Towards global scale full-waveform inversion

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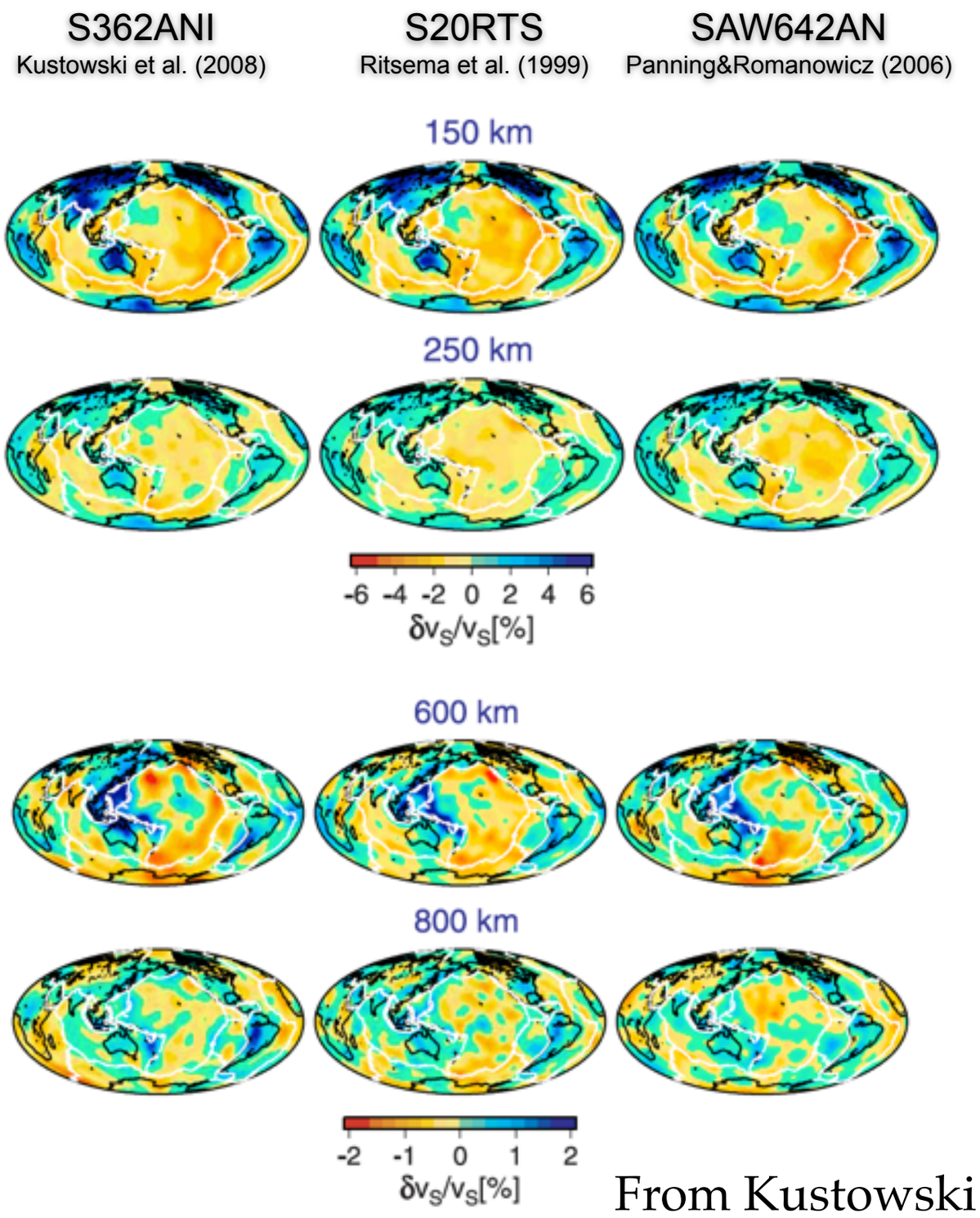
What we mean by full-waveform tomography

- Forward simulations in 3D models
- Fréchet kernels in 3D background models
- Use of complete seismograms at three components
- Use of both phase and amplitudes

Towards

global adjoint tomography

Global tomography



- mostly based on ray theory, recently finite-frequency effects are also taken into account
- 1D background models
- Combination of different data sets
- Crustal corrections

From Kustowski et al. (2008)

