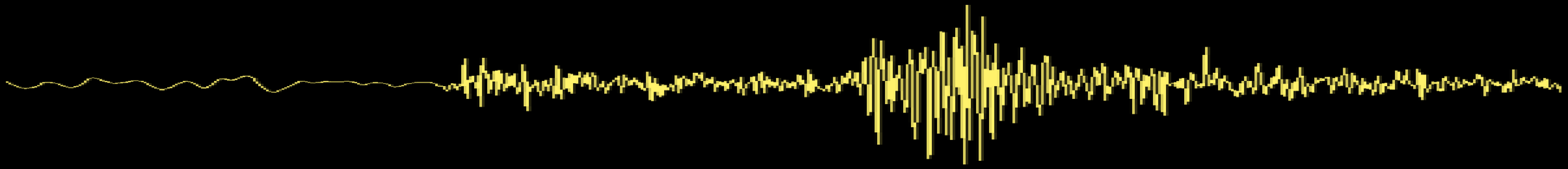

From Earth to Venus: What can we learn from seismic wavefield simulation

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justinko@ntu.edu.tw

May-31-2019@NCU

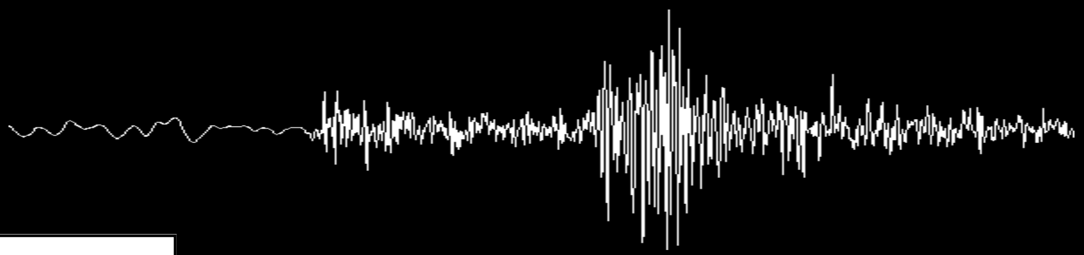
Take home message

We identify a high-velocity slab-like fragment beneath the southeastern US. This anomaly has a 100-km thick core with relatively sharp edges on both sides, which can be related to the Hess Conjugate.

We can model the infrasonic waves using GPU-accelerated FD simulator

We develop a novel full waveform inversion scheme using asymptomatic method. The computational cost is extremely low compared to adjoint method.

The beauty of seismology



Courtesy of Tarje Nissen-Meyer

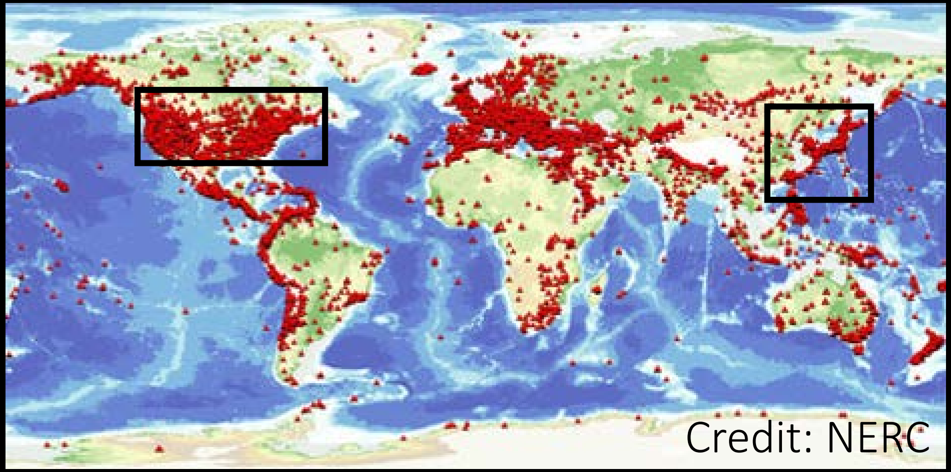
Different seismic phases

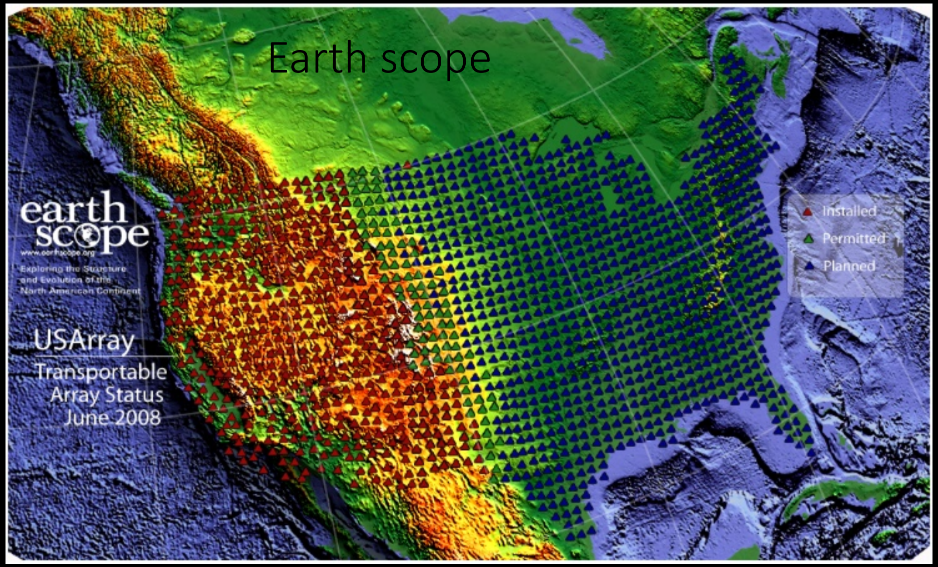
Detect fast or slow anomalies

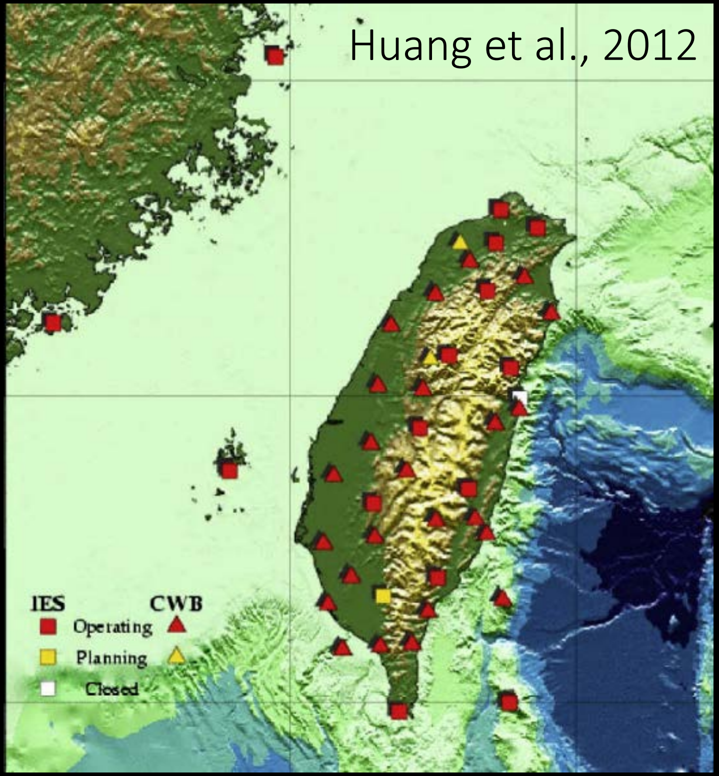
The earthquake, the receiver and the structure

Credit: John Nelson, IDV Solutions.

The earthquake, the receiver and the structure





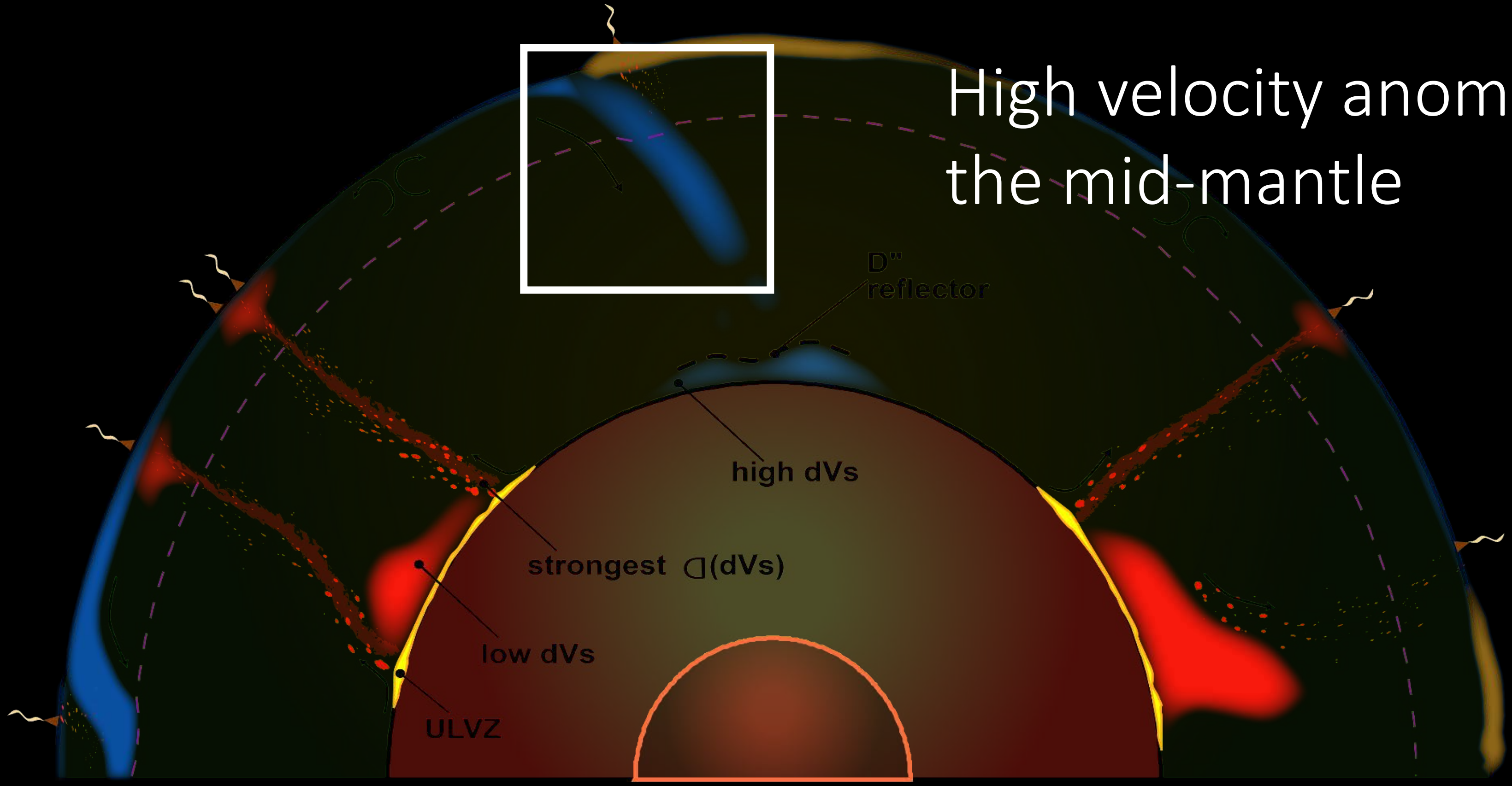


Global & Local seismic networks

On land

OBS

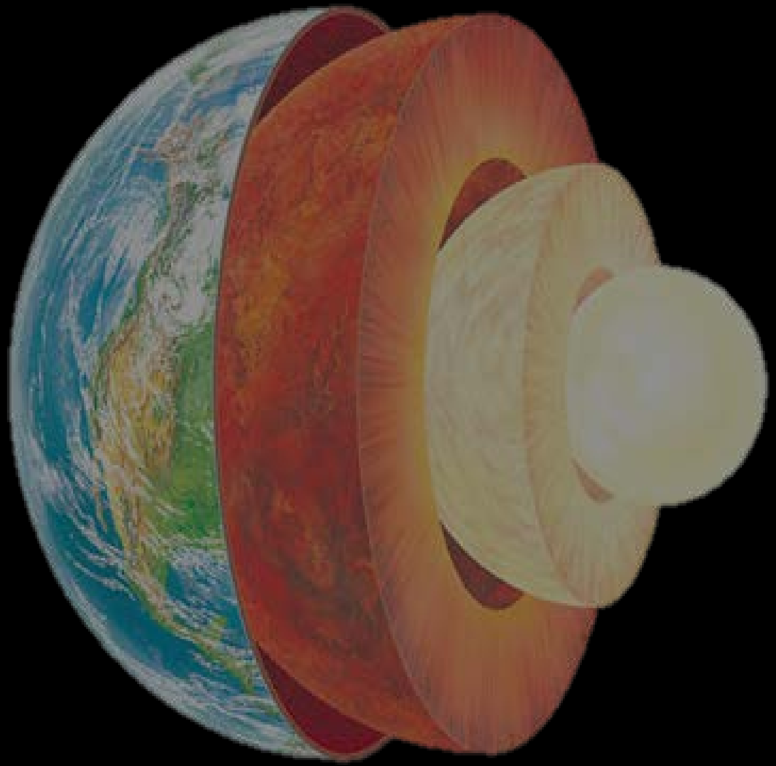
The earthquake, the receiver and the structure



High velocity anomaly in the mid-mantle

After Throne et al., 2004

The way to image the Earth's interior

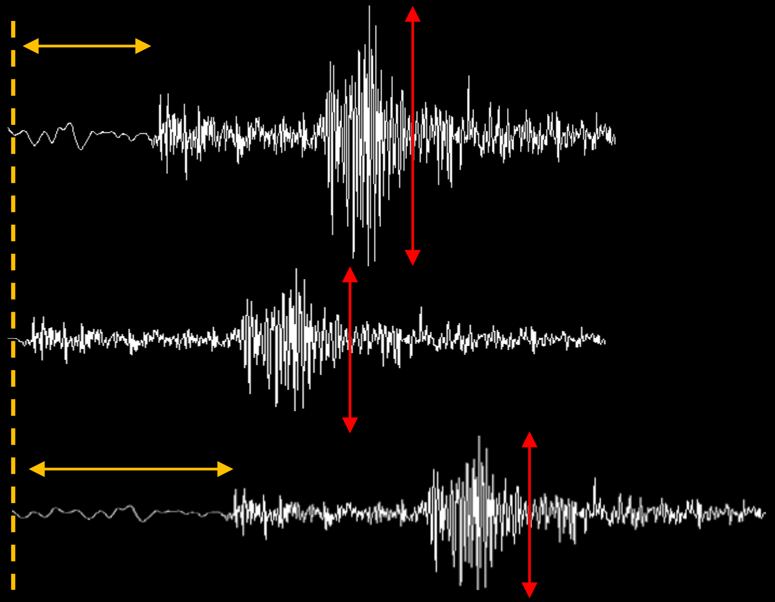


A. Forward

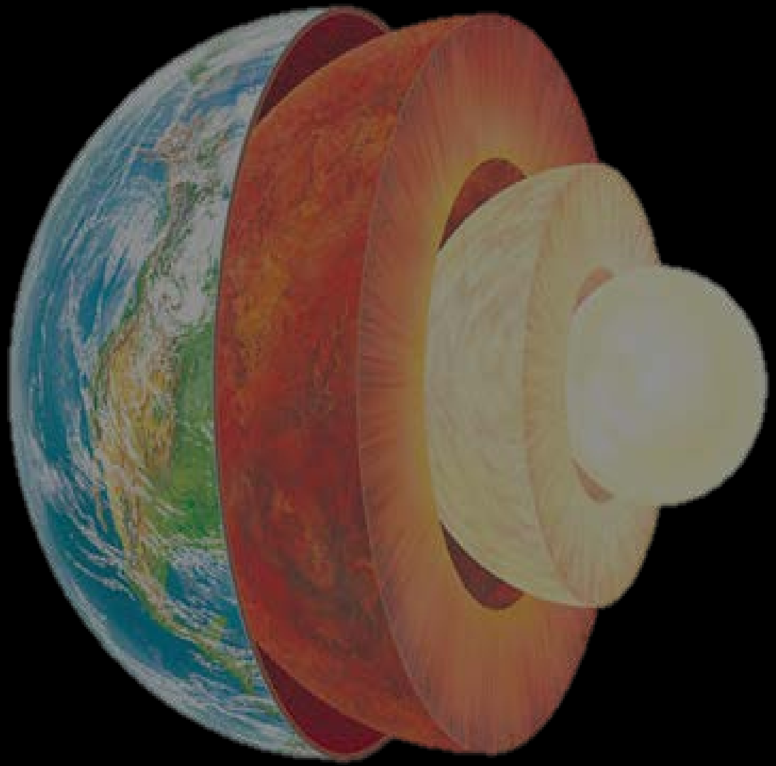
Waveform modeling approach

Seismic tomography

B. Inverse

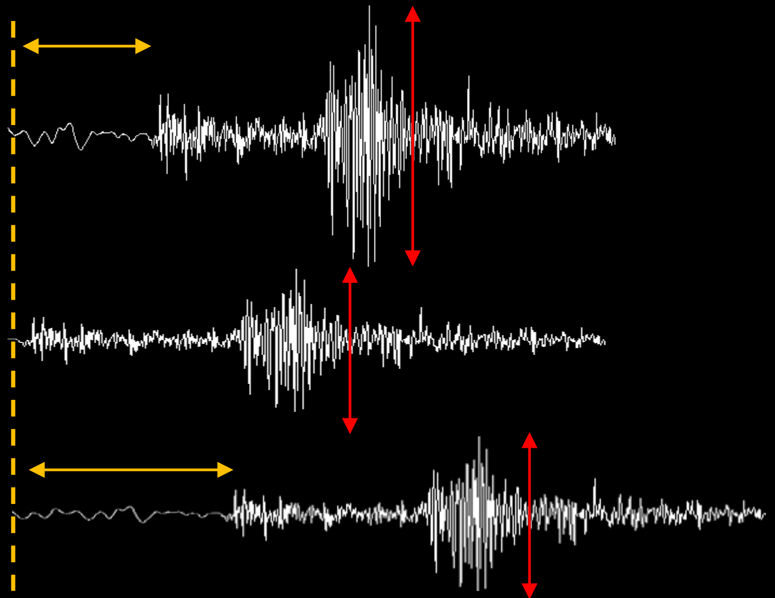


The way to image the Earth's interior



B. Inverse

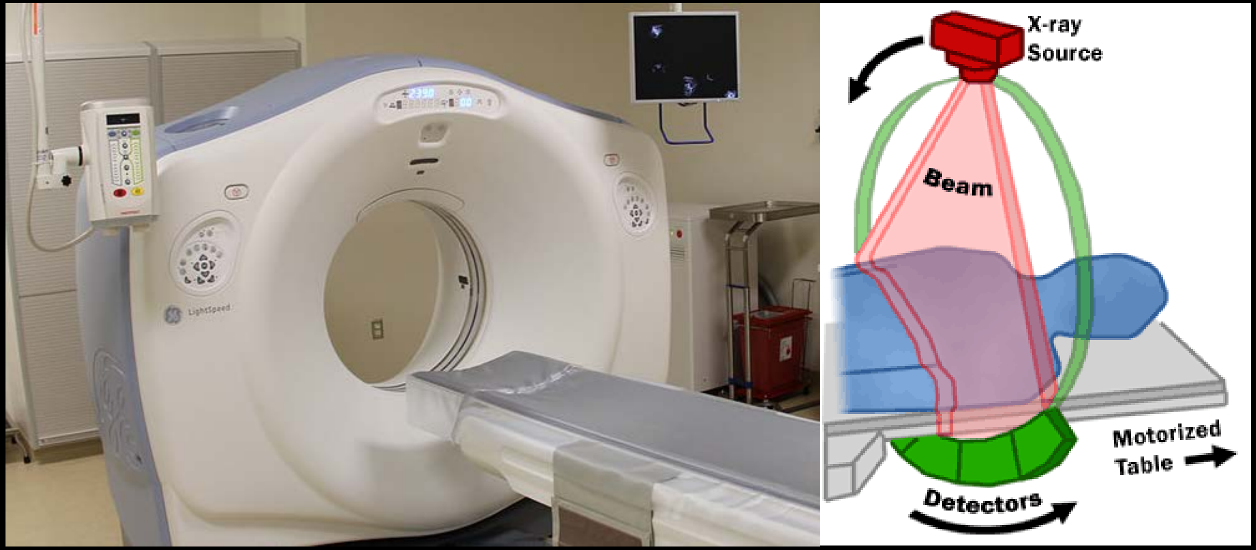
Seismic tomography



Inverse approach – Seismic tomography

- Medical computed tomography (CT)

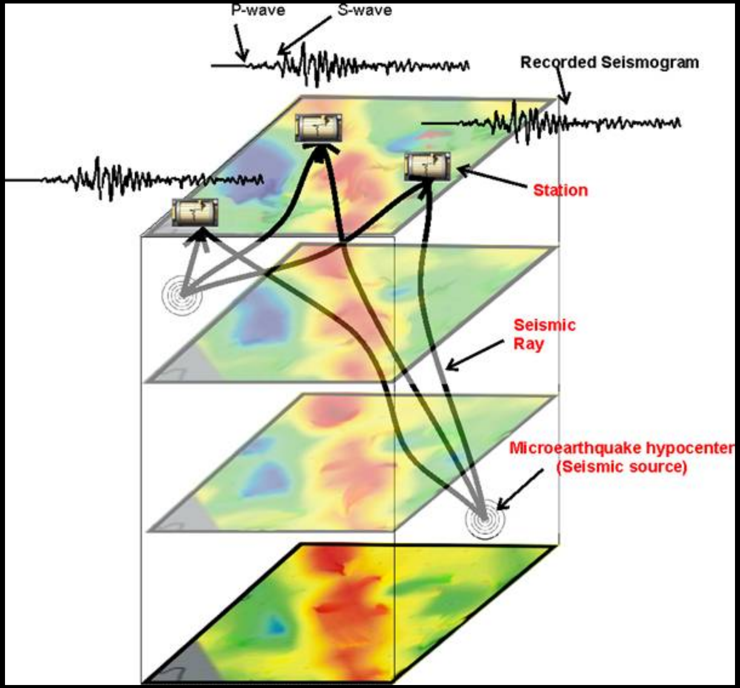
X-ray (linear)



Wikipedia

- Seismic tomography

Seismic waves (curved)



Landtech Geophysics

Inverse approach – Seismic tomography

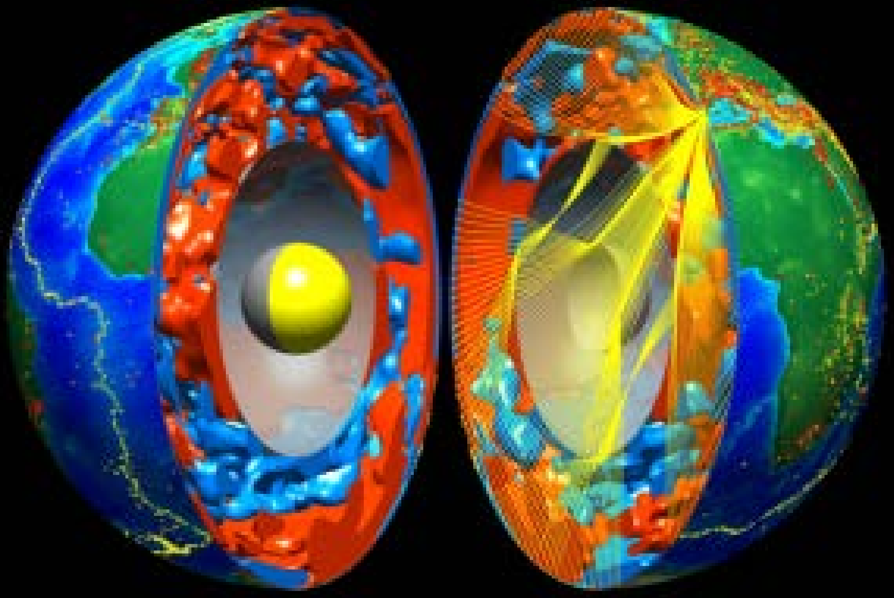
- Medical computed tomography (CT)

Combination of X-ray profiles (different angles)

Wikipedia

- Seismic tomography

Combination of seismic ray paths



Credit: Nathan Simmons

Problematic on seismic tomography

- Smoothed/damped images
  - penalty function

PART I

- Computationally expensive
  - Finite-frequency kernels
  - Full waveforms

PART II

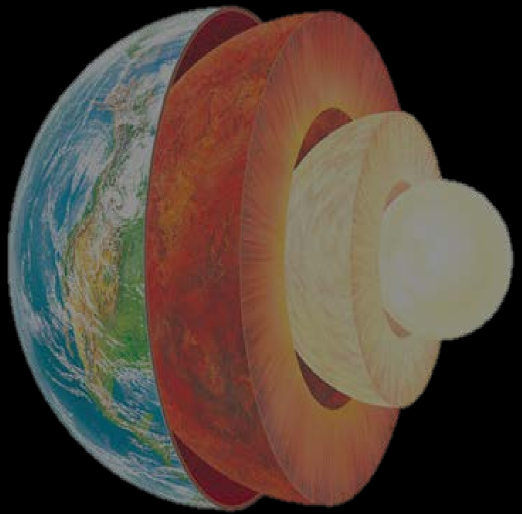
- Not for the high frequency data (Full waveform inversion)

Problematic on seismic tomography

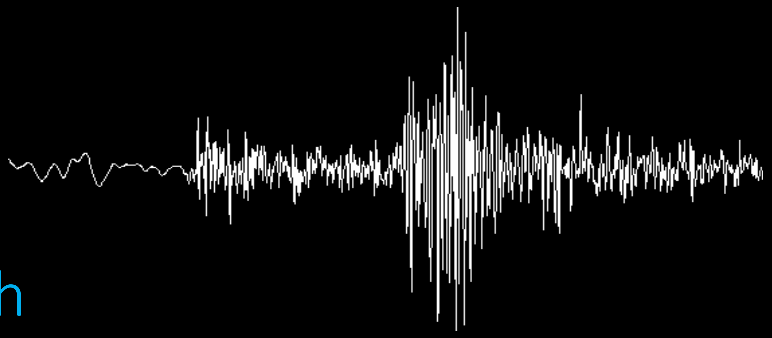
- Smoothed/damped images
  - penalty function

PART I

Remedy: Forward waveform modeling



A. Forward



Waveform modeling approach

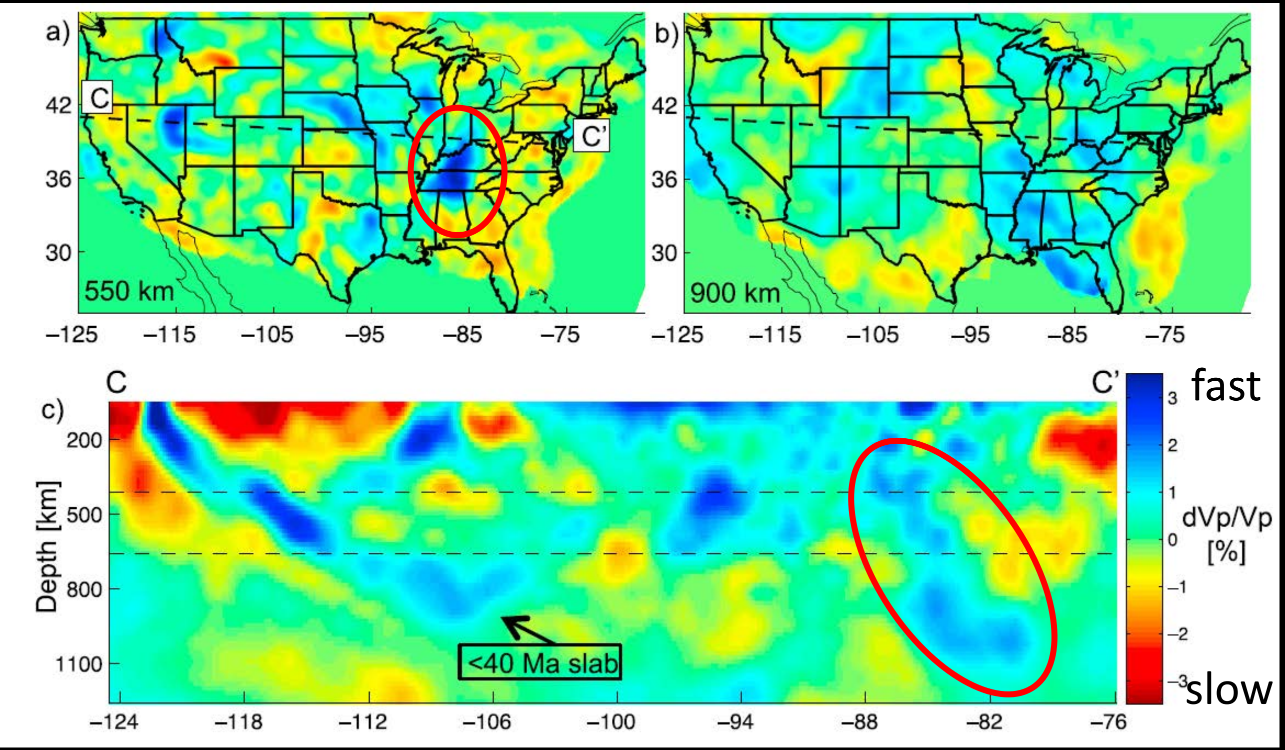
Lower Mantle Substructure Embedded in the Farallon Plate: The Hess Conjugate

Justin Yen-Ting Ko[1,2], Don V. Helmberger[2], Huilin Wang[2], Zhongwen Zhan[2]

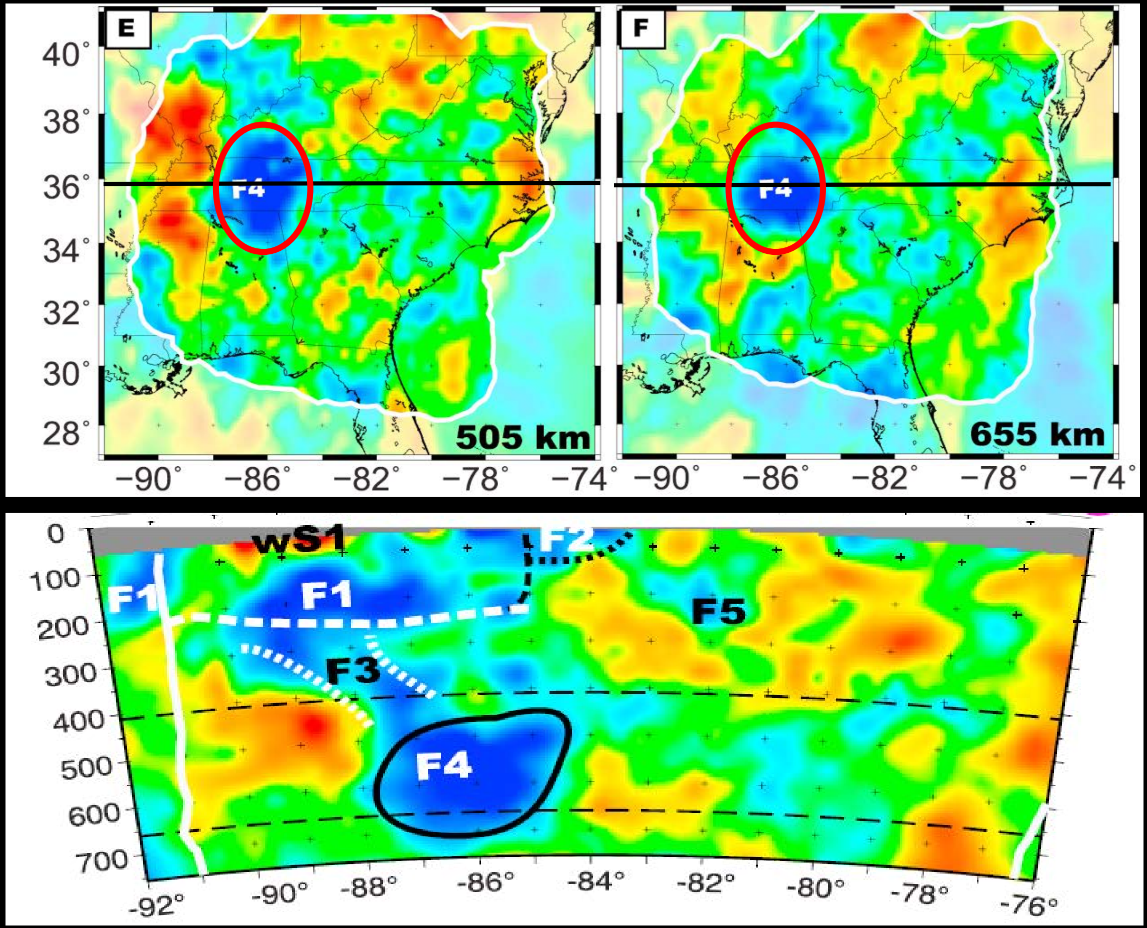
1. Institute of Oceanography, National Taiwan University
2. Seismological Laboratory, California Institute of Technology, CA 91125, USA

