Quantification of Topography Effect on Seismic Ground Motion: A Case Study in Northern Taiwan

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Motivations for Studying Topography Effect

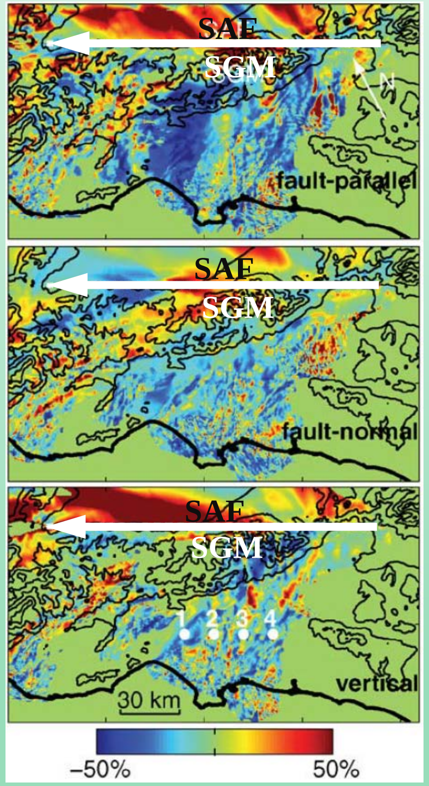
- The Earth is not flat. Some regions have drastic variation in surface relief, e.g. ±4 km in Taiwan region over ~100-km distance.

- Topography affects wave propagation and therefore arrival times and amplitudes of seismic waves

- Neglecting topography:
  - Topography-induced travel time anomalies introduce biases in seismic tomography models
  - Topography-induced amplitude anomalies lead to unrealistic ground motion predictions

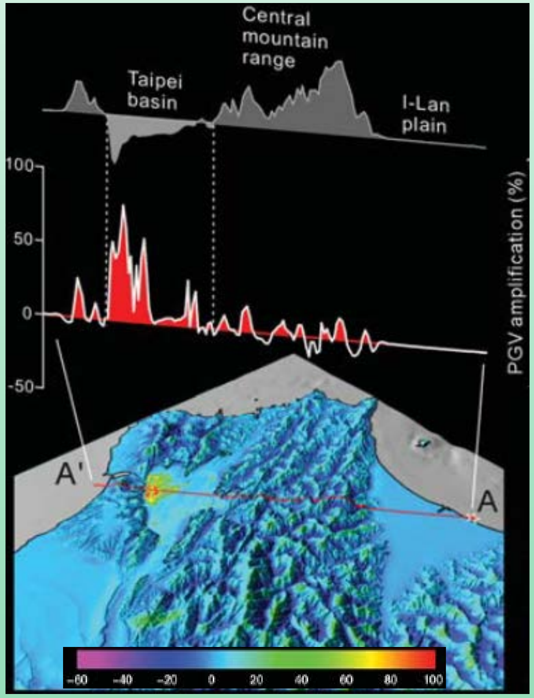
Studying Topography Effects on Ground Motion by Numerical Simulations

Southern California



Ma et al. (2007)

Northern Taiwan



Lee et al. (2009)

- Surface topography influences the intensity of ground motion by focusing, defocusing and scattering of seismic waves.
- Topography has been ignored in most ground motion studies, leading to biases in PGV and PGA predictions.

Numerical simulations show that the effect of topography on PGV predictions can be up to ±50% for ground motion of ~0.5 Hz (Ma et al., 2007; Lee et al., 2009).

Finite-difference Method (FDM)

- Newton's second law:

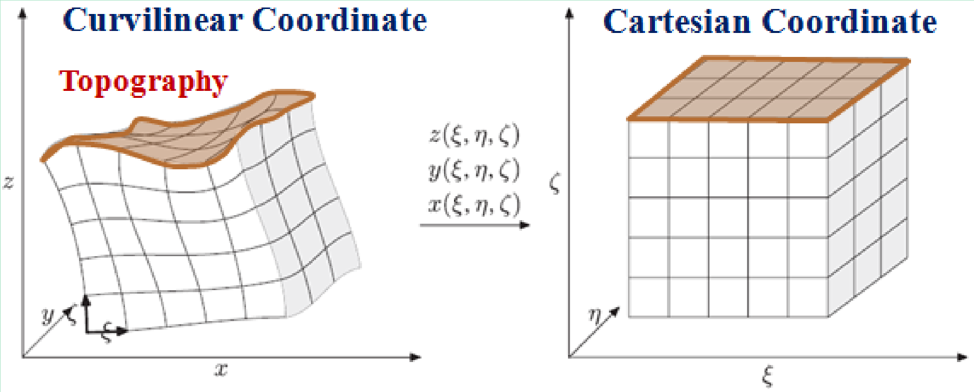
$$\rho \frac{\partial \mathbf{v}}{\partial t} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{f},$$

- Hooke's Law:

$$\frac{\partial \boldsymbol{\sigma}}{\partial t} = \mathbf{C} : \frac{1}{2}[\nabla \mathbf{v} + (\nabla \mathbf{v})^T] - \mathbf{m}',$$

- Surface topography : curvilinear grids transformed to Cartesian grids

- FDM code by Zhang et al. (2012)
- Grid spacing: 300 m horizontally and variable vertically (171.4 m near surface and increasing to 782.6 m at ~ 60-km).
- Accurate waveforms up to 0.8 Hz
- FD simulations on the IES HPC cluster

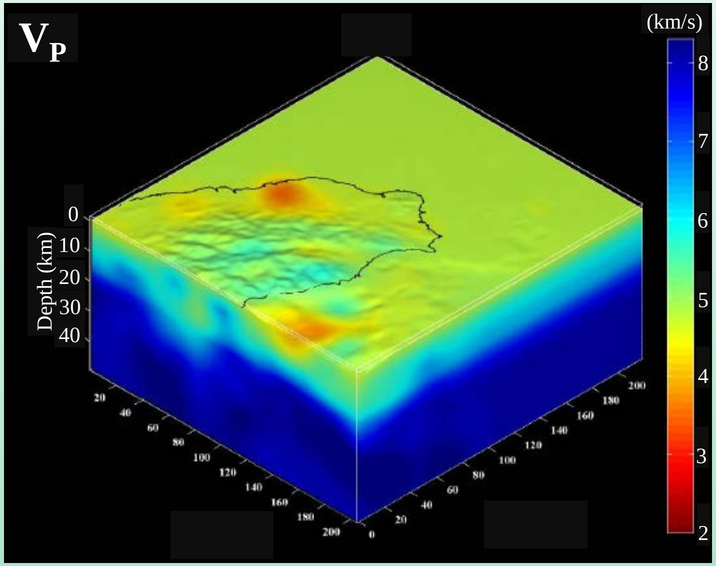


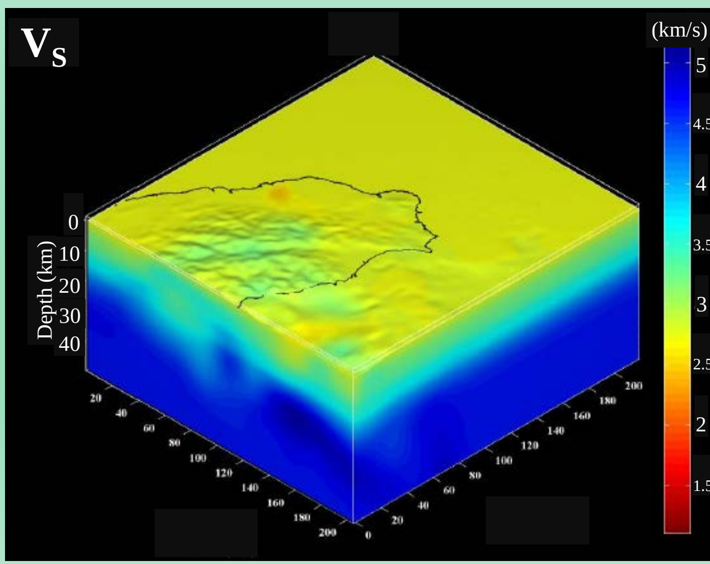
Zhang et al. (2012)

