(Gargèse, 14 May 2015)

Passive imaging of crust and mantle structure

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[3] Now at: University of Science and Technology China (USTC)
[4] Now at: CGG Veritas, Houston
[5] Now at: University of Maryland

Research sponsored by

Overview of lecture:

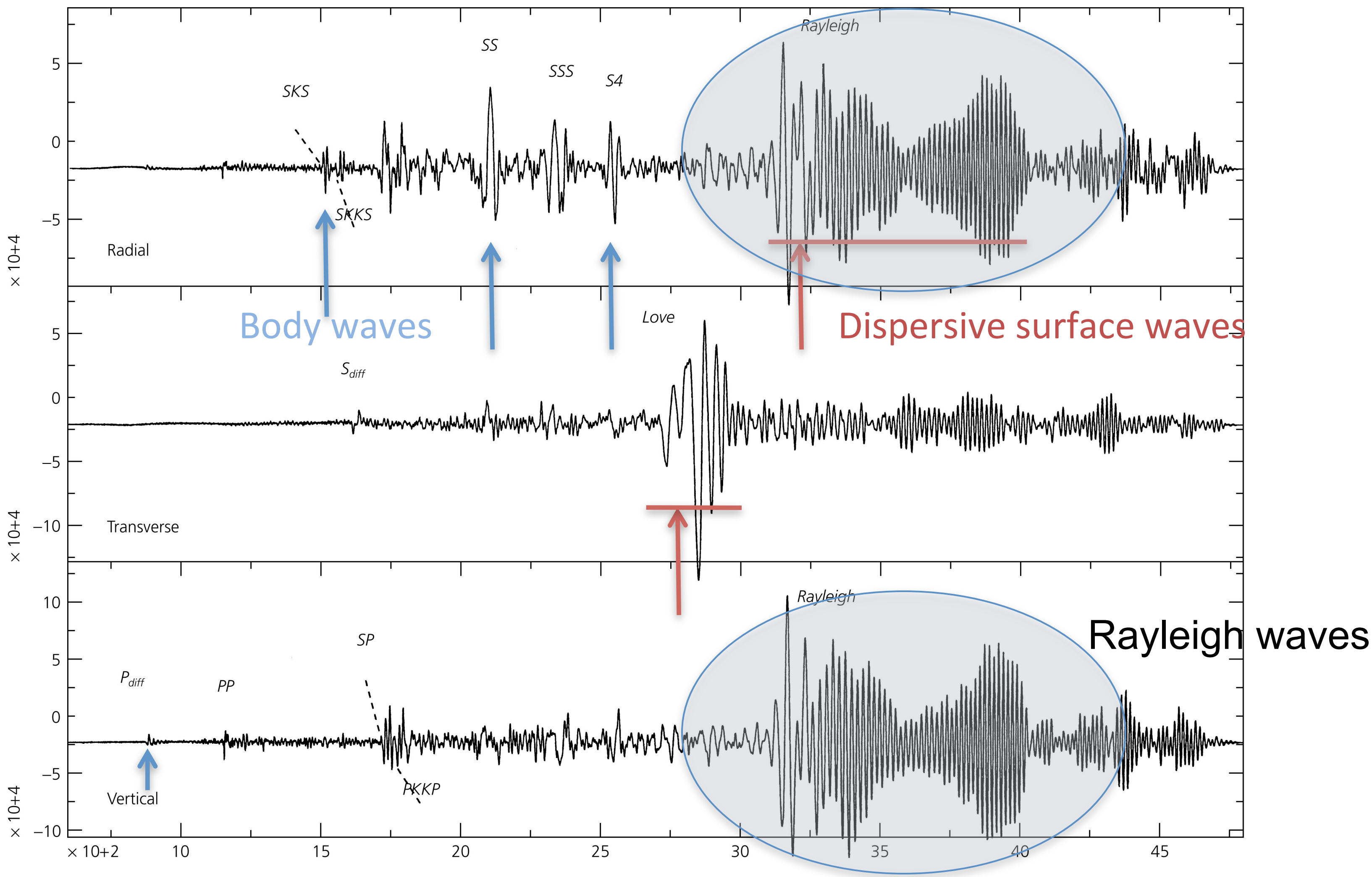
1. **Introduction/background**

2. **Ambient noise and surface wave tomography (MIT, 2005-2015)**
   - Traditional transmission tomography:
     - combining ambient noise and earthquake data
     - quantifying and correcting for uneven noise distribution
     - azimuthal anisotropy
     - radial anisotropy
   - Eikonal tomography
   - Adjoint tomography with ambient noise data

3. **Interferometry of teleseismic body waves – concept**

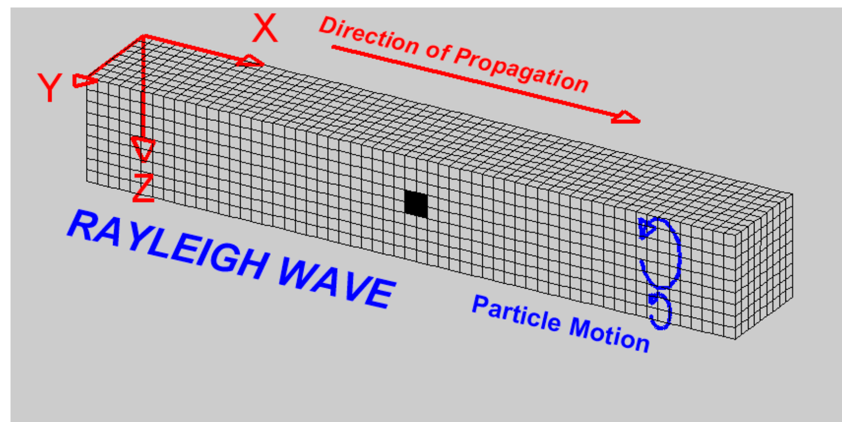
4. **Imaging with multiples – just some thoughts …**

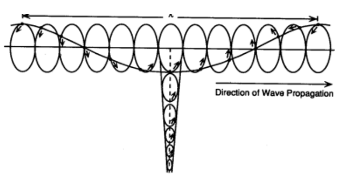
Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.

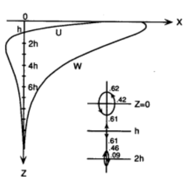


From Stein and Wysession

‘Surface and guided waves’: waves trapped in the shallow layers or a wave guide (such as Love waves in the Earth, acoustic waves in the oceanic SOFAR, ….)



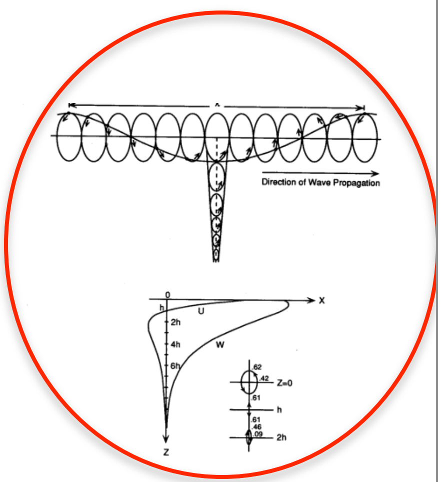


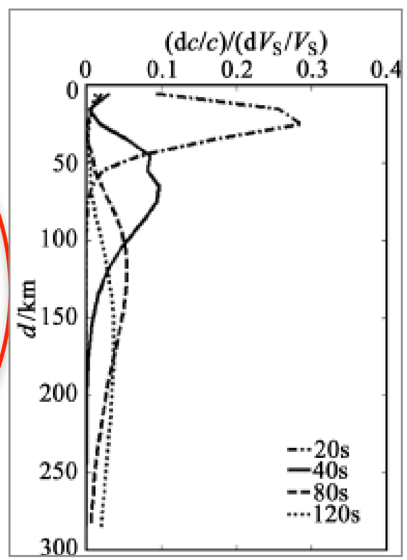


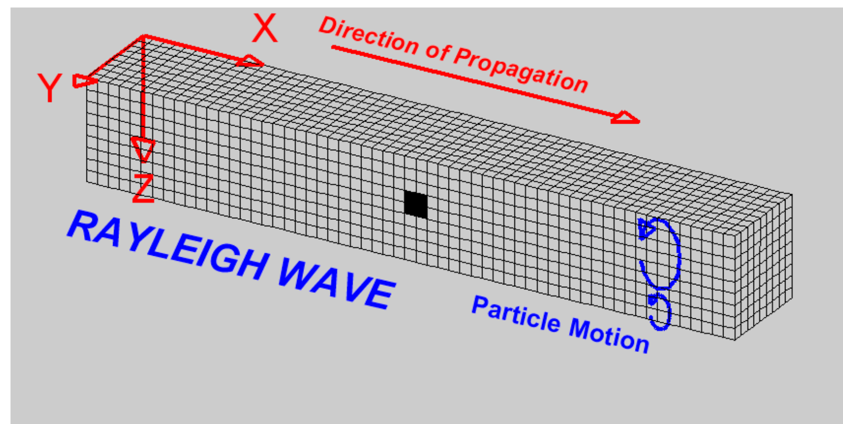
Eigenfunction

Courtesy: Campillo (Cargese, 2011)

‘Surface and guided waves’: waves trapped in the shallow layers or a wave guide (such as Love waves in the Earth, acoustic waves in the oceanic SOFAR, ….)







frequency proxy for depth

Courtesy: Campillo (Cargese, 2011)

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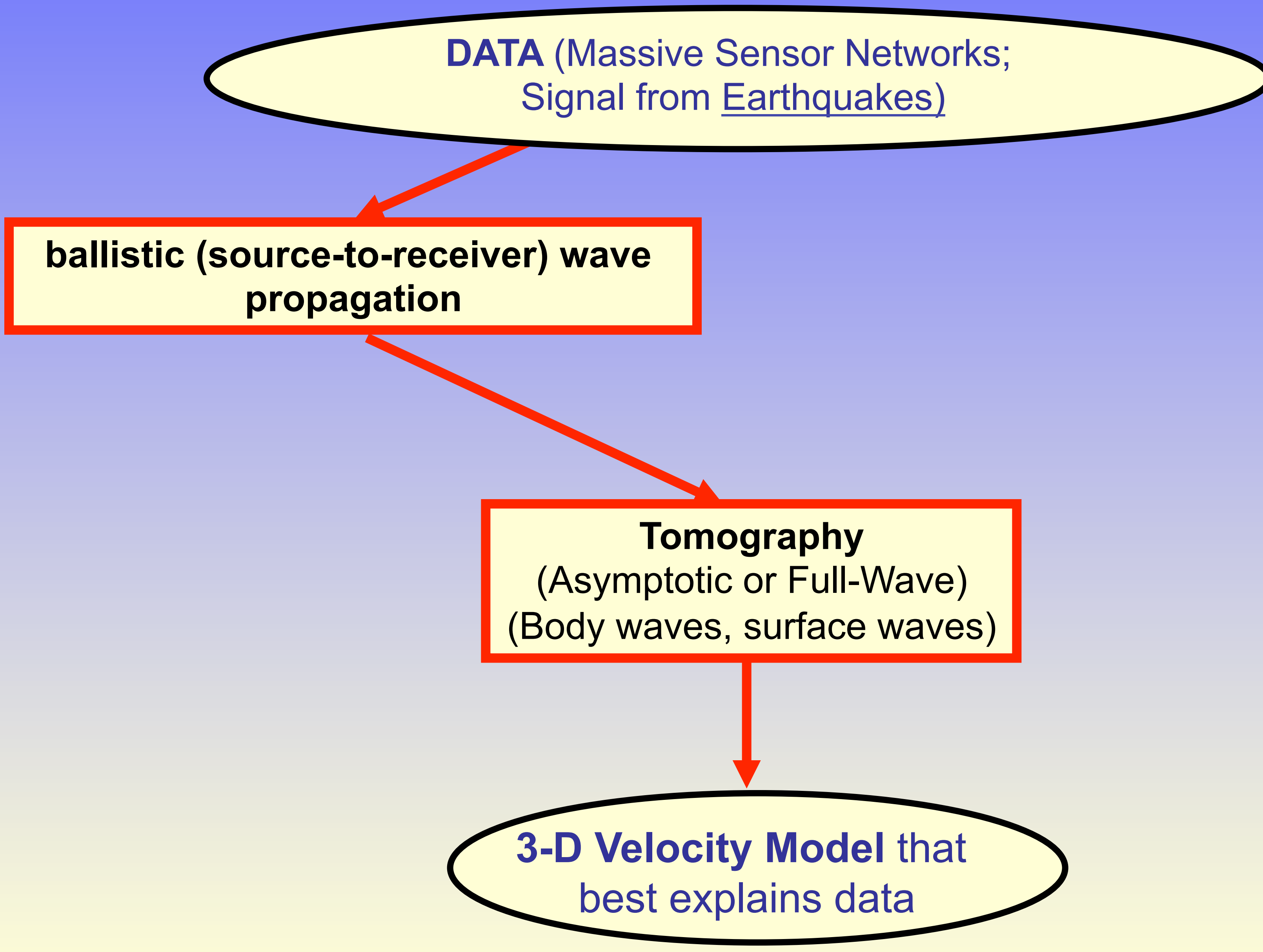
   - Adjoint tomography with ambient noise data

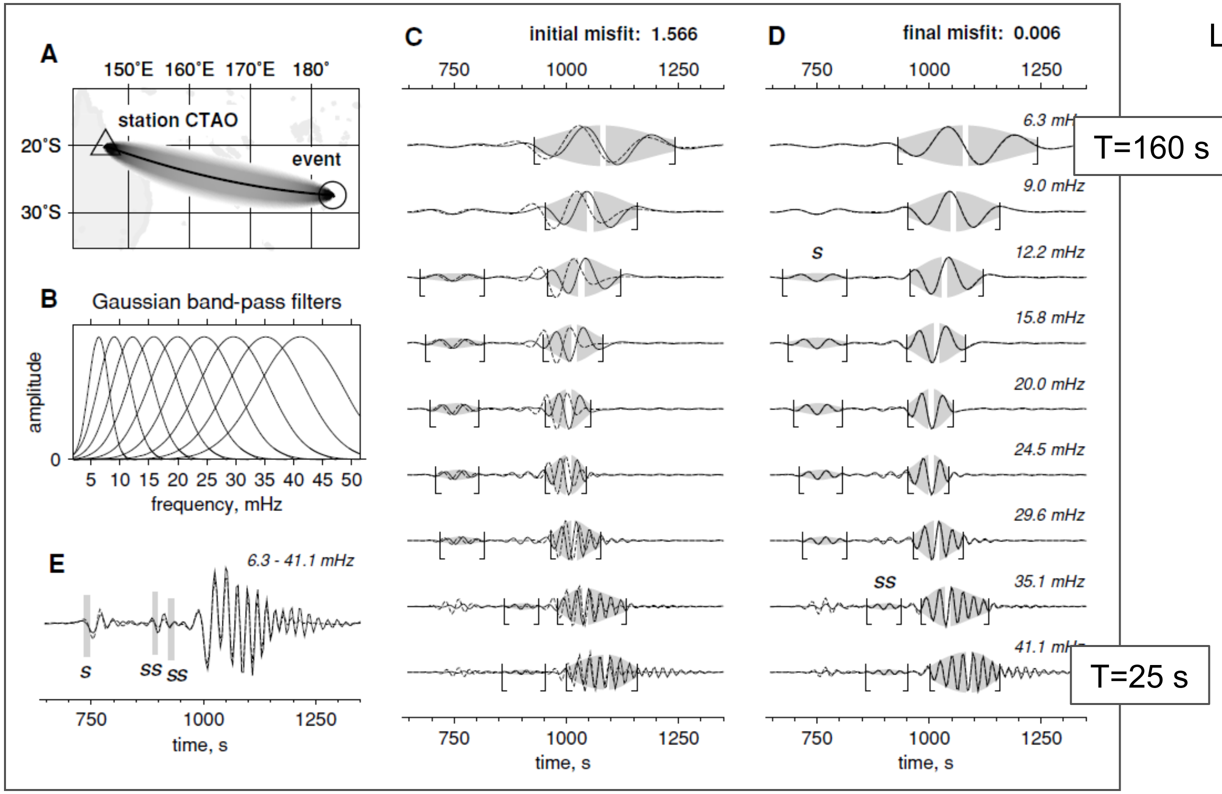
3. **Interferometry of teleseismic body waves**

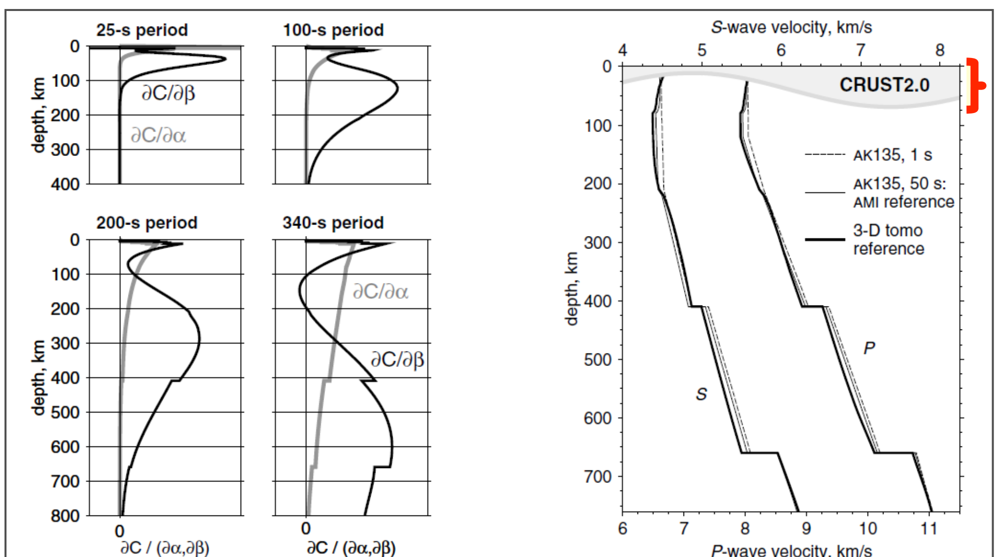
4. **Imaging with multiples**

Traditional Approach to Tomography



Lebedev and Van der Hilst (*GJI*, 2008)



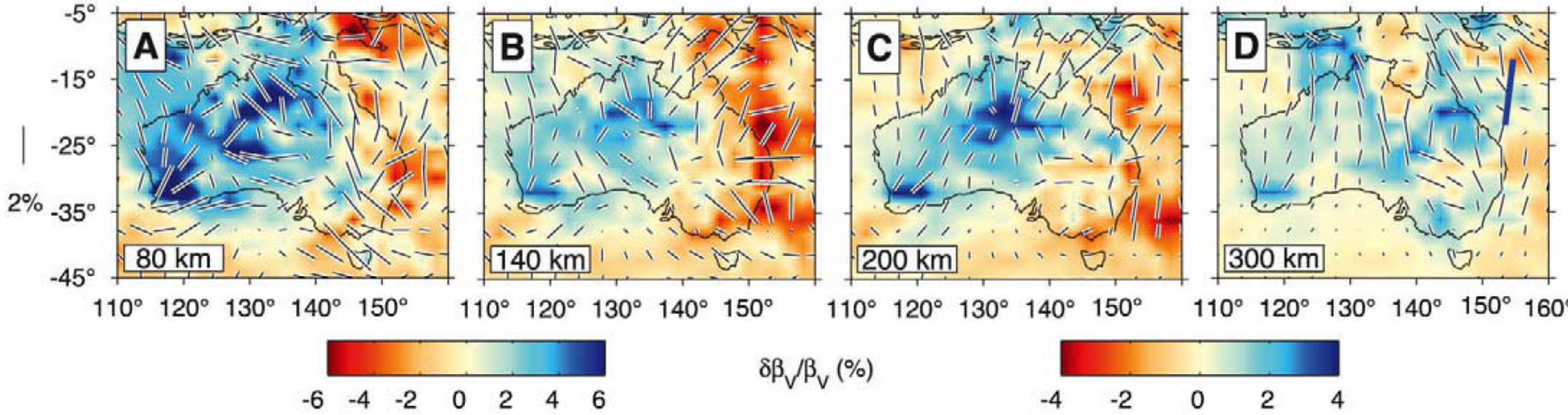


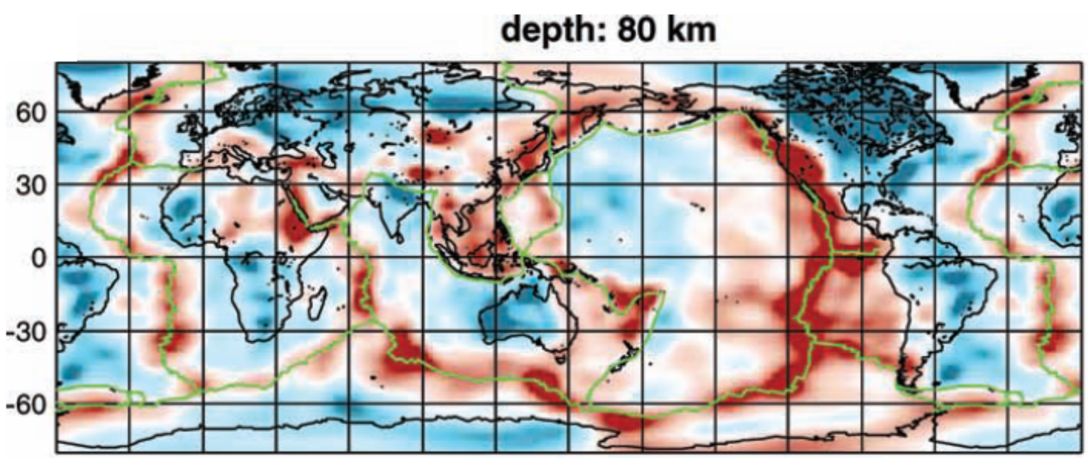
Crust = Problem!

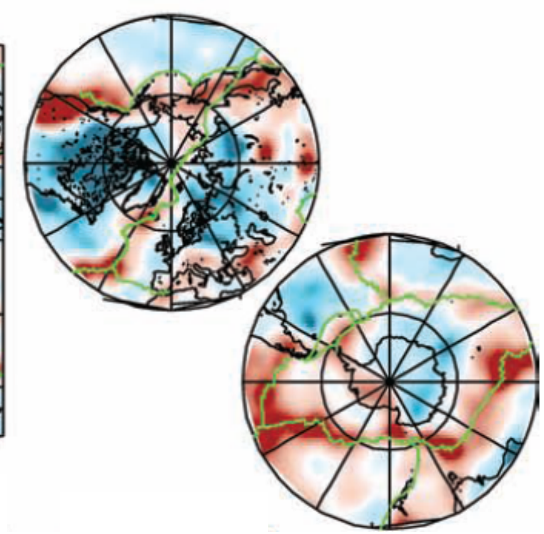
Examples from traditional surface wave tomography with earthquake waves: relatively low frequencies → deep structures

T > 30 s → upper mantle

Simons and Van der Hilst (*EPSL*, 2008)

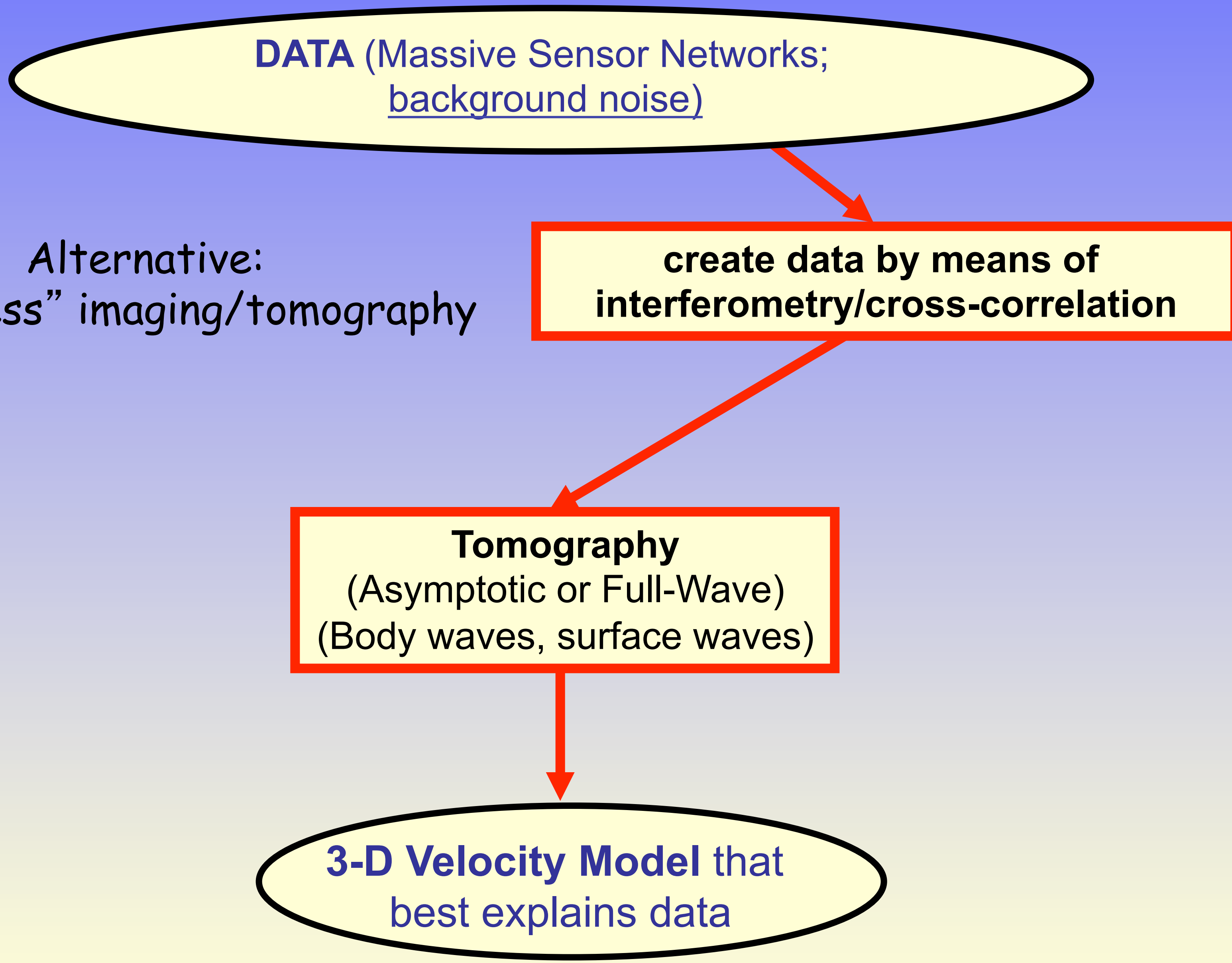






Lebedev and Van der Hilst (*GJI*, 2008)

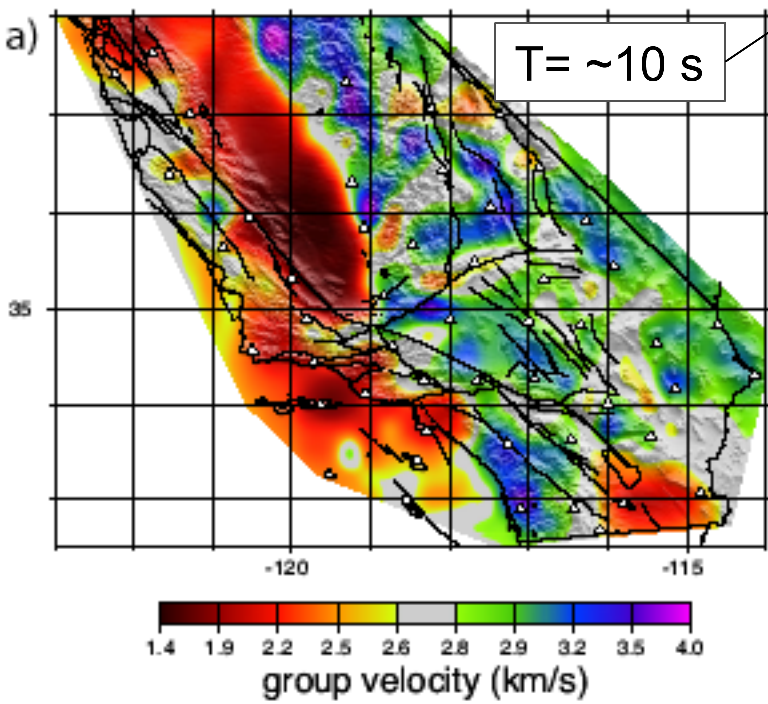
Ambient Noise Tomography



Alternative:
"sourceless" imaging/tomography

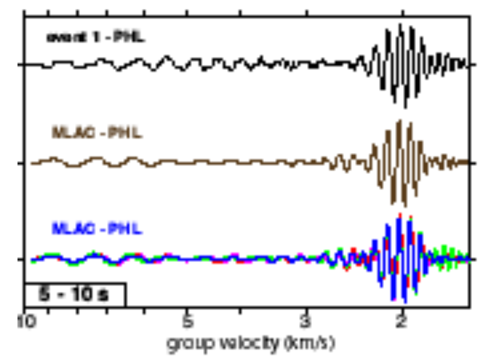
Shapiro, N.M., M. Campillo, L. Stehly, and M.H. Ritzwoller, 2005, High-Resolution Surface-Wave Tomography from Ambient Seismic Noise: Science **307**:1615-1618

T < 30 s → Crust



A map of Surface-wave Velocity in California

Obtained from correlating seismic noise

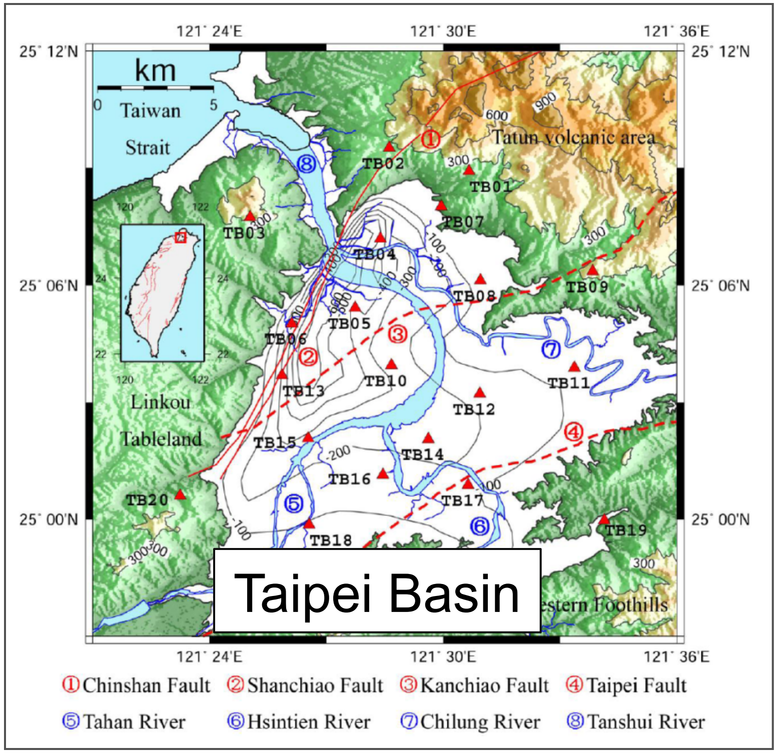


earthquake

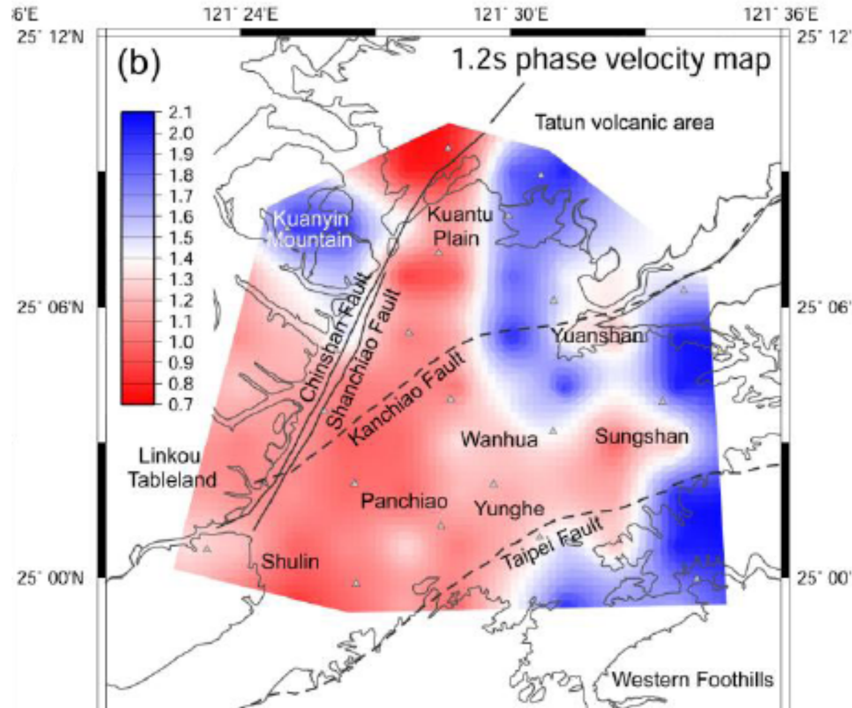
1 year of correlations

4 one-month correlations

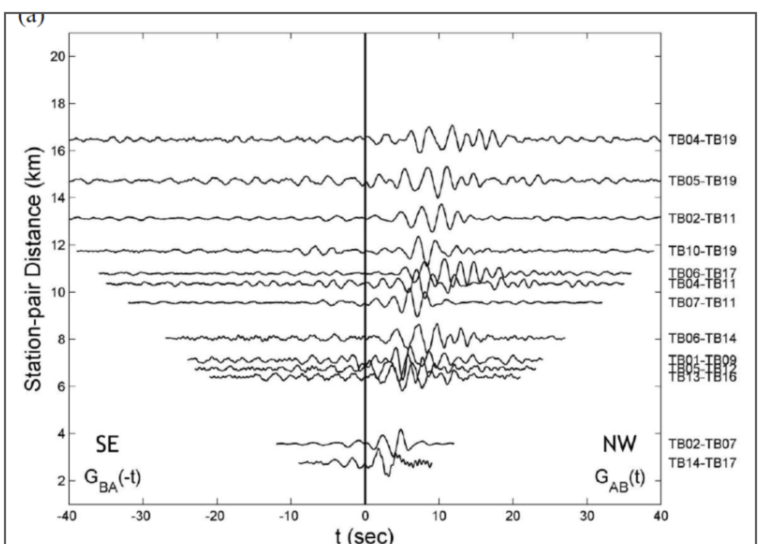
also Sabra, et al Surface wave tomography from microseisms in Southern California Geophys Res Lett **32** (2005)