Problematic on travel-time tomography

High velocity anomaly



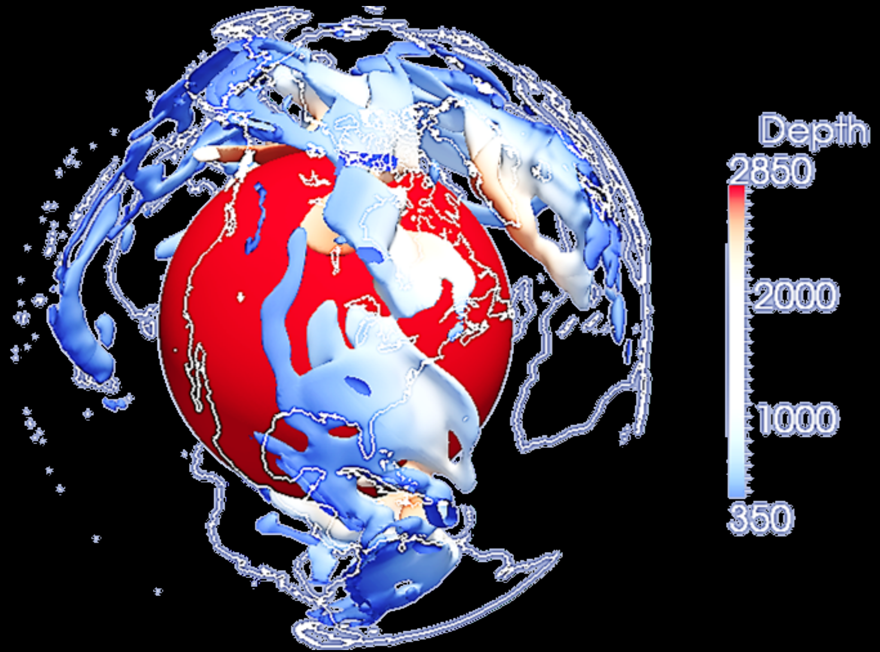
Schmandt and Lin, 2015

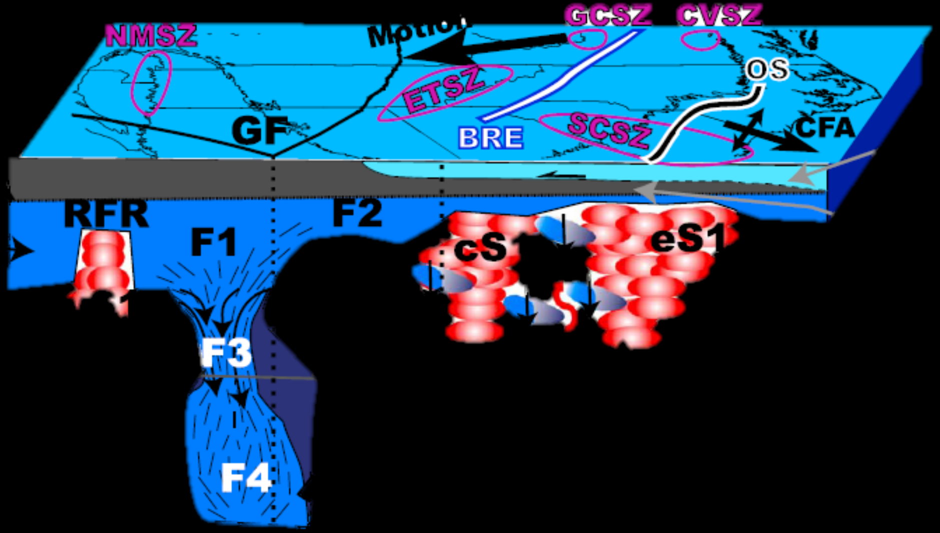


Biryol et al., 2016

Subduction-related

Delamination or drip





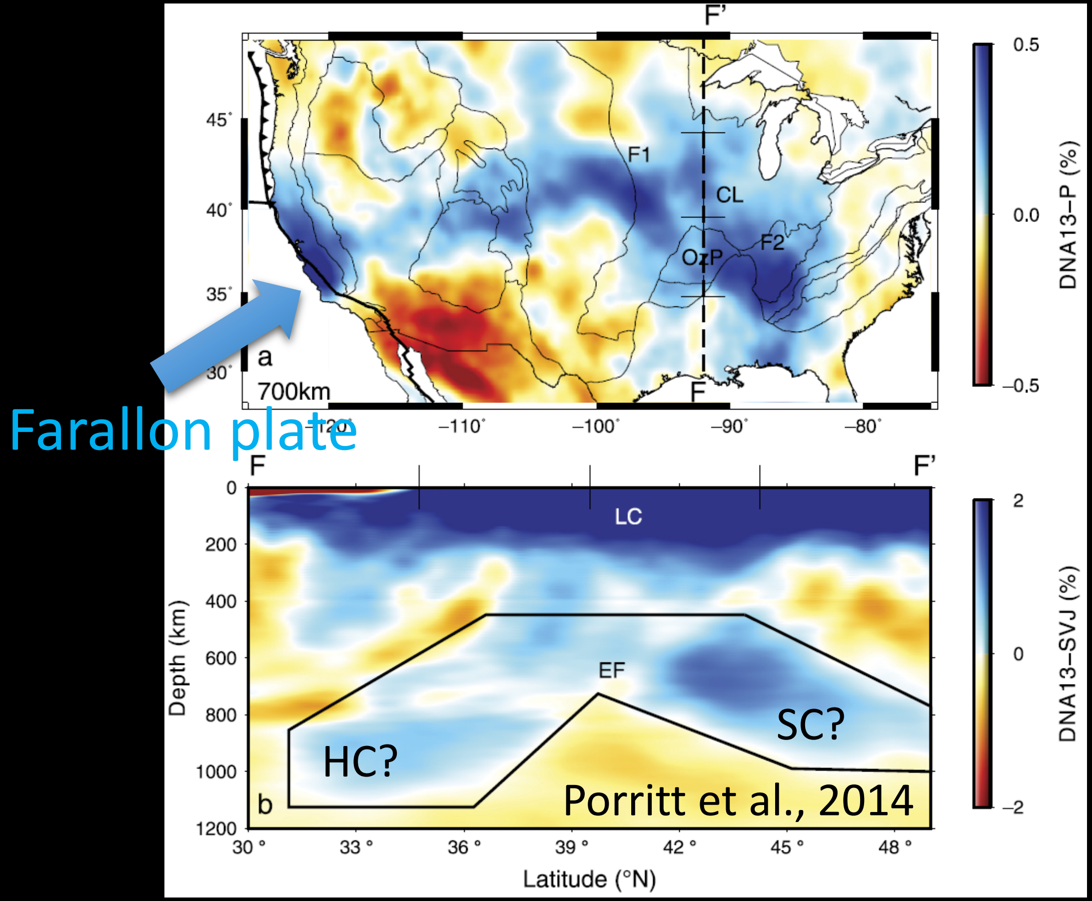
Wang et al., 2017

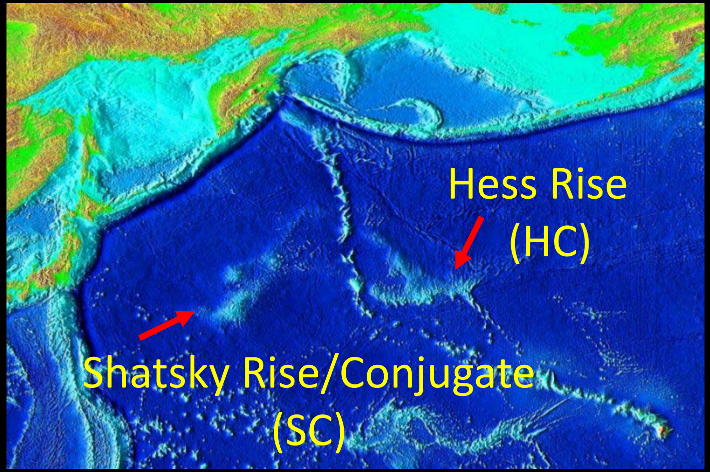
The same seismic signature

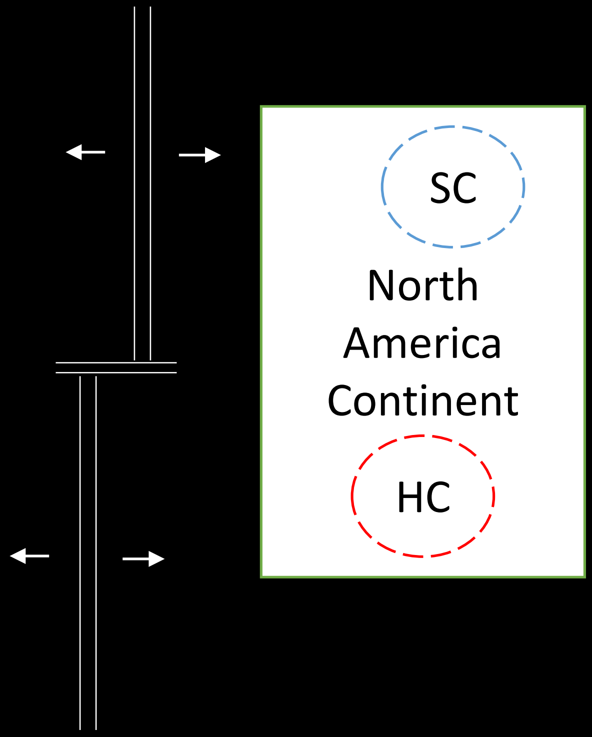
Biryol et al., 2016

Scenario I - Subduction-related remnants

Farallon plate subduction/Oceanic plateau subduction

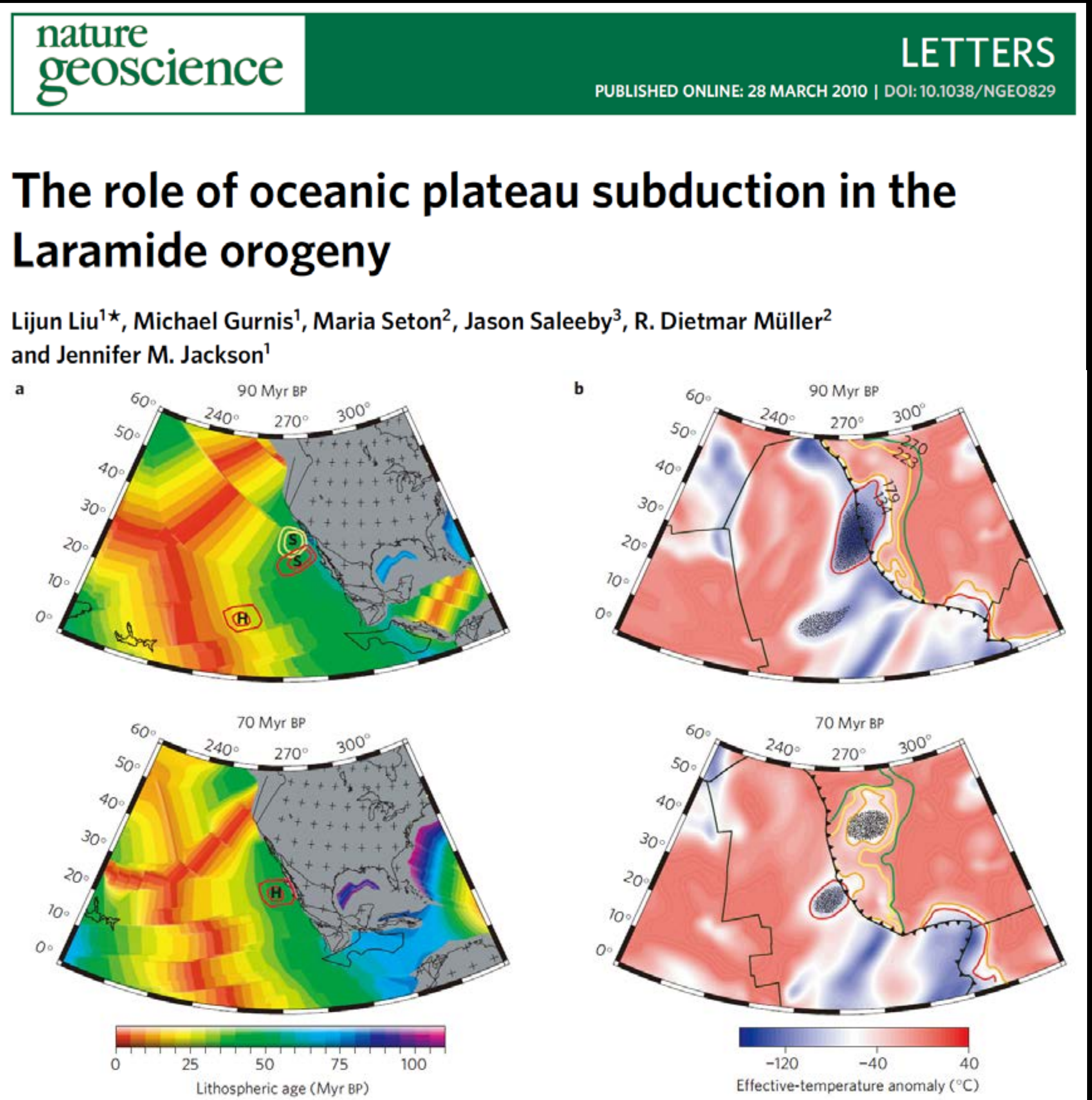






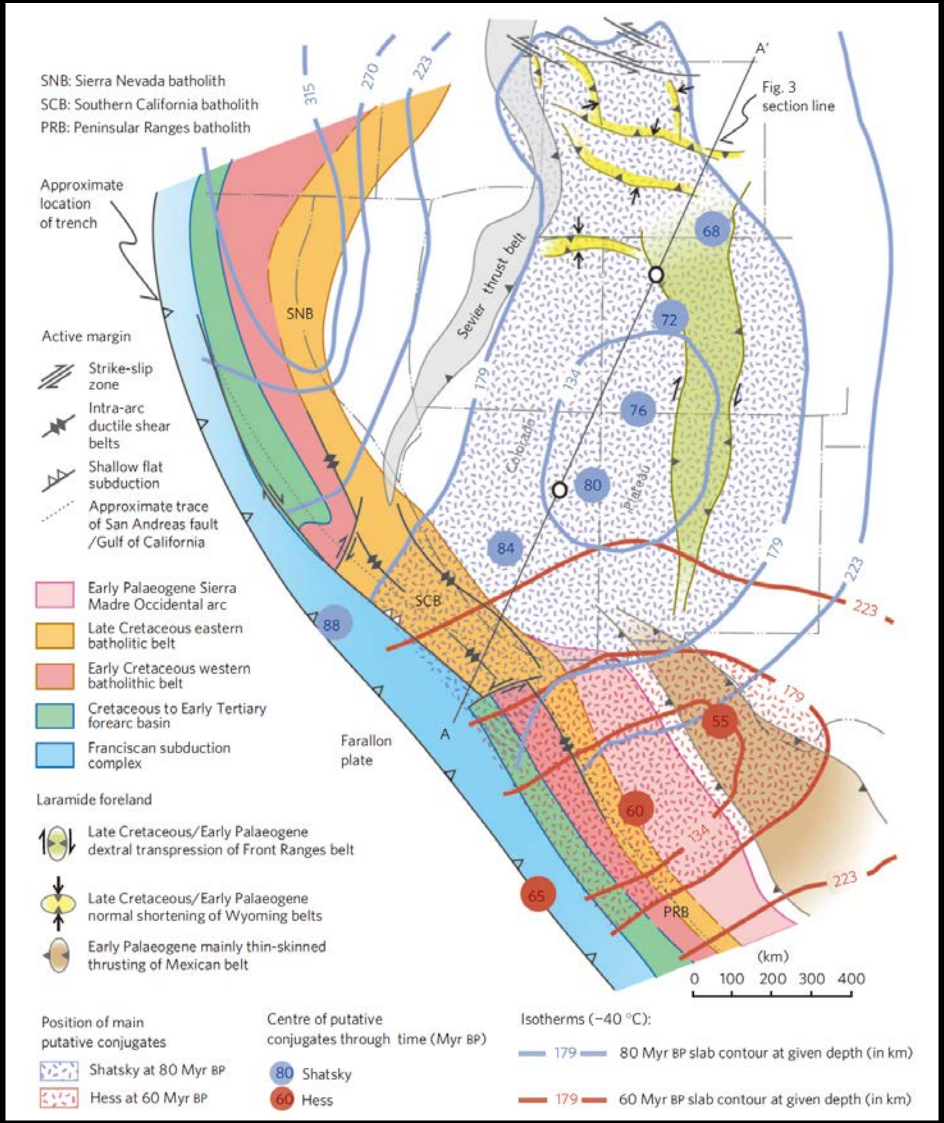
Pacific oceanic ridge

Scenario I – Subduction-related remnants

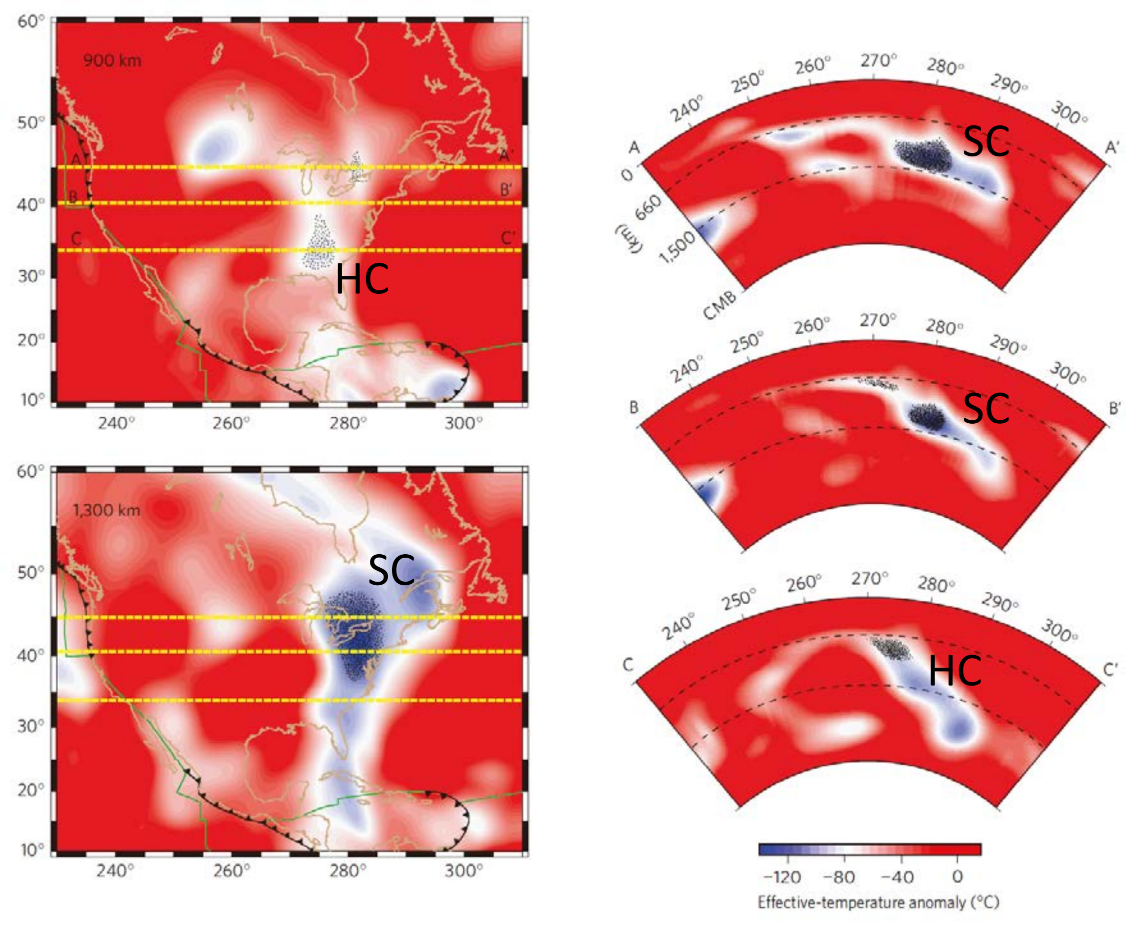

nature geoscience
LETTERS
PUBLISHED ONLINE: 28 MARCH 2010 | DOI: 10.1038/NGEO829

The role of oceanic plateau subduction in the Laramide orogeny

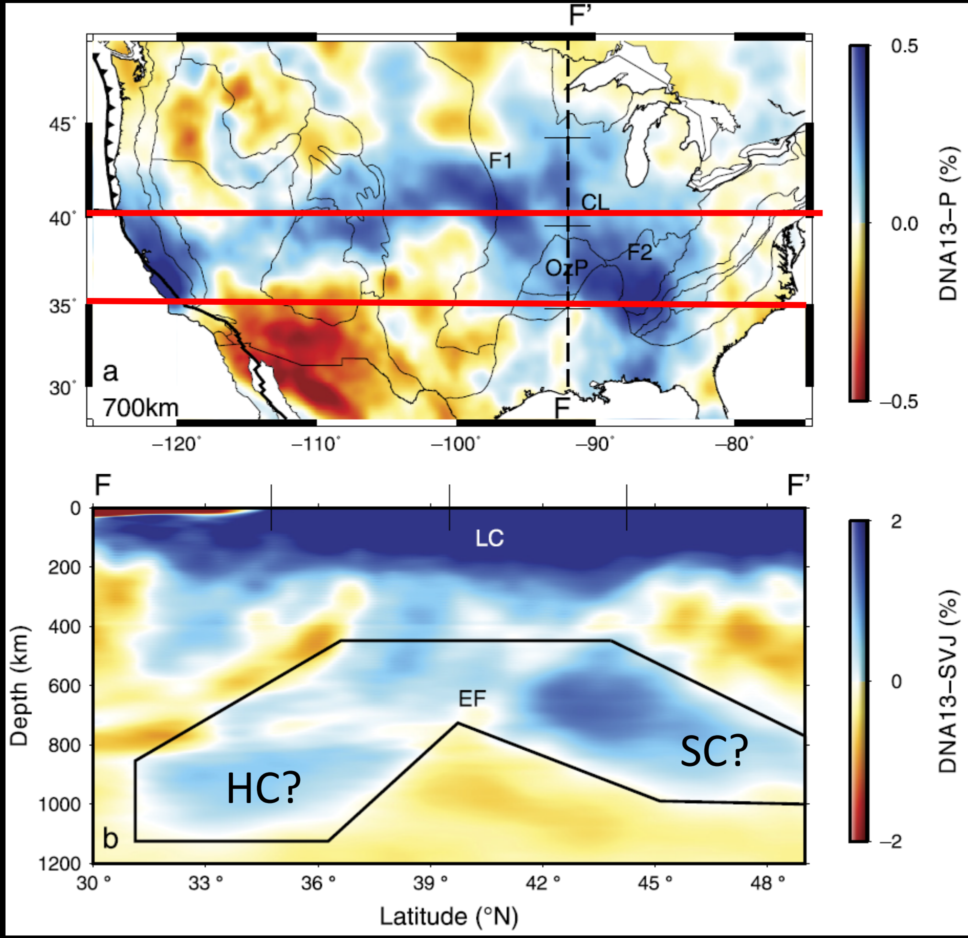
Lijun Liu[1]*, Michael Gurnis[1], Maria Seton[2], Jason Saleeby[3], R. Dietmar Müller[2] and Jennifer M. Jackson[1]



Scenario I – Subduction-related remnants

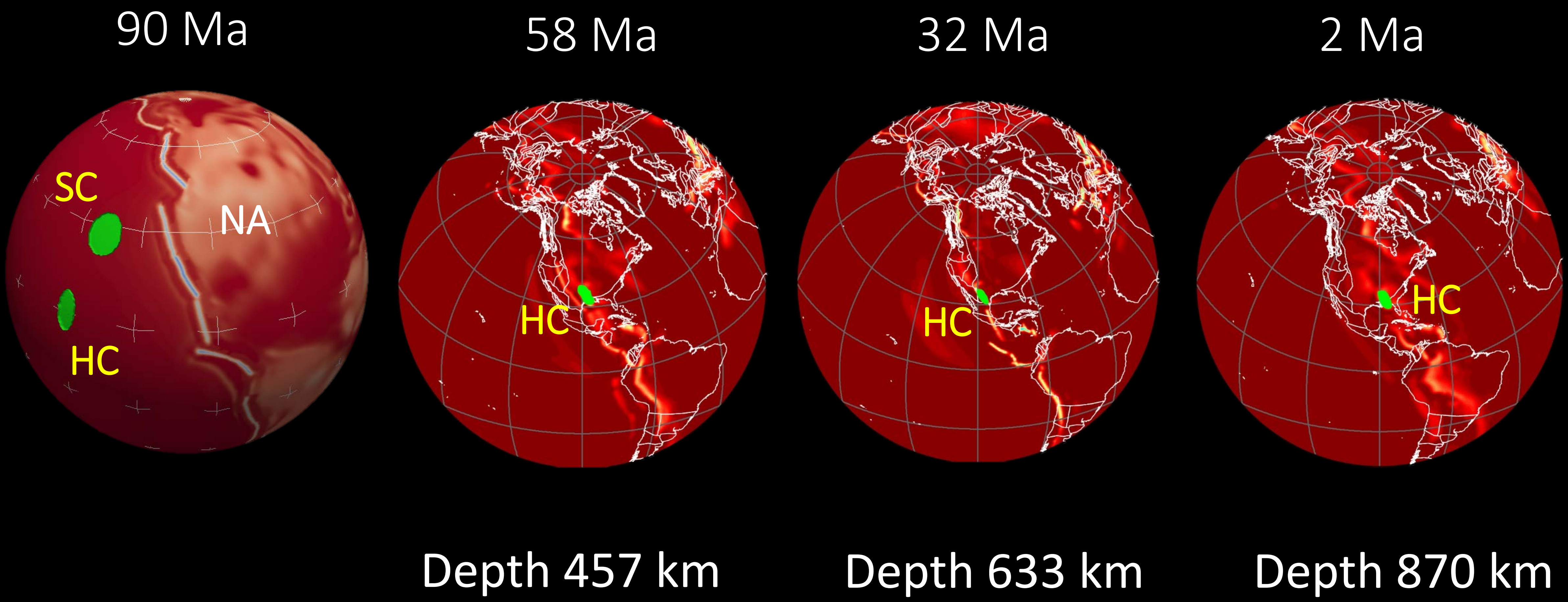


Liu et al., 2010

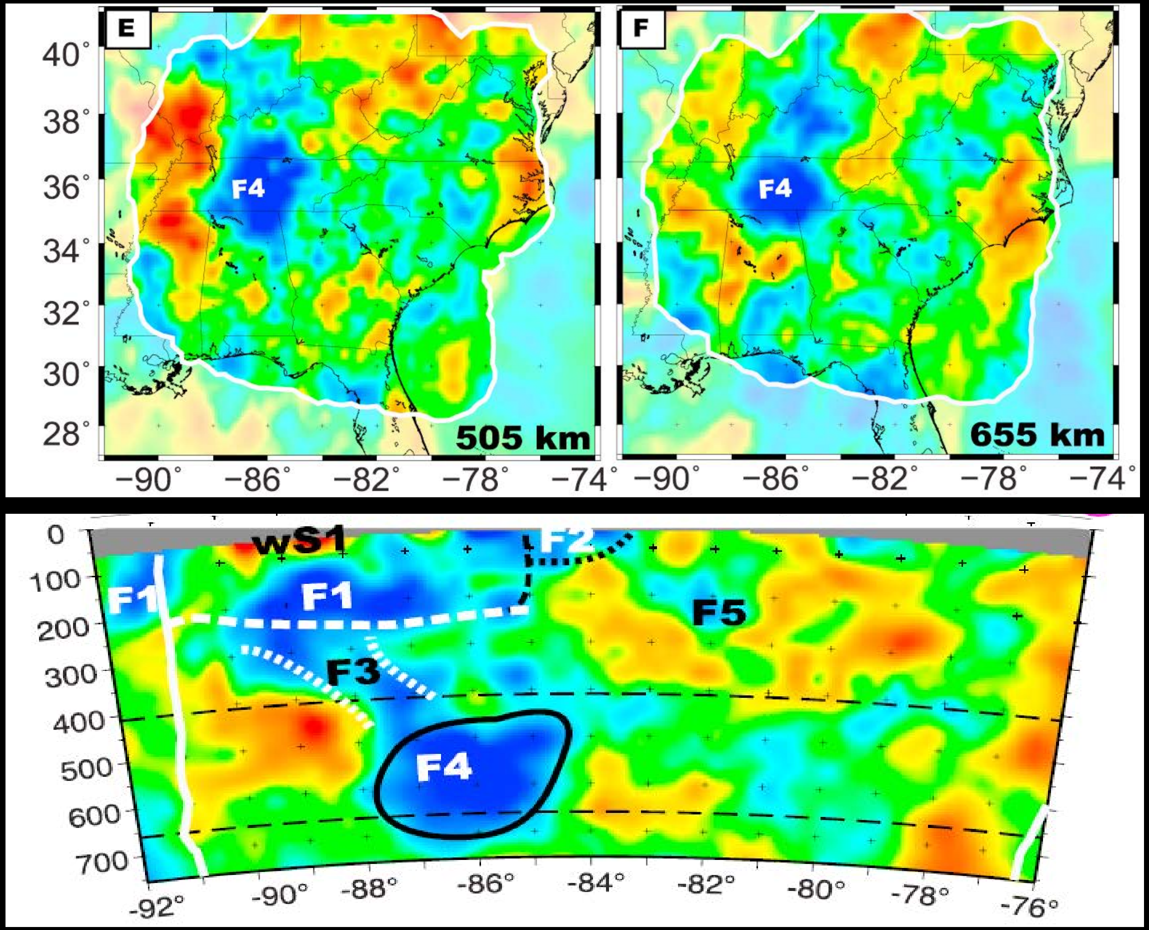


Porritt et al., 2014

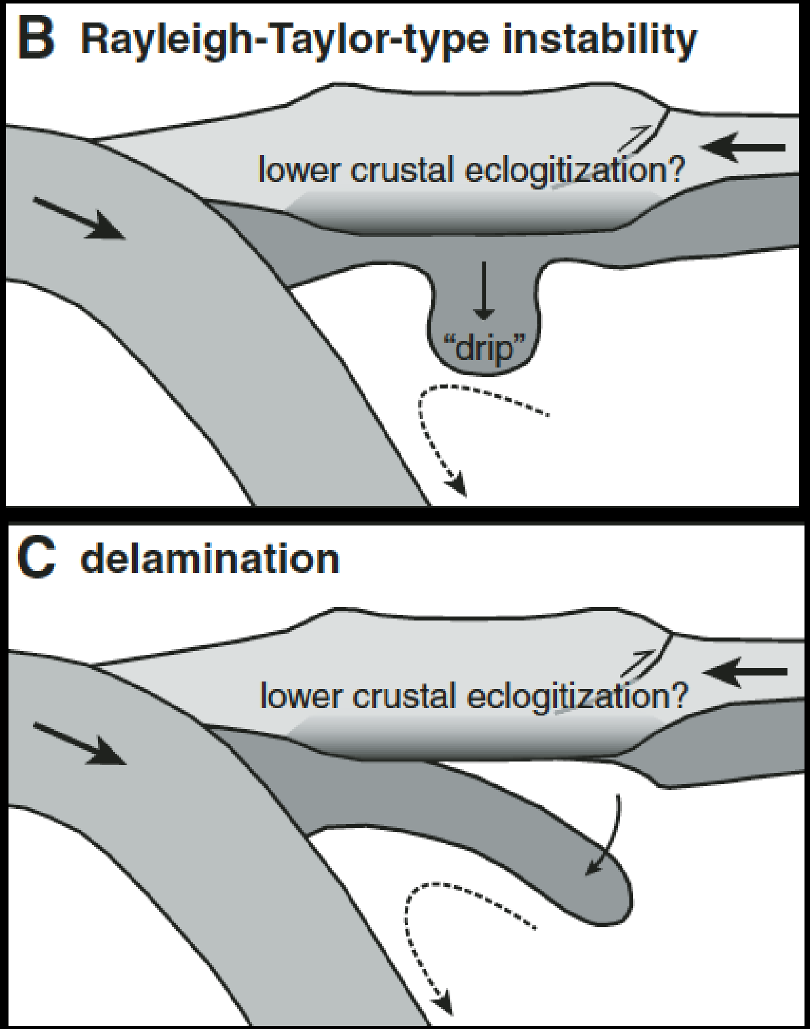
Scenario I – Subduction-related remnants



