(Cargèse,7 June 2017)

"Imaging Earth's crust and mantle with scattered seismic waves"

R. van der Hilst[1]
with M. de Hoop[2], M. Campillo[1,3], X.-F. Shang[1,4], C. Yu[1,5], L. Day[1,6]

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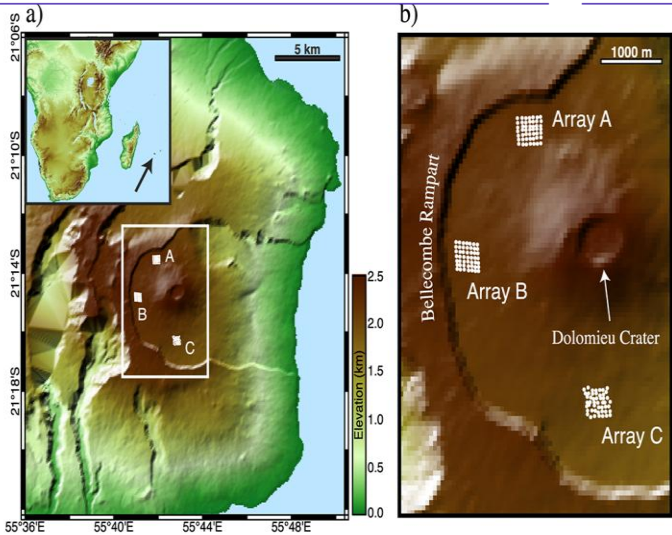
[6] Now at: Imperial College, London

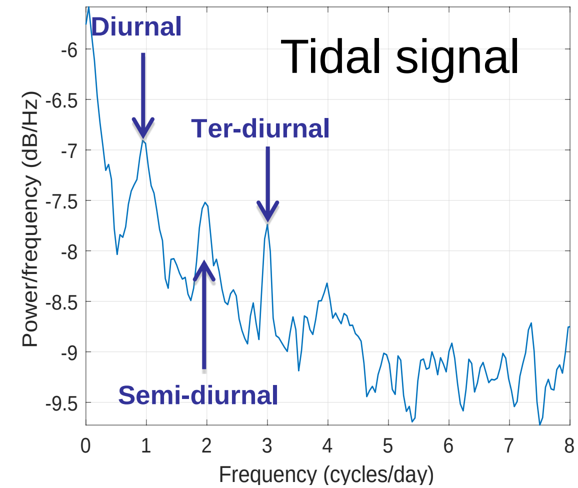
Research sponsored by

Noise-Based Measurements of Tidal- and Thermal-Induced Seismic Wave Speed Changes

Shujuan Mao[1], Michel Campillo[1, 2], Robert van der Hilst[1], Florent Brenguier[2], Gregor Hillers[2], Laurent Stehly[2] (1) Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences; (2) University Grenoble Alpes, ISTerre Institute of Earth Sciences

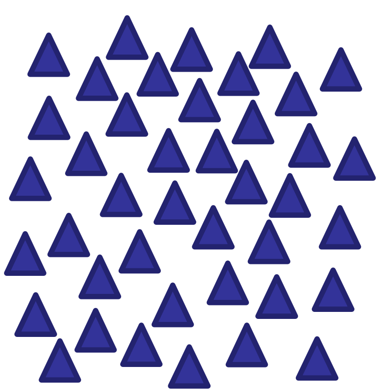


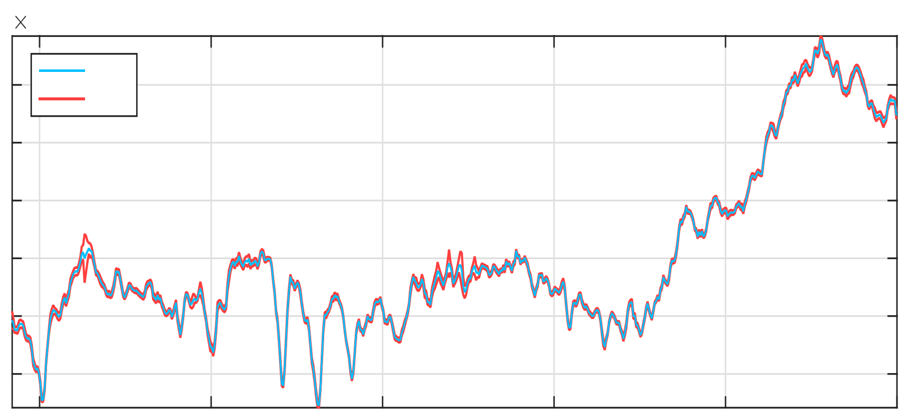
Poster by Shujuan Mao later this week



Large Dense Array

dv/v





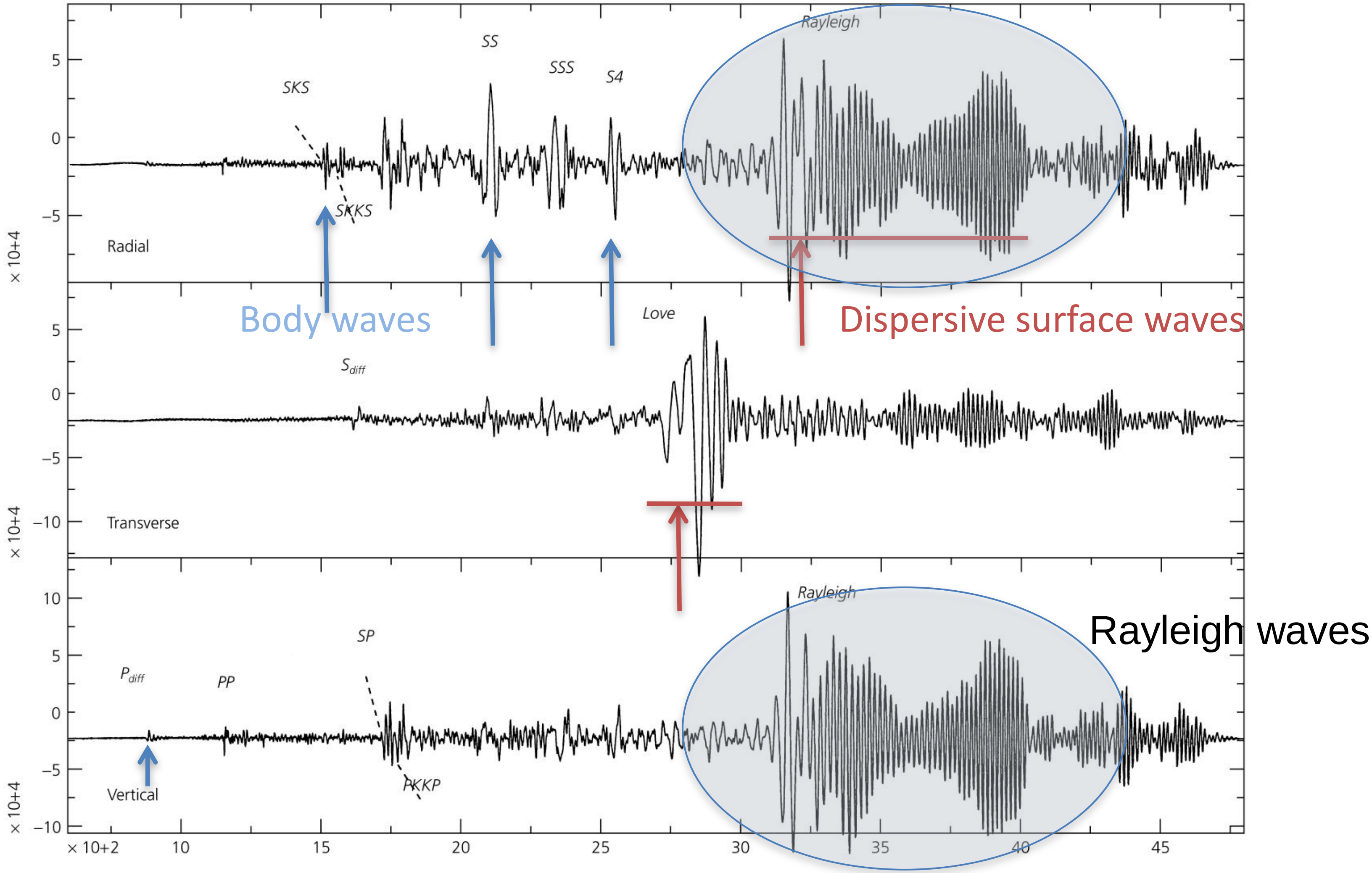
Overview of lecture:

1. **Introduction/background**

2. **Ambient noise and surface wave tomography (MIT, 2005-2015)**
   - combining ambient noise and earthquake data
   - ~~quantifying and correcting for uneven noise distribution~~
   - ~~azimuthal anisotropy~~
   - radial anisotropy
   - adjoint tomography with ambient noise data
   - joint inversion dispersion data and receiver functions

3. **Imaging of interfaces**

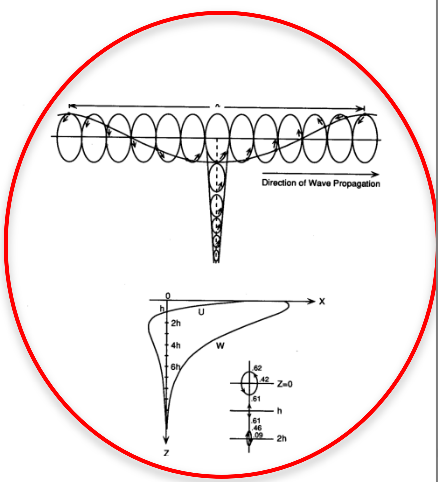
Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.

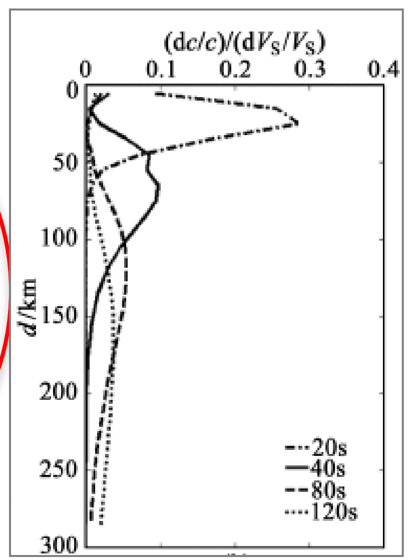


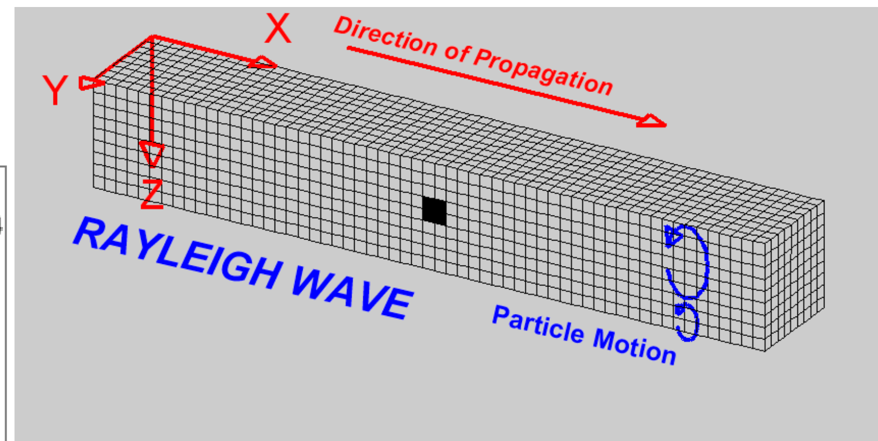
From Stein and Wysession

‘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, ….)

Rayleigh wave at the surface of an half-space:







frequency proxy for depth

Courtesy: Campillo (Cargese, 2011)

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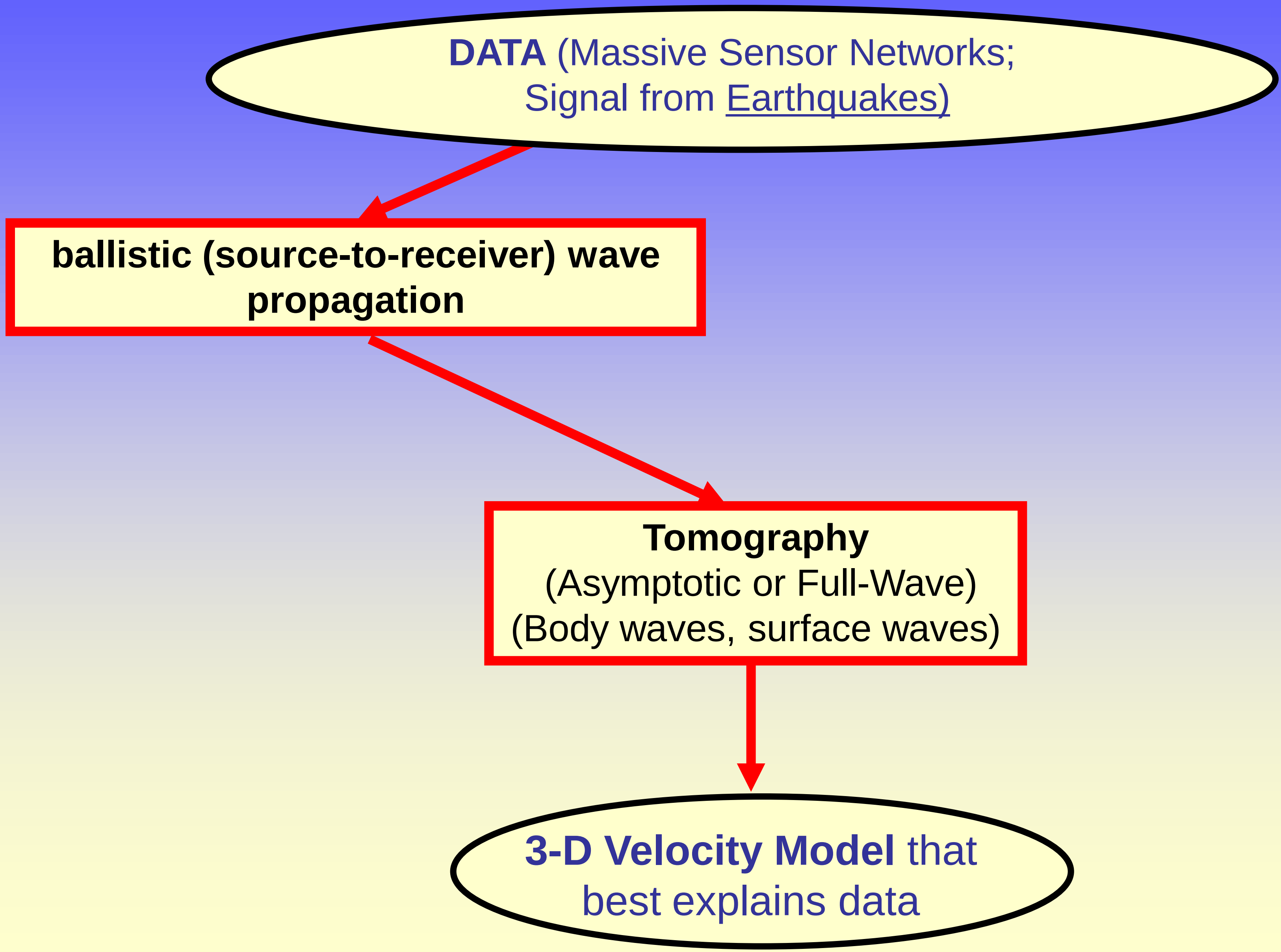
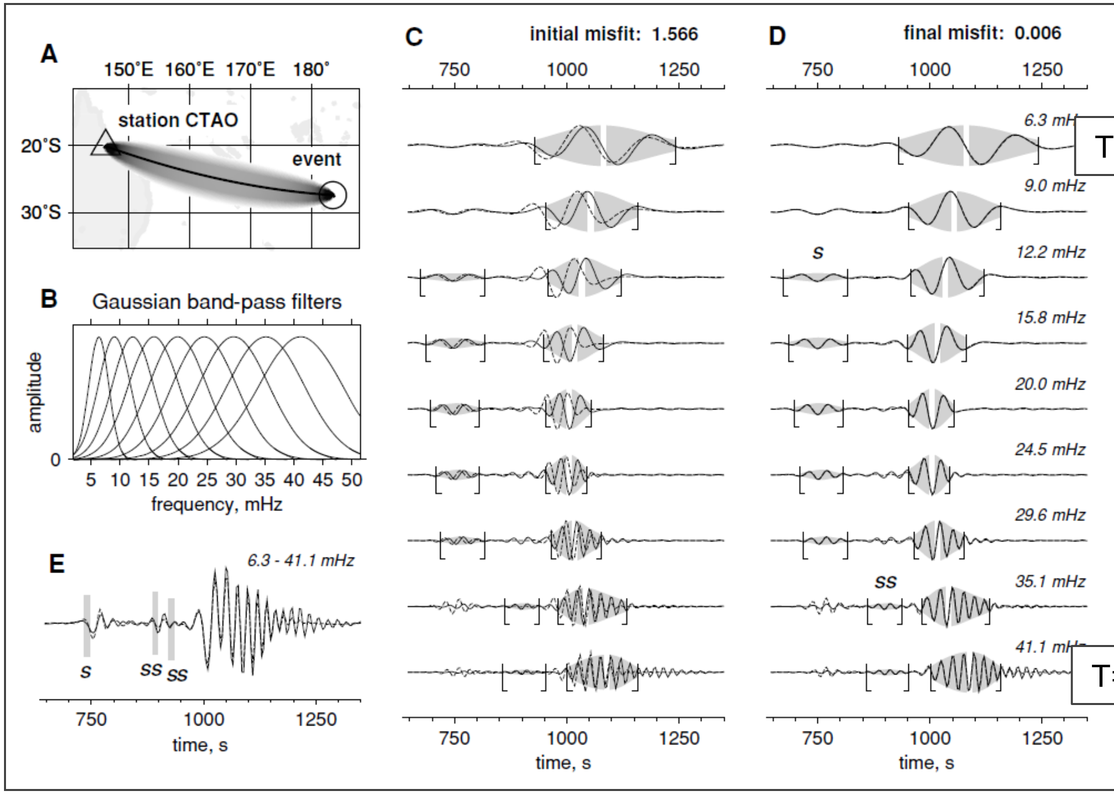
Traditional Approach to Tomography

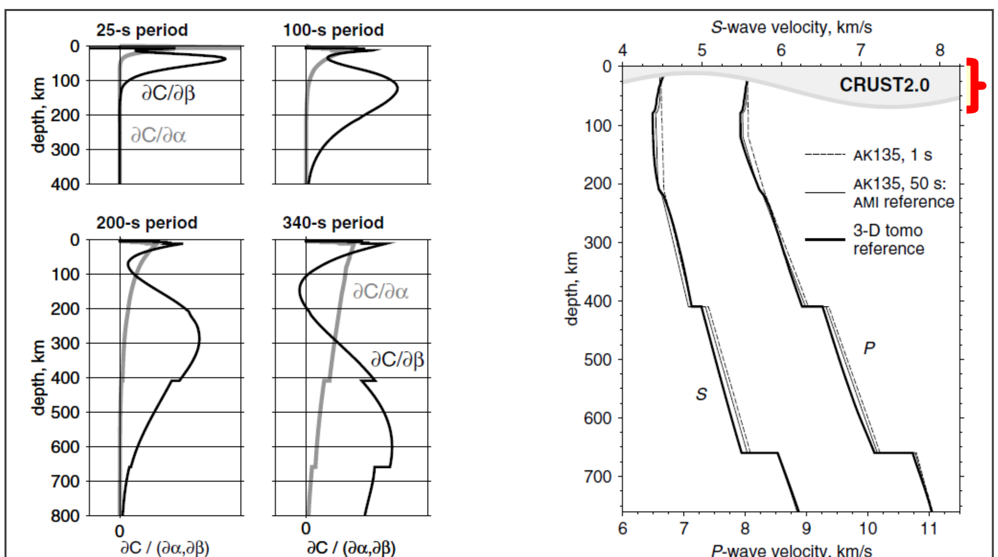


Lebedev and Van der Hilst (*GJI*, 2008)