Challenges in global tomography

- Theoretical limitations
  - Finite-frequency effects have become important

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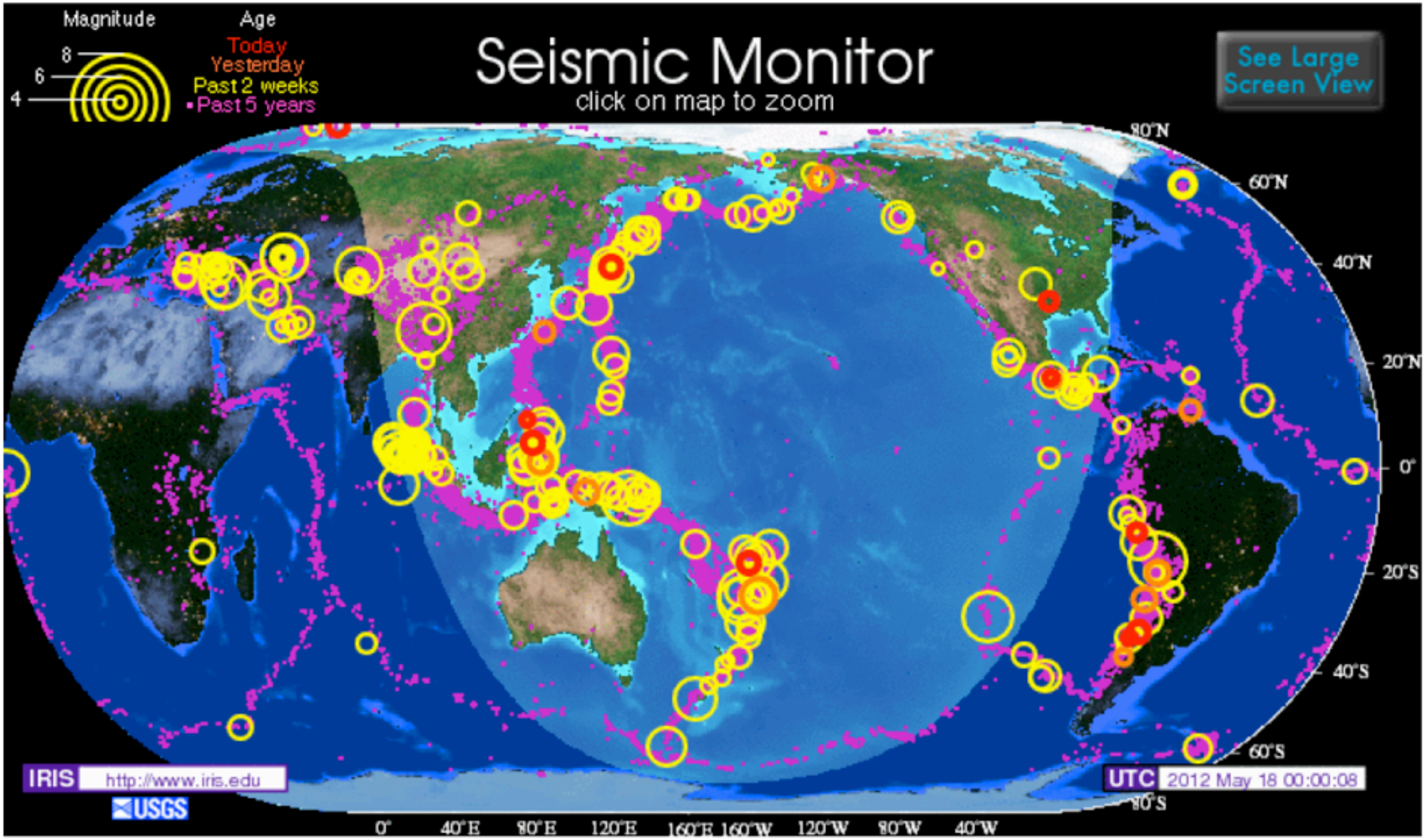
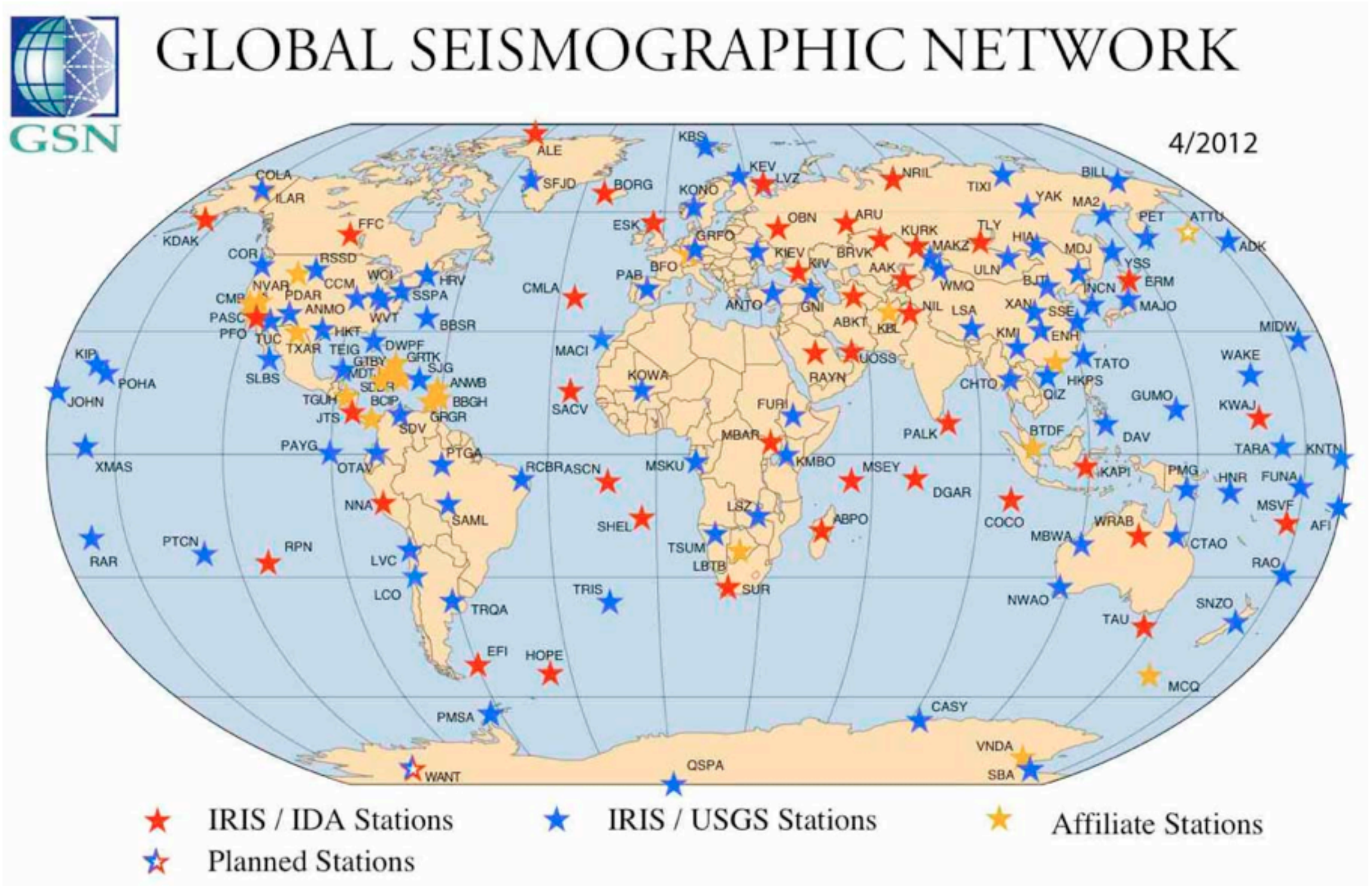
- Data coverage
  - Uneven distribution of earthquakes and stations on the globe