Scenario II – delamination or drip



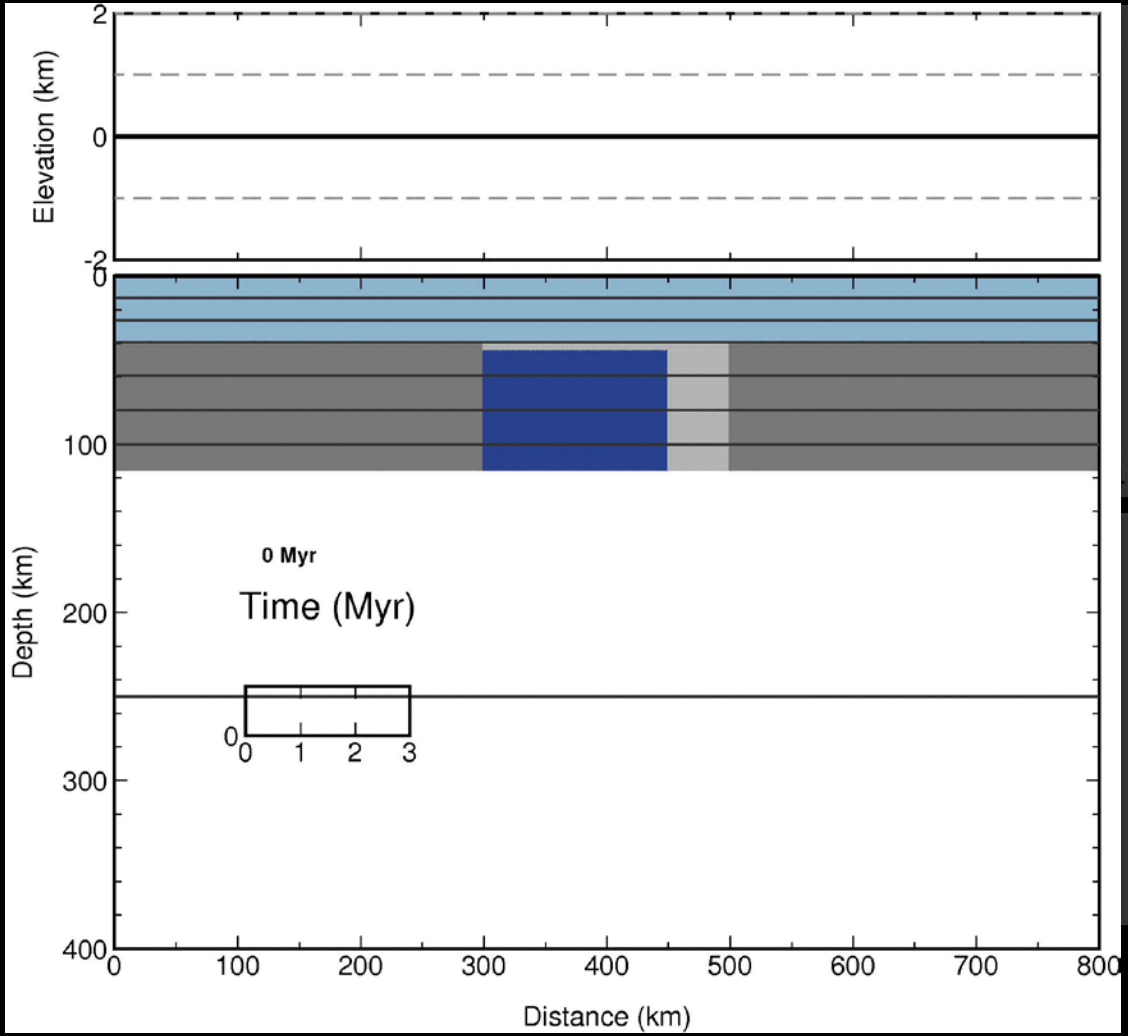
Biryol et al., 2016

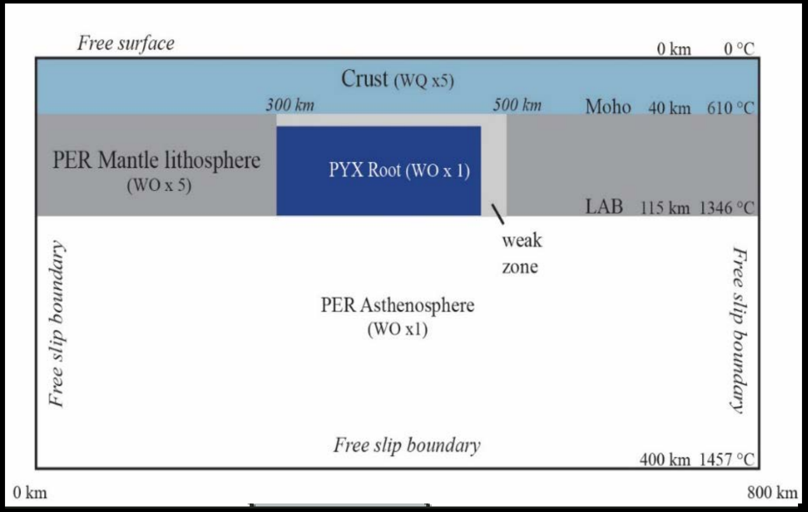


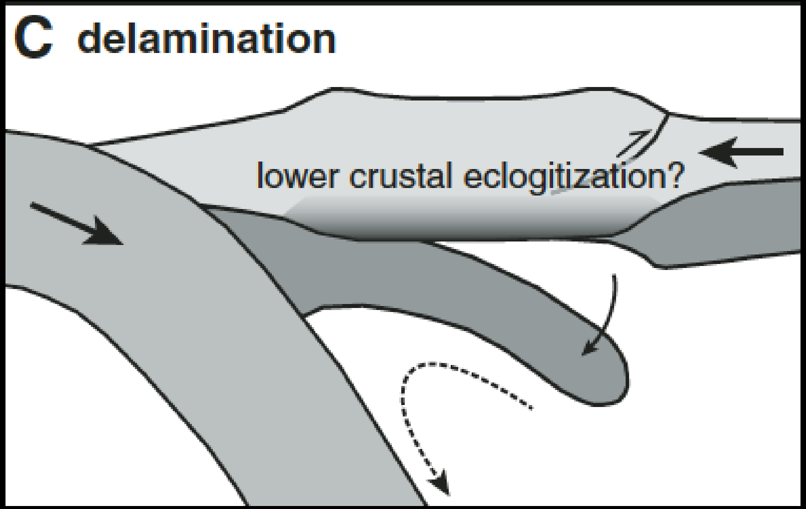
Wang et al., 2016

Scenario II – delamination or drip

- Thinner lithosphere
- Volcanism





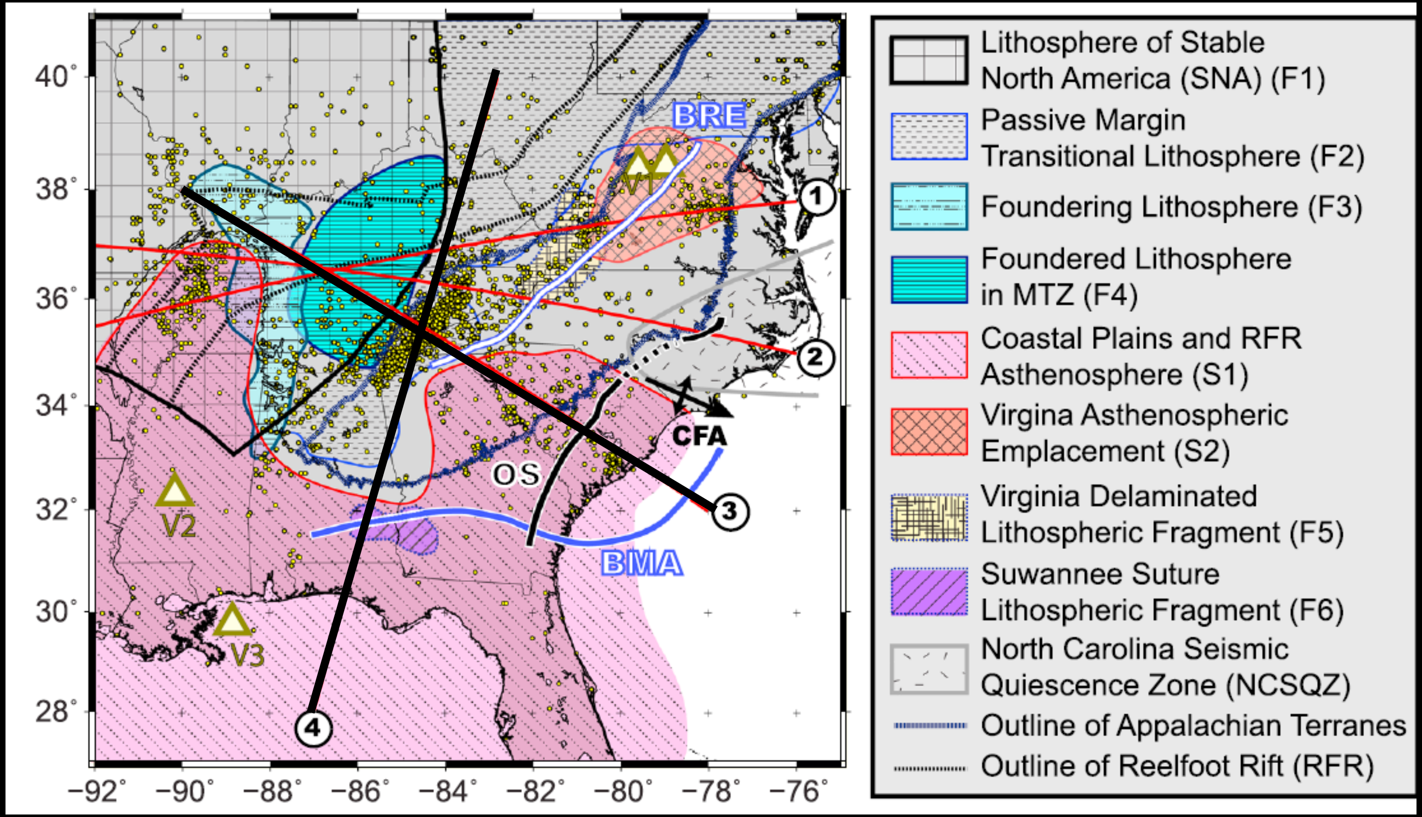


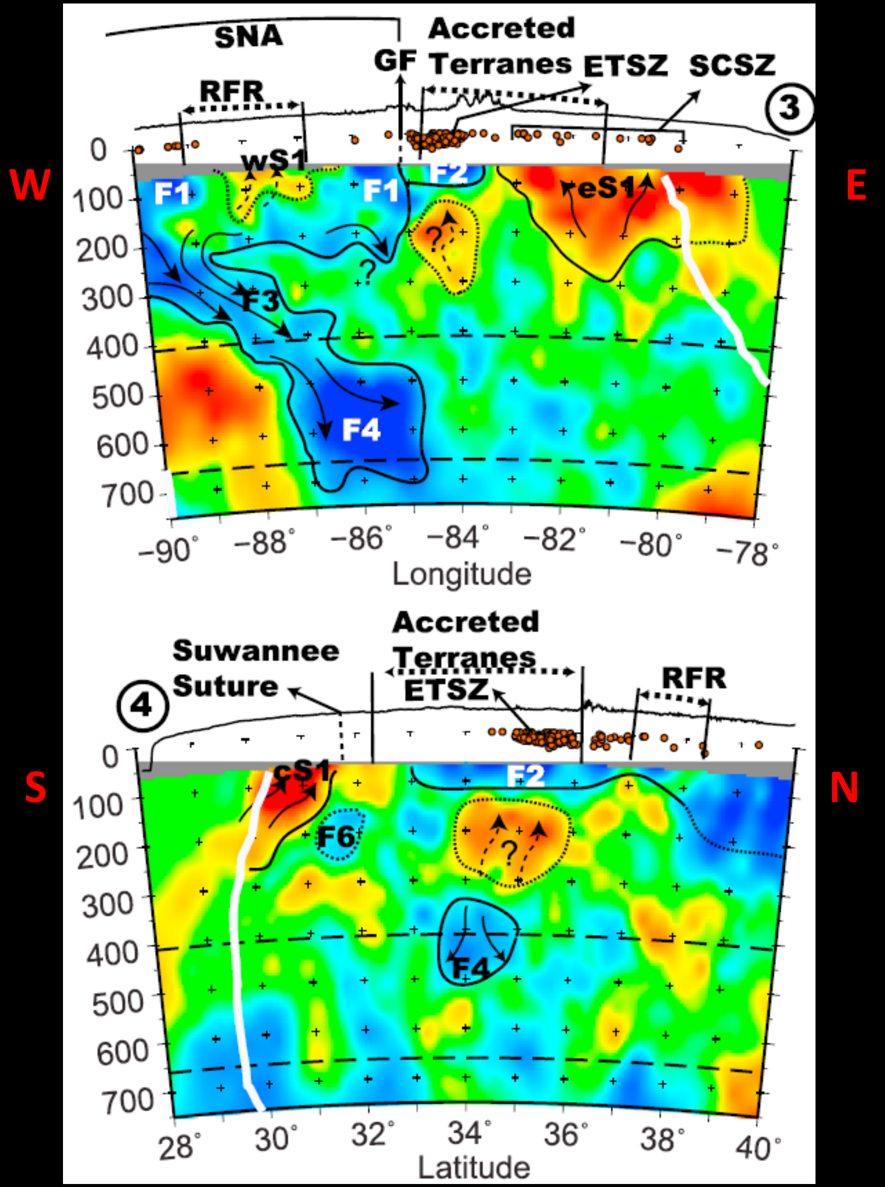
Wang et al., 2016

Scenario II – delamination or drip

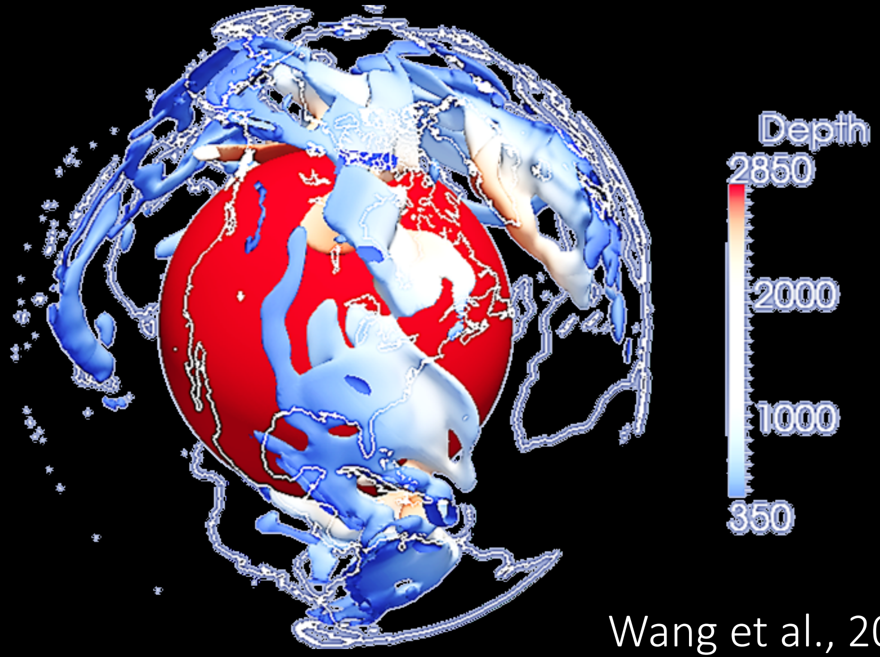
Lithospheric removal

Thinner lithosphere/volcanism

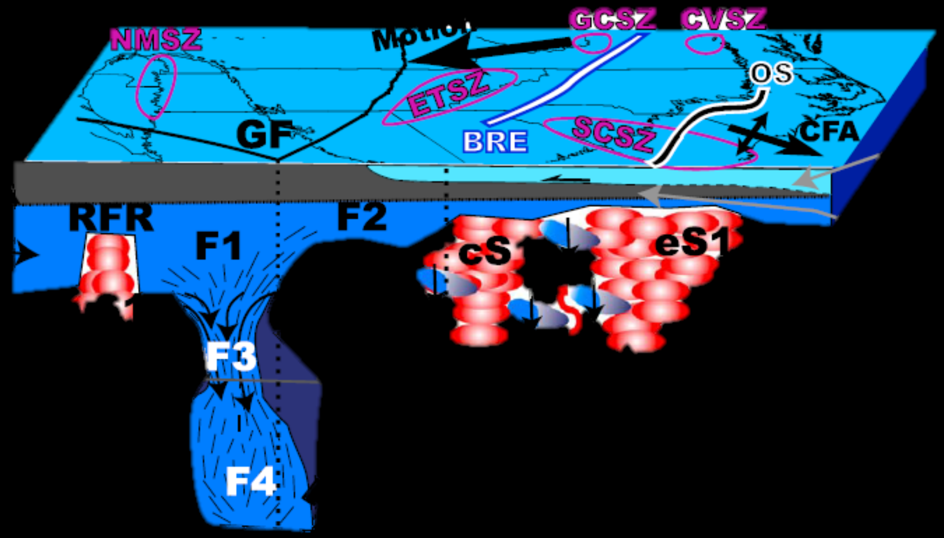




Biryol et al., 2016



Wang et al., 2017



Biryol et al., 2016

Why the high velocity remnants in the mid/deep mantle are important?

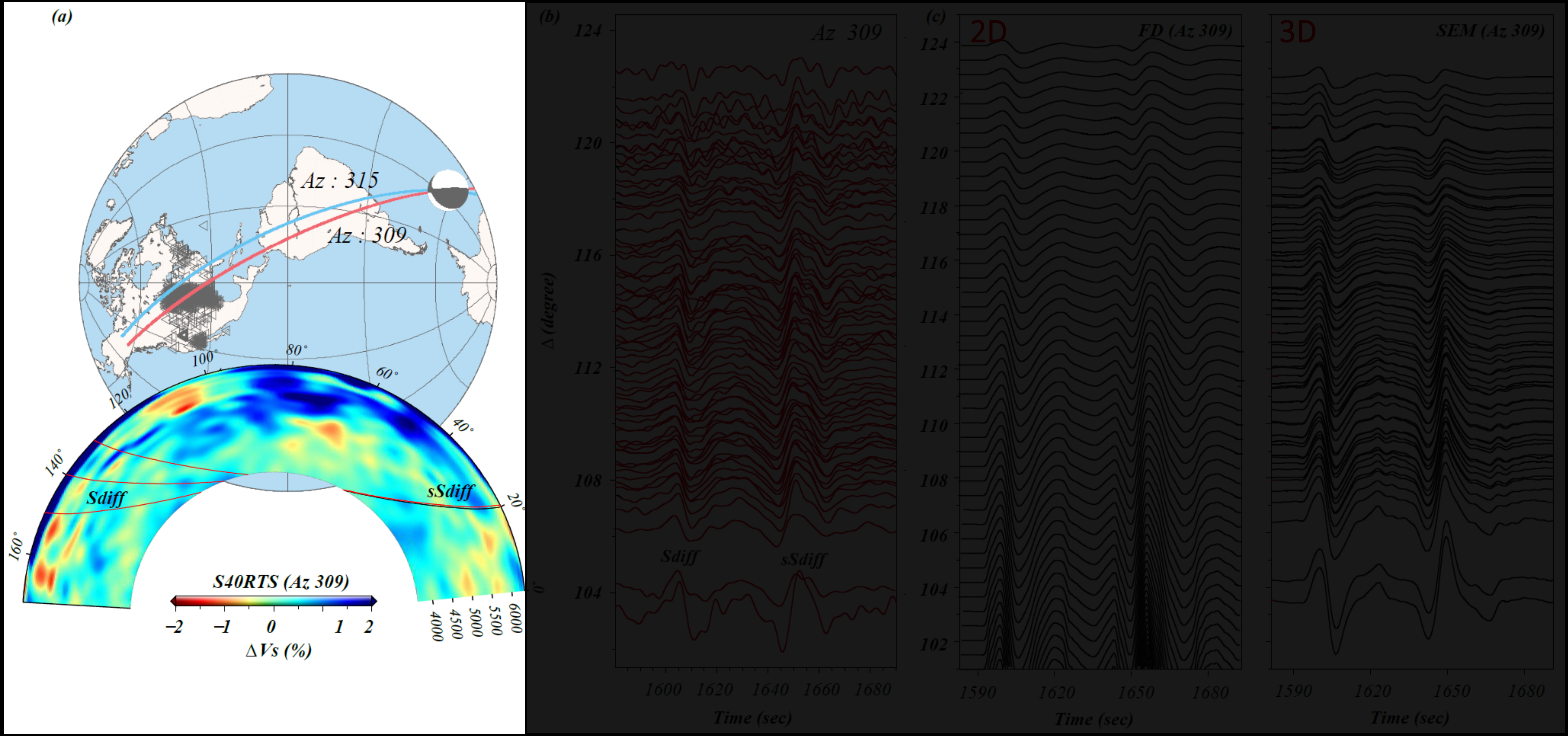
1. Evolution of the surface tectonics (e.g., subduction process)
2. Mantle dynamics (e.g., Thermal structure)

Seismic tomography vs waveform modeling

- Travel-time tomography
  - Damped/smoothed images
  - Non-disturbed waveforms

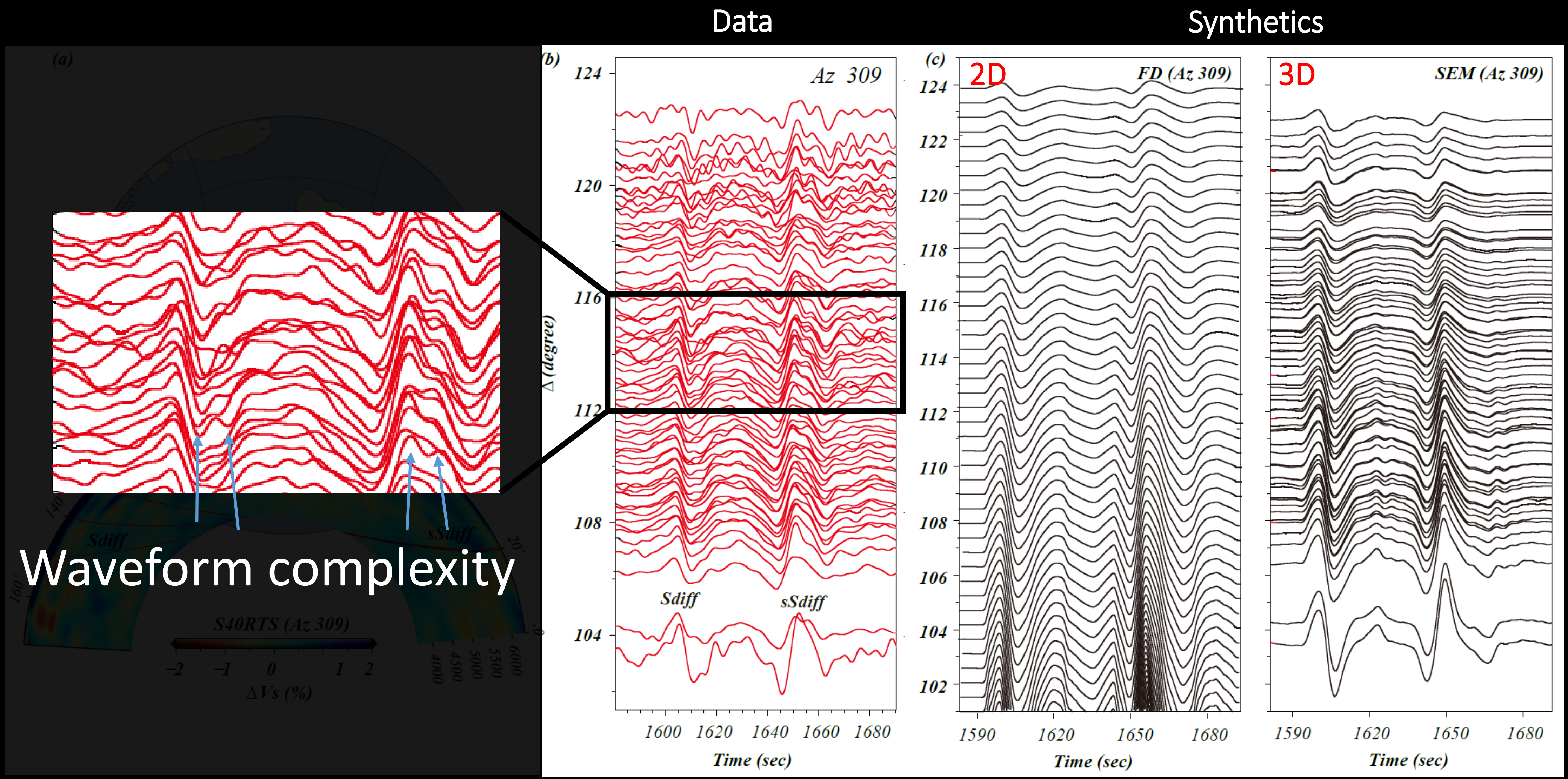
- Waveform modeling approach
  - Stress the effects of velocity structure on waveforms
  - Small scale structure or sharp edge of structure

Seismic tomography vs waveform modeling



Ko and Helmberger, in prep.

Seismic tomography vs waveform modeling



Ko and Helmberger, in prep.

Seismic tomography vs waveform modeling

- Travel-time tomography
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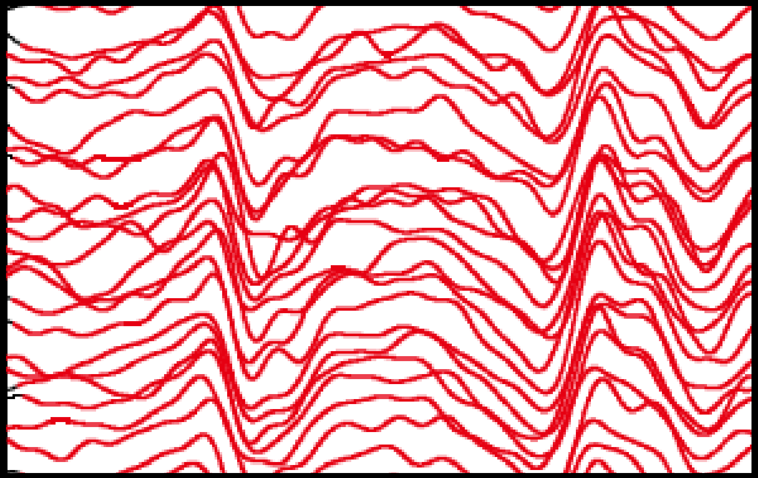
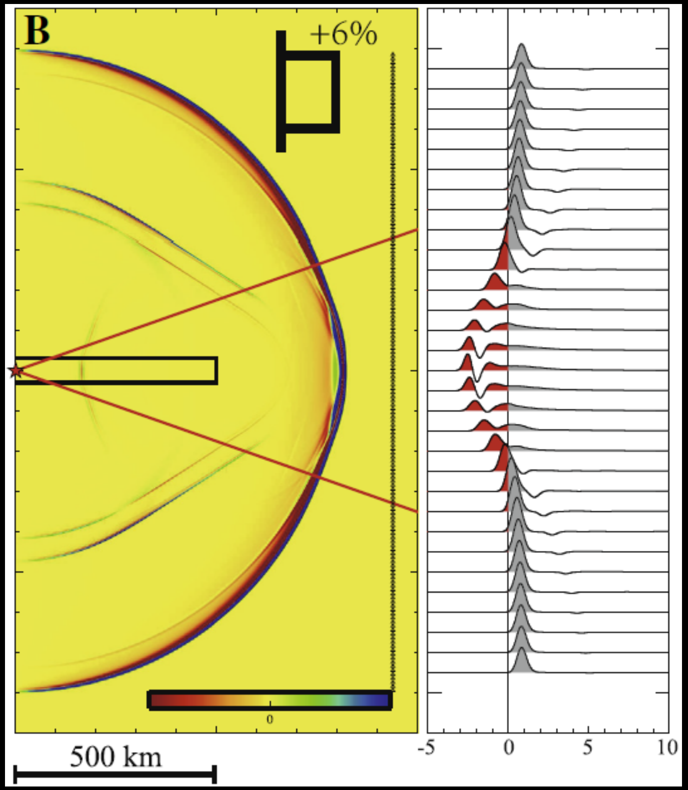


- Waveform modeling approach
  - Stress the effects of velocity structure on waveforms
  - Small scale structure or sharp edge of structure

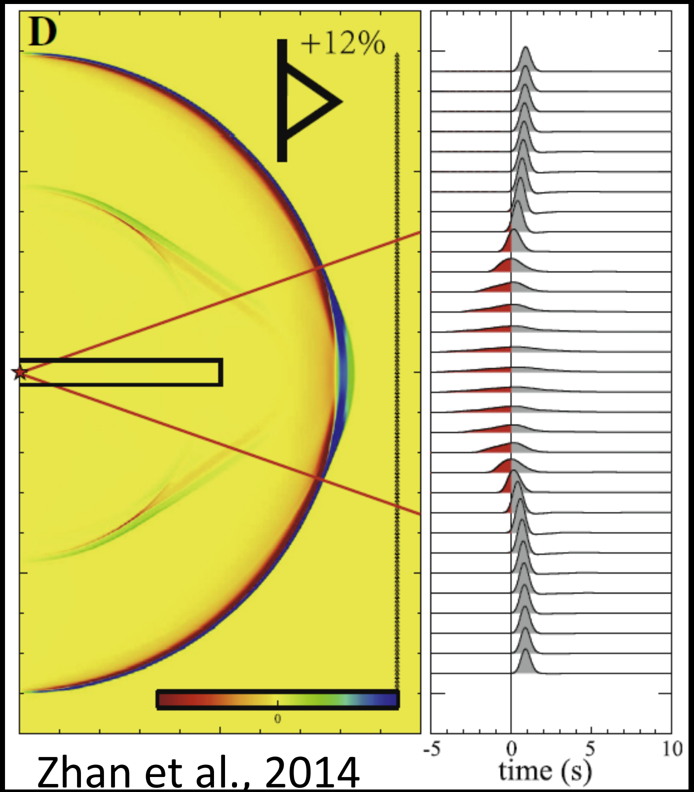
Waveform distortions and complexities

- Travel-time, amplitude and **waveform shape**
- Better constraints on the **sharpness** and morphology of anomalies

Sharp velocity boundary

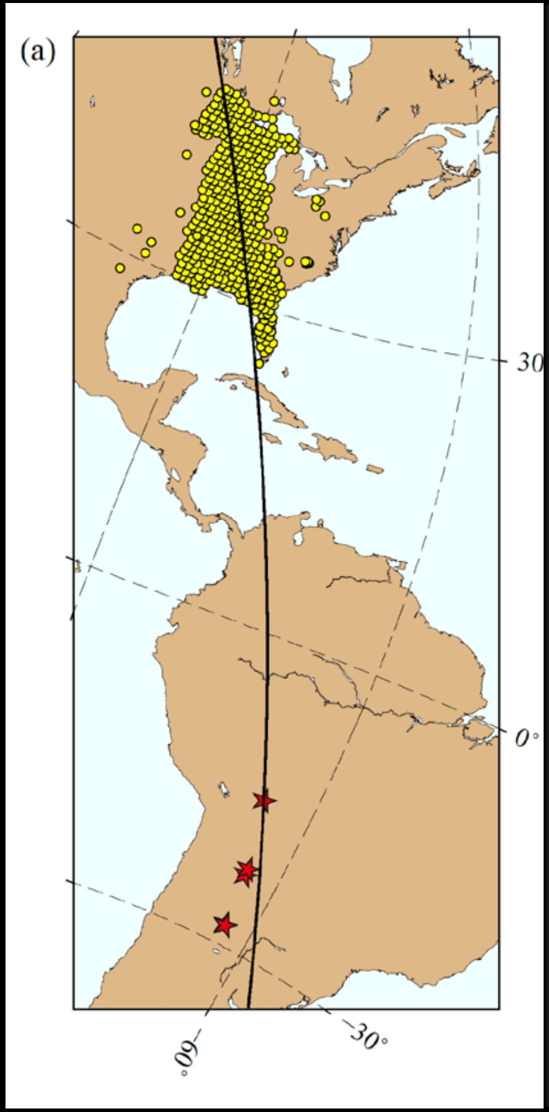


Smoothed velocity boundary

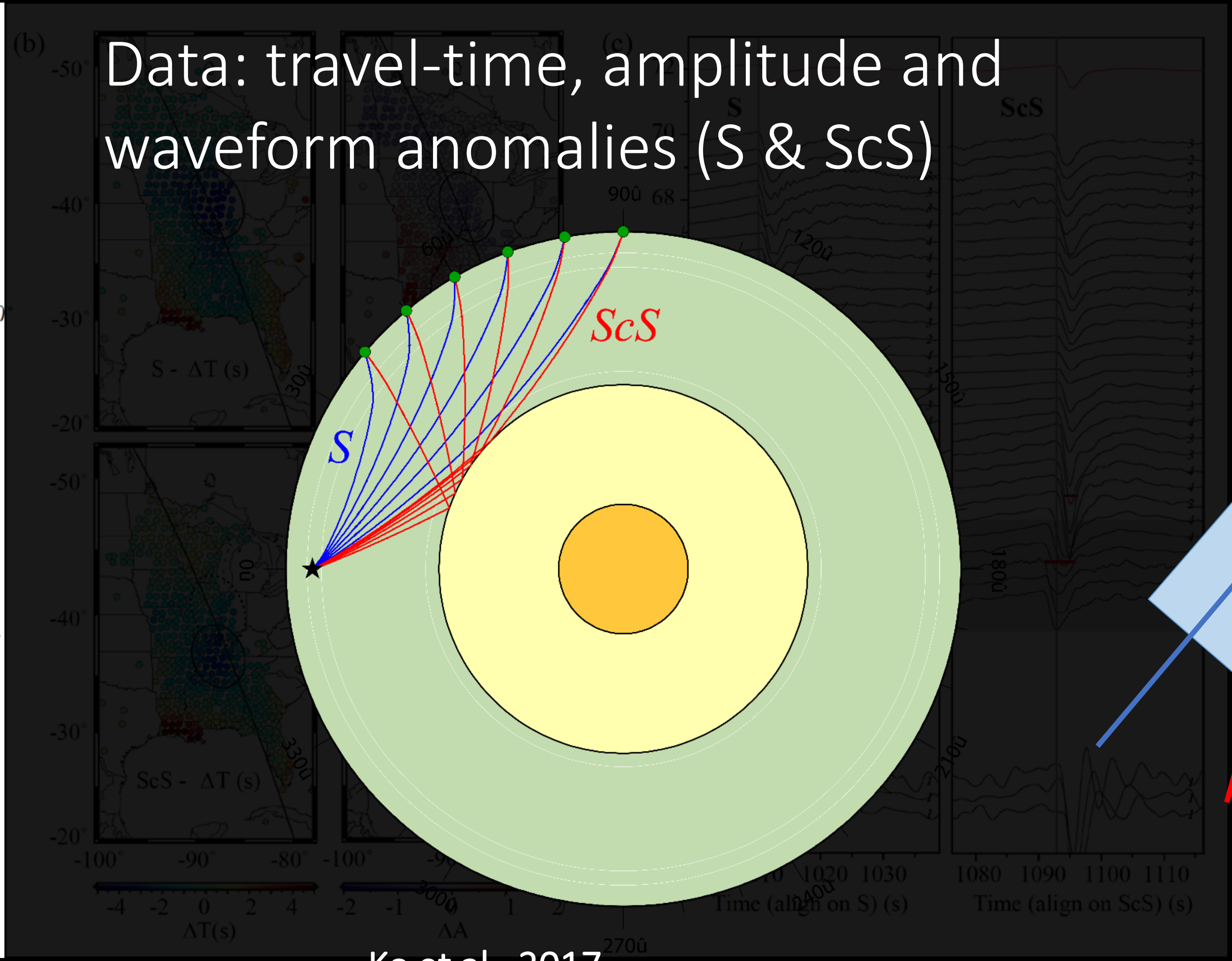


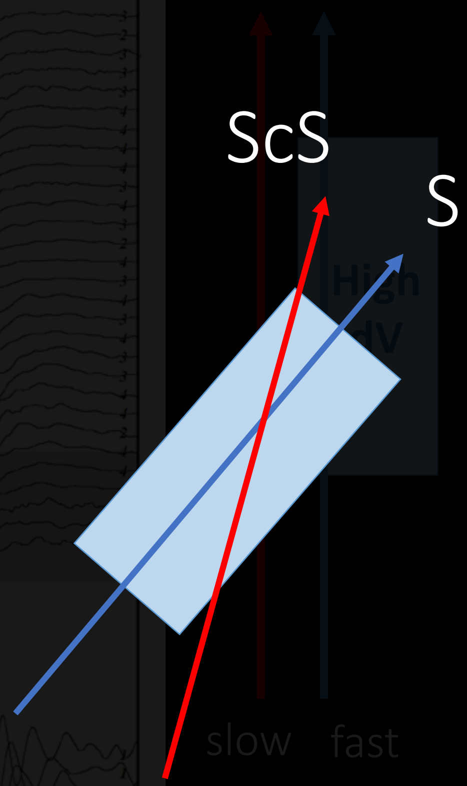
Zhan et al., 2014

Seismic observations



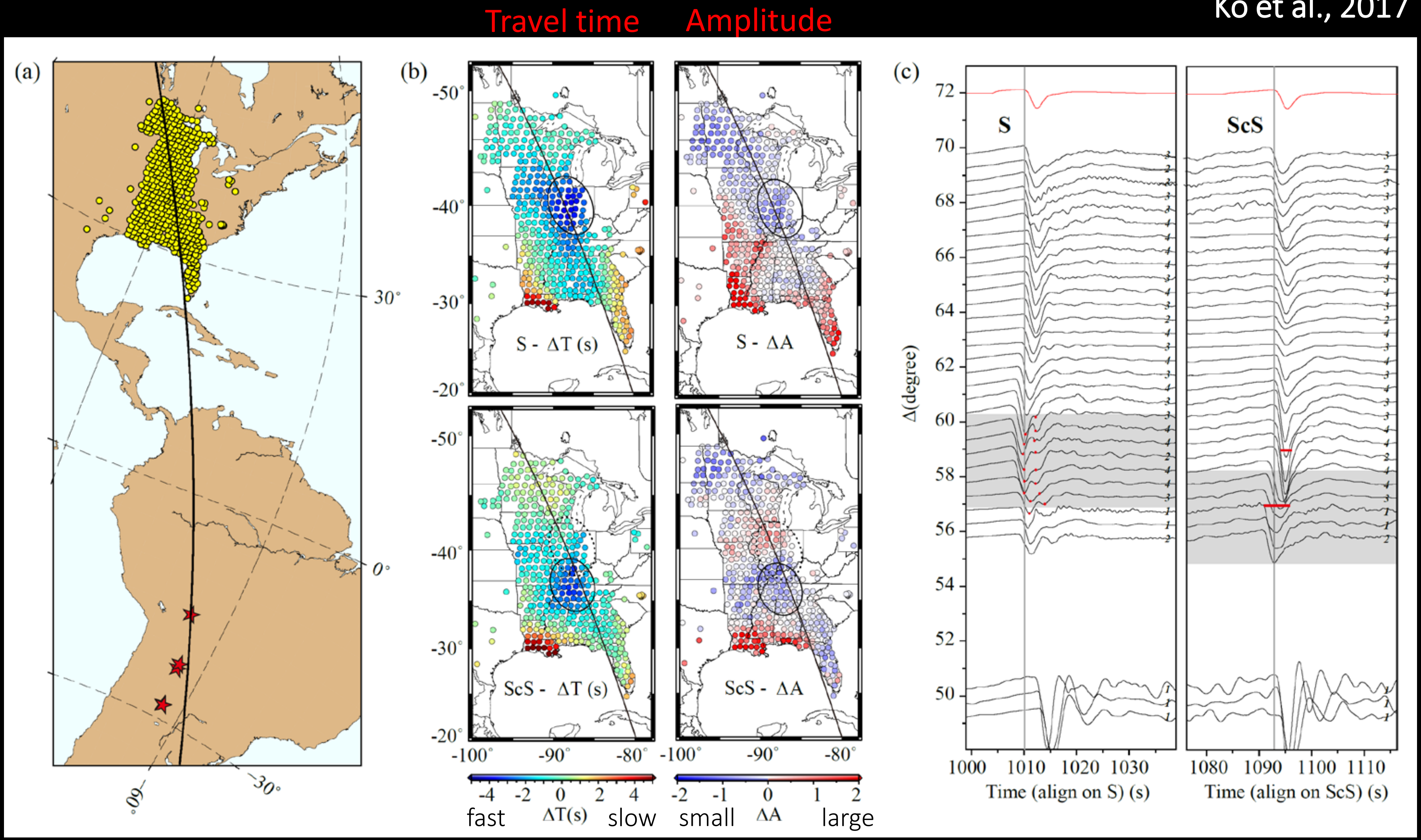
Data: travel-time, amplitude and waveform anomalies (S & ScS)