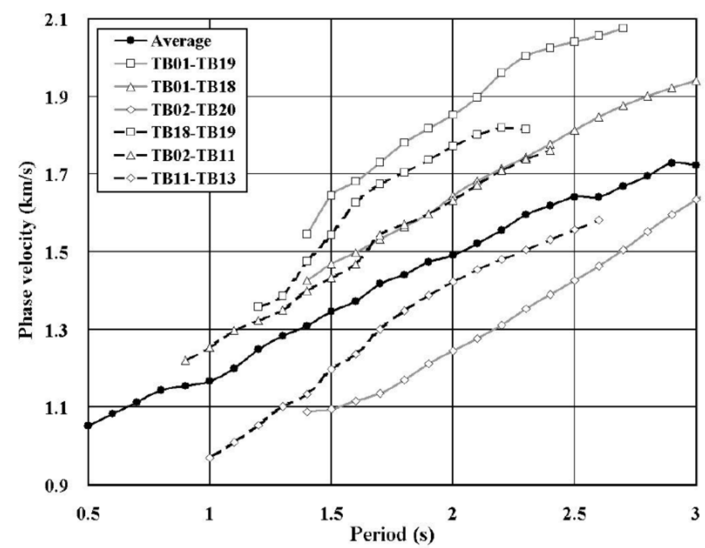


Huang et al. (BSSA, 2010)

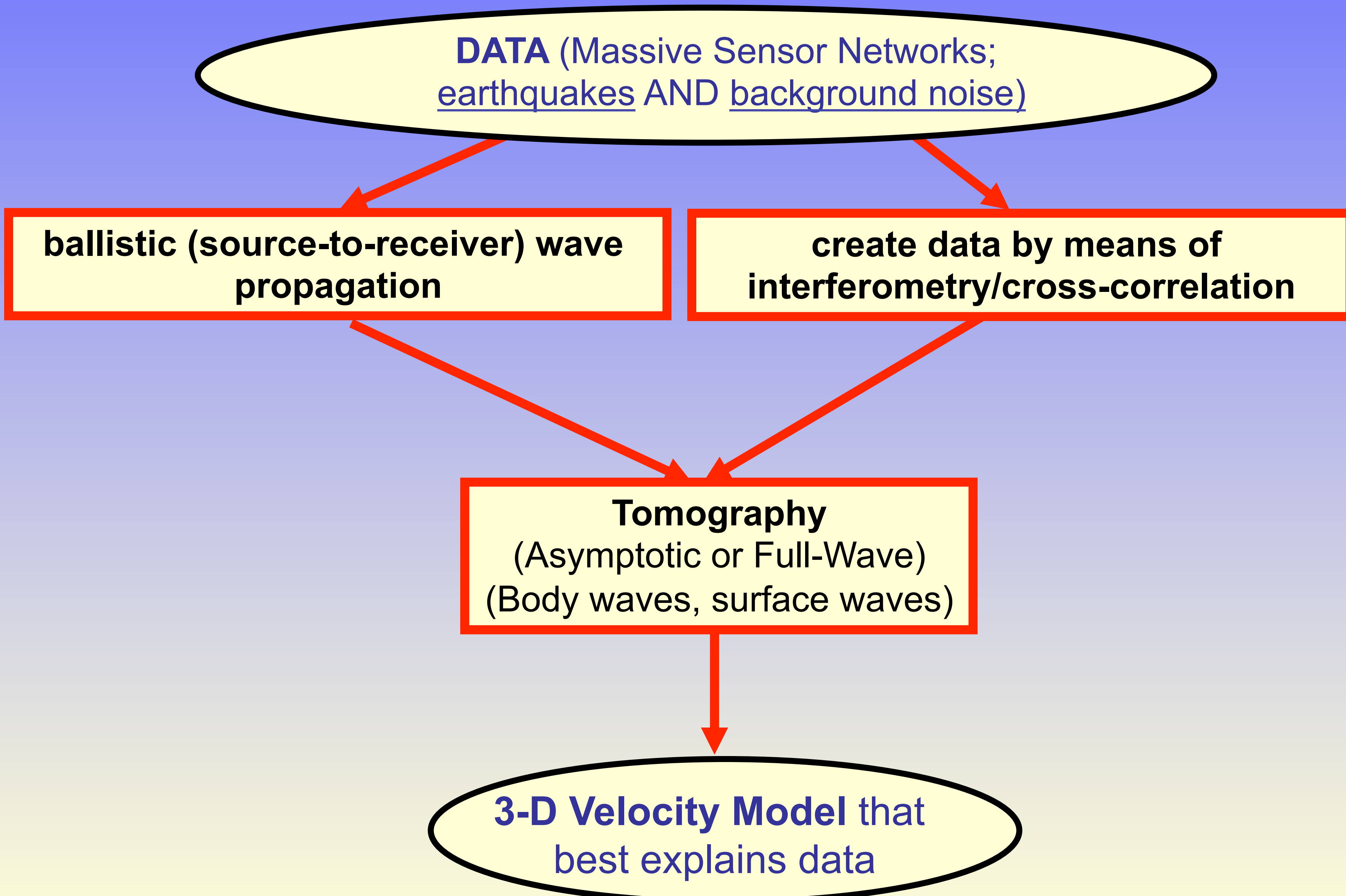


0.3-2.0 Hz (Sedimentary) Basins





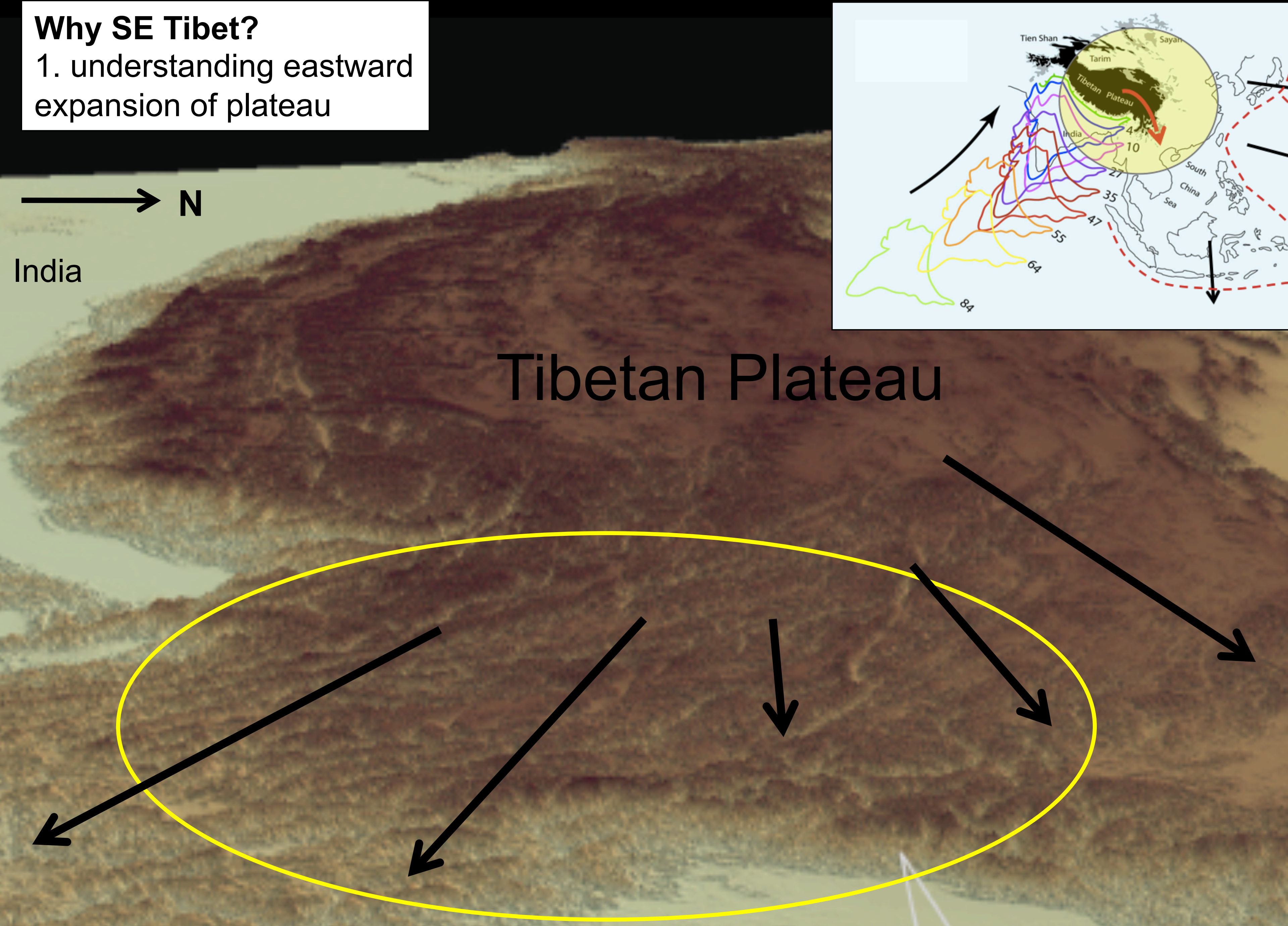
Use both ‘active’ and ‘passive’ data




Field Projects Sichuan & Yunnan Provinces and E. Tibet (2003-2004)
Crust-Mantle study E Tibet – SW China
Tibetan Plateau
LSA
Lehigh array
MIT array
Sichuan Basin
KMI
Red River
33
31
29
27
25
23
92
94
96
98
100
102
104

Why SE Tibet?

1. understanding eastward expansion of plateau



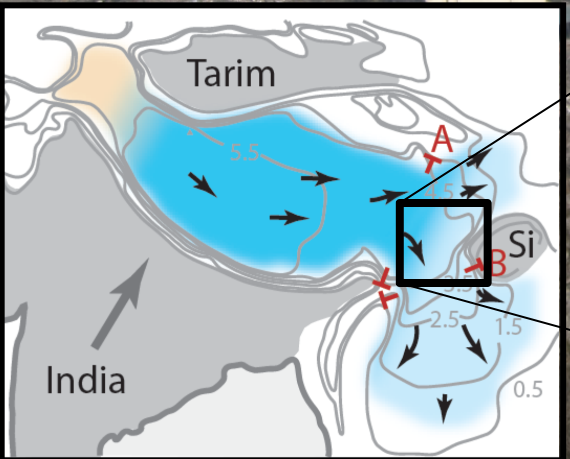
Why SE Tibet?

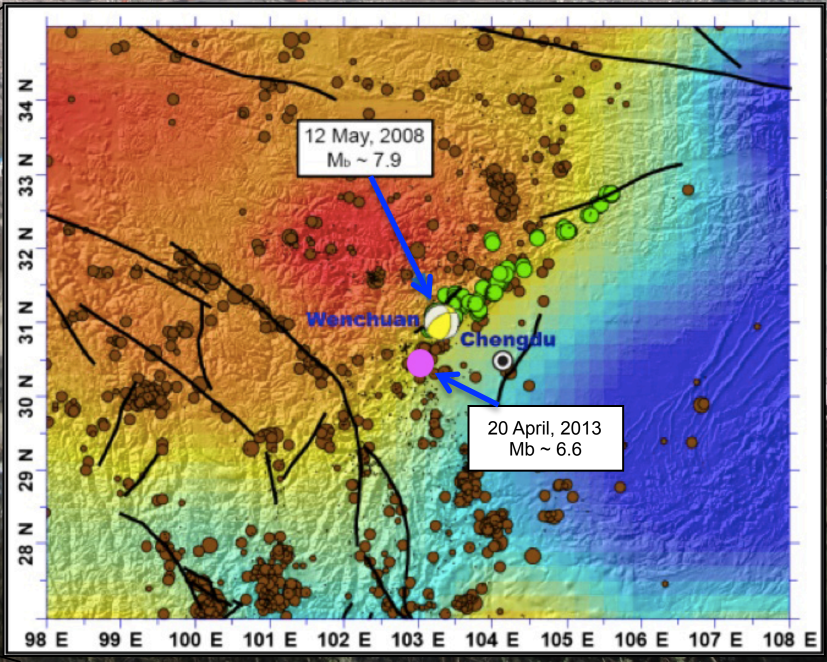
2. Southern end of Trans China Seismicity Belt

E.g. Sichuan, 12 May 2008

~80,000 people killed …

(Yingxiu, January 2009)



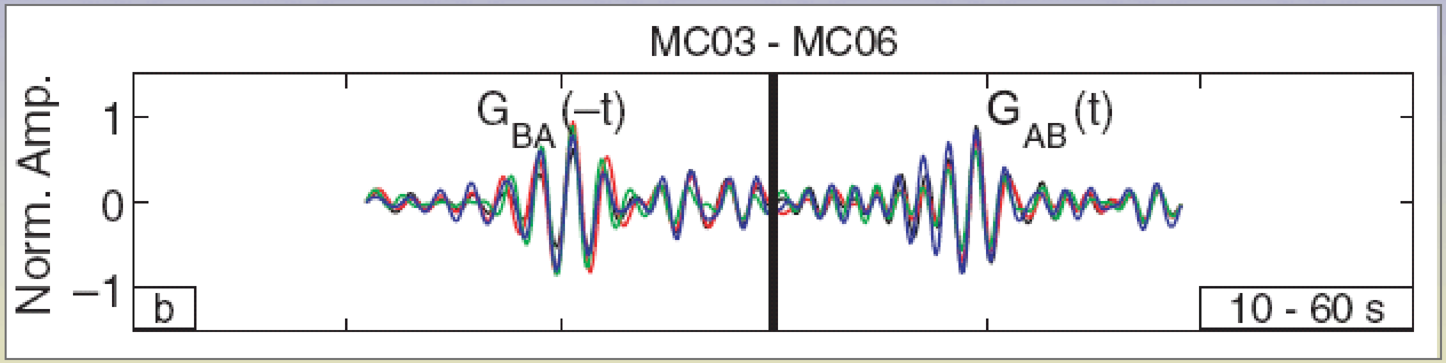


Interferometry:

long-term noise correlation → new data for crustal tomography

$$\frac{dC_{AB}(t)}{dt} \approx -\hat{G}_{AB}(t) + \hat{G}_{BA}(-t) \approx -G_{AB}(t) + G_{BA}(-t).$$

G = Green's function

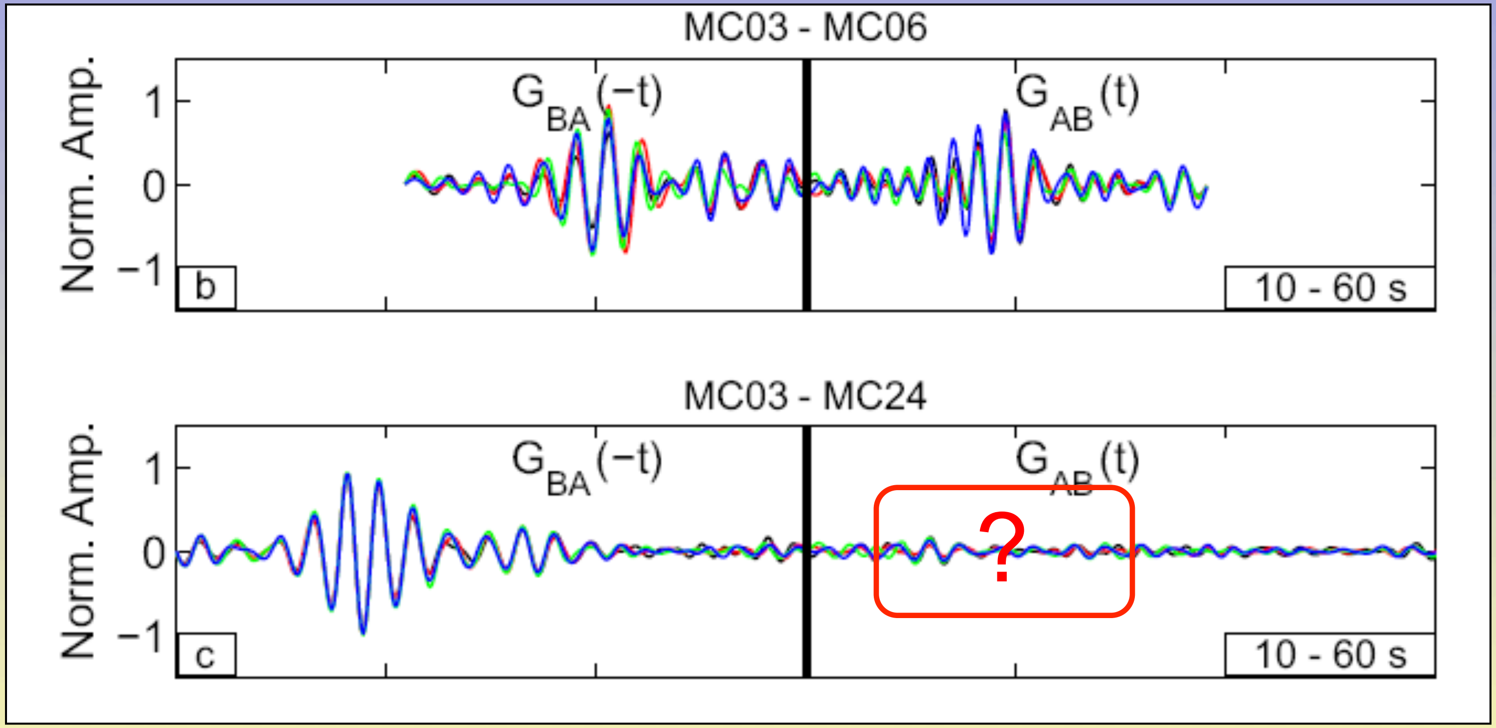


Yao et al. (*GJI*, 2006)

Interferometry:

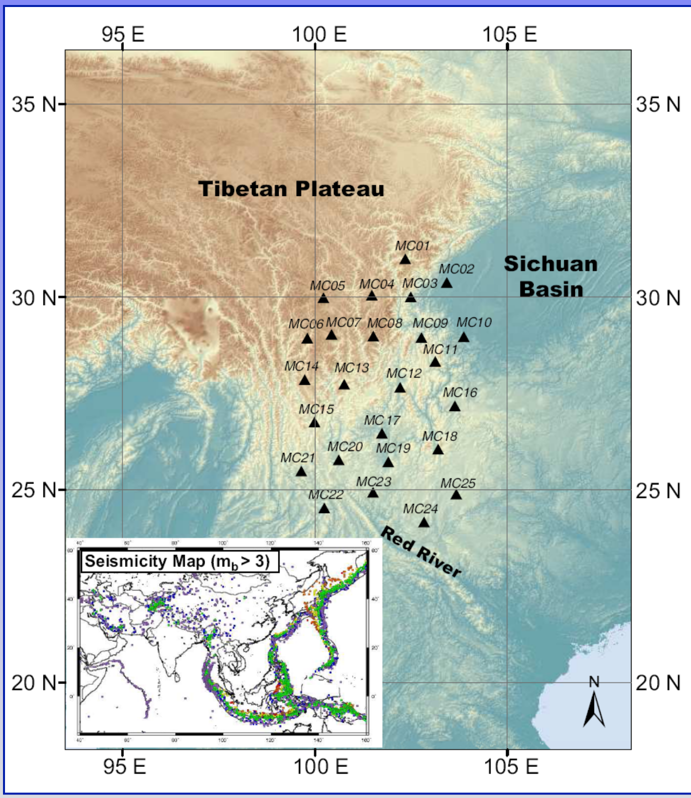
long-term noise correlation → new data for crustal tomography

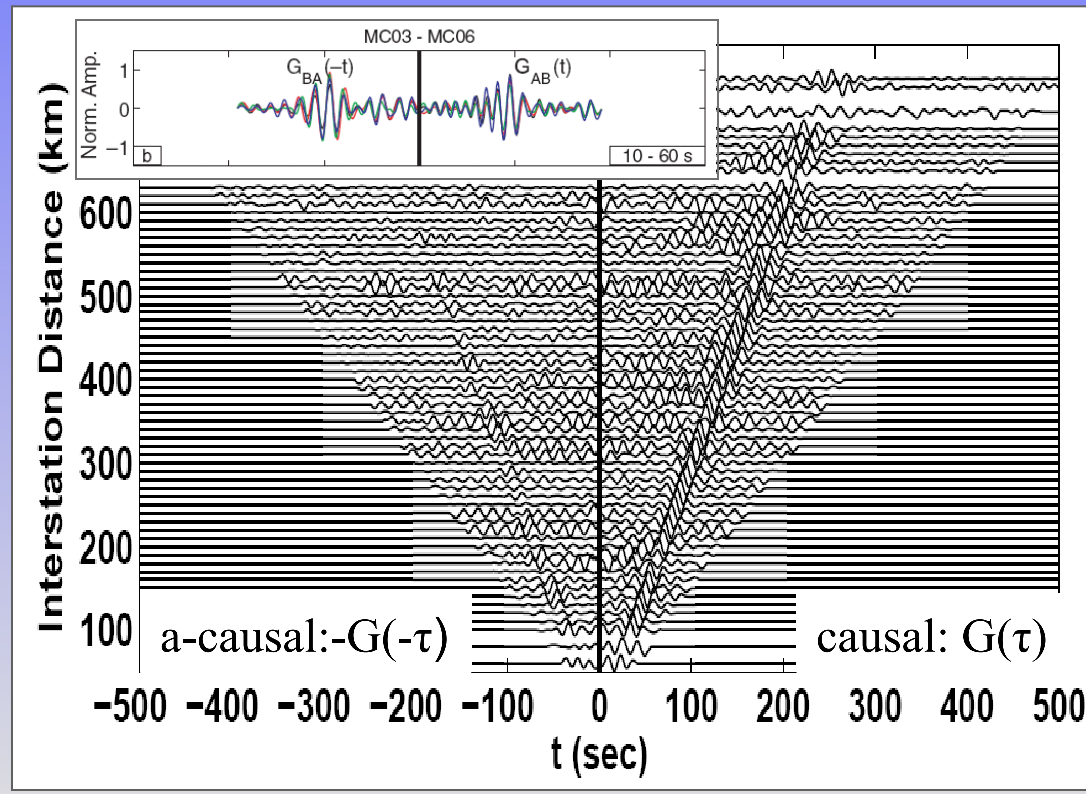
(simple in concept, but devil is in the detail …)



Yao et al. (*GJI*, 2006)

Crust and Lithosphere:
Multi-resolution surface wave tomography



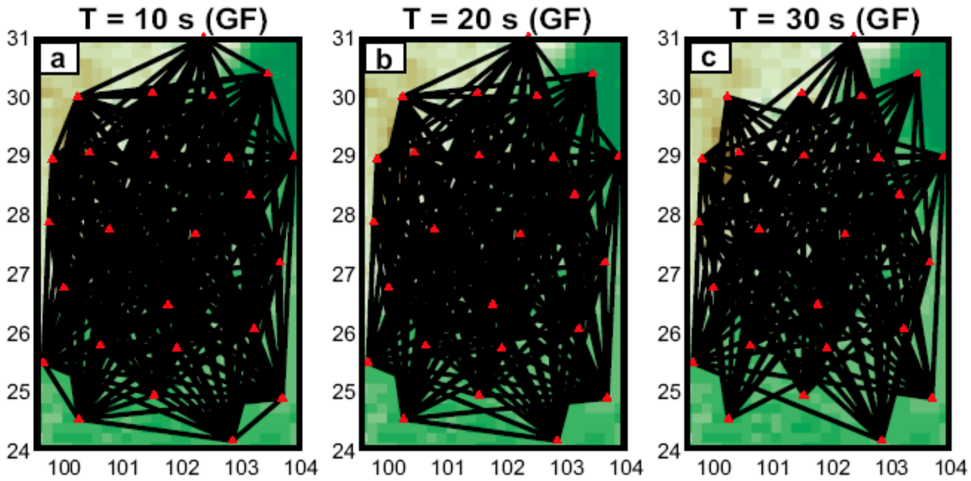


Seismic interferometry → estimate data from background “noise”

(NB we ignore asymmetry and sum causal and a-causal signals)

Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

Example: “ambient noise” surface wave tomography

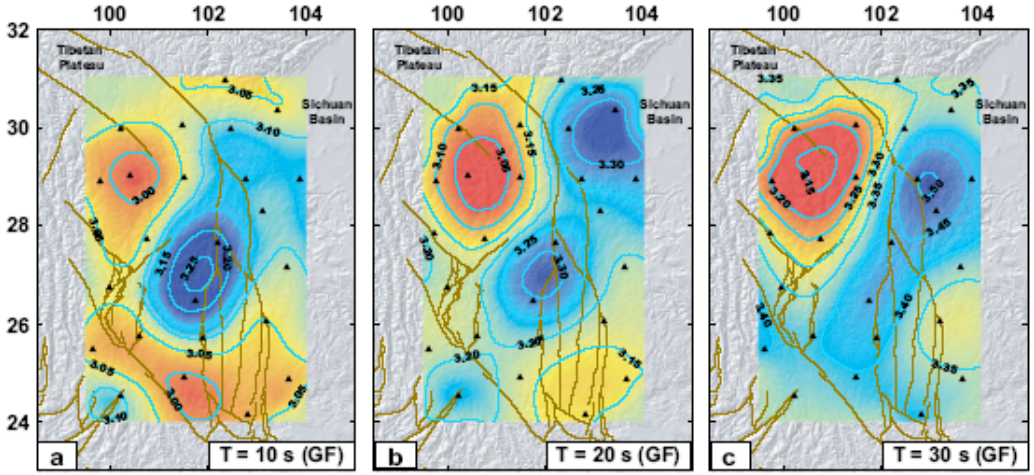


“source”-receiver pairs at different periods

Interferometry (scattering) → works well for relatively short periods (high frequency)

Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

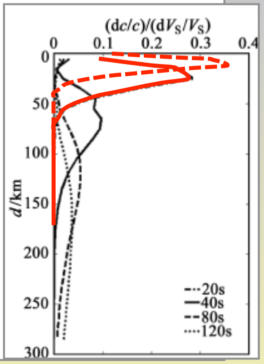
Example: "ambient noise" surface wave tomography



Phase velocity maps at different periods

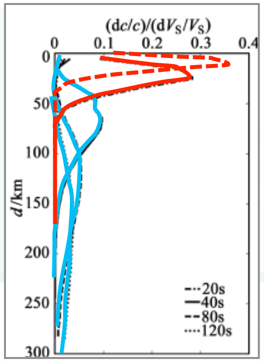
Interferometry (scattering) → relatively short periods (high frequency)

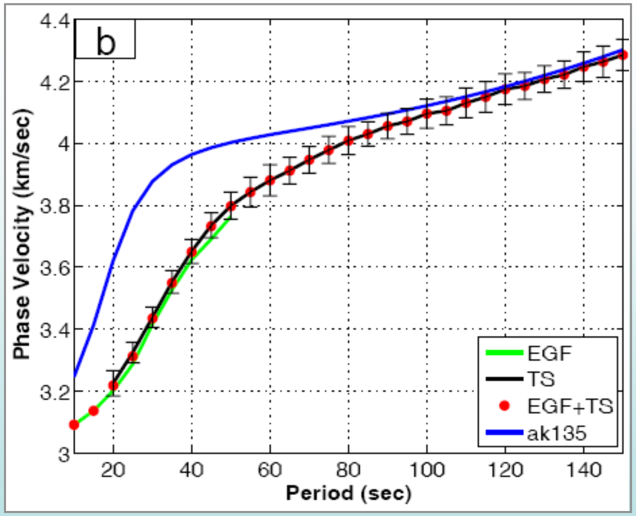
For surface wave tomography that means: "shallow" sub-surface

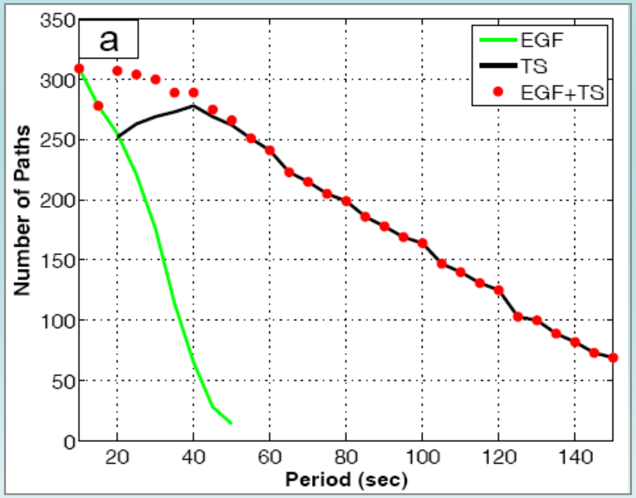


Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

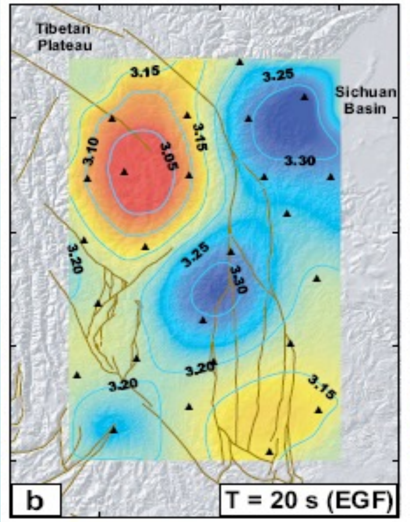
Combination of ambient noise and earthquake data:
extend frequency range → extend depth range

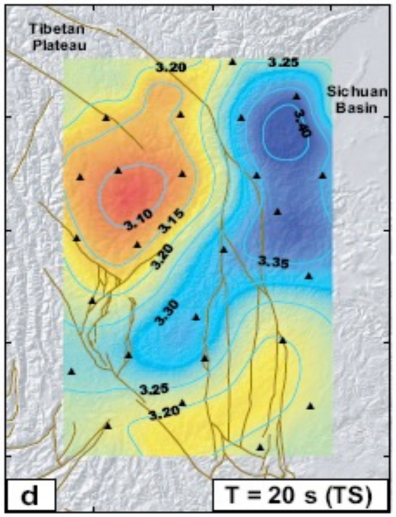






At overlapping periods, Rayleigh wave phase velocities from EGF (from 10 months Z-comp. data) and TS analyses are similar