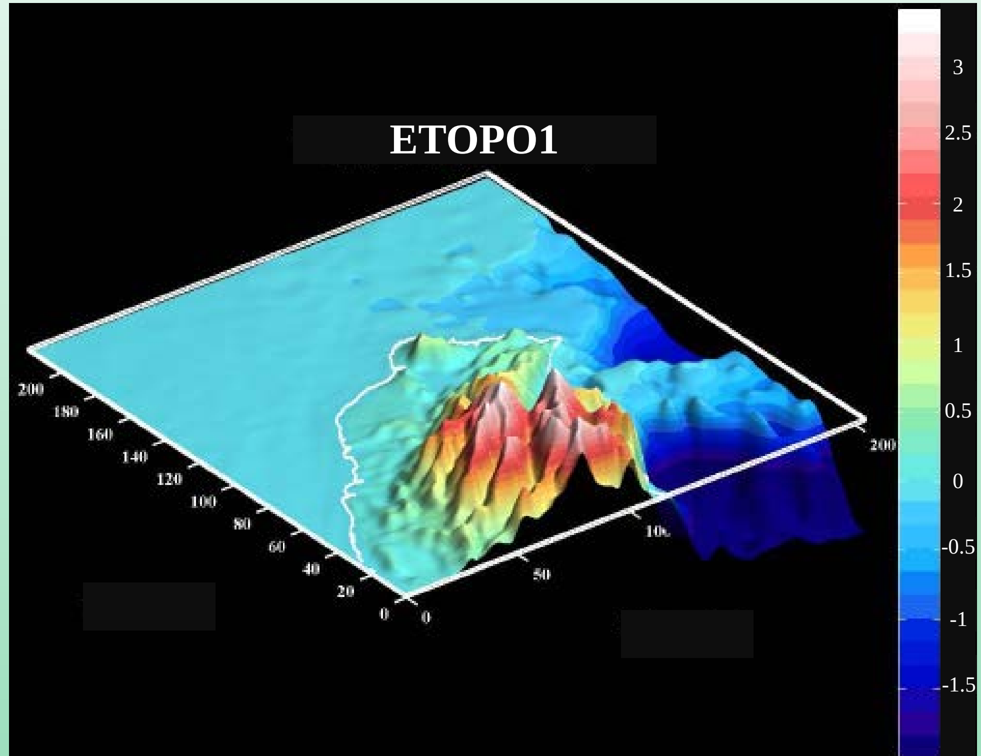
$$\frac{\partial \mathbf{V}}{\partial t} = \mathbf{A}\frac{\partial \mathbf{V}}{\partial x} + \mathbf{B}\frac{\partial \mathbf{V}}{\partial y} + \mathbf{C}\frac{\partial \mathbf{V}}{\partial z} + \mathbf{F},$$

$$\frac{\partial \mathbf{U}}{\partial t} = \tilde{\mathbf{A}}\frac{\partial \mathbf{U}}{\partial \xi} + \tilde{\mathbf{B}}\frac{\partial \mathbf{U}}{\partial \eta} + \tilde{\mathbf{C}}\frac{\partial \mathbf{U}}{\partial \zeta} + \mathbf{F},$$

Taiwan: 3D Model and Topography

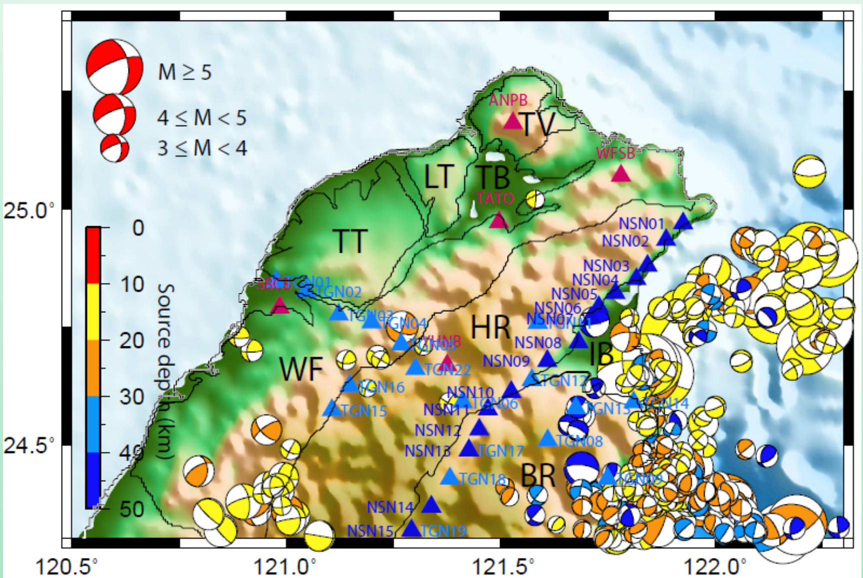




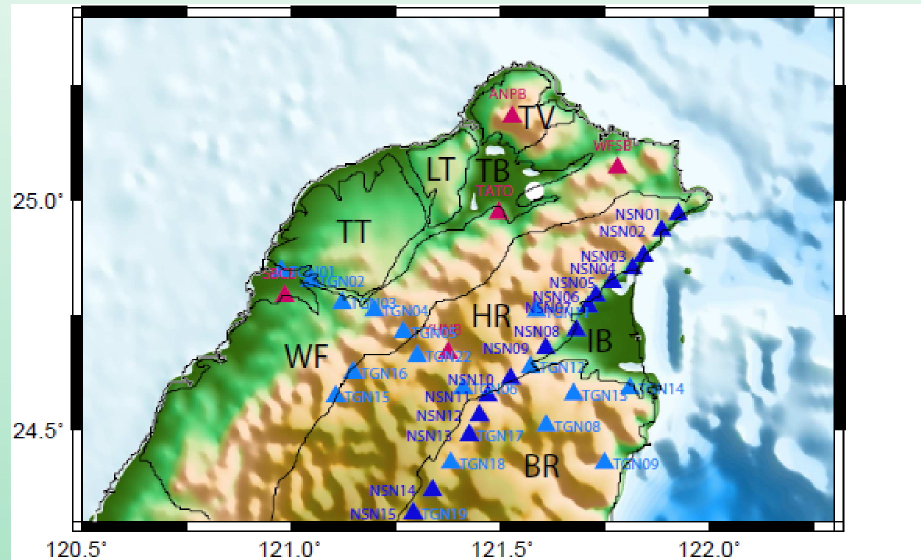


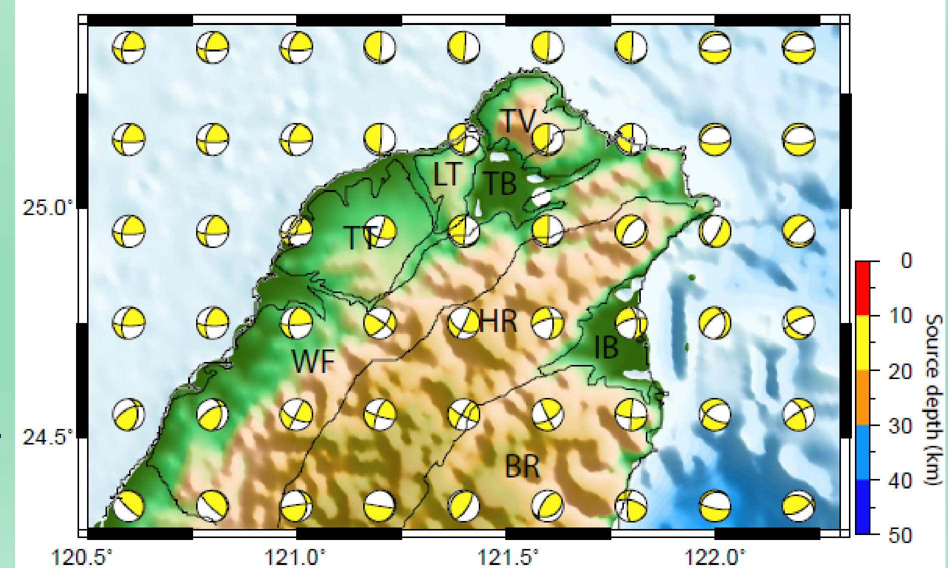
- Regional model from travel time tomography (Kuo-Chen et al., 2012).
- ETOPO1 topography: 1 arc-minute (~1.85 km). Up to ~6 km topography contrast over 100-km distance in northern Taiwan.