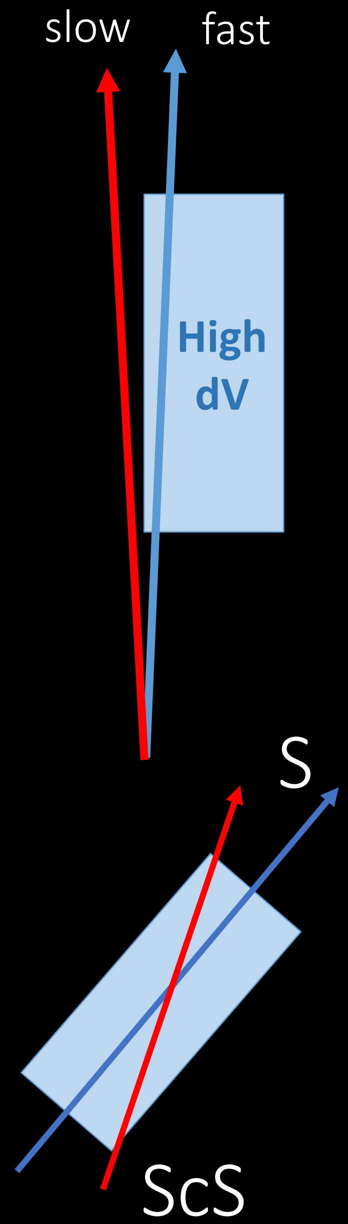




Ko et al., 2017

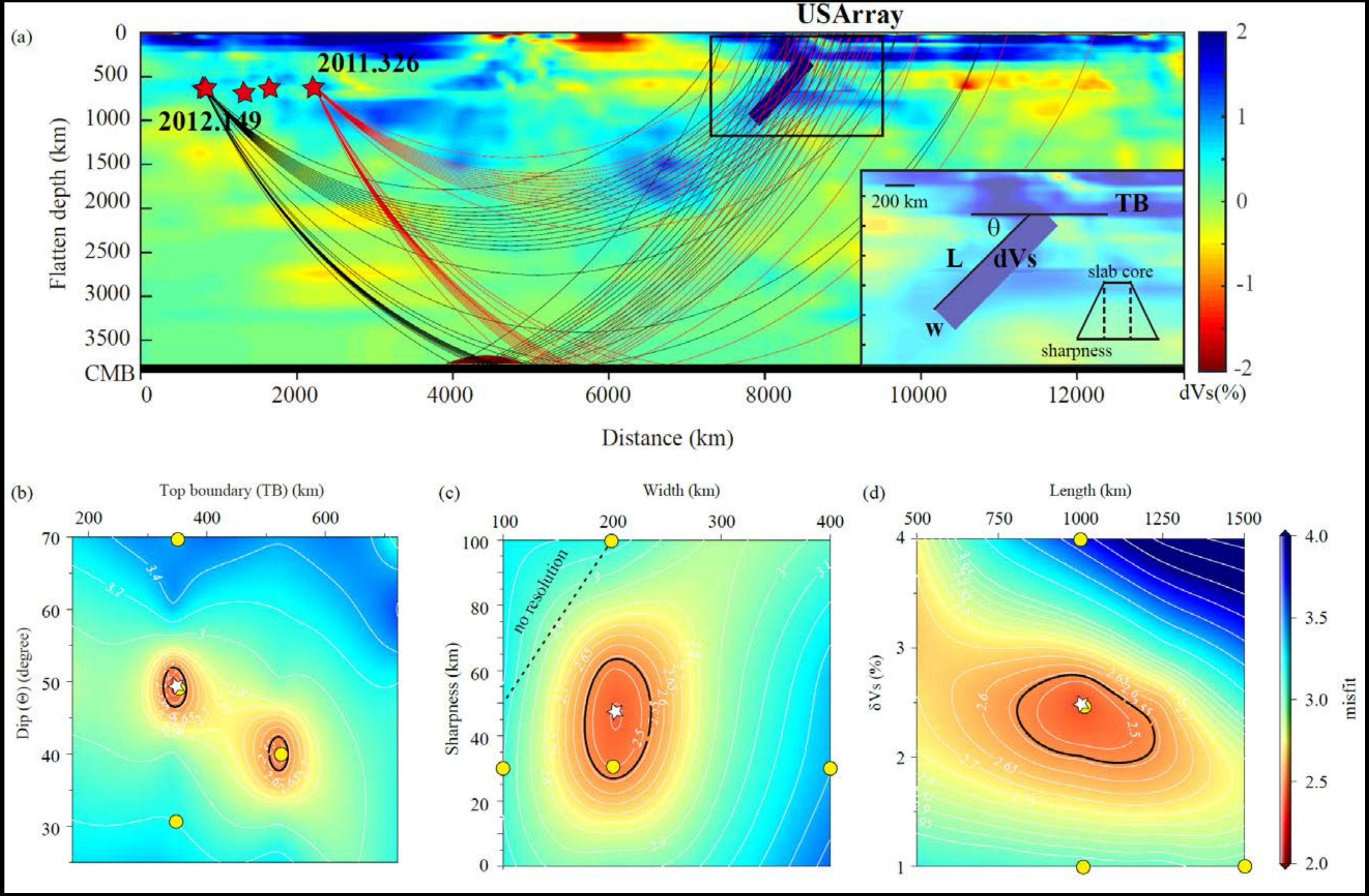
Seismic observations





The optimal 2D model

Grid search from a library of idealized slab models



$$\min \sum_{i=1}^{5} \{\Delta T + \Delta A + \Delta W\}$$

Data-Synthetics

i: 5 different events at different distances

Sharp edges

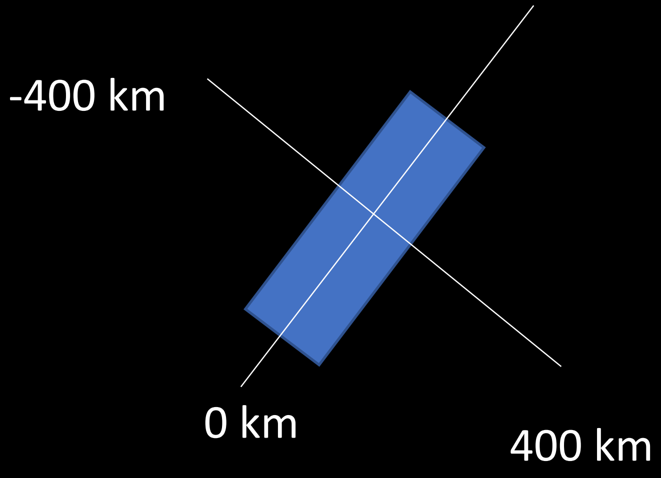
Ko et al., 2017

The comparison of the effective thickness

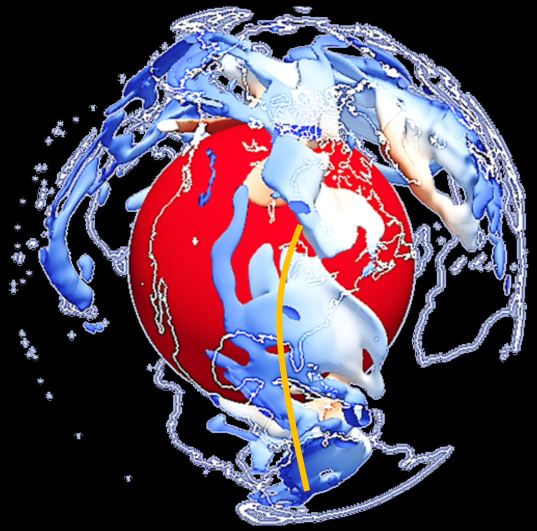
Purely thermal

Key measurement: Structural sharpness (velocity gradient)

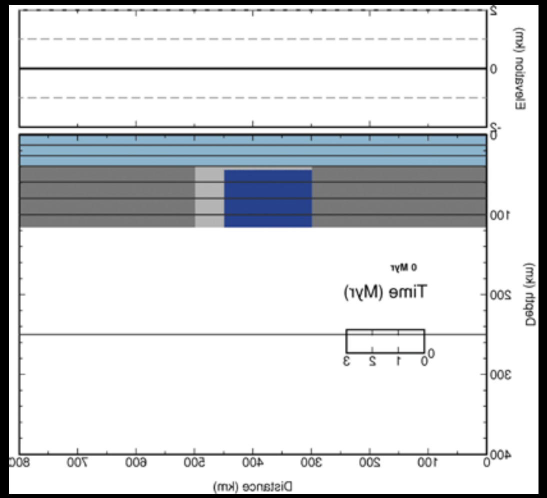
3D & optimal model

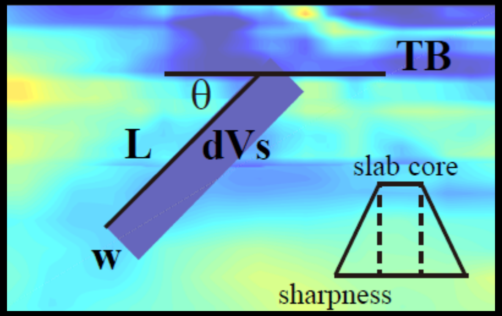


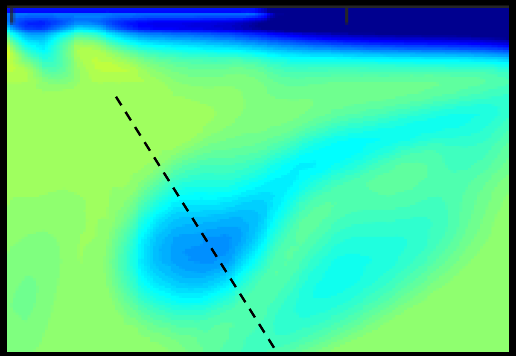
Thermal slab

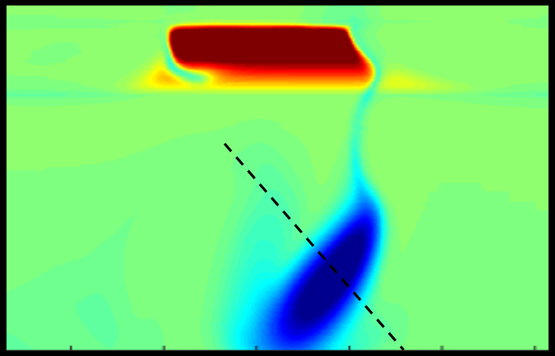


Thermal delamination

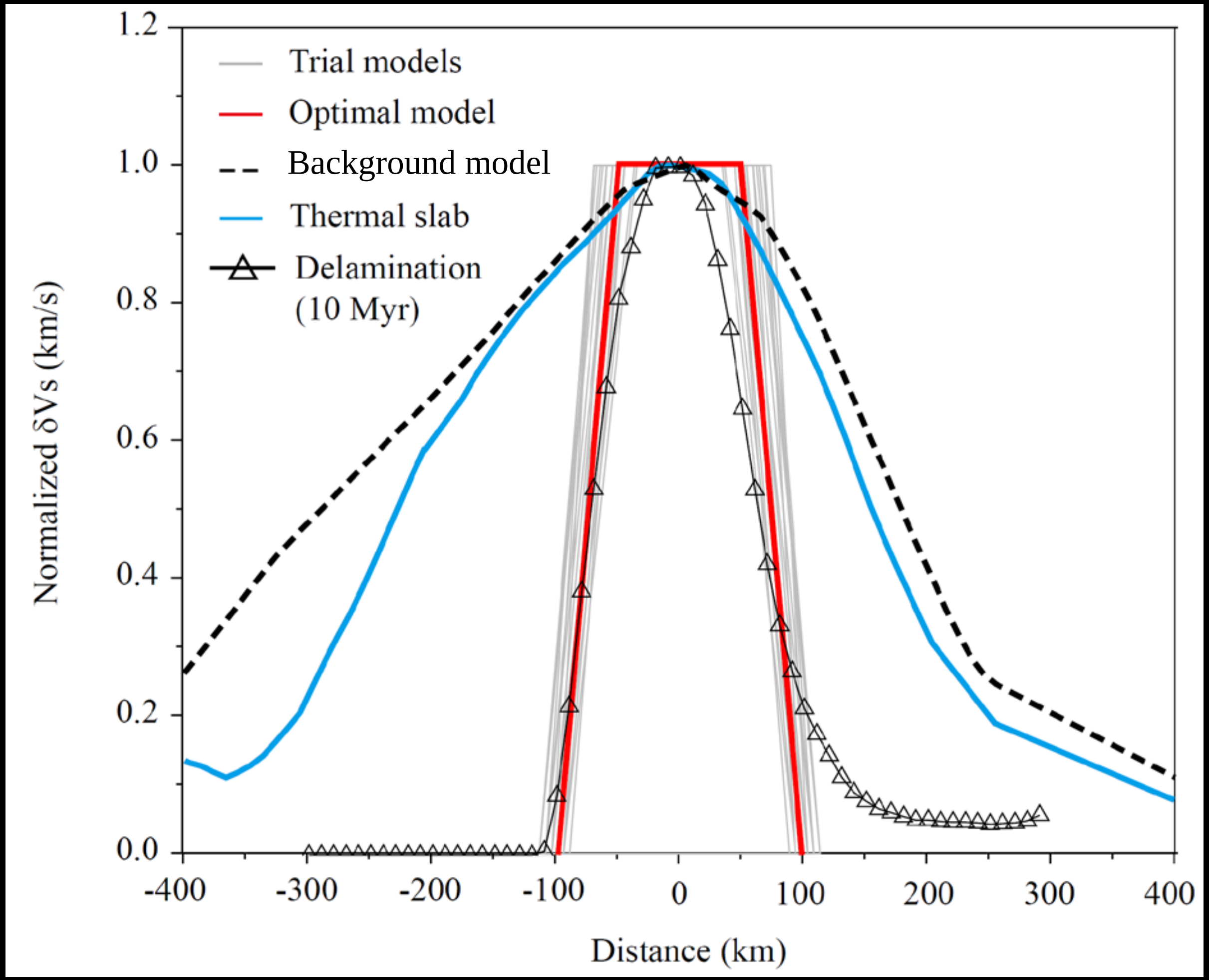








The comparison of the effective thickness



Ko et al., 2017

Purely thermal

✓ Delamination

X Subduction-related

Thermal-chemically distinct

✓ Delamination

✓ Subduction-related

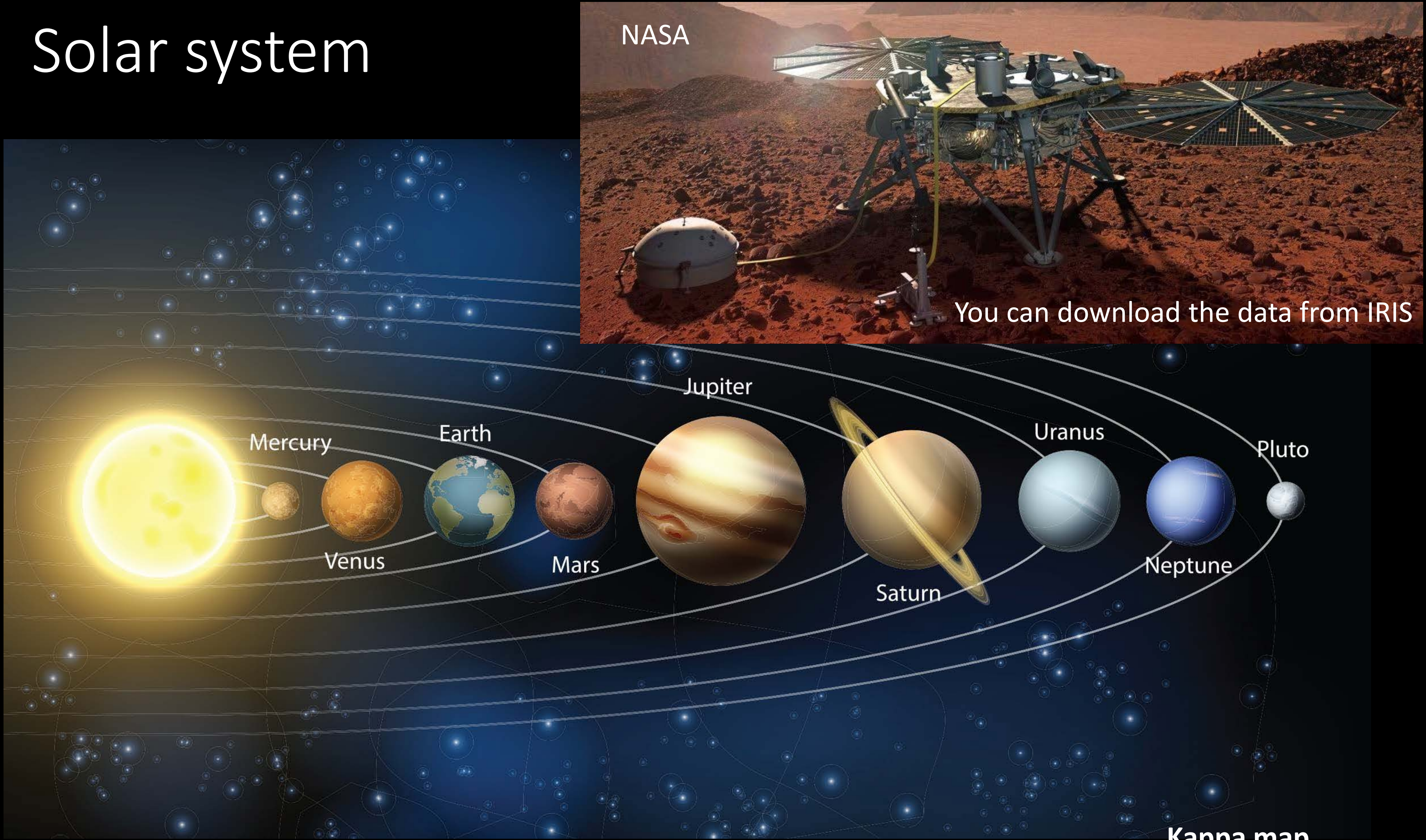
Planetary Seismology- Venus

Justin Yen-Ting Ko[1,2]

J.M. Jackson[2], J. A. Cutts[3], M. Pauken[3], A. Komjathy[3], S. Smrekar[3], S. Kedar[3], D. Mimoun[4], R. Garcia[4], G. Schubert[5], S. Lebonnois[6], D.J Stevenson[2], P. Lognonné [7], Z. Zhan[2], V. Tsai[2]

[1]*Institute of Oceanography, National Taiwan University*
[2]*Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, U.S.A.*
[3]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, U.S.A*
[4]*Institut Supérieur de l'Aéronautique et de l'Espace, Toulouse, France*
[5]*University of California, Los Angeles, CA, U.S.A.*
[6]*Laboratoire de Meteorologie Dynamique, Jussieu, Paris, France*
[7]*Université Paris Diderot, Institut de Physique du Globe de Paris, Paris, France*

Solar system



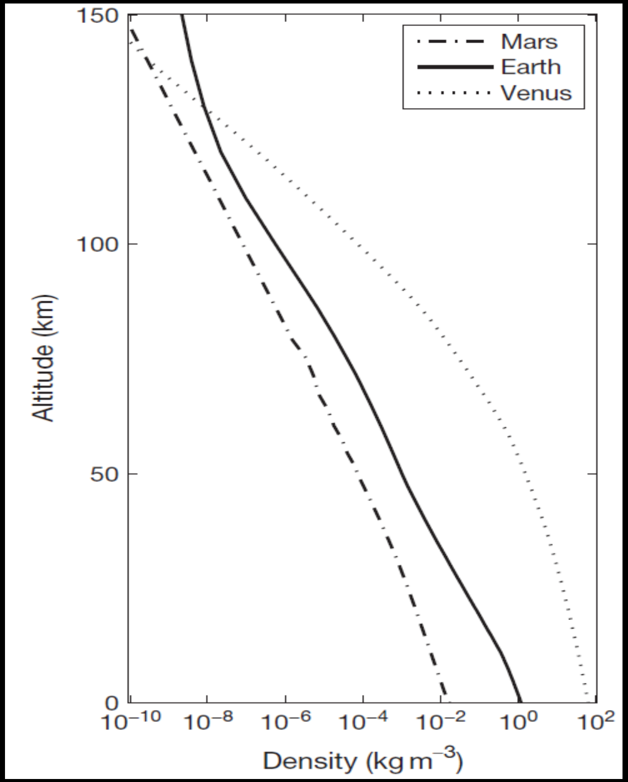
Kappa map

Comparison

The four terrestrial (meaning 'Earth-like') planets of our inner Solar System

	Venus	Earth
Mass	4.87×10^{24} kg	5.98×10^{24} kg
Radius	6052 km	6378 km
Density	5250 kg/m^3	5520 kg/m^3

Comparison



Earth: Acoustic waves generated by the Rayleigh surface waves have been observed in the far field of very large (Ms > 7) quakes but also in the near-field of smaller quakes (GPS).

Venus: ?

- A larger atmospheric density at the surface
- Much stronger atmospheric coupling
- Larger acoustic impedance of the atmosphere

Table 2 Atmospheric coupling parameters for Venus, Earth, and Mars

	Crust	*Earth*	*Mars*	*Venus*
Surface sound speed ($m\ s^{-1}$)	5800	340	214	426
Surface density ($kg\ m^{-3}$)	2600	1.225	0.0175	65
Acoustic impedance ratio/crust	1	2.76e−5	2.48e−7	1.83e−3
Energy transfer $\left(E = \frac{Q}{\pi} \frac{\rho_{air} c_{air}}{\rho_{int} c_{int}}\right)$ $(Q = 100)$		8.8e−4	7.9e−7	5.8e−2
High-Q atmospheric resonances (mHz)		3.7	2.05	3.10; 4.15

Solar System Exploration Technology Office

Techniques and Technologies for probing Venus Interior
KISS Development Program

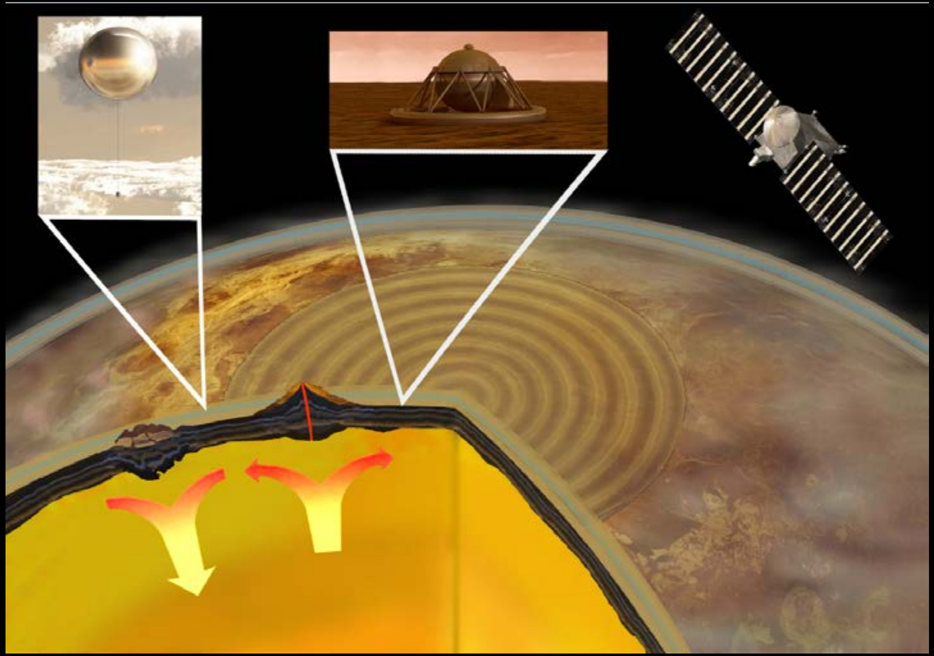
Prof. Jennifer Jackson, Campus PI Dr. James Cutts, JPL co PI

Objective

- Probing the interior of Venus that exploit its **dense atmosphere** and tolerate its high surface temperatures

Key Tasks and Products

- **Balloon** infrasound testbed
- Infrasonic sensor payload
- Lab studies of Venus analog rocks
- Modeling of infrasound background
- **Modeling of atmospheric excitation of seismic waves (infrasonic waves)**
- **Modeling of quake signatures**



How does it works?

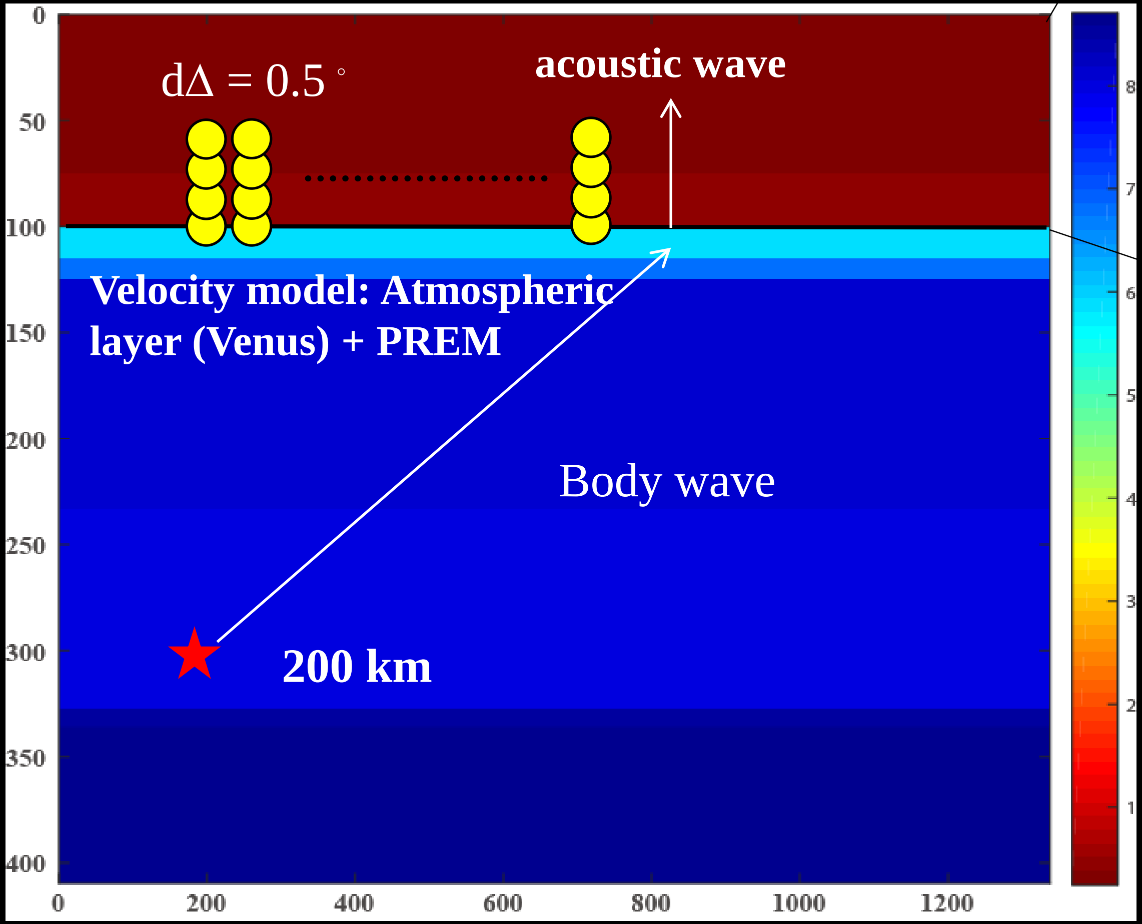
The dense atmosphere of Venus, which efficiently couples seismic energy into the atmosphere as infrasonic waves, enables an alternative to conventional seismology: detection of infrasonic waves in the upper atmosphere using either high altitude balloons or orbiting spacecraft.