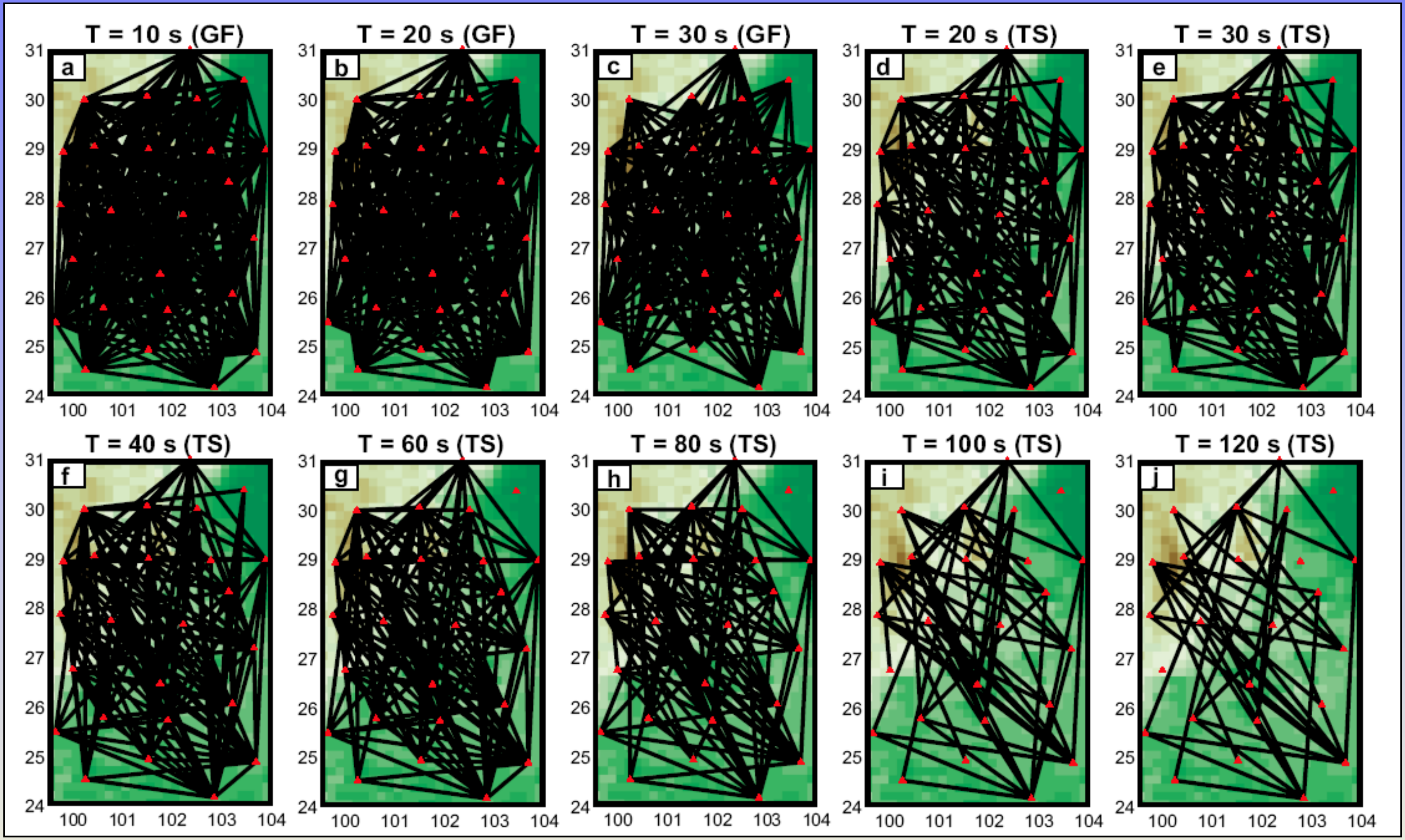




- TS slightly higher (< 0.7%) due to differences in finite frequency effect
- Difference << medium perturbations (< 10%)

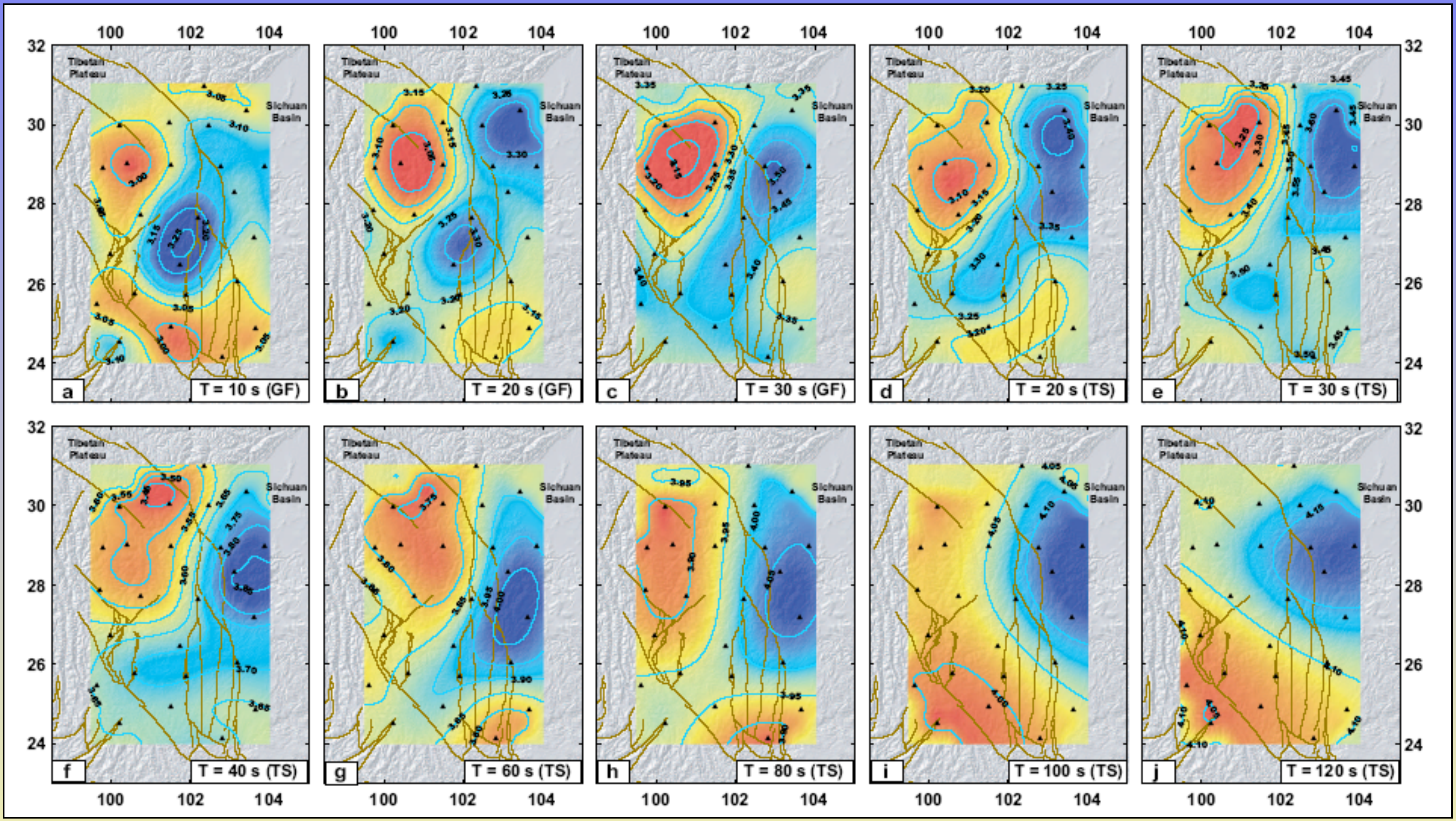
Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

Multi-resolution surface wave tomography



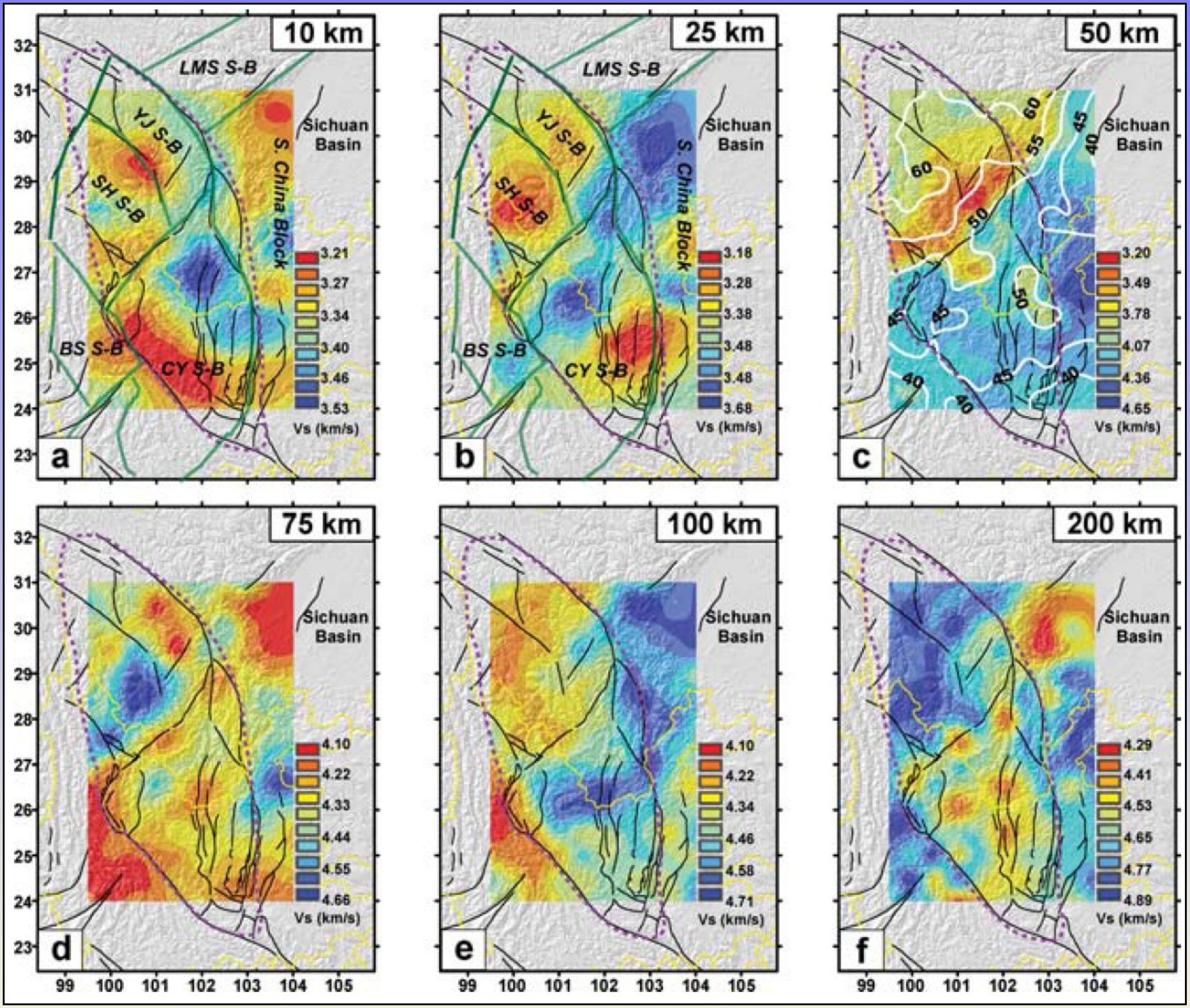
Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

Phase velocity maps at different periods



Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

Multi-resolution surface wave tomography



Yao, Beghein, and Van der Hilst (*GJI*, 2008)

Anisotropy I: Azimuthal Anisotropy

(i.e., dependence of wavespeed on direction of propagation in horizontal plane)

- Step 1: inter-station phase velocities from **EGF** → azimuthally anisotropic phase velocity maps

$$c(\omega,\psi) = c_0(\omega)[1 + a_0(\omega) + a_1(\omega)\cos 2\psi + a_2(\omega)\sin 2\psi]$$

- Step 2: phase velocity maps → shear wave speed & anisotropy

$$\delta c_R(x,y,\omega,\psi) \approx \int_0^H \left[\frac{\partial c_R}{\partial L}\left(\delta L + G_c \cos 2\psi + G_s \sin 2\psi\right)\right]\frac{dz}{\Delta h}$$

At each point (x,y), the reference crustal thickness is constrained from receiver functions (Xu et al., 2007; Zurek et al, 2005)

$$\hat{\beta}_{SV} \approx \beta_{SV}\left(1 + \frac{G_c}{2L}\cos 2\psi + \frac{G_s}{2L}\sin 2\psi\right)$$

Transverse isotropic V_{sv}: $\beta_{SV} = \sqrt{L/\rho}$

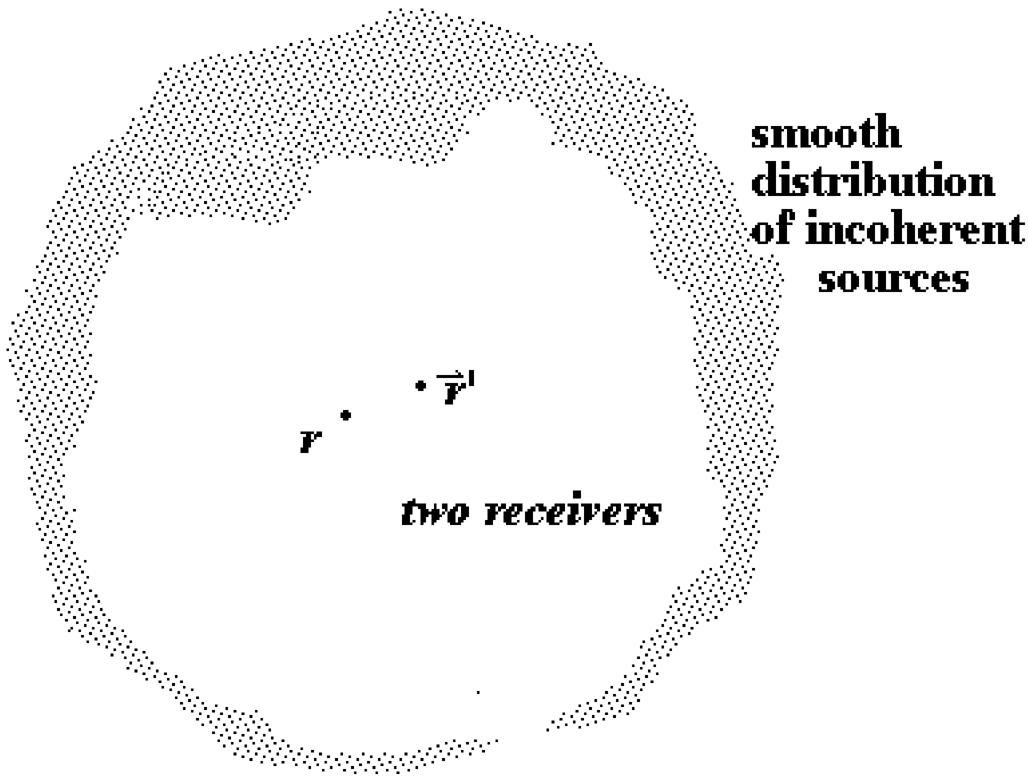
Magnitude of azimuthal aniso : $A_{SV} = \frac{1}{2L}\sqrt{(G_c)^2 + (G_s)^2}$

Fast axis of azimuthal aniso : $\phi = \frac{1}{2}\tan^{-1}\left(G_s/G_c\right)$

Yao, Van der Hilst, Montagner (*JGR*, 2010)

"Ponderosity" (i.e. angular weighting of incident intensity)

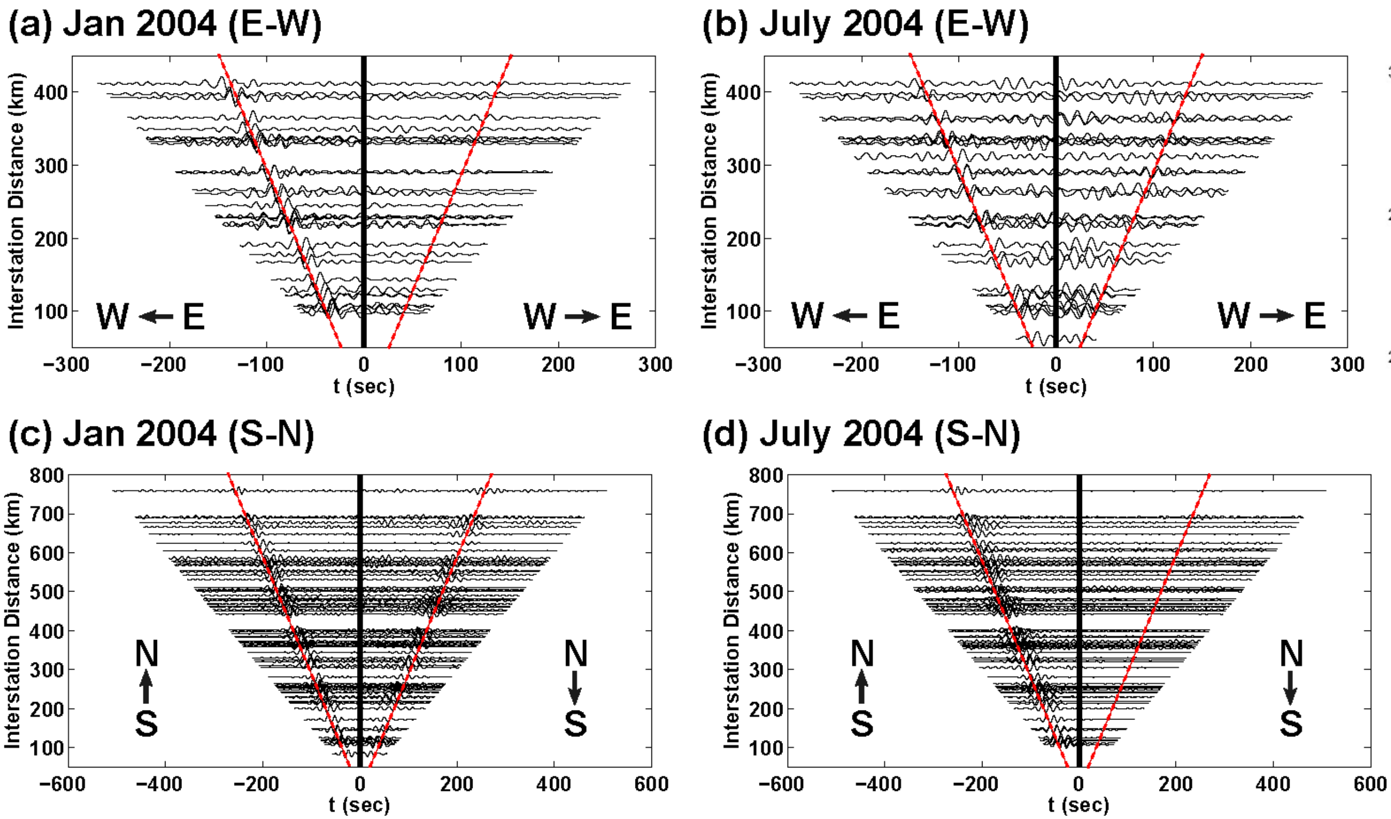
What is the effect of uneven noise distribution on estimates of elastic anisotropy?
That is, what happens if the intensity of incident field itself is anisotropic?

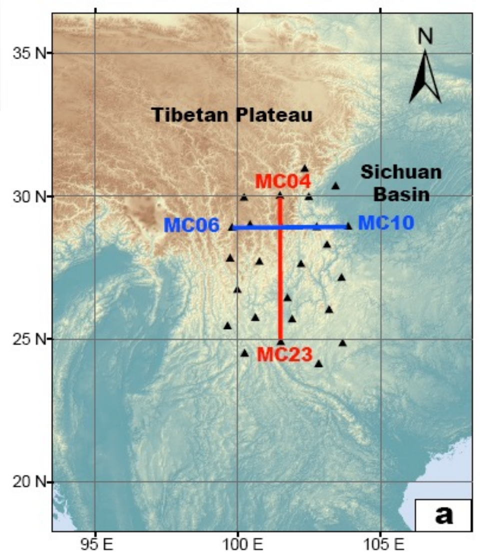


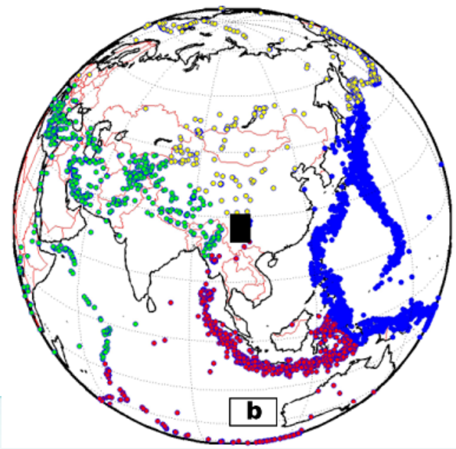
Courtesy: Weaver (Cargese, 2011)
Froment et al. (2009)

Recovery of surface wave GF in SE Tibet from ambient noise

(onebit) cross-correlation of monthly continuous data (10-20s)





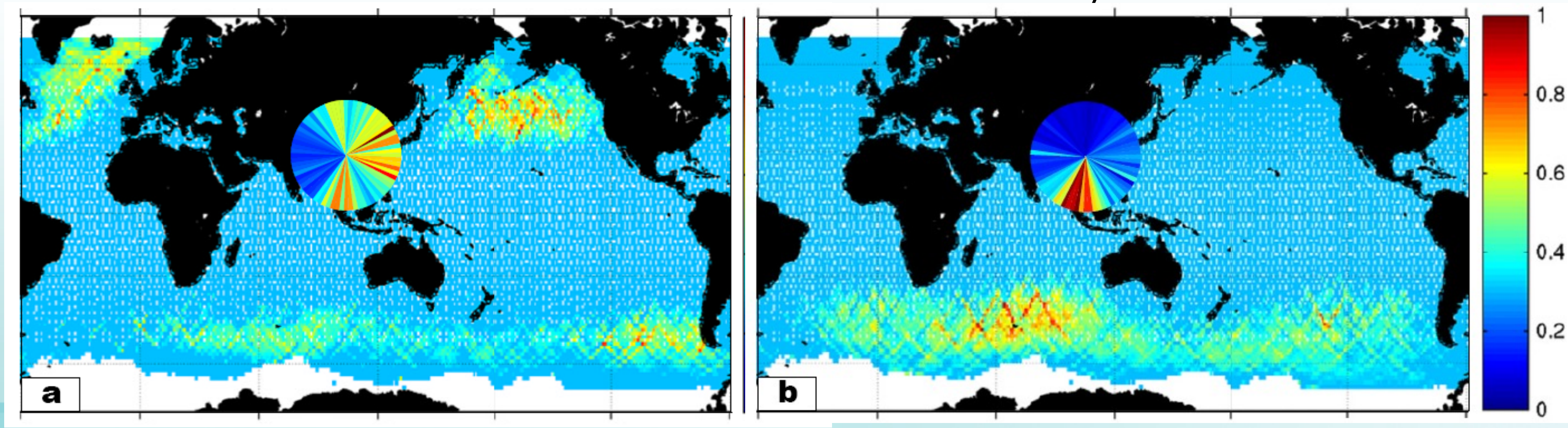


Seasonal variation of ambient noise energy (10-20s)

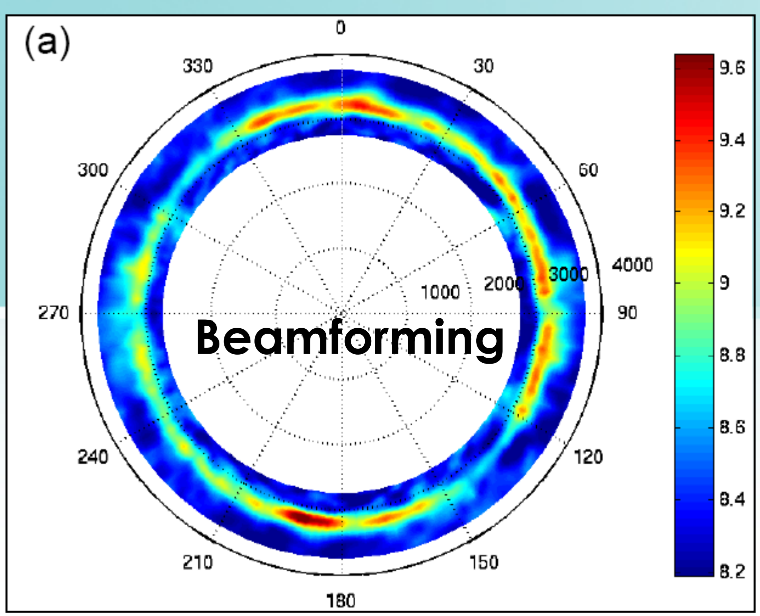
Yao et al. (*PEPI*, 2009)

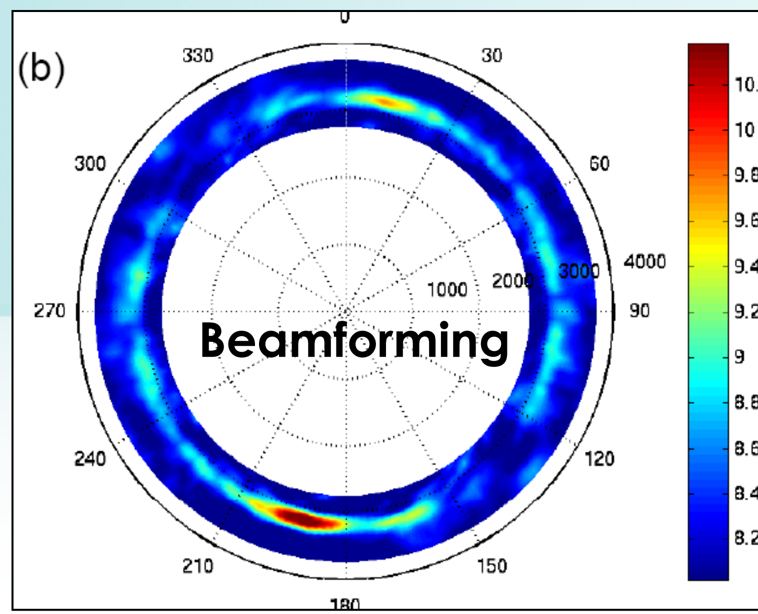
Yao et al. (*PEPI*, 2009)

Jan 2004 July 2004



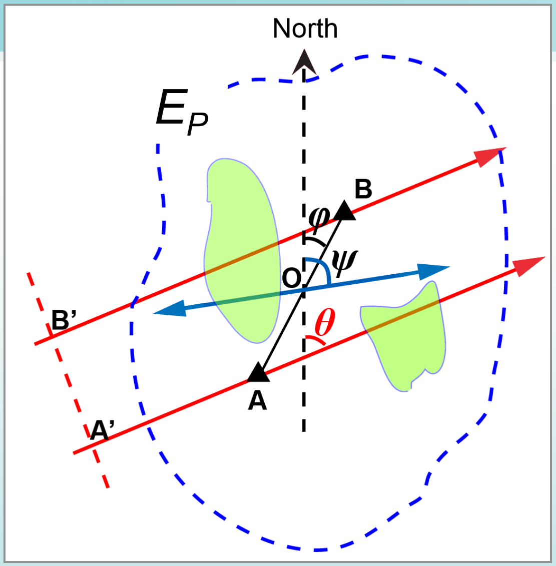
- **Correlation of ambient noise energy (10-20s) with ocean wave activity**
  (background image: normalized global ocean wave height in winter time (a) and in summer time (b), modified from Stehly et al., 2006)

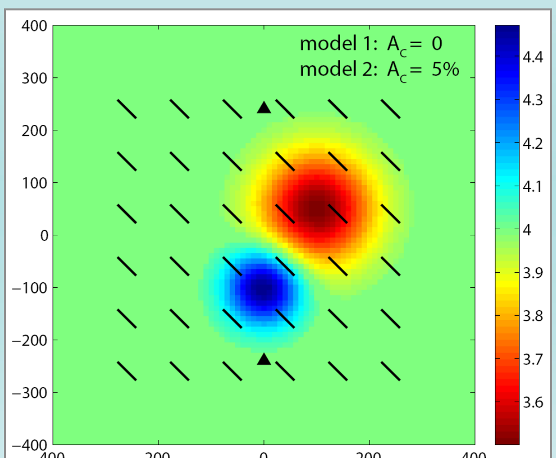


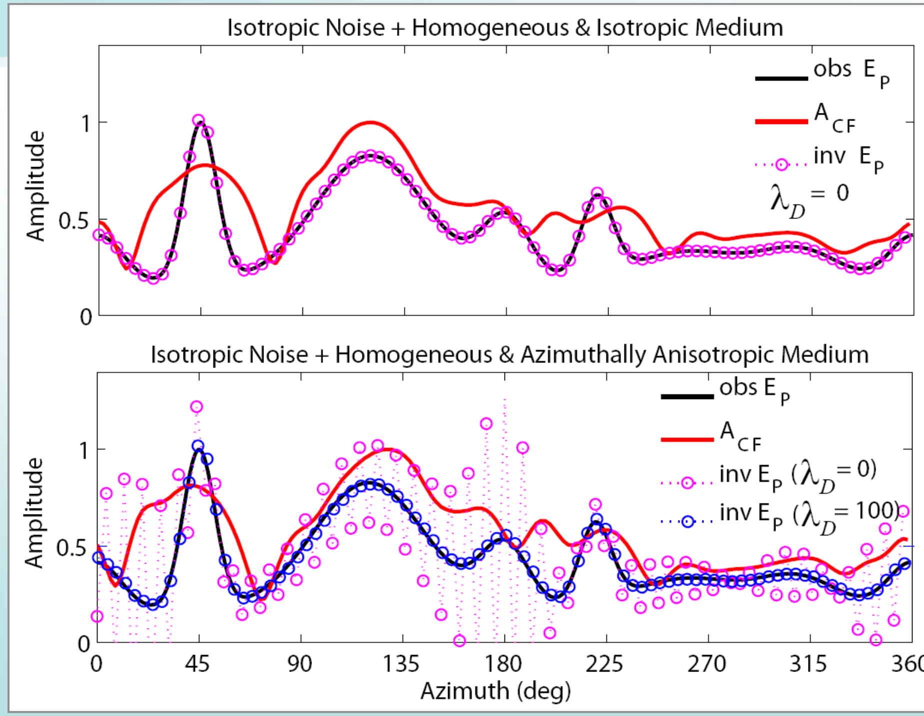


Uneven noise energy distribution + medium heterogeneity/anisotropy

imperfect recovery of **G** → bias in dispersion measurement.







$$C_{AB}(\omega,t)=\int_0^{2\pi} E_P(\omega,\theta)\cos\left[\omega(t-\delta t)\right]H(t,\delta t)d\theta$$

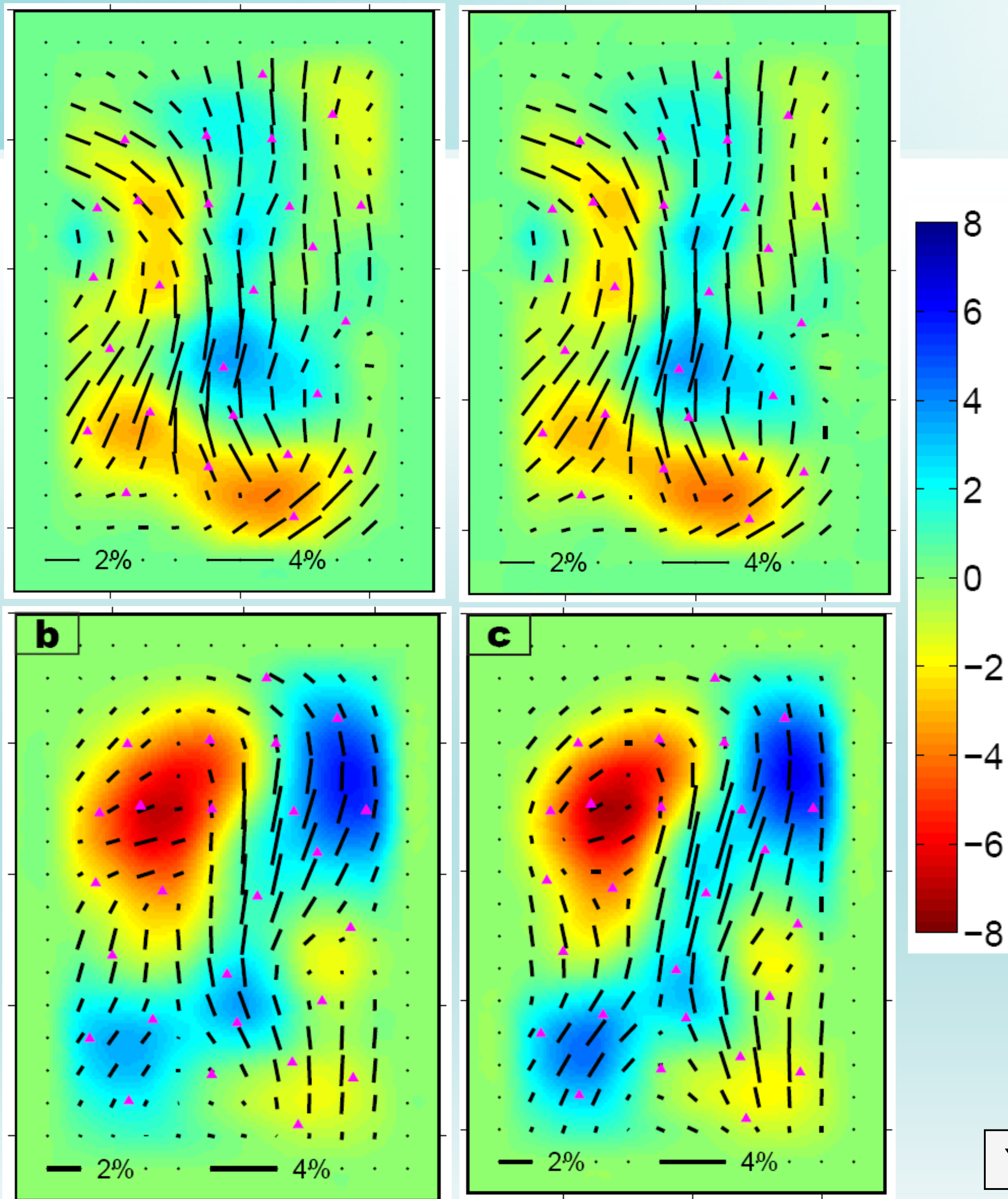
Incoming plane wave (ambient noise) energy