Sources and Stations



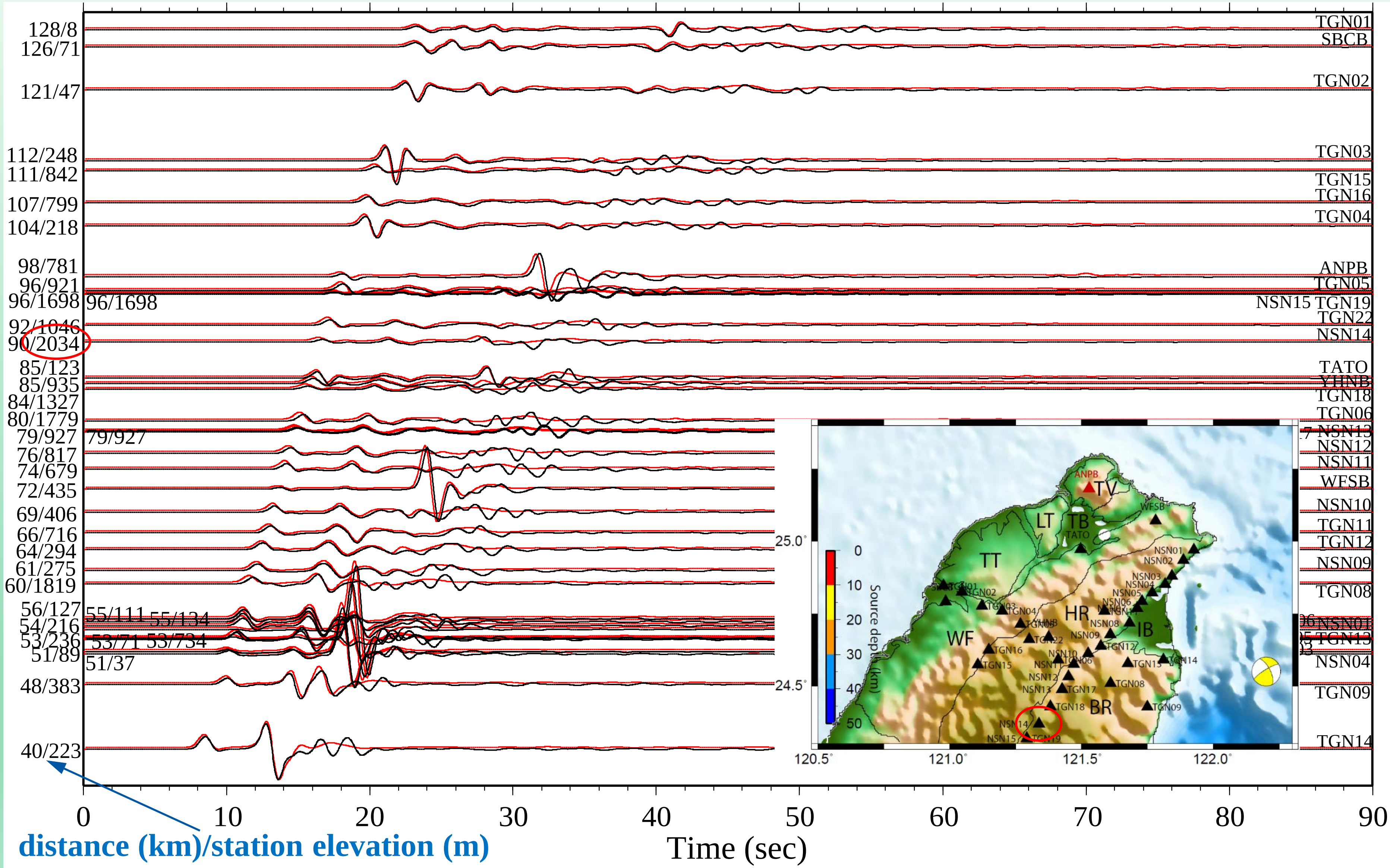
38 Stations (BATS and TAIGER)





- Use 54 x 3 sources (at depths **7**, **15** and **23** km) to examine P and S waves coming from a variety of directions.
- Compute waveforms from the 162 sources to all 38 stations with and without topography and measure the differences in their P- and S-wave travel times and amplitudes.

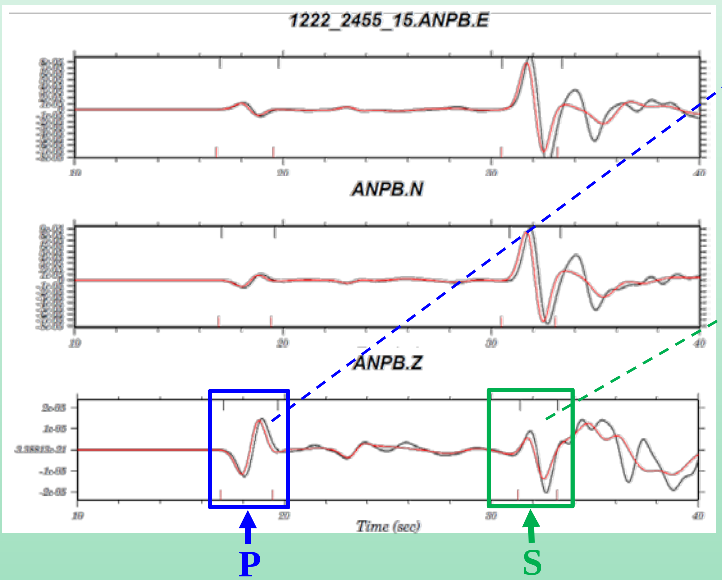
Comparison of Waveforms (Z component)