Model setup

Δ = 5 °

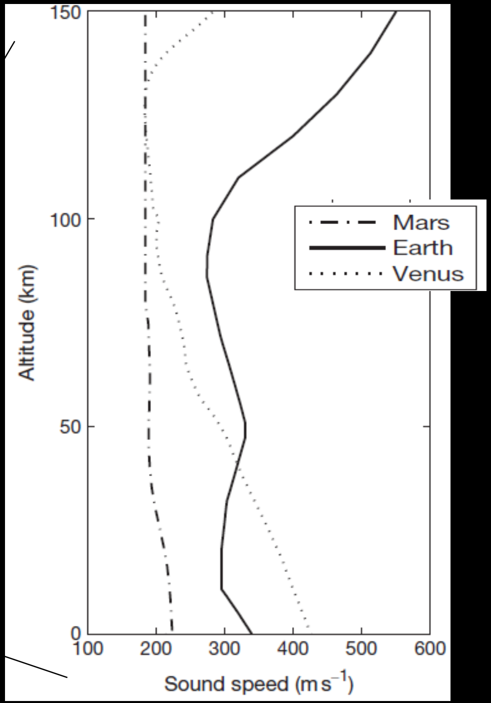
100 km

surface



Depth (km)

Distance (km)



Model setting:

dh = 0.1 km

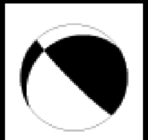
dt = 0.0021

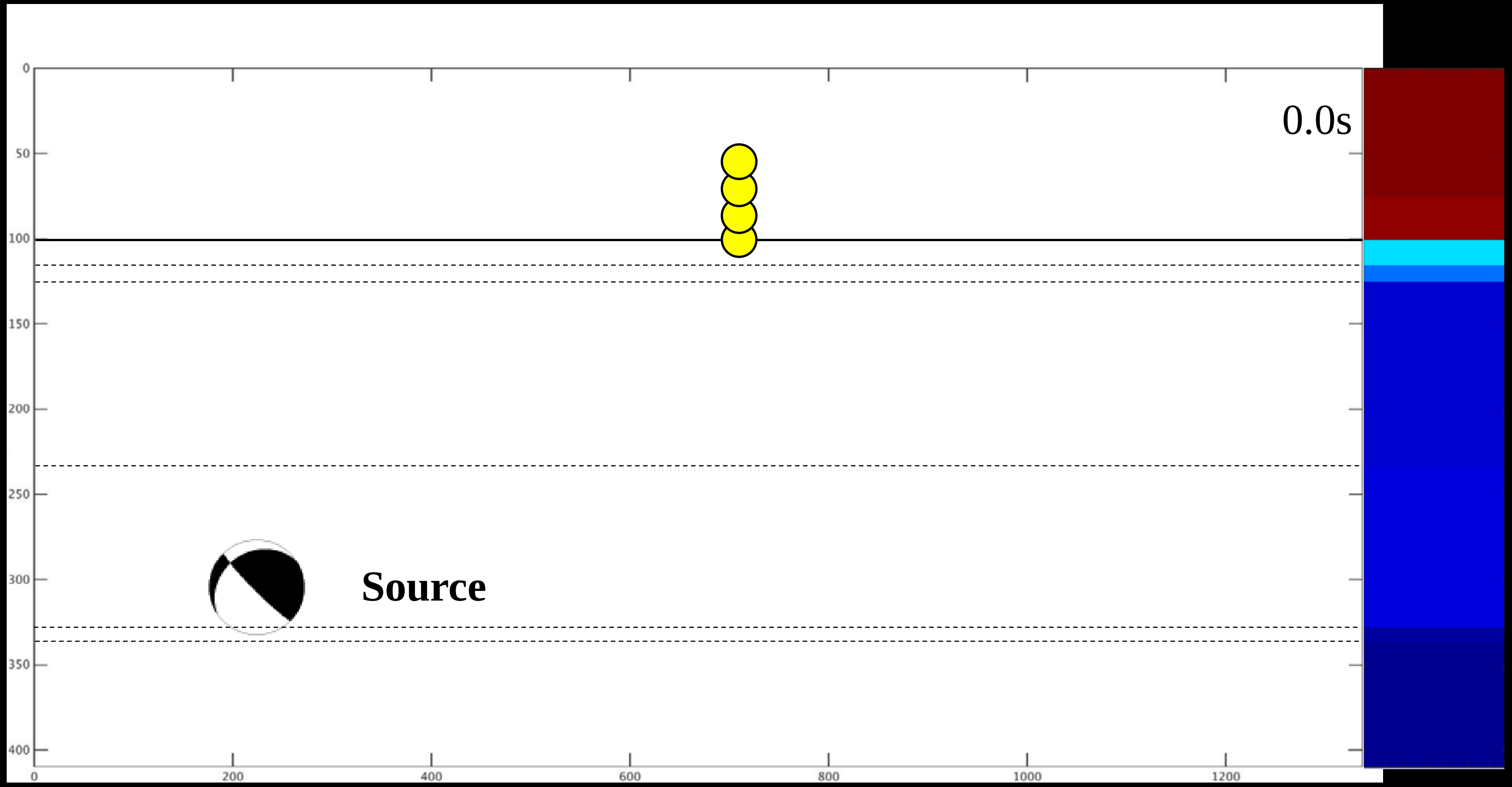
Maxf ~ 0.45 Hz

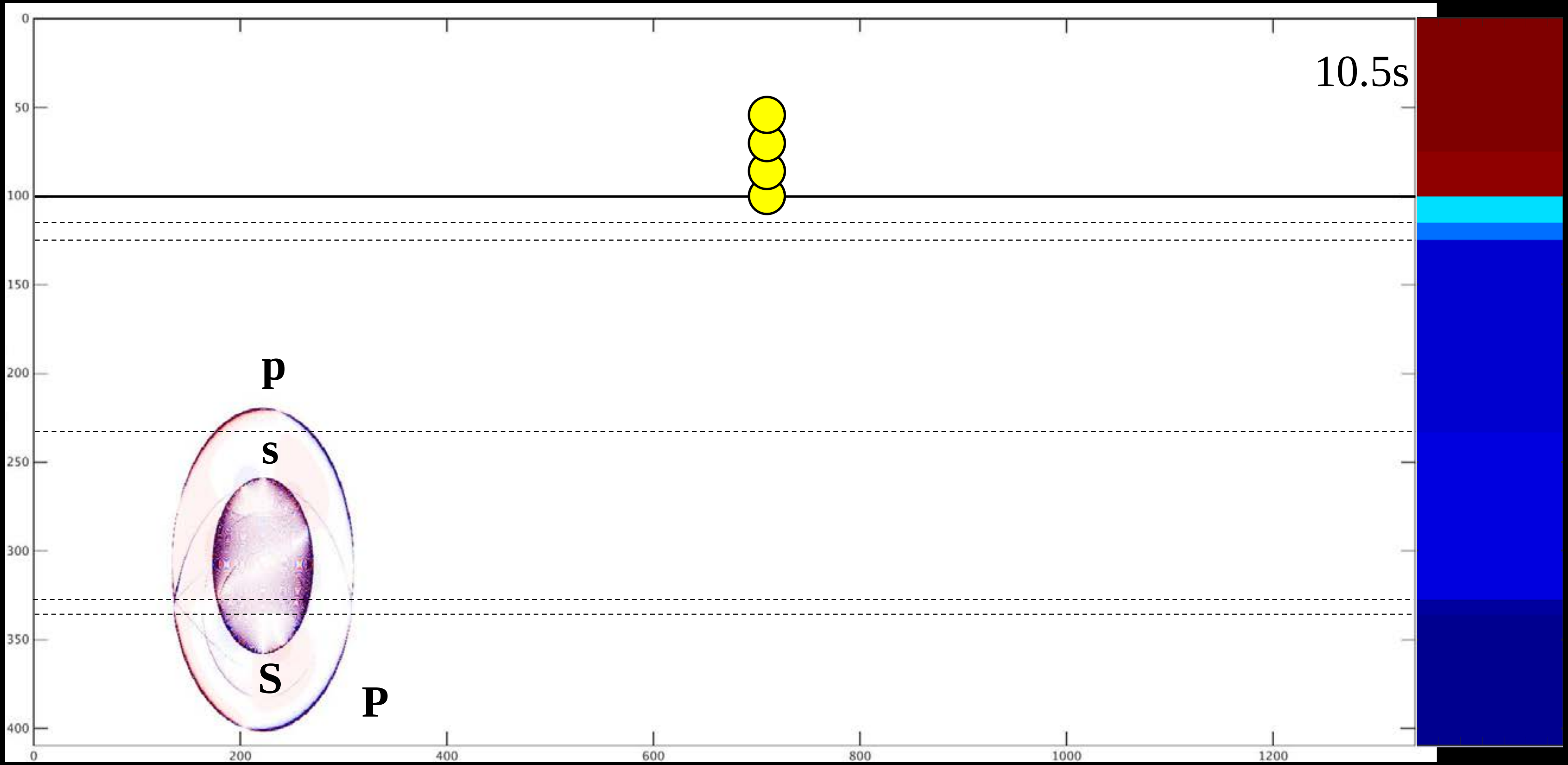
No attenuation

Source type:

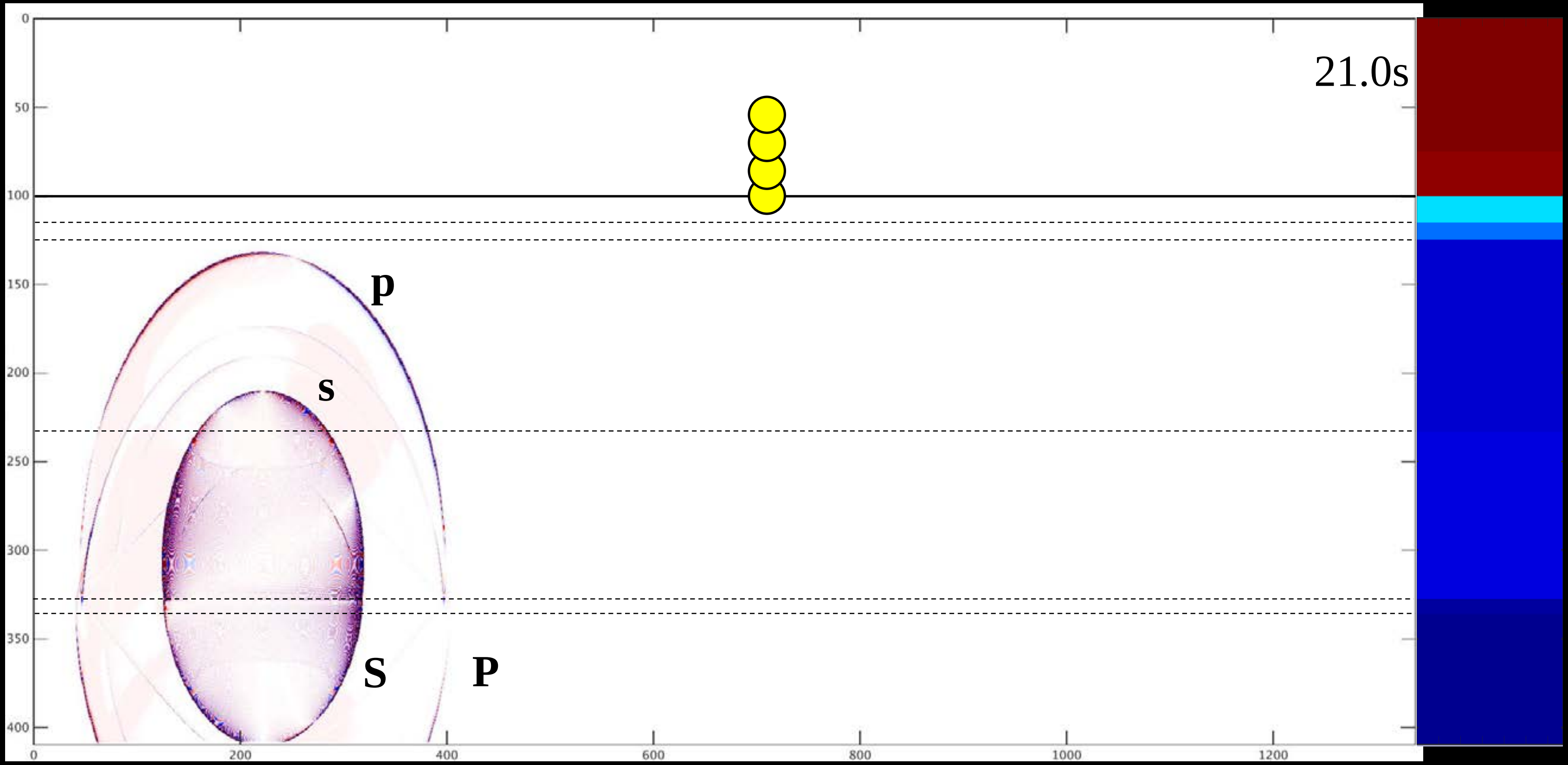
Double couple

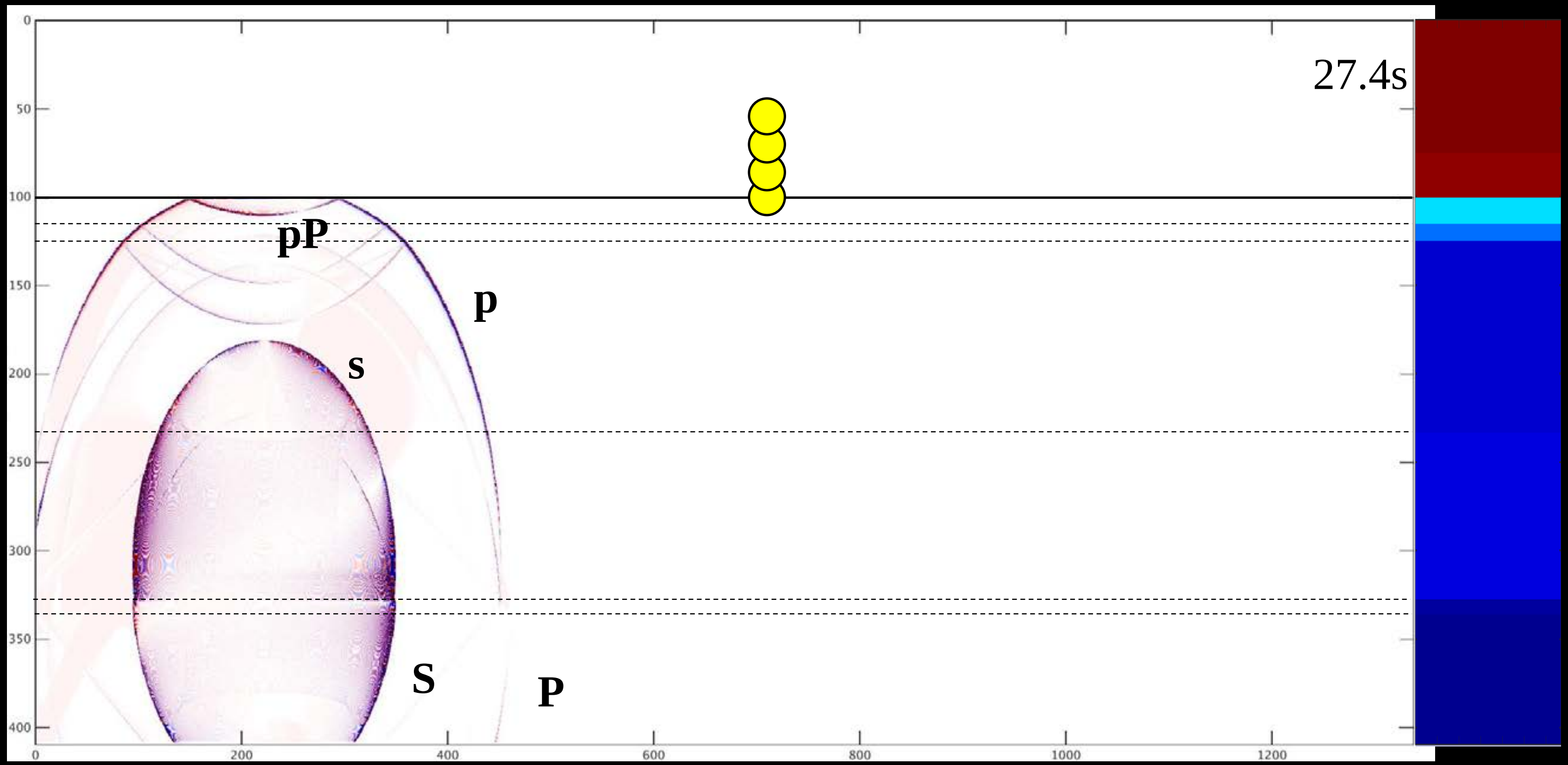


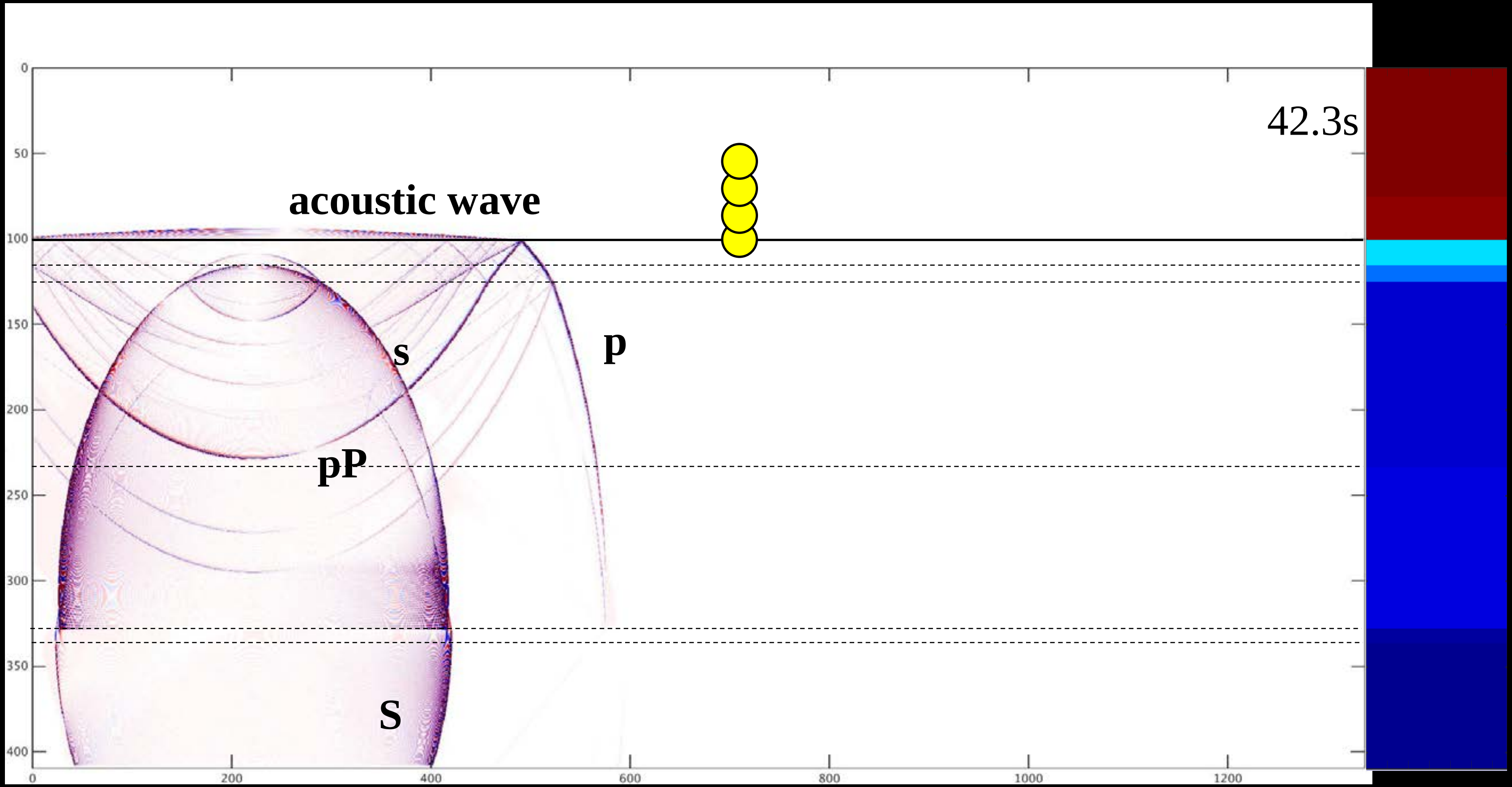

0.0s
Source



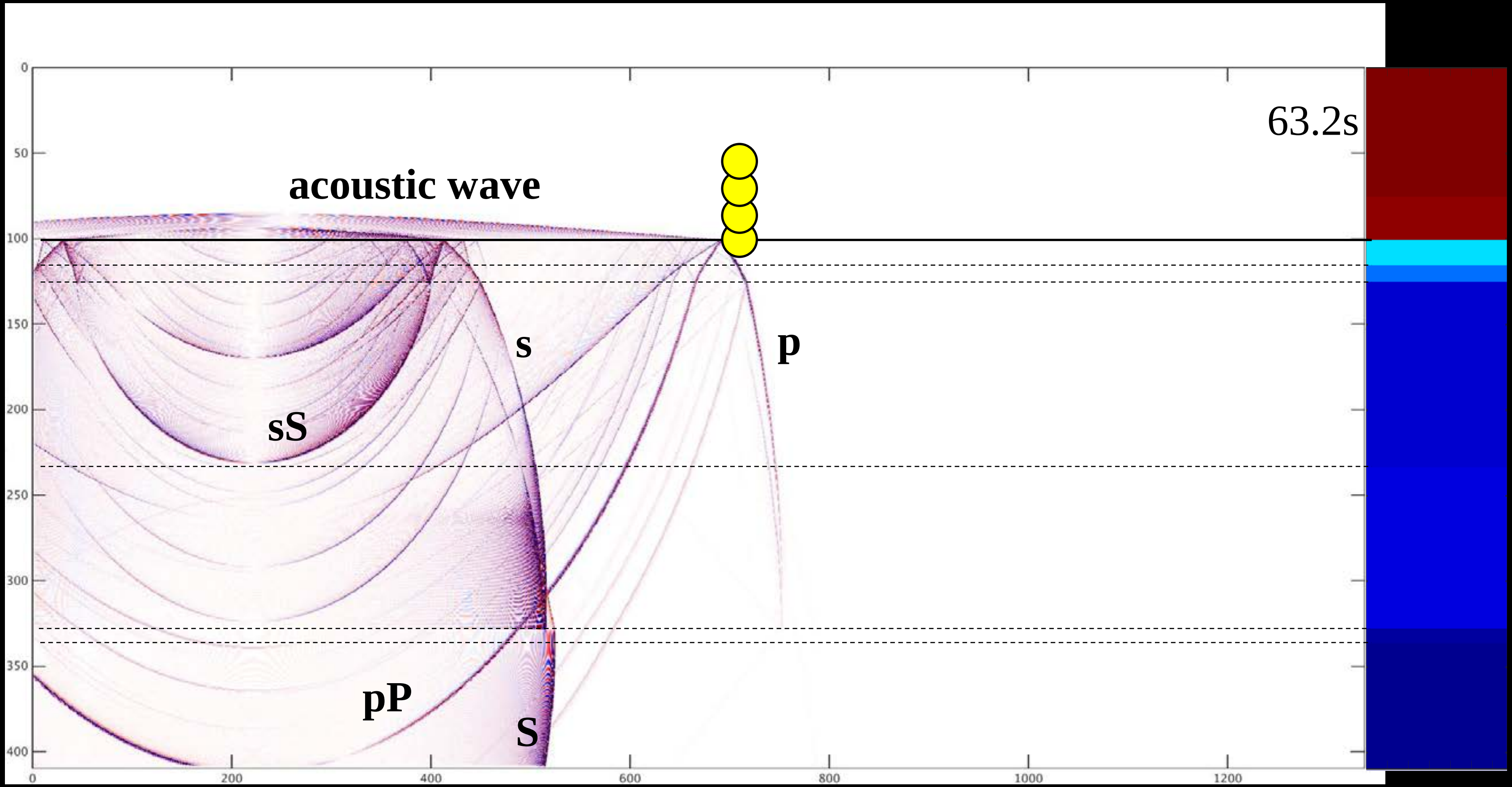
10.5s
p
s
S
P


21.0s
p
s
S
P
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200

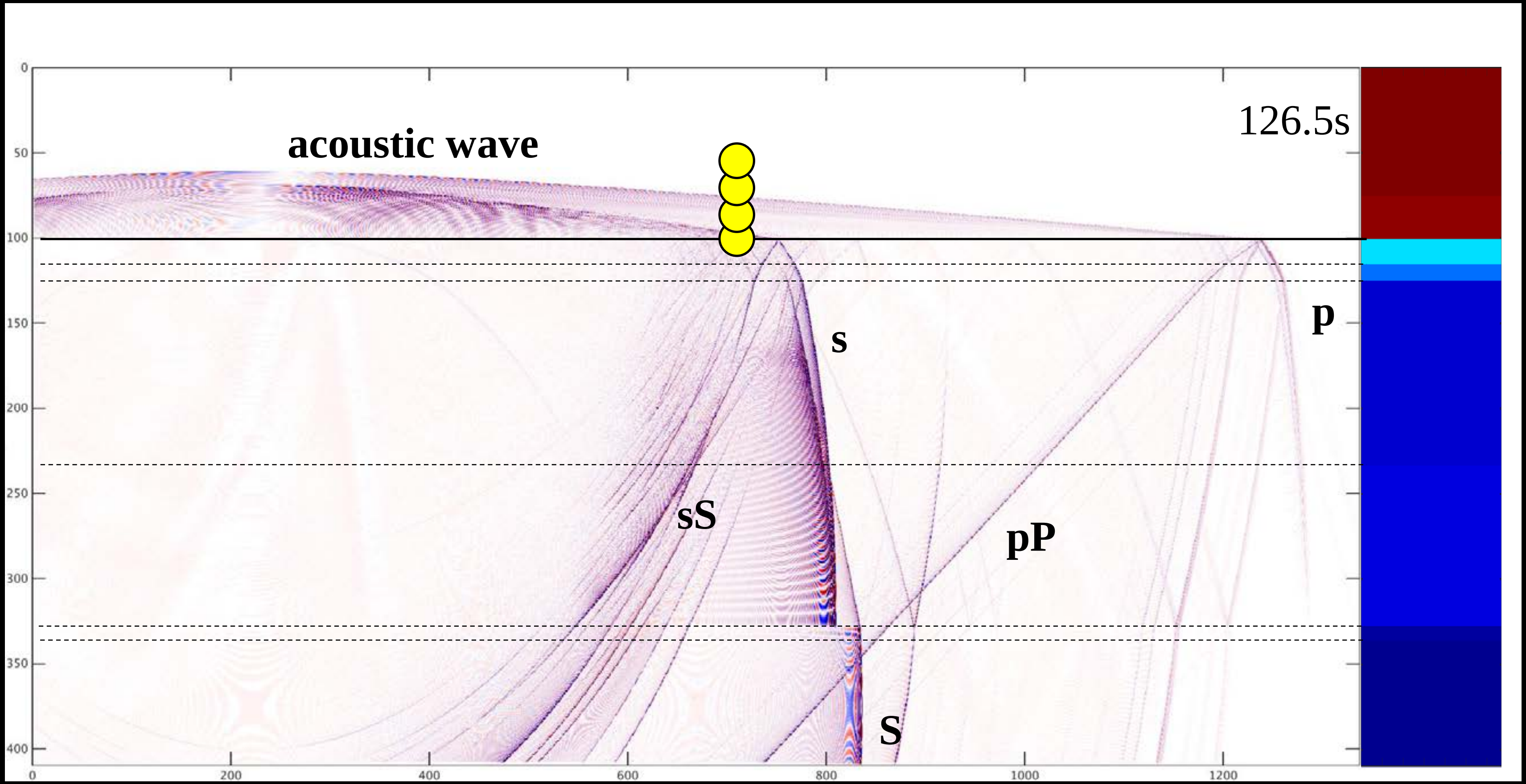

27.4s
pP
p
s
S
P

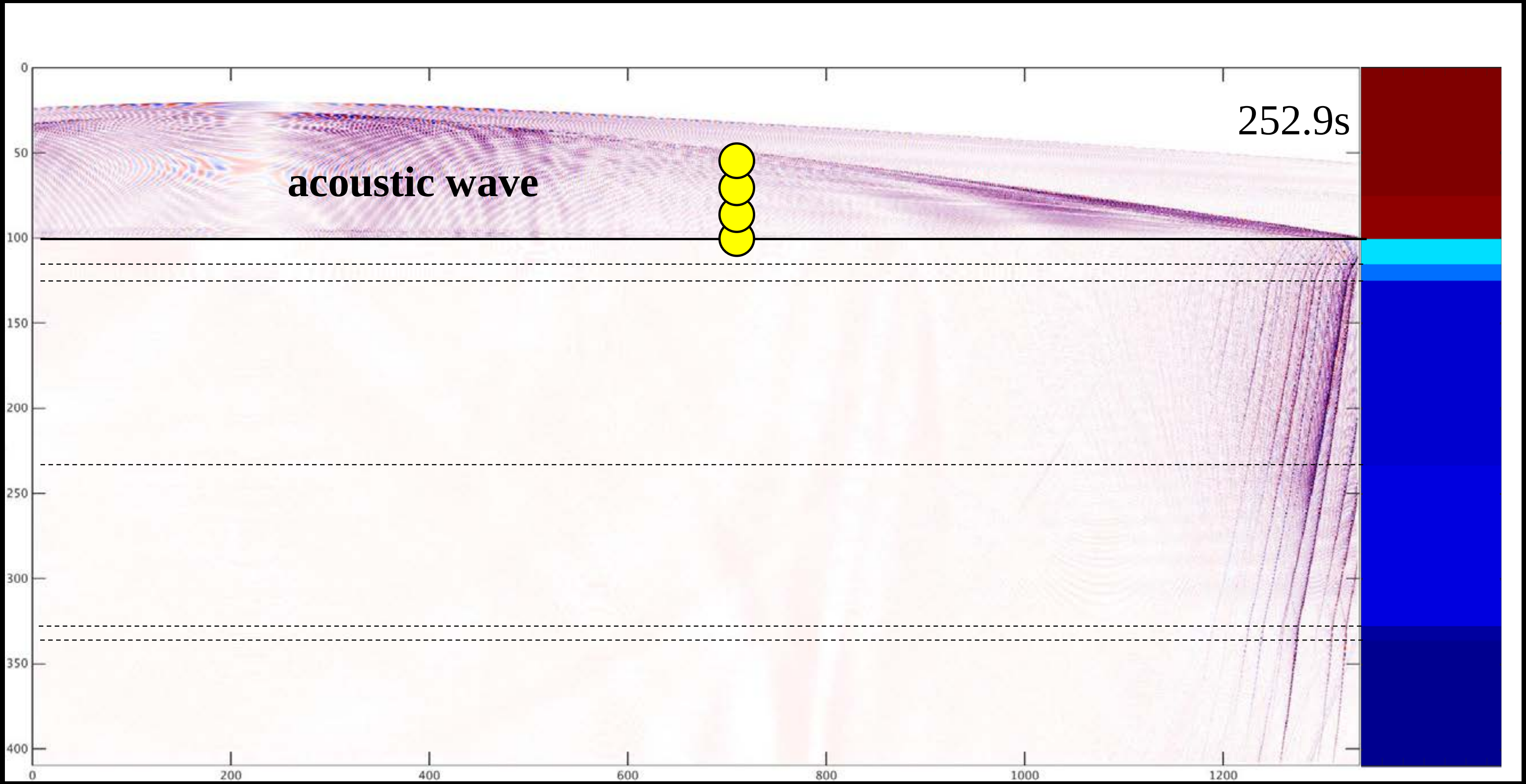


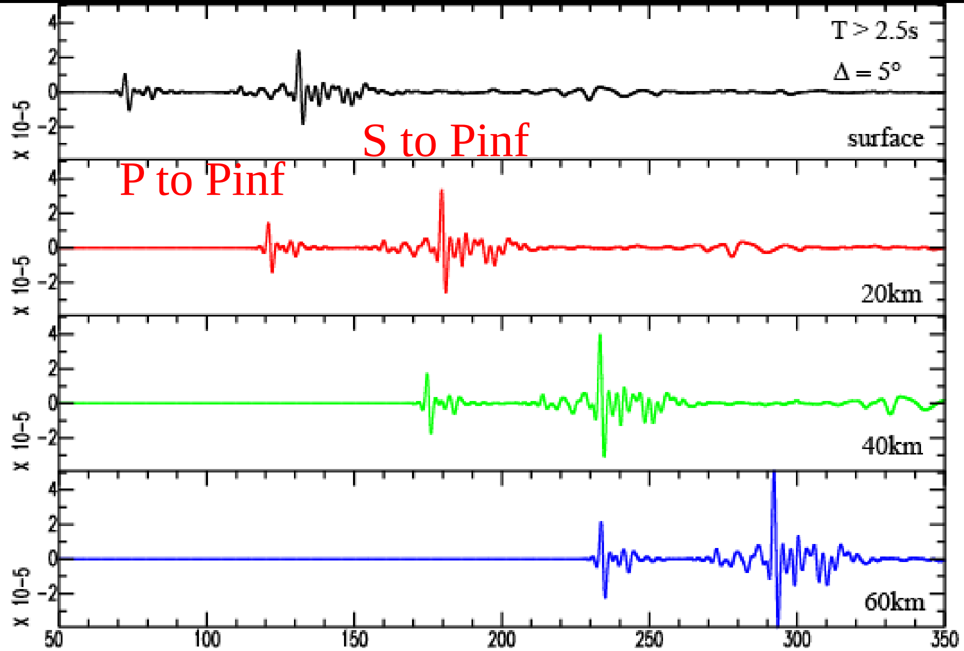
42.3s
acoustic wave
s
p
pP
S

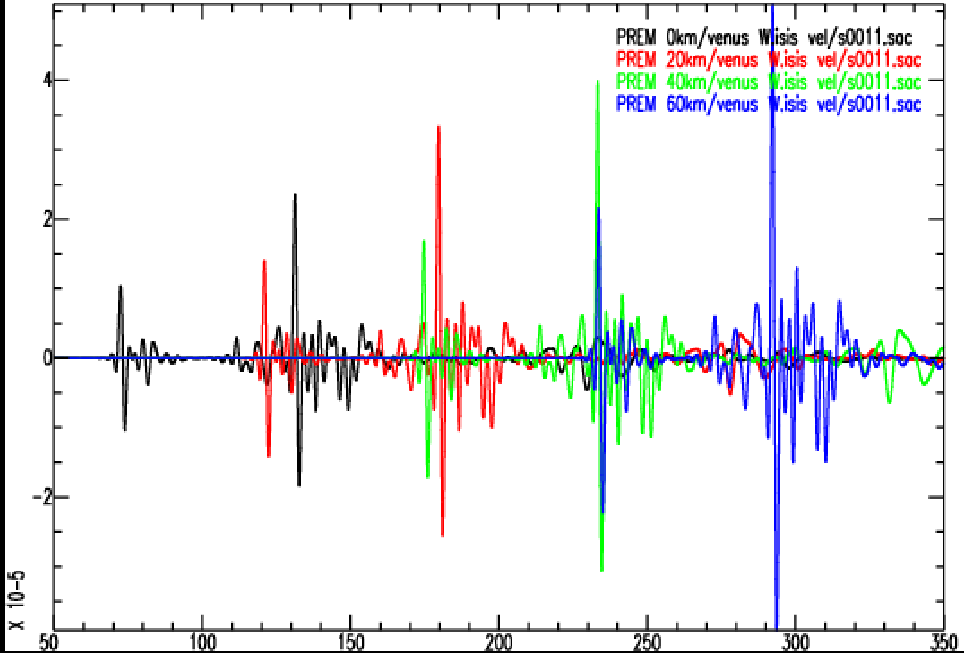


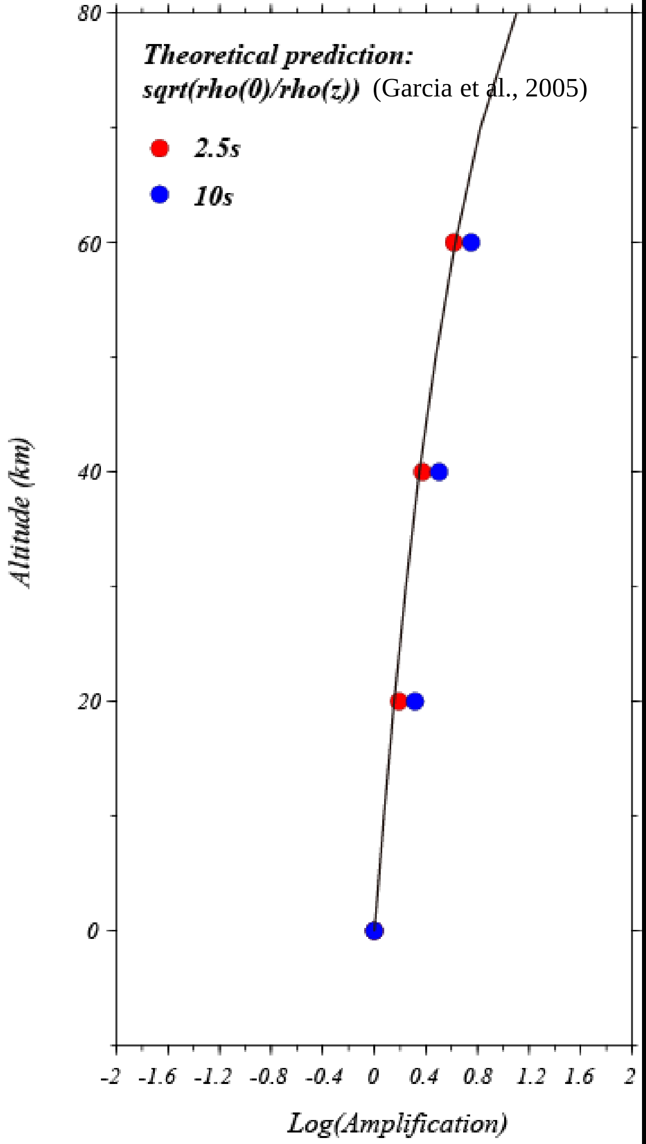
63.2s
acoustic wave
s
p
sS
pP
S


126.5s
acoustic wave
p
s
sS
pP
S


252.9s
acoustic wave
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200


T > 2.5s
Δ = 5°
surface
S to Pinf
P to Pinf
20km
40km
60km
x 10-5

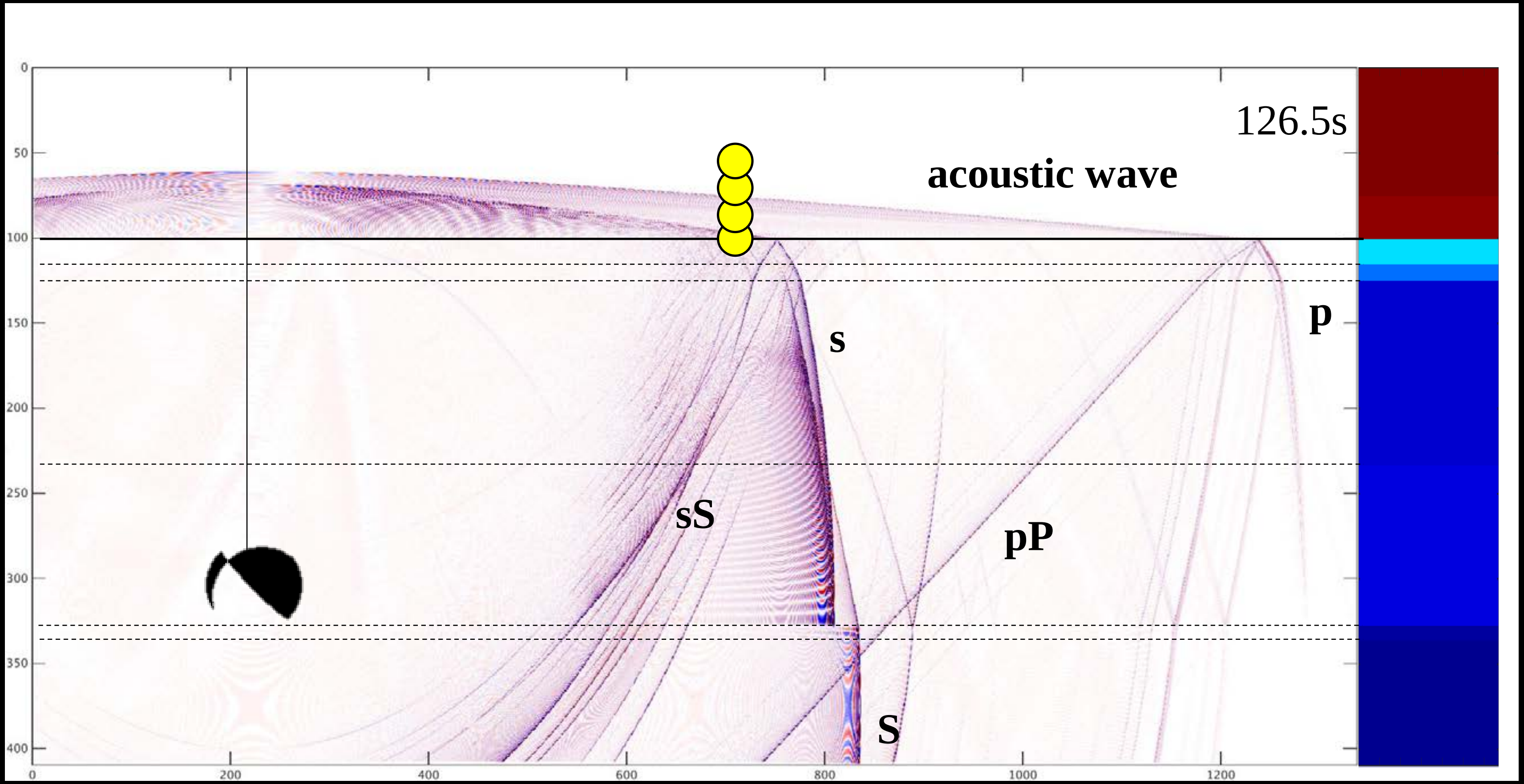

PREM 0km/venus W.isis vel/s0011.sac
PREM 20km/venus W.isis vel/s0011.sac
PREM 40km/venus W.isis vel/s0011.sac
PREM 60km/venus W.isis vel/s0011.sac
x 10-5