World seismicity

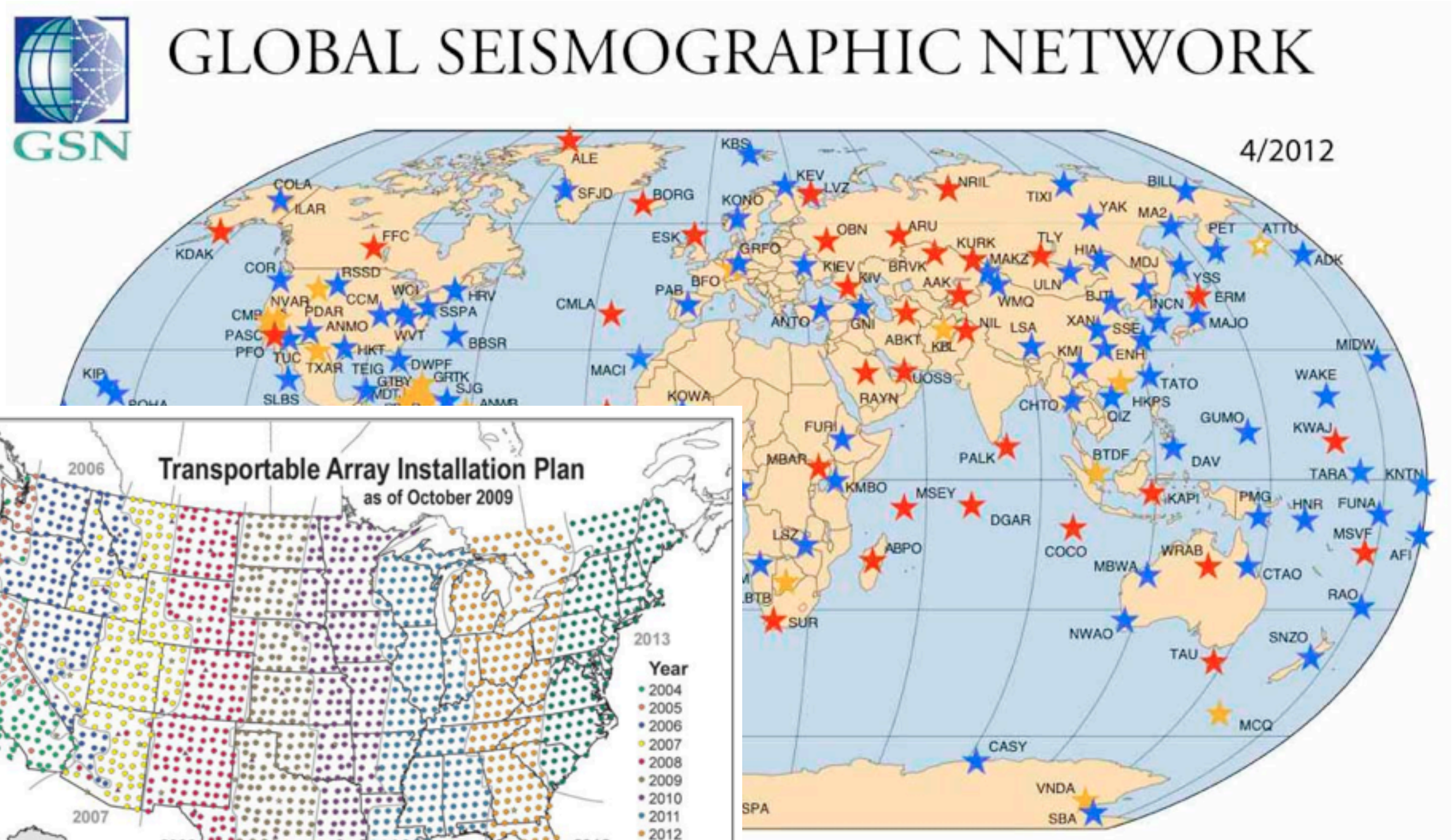


http://www.iris.edu/dms/seismon.htm

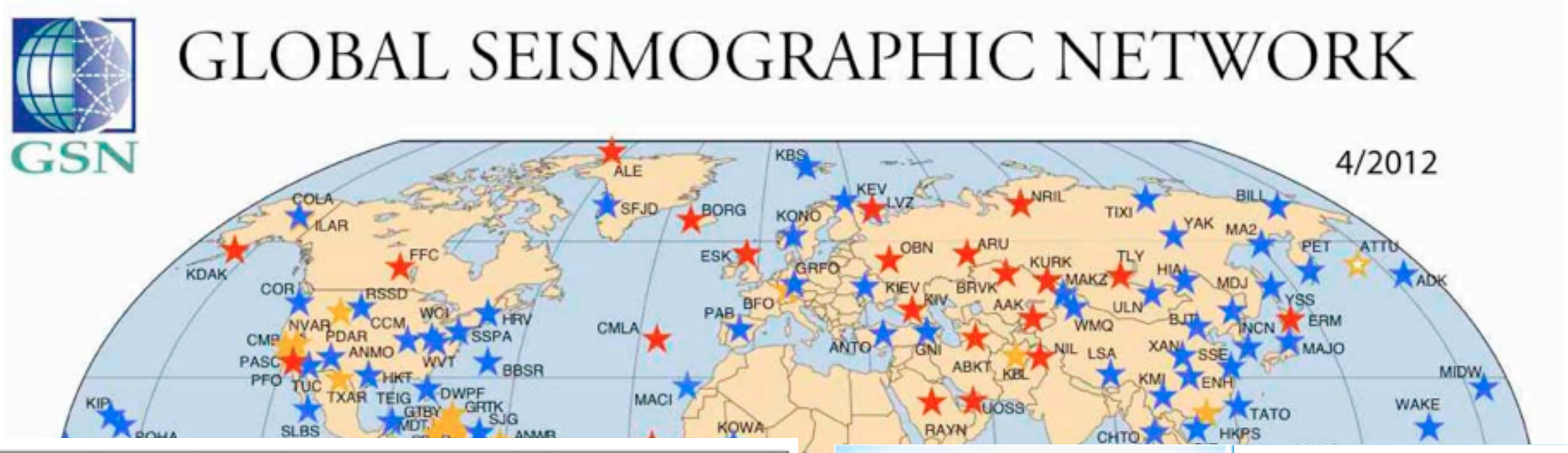
Seismic stations

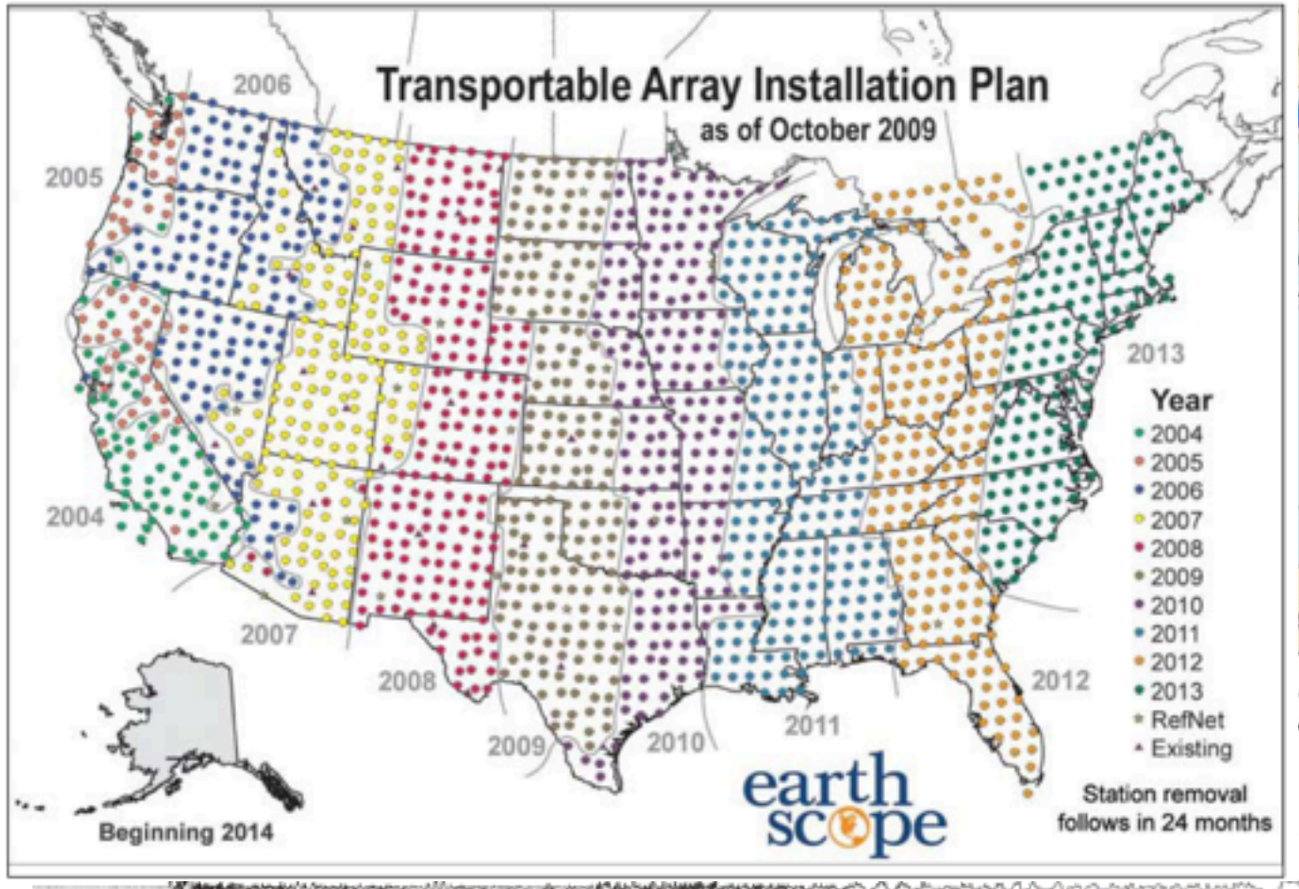


Seismic stations

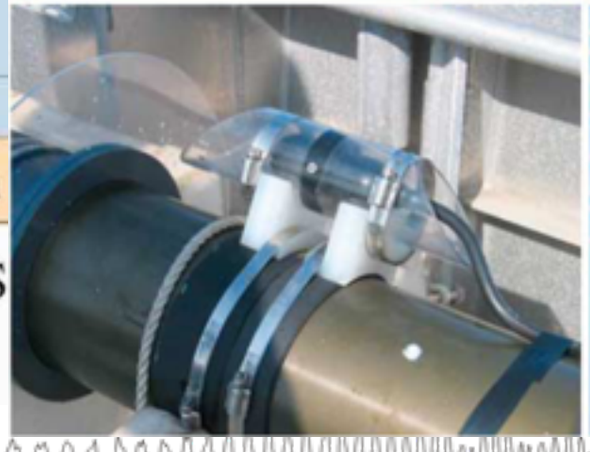


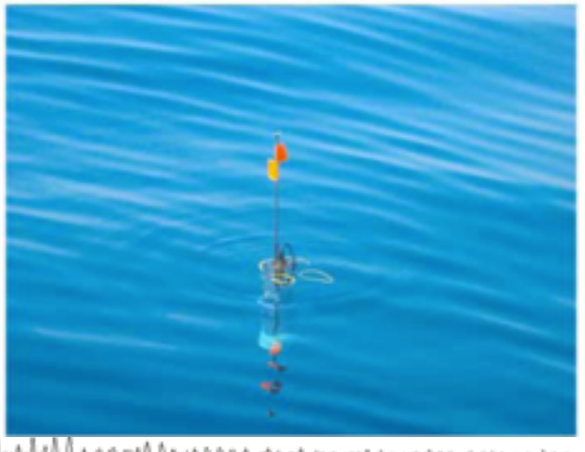
Seismic stations





Simons et al. 2009





Challenges in global tomography

- Theoretical limitations
  - Finite-frequency effects have become important
- Data coverage
  - Uneven distribution of earthquakes and stations on the globe
  - Usable data is subjected to the forward theory

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- Theoretical limitations
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- Data coverage
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  - Usable data is subjected to the forward theory
- Crustal effects
  - Can be highly nonlinear, thus “crustal corrections” are questionable

3D wave simulations - Adjoint tomography

- Full nonlinearity of wave propagation
- Dramatic increase in usable data, resulting better data coverage
- 3D background models help reduce nonlinearity of problem
- Iterative update of models
- No crustal corrections!