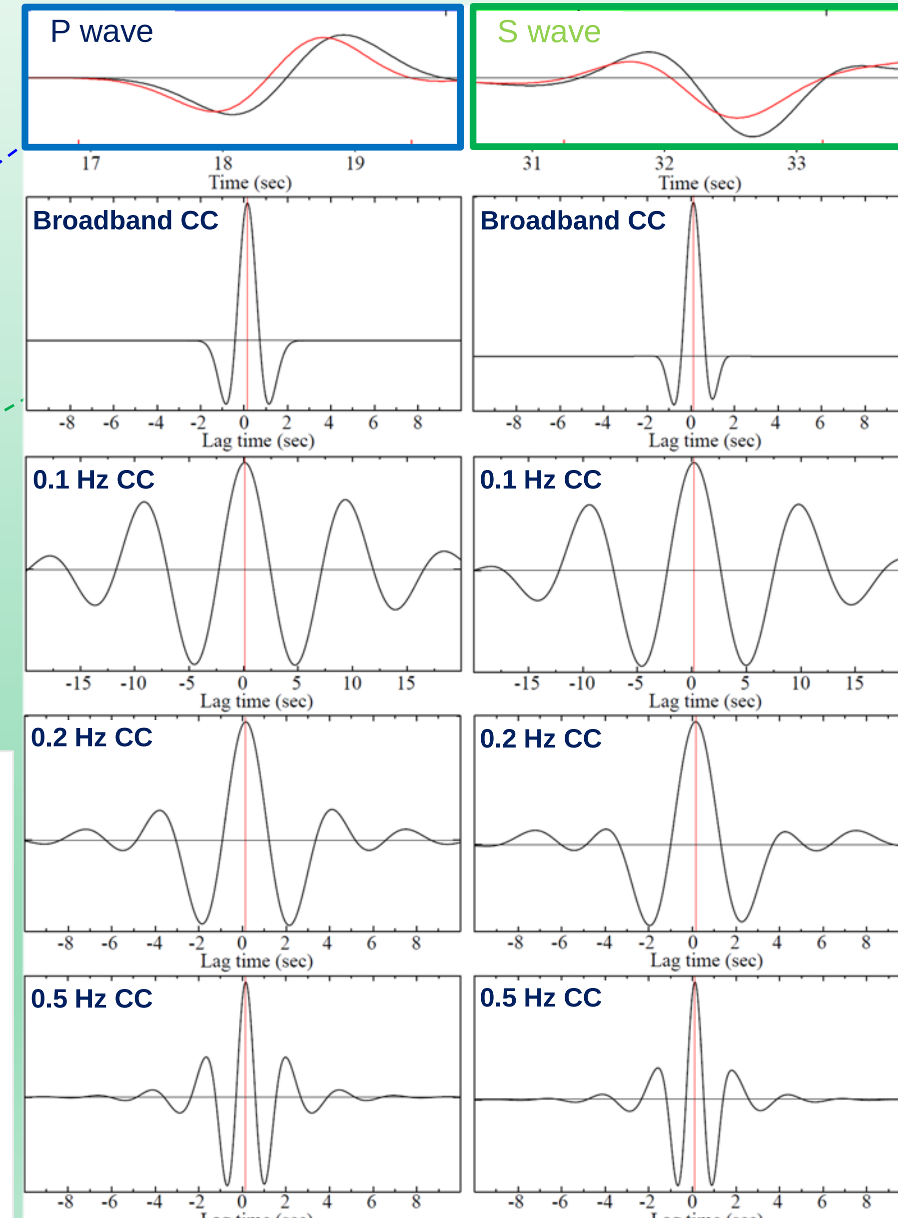


Black: “*record*” (with topography) **Red: “*Synthetics*” (flat surface)**

Measuring Time and Amplitude Anomalies

- "*Record*" and "*synthetics*" with and without topography





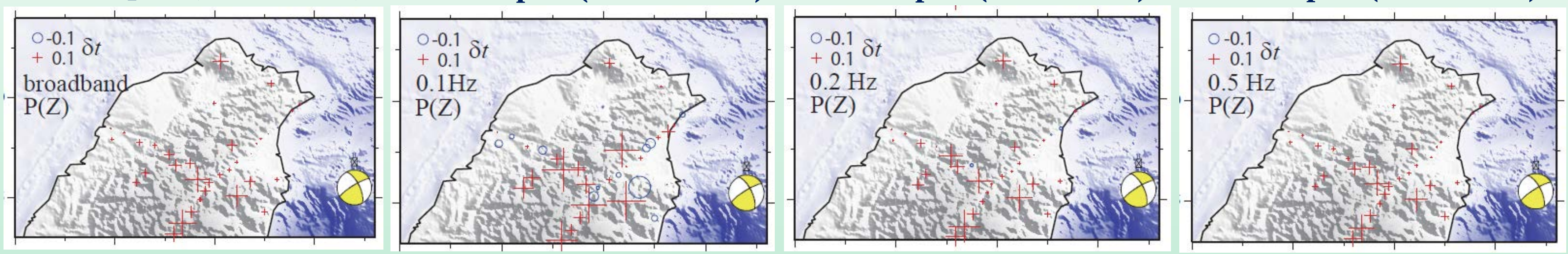
- Compute *synthetic* autocorrelation C_A and *record*-*synthetic* crosscorrelation C_C
- Bandpass filter the correlations around 3 frequencies: 0.1Hz, 0.2Hz and 0.5Hz
- Time anomaly: lag time of C_C^{max}

  Amplitude anomaly: $\delta \ln A = \dfrac{C_C^{max} - C_A^{max}}{C_A^{max}}$

Frequency-dependence of Topography Effect

Z-comp. P (broadband) Z-comp. P (0.1Hz/10sec) Z-comp. P (0.2Hz/5sec) Z-comp. P (0.5Hz/2sec)

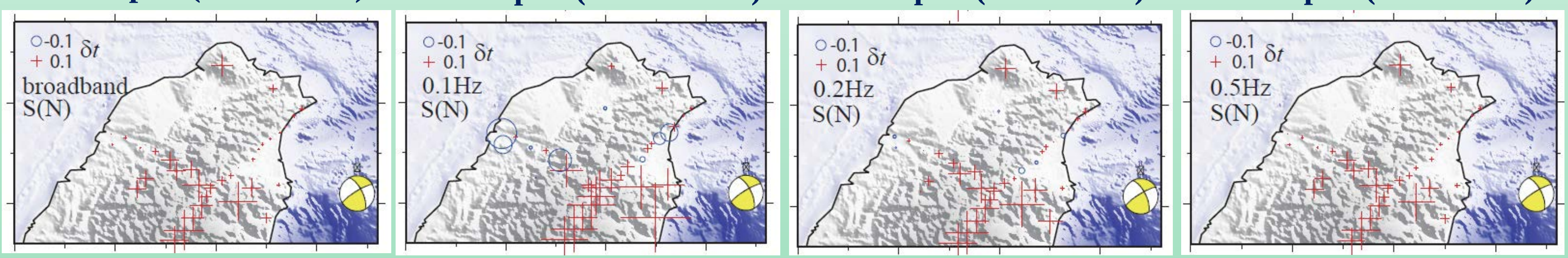
δt



P-wave arrival time is more delayed at higher elevation and longer period, up to 0.4 sec.

N-comp. S (broadband) N-comp. S (0.1Hz/10sec) N-comp. S (0.2Hz/5sec) N-comp. S (0.5Hz/2sec)

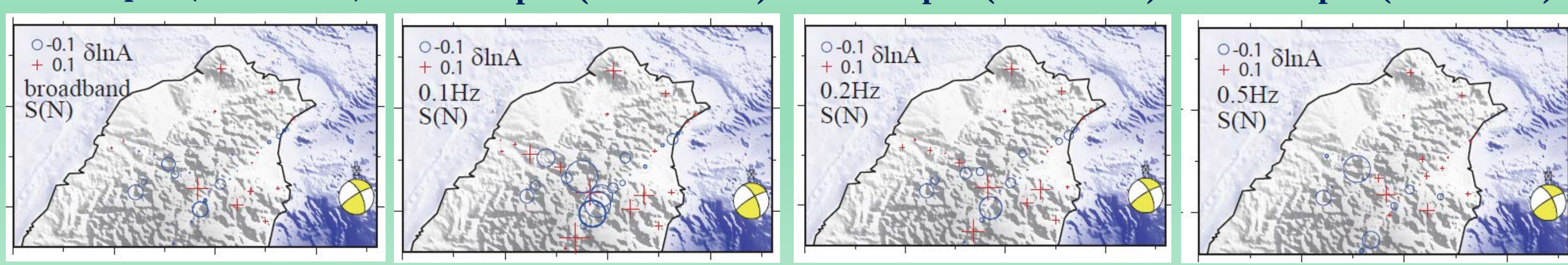
δt



S-wave arrival time is more delayed at higher elevation and longer period, up to 0.7 s.

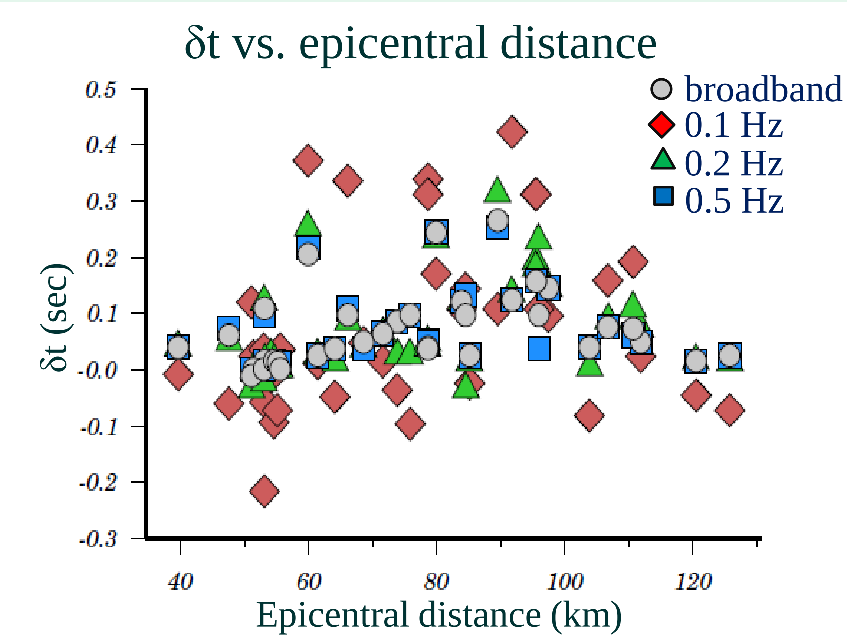
N-comp. S (broadband) N-comp. S (0.1Hz/10sec) N-comp. S (0.2Hz/5sec) N-comp. S (0.5Hz/2sec)