Yao and Van der Hilst (*GJI*, 2009)

Before bias correction **After bias correction**

10 s

25 s



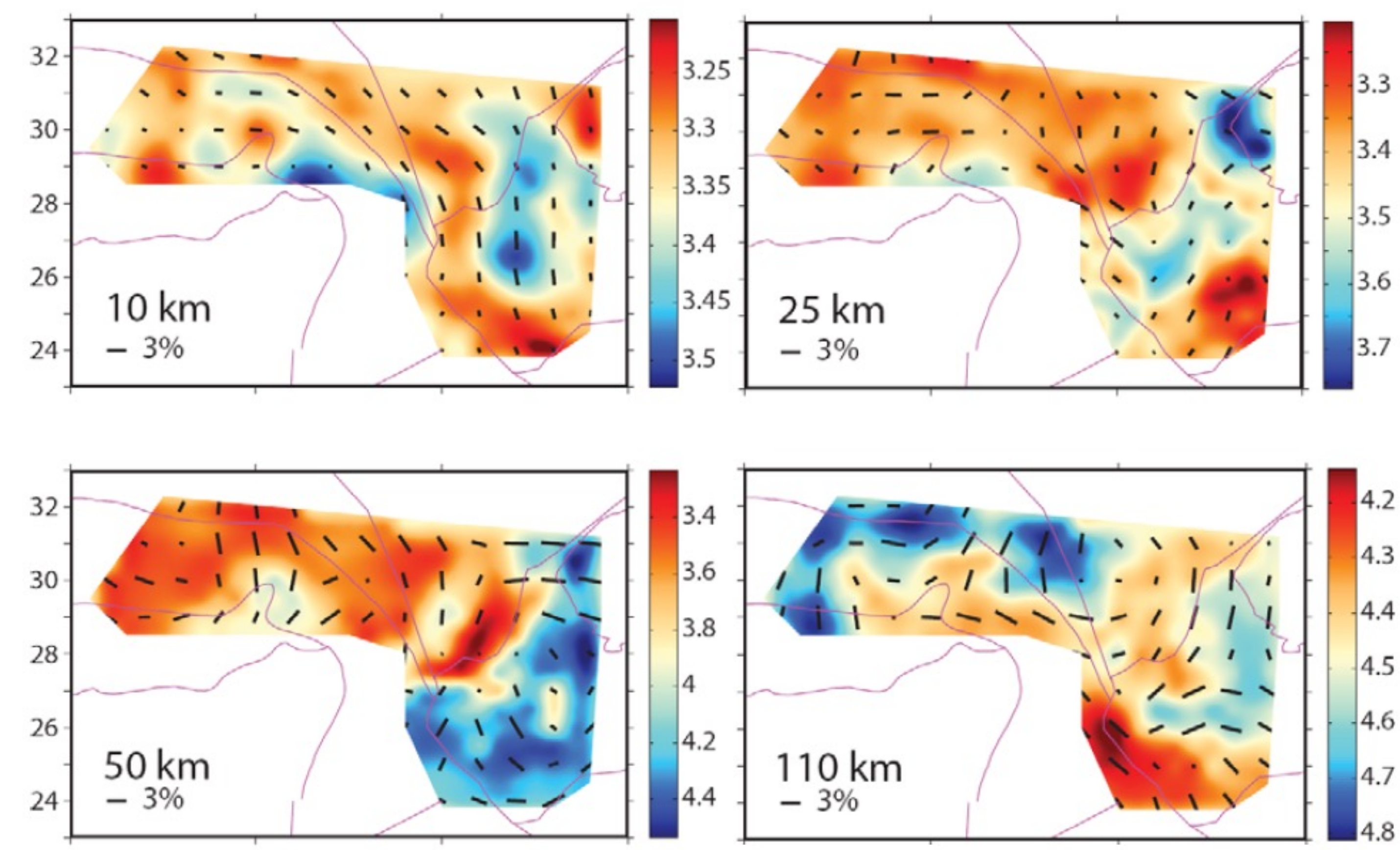
Effect on phase velocity is small …

(see also remarks by Weaver, last Monday)

… and will be neglected

Yao & Van der Hilst (GJI, 2009)

3D lithospheric heterogeneity & azimuthal anisotropy



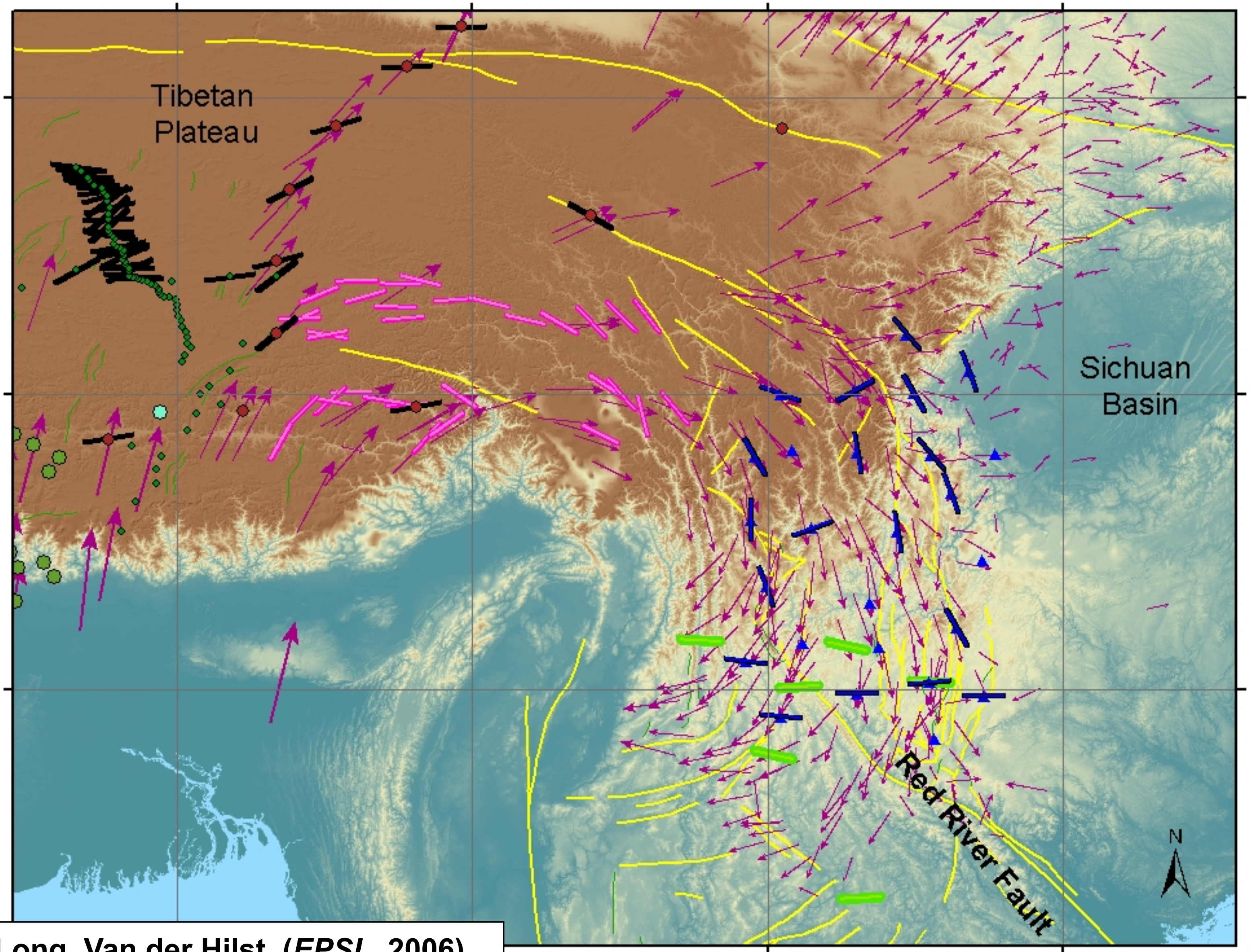
Complicated deformation pattern:

Upper crust: consistent with clockwise rotation (GPS)

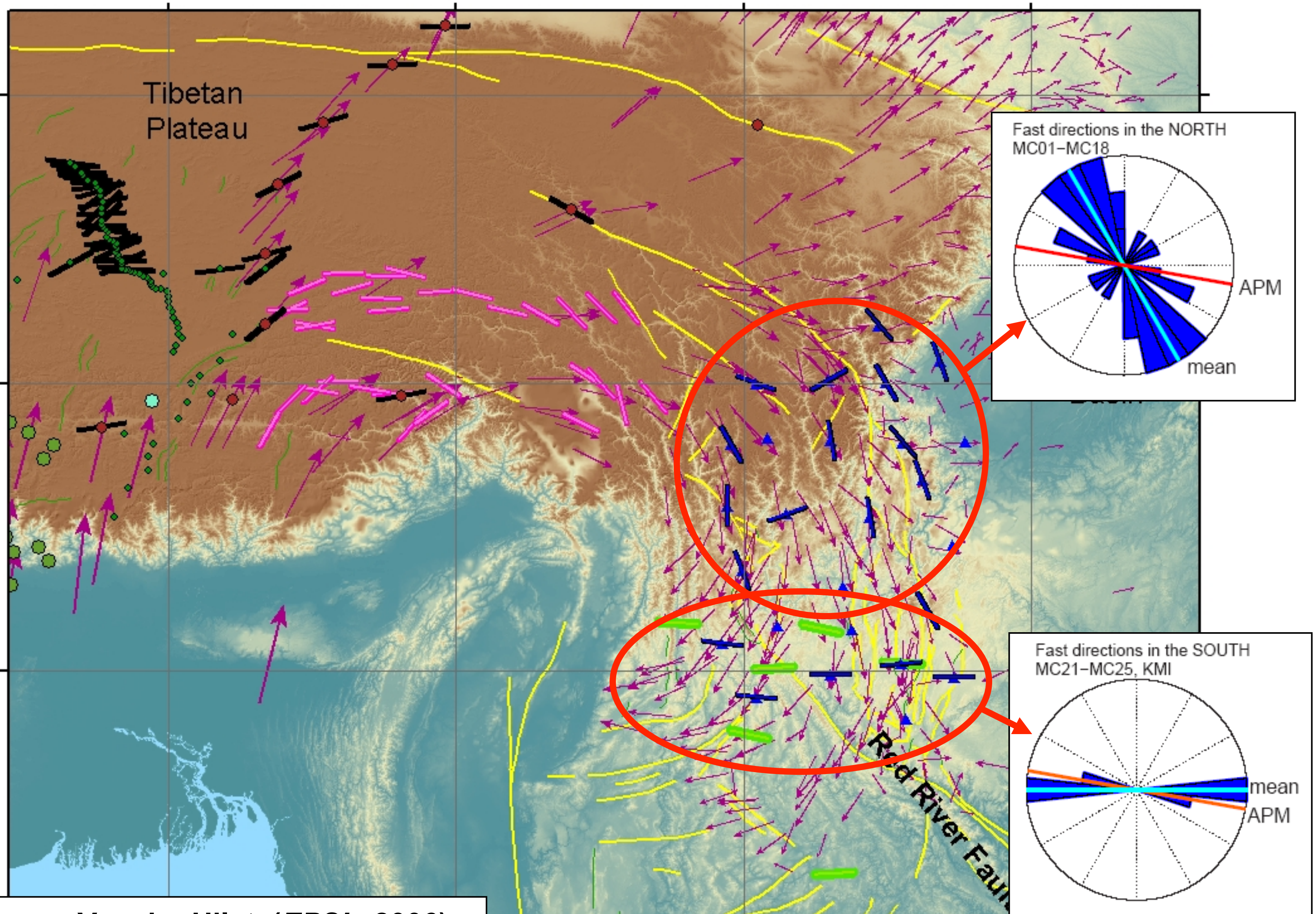
Uppermost mantle: fast direction along the LVZ of the margin of Yangtze block

Yao, Van der Hilst, and Montagner (JGR, 2010)

SKS splitting (~ azimuthal anisotropy) and GPS (purple arrows)

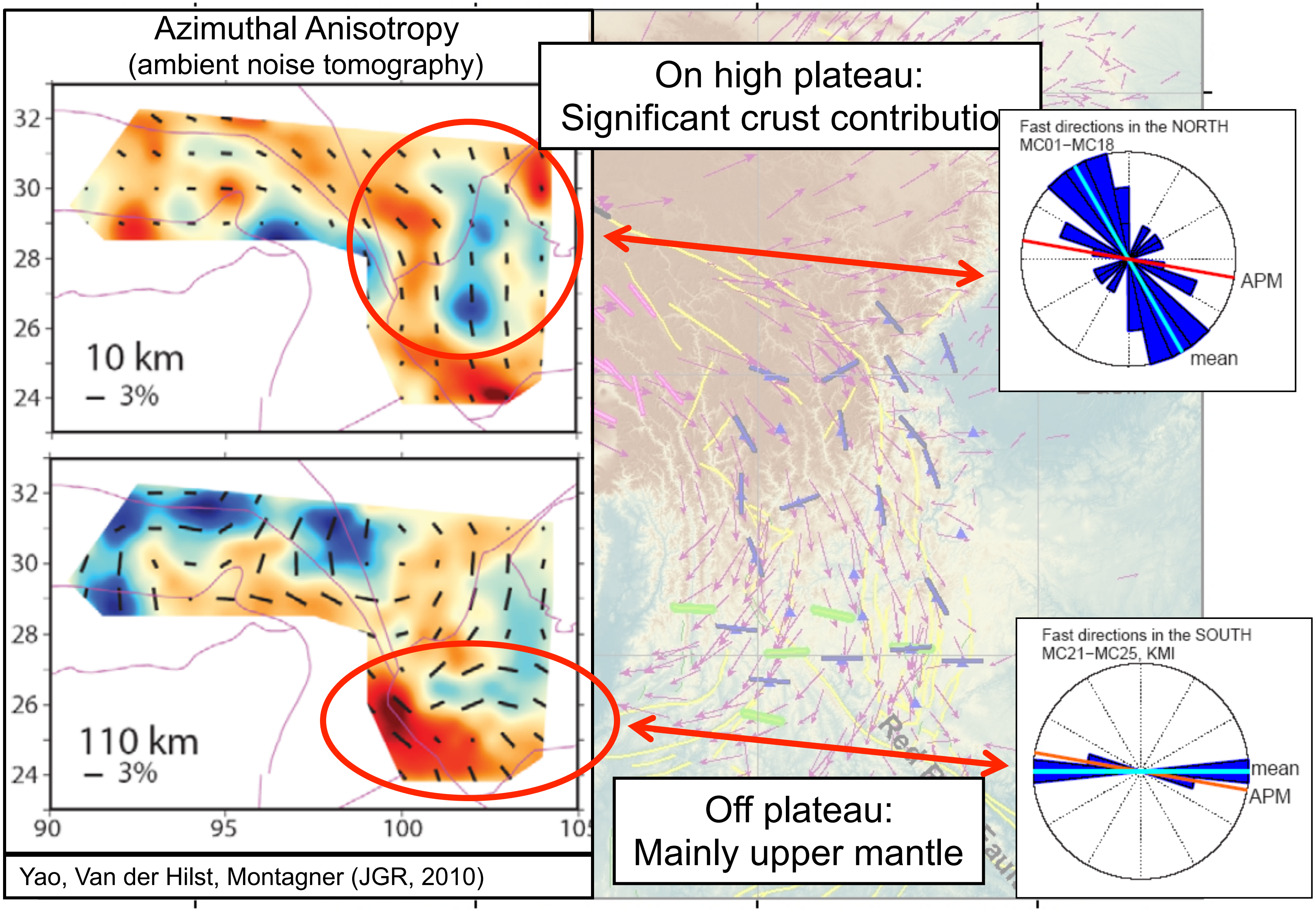


Lev, Long, Van der Hilst (*EPSL*, 2006)
Sol et al. (*Geology*, 2007)

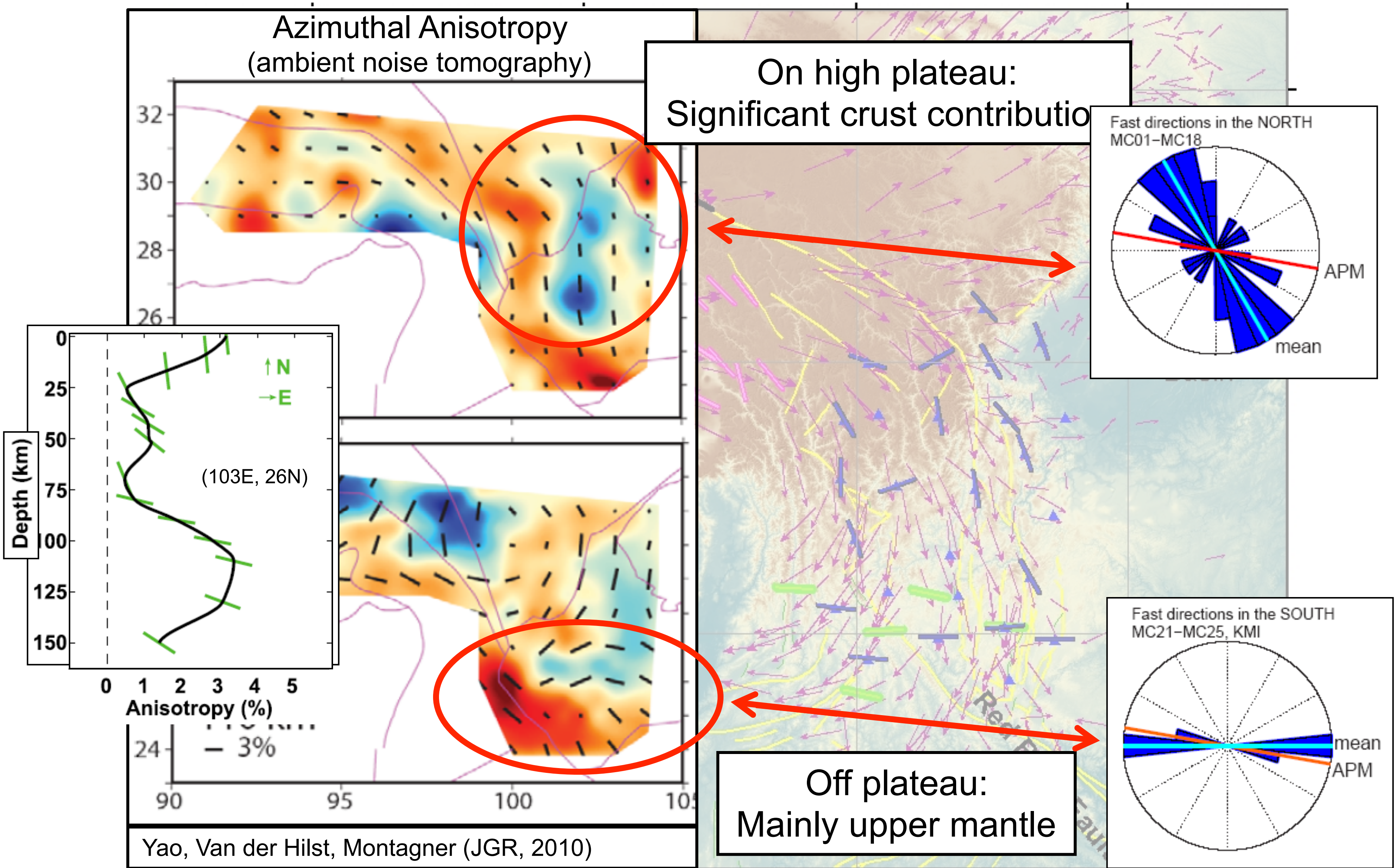


Lev, Long, Van der Hilst (*EPSL*, 2006)
Sol et al. (*Geology*, 2007)

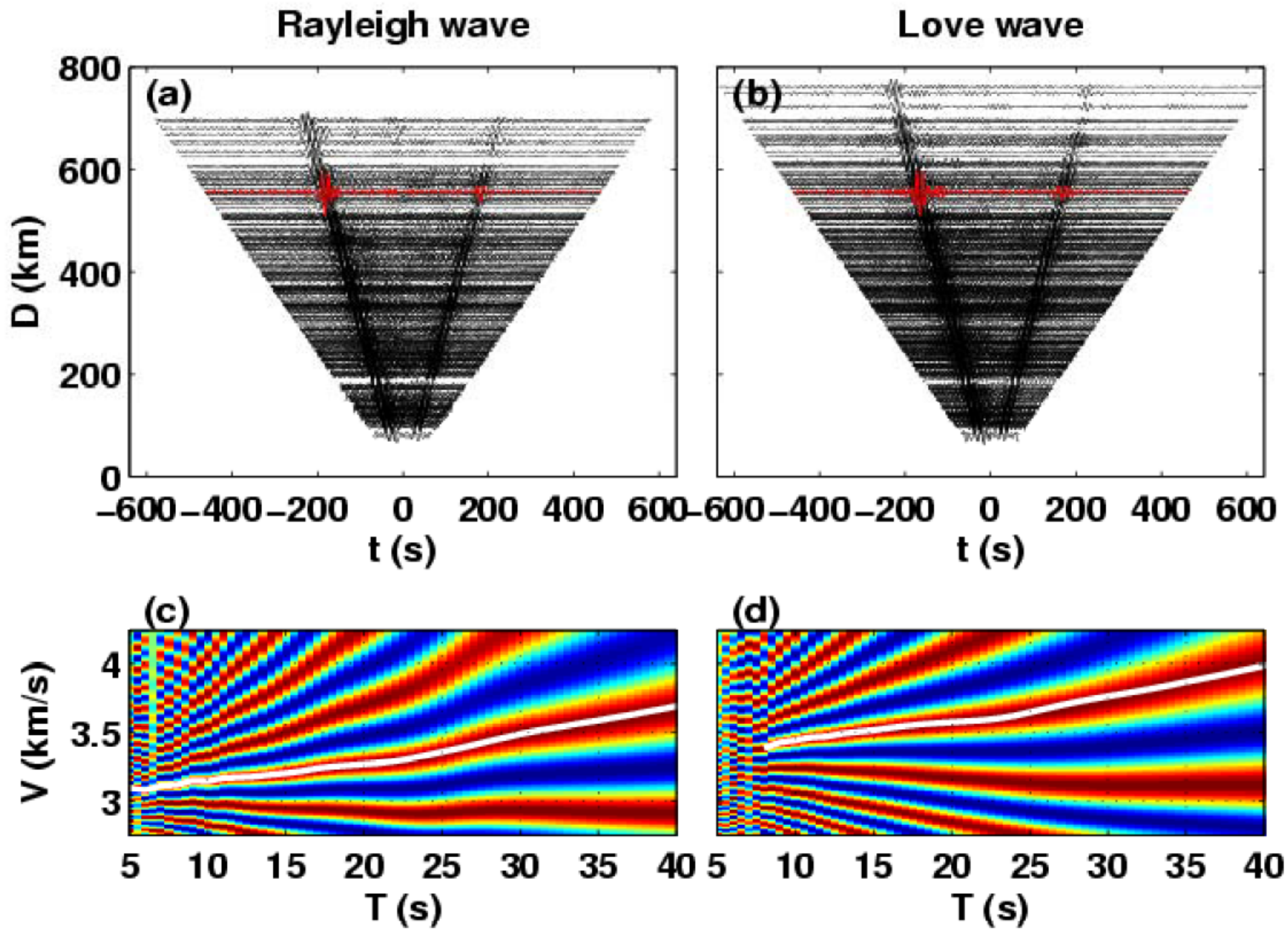
strong variation of azimuthal anisotropy with depth



strong variation of azimuthal anisotropy with depth



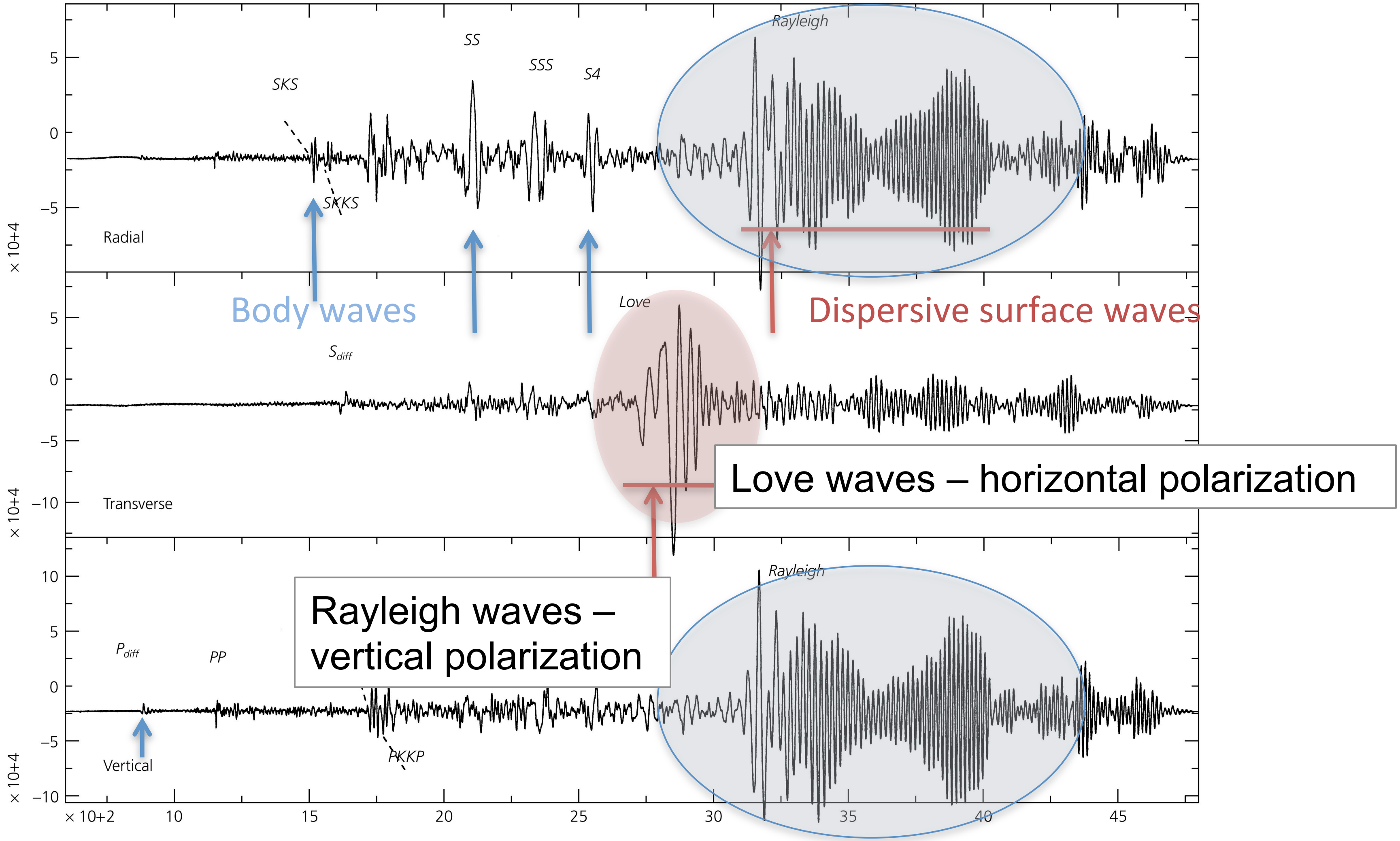
Anisotropy II: Radial Anisotropy from joint inversion of Love and Rayleigh wave dispersion (empirical Green's functions for noise correlation).