T=160 s

T=25 s

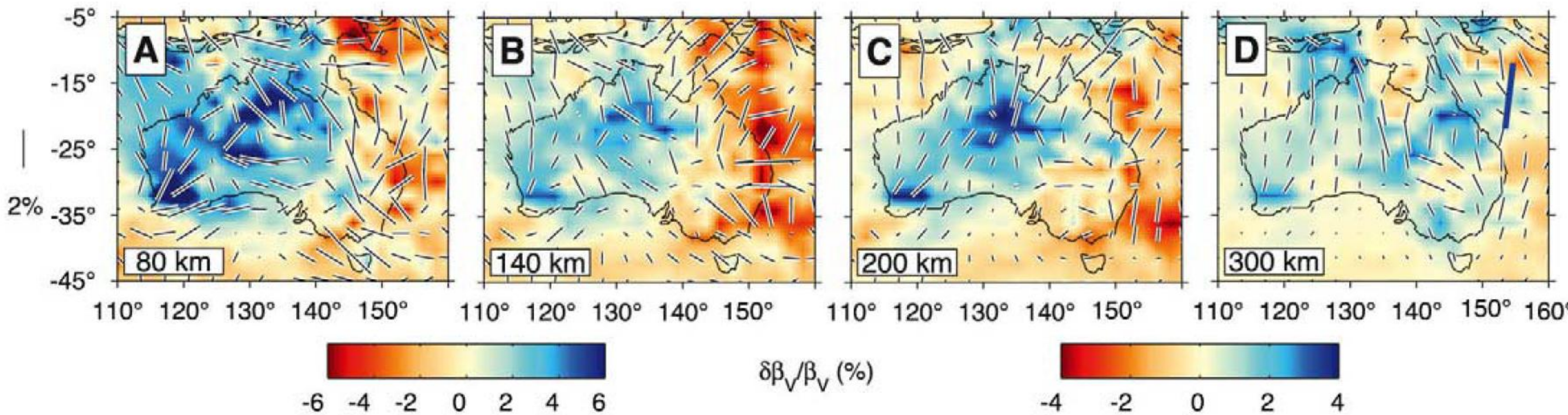


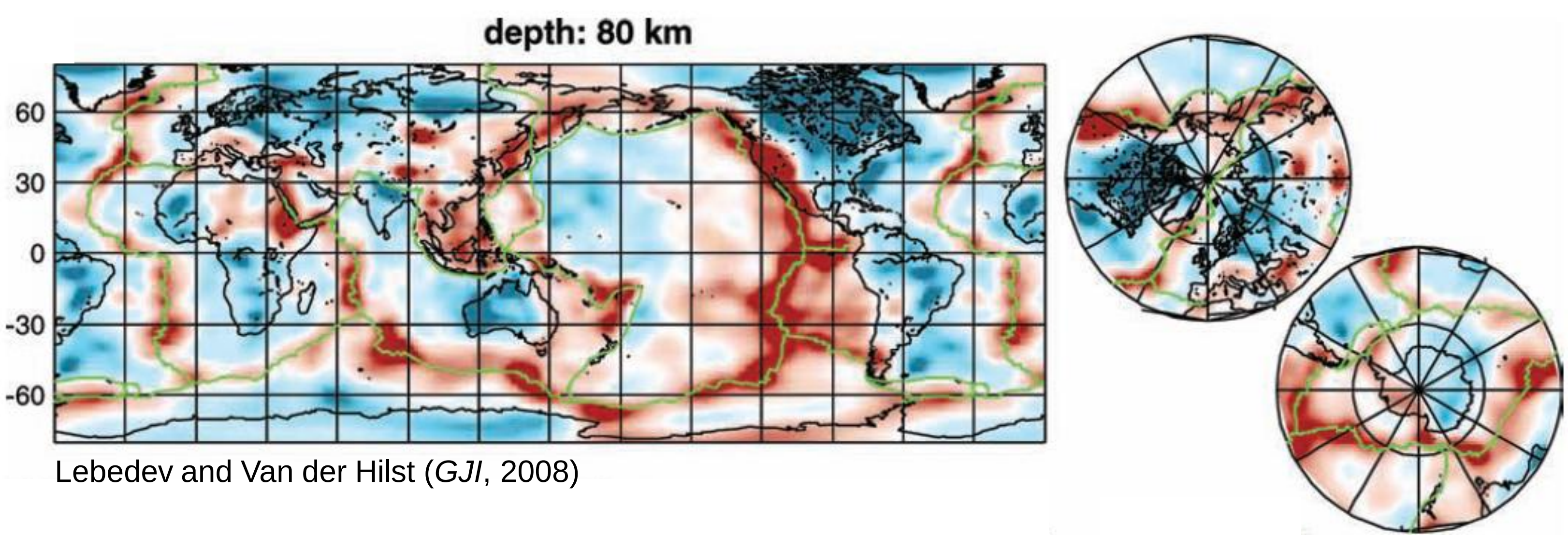
Crust = Problem!

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*, 2003)





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

Ambient Noise Tomography

DATA (Massive Sensor Networks; background noise)

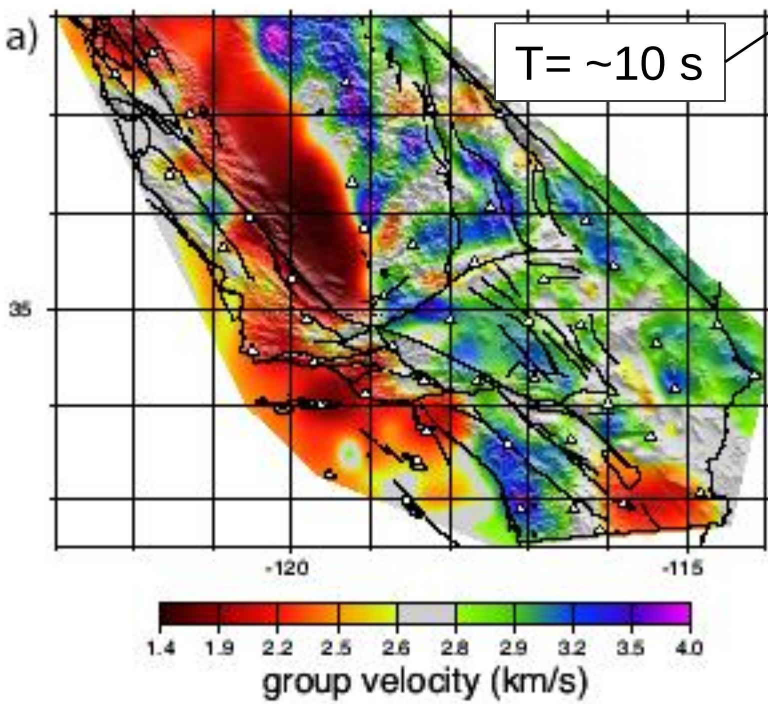
Alternative:
"sourceless" imaging/tomography

create data by means of interferometry/cross-correlation

Tomography
(Asymptotic or Full-Wave)
(Body waves, surface waves)

3-D Velocity Model that best explains data

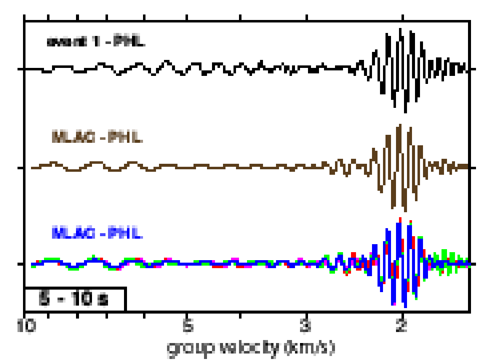
Shapiro, N.M., M. Campillo, L. Stehly, and M.H. Ritzwoller, 2005, High-Resolution Surface-Wave Tomography from Ambient Seismic Noise: Science **307**:1615-1618



T < 30 s → Crust

A map of Surface-wave Velocity in California

Obtained from correlating seismic noise



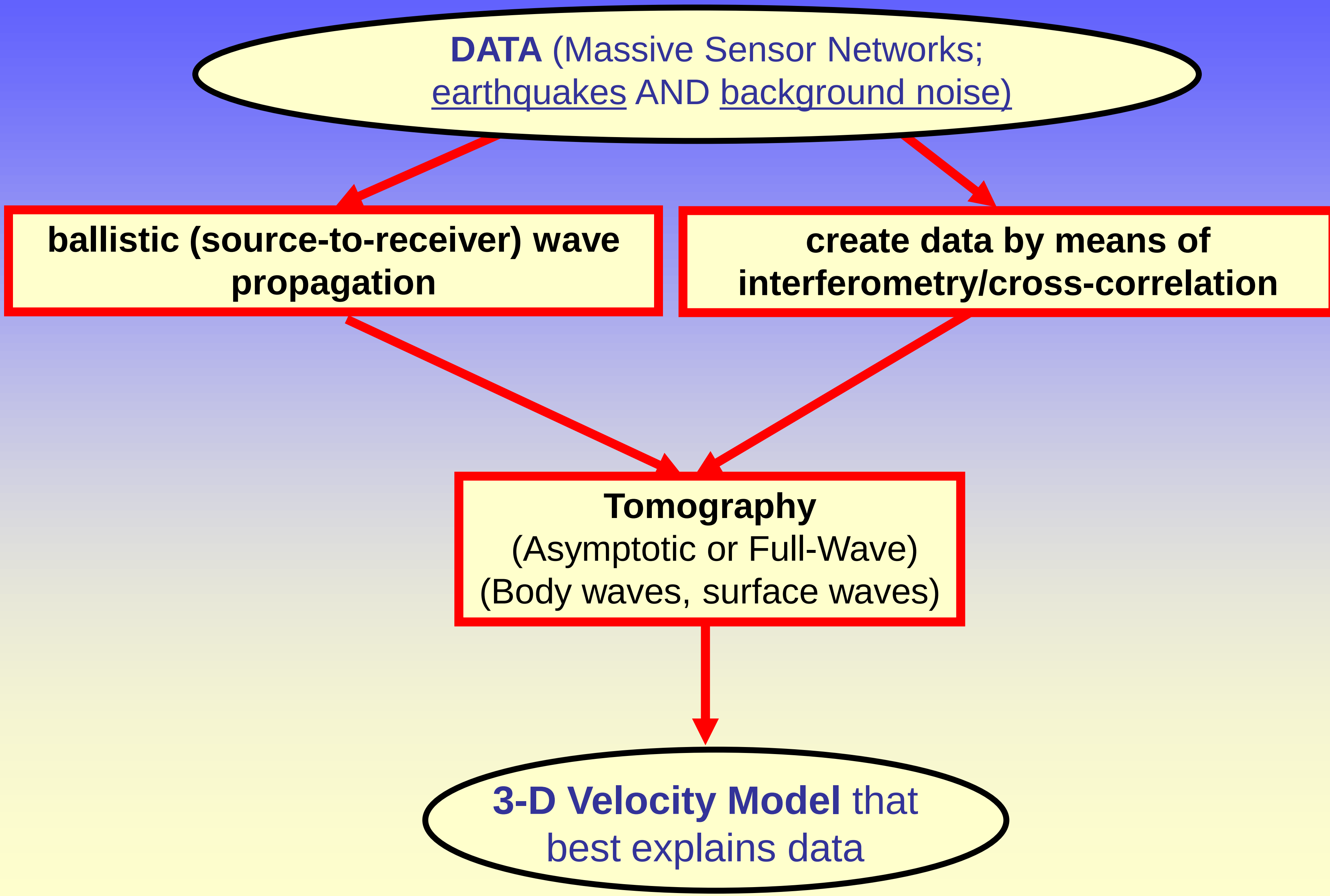
earthquake

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)

Use both ‘active’ and ‘passive’ data

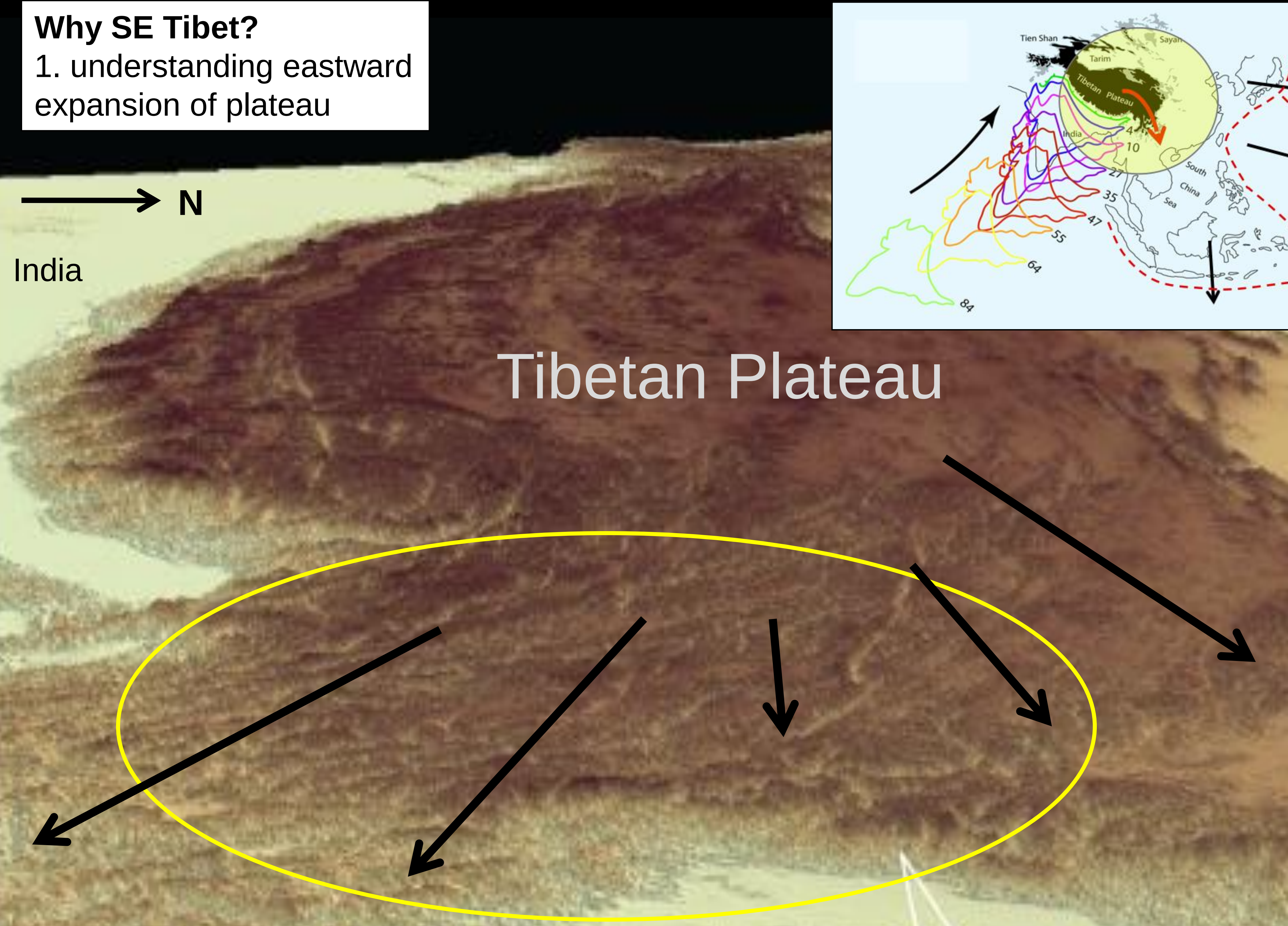


Field Projects Sichuan & Yunnan Provinces and E. Tibet (2003-2004)

Crust-Mantle study E Tibet – SW China

Why SE Tibet?

1. understanding eastward expansion of plateau



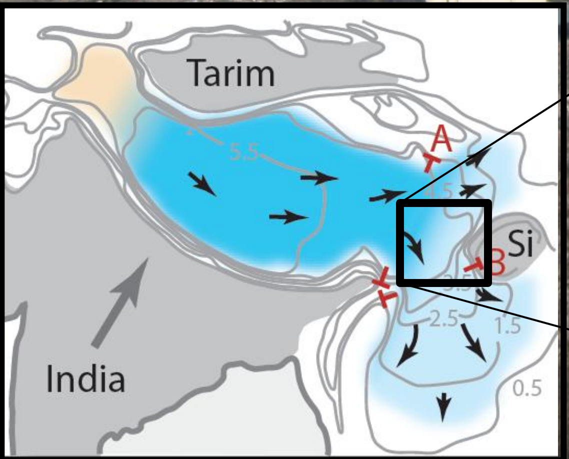
Why SE Tibet?

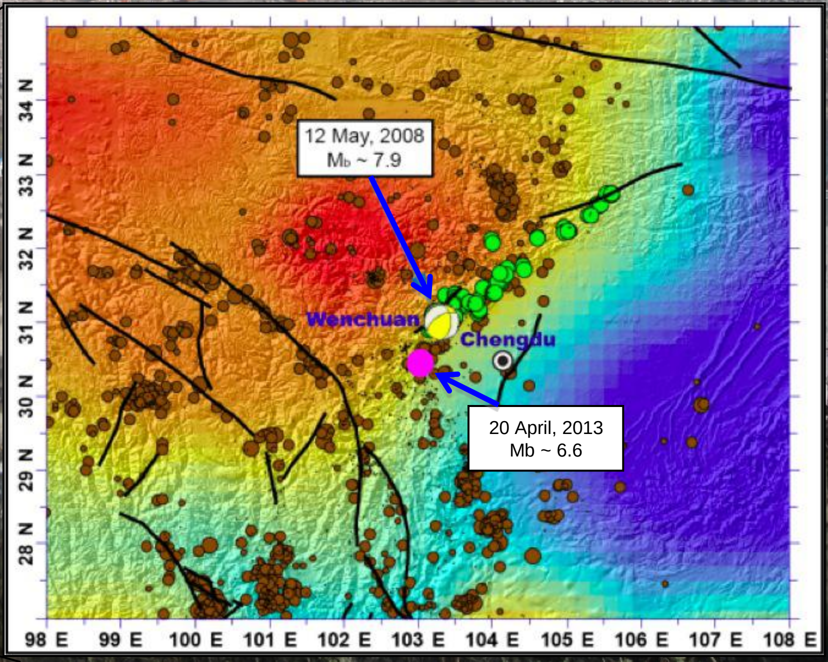
2. Southern end of Trans China Seismicity Belt

(Yingxiu, January 2009)