Outline

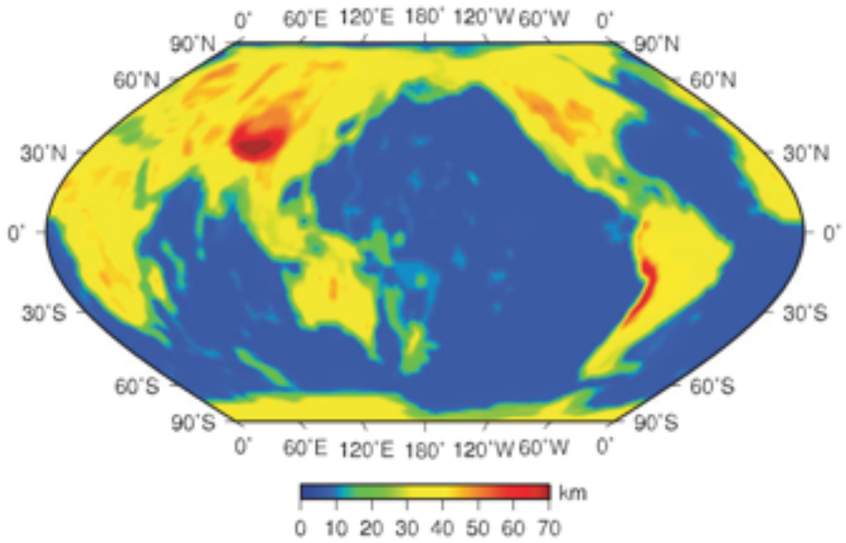
- Numerical simulations
- Source inversions
- Adjoint tomography
  - 1st iteration results!

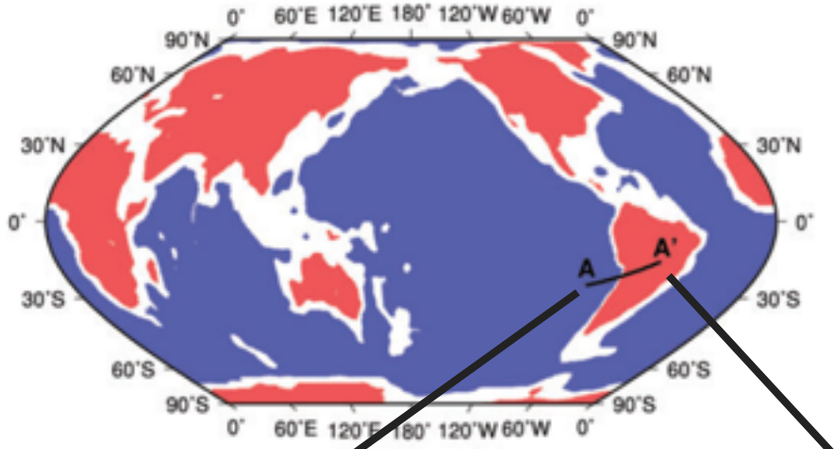
Numerical simulations

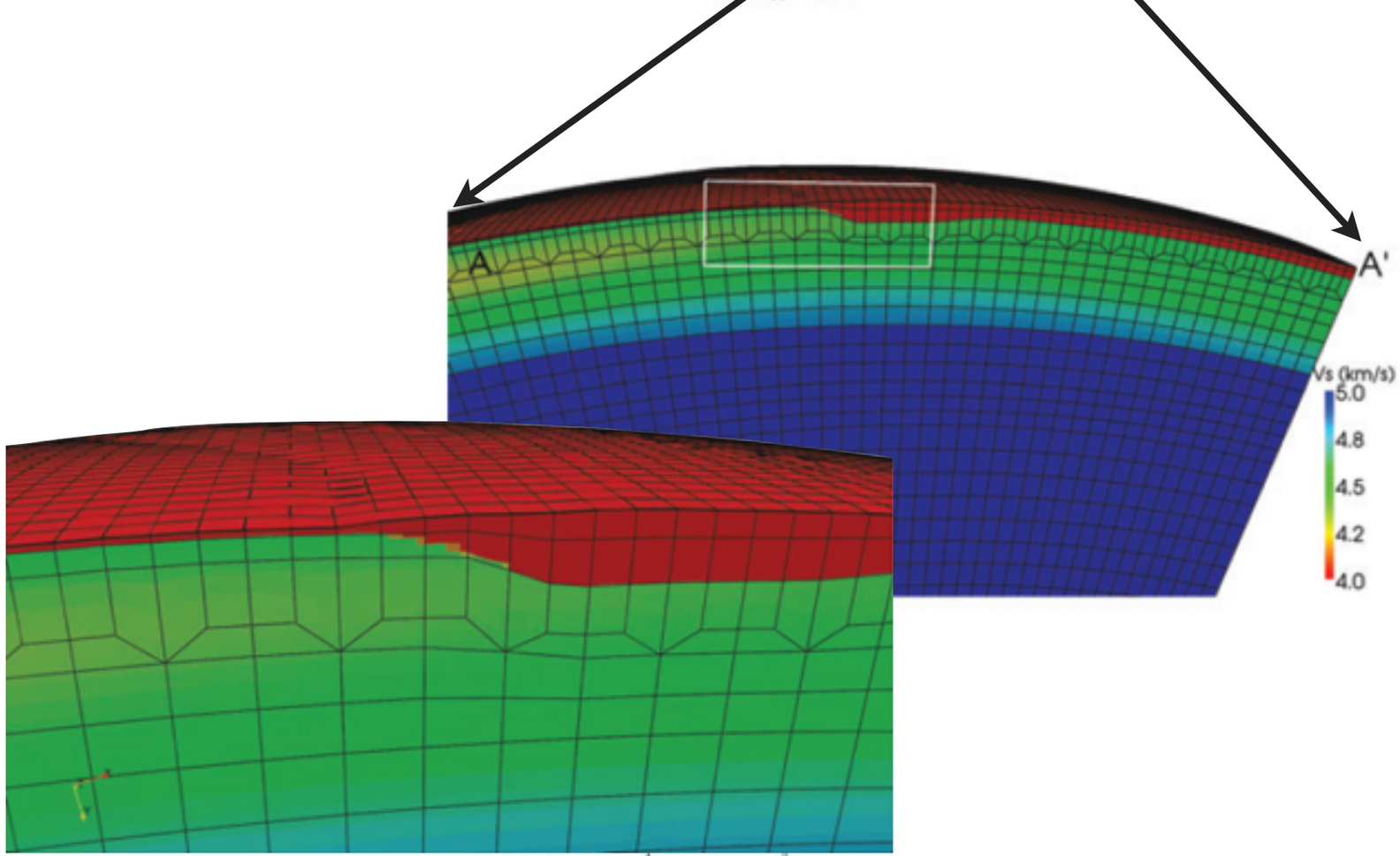
- SPECFEM3D_GLOBE (Komatitsch & Tromp 2002)
- 3D Reference model: S362ANI (Kustowski et al. 2008) + Crust2.0 (Bassin et al. 2000)
- Topography / bathymetry / attenuation / ellipticity / rotation / gravity
- Length of seismograms = 100 m
- Tmin = ~27 s