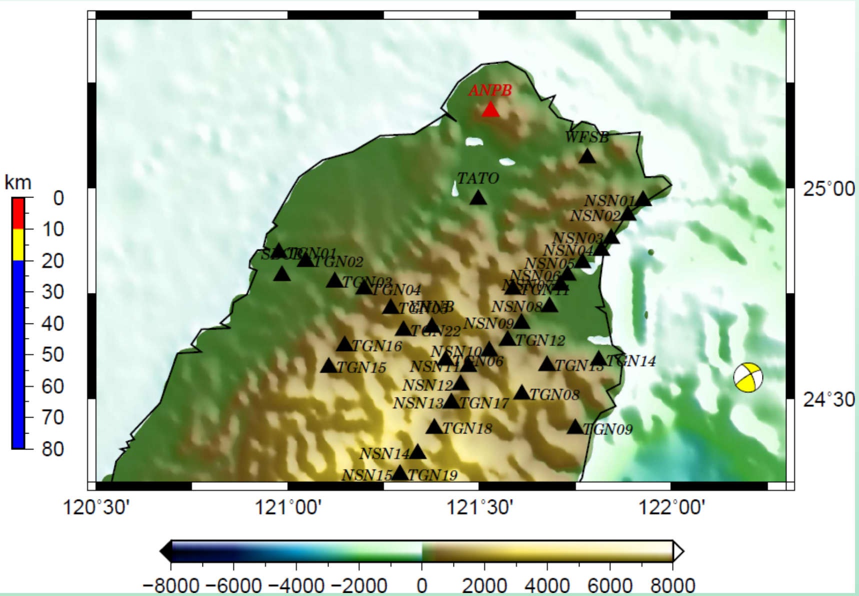
δlnA



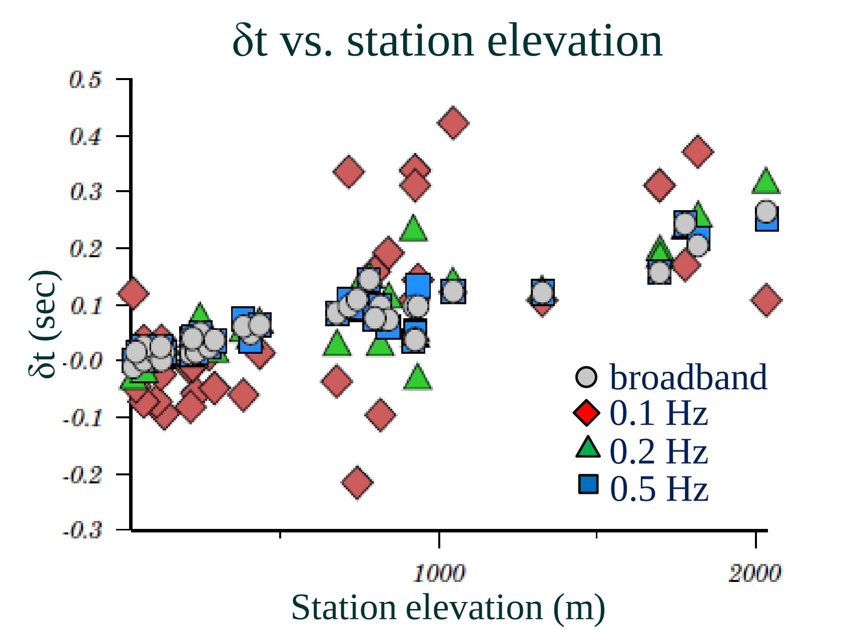
Topography effect on S-wave amplitude has a complex pattern.

P-wave Travel Time Anomalies due to Topography

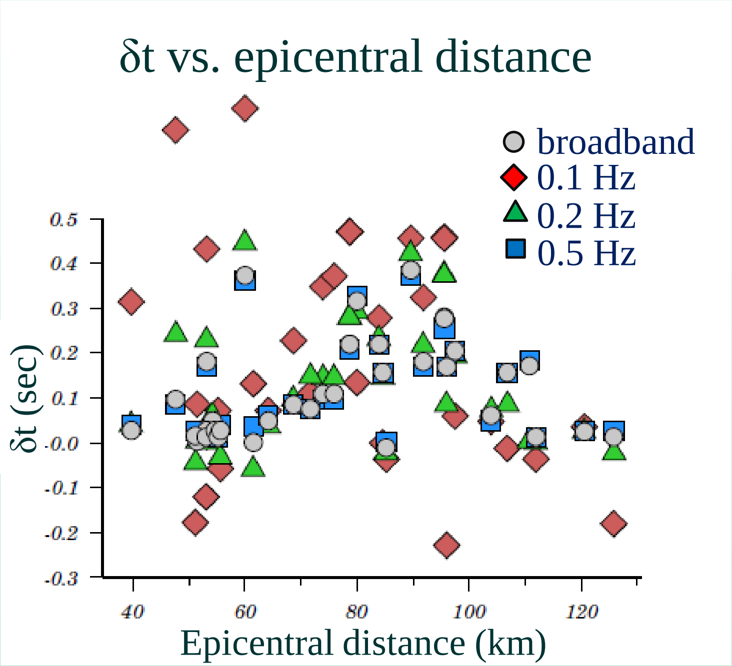


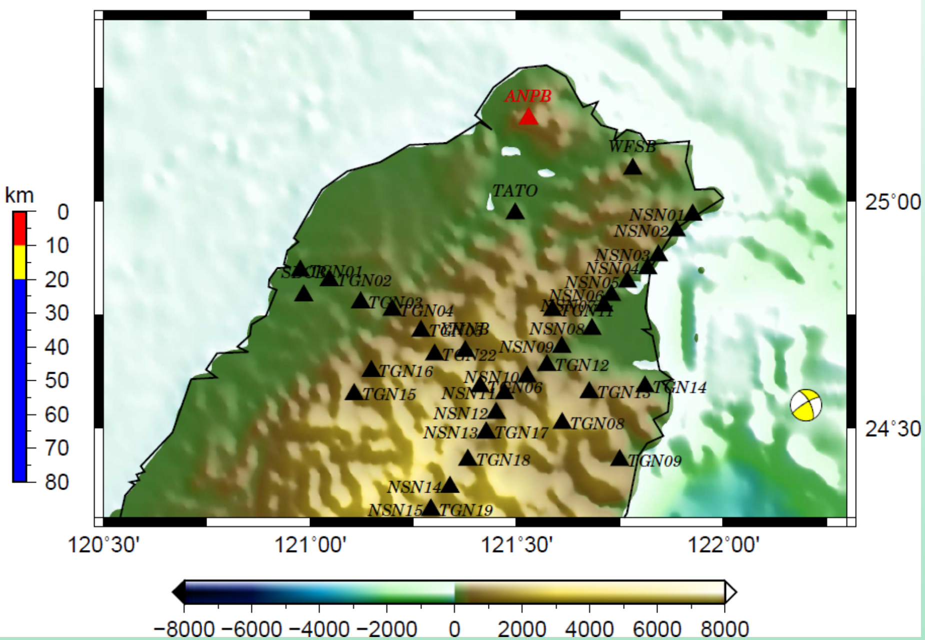


- P-wave delay times due to topography can be up to ~0.4 s.
- Delay times from topography have no clear relationship with epicentral distance; increase with elevation.
- Delay times have larger variation at longer periods (red and green symbols) due to finite-frequency effect.