Theoretical prediction:
sqrt(rho(0)/rho(z)) (Garcia et al., 2005)
2.5s
10s
Altitude (km)
Log(Amplification)

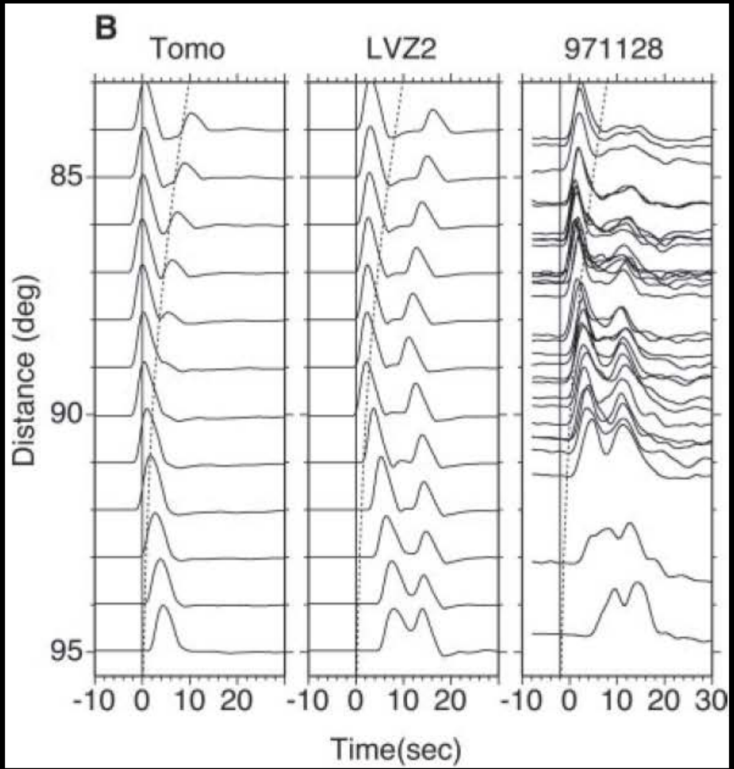
One station

1. **Differential time (s-p)**
2. **The slope of acoustic waves**

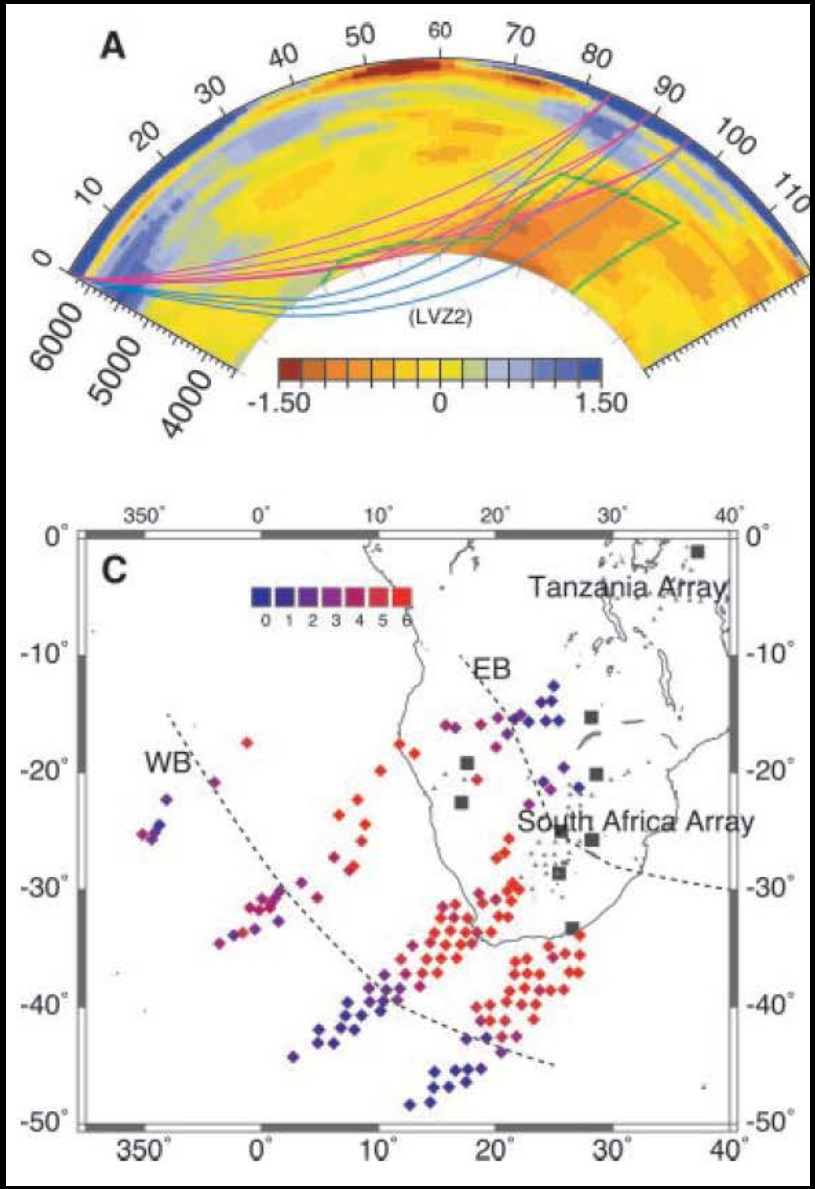
→ Event depth (should be ok)



Donald Knuth:
“Science is what we understand well enough to explain to a computer. Art is everything else we do.”



Ni et al., 2002



Thank you

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Problematic on seismic tomography

- Smoothed/damped images
  - penalty function

- Computationally expensive
  - Finite-frequency kernels
  - Full waveforms

PART II

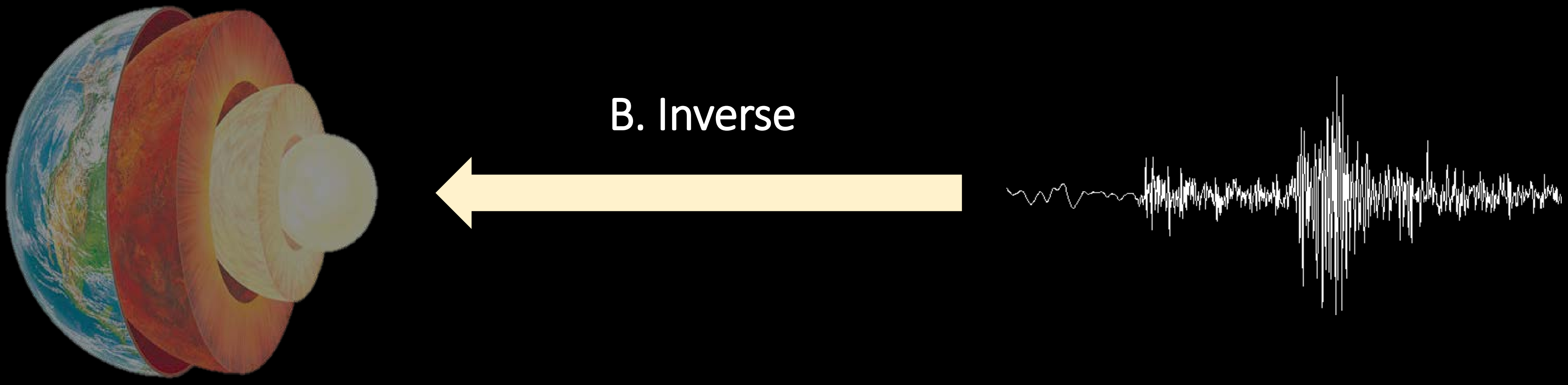
- Not for the high frequency data (Full waveform inversion)

Another possibility for tomographic approach

An efficient way to invert seismic structure using full waveforms

Justin Yen-Ting Ko & Zhongwen Zhan

Seismological Laboratory, California Institute of Technology, CA 91125, USA



Seismic tomography

Solved as an Inverse problem

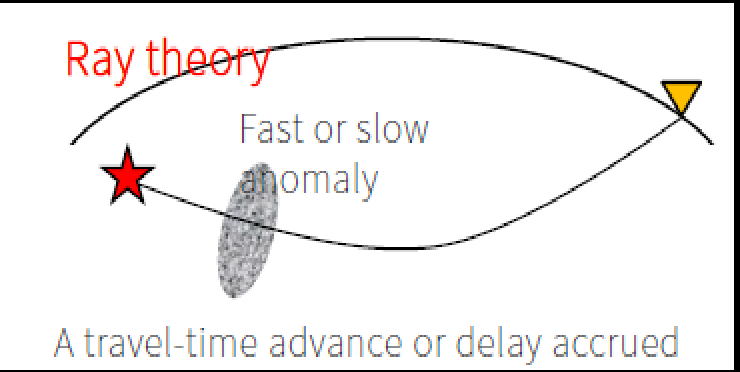
d	=	G	M
Travel time Amplitude Waveforms		Green's function Sensitivity Kernel	Structure
Known		"Known"	Unknown

Sensitivity kernel & Forward Rule (Gm=d)

A solution of wave equation

Ray theory

Finite-frequency theory + adjoint approach

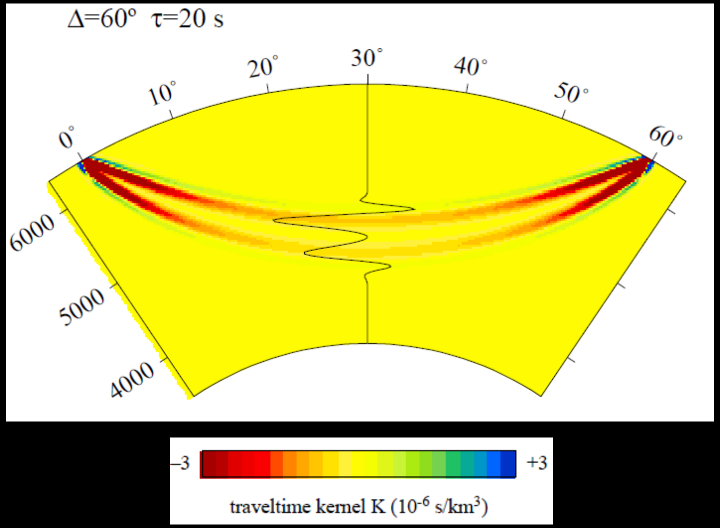


Asymptotic ray series representation of the seismic wavefield

RAY-THEORETICAL KERNEL

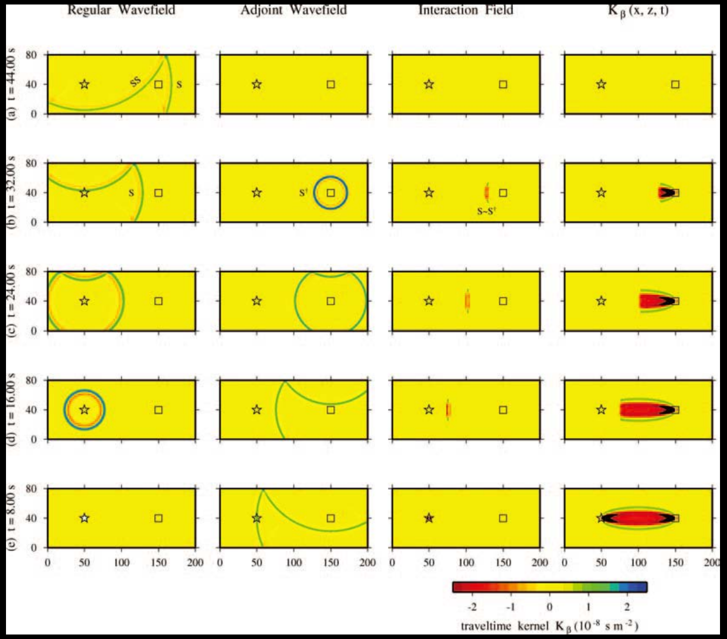
Dahlen et al. (2000)

Hung et al. (2000)



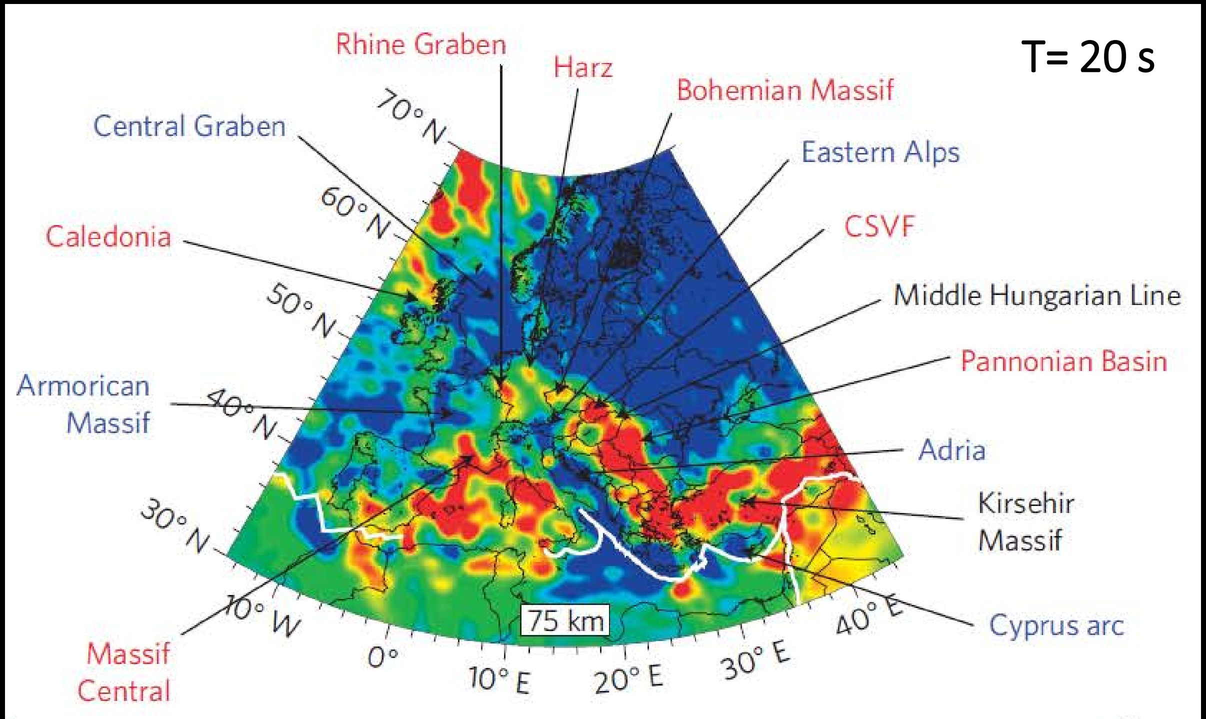
ADJOINT KERNEL

Tromp et al. (2005)



What is the next

- Ray theory vs **Finite-frequency theory**
- Travel time vs **Full waveform approach**



Zhu et al. (2012)

30 iterations
2.3 million cpu hrs

Pros

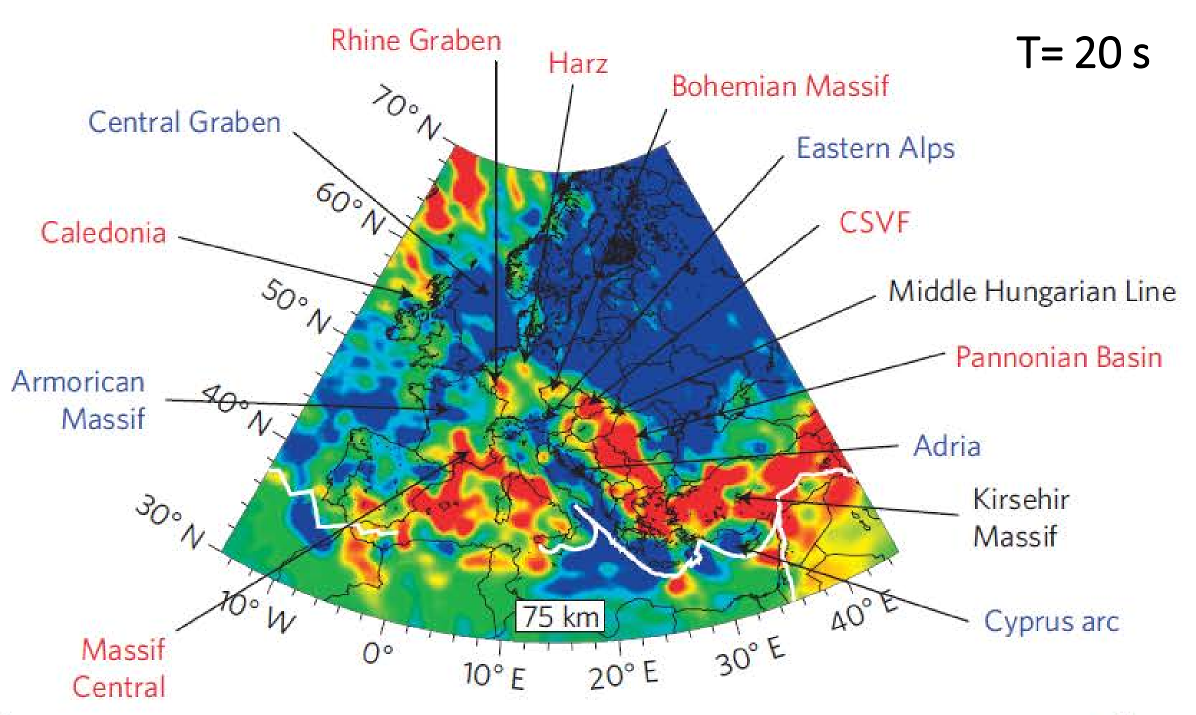
- High resolution

Cons

- Computationally expensive
- High demand for storage space
- Relatively low frequency data (e.g., 20s)

What is the next

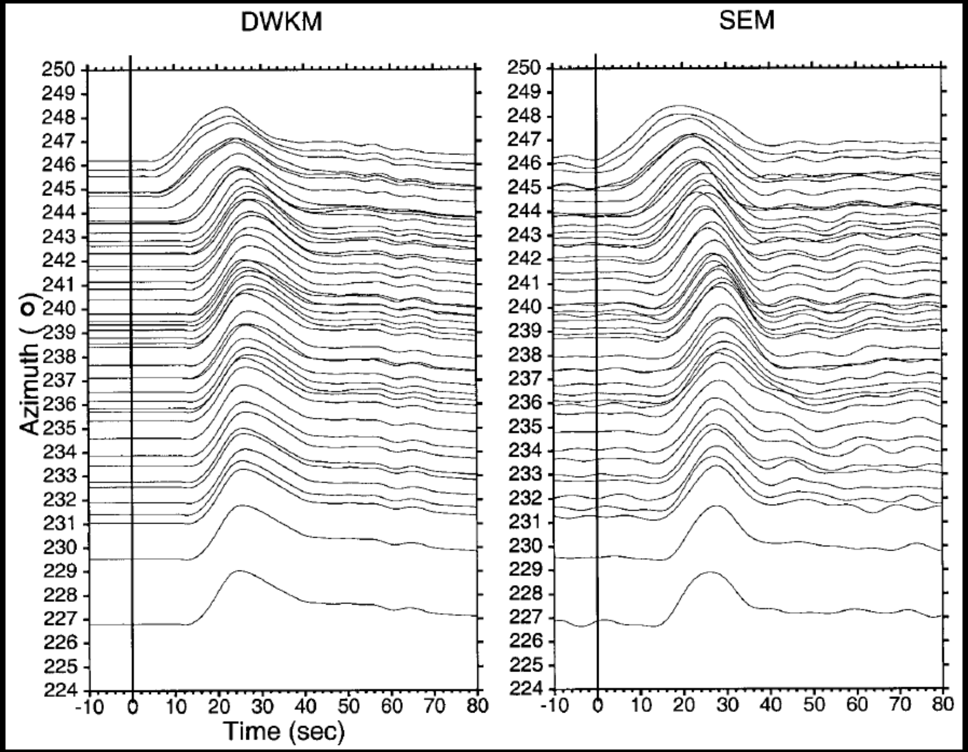
- Ray theory vs **Finite-frequency theory**
- Travel time vs **Full waveform approach**



Zhu et al. (2012)

30 iterations
2.3 million cpu hrs

- An alternative efficient way
- High frequency waveforms

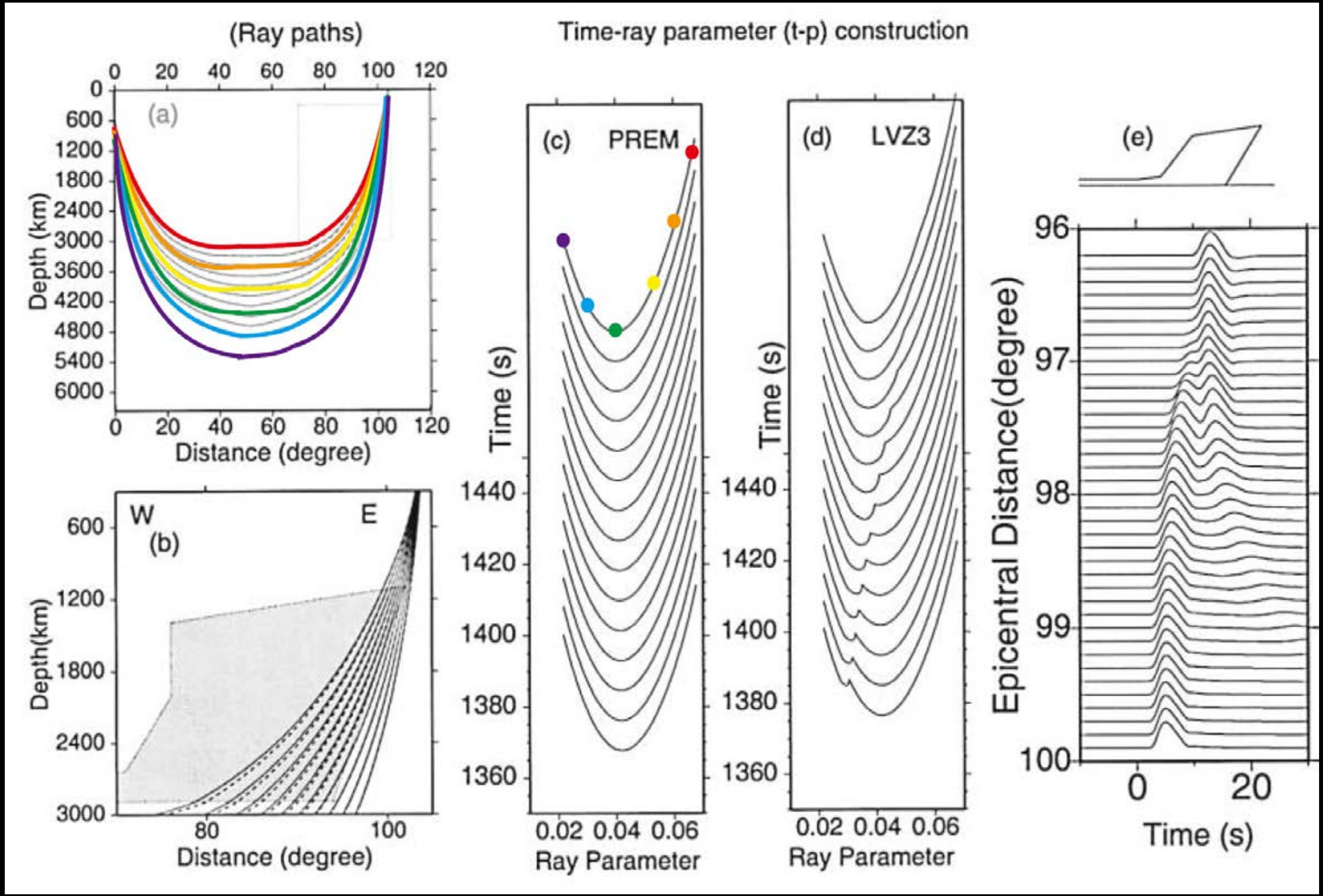


Smoothed model

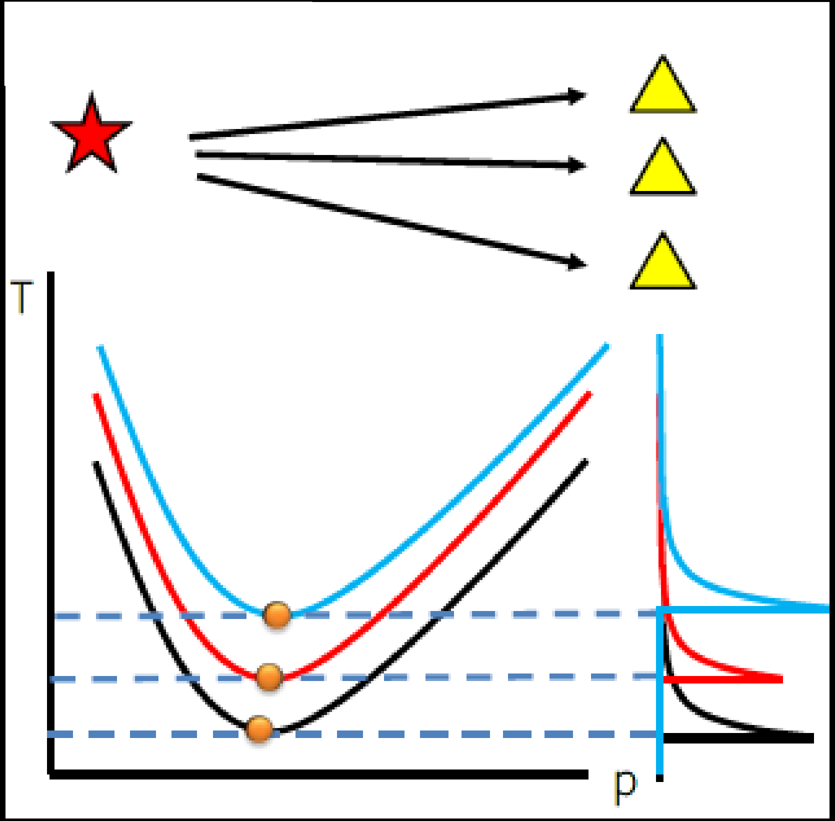
Helmberger and Ni, 2005

WKM synthetics

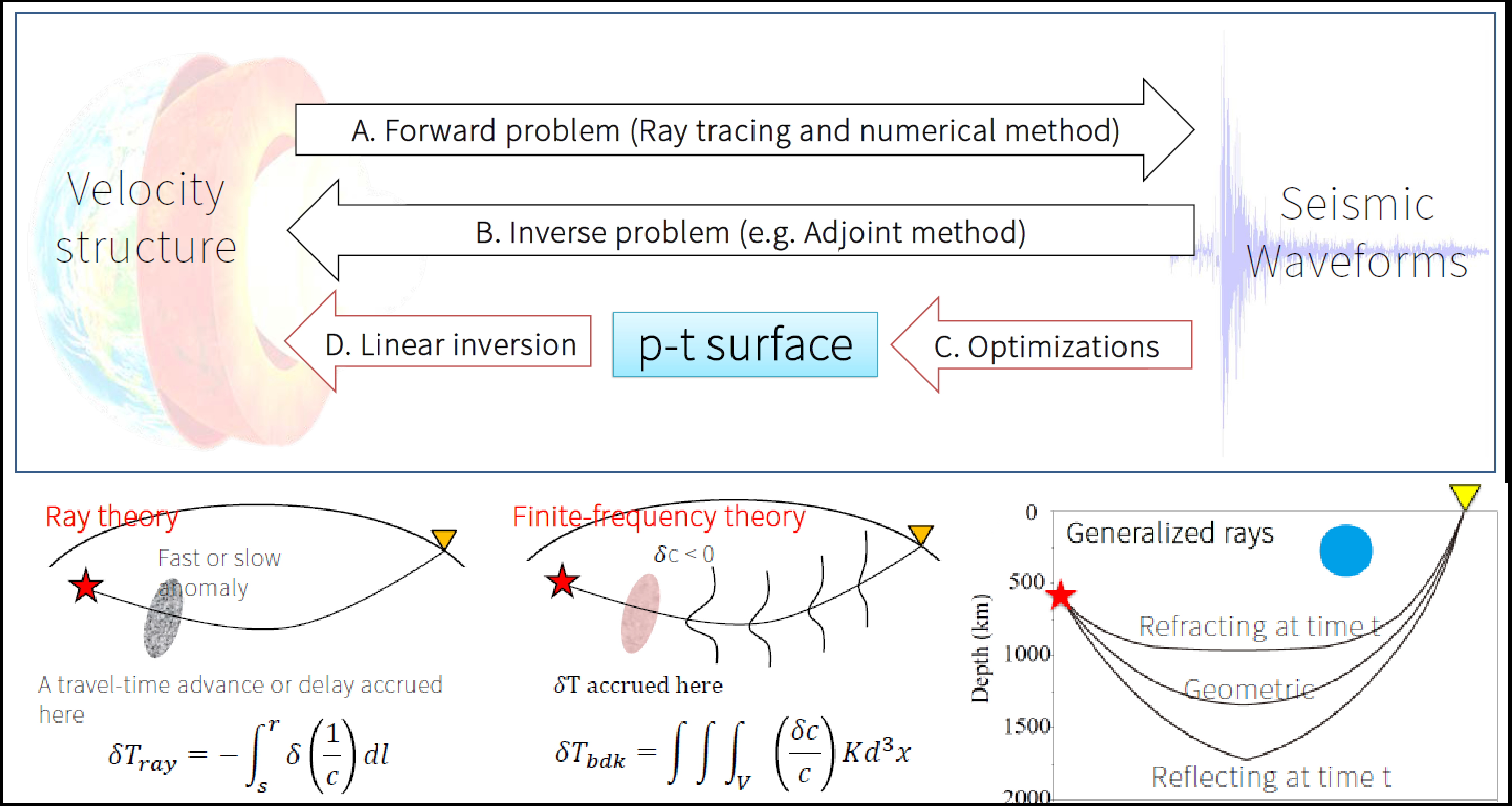
Using generalized ray



$$\varphi = \mathrm{Im} \sum_{i=1}^{n} SR_j\,(p)\frac{\sqrt{p}}{\eta_j}R(p)\Pi_i(p)\left(\frac{dp_i}{dt_i}\right)$$



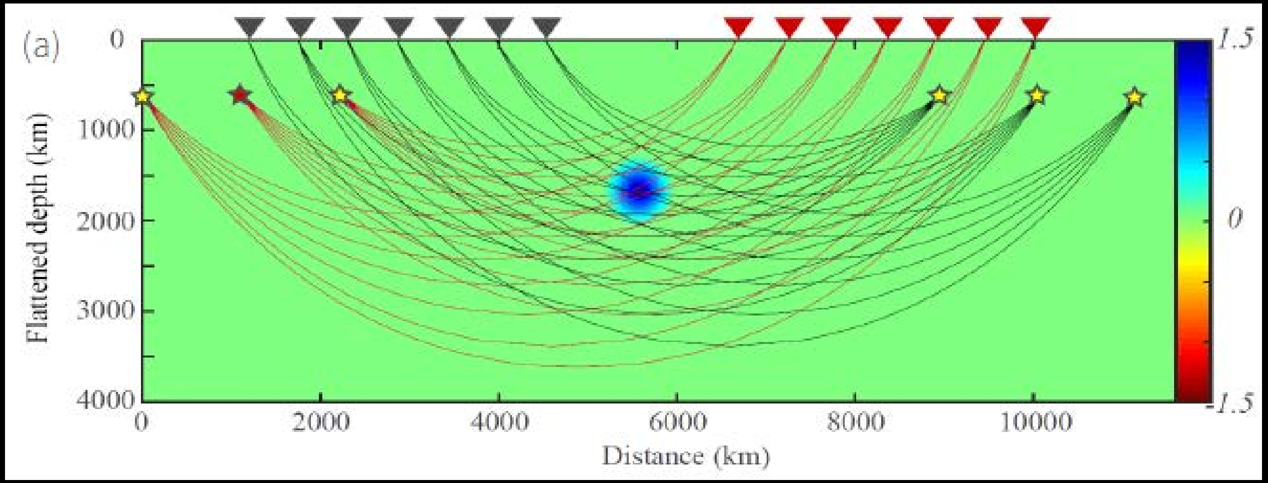
Helmberger and Ni, 2005

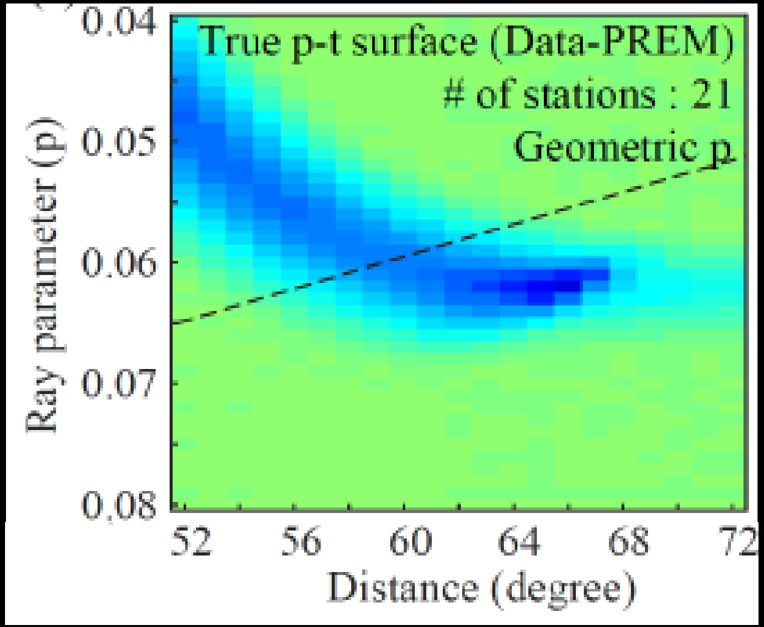


Ko and Zhan, 2018, in prep.