Huang, Yao, and Van der Hilst (GRL, 2010)

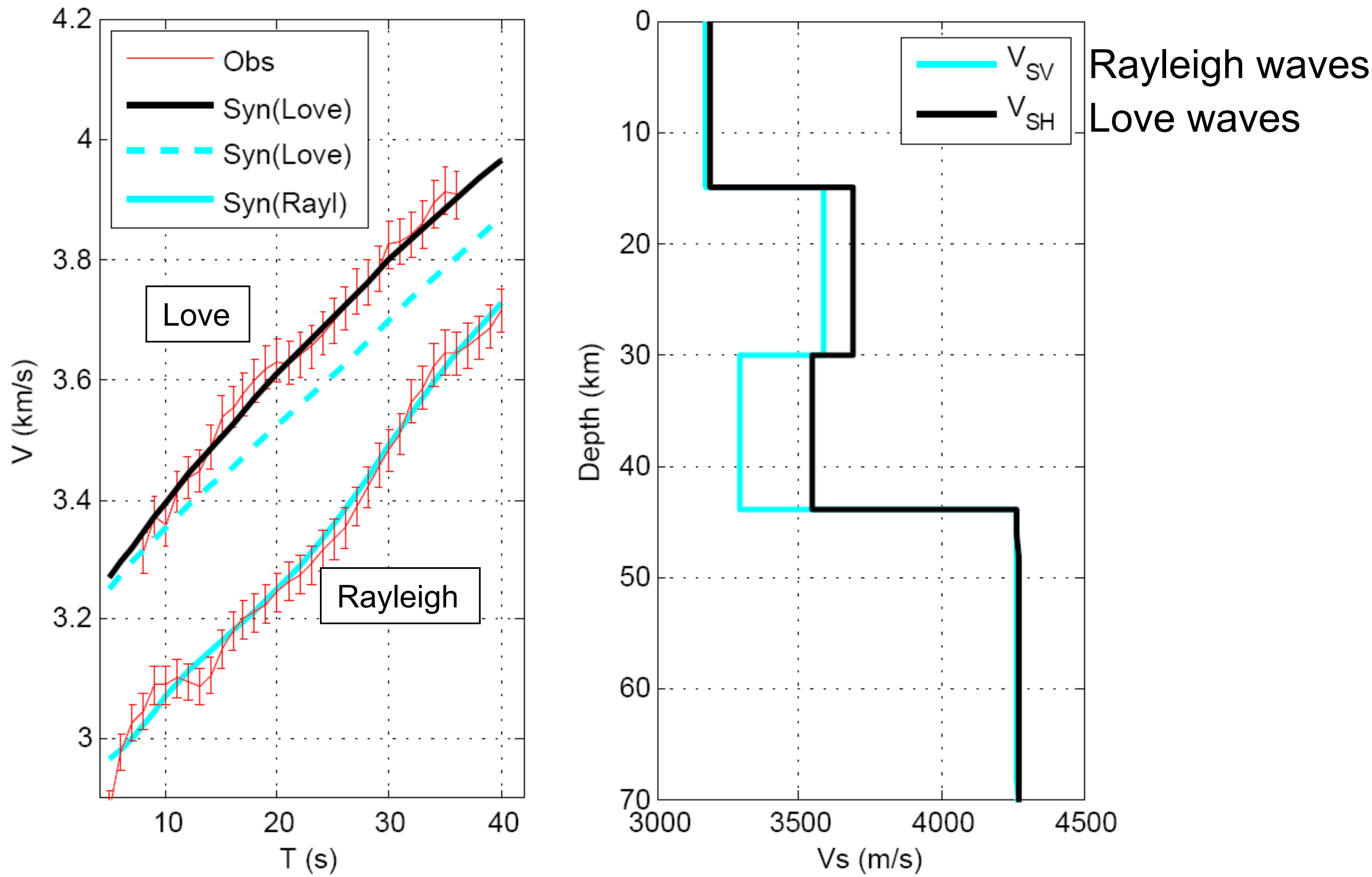
Anisotropy II: Radial Anisotropy (or: transverse *isotropy*)

(i.e., difference between wavespeed of horizontally and vertically polarized waves)



From Stein and Wysession

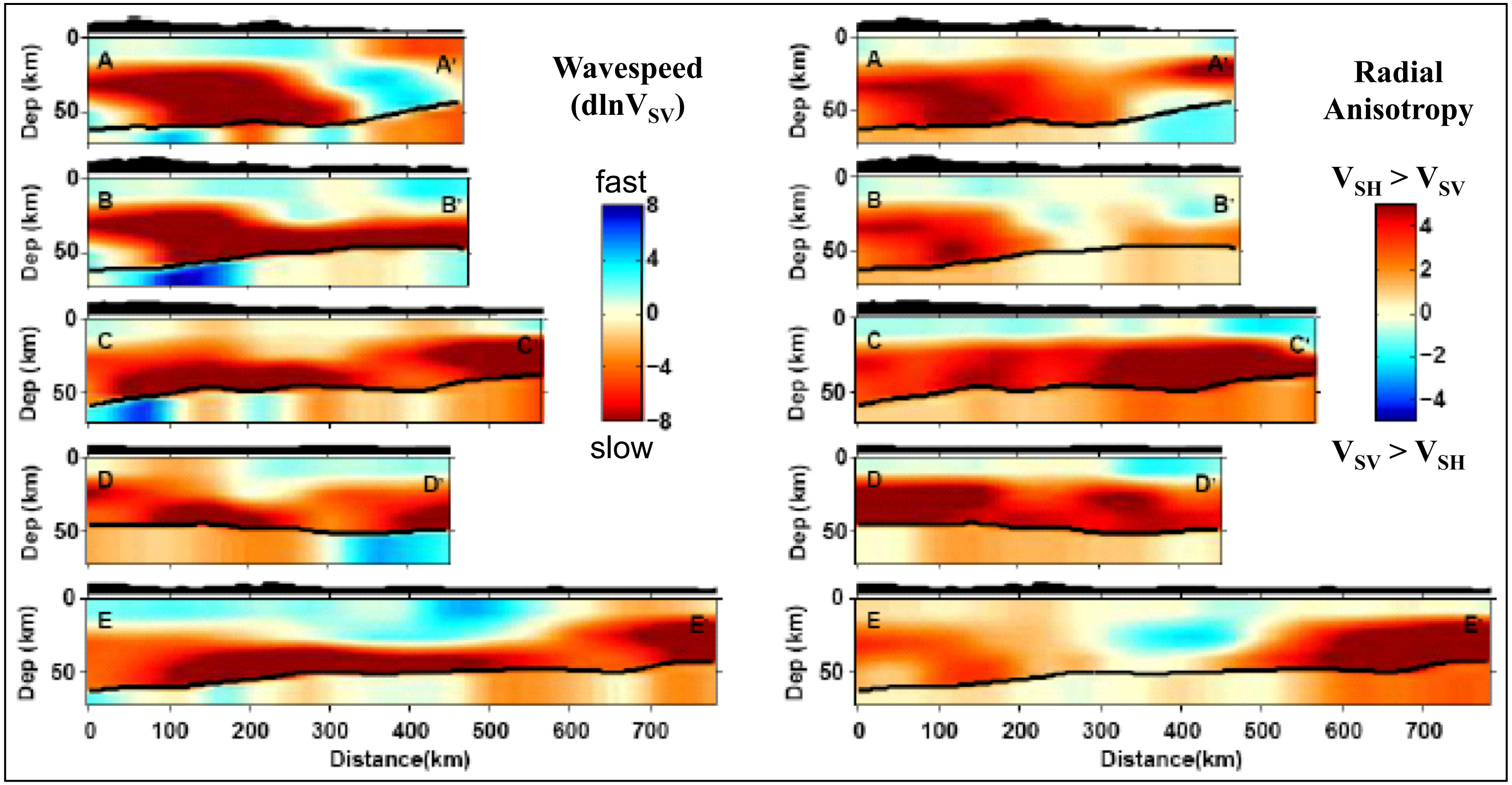
Radial Anisotropy (from Love and Rayleigh wave dispersion)

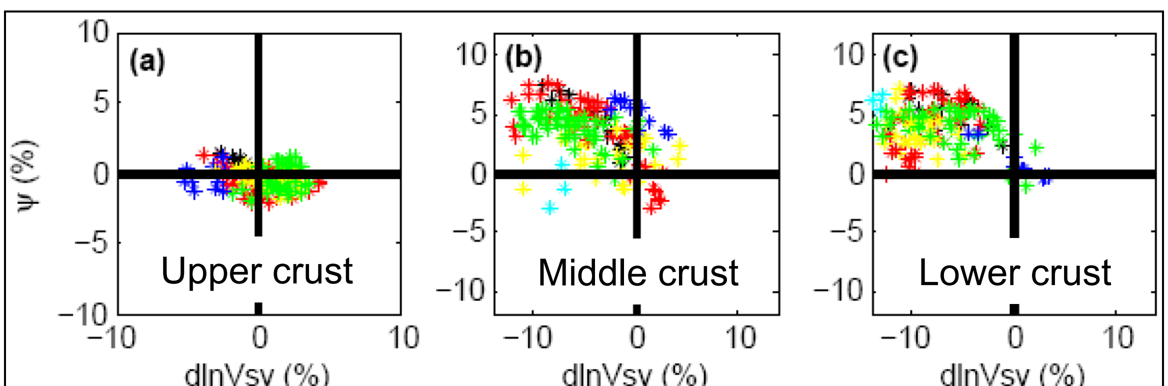


Huang, Yao, and Van der Hilst (GRL, 2010)

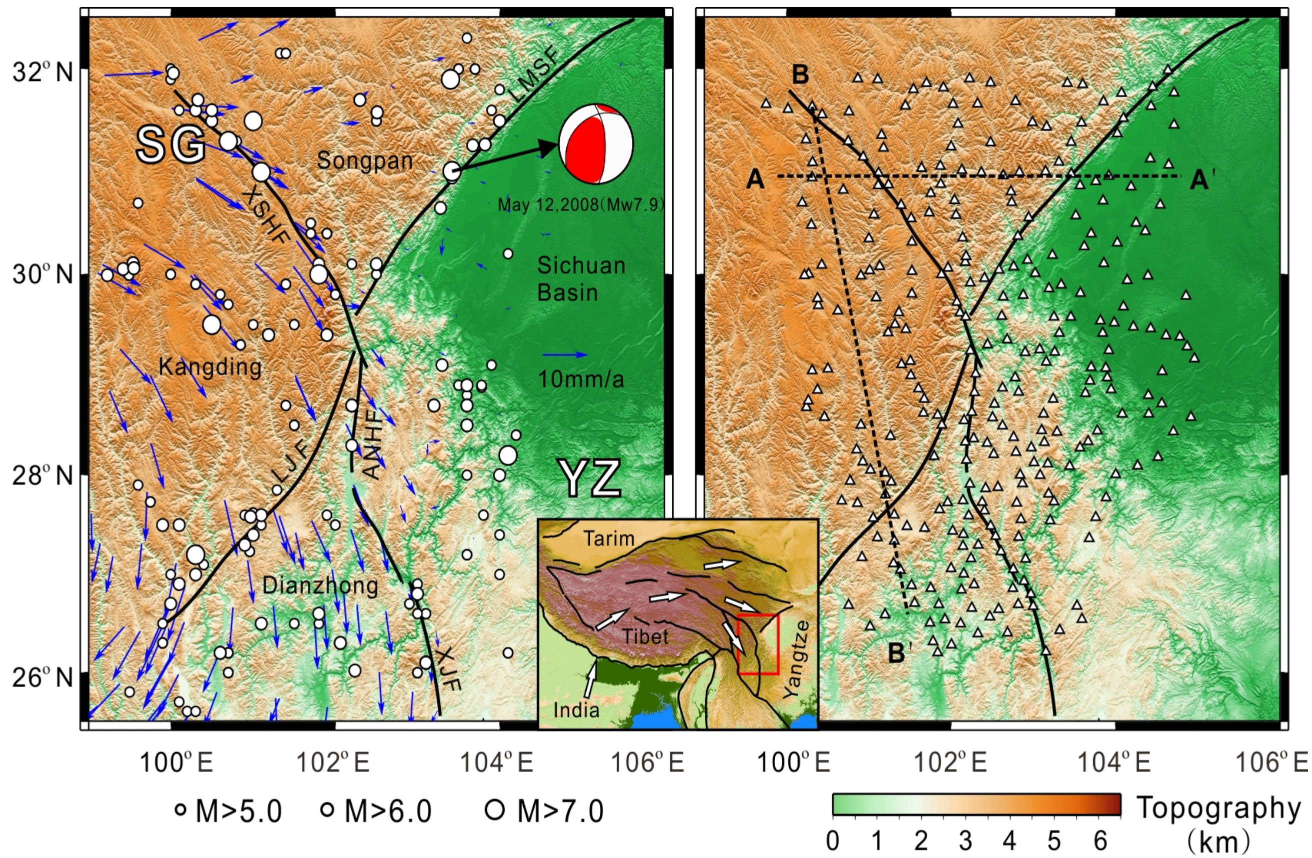
Huang, Yao, and Van der Hilst (GRL, 2010)

Strong correlation with LVZs → horizontal flow in weak zones?





High resolution studies with dense seismograph arrays

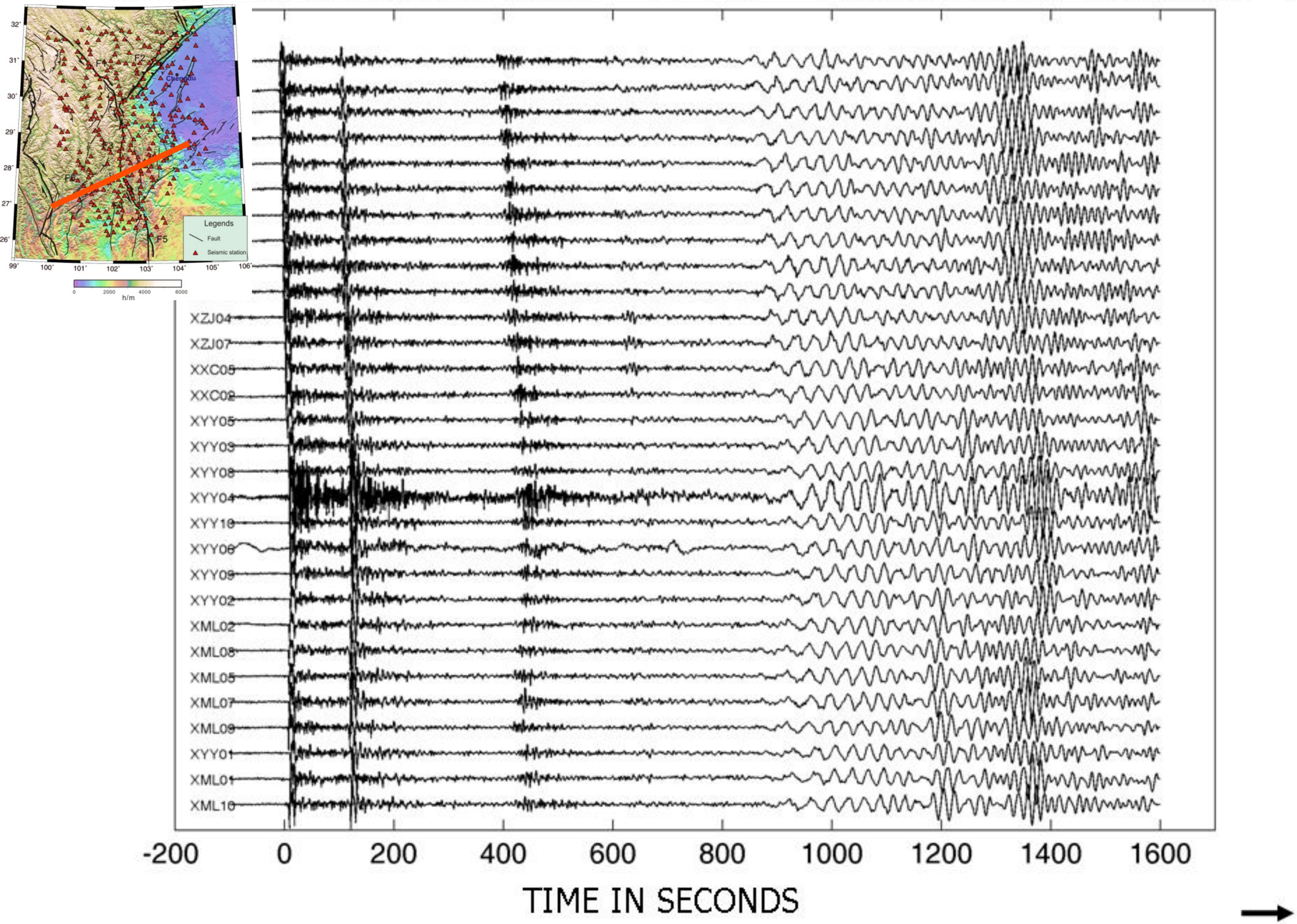


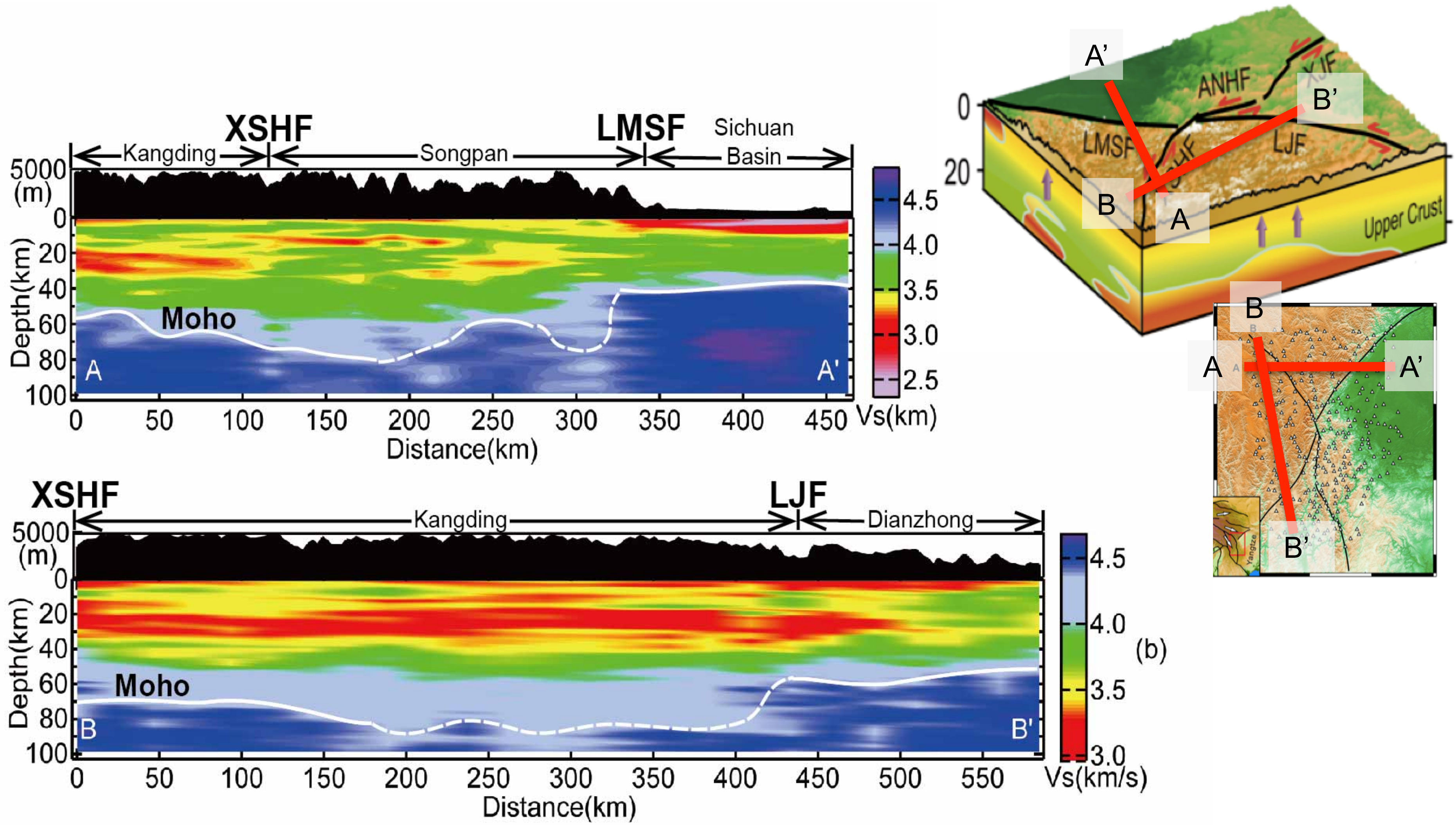
Geological setting and station map of the movable dense seismograph array in western Sichuan (State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration). Black solid lines: major faults; blue triangles: stations; yellow circles: earthquakes (Ms ≥ 5.0,1901-2010, 2008 Wenchuan focal mechanism); blue arrows: crustal motion relative to the Yangze craton from GPS; red dash lines: seismic profile.

[SB=Sichuan Basin; YZ=Yangtze block; CD=Chundian unit; SG= Songpan-Ganze unit]
[XSH=Xiangshuihe; LMS=Longmen Shan; ANH=Anninghe; LJ=Lijiang fault]

Liu et al. (Nature Geosciences, 2014)

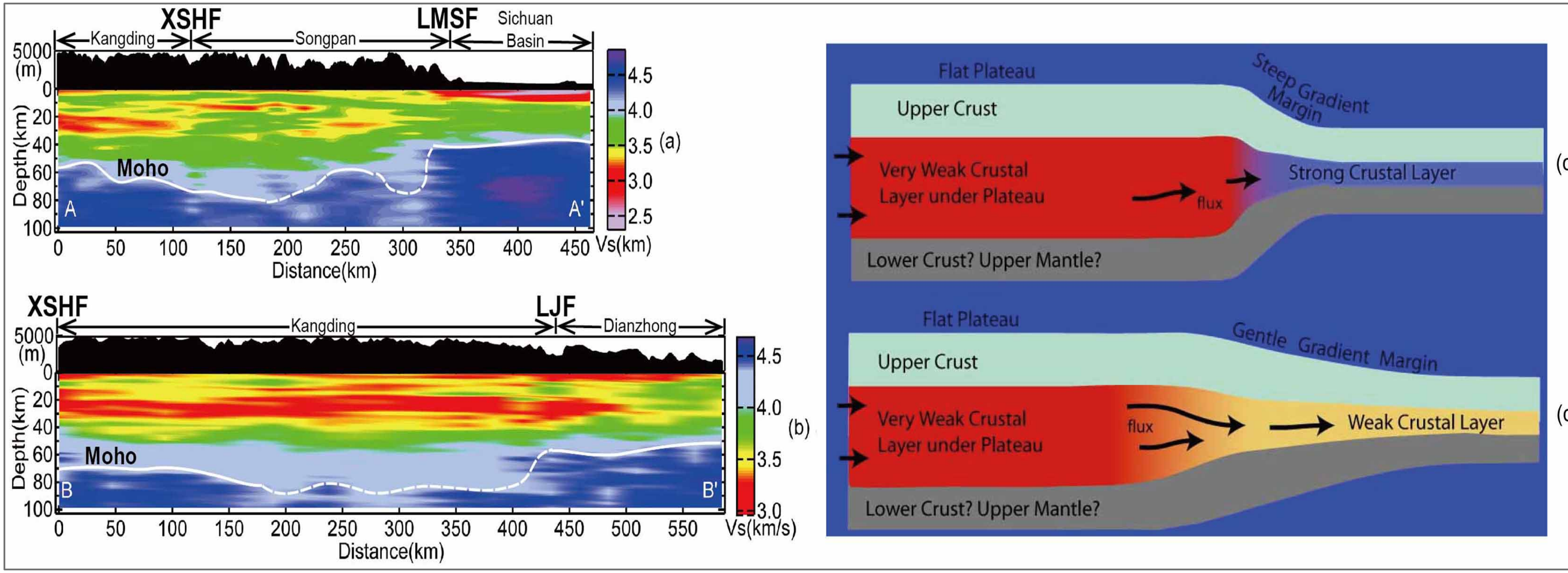
January 13,2007 04h23m21.16s MB 7.3 Location:46.243° N, 154.524° E





Topography and shear wavespeed variations from joint inversion of P-receiver functions and Ambient Noise (Rayleigh wave) Tomography across region of steep relief (A-A'; top) and gentle topographic gradient (B-B'; bottom).

Liu et al. (Nature Geosciences, 2014)



Crustal structure constrained by waveform data obtained by a dense seismography array in western Sichuan.

Concept: canonical channel flow model. (Figure courtesy of L. Royden, MIT).

Liu et al. (Nature Geosciences, 2014)

Overview of lecture:

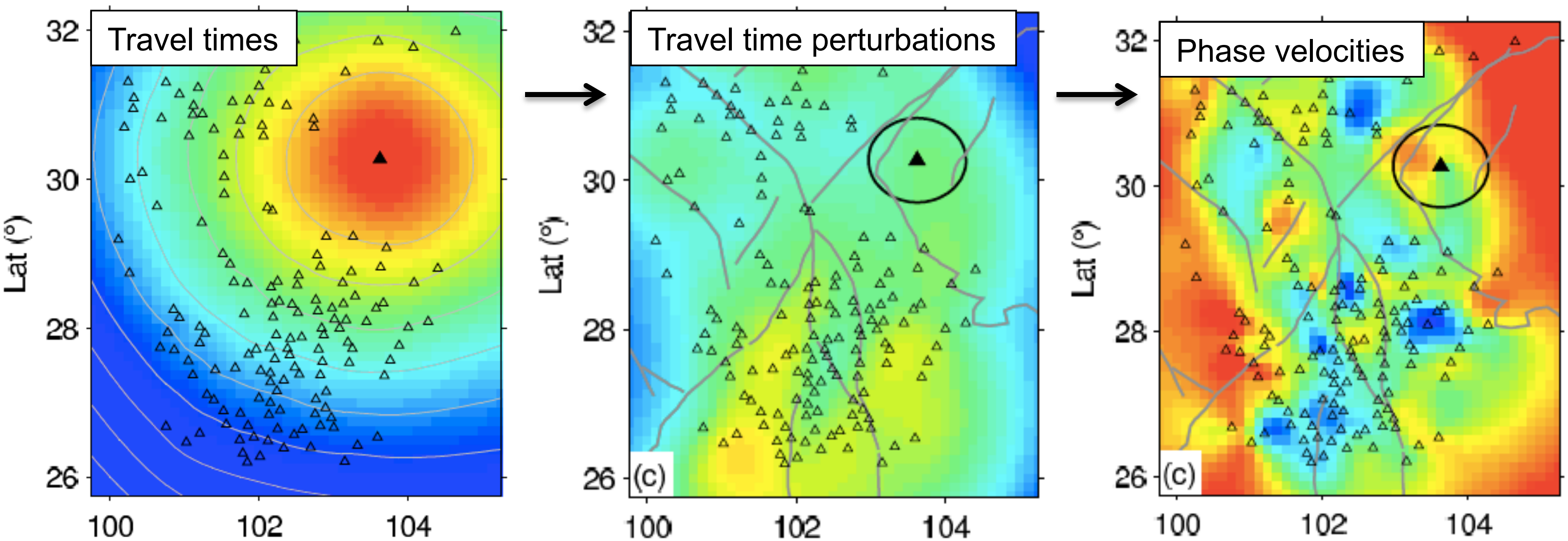
1. **Introduction/background**

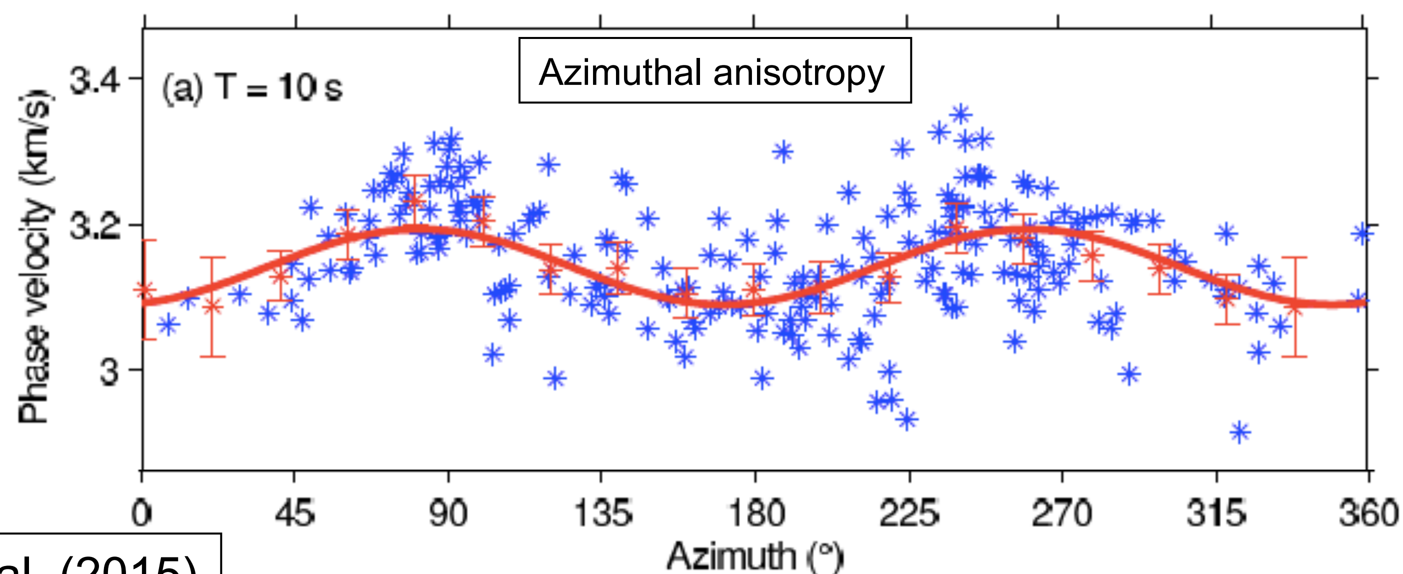
2. **Ambient noise and surface wave tomography (MIT, 2005-2015)**
    - Traditional transmission tomography:
        - combining ambient noise and earthquake data
        - quantifying and correcting for uneven noise distribution
        - azimuthal anisotropy
        - radial anisotropy
    - **Eikonal tomography**
    - Adjoint tomography with ambient noise data

3. **Interferometry of teleseismic body waves**

4. **Imaging with multiples**

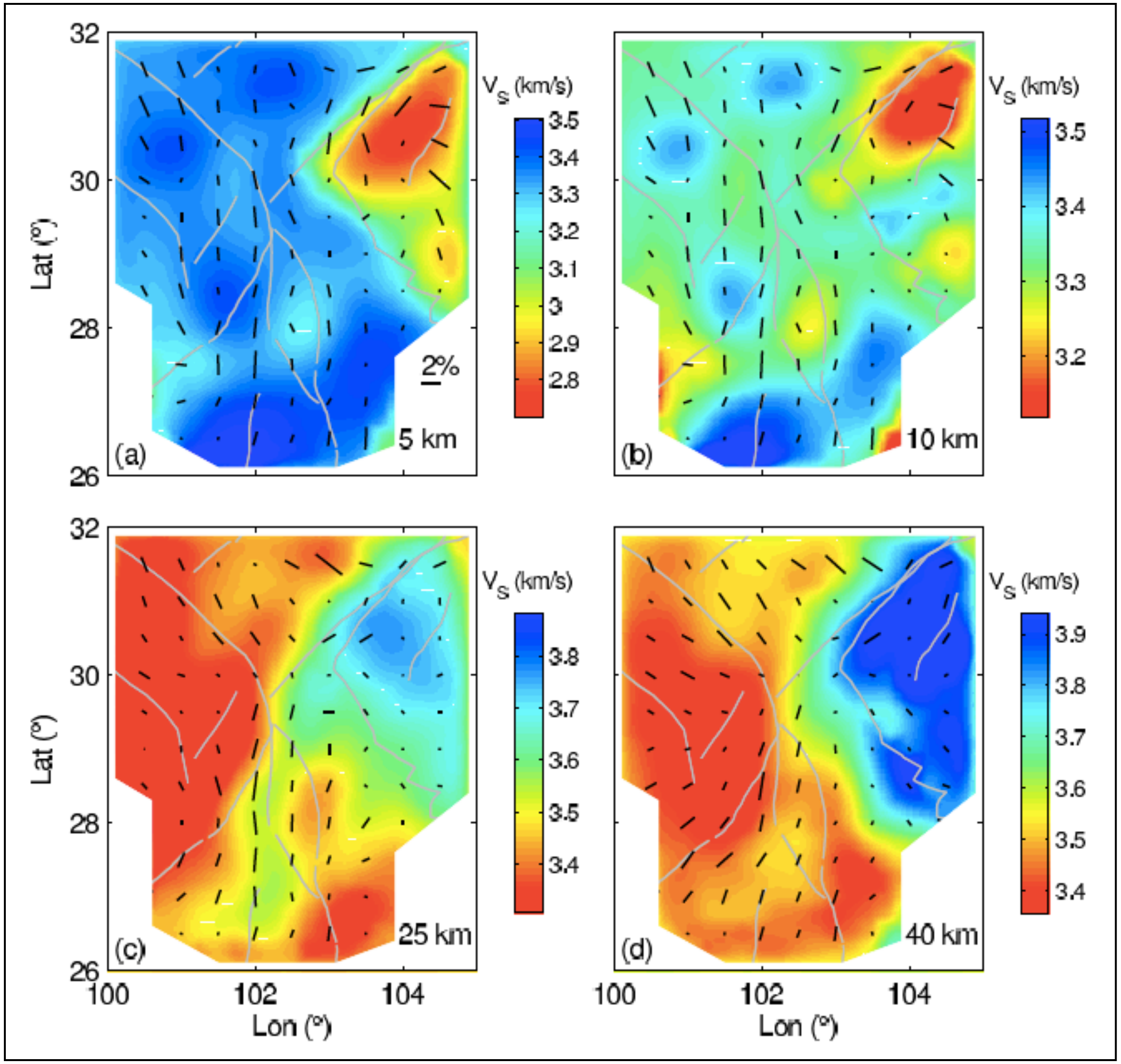
Eikonal Tomography: interpolation of travel time *perturbations* instead of travel times





Huang et al. (2015)

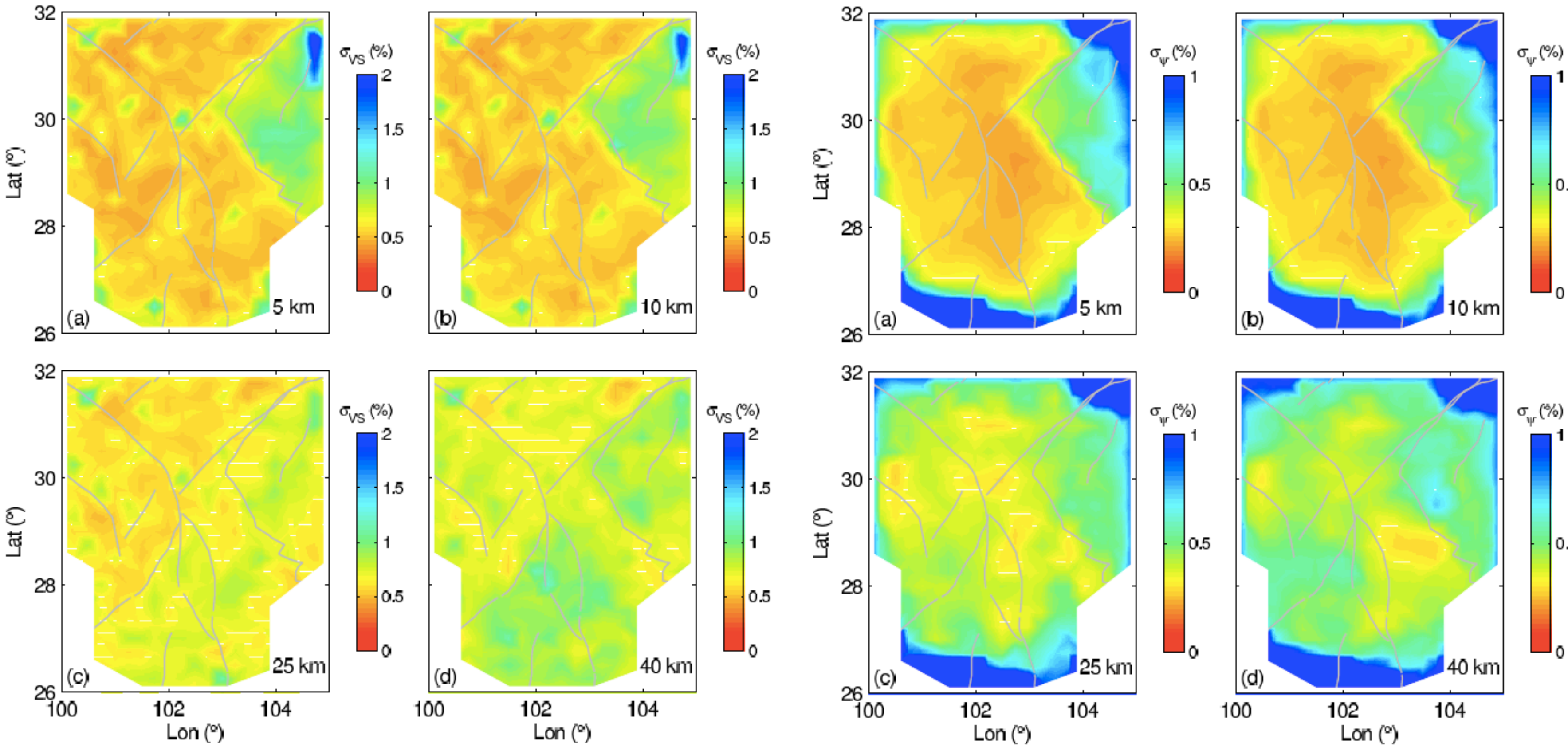
Eikonal Tomography: interpolation of travel time *perturbations* instead of travel times