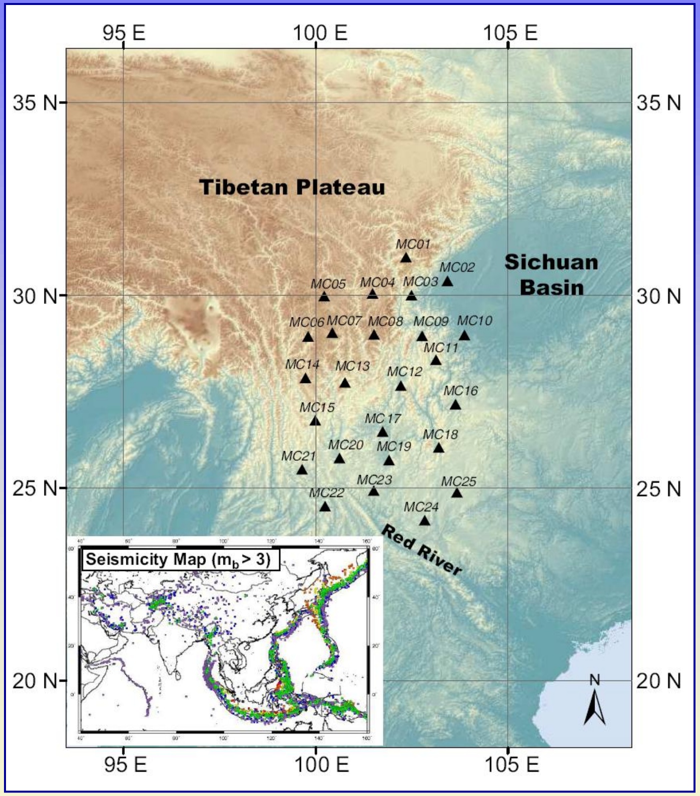
E.g. Sichuan, 12 May 2008

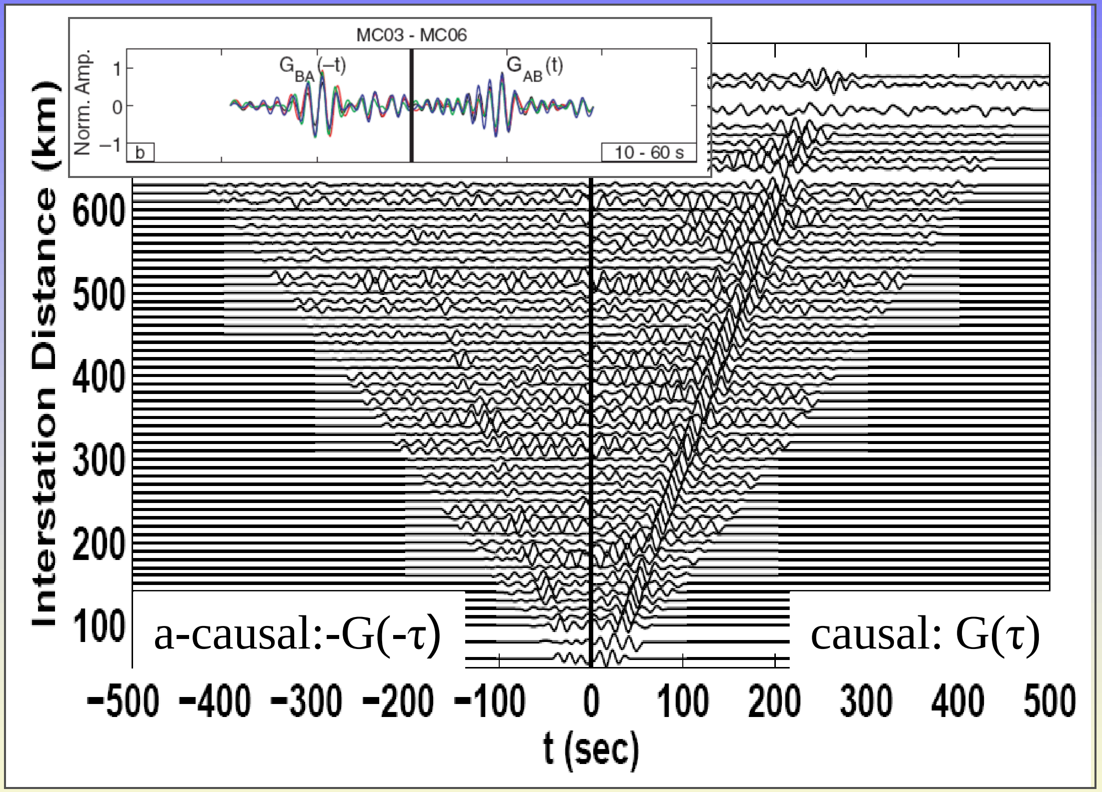
~80,000 people killed …





Crust and Lithosphere:
Multi-resolution surface wave tomography

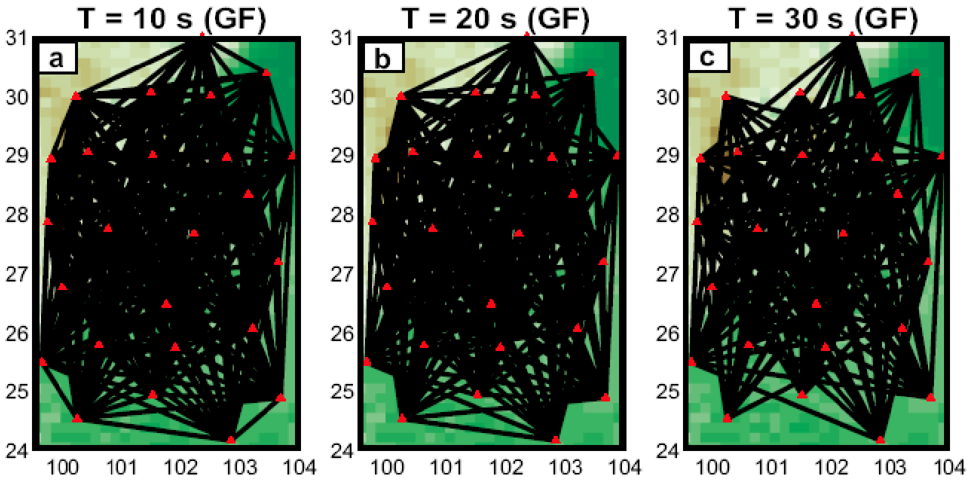




Seismic interferometry → estimate data from background "noise"
(NB we ignore asymmetry and sum causal and a-causal signals)

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

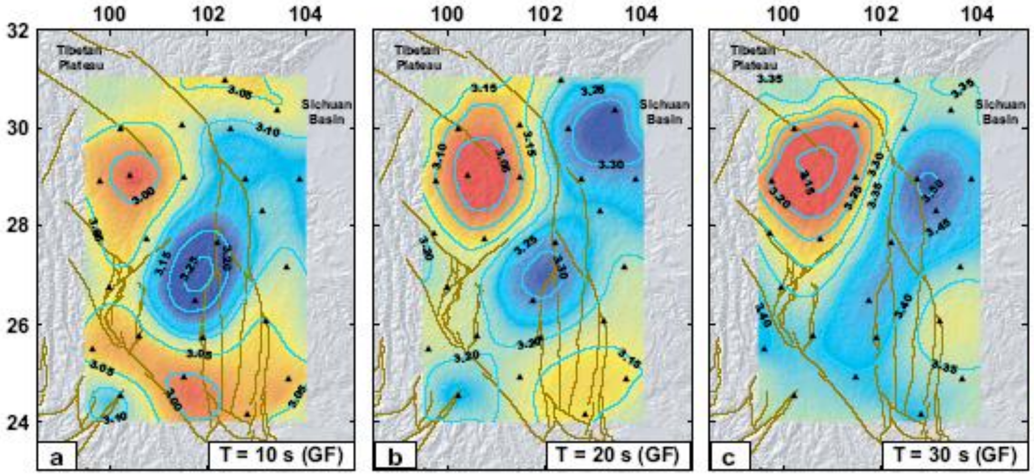
Example: "ambient noise" surface wave tomography



"source"-receiver pairs at different periods

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

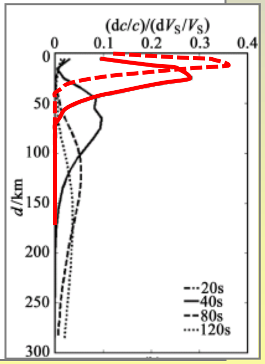
Example: “ambient noise” surface wave tomography



Phase velocity maps at different periods

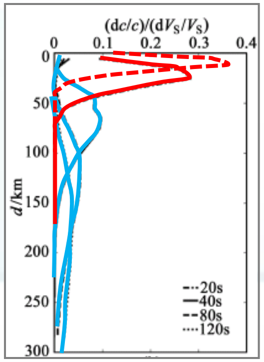
Interferometry (scattering) → relatively short periods (high frequency)

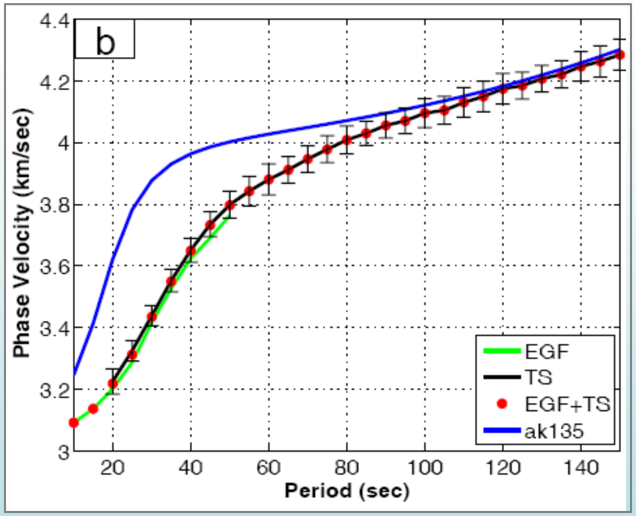
For surface wave tomography that means: “shallow” sub-surface

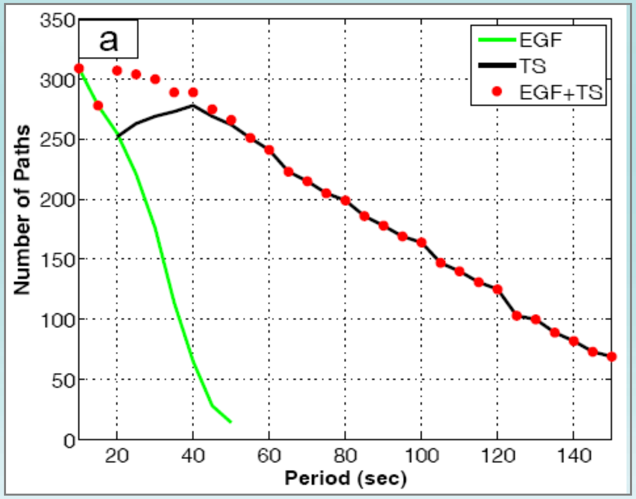


Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

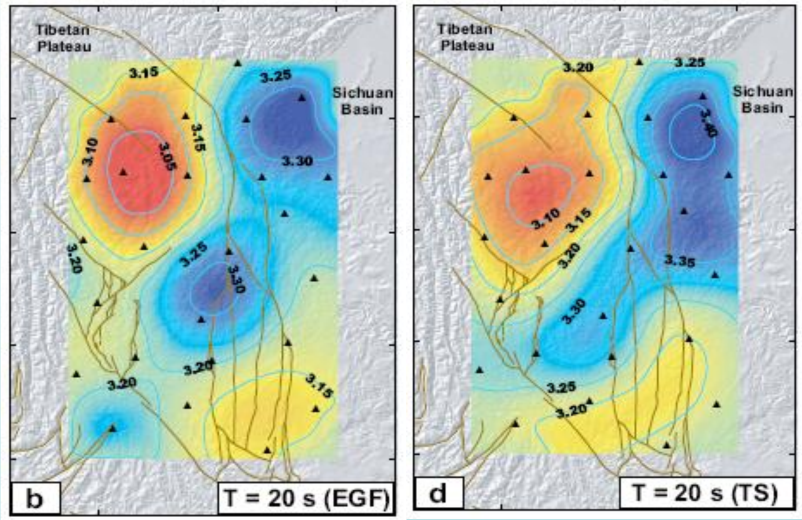
Combination of ambient noise and earthquake data:
extend frequency range → extend depth range







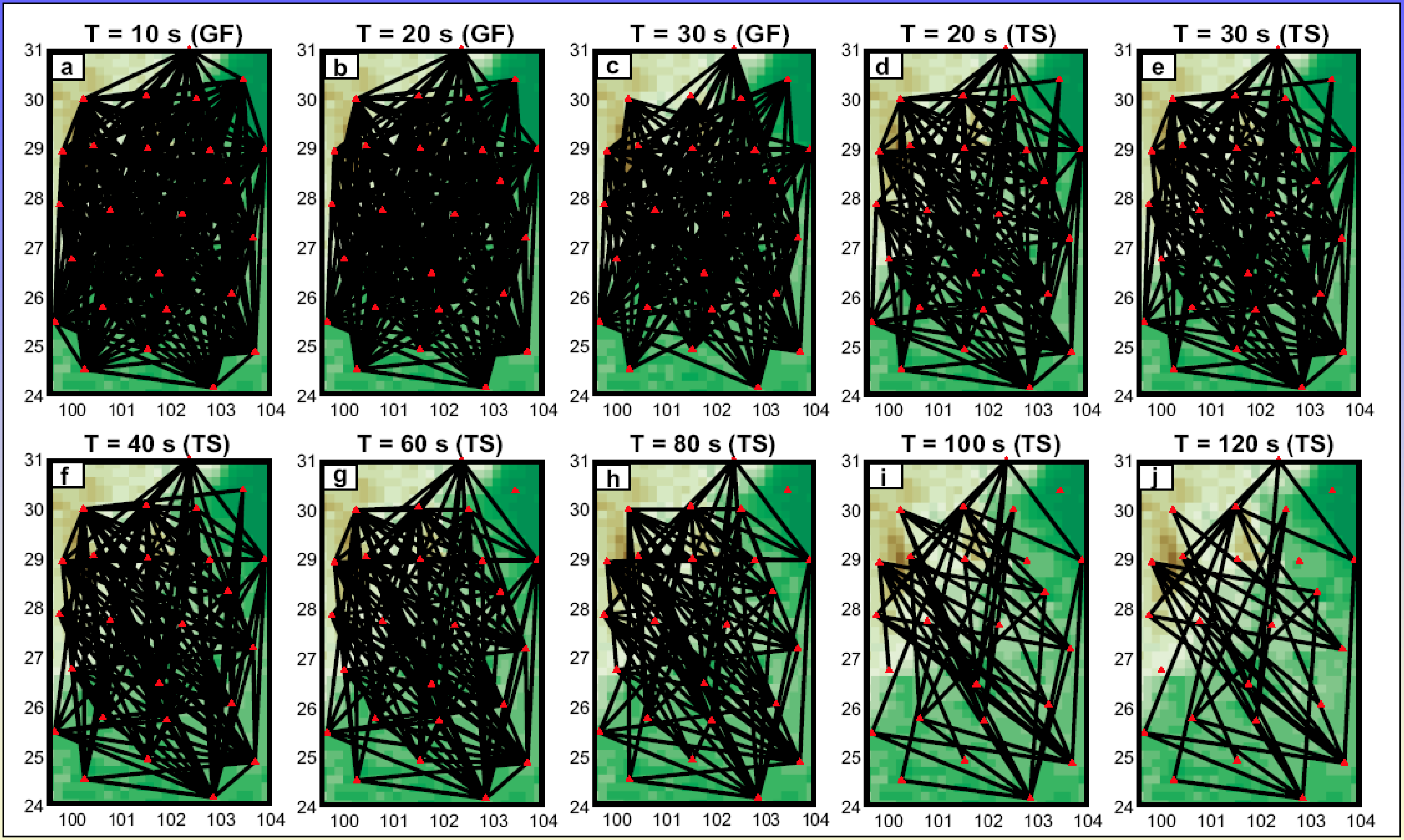
At overlapping periods, Rayleigh wave phase velocities from EGF (from 10 months Z-comp. data) and TS analyses are similar



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

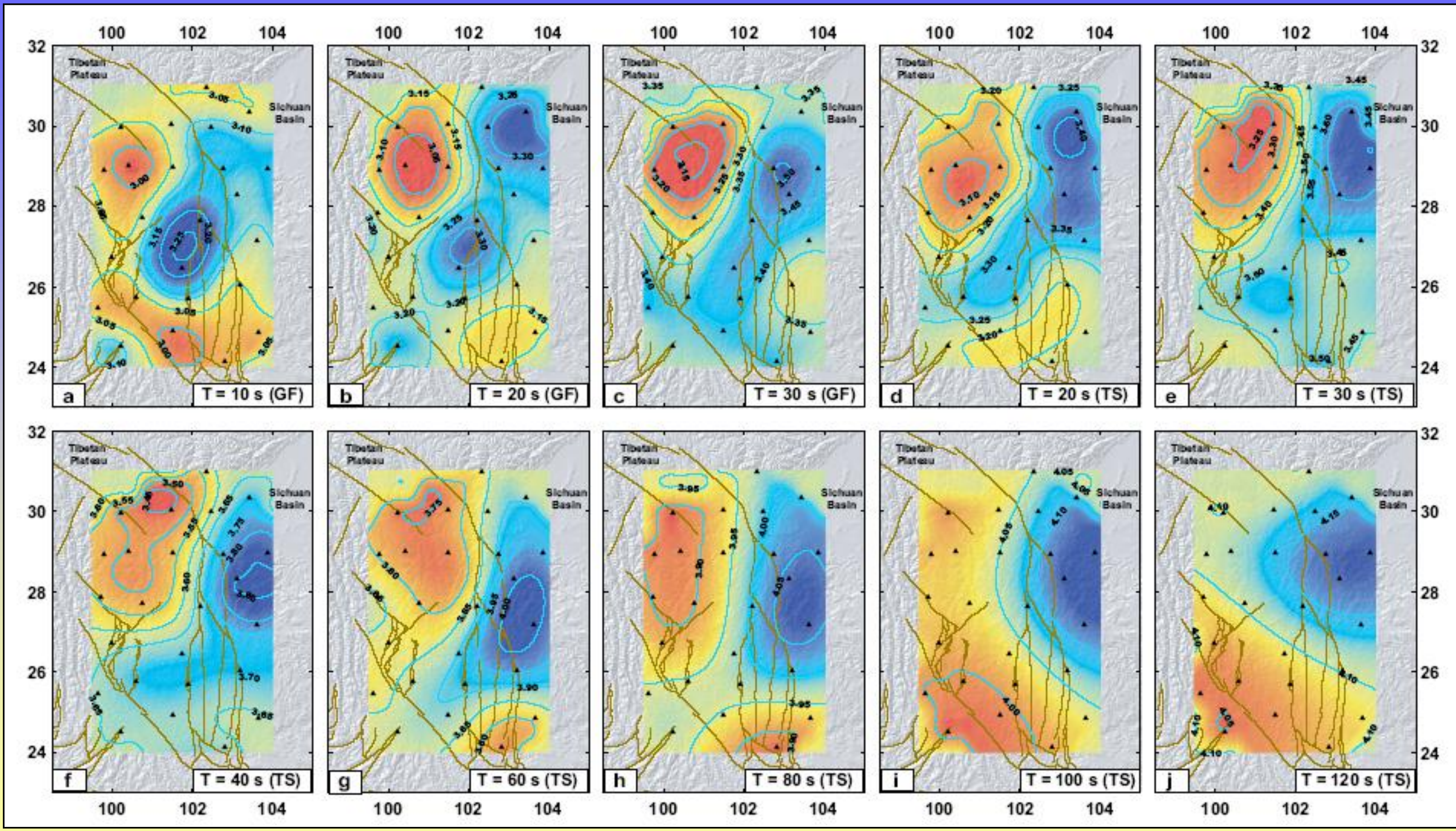
Yao, Van der Hilst, and De Hoop (*GJI*, 2006)

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)