S-wave Travel Time Anomalies due to Topography





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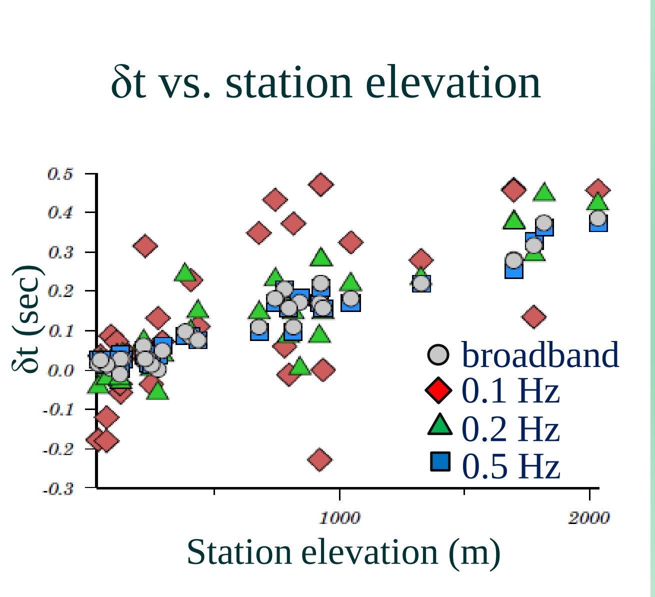
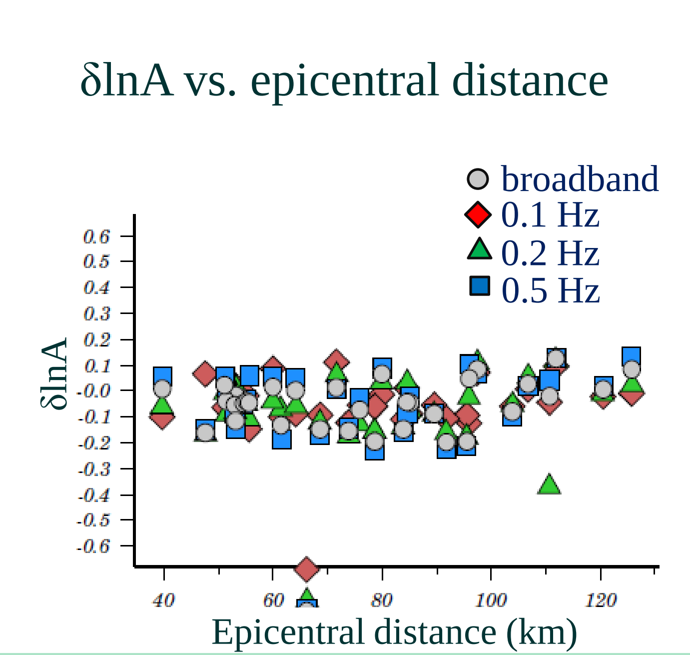
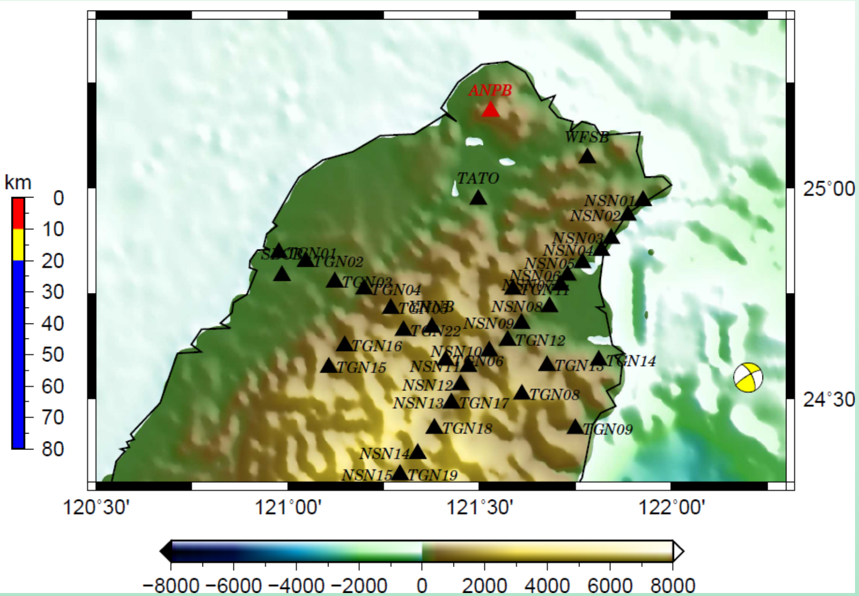
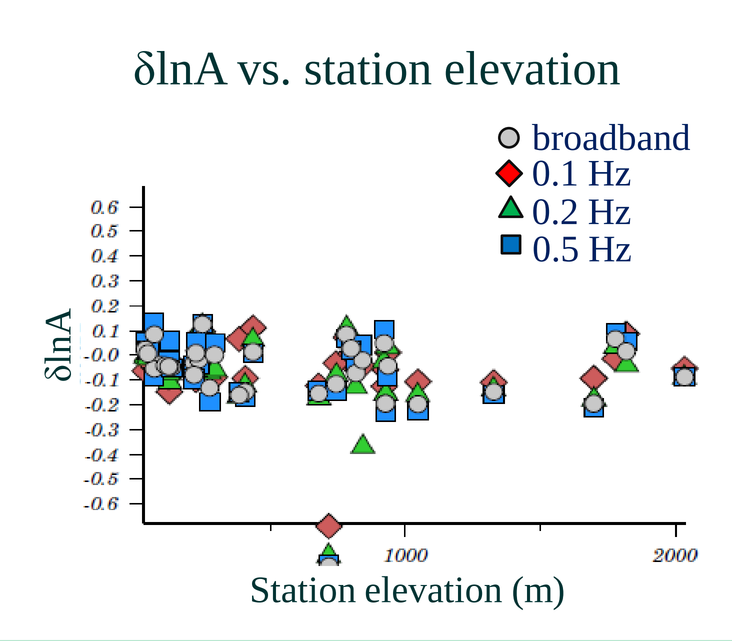


S-wave Amplitude Anomalies due to Topography



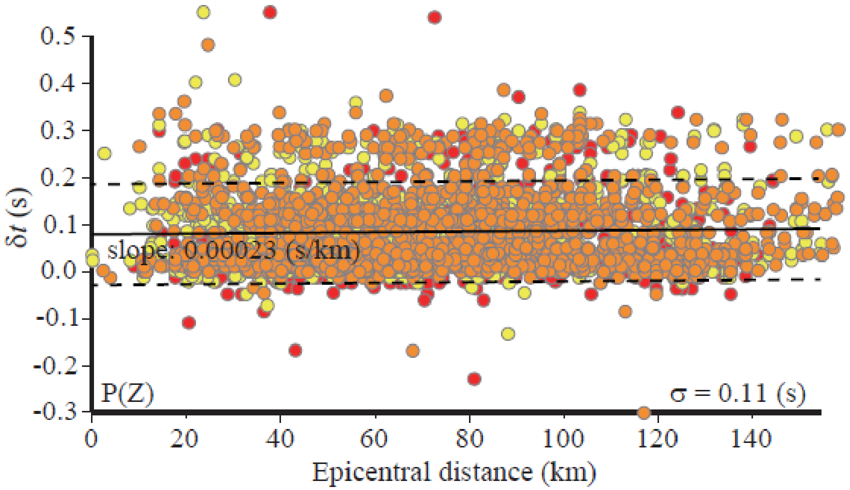




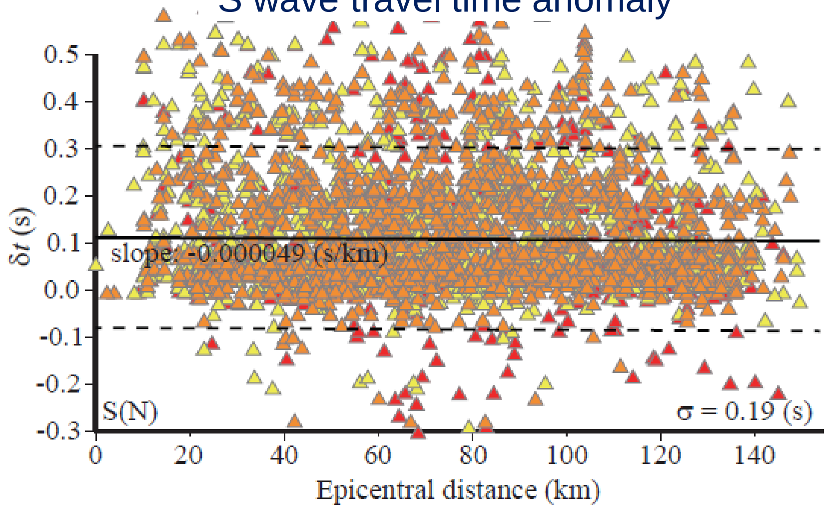
- S-wave amplitude anomalies due to topography have slightly negative mean, i.e. amplitude reduction.
- Topography effect on amplitudes has no clear relation with either distance or station elevation.