Huang et al. (2015)

Eikonal Tomography: interpolation of travel time *perturbations* instead of travel times

Standard errors for Vs | Standard errors for anisotropy



Robust estimation of heterogeneity and (azimuthal) anisotropy,
but lower spatial resolution than traditional tomography due to interpolation

Huang et al. (2015)

Overview of lecture:

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AGU PUBLICATIONS

Geophysical Research Letters

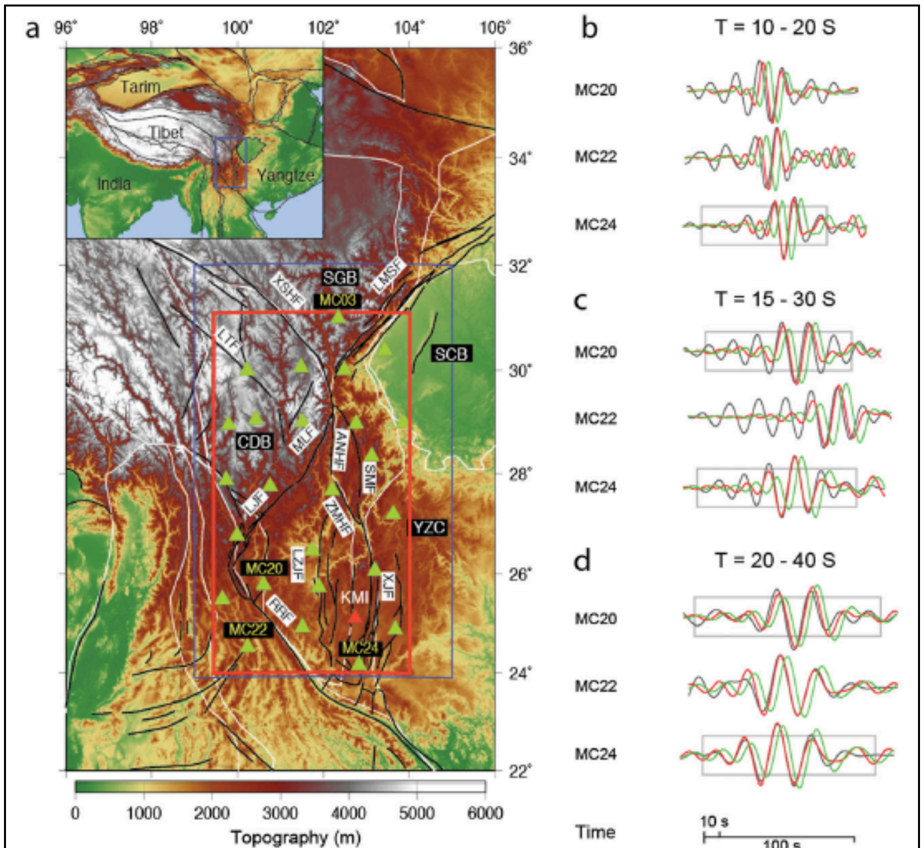
RESEARCH LETTER

10.1002/2013GL058476

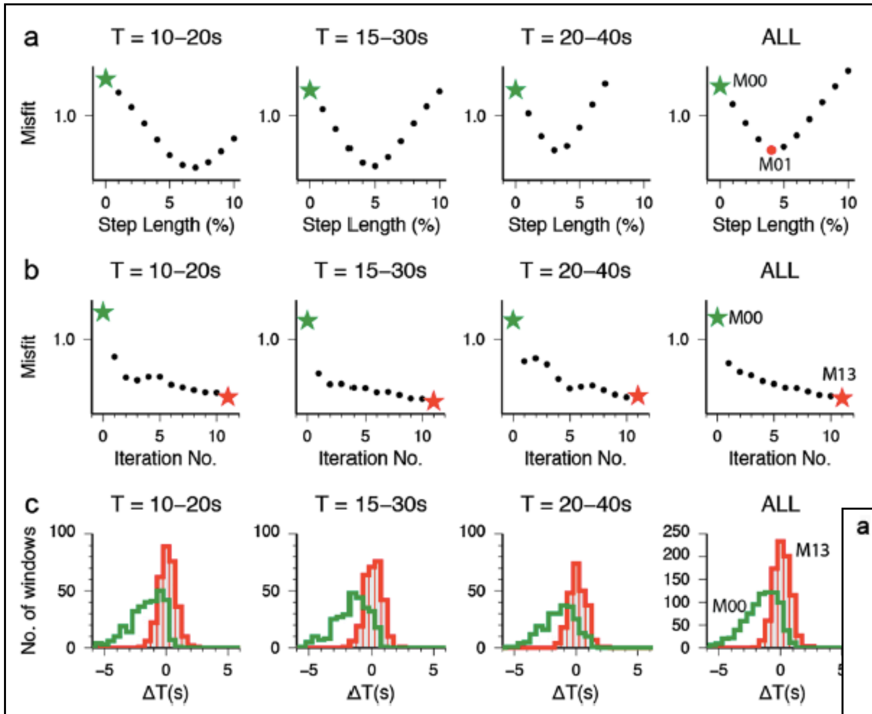
Key Points:
- Ambient noise adjoint tomography refines the SE Tibet crustal model

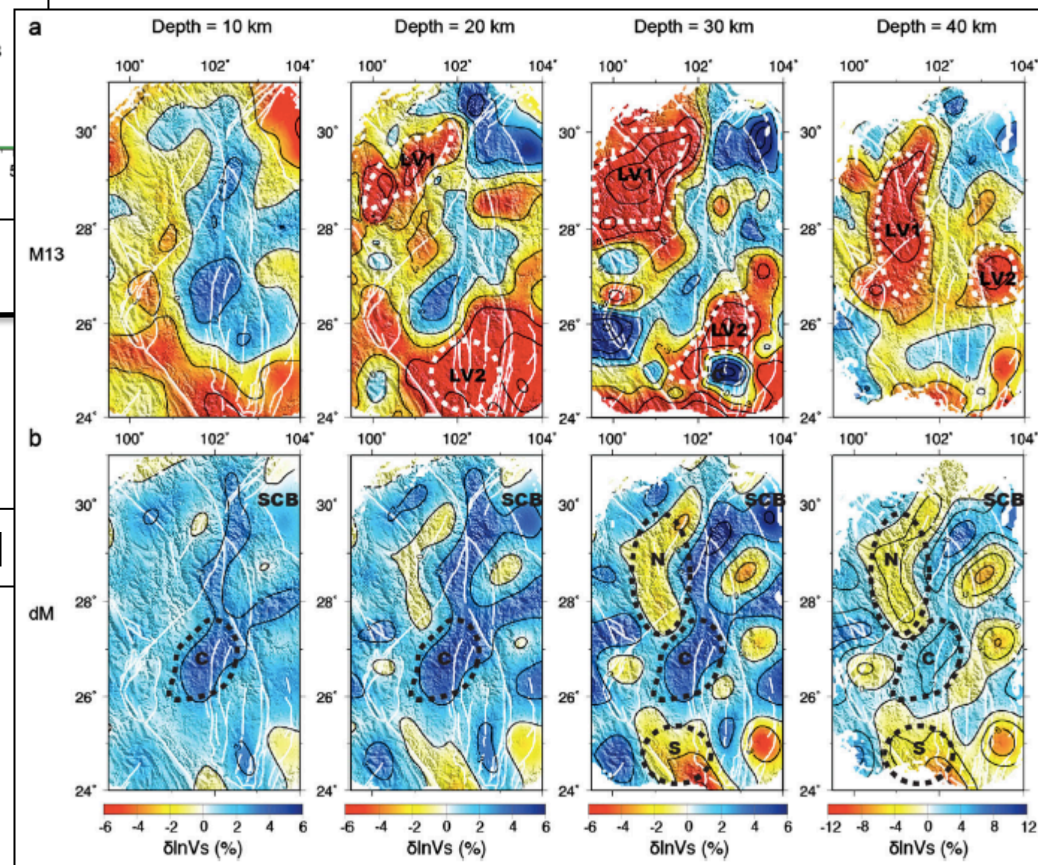
Low wave speed zones in the crust beneath SE Tibet revealed by ambient noise adjoint tomography

Min Chen[1,2], Hui Huang[1], Huajian Yao[1,3], Rob van der Hilst[1], and Fenglin Niu[2,4]



Chen et al (GRL, 2014)





Result after 13 iterations

Difference from starting model

Chen et al (GRL, 2014)

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     - radial anisotropy
   - Eikonal tomography
   - Adjoint tomography with ambient noise data

3. **Interferometry of teleseismic body waves – concept**

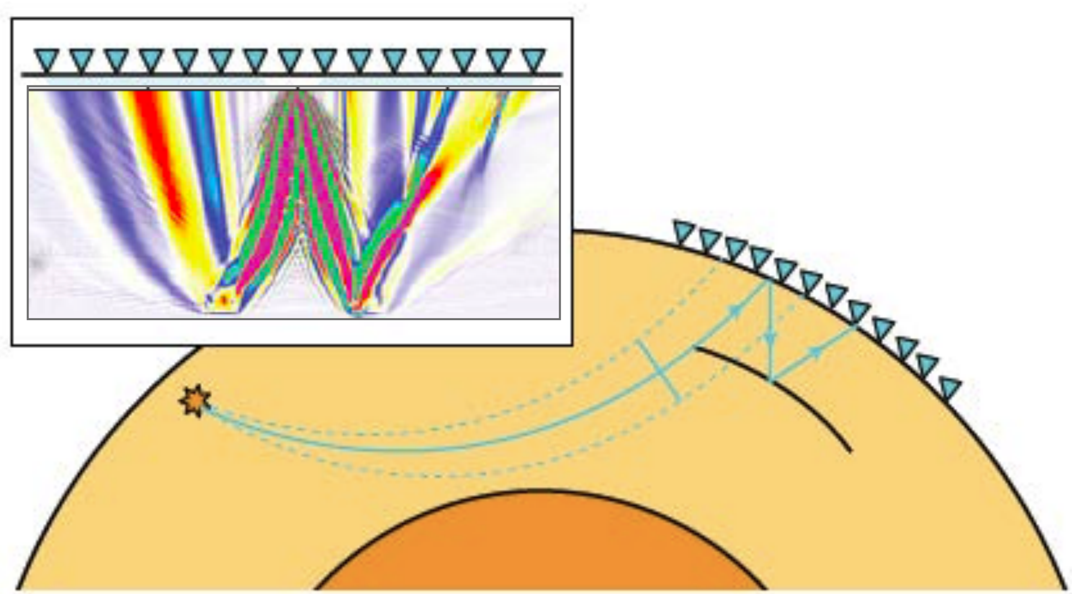
4. **Imaging with multiples**

Teleseismic wave-equation reflection tomography using free surface reflected phases

S. Burdick[1], M. V. de Hoop[2], S. Wang[2] R. D. van der Hilst[1]
[1] Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology Cambridge, MA 02139, USA
[2] Department of Mathematics, Purdue University

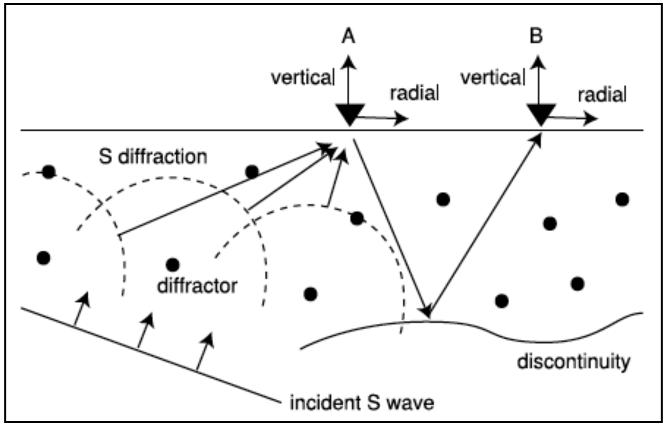
"Remote sensing"

Estimating wavespeed variations beneath an array using waves coming from distant sources.



Construct images from converted and multiply-reflected teleseismic phases (NB the source can be 'ambient noise')

For instance, imaging of the slab interface



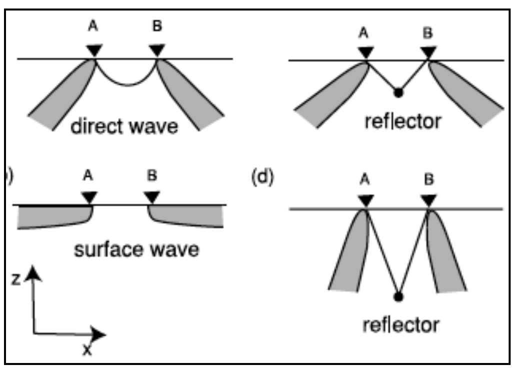
Seismic interferometry of teleseismic *S*-wave coda for retrieval of body waves: an application to the Philippine Sea slab underneath the Japanese Islands

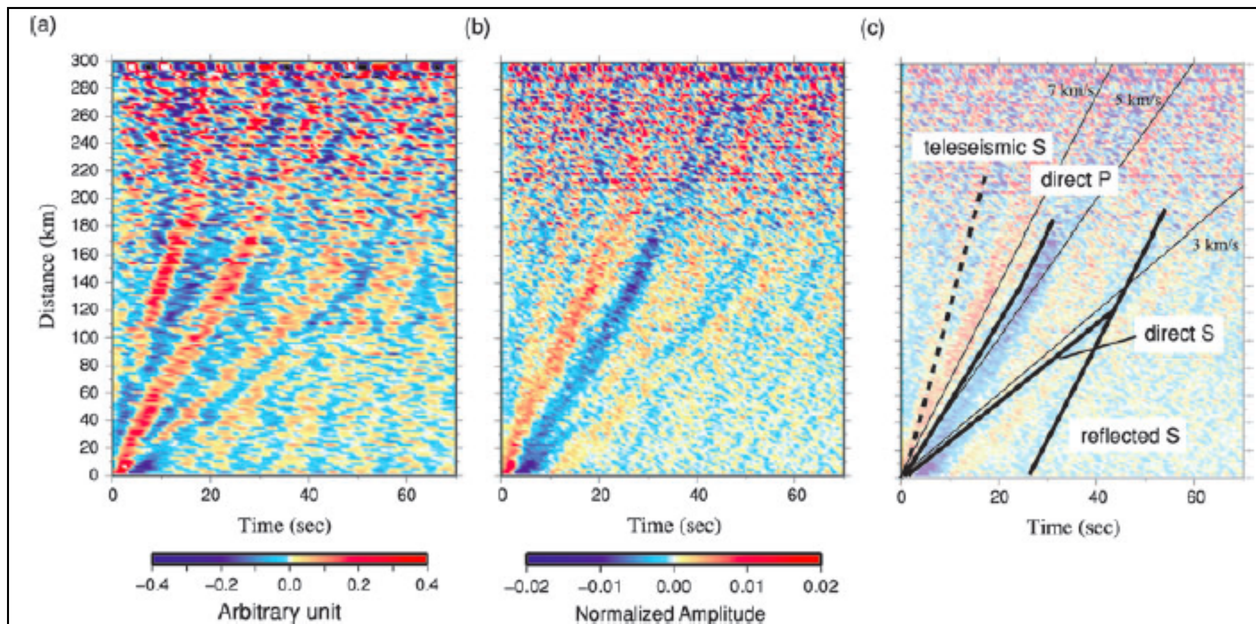
Takashi Tonegawa,[1] Kiwamu Nishida,[1] Toshiki Watanabe[2] and Katsuhiko Shiomi[3]

[1] *Earthquake Research Institute, Univ. of Tokyo,* 1-1-1, *Yayoi, Bunkyo-ku, Tokyo* 113-0032, *Japan. E-mail: tonegawa@eri.u-tokyo.ac.jp*
[2] *Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya* 464-8602, *Japan*
[3] *National Research Institute for Earth Science and Disaster Prevention,* 3-1, *Tennodai, Tsukuba, Ibaraki* 305-0006, *Japan*

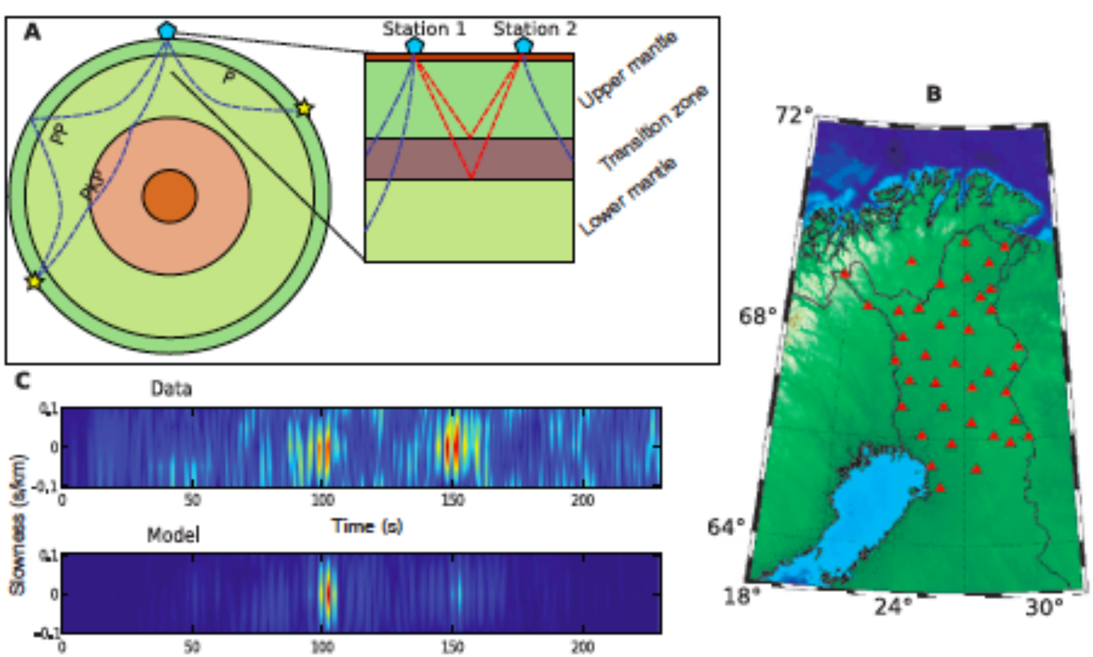
Accepted 2009 May 11. Received 2009 April 20; in original form 2009 January 22

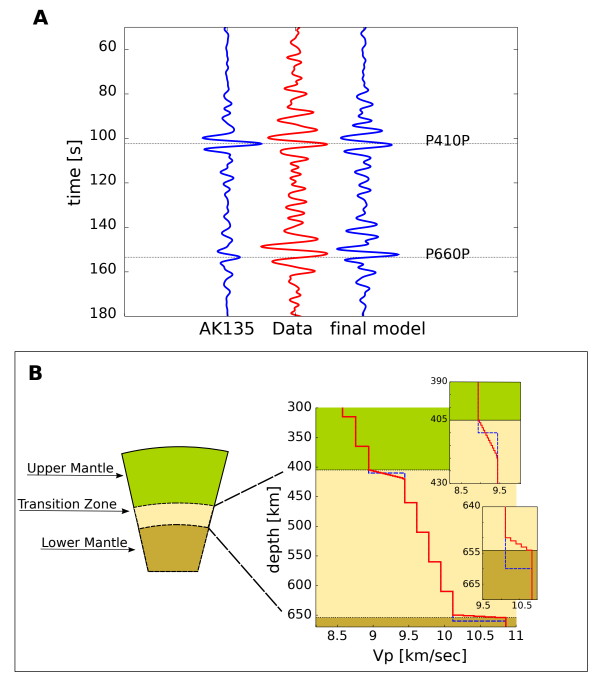
Tonegawa et al. (GJI, 2009)





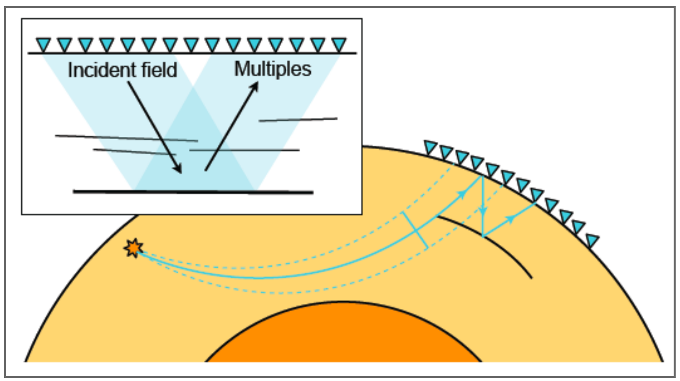
Or passive imaging: Earth's mantle discontinuities from ambient seismic noise.

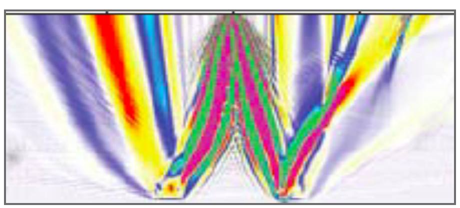




Poli et al. (Science, 2012)

Construct images from converted and multiply-reflected teleseismic phases

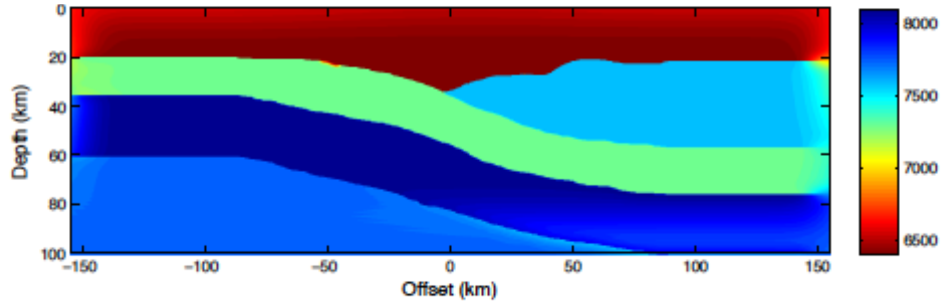




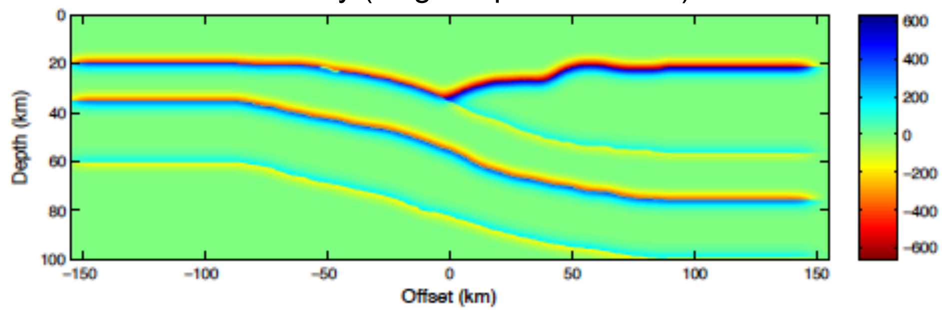
Wave-equation reflection tomography → full finite frequency (De Hoop et al., (GJI, 2006)

Burdick et al. (GJI, 2014)

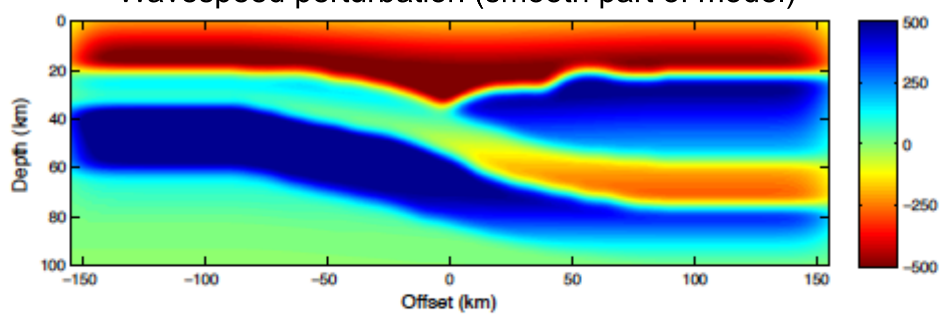
Actual model (used to create synthetic data)



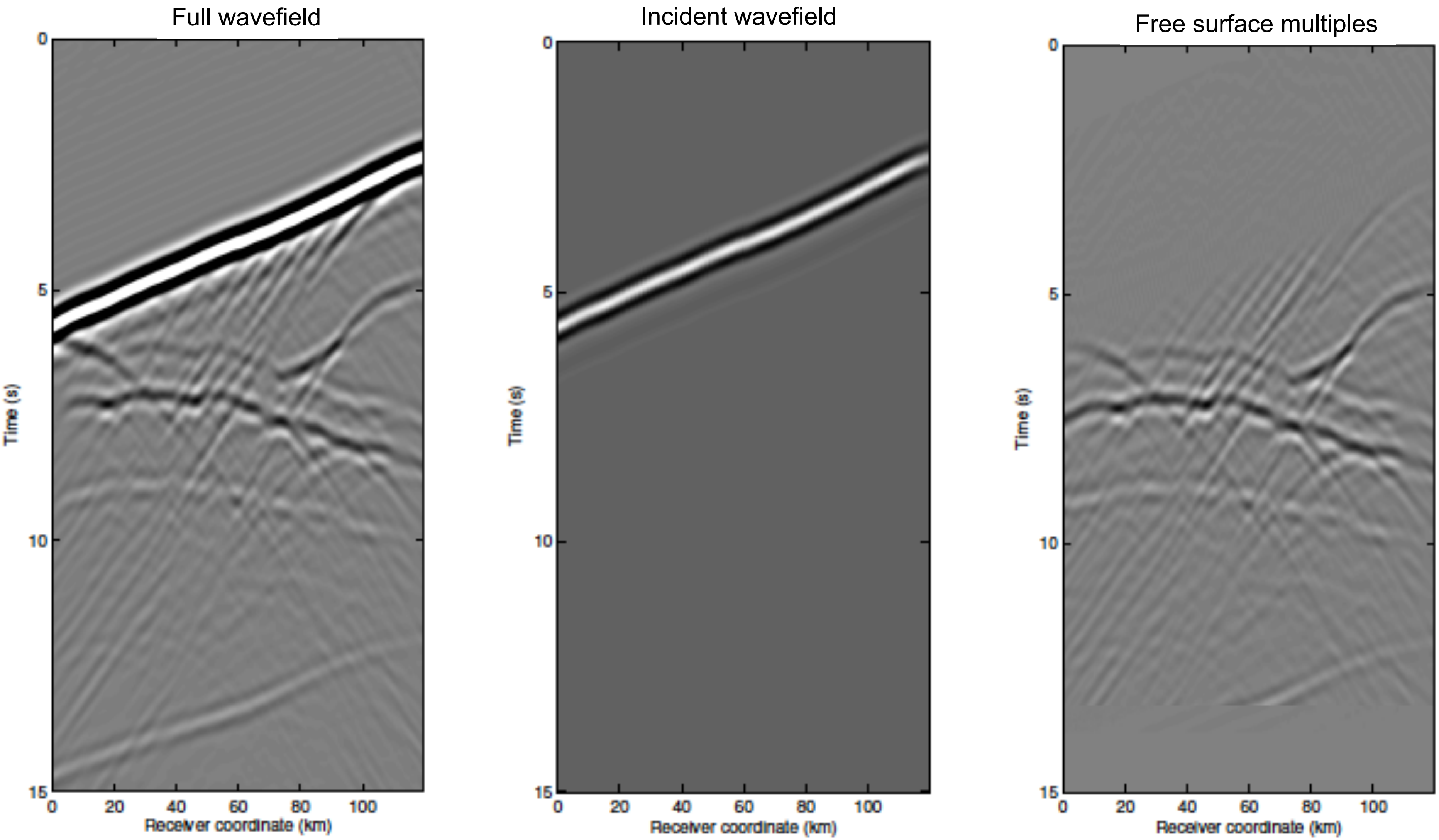
Reflectivity (singular part of model)



Wavespeed perturbation (smooth part of model)

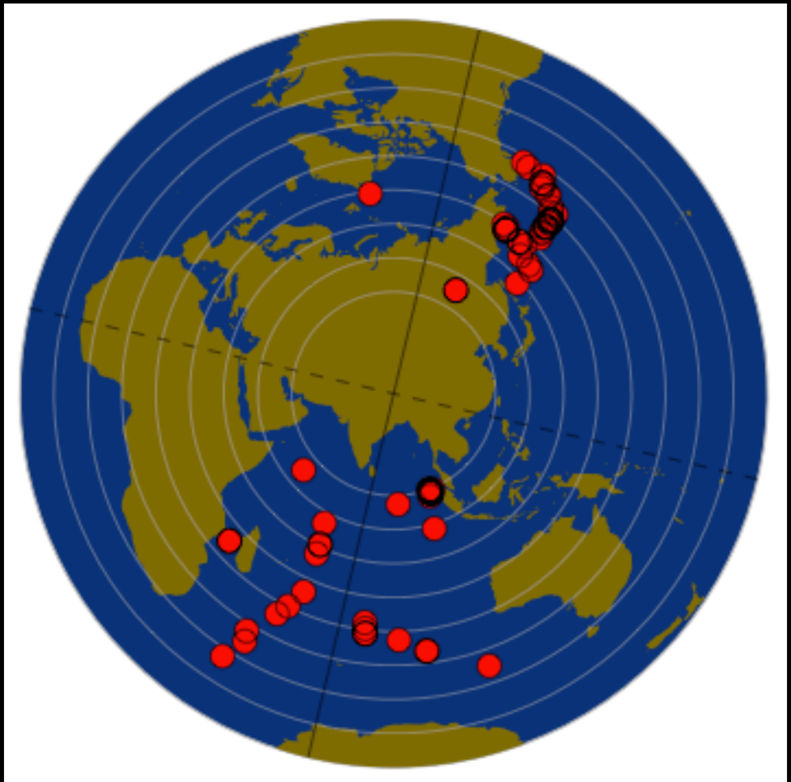


Separation of the direct and multiple fields: interferometry/cross-correlation



Burdick et al. (GJI, 2014)

Challenges of teleseismic data



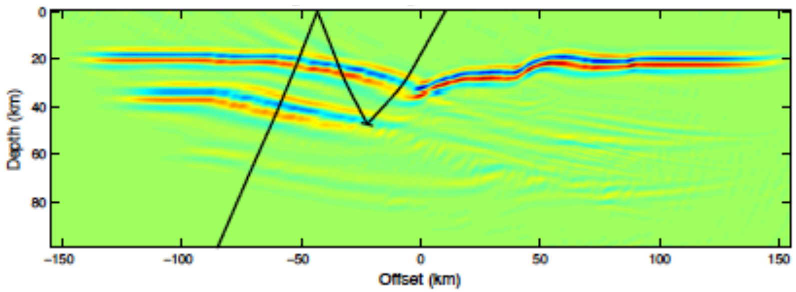
Events magnitude > 5.0
< 30° from great circle arc

1) Limited global seismicity & irregular array configurations → limited angular and azimuthal data → Angle domain annihilation not effective

Burdick et al. (GJI, 2014)

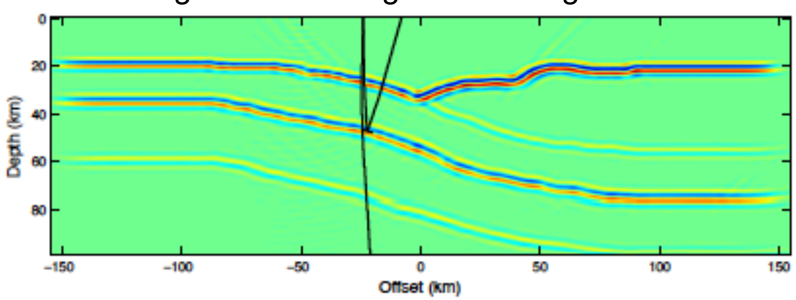
Single source images formed using inverse scattering for teleseismic sources arriving from different directions