Implementation of crust in simulations

Smoothed Moho depths
from Crust2.0

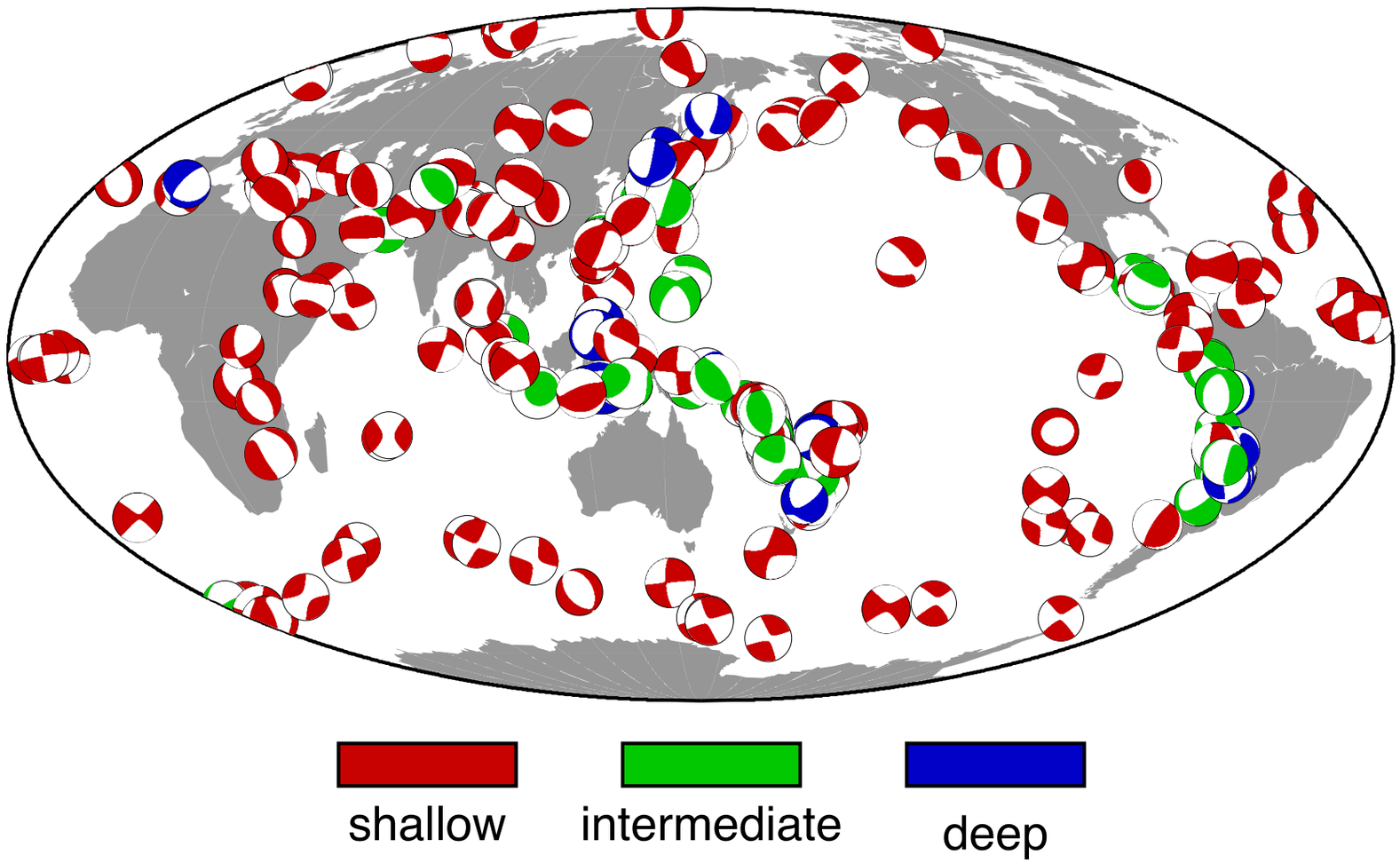






Moho is honored
if crustal thickness is
≤15 km and ≥35 km.