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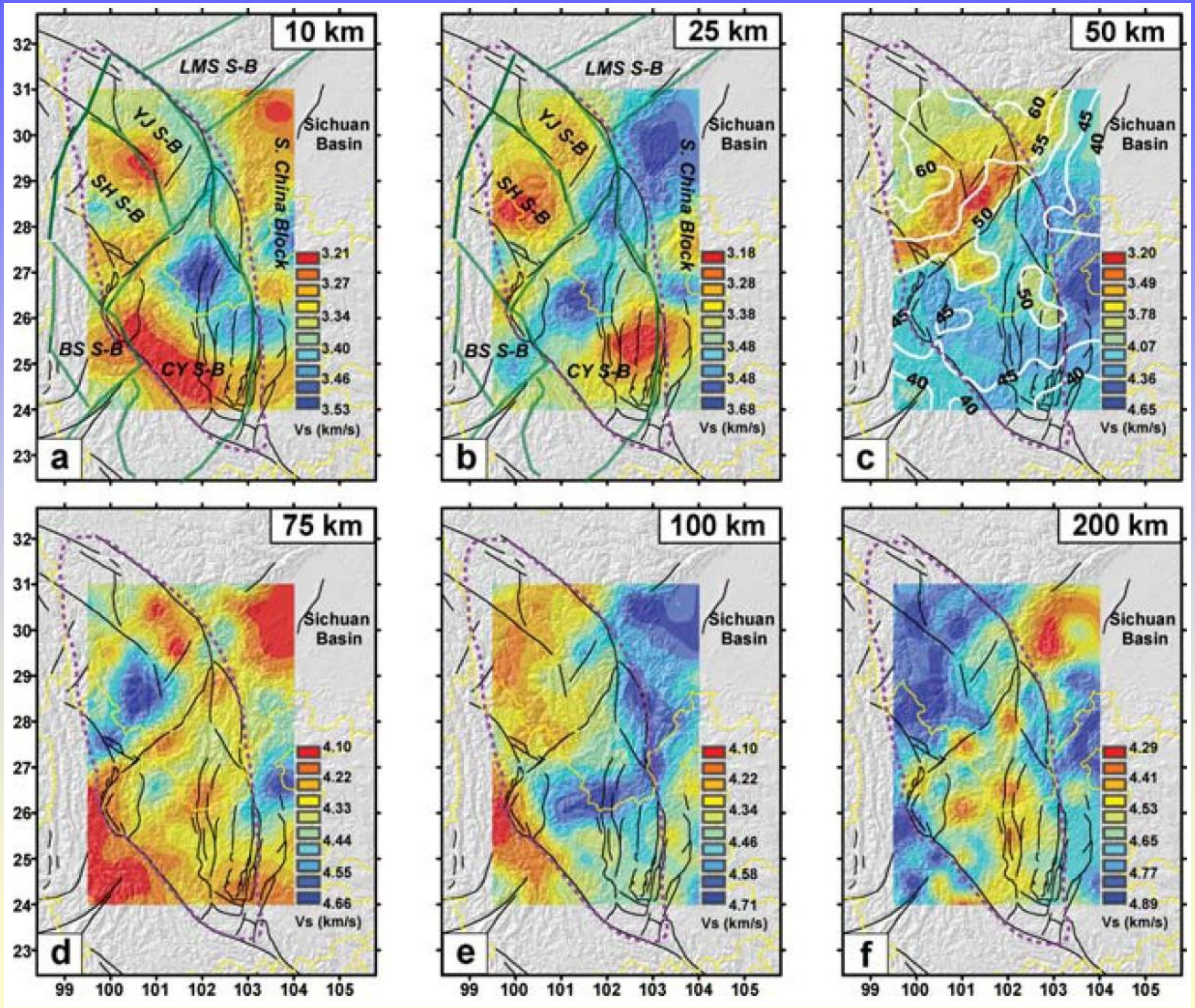

Yao, Beghein, and Van der Hilst (*GJI*, 2006)

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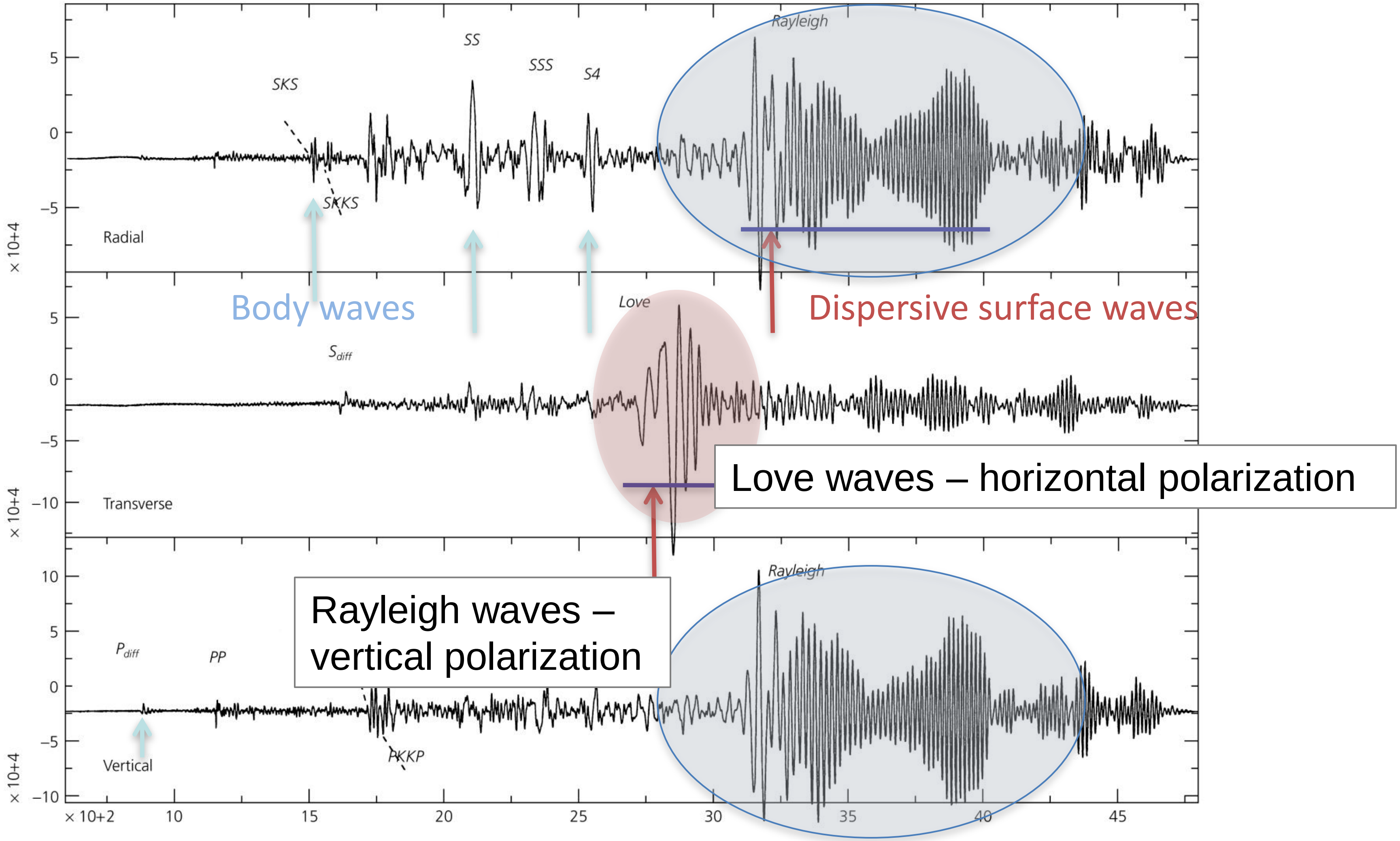
3. **Imaging of interfaces**

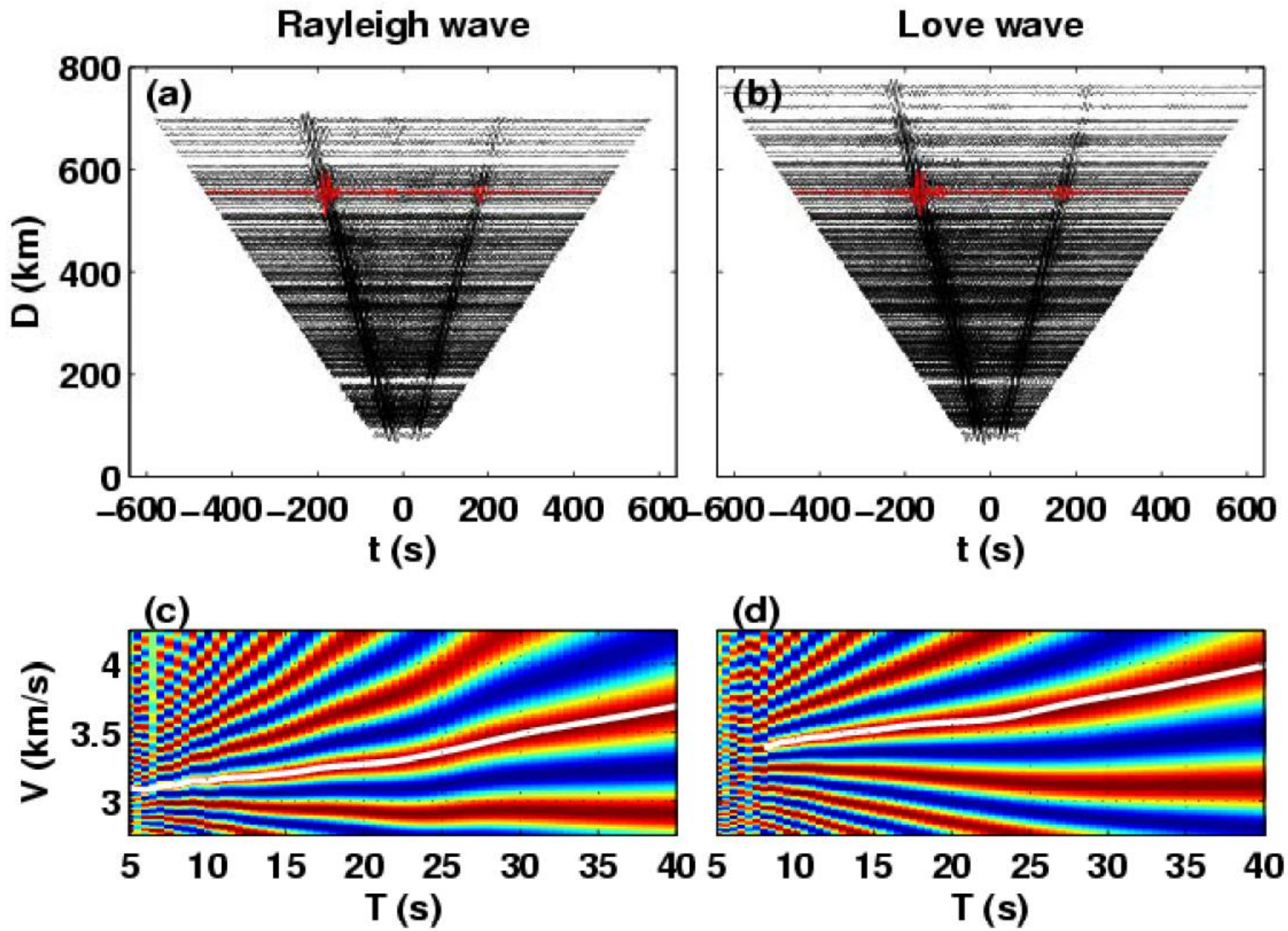
Anisotropy II: Radial Anisotropy (or: transverse *isotropy*)

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



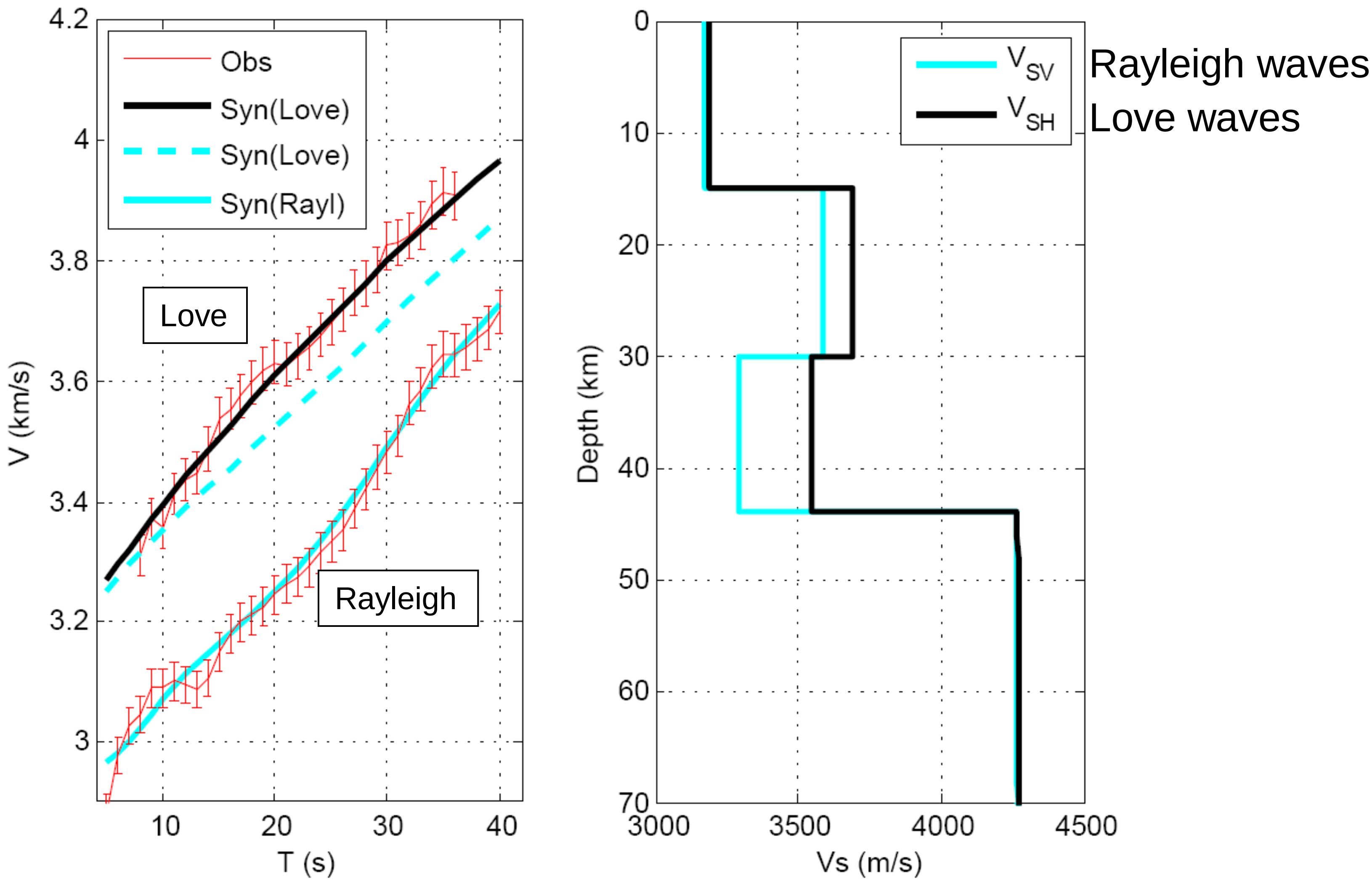
From Stein and Wysession

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



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

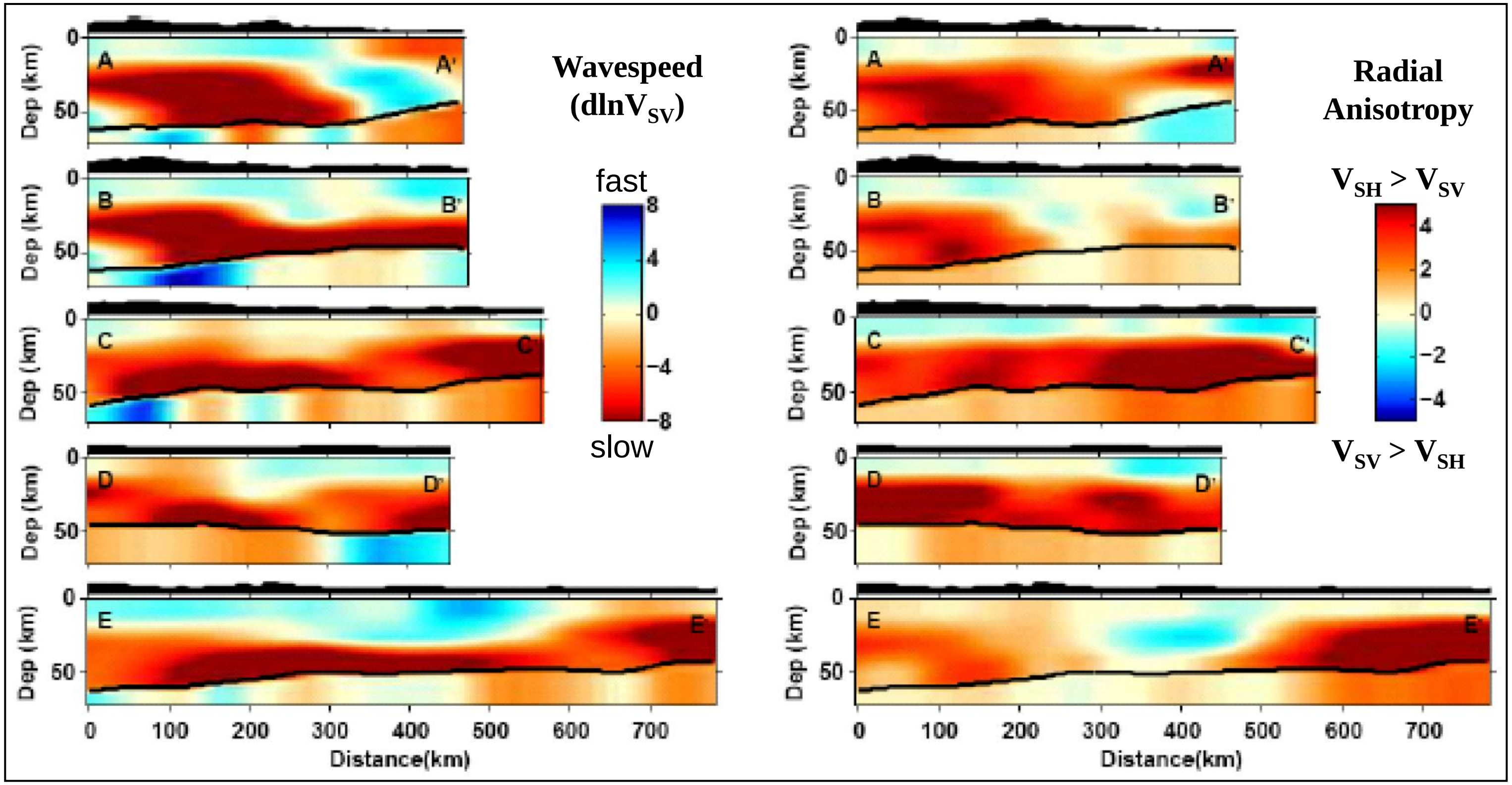
Radial Anisotropy (from Love and Rayleigh wave dispersion)

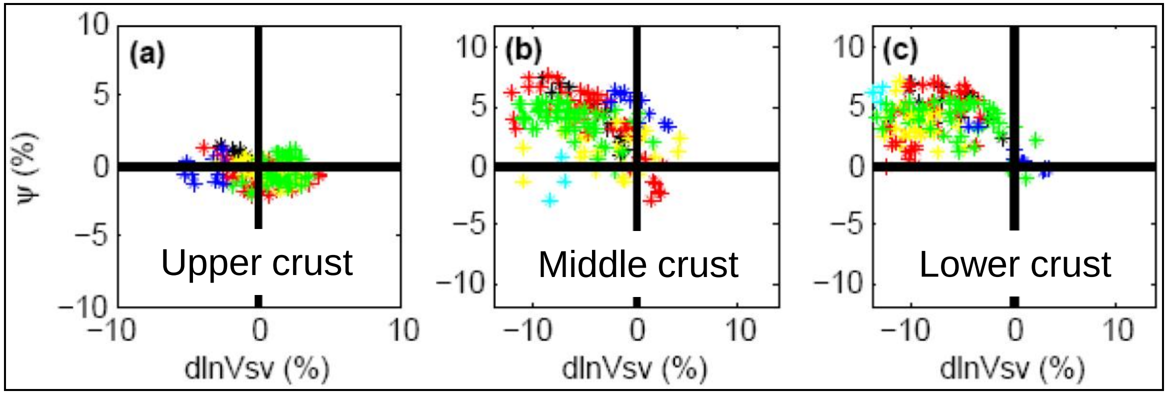


Huang, Yao, and Van der Hilst (GRL, 2010)

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

Strong correlation with LVZs → horizontal flow in weak zones?