Single source image for 23.7 deg incidence



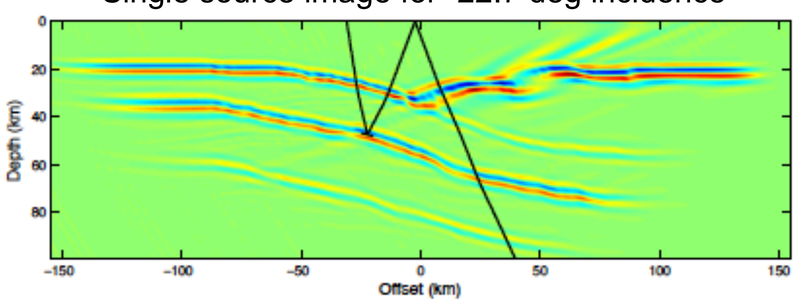
(a)

Single source image for 1.3 deg incidence



(b)

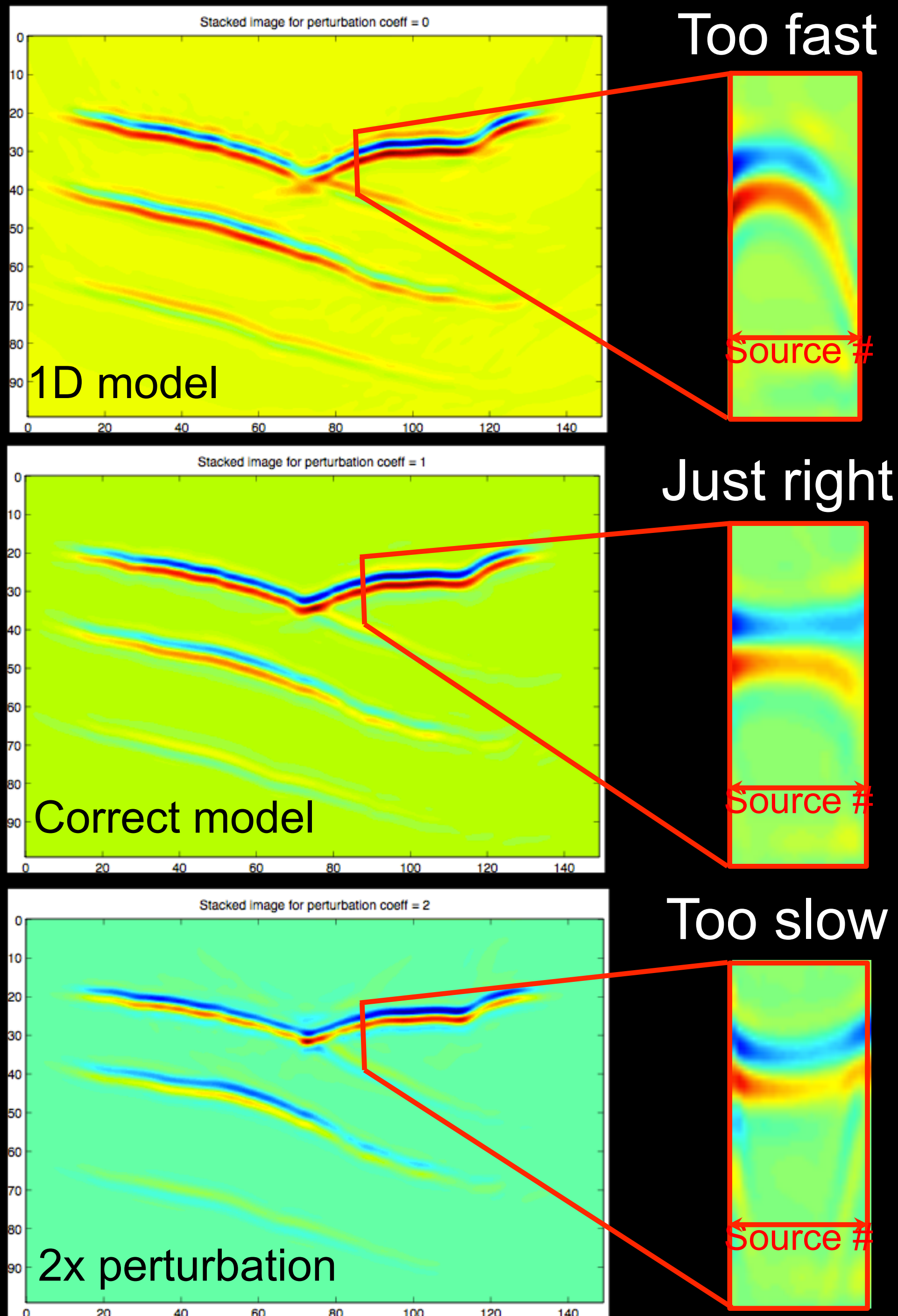
Single source image for -22.7 deg incidence



Power norm error function

- **correlation of images** sources → maximum correlation gives best optimal velocity model
- More robust than error function based on depth move-out (angle domain annihilation)

Burdick et al. (GJI, 2014)



Residual moveout in source-index image gathers

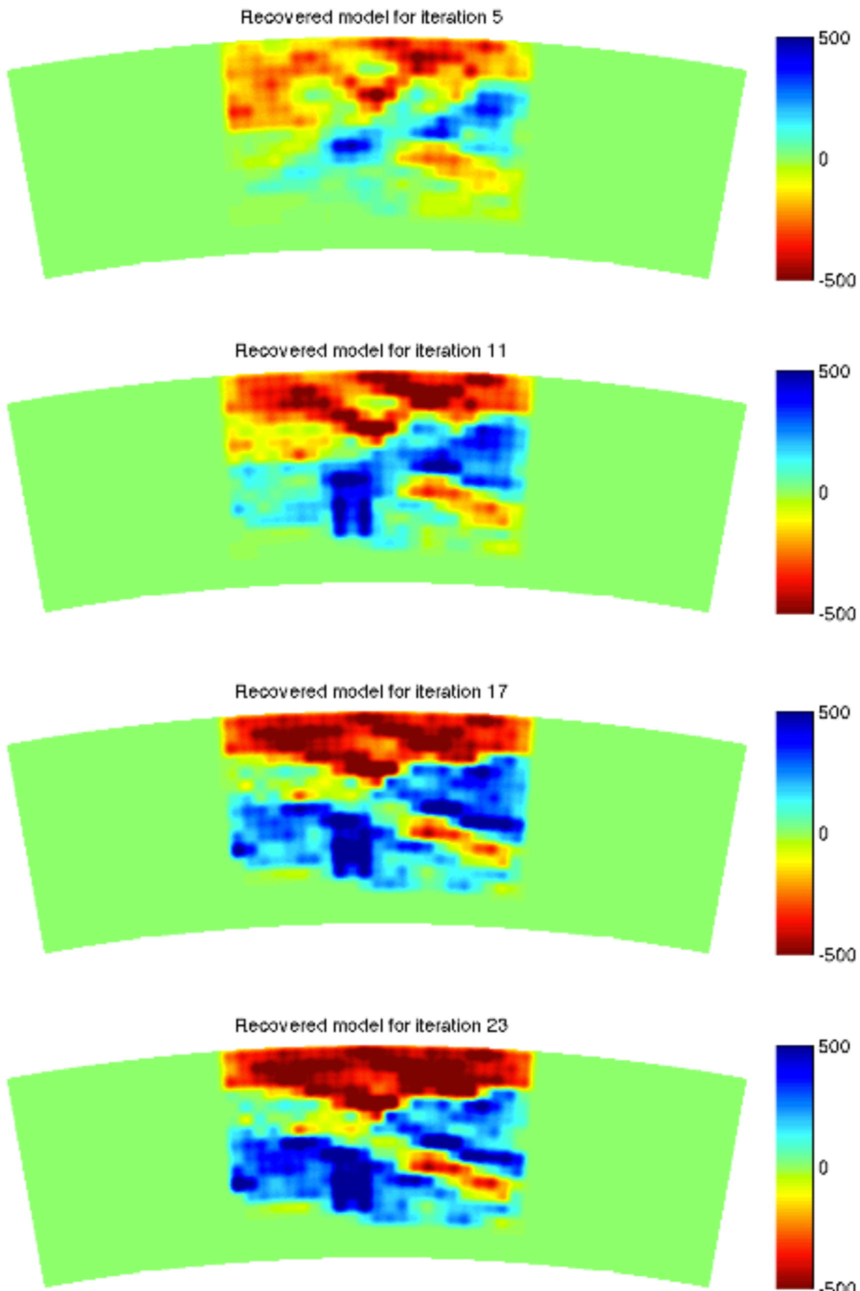
Incorrect model creates measurable moveout in single-source images

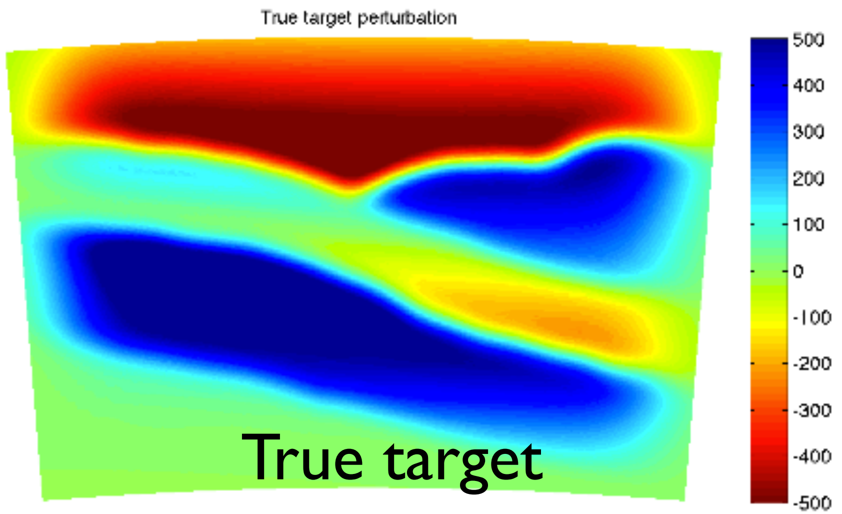
Best way to quantify error? → misfit criterion

Burdick et al. (GJI, 2014)

Preliminary results

Inversion with fine basis, spherical coordinates





Burdick et al. (GJI, 2014)

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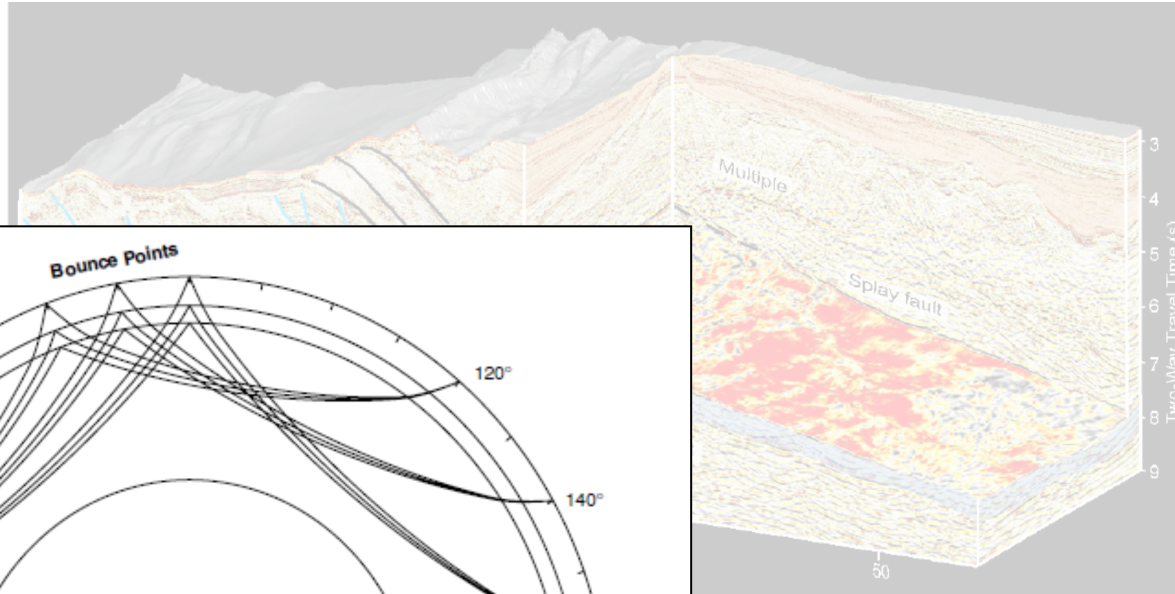
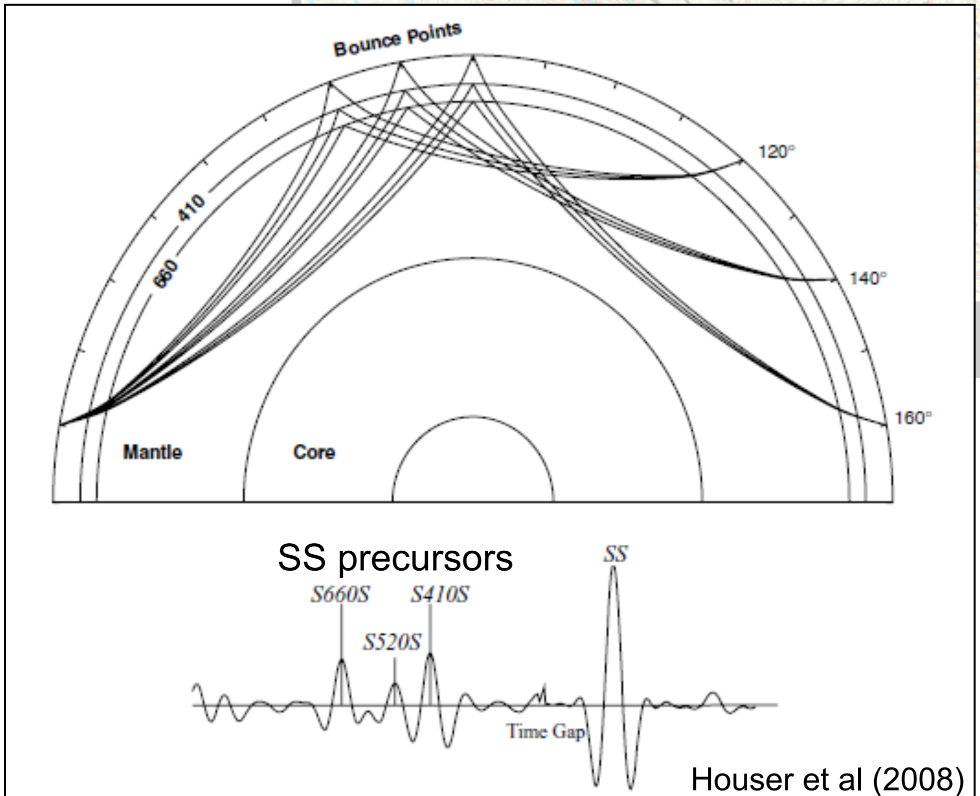
3. **Interferometry of teleseismic body waves**

4. **Imaging with multiples – just some thoughts**

With the many terabytes of seismic data from global networks …
… can we do high-resolution exploration seismics in the mantle?





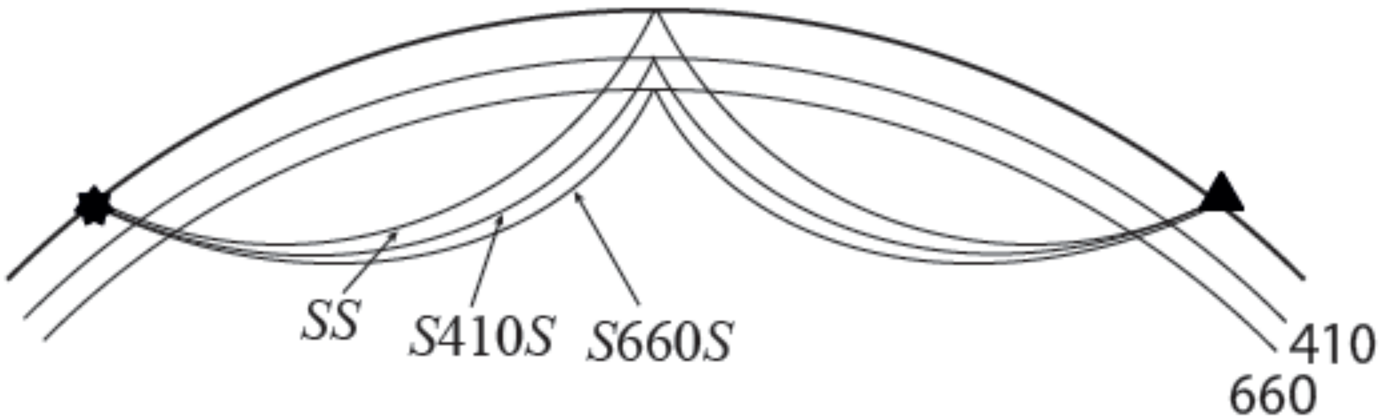
Houser et al (2008)

Imaging the Transition Zone with the SS wavefield

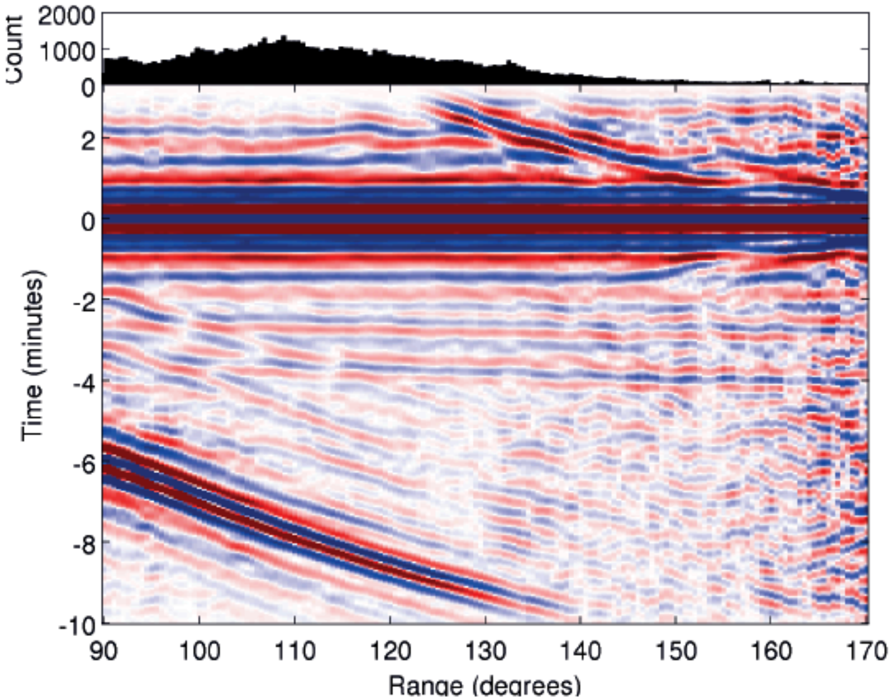
(i.e.,underside reflections)

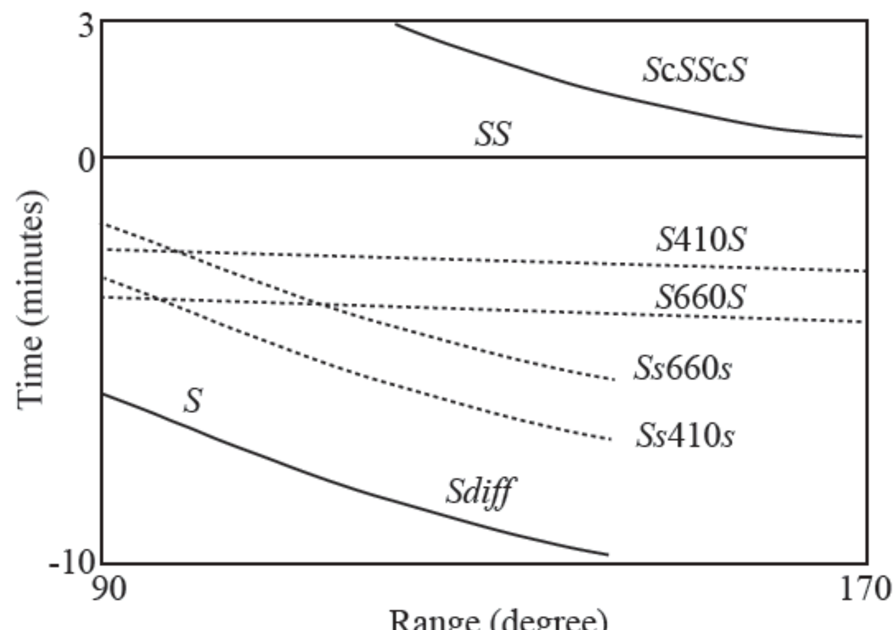
PhD Research: Cao Qin, Yu Chunquan
(supported by CSEDI and CMG Programs of National Science Foundation)

Transition zone imaging with SS precursors

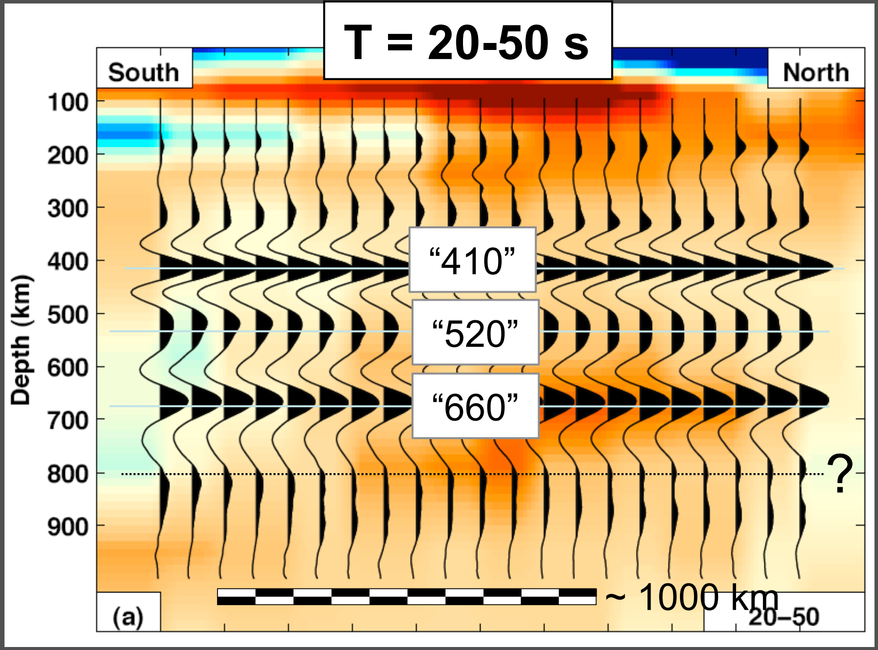


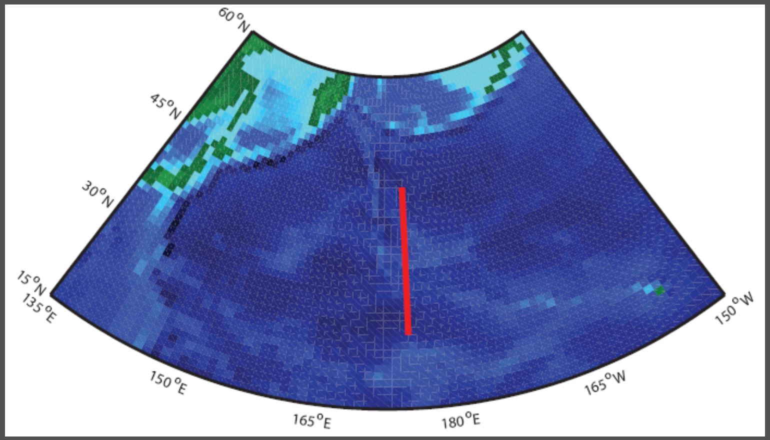
SS stacks





reflection seismology with SS data

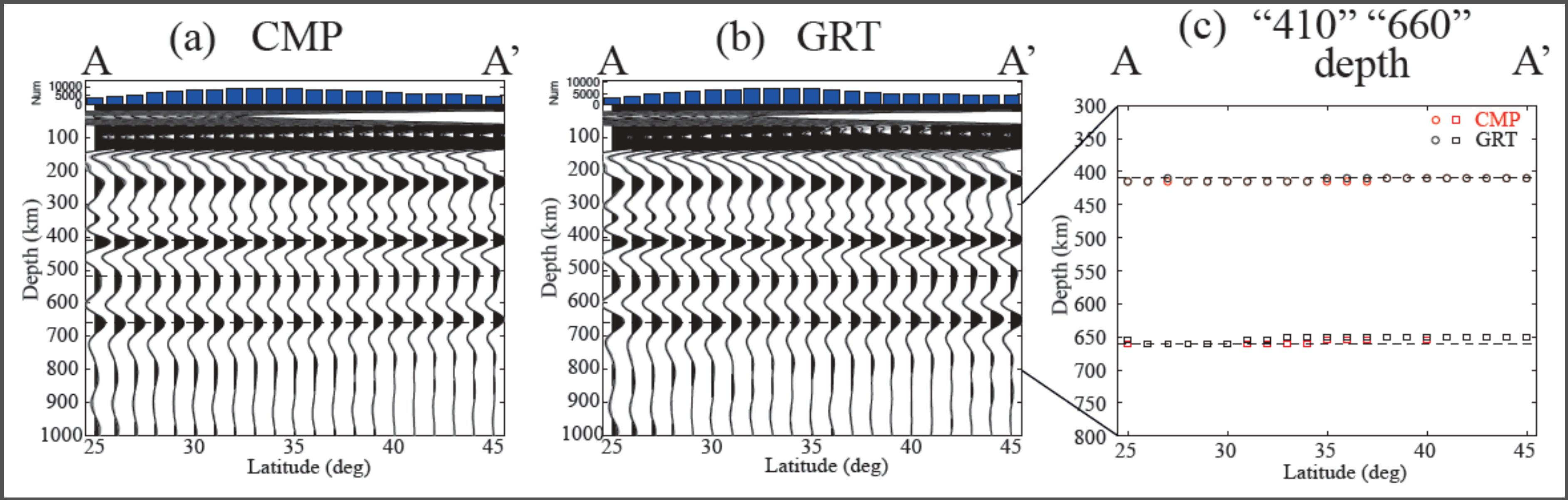


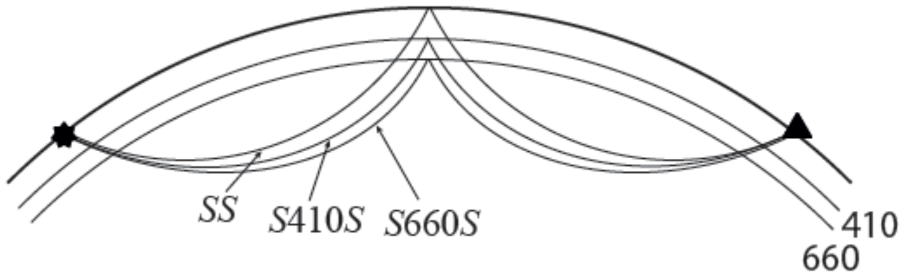


Cao et al. (PEPI, 2010)

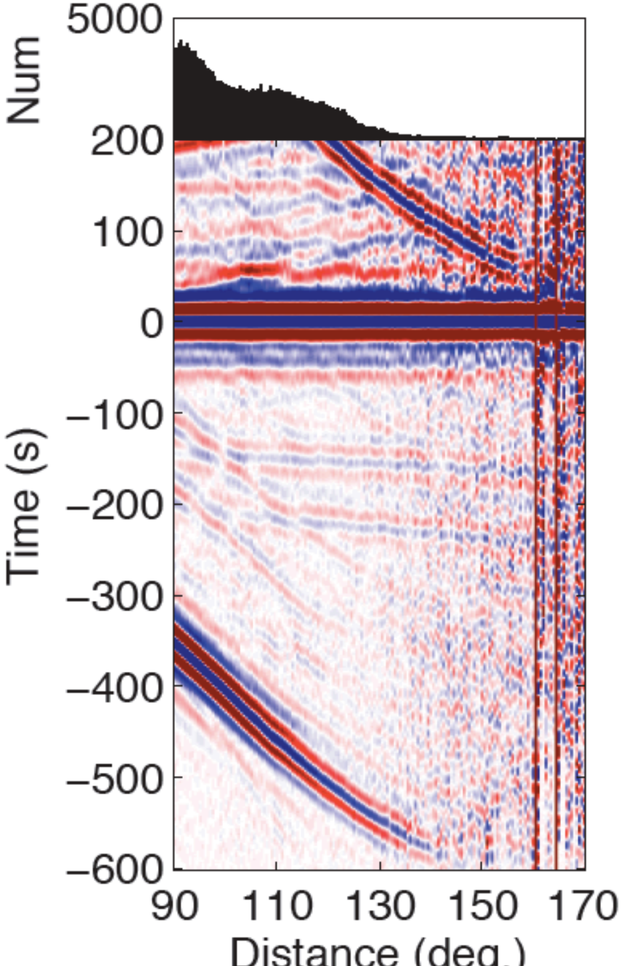
(data - IRIS-DMC)

Shang et al (in prep)

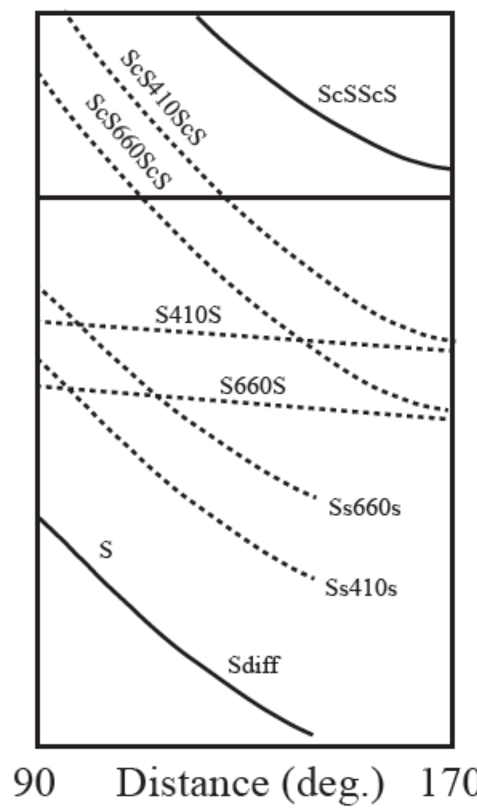




Waveform stacks

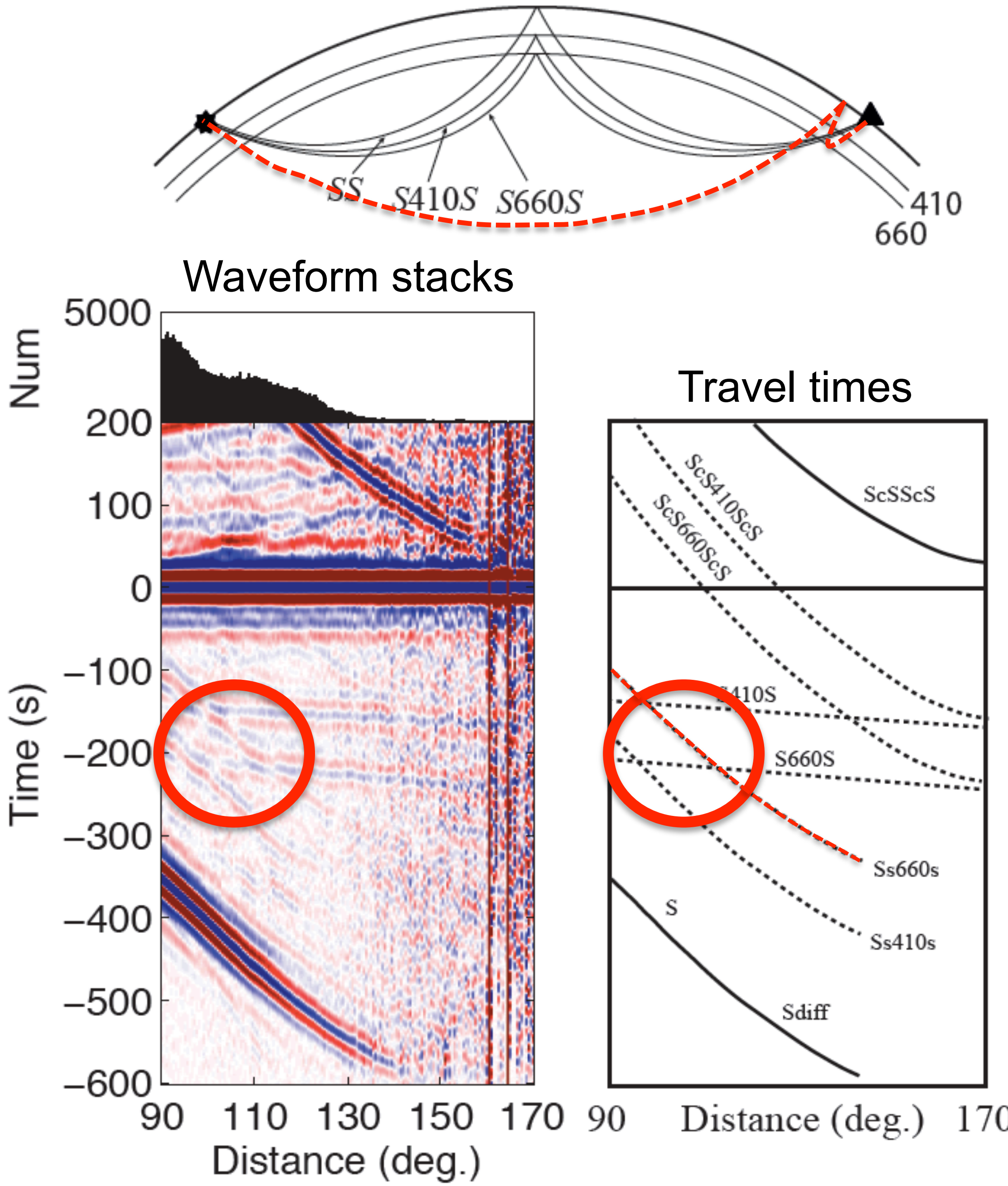


Travel times



What can go wrong?