PT surface

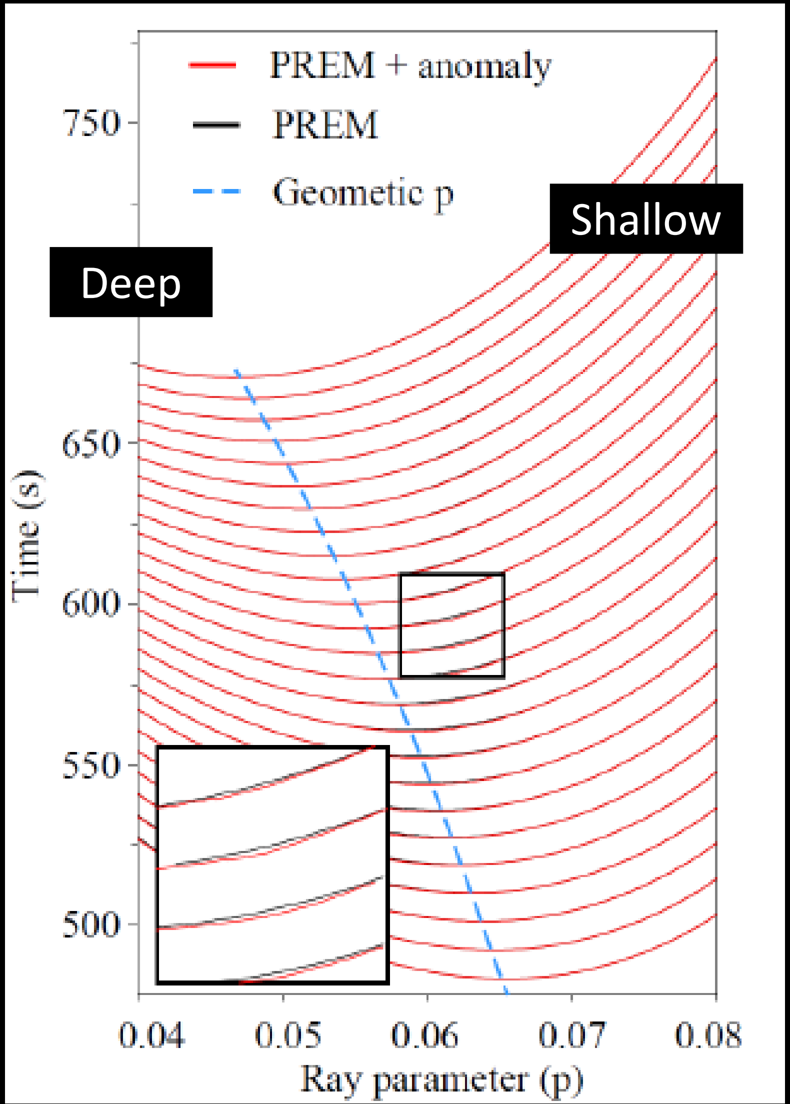
Ko and Zhan, 2018, in prep.





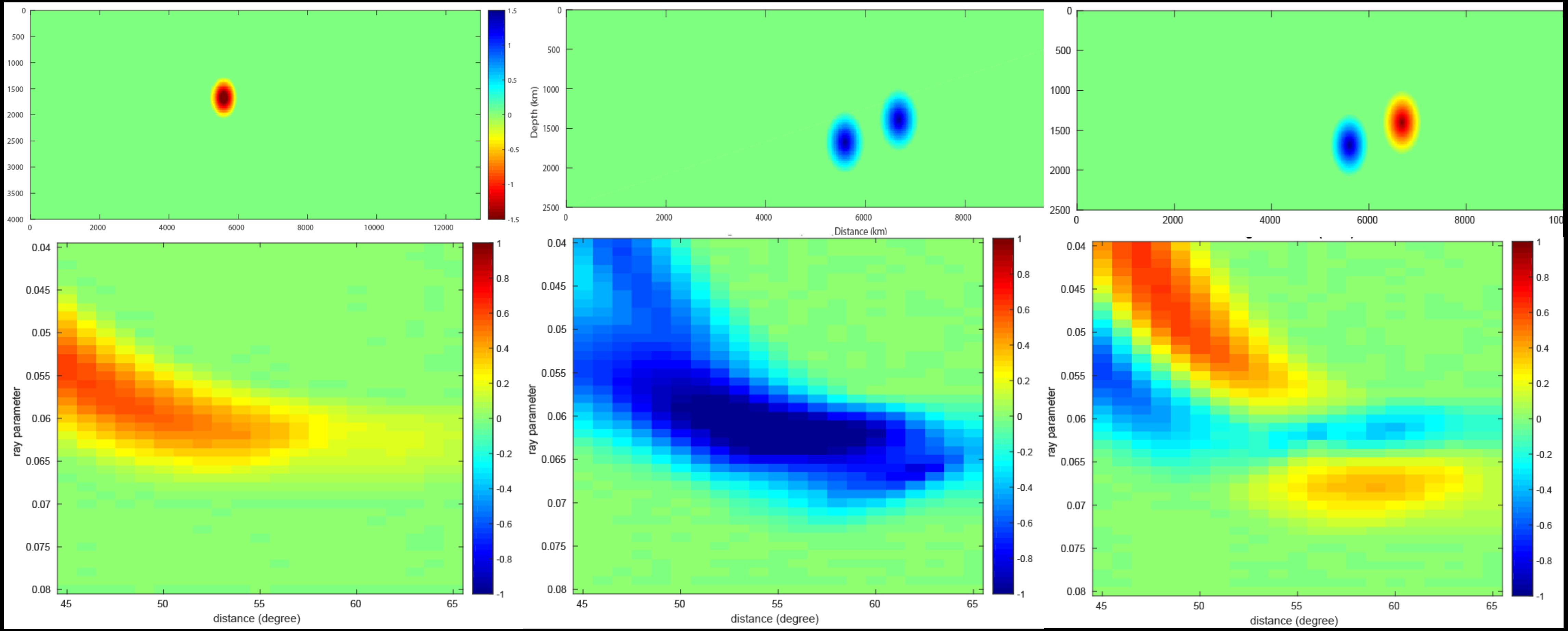
Deep

Shallow



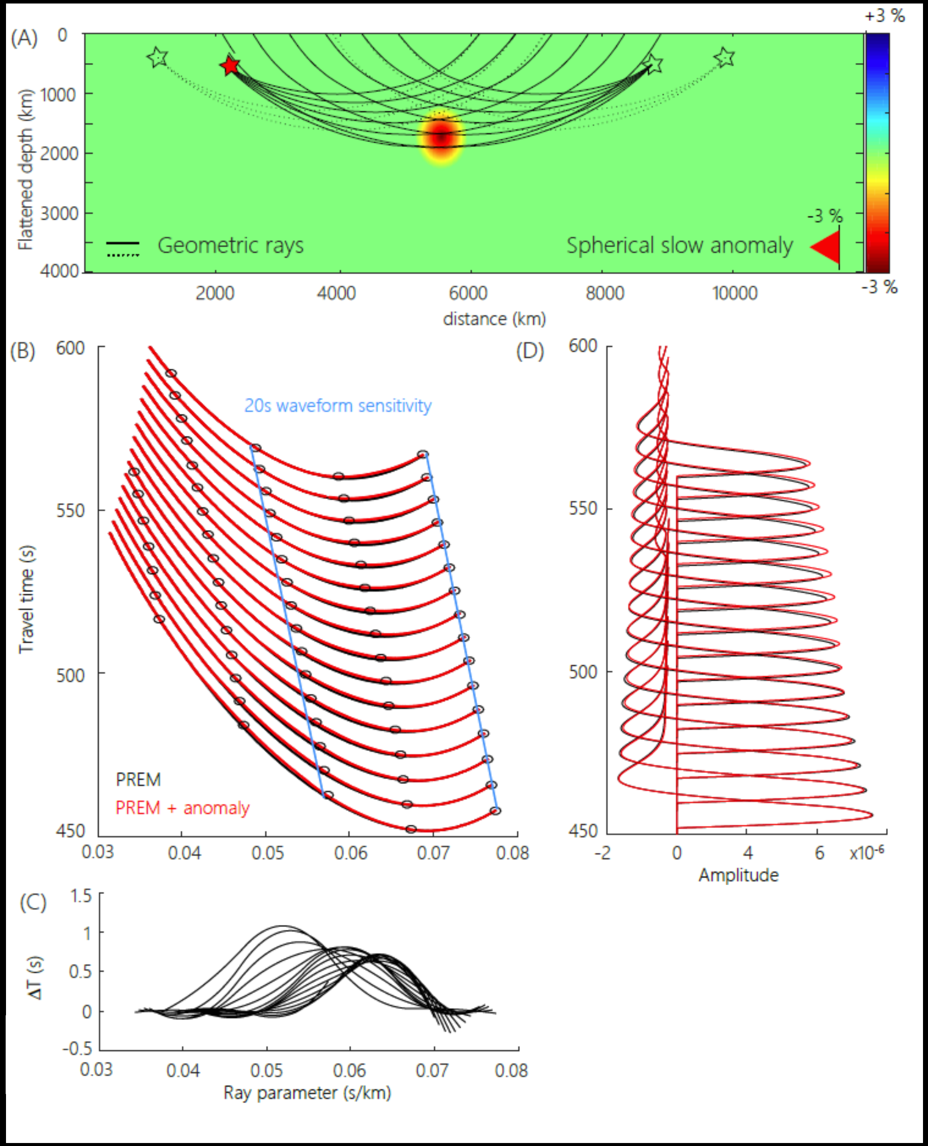
PT surface

Ko and Zhan, 2018, in prep.

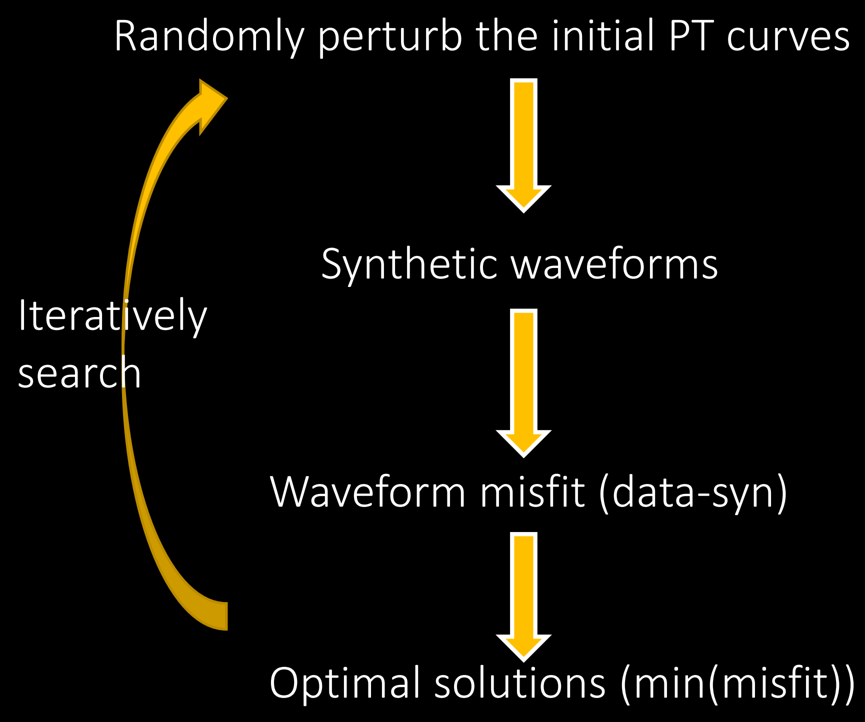


Question: How can we get the correct PT surface starting from initial model?

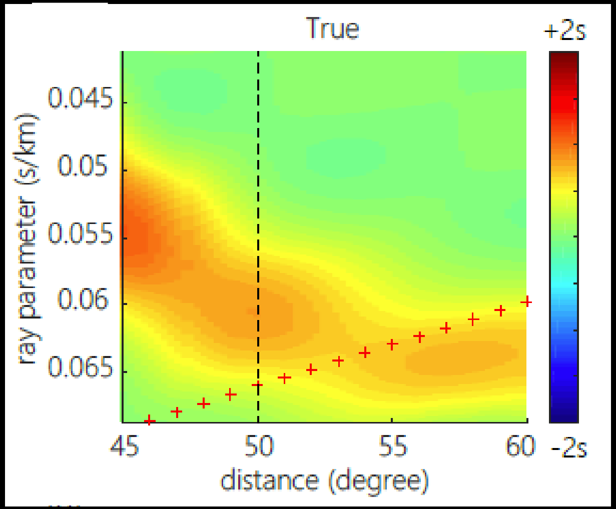
Asymptotic waveform inversion (AWI)

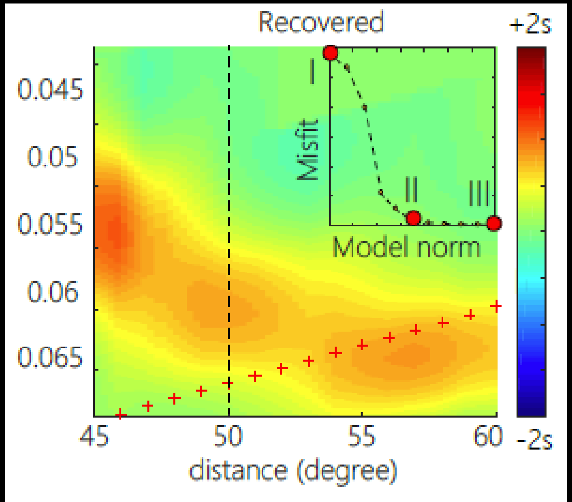


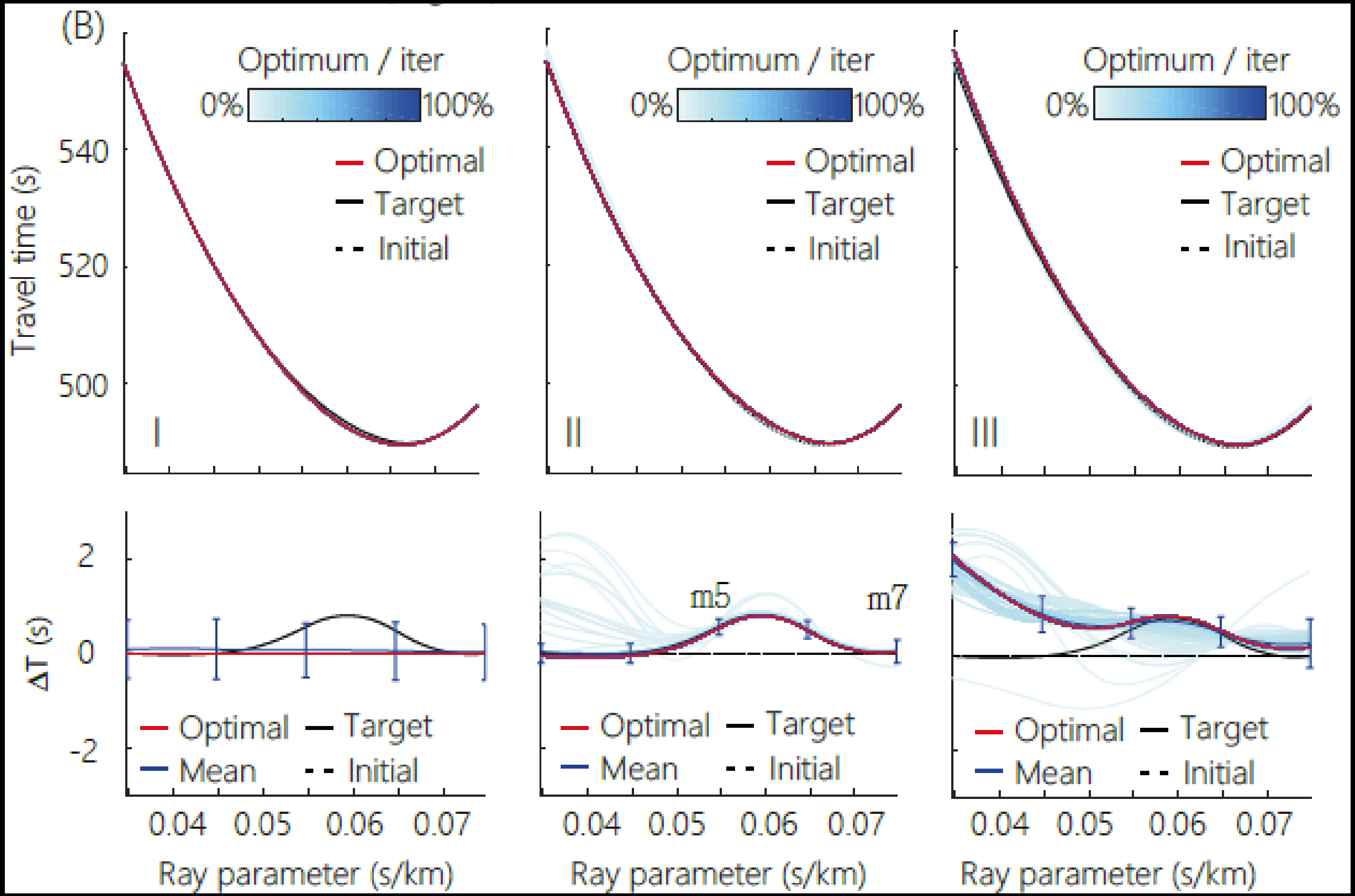
Genetic algorithm (GA)
Neighborhood Algorithm (NA)
Random samples



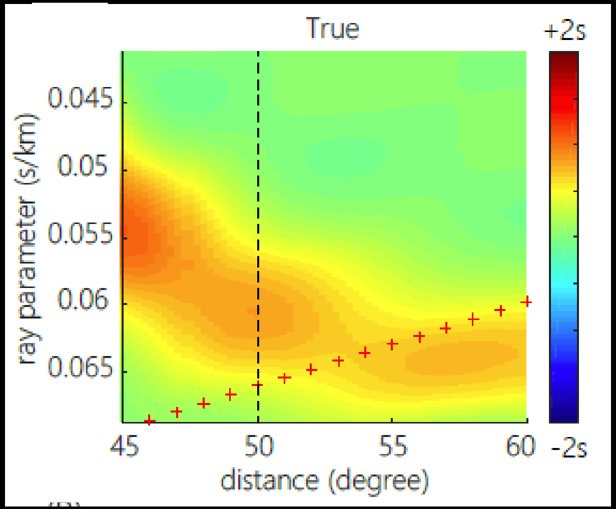
Asymptotic waveform inversion (AWI)

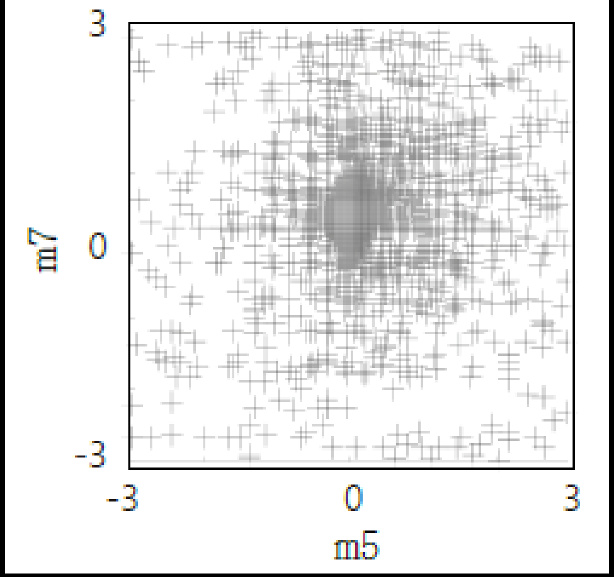


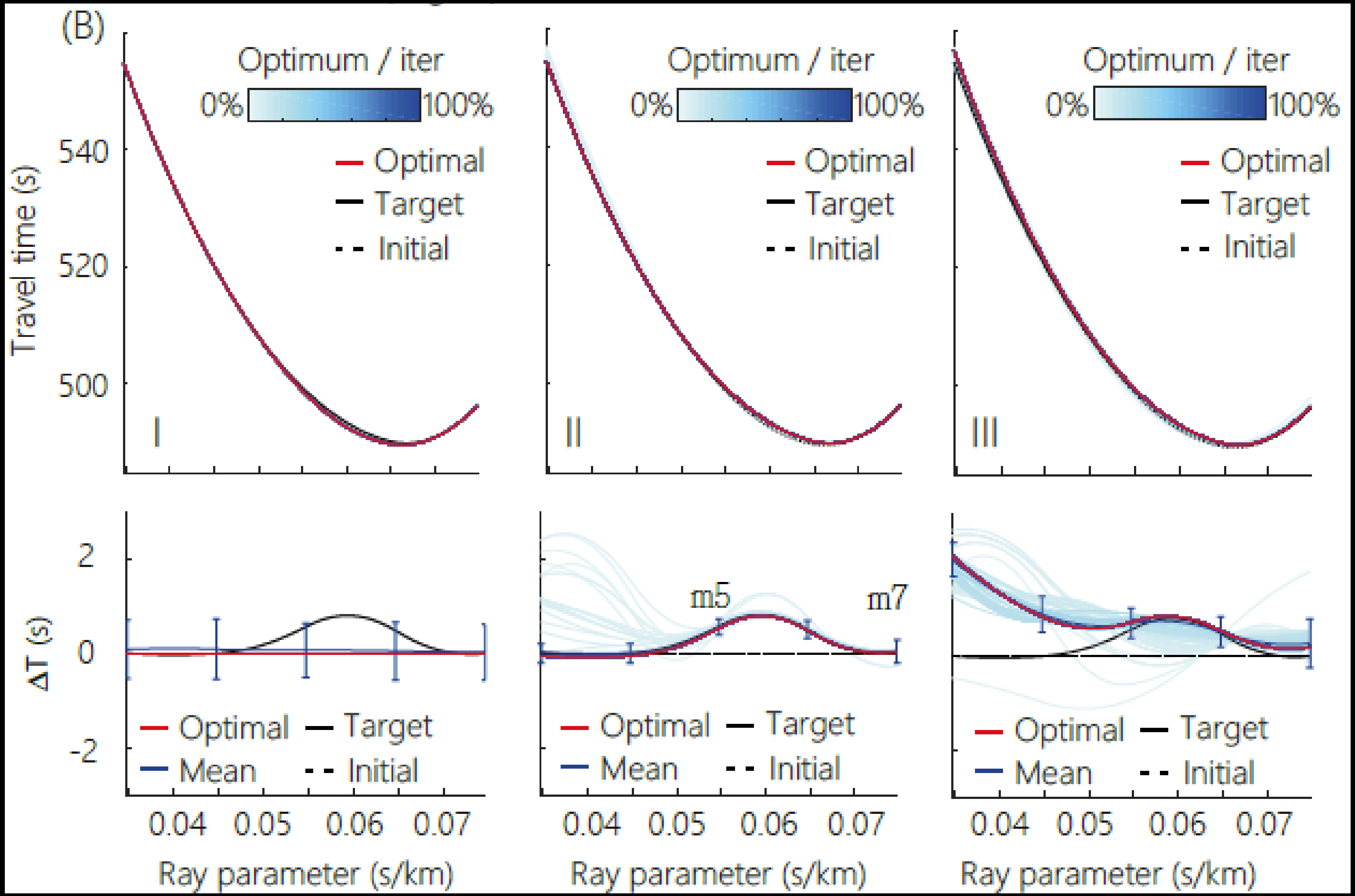




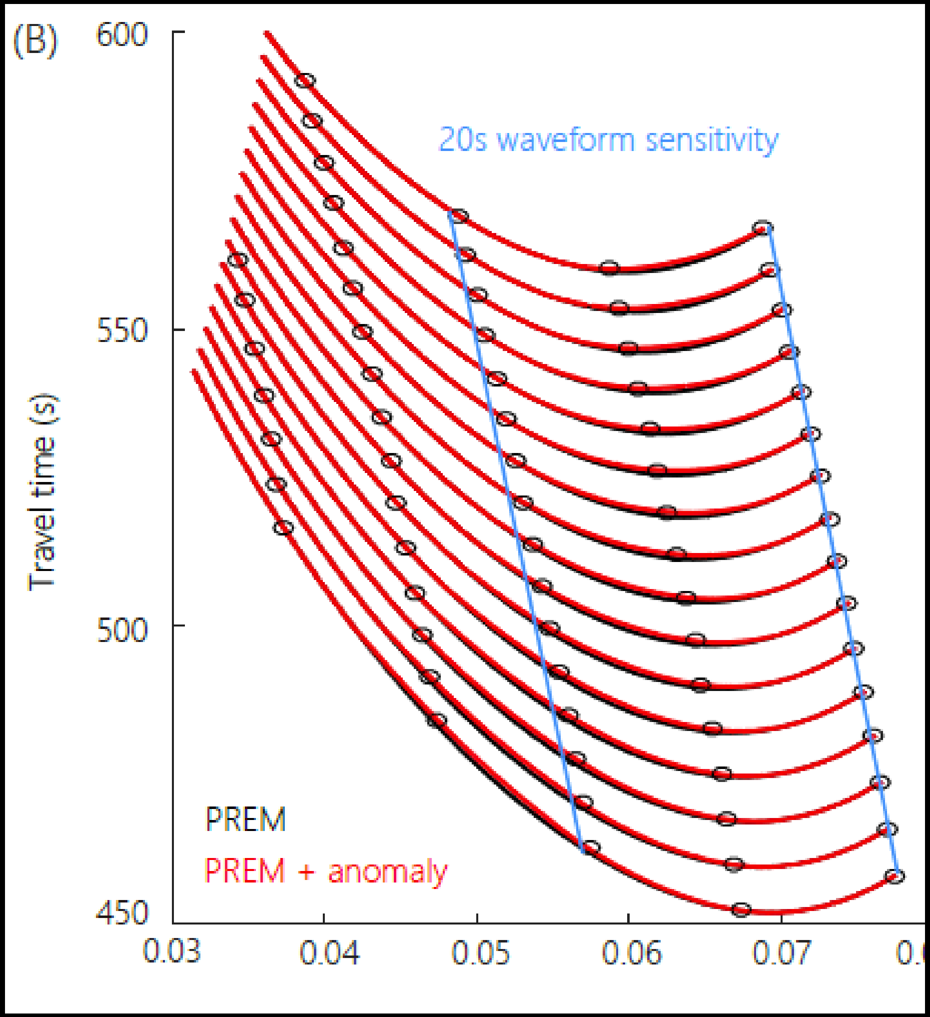
Asymptotic waveform inversion (AWI)

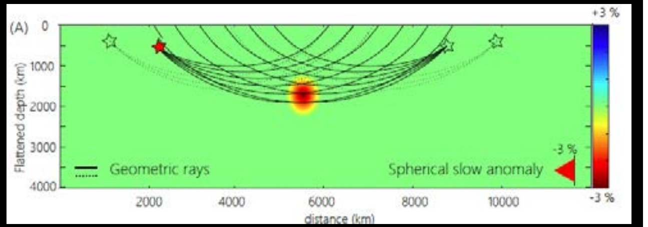




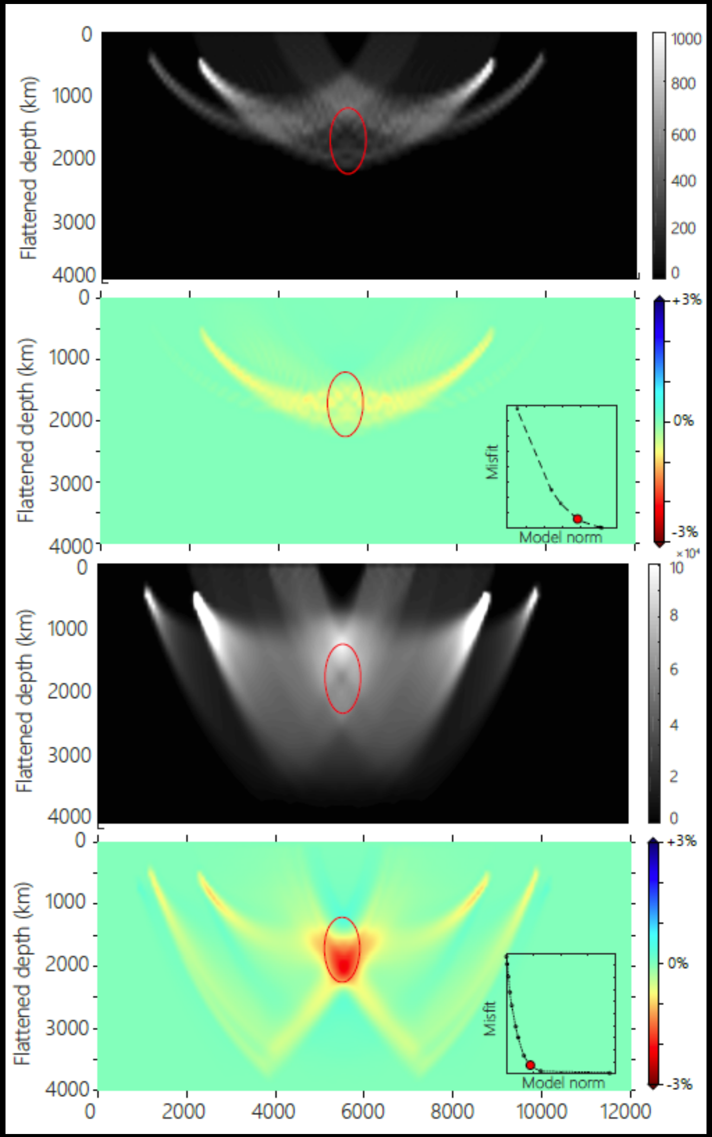


Asymptotic waveform inversion (AWI)





G m = d

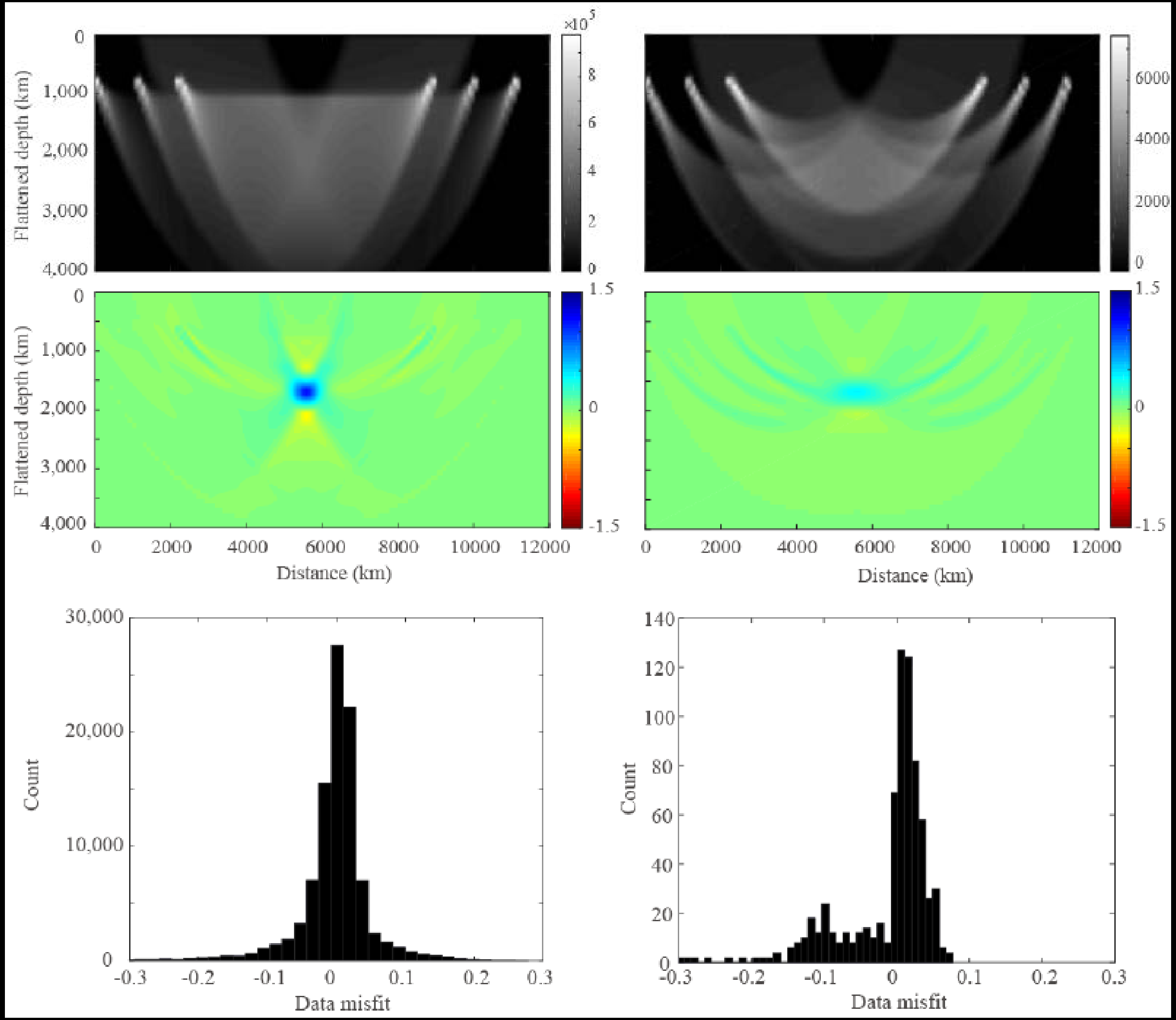


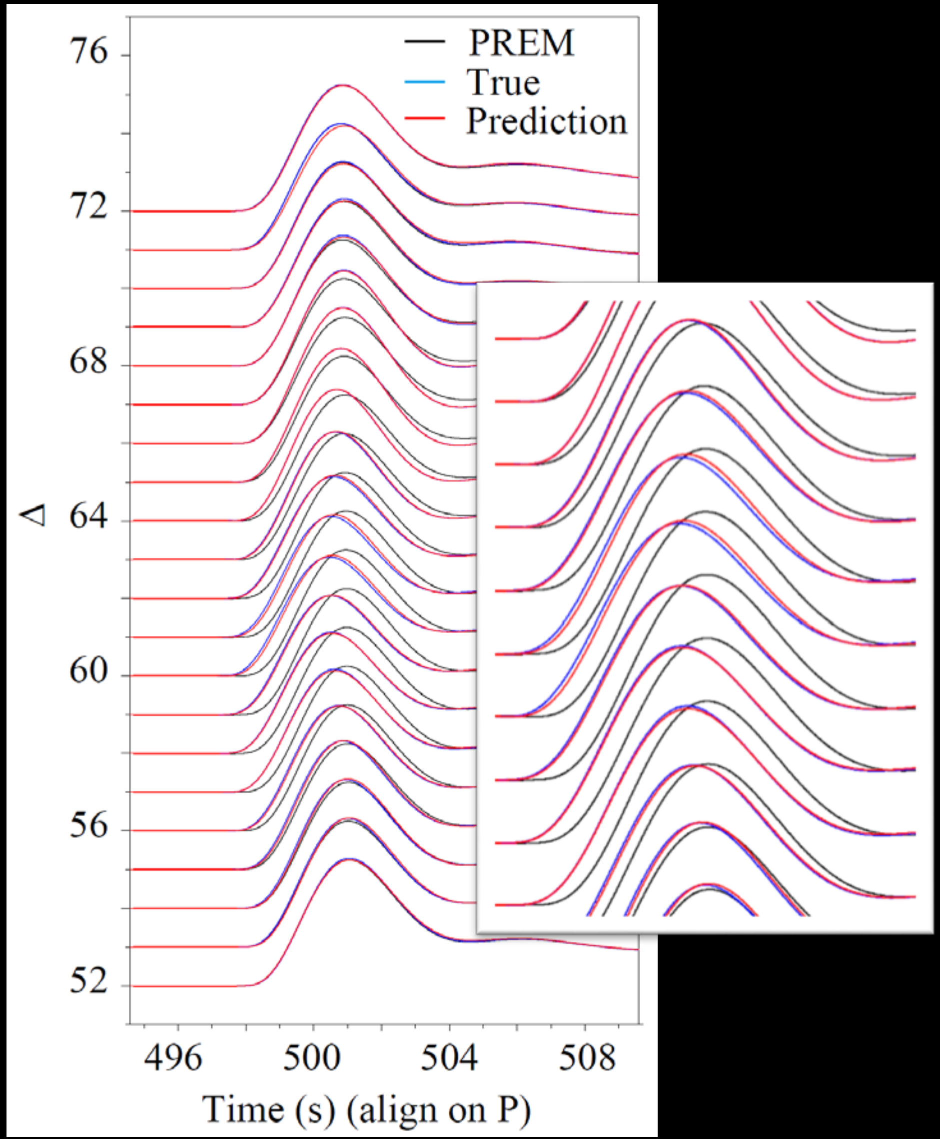
PT surface → Velocity structure

PT tomography

Traveltime tomography

Ko and Zhan, 2018, in prep.