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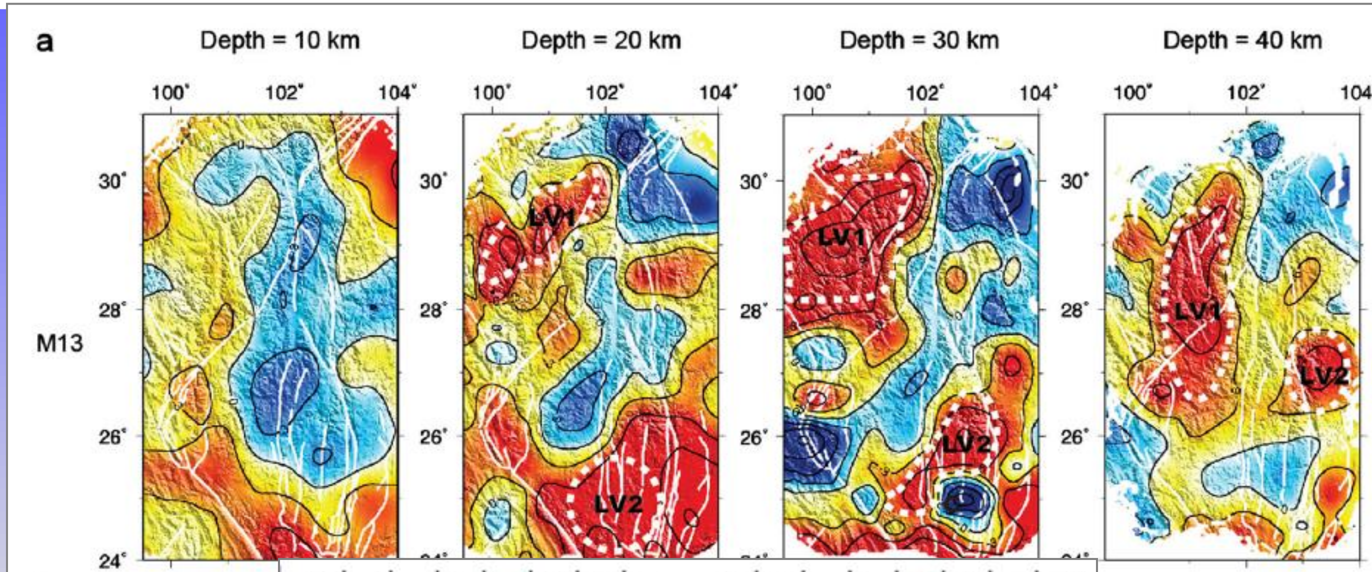
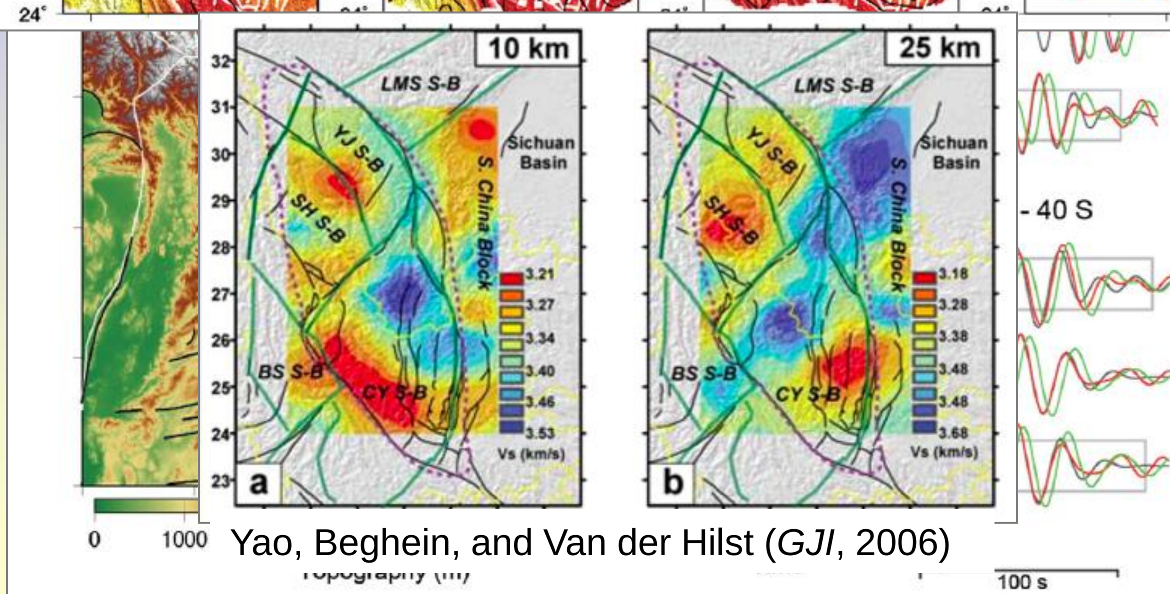
3. **Imaging of interfaces**

RESEARCH LETTER
10.1002/2013GL058476

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]





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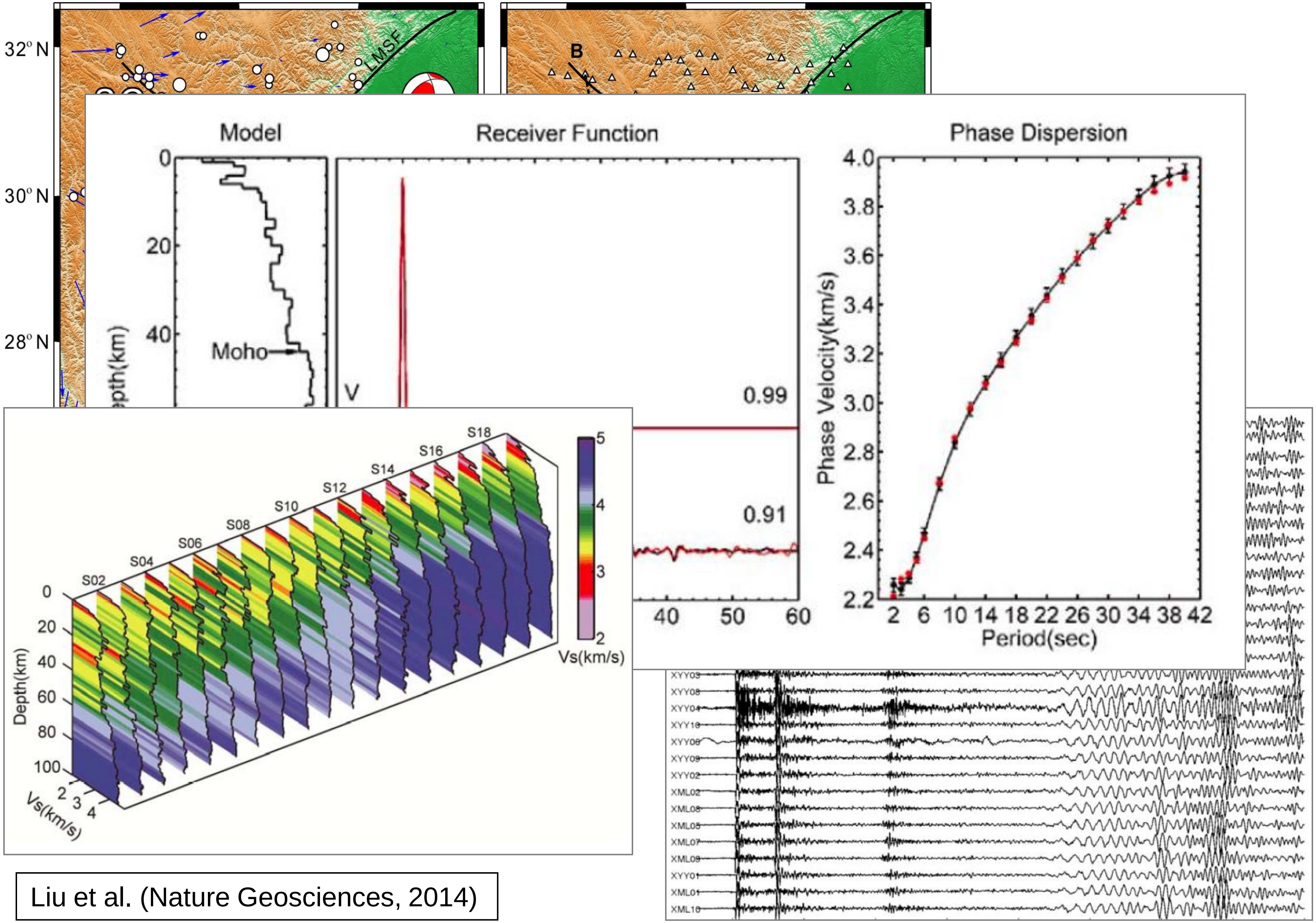
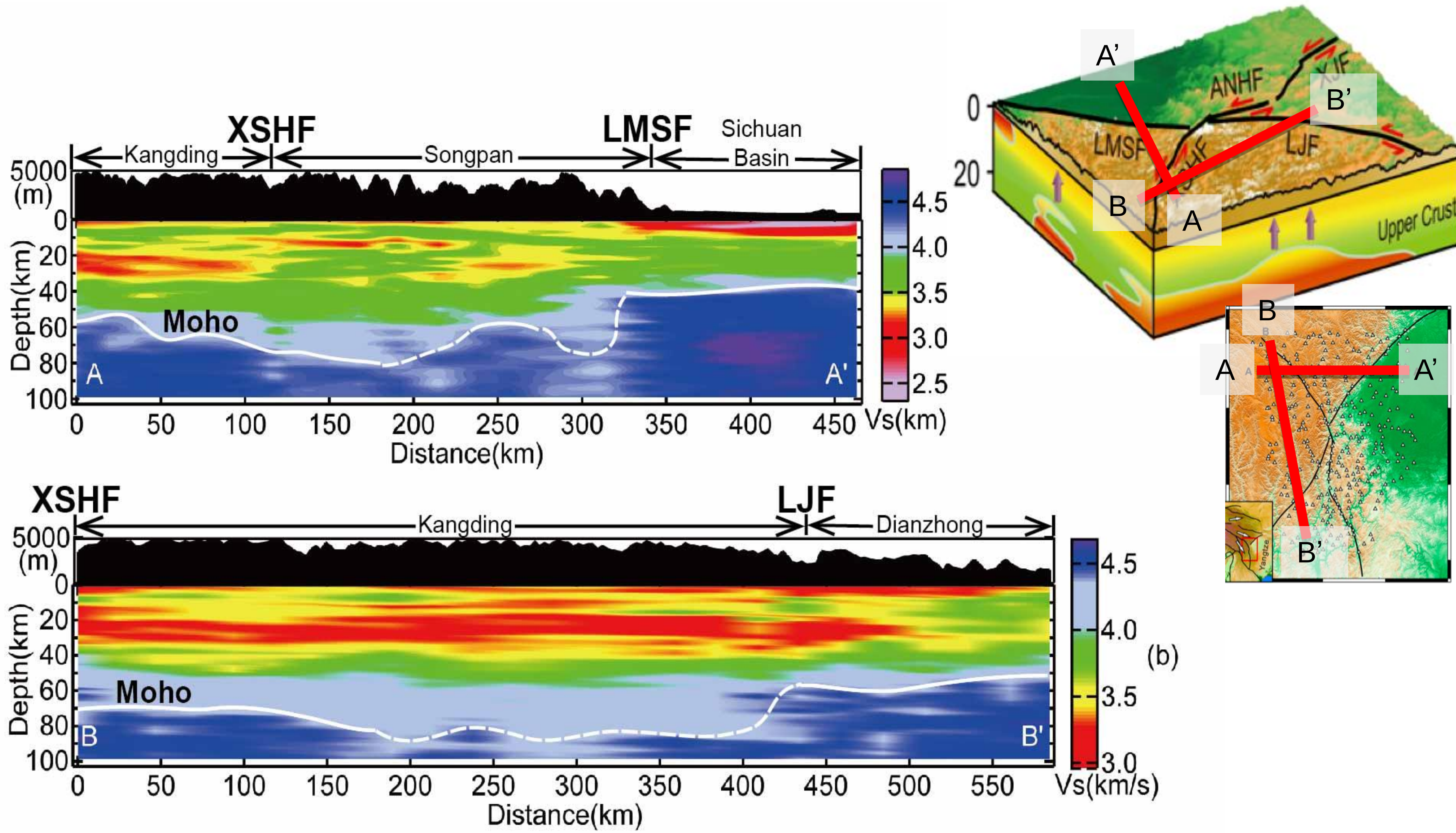
3. **Imaging of interfaces**

High resolution studies with dense seismograph arrays

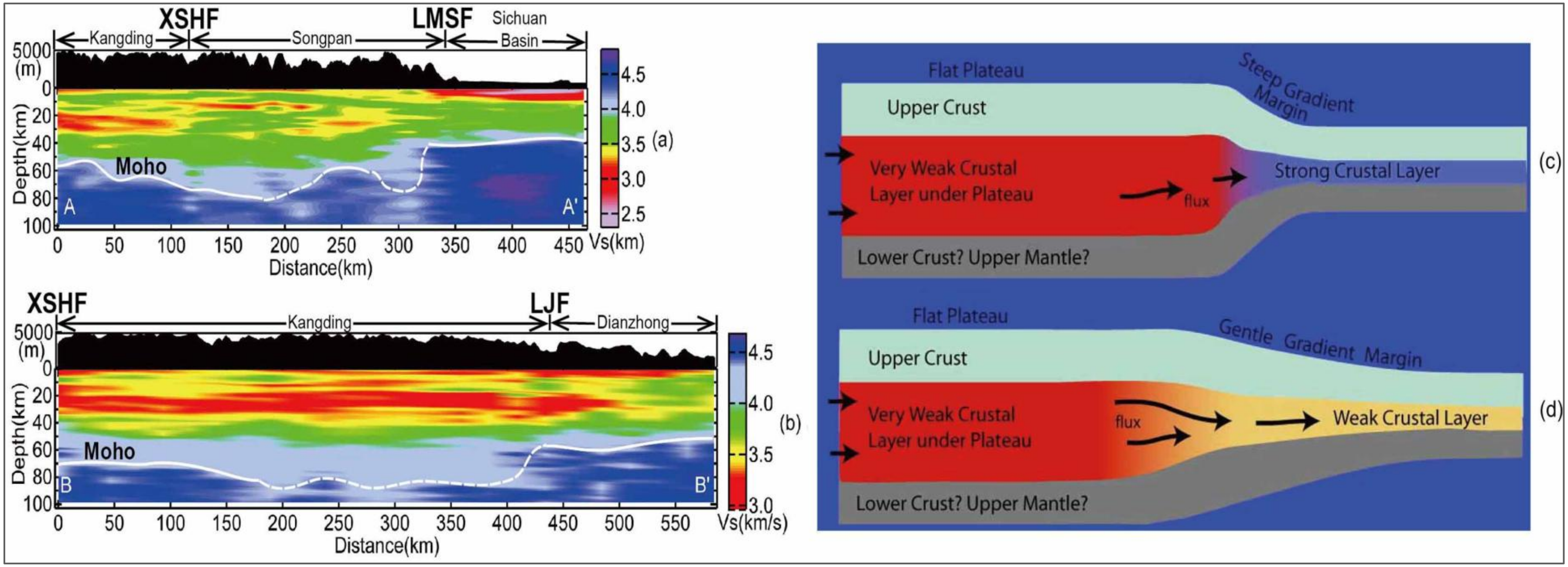


Liu et al. (Nature Geosciences, 2014)



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)

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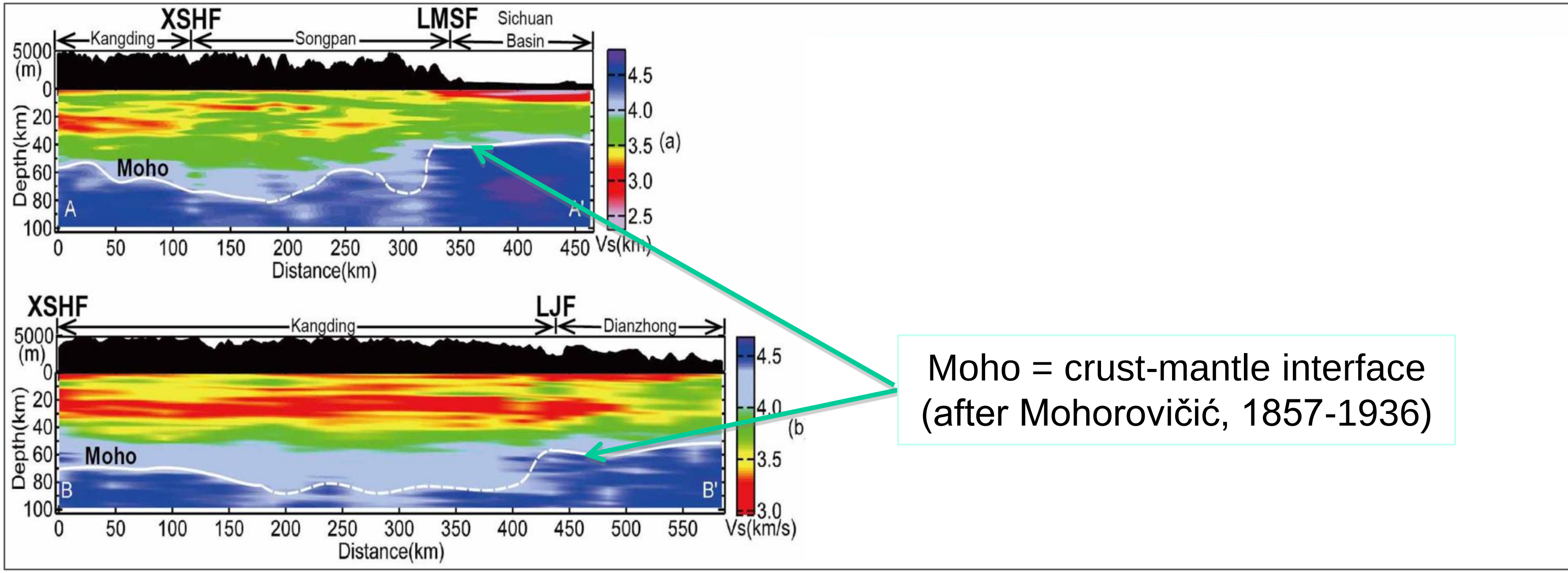
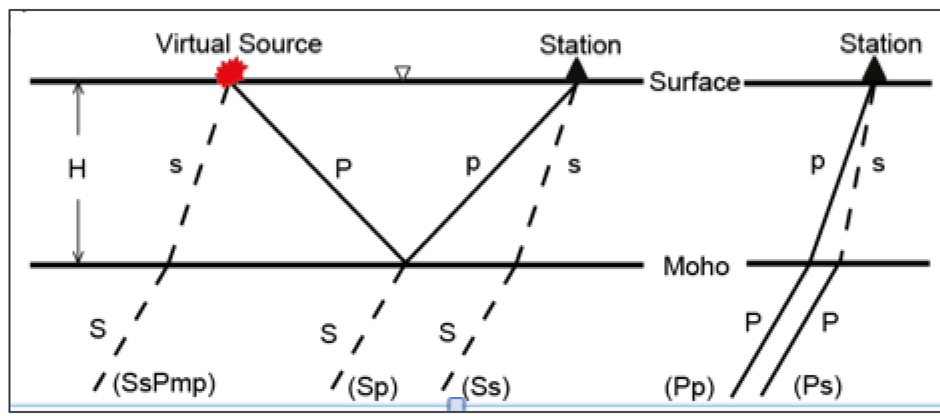
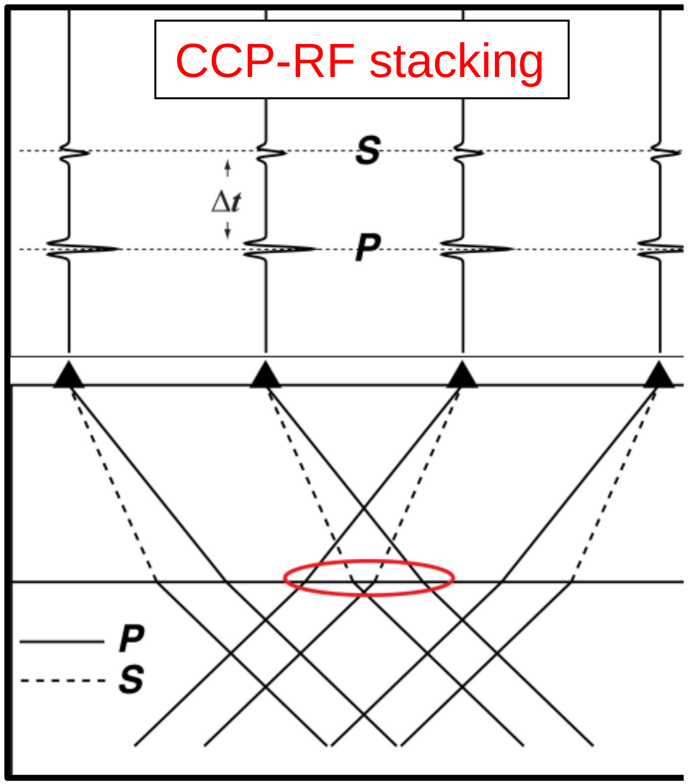


