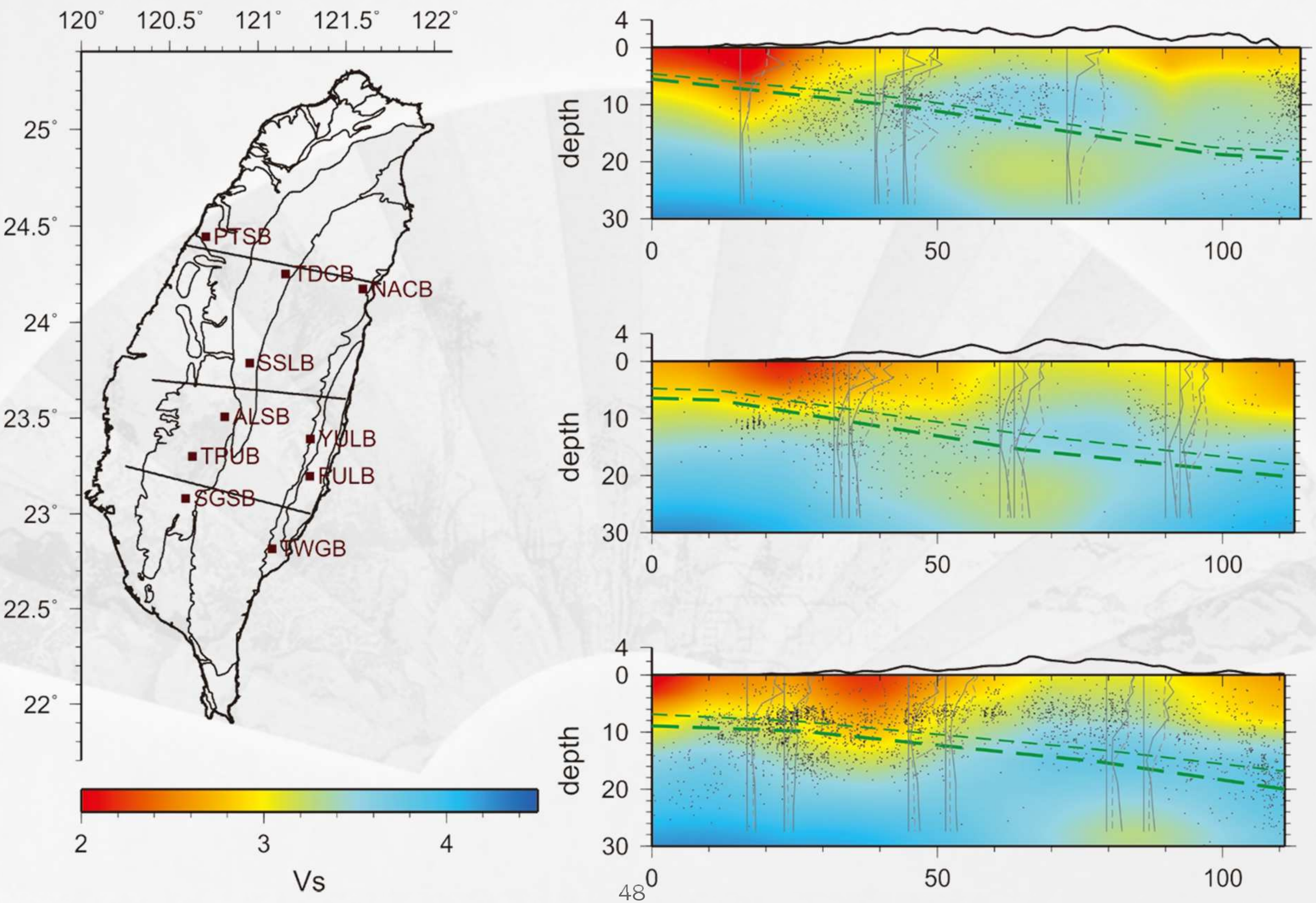
ATB: no-slip boundary condition

ATB ≠detachment

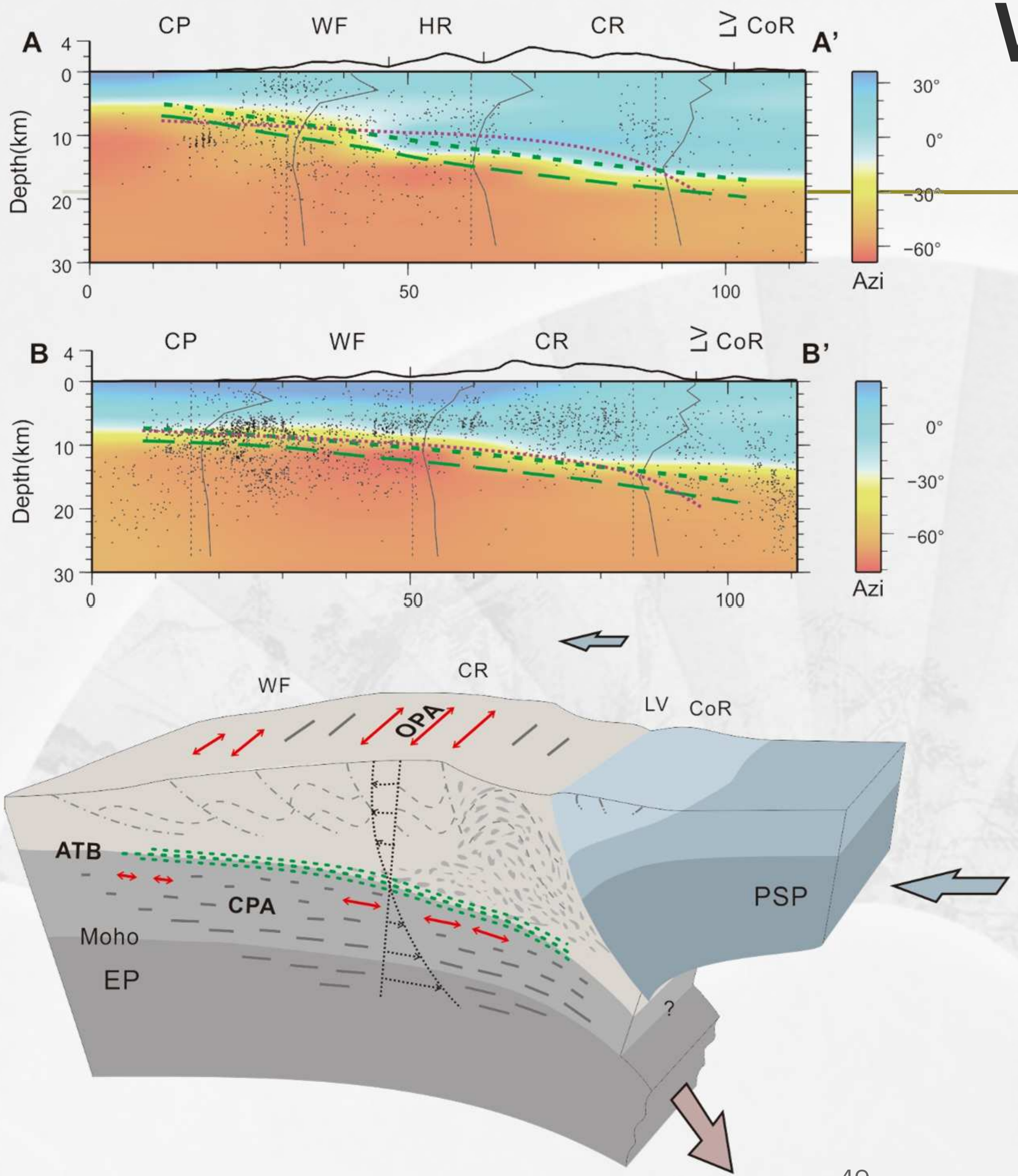
(Carena et al., 2002)

Misfit = $atan[(Z-Z_0)/dZ]/2+ \Phi_0- \Phi (Z)$

Velocity profiles



Weak layer in mid- to lower crust?



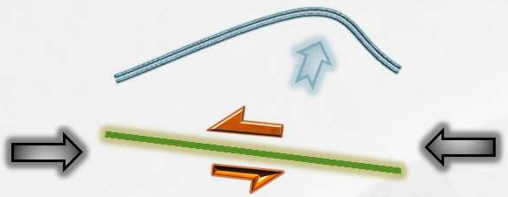
- High temperature
- Low seismicity
- 3D body wave models
- GPS observations
- Thermo-mechanical numerical experiments
- Magnetotelluric results

Upper crust: OPA

Mid- to Lower-crust: CPA

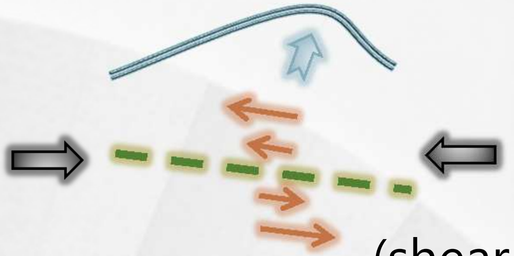
➔ Shear zone

Thin-skinned ?



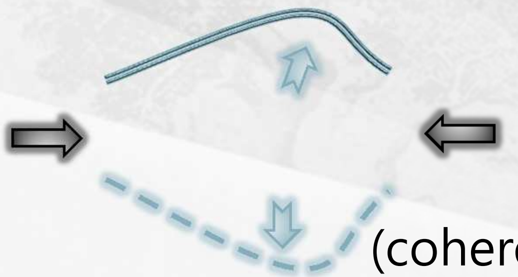
(no deformation)

Coupled layered deformation



(shear zone)

Thick-skinned ?



(coherent deformation)

<u>Thin-skinned</u>

v shortening & uplift in the upper layer

x decoupled and no deformation beneath décollement

<u>Thick-skinned</u>

v coupled, deformed lower crust

x coherent deformation

Summary

- Our 3D model provides complementary information to those provided by high resolution 3D body wave models in Taiwan.

- Orthogonal patterns of anisotropy at shallow and middle crust :

1. Characteristics in convergence plate boundary with a weaker lower crust.
2. This lower crustal shearing is interpreted as driven by the continuous sinking of the Eurasian mantle lithosphere when the surface of the plate is coupled with the orogen.

END

- Thanks for your attention