255 global CMT earthquakes



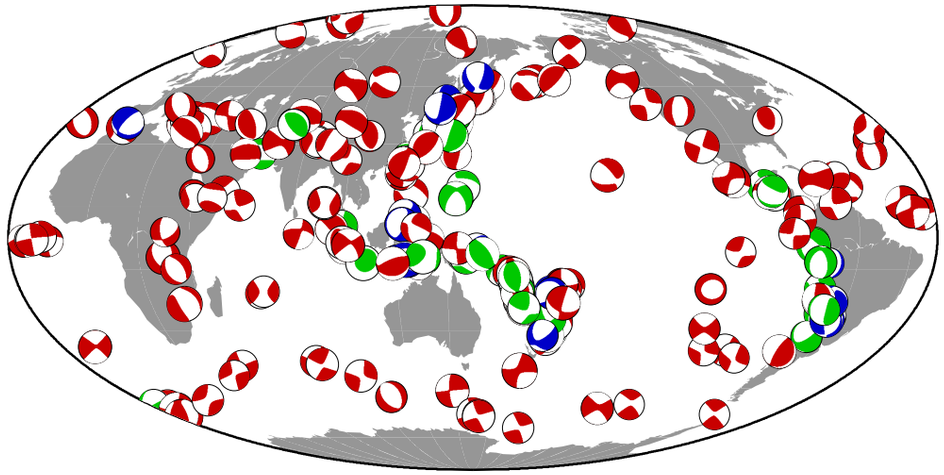
$5.8 \leq Mw \leq 7.0$

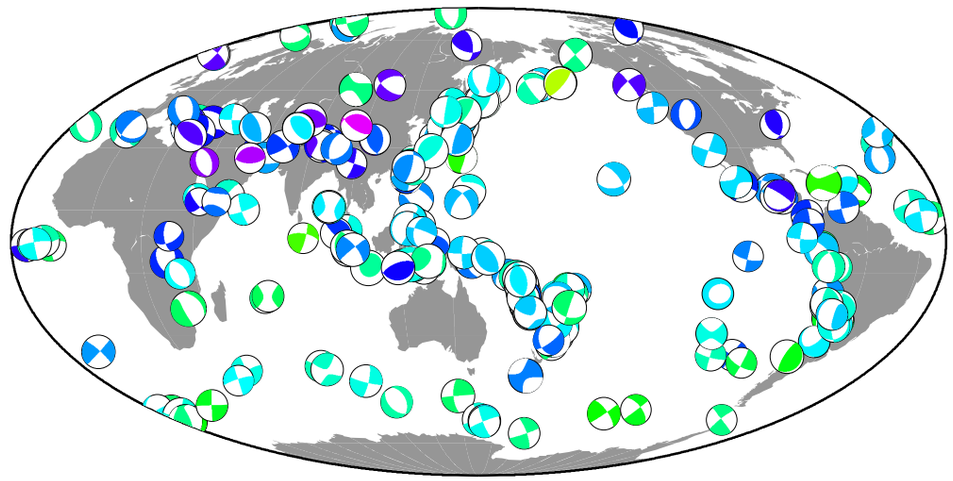
shallow: $d \leq 50$ km

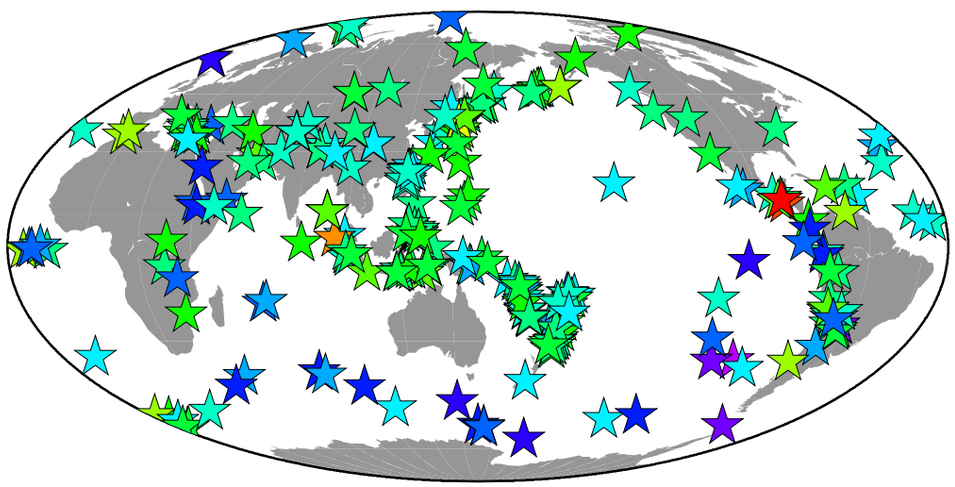
intermediate: $50 \text{ km} < d \leq 300$ km