Imaging of the Moho with Converted Waves (P-to-S or S-to-P)



Yu et al.(EPSL, 2012)

Traditional approach (concept)

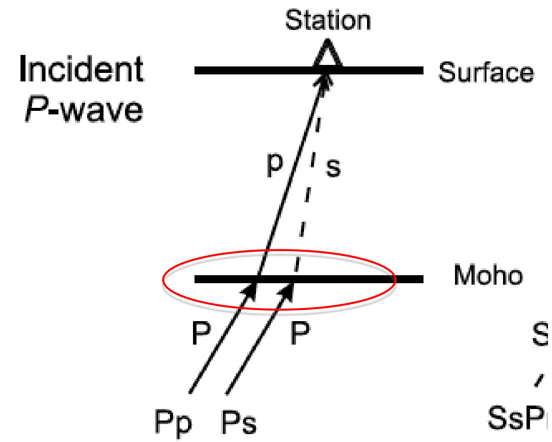


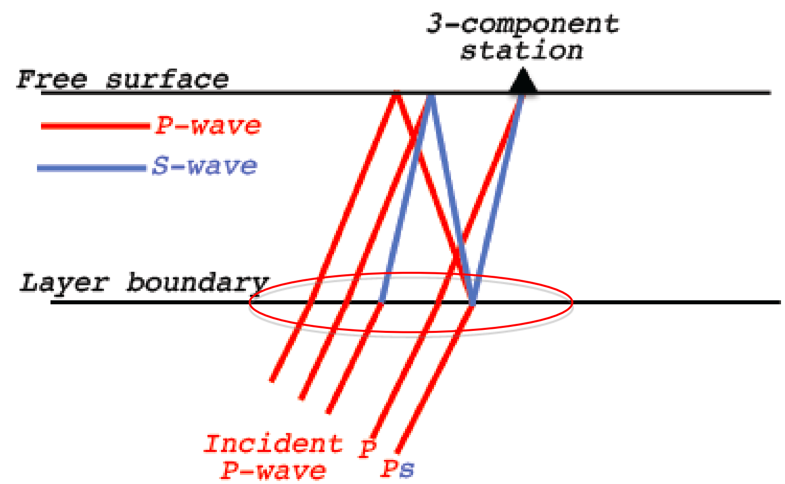
Common Conversion Point stacks of converted waves (Receiver Functions):

- Time differences mapped directly to depth

- **Horizontal interfaces**

Imaging with converted waves





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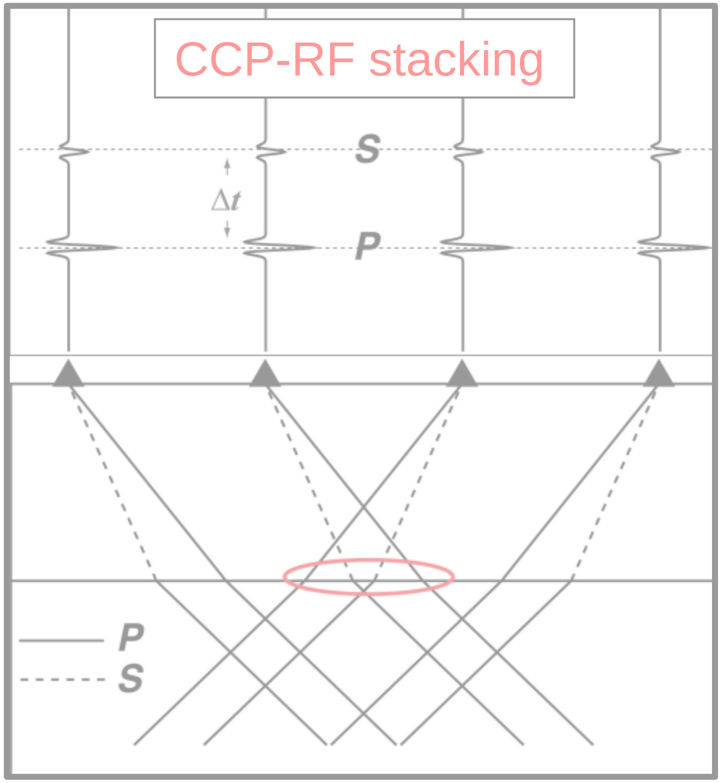
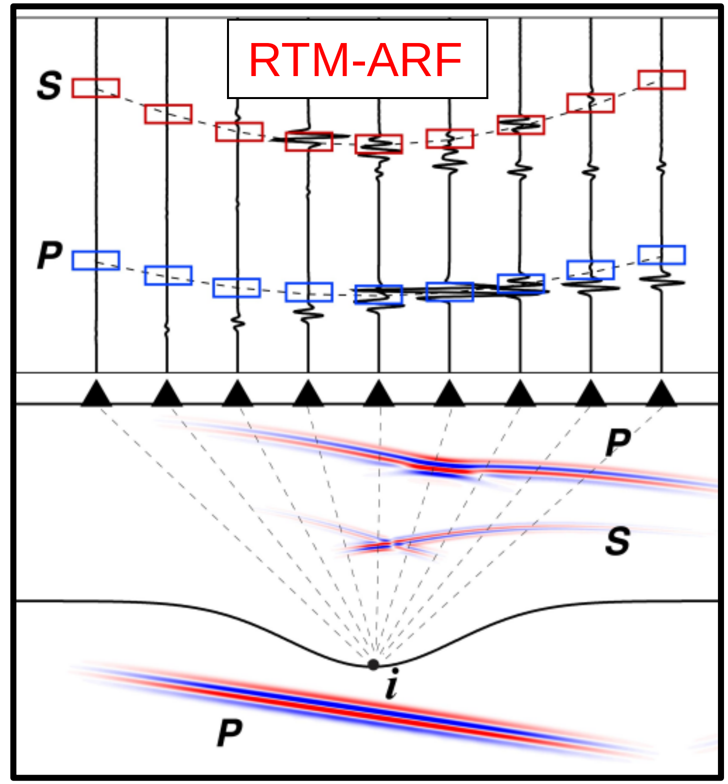


Shang et al. (GRL, 2012)



Common **C**onversion **P**oint stacks of converted waves (**R**eceiver **F**unctions):

- Time differences mapped directly to depth
- Horizontal interfaces

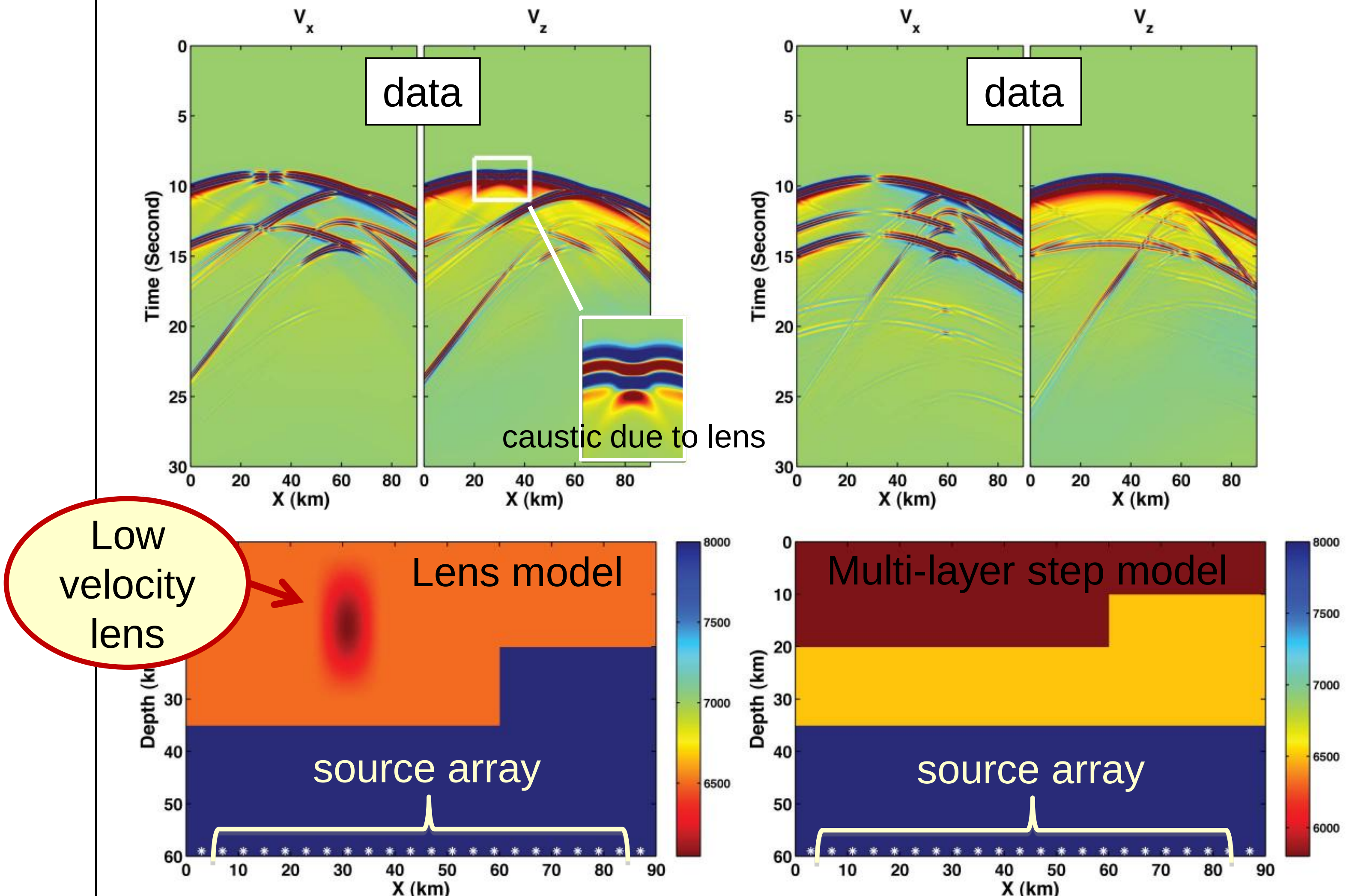
Reverse **T**ime **M**igration of **A**rray **R**eceiver **F**unctions:

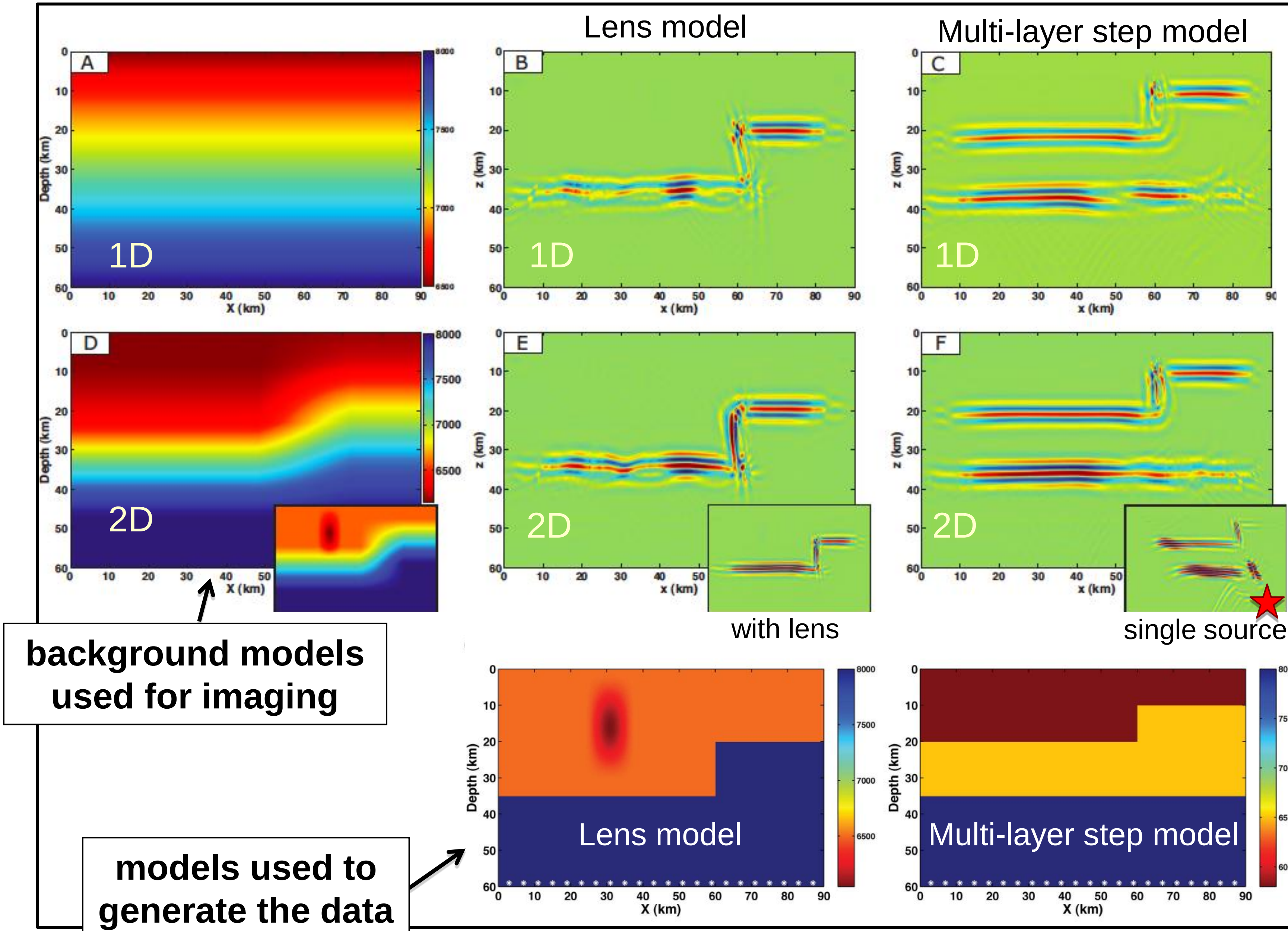
-Cross-correlations: incoming & time reversed and *P* & *S* waves (“imaging condition“)

-No assumption on structure

Shang, De Hoop, Van der Hilst (GRL, 2012)

Synthetic experiments for two test models

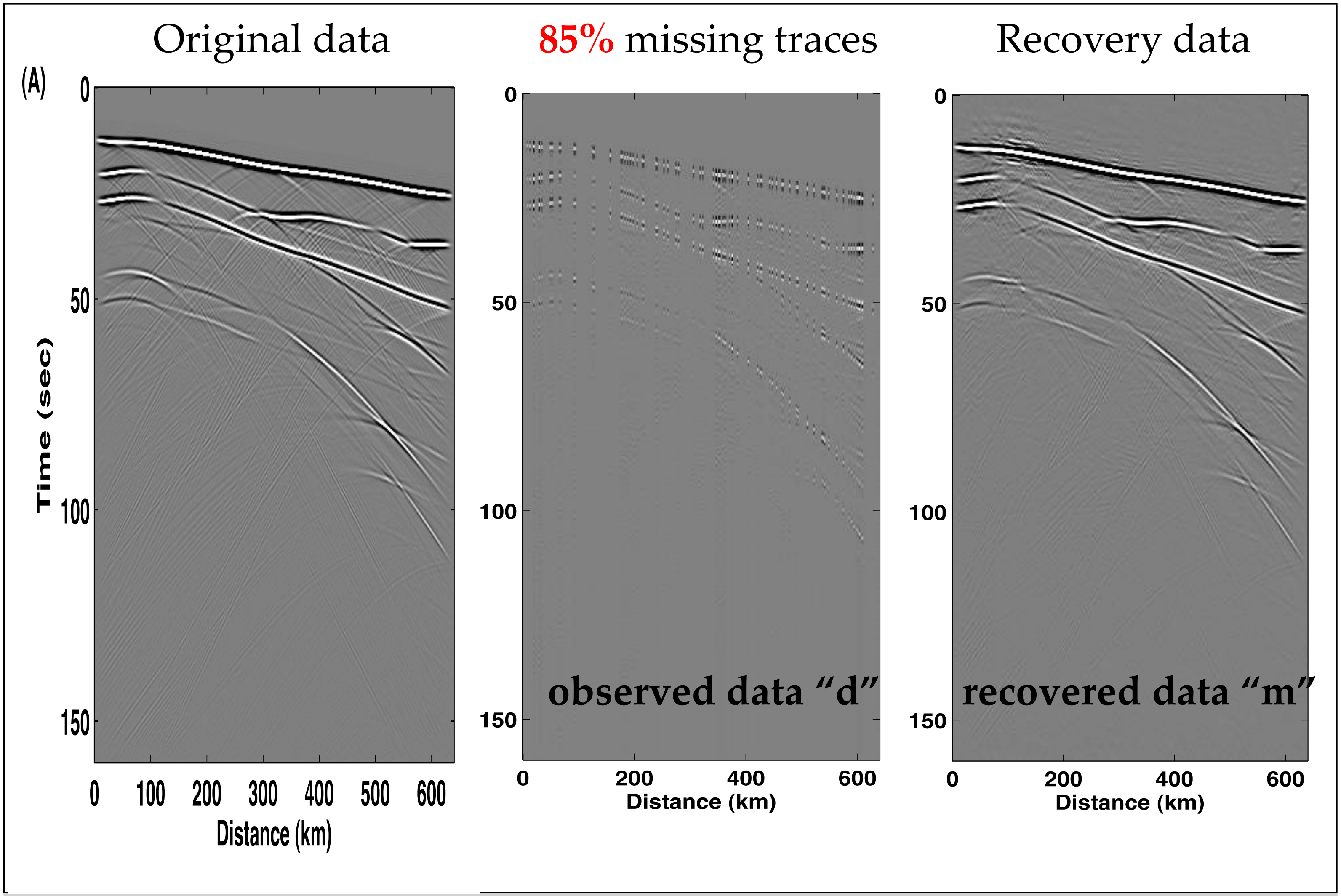




Lens model
Multi-layer step model
A
B
C
D
E
F
1D
2D
Depth (km)
z (km)
X (km)
x (km)
with lens
single source
background models used for imaging
models used to generate the data
Lens model
Multi-layer step model

Promising but …
… important practical considerations:

- Need good starting model (2- or 3D structure, e.g., from ambient noise or wave equation reflection tomography)
- Need to have densely sampled wavefield (preferably on a regular grid) → not always available → need interpolation → wave field *continuation*



Wave field continuation

Sparsity Promoting Interpolation

$$\mathbf{d} = \mathbf{G}\mathbf{m} + \mathbf{n}$$

d: observed data
m: recovered (interpolated) data
G: sampling operator
n: noise

$$\mathbf{m} = \mathbf{C}^T\mathbf{x}$$
$$\mathbf{A} = \mathbf{G}\mathbf{C}^\mathbf{T}$$