Yu et al. (in prep)

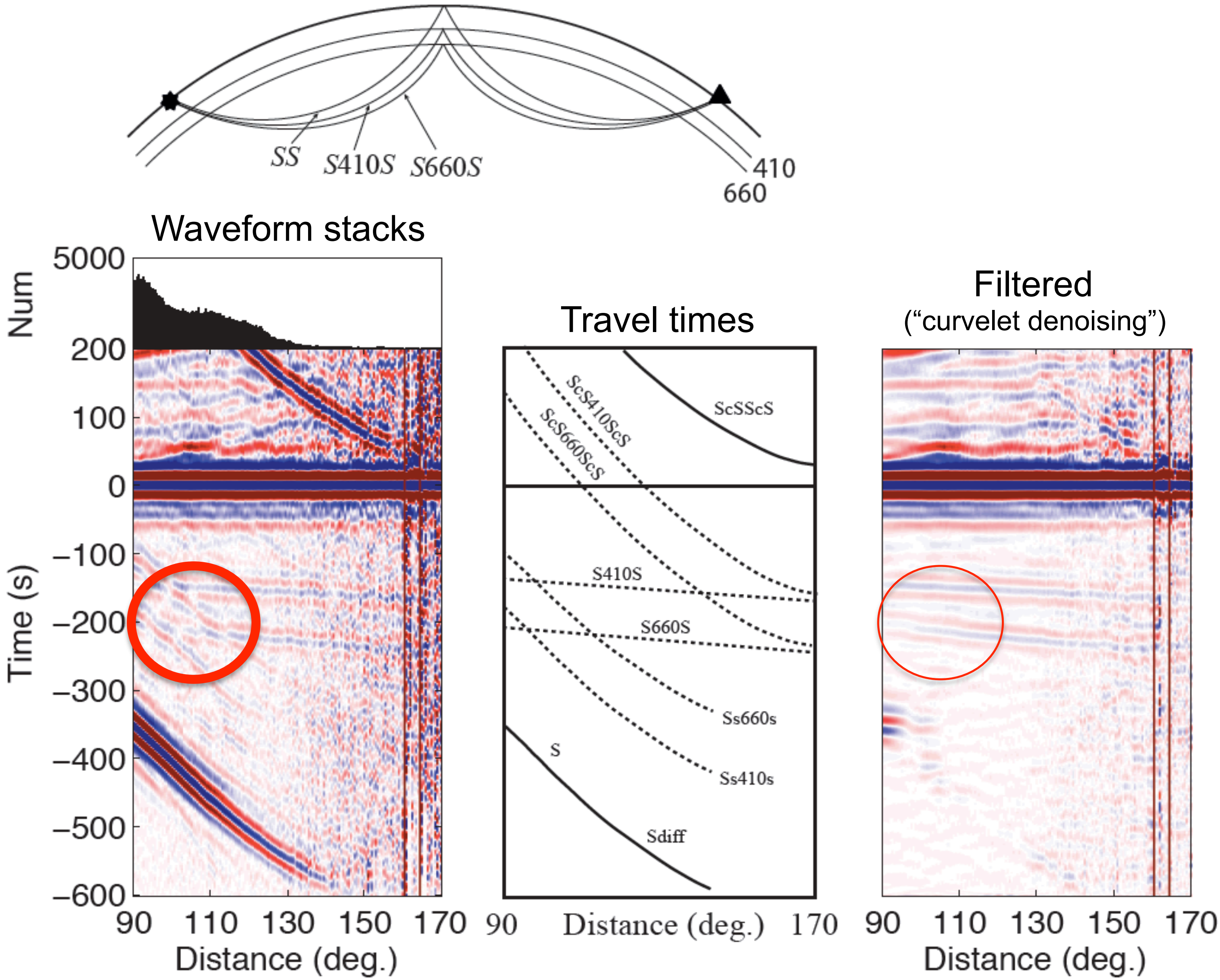


What can go wrong?

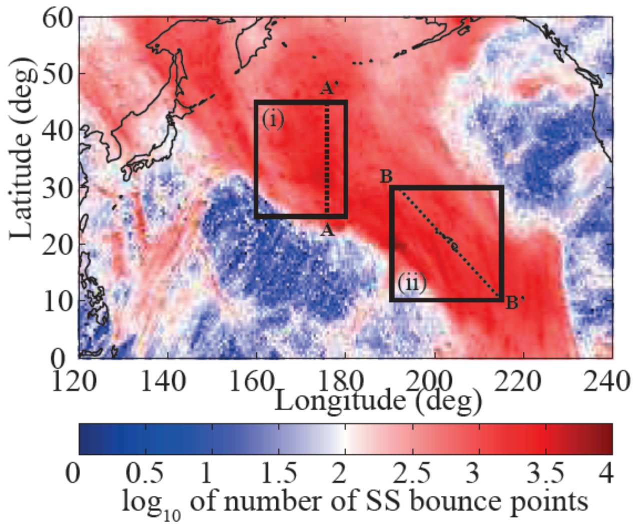
Interfering phases!

(e.g. multiples)

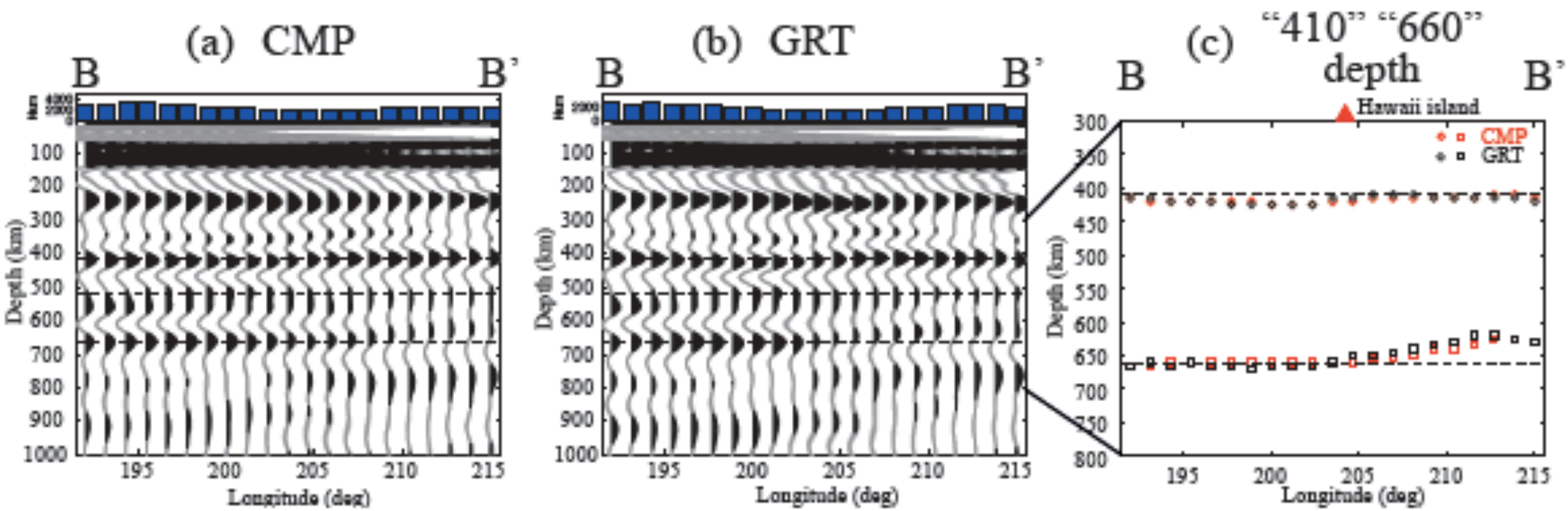
Yu et al. (in prep)



SS
S410S
S660S
410
660
Waveform stacks
Num
5000
200
Time (s)
100
0
−100
−200
−300
−400
−500
−600
90
110
130
150
170
Distance (deg.)
Travel times
ScS410ScS
ScS660ScS
ScSScS
S410S
S660S
Ss660s
Ss410s
S
Sdiff
Filtered
(“curvelet denoising”)

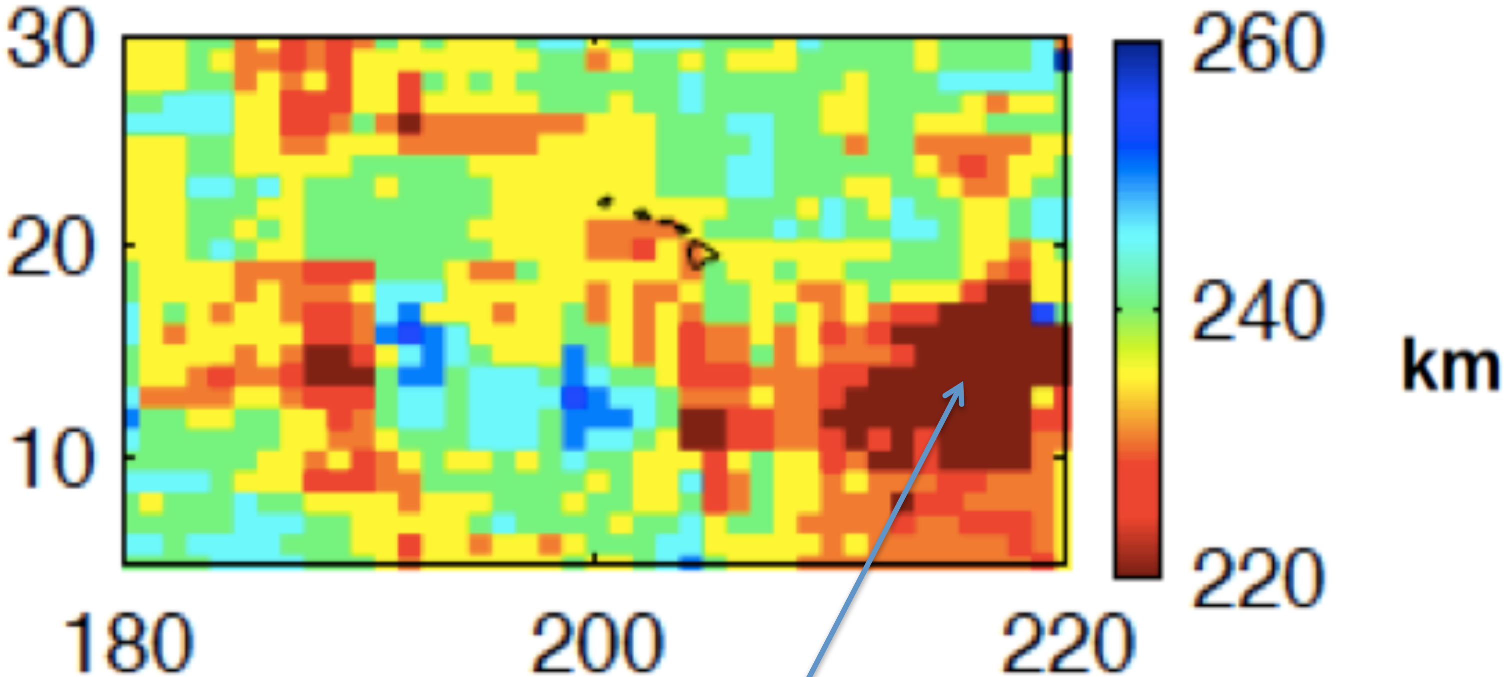


Latest results for Hawaii
(Chunquan Yu, MIT)

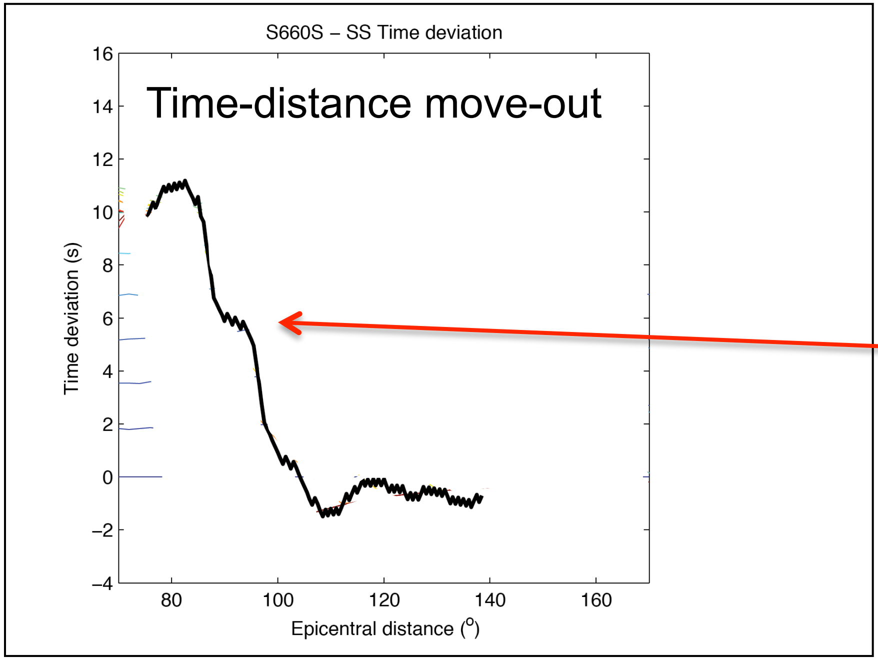


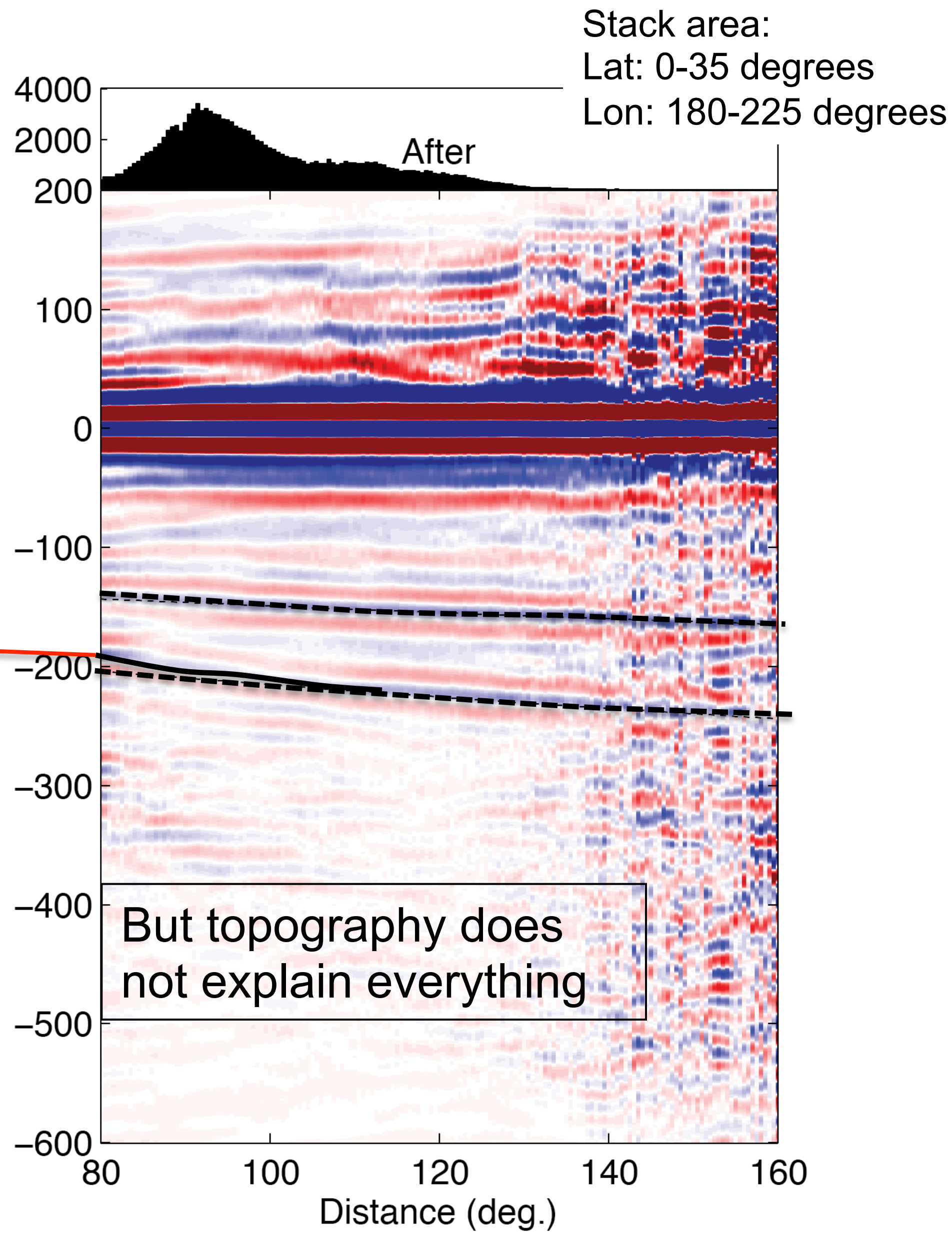
B-B': Hawaii – Central Pacific

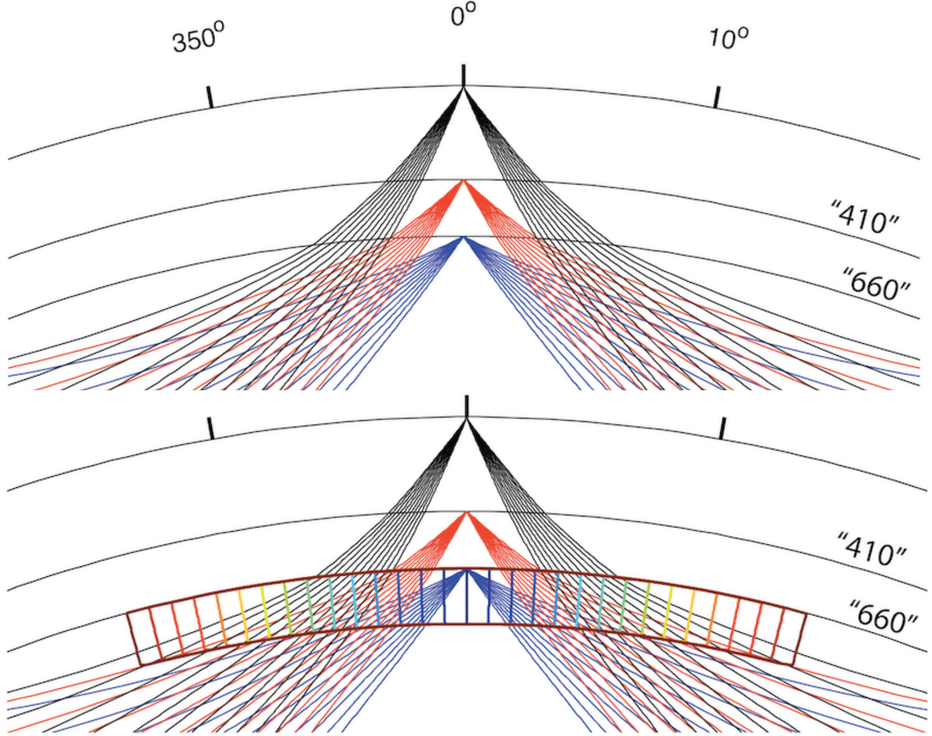
Preliminary result: Yu Chunquan (MIT)



Thin transition zone SE of Hawaii → high temperatures?

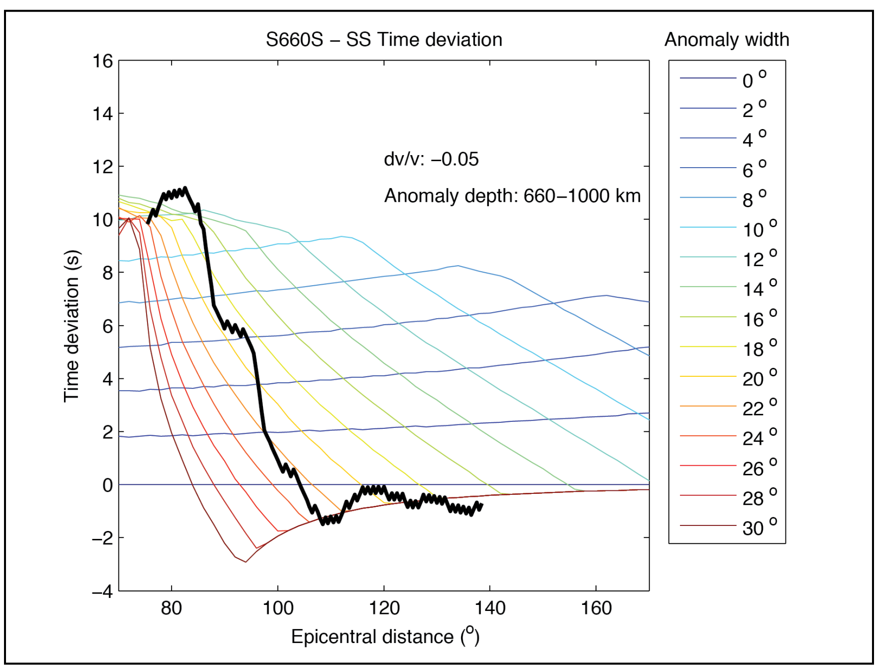

S660S – SS Time deviation
Time-distance move-out
Time deviation (s)
Epicentral distance (°)
16
14
12
10
8
6
4
2
0
−2
−4
80
100
120
140
160

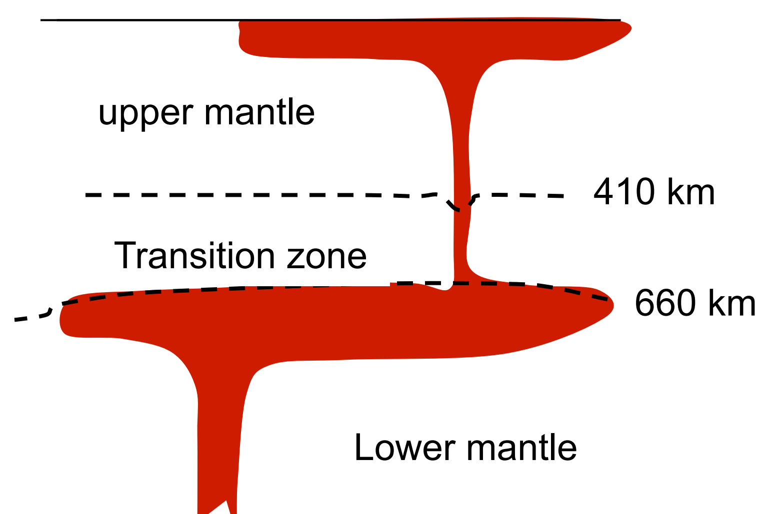

Stack area:
Lat: 0-35 degrees
Lon: 180-225 degrees
4000
2000
200
After
100
0
−100
−200
−300
−400
−500
−600
80
100
120
140
160
Distance (deg.)
But topography does
not explain everything



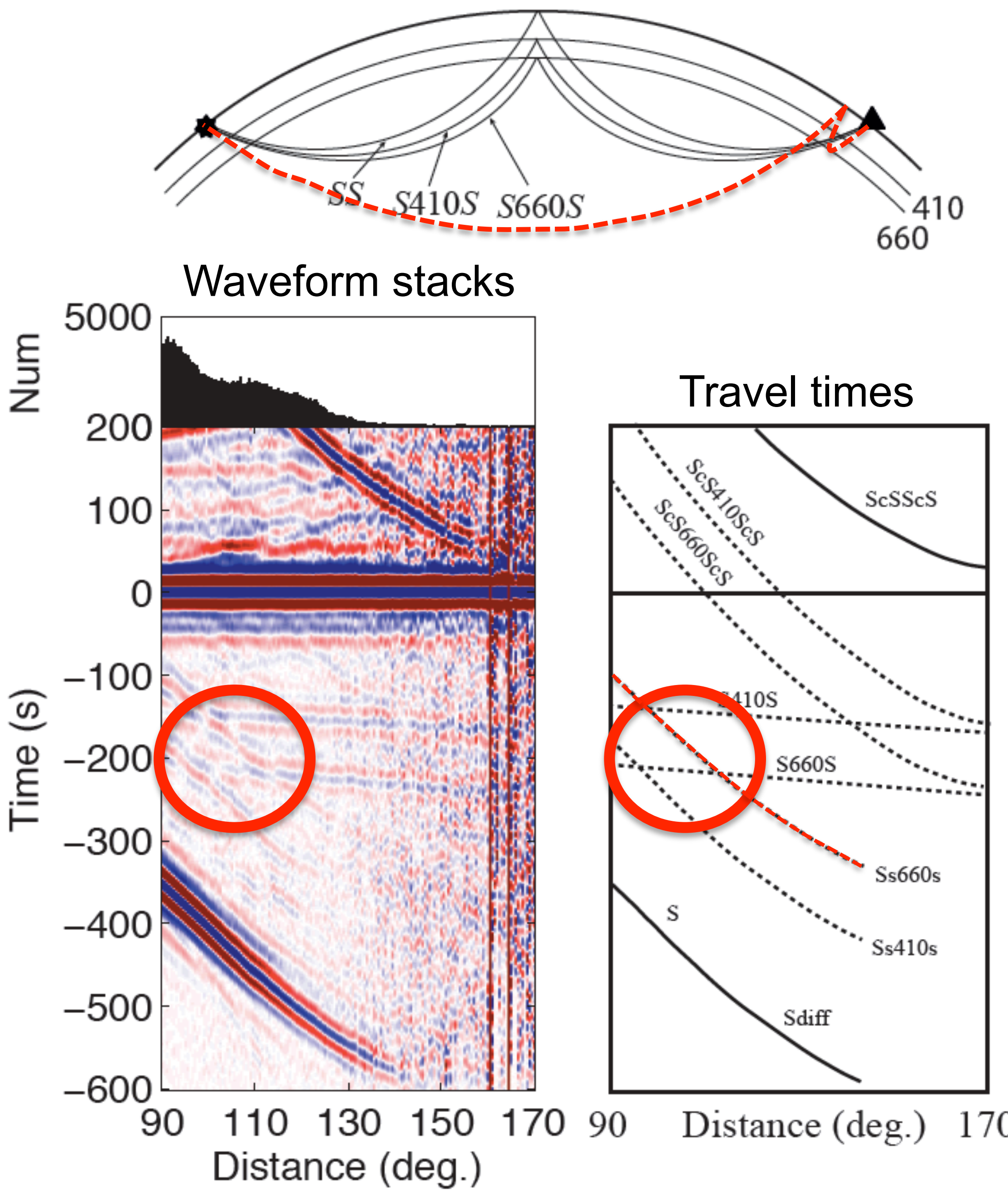
Move-out in exploration seismics?
→ Find the move-out velocity!

→ Low velocity zone below "660"
(of varying horizontal extent)





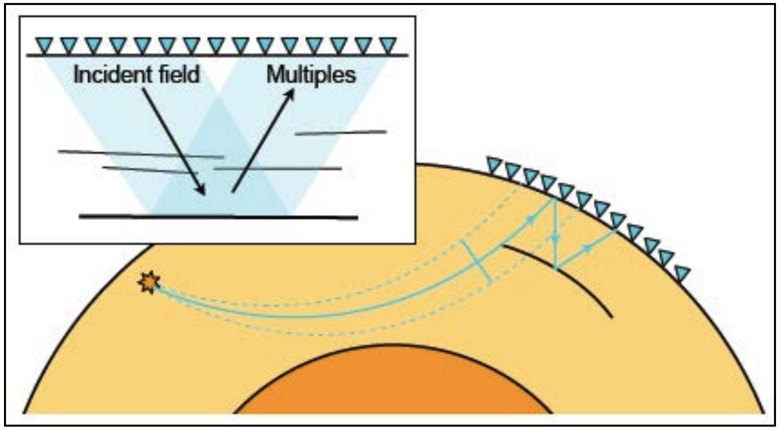
Complex upwelling beneath Hawaii?



Next step: use the multiples for imaging or velocity analysis (e.g. using the method for wave equation reflection tomography due to Burdick et al. (GJI, 2014)

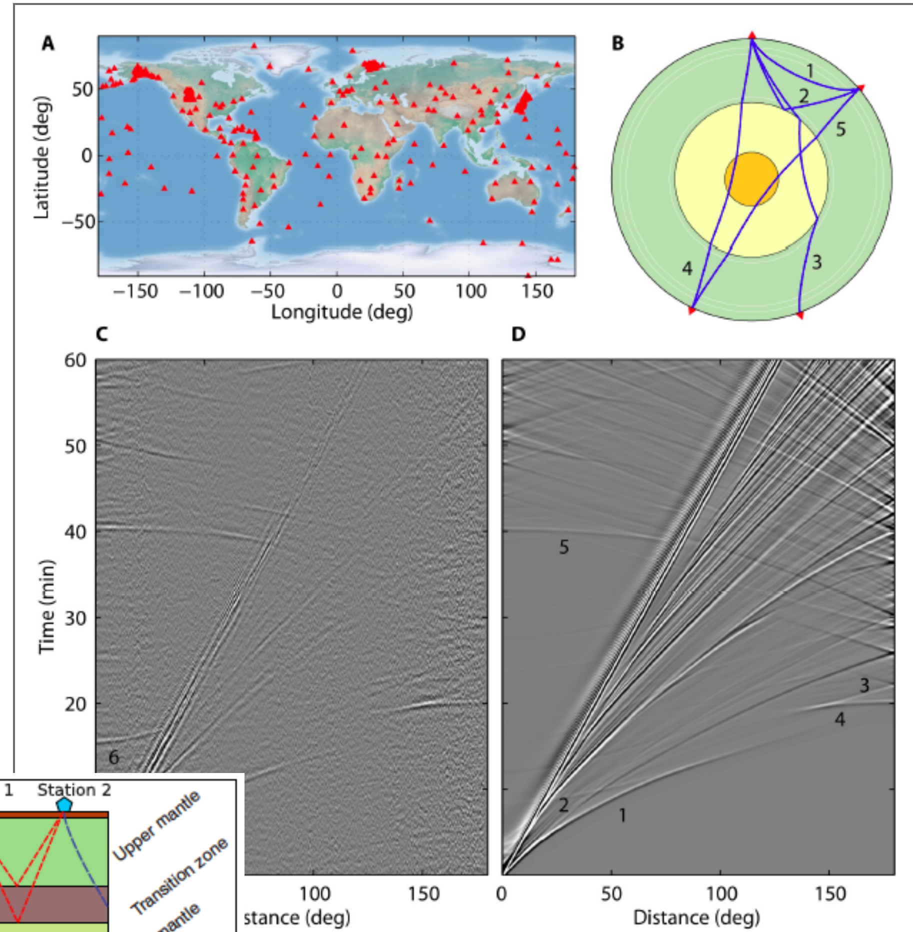
Yu et al. (in prep)

Cargese ~~2015 (or~~ 2017~~)~~?

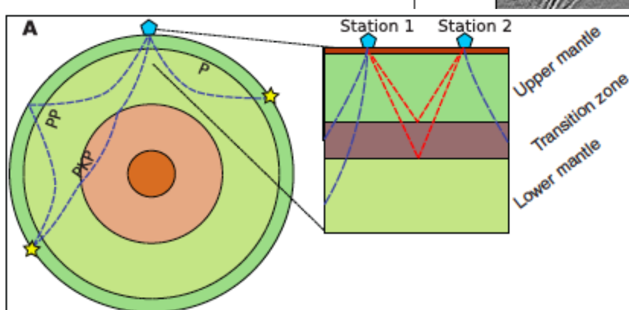


Burdick et al (GJI, submitted)

+



Poli et al (Science, 2012)



Boué et al. (2014)