Topography Effects vs. Distance

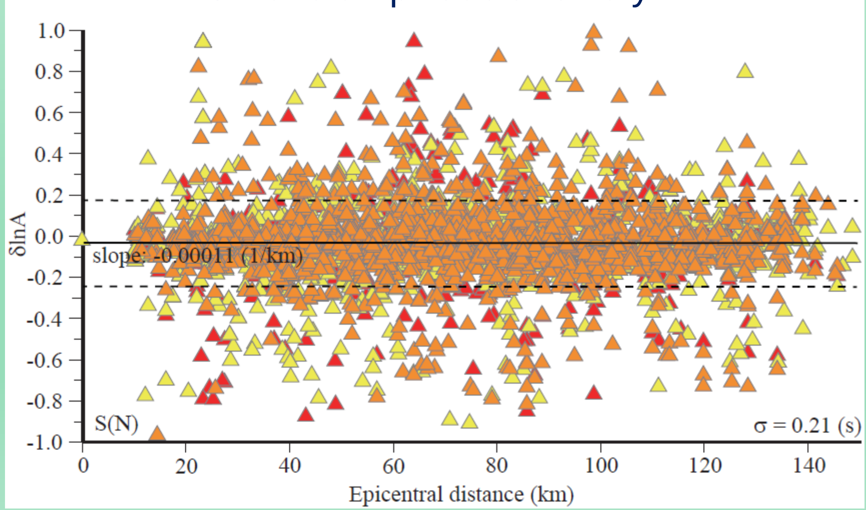
P wave travel time anomaly



S wave travel time anomaly



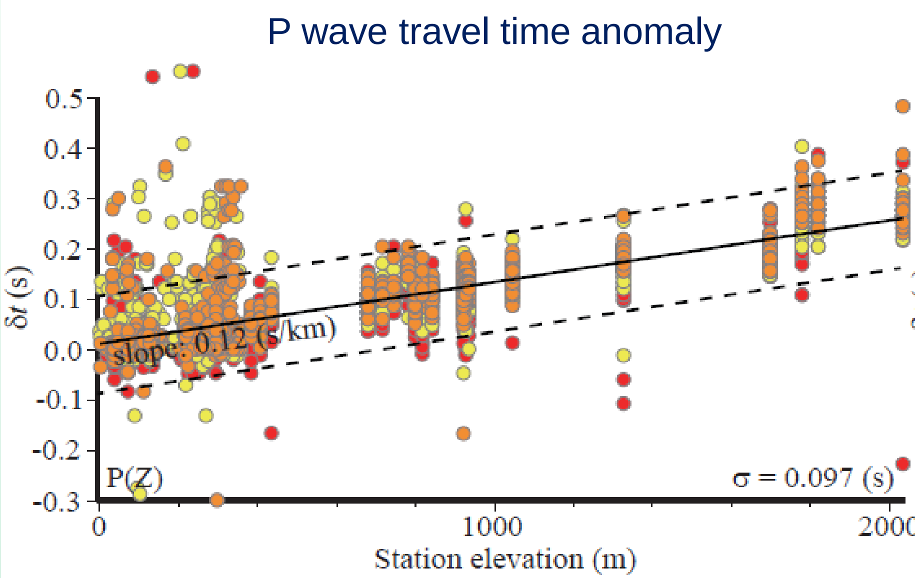
S wave amplitude anomaly

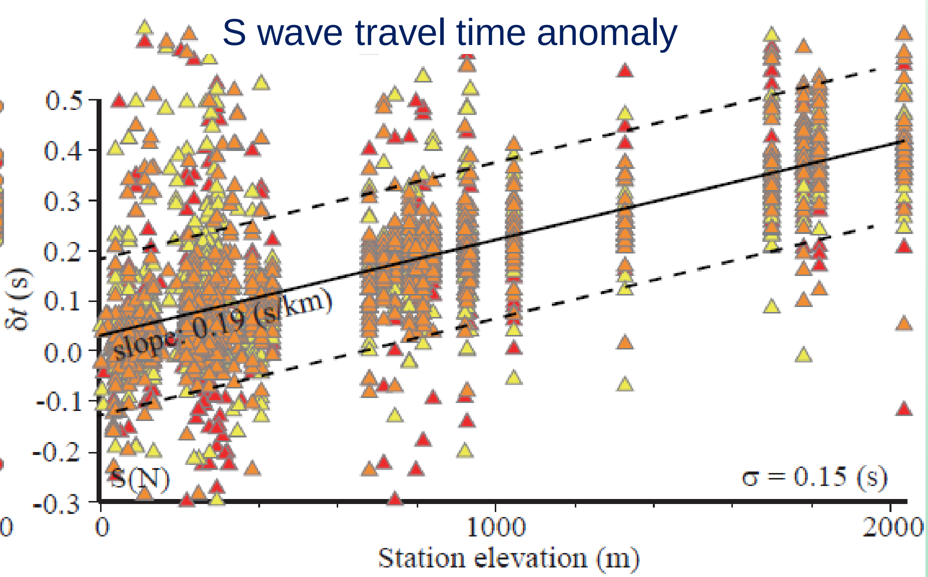


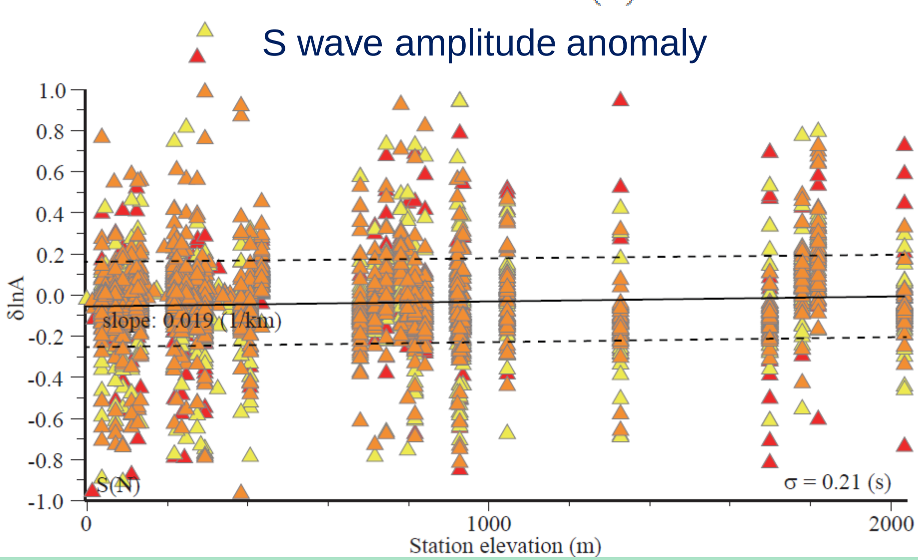
- In northern Taiwan, topography induces up to 0.4 s and 0.7 s in P- and S-wave delay times, respectively, and up to 80% in S-wave amplitude anomaly.
- P- and S-wave delay times have positive means and no dependence on distance
- Amplitude anomalies for S wave have slightly negative mean and no dependence on distance.