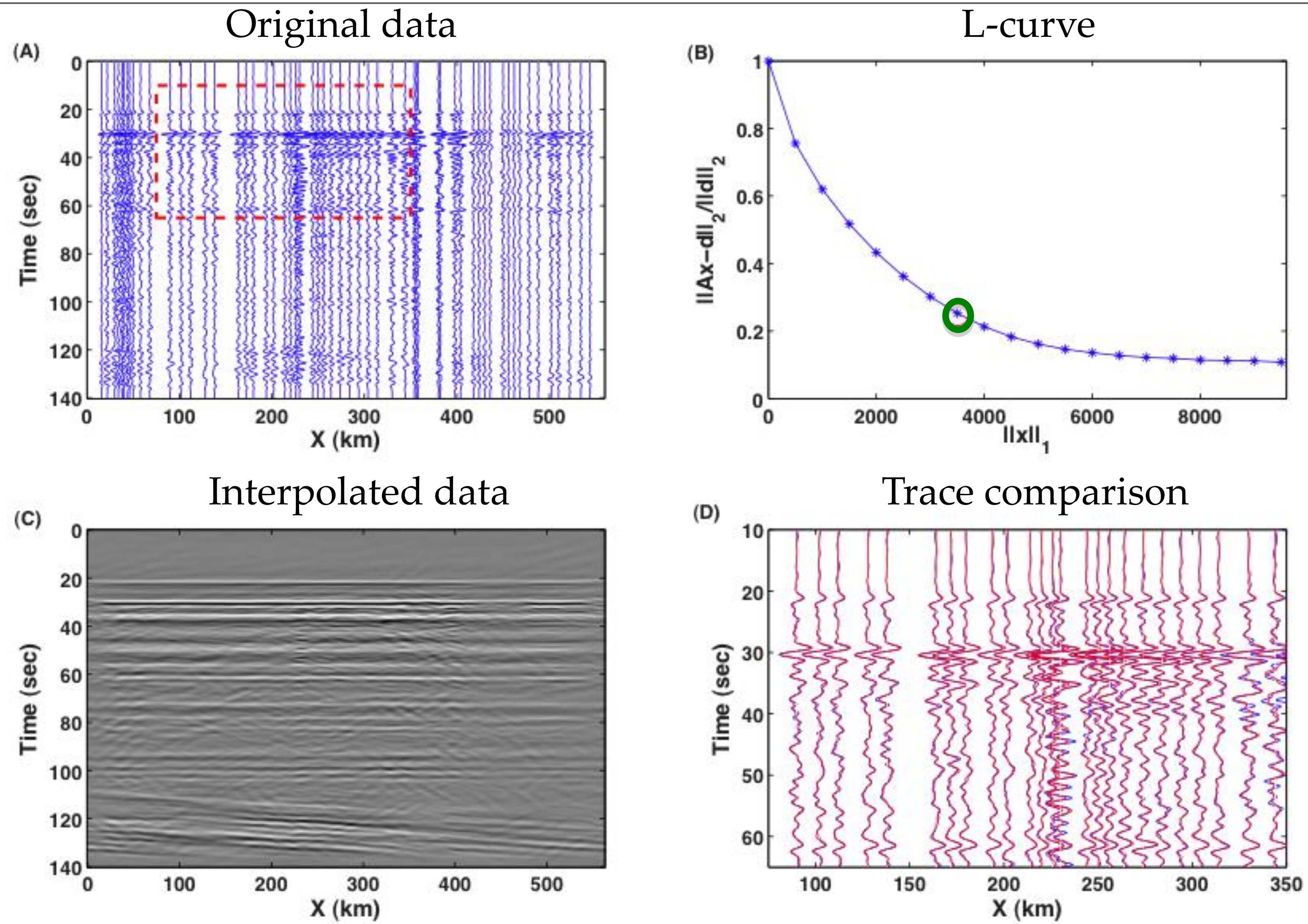
x: curvelet coefficients
$\mathbf{C^T}$: inverse curvelet transform

Minimize

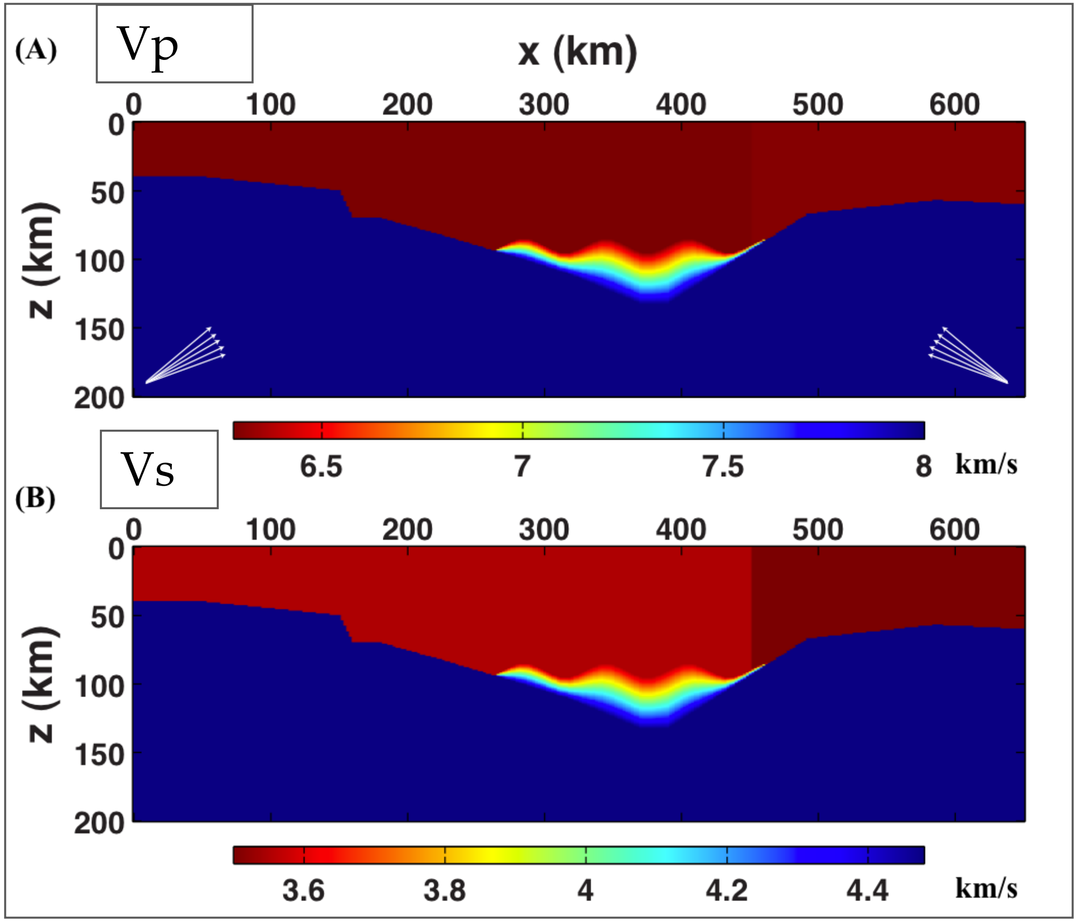
$$J = \frac{1}{2}\left\|\mathbf{d} - \mathbf{A}\mathbf{x}\right\|_2^2 + \lambda\left\|\mathbf{x}\right\|_1$$

Shang, De Hoop, and Van der Hilst (*GJI, 2017*)

Real Data Example



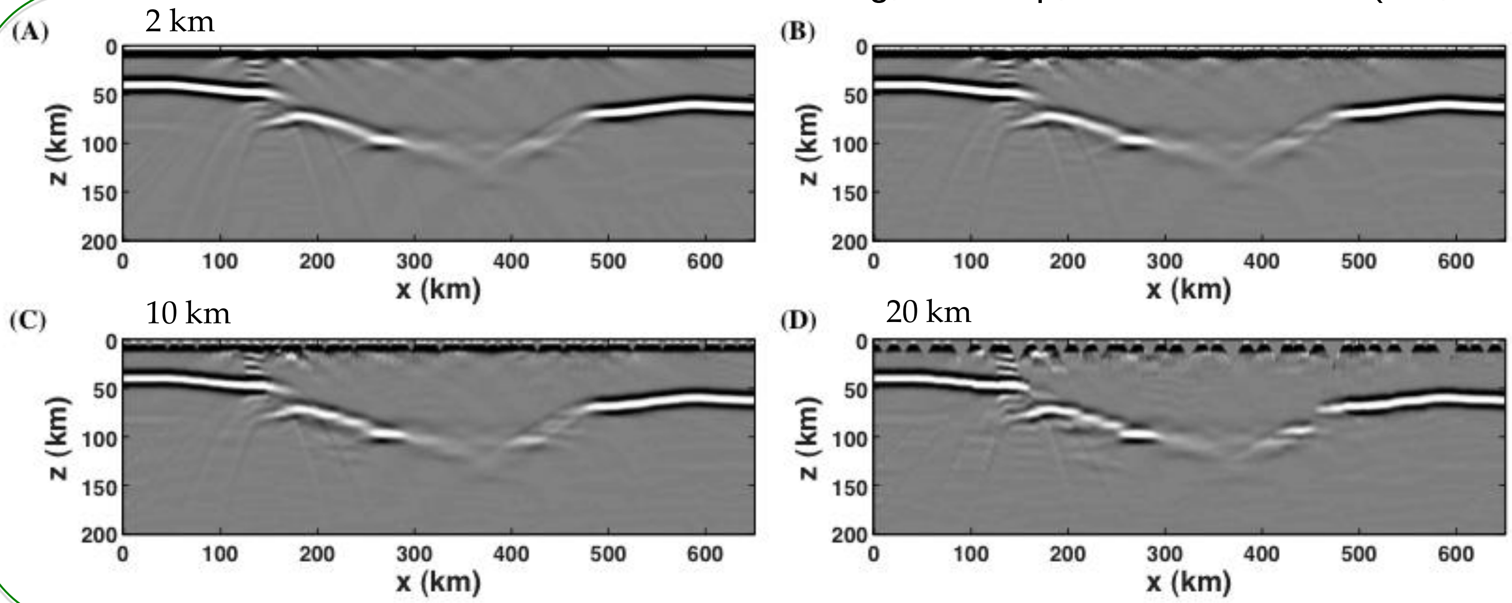
Application to Sparsely Sampled Synthetic data



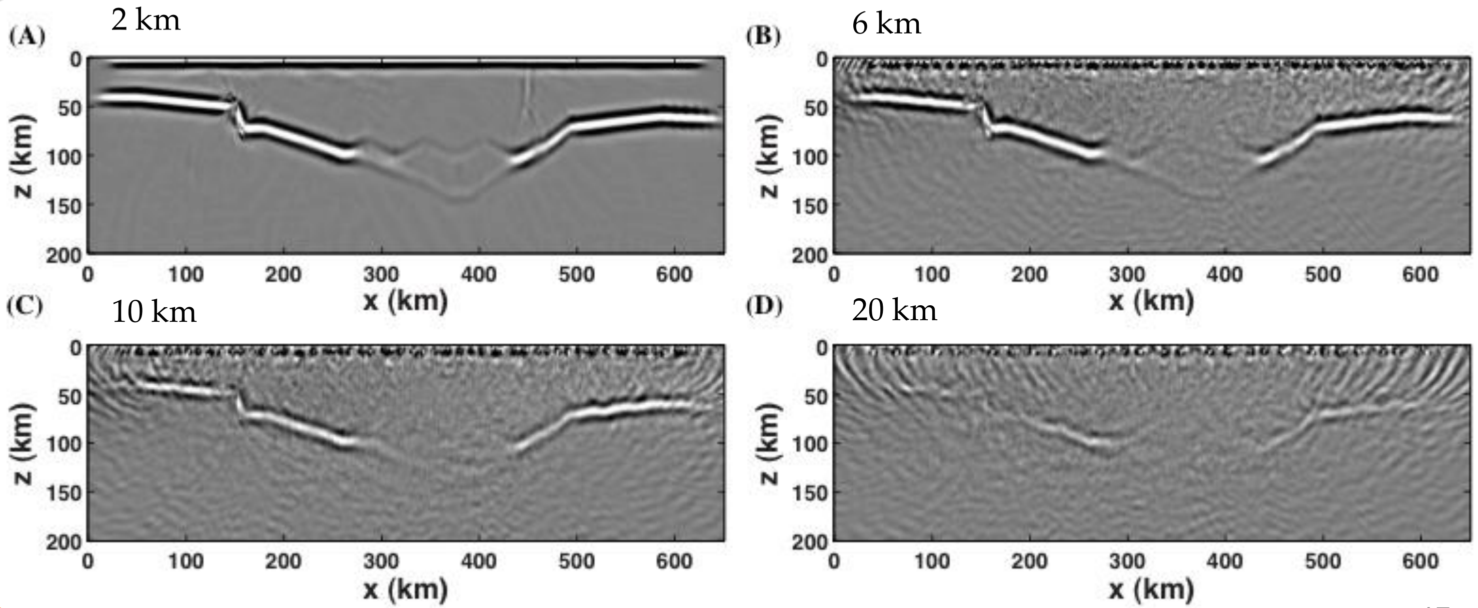
- 10 plane *P* waves
  (incident angle: 20~40 degree)
- Source central frequency: 0.5 Hz
- Station interval: 2, 6, 10 and 20 km

Shang, De Hoop, and Van der Hilst (*GJI, 2017*)

CCP

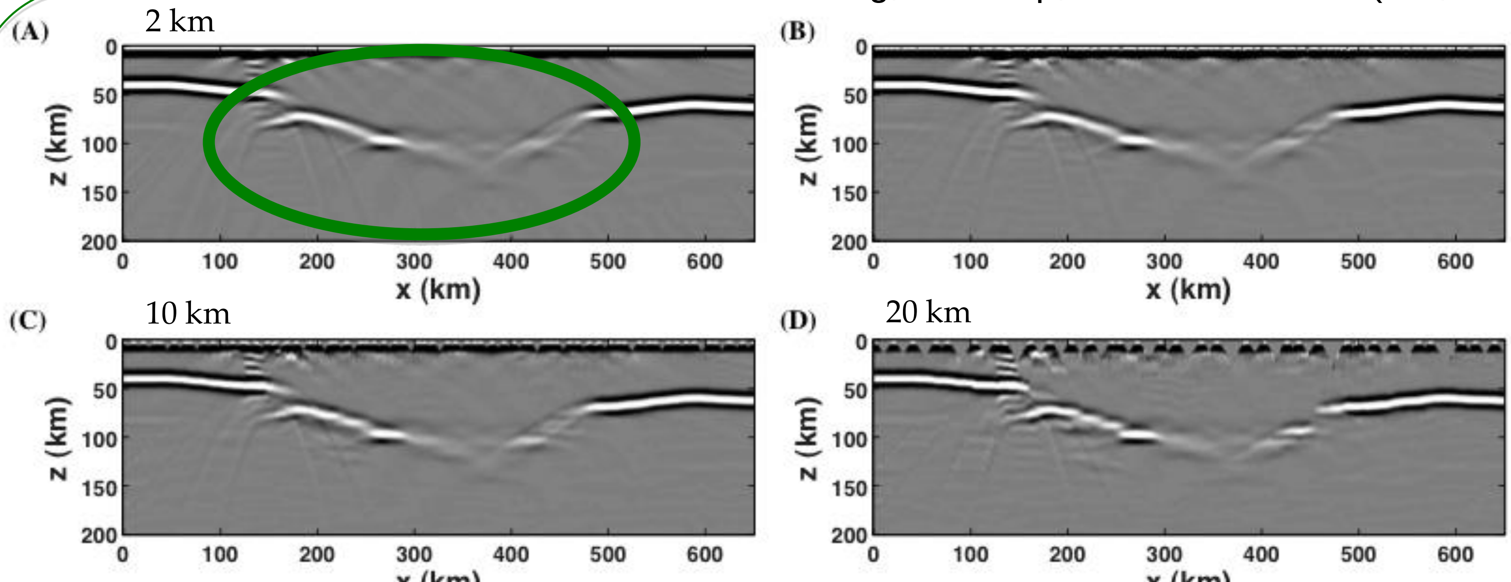


RTM without interp



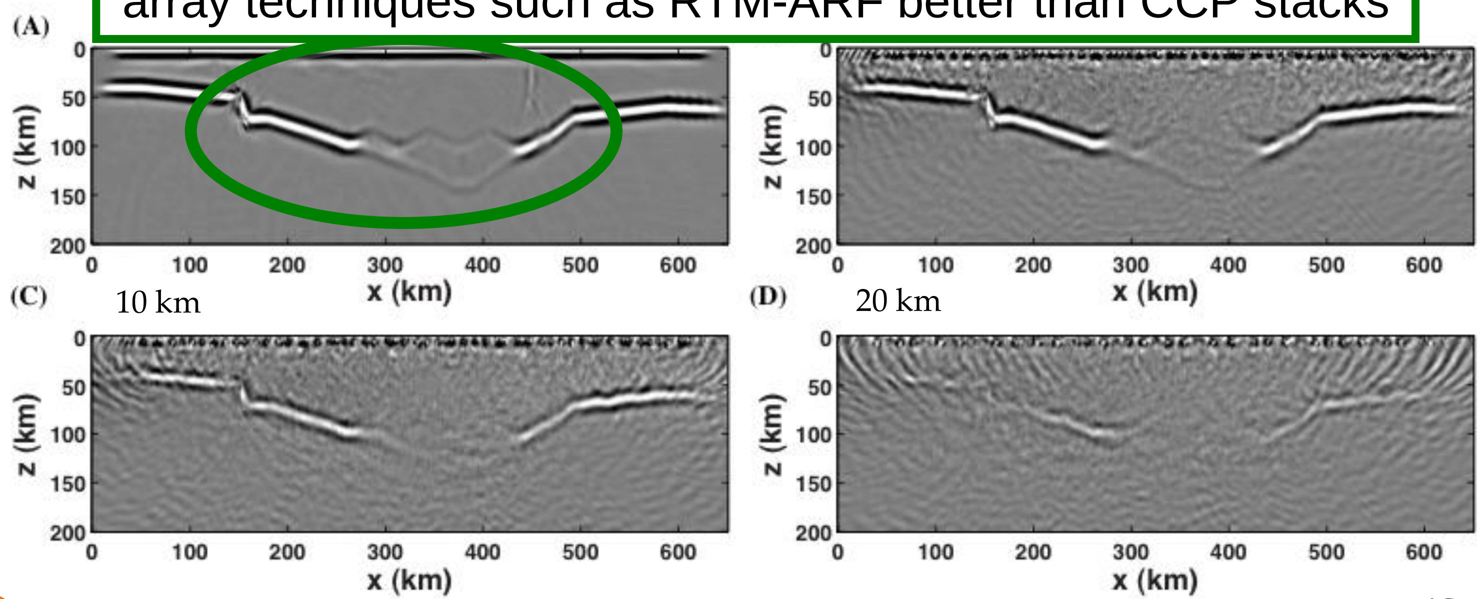
Shang, De Hoop, and Van der Hilst (*GJI, 2017*)