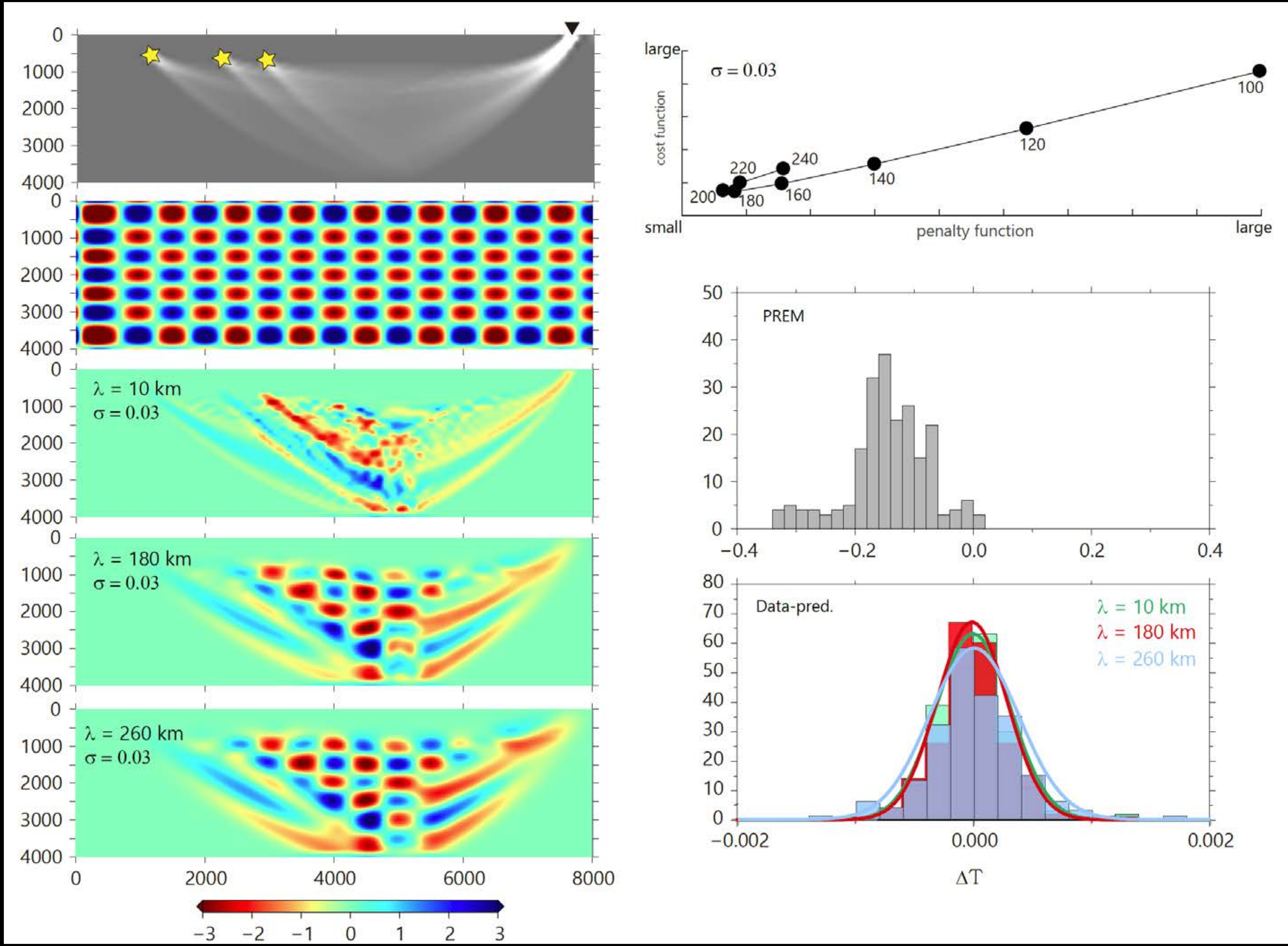


Checkboard Test

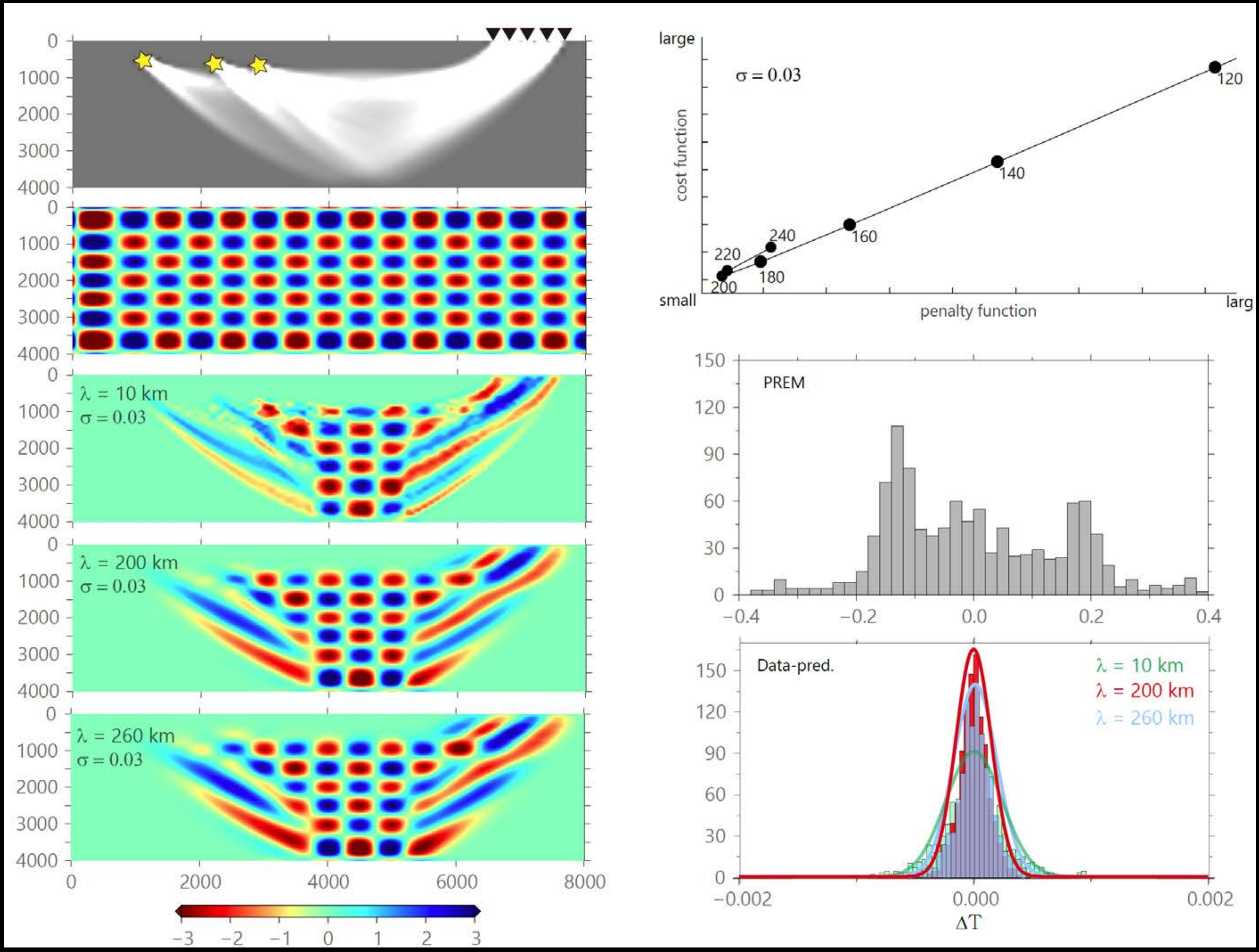
$$
\begin{aligned}
2\,S(\mathbf{m}) &= \|\,\mathbf{g}(\mathbf{m}) - \mathbf{d}_{\mathrm{obs}}\,\|_{\mathrm{D}}^{2} + \|\,\mathbf{m} - \mathbf{m}_{\mathrm{prior}}\,\|_{\mathrm{M}}^{2} \\
&= (\mathbf{g}(\mathbf{m}) - \mathbf{d}_{\mathrm{obs}})^{t}\,\mathbf{C}_{\mathrm{D}}^{-1}\,(\mathbf{g}(\mathbf{m}) - \mathbf{d}_{\mathrm{obs}}) + (\mathbf{m} - \mathbf{m}_{\mathrm{prior}})^{t}\,\mathbf{C}_{\mathrm{M}}^{-1}\,(\mathbf{m} - \mathbf{m}_{\mathrm{prior}})
\end{aligned}
$$

Cost func. = Data misfit + Penalty func.

Cd = I; Cm = sig^2 * exp((x-x0)/lamda^2+(z-z0)/lamda^2)

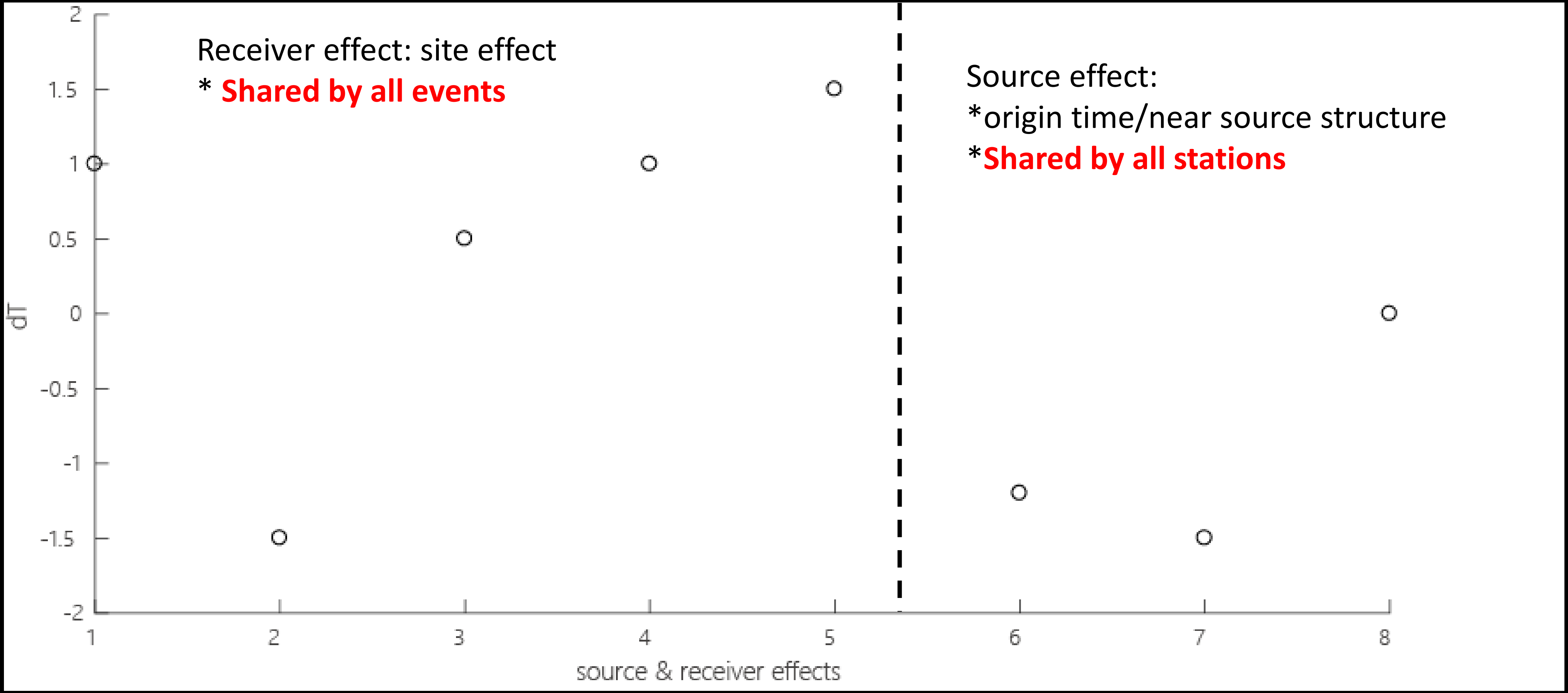


λ = 10 km
σ = 0.03
λ = 180 km
σ = 0.03
λ = 260 km
σ = 0.03
0
2000
4000
6000
8000
−3 −2 −1 0 1 2 3
large
σ = 0.03
cost function
100
120
140
160
180
200
220
240
small
penalty function
large
PREM
−0.4 −0.2 0.0 0.2 0.4
Data-pred.
λ = 10 km
λ = 180 km
λ = 260 km
−0.002 0.000 0.002
ΔT

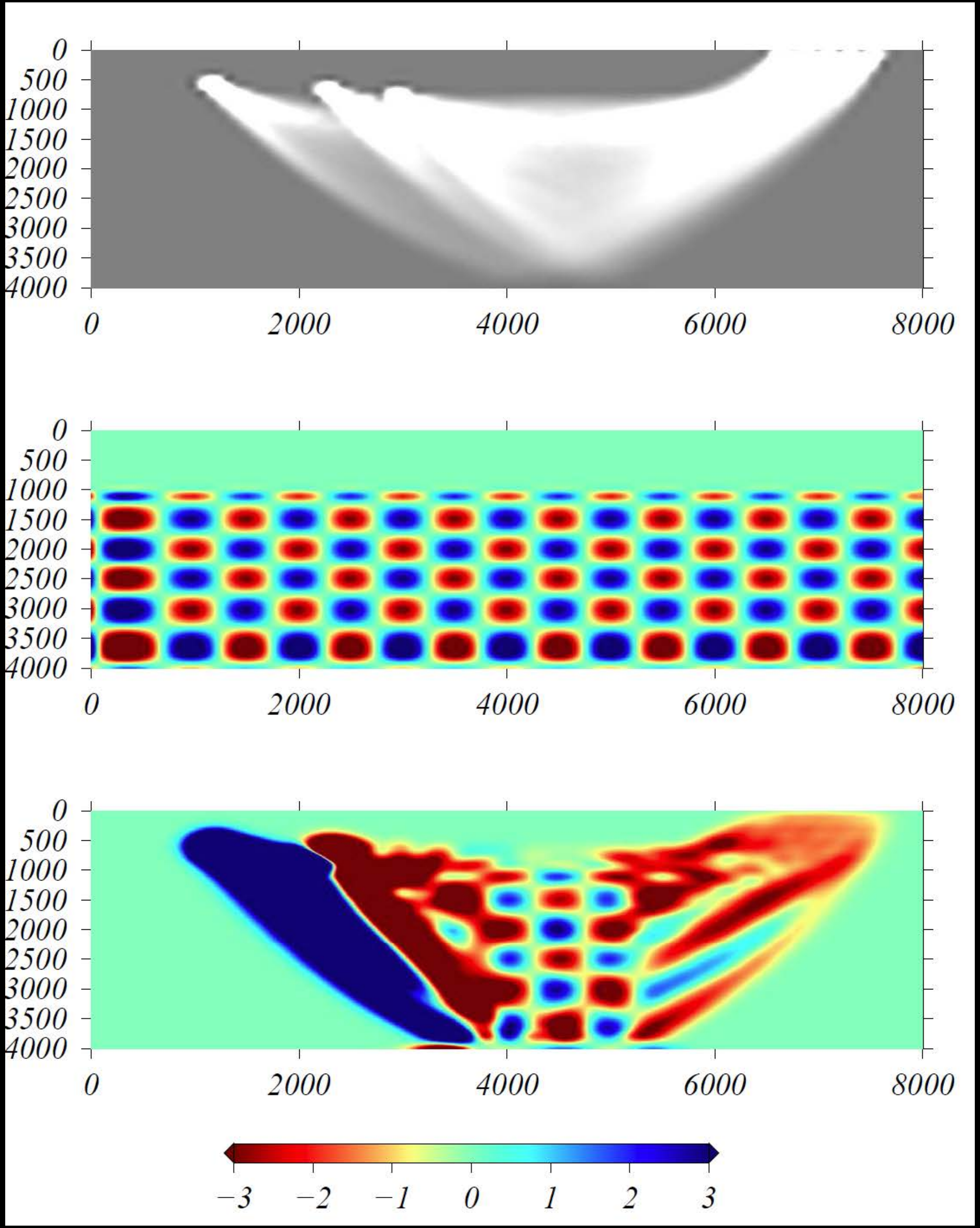


λ = 10 km
σ = 0.03
λ = 200 km
σ = 0.03
λ = 260 km
σ = 0.03
large
σ = 0.03
cost function
small
penalty function
larg
120
140
160
240
220
180
200
PREM
Data-pred.
λ = 10 km
λ = 200 km
λ = 260 km
ΔT

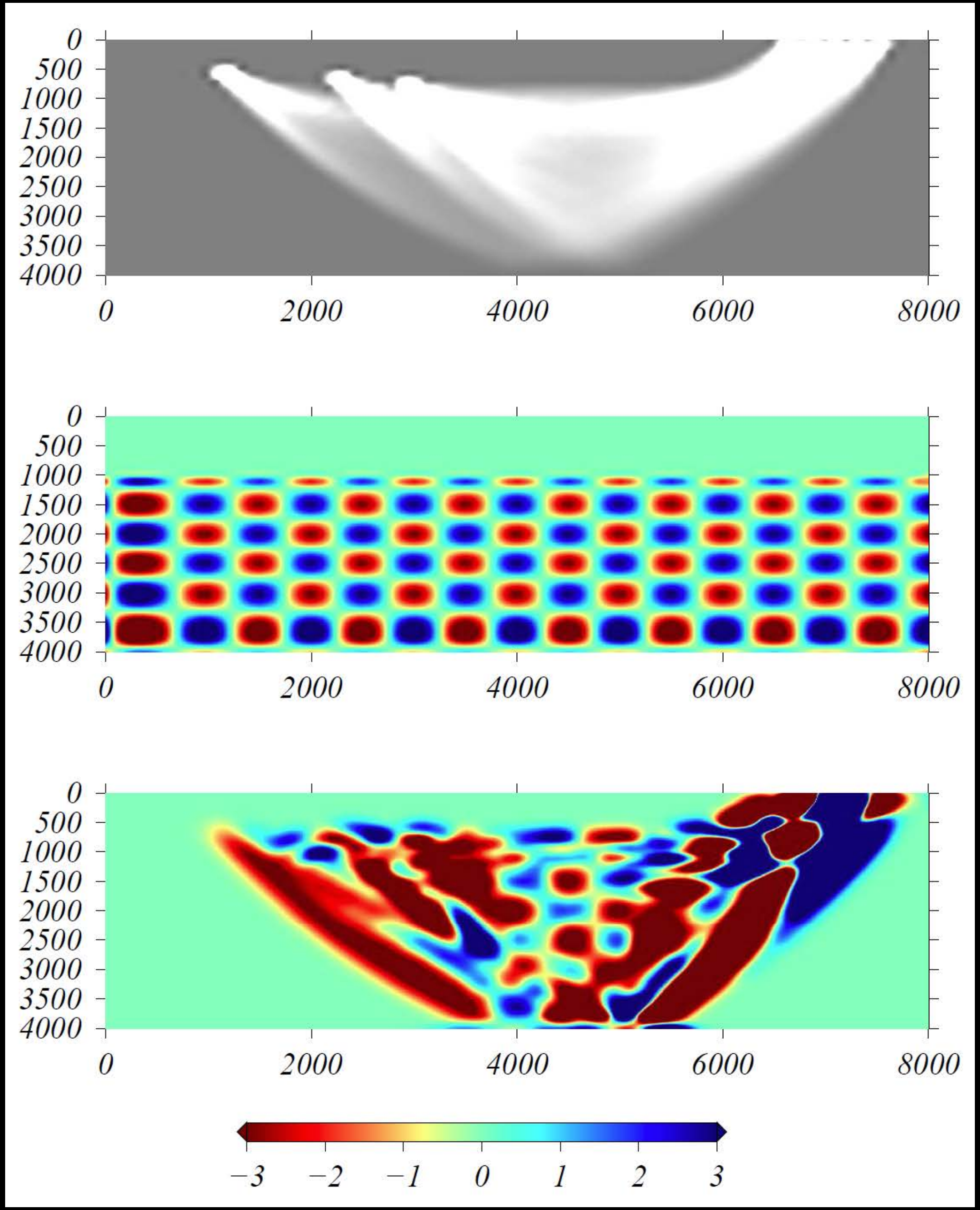
Source and receiver effects

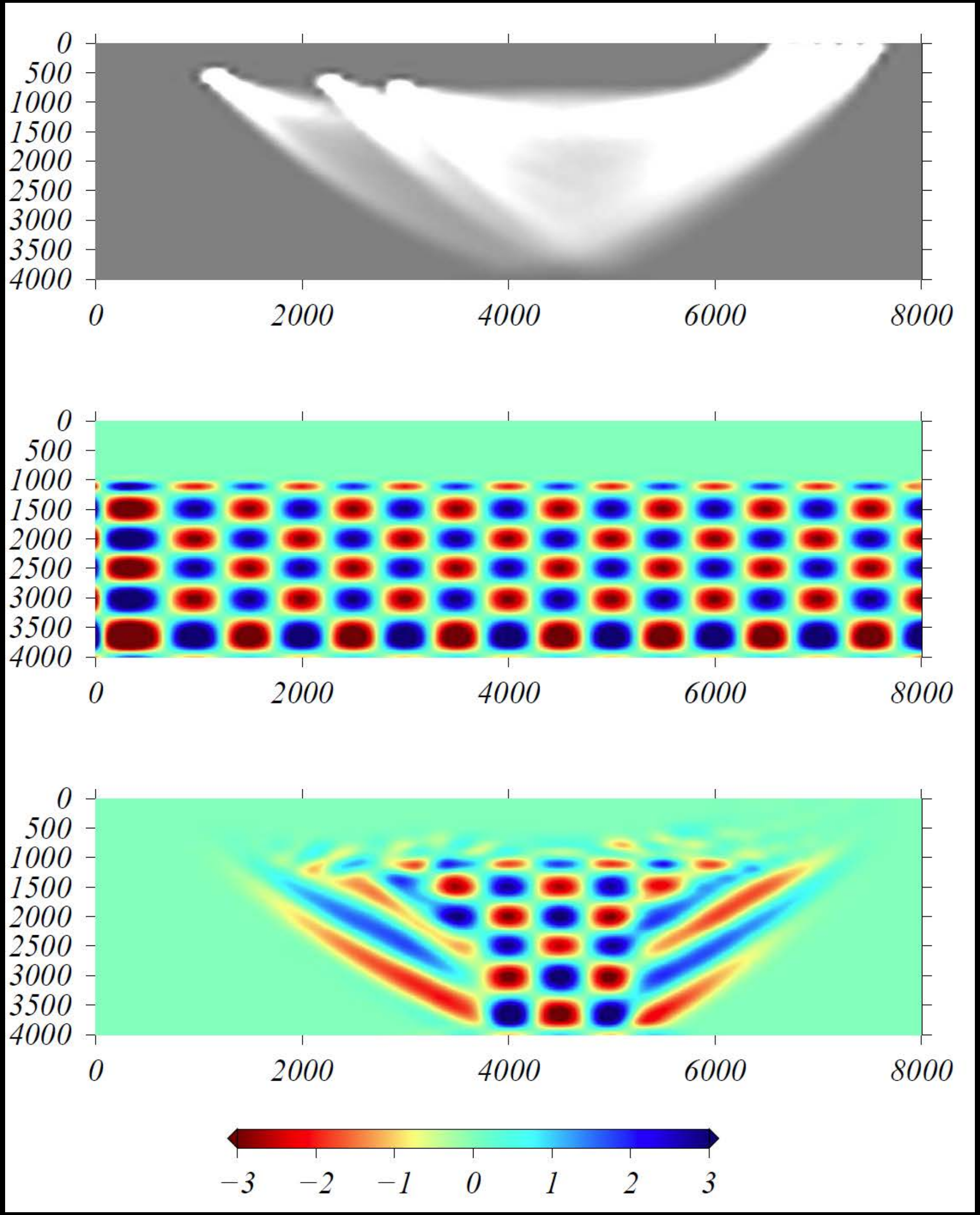


Source errors

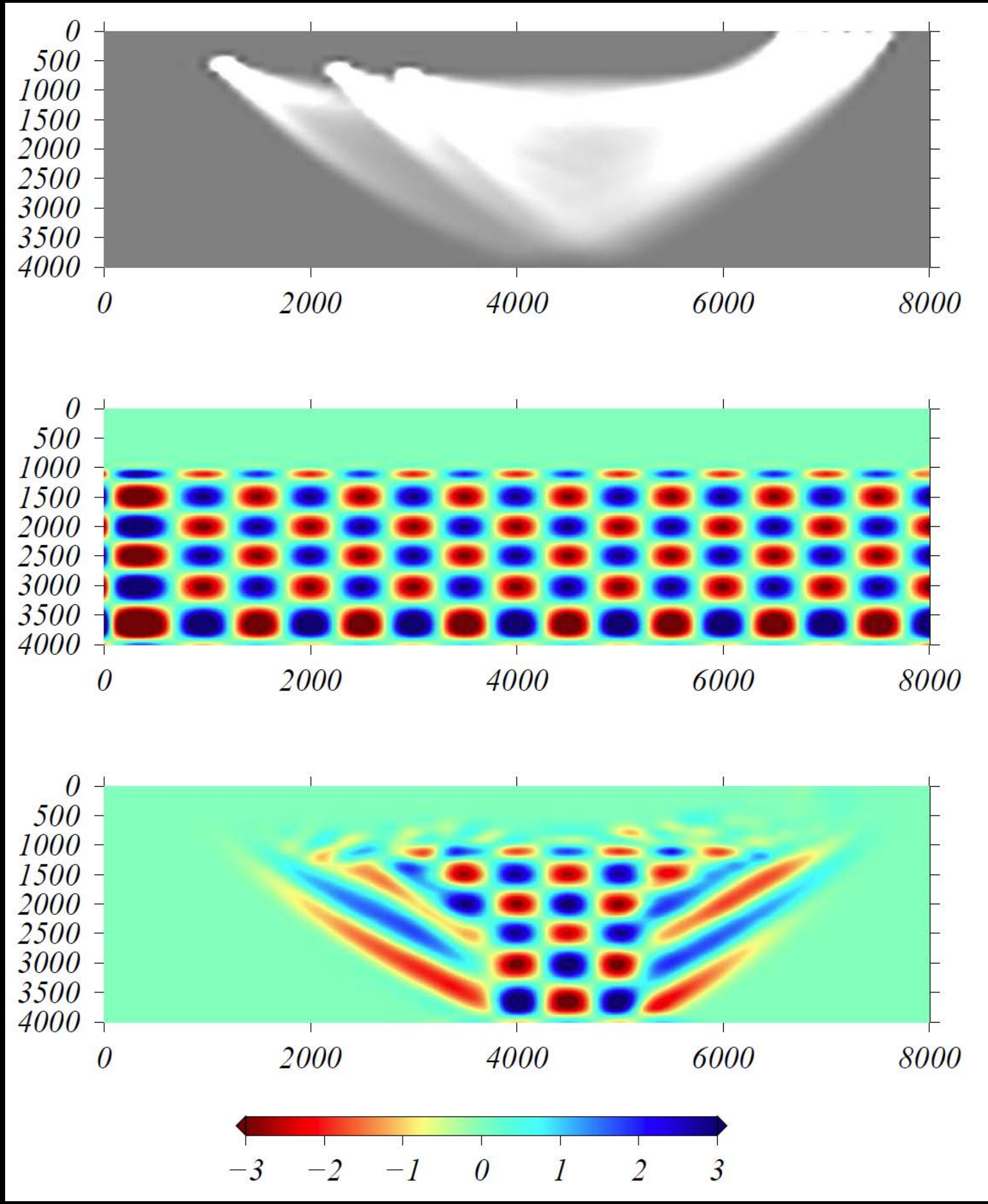


Site effects



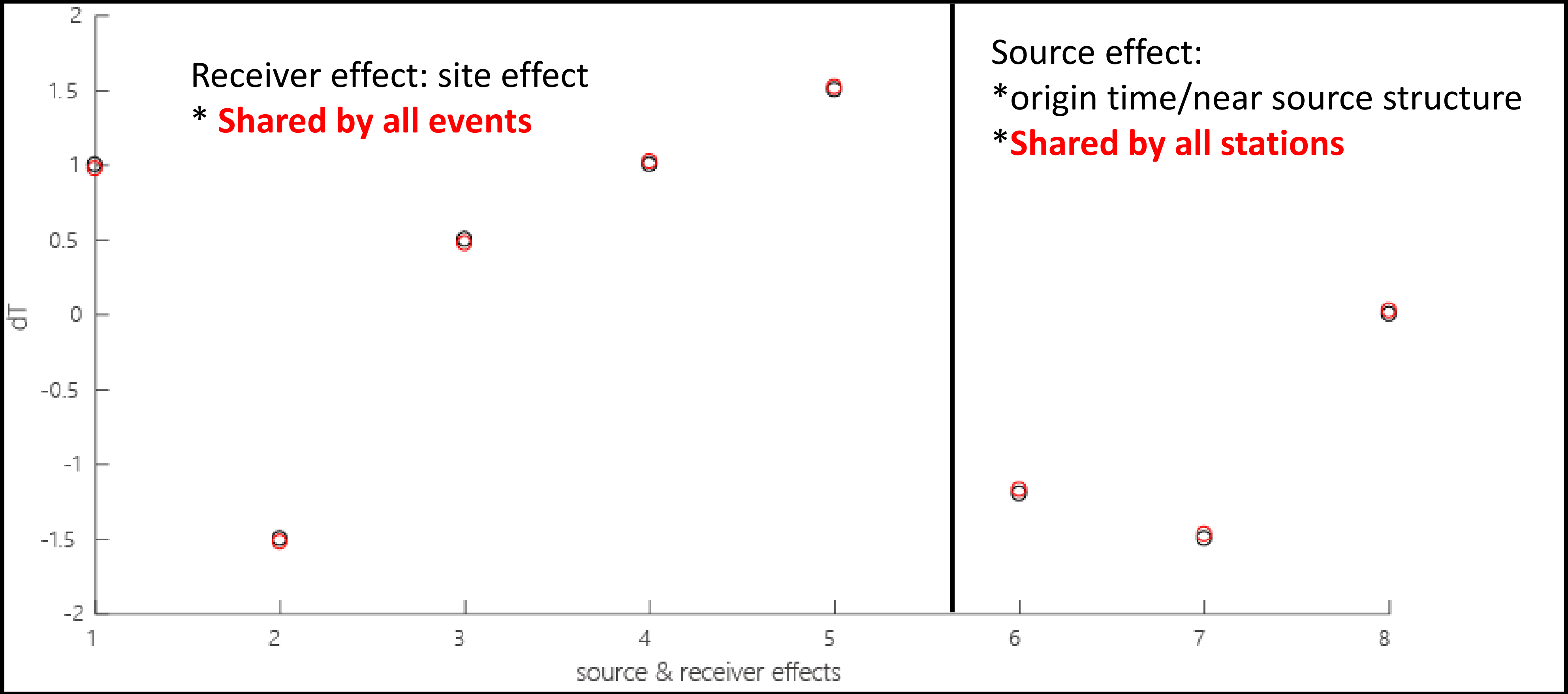


0
500
1000
1500
2000
2500
3000
3500
4000
0
2000
4000
6000
8000
−3
−2
−1
0
1
2
3



0
500
1000
1500
2000
2500
3000
3500
4000
0
2000
4000
6000
8000
−3
−2
−1
0
1
2
3

Source and receiver effects



Summary

- While the AWM/WKM does not work for full seismograms, it demonstrates high accuracy for important seismic phases (e.g., P and S) for typical/enhanced velocity anomalies considered in Earth's middle and lower mantle.

- AWI provides more realistic uncertainty estimates and can be used to efficiently invert the velocity model.

- Work in progress: The realistic tomographic model or relatively sharp anomaly

Thank you

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