Source Depths: ● 7 km ● 15 km ● 23 km

Topography Effects vs. Station Elevation







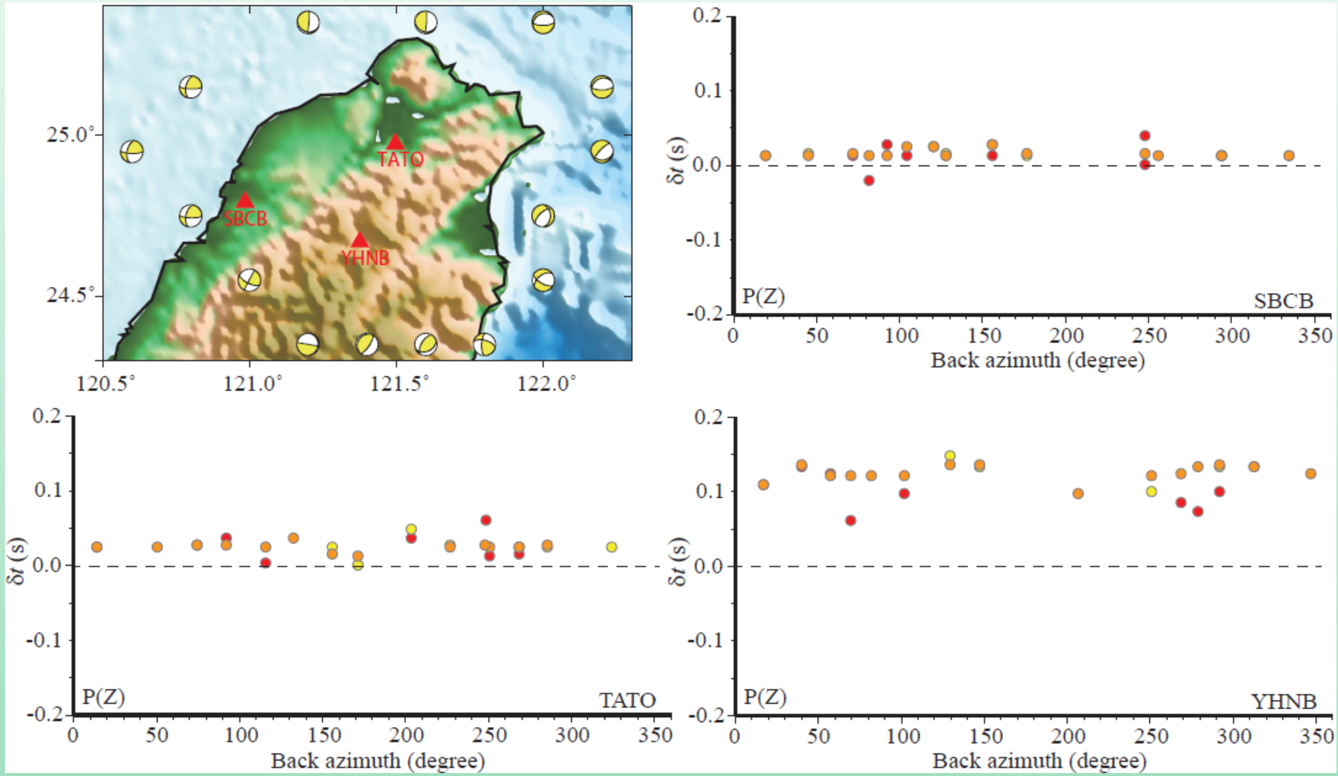
- Delay times for P and S waves increase with station elevation.
- Increase of S-wave delay times with station elevation is nearly twice as fast as P wave delay times.
- Amplitude anomalies for S wave have no dependence on station elevation.

Source Depths: ● 7 km ● 15 km ● 23 km

Variation with Back Azimuth: P-wave Travel Times

Source Depths

- 7 km
- 15 km
- 23 km



SBCB : Western Foothills with a low elevation of ~70.6 m
TATO : Taipei Basin with an elevation of ~123.0 m
YHNB : Central Range with a relatively high elevation of 934.9 m.

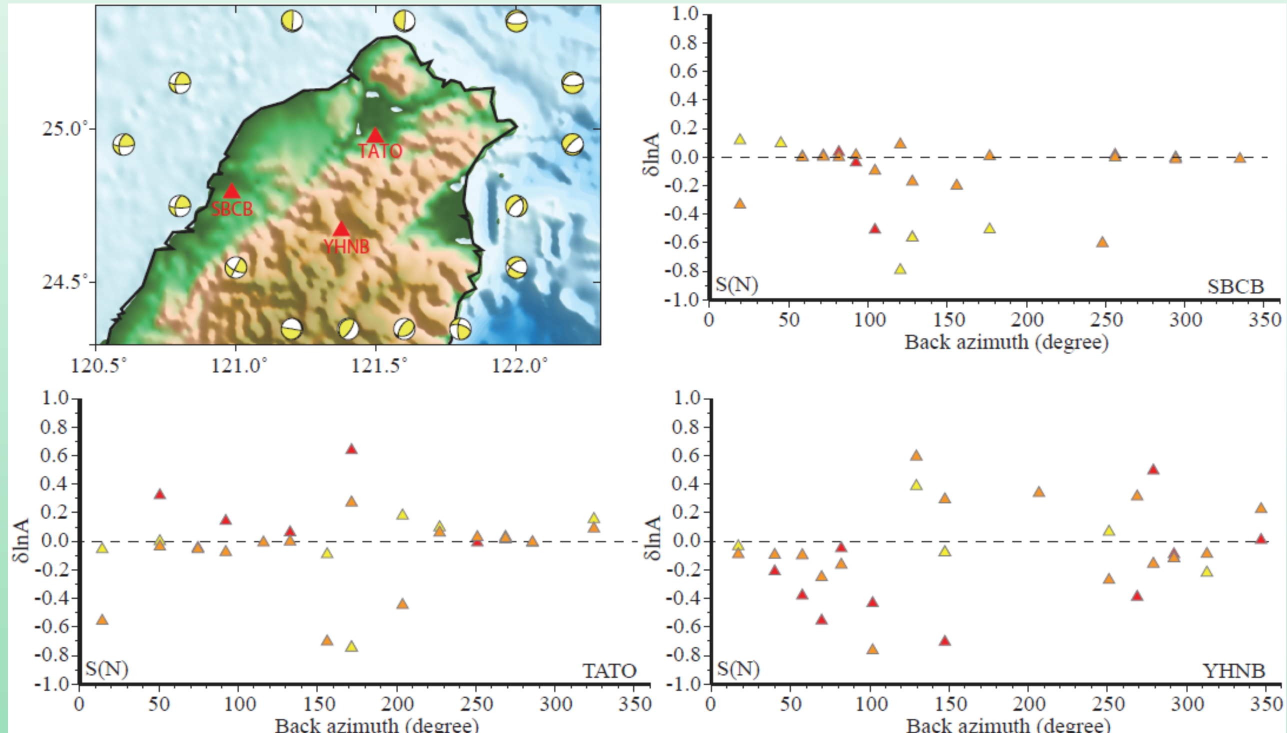
Topography-induced delay times δt :

- No clear variation in the topography-induced P-wave delay times with back azimuth.
- Clearly positive with larger values at high-elevation YHNB and smaller values at low-elevation SBCB.

Variation with Back Azimuth: S-wave Amplitudes

Source Depths

- 7 km
- 15 km
- 23 km



Topography-induced amplitude anomalies δlnA:

- Amplitude anomalies show complex variation with azimuth.
- A majority of amplitude anomalies are negative (reduction).

Summary

- In northern Taiwan, topography induces up to 0.4 s and 0.7 s in P- and S-wave delay times, respectively, and up to 80% in S-wave amplitude anomaly.
- Topography effect leads to positive anomalies in P- and S-wave travel times (delays), and slightly negative anomalies in S-wave amplitudes (reduction).
- Delay times increase with station elevation but have no dependence on epicentral distance. Amplitude anomalies do not depend on either station elevation or epicentral distance.
- Topography-induced travel time delays do not vary with azimuth; whereas topography effect on amplitude varies with azimuth in a complex fashion.