CCP



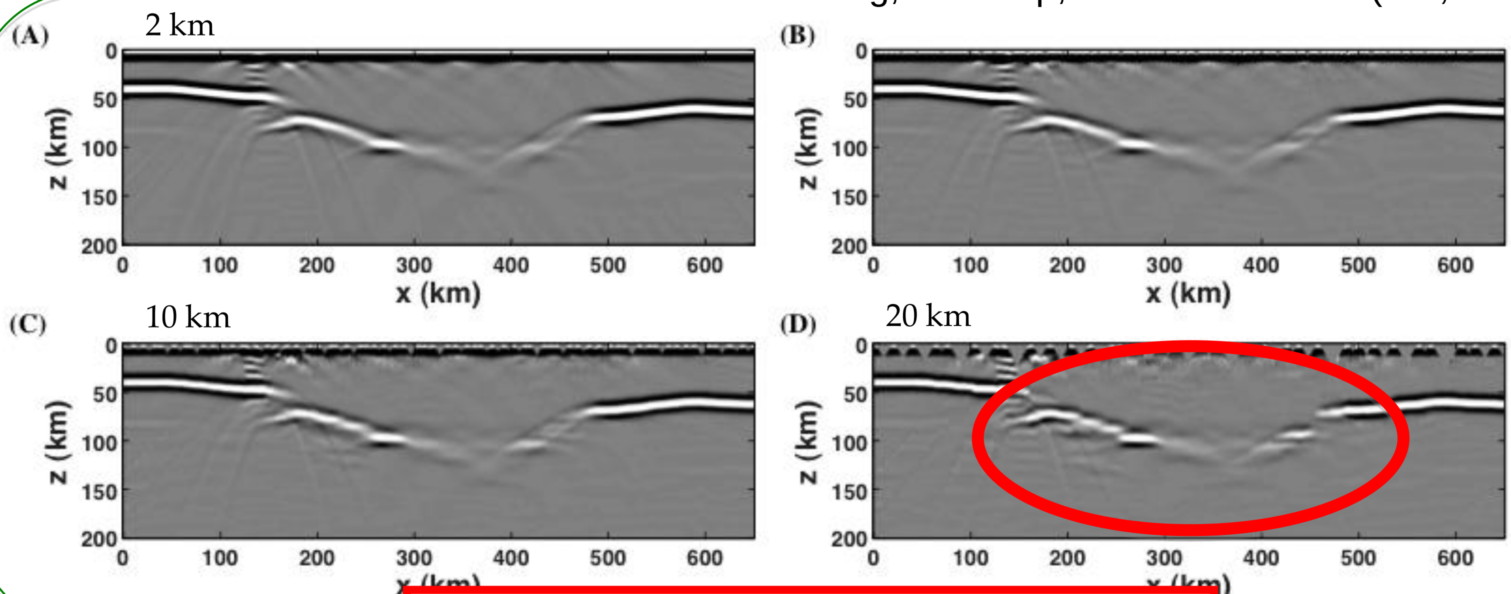
If station spacing is small:
array techniques such as RTM-ARF better than CCP stacks

RTM without interp



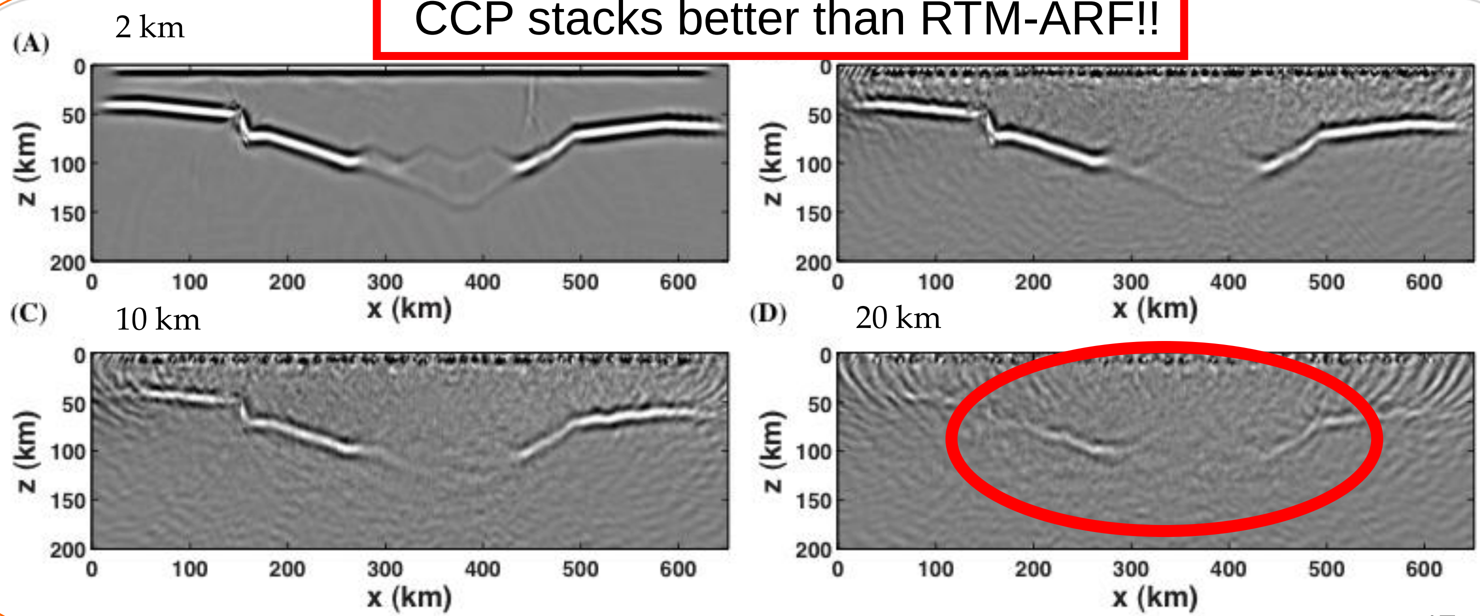
Shang, De Hoop, and Van der Hilst (*GJI, 2017*)

CCP



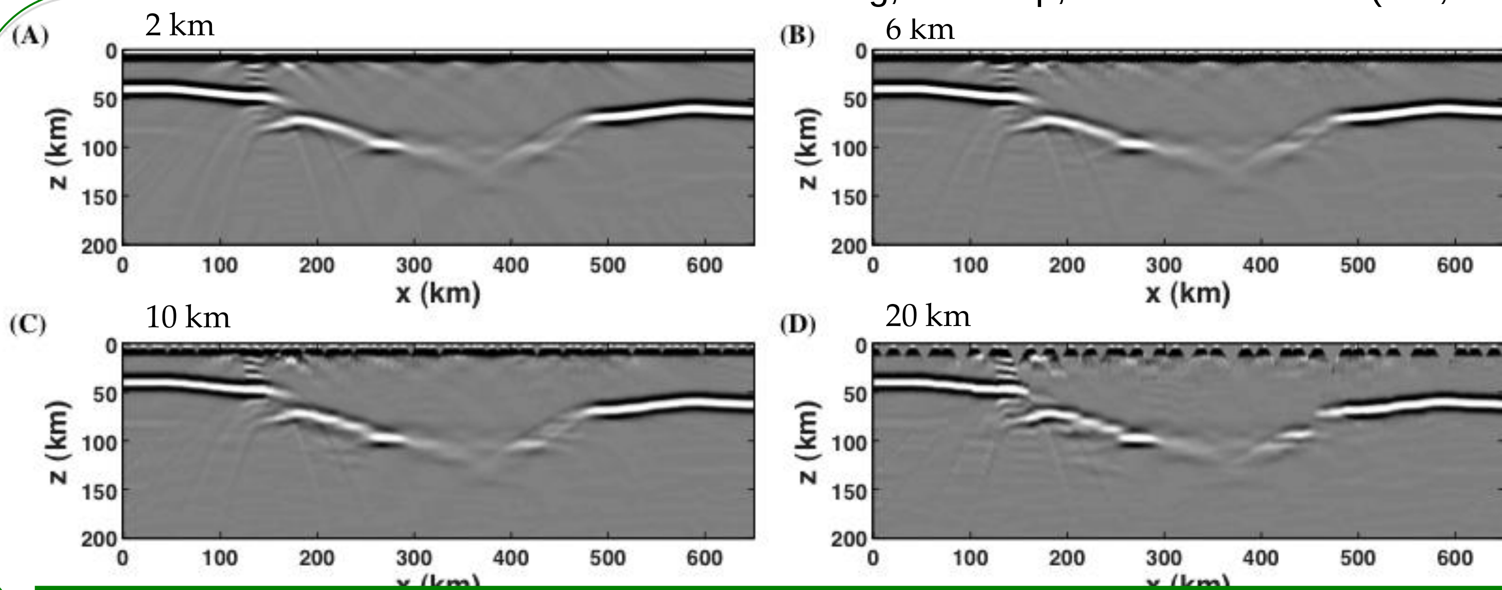
BUT: if station spacing is too large:
CCP stacks better than RTM-ARF!!

RTM without interp



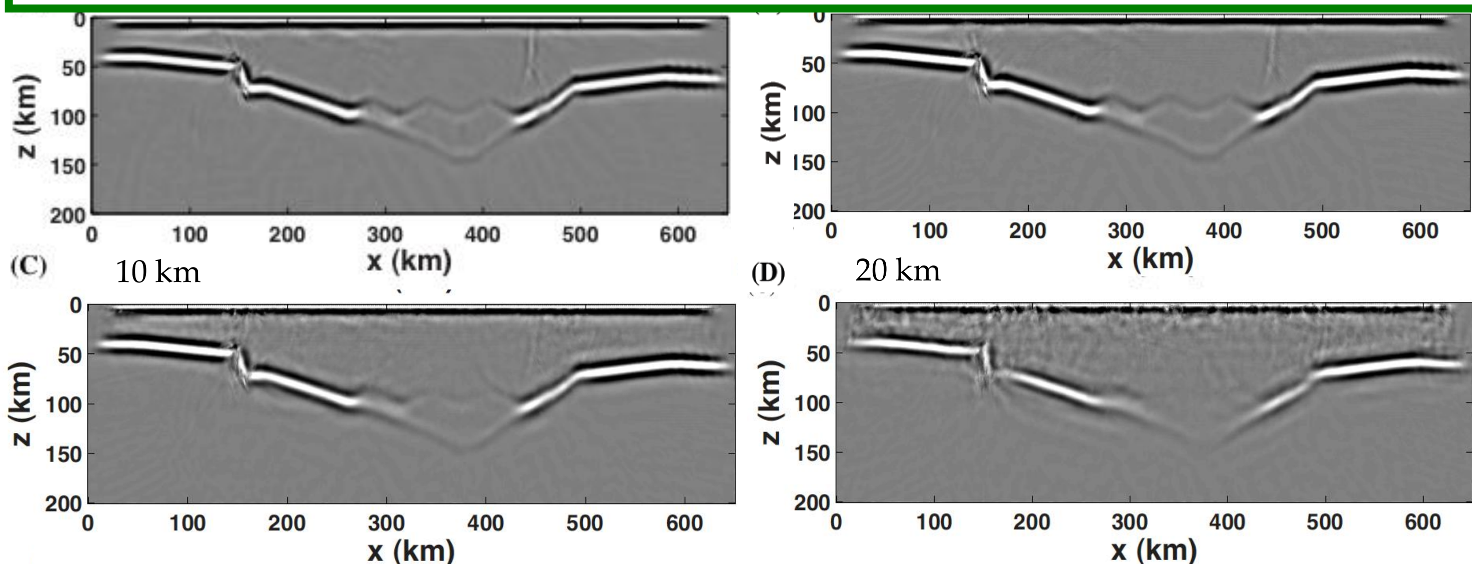
Shang, De Hoop, and Van der Hilst (*GJI, 2017*)

CCP



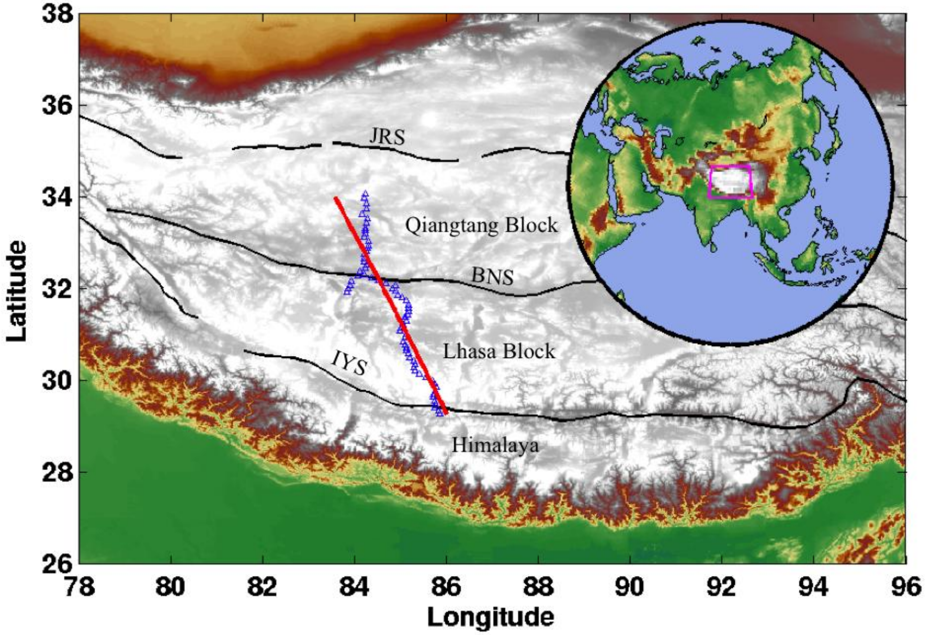
With interpolation/data continuation:
array techniques such as RTM-ARF always better than CCP stacks

RTM after interp

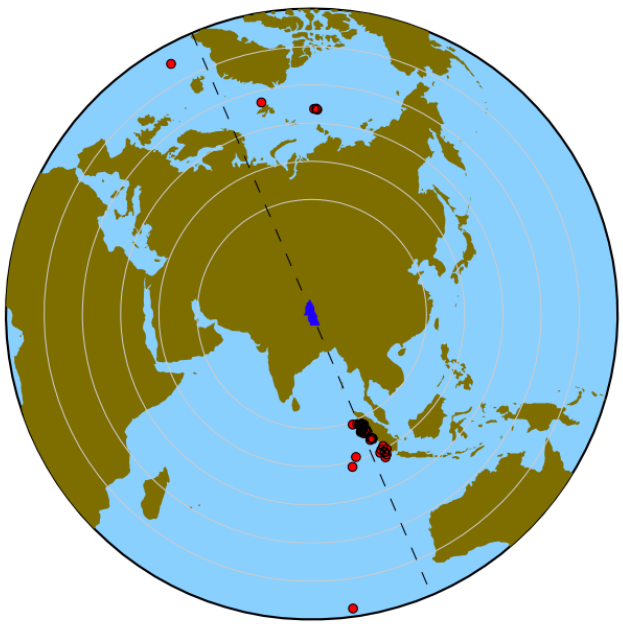


Shang, De Hoop, and Van der Hilst (*GJI*, 2017)

Application to Hi-CLIMB data – Preliminary Result

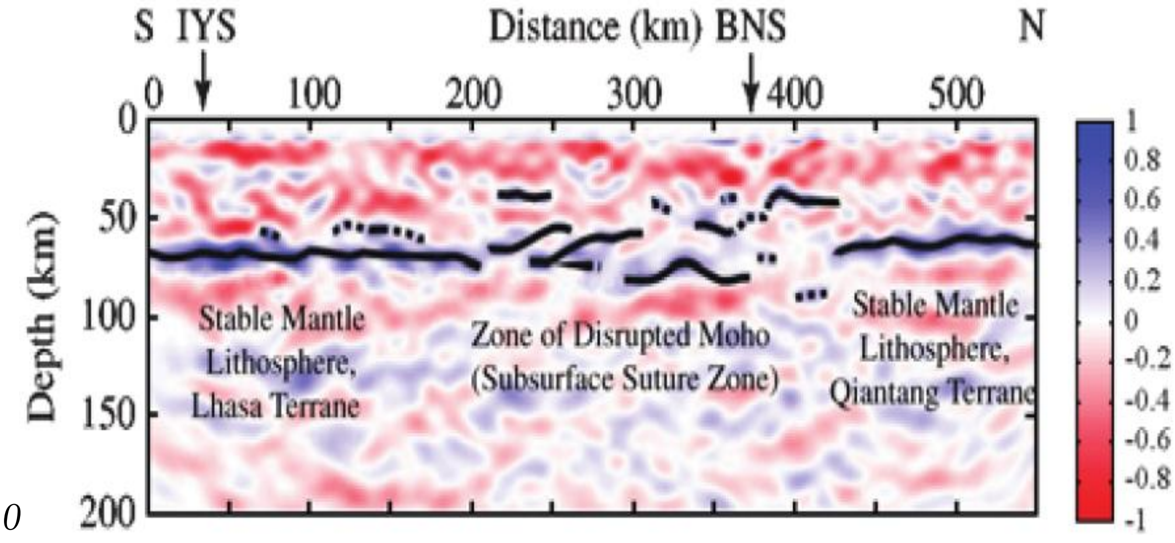


- 71 stations
- Station spacing: 2~40 km
  average interval: 10 km



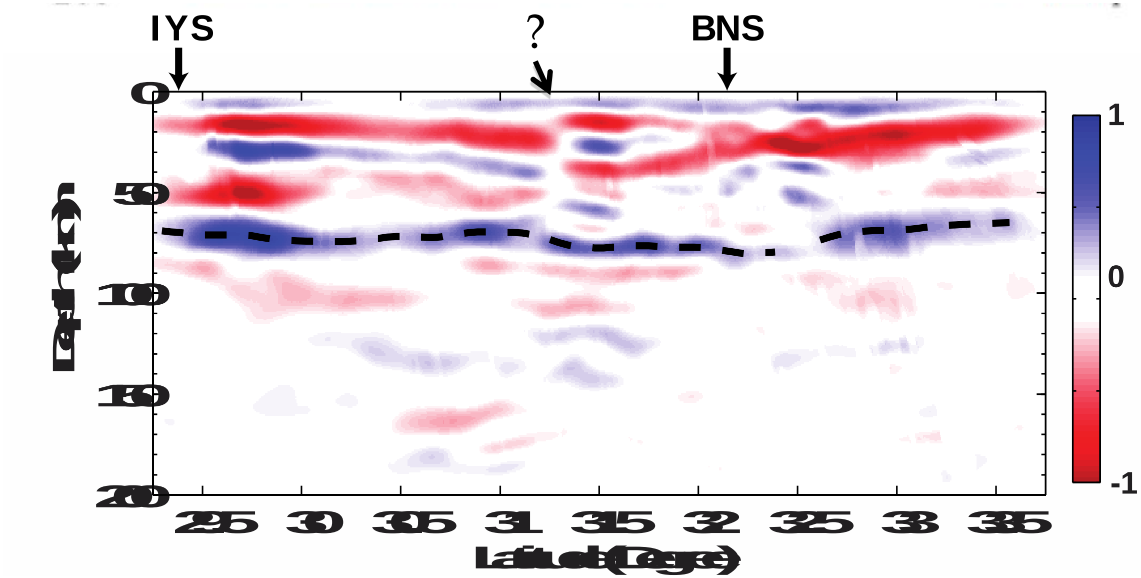
- 75 events, 70 from SE, 5 from NW
- Epicentral-distance: 30~80 degree

Gaussian beam migration

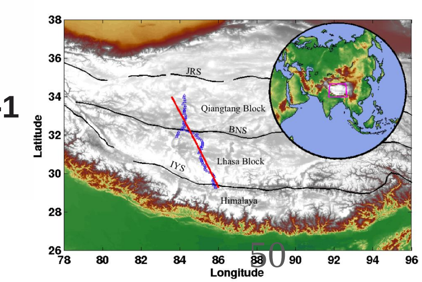


Nowack et al. 2010

RTM

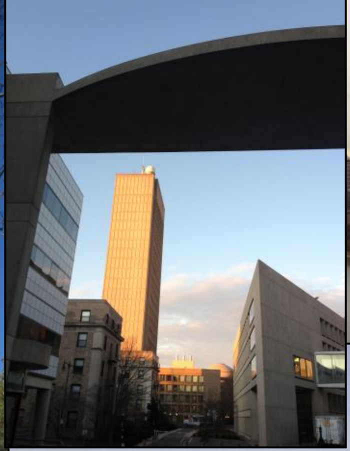


Shang et al. (2014)



Some conclusions:

- Complex structures → underlying assumptions limit resolution and accuracy → just adding stations (and reducing station spacing) gives diminishing returns!!
- Need better imaging methods to make the best use of dense array data → array methods, like reverse time migration (RTM) → Ideal spacing depends on frequency and depth of target (2-5 km for crustal imaging).
- But: Need powerful data–preprocessing to enable application of RTM type techniques in earthquake seismology (to mitigate effects of uneven sampling).
- Without such pre-processing, conventional (single-station) methods may work better than array methods on poorly sampled data.



Thank You