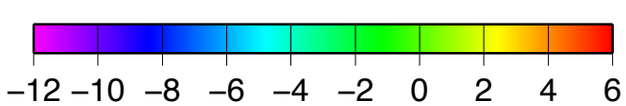
deep: $d > 300$ km

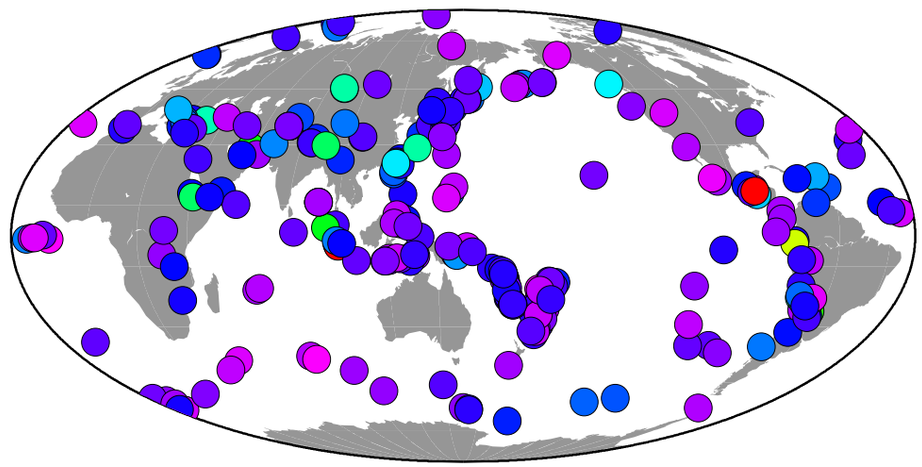
Source inversions - summary

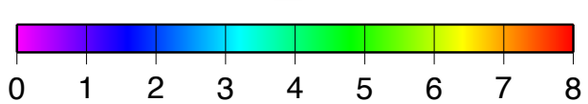






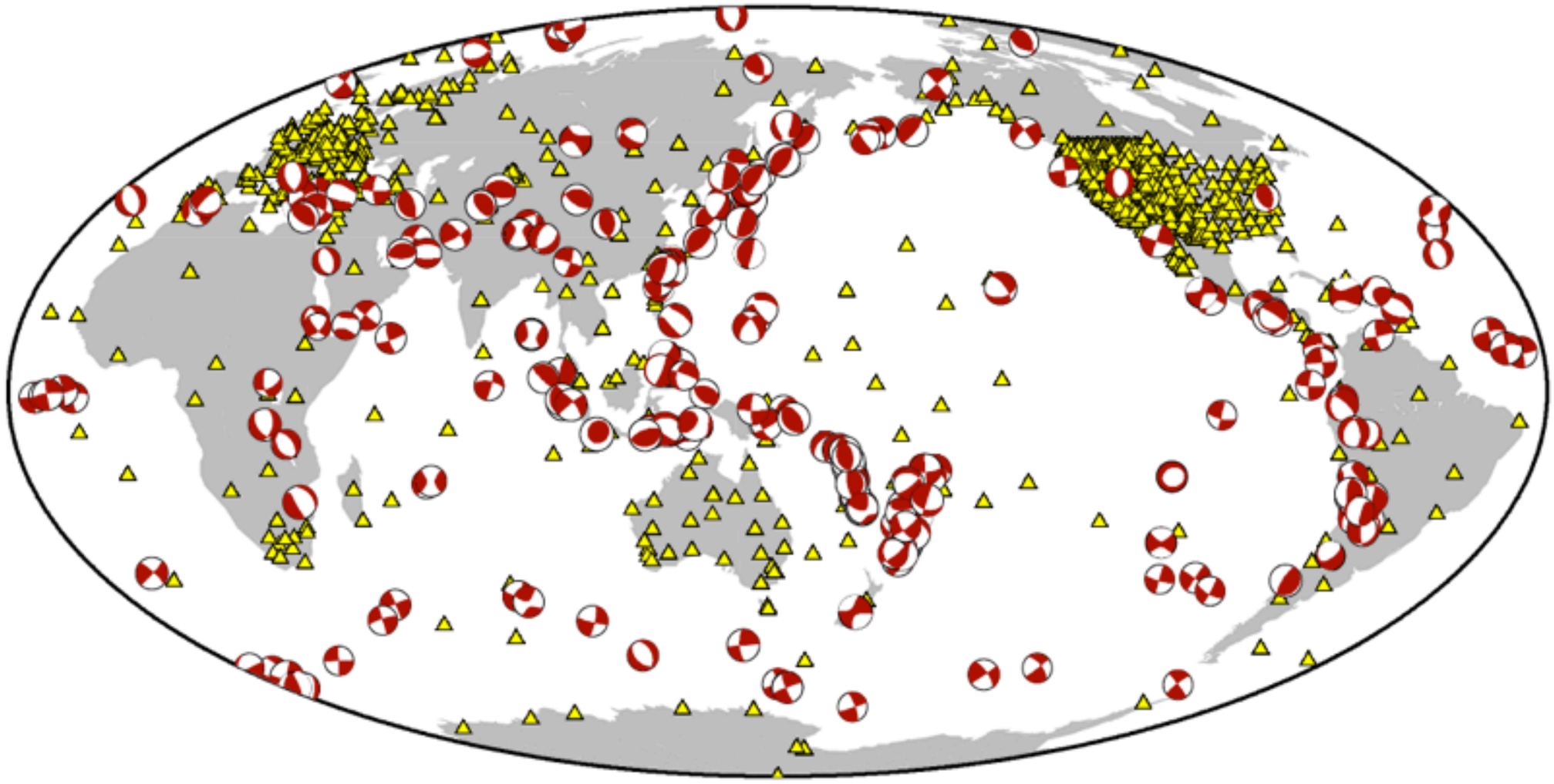






Adjoint tomography

Earthquake-station distribution



253 global CMT events ($5.8 \leq Mw \leq 7.0$)

Data from IRIS & ORFEUS

Inversion strategies

Multitaper traveltime measurements

$$\chi_c = \frac{1}{N_c} \sum_{s=1}^{S} \sum_{i=1}^{N_c^s} \int w_i(\omega) \left[\frac{\Delta\tau_i(\omega)}{\sigma_i(\omega)} \right]^2 d\omega$$

χ_c : misfit per category

N_c : number of picks per category

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$$\chi^{total} = \chi^{27-60s} + \chi^{60-120s}$$

1) P-SV on vertical

2) P-SV on radial

3) SH on transverse

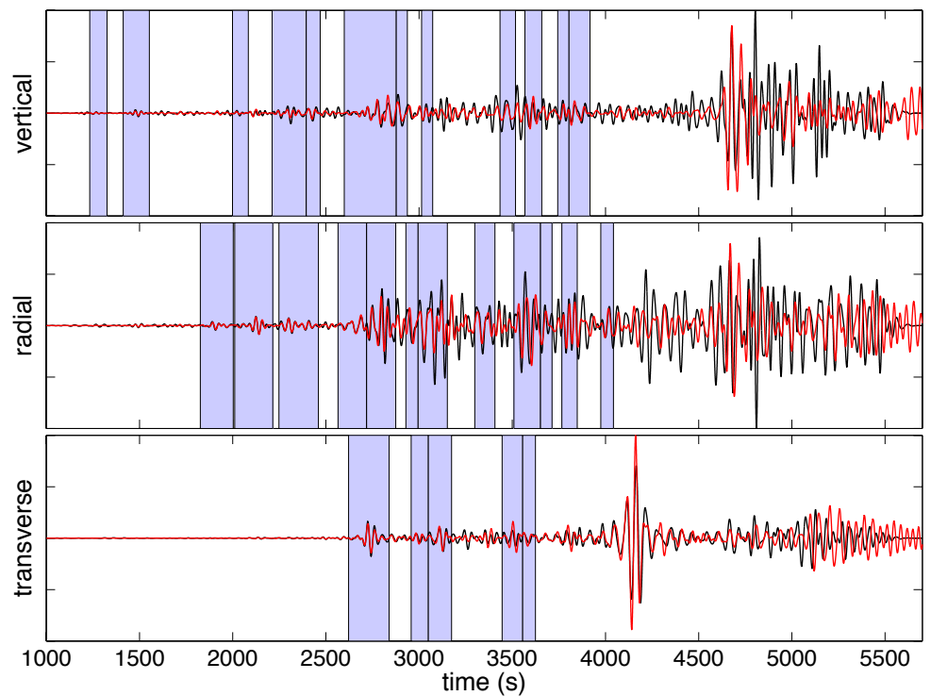
4) P-SV-Rayleigh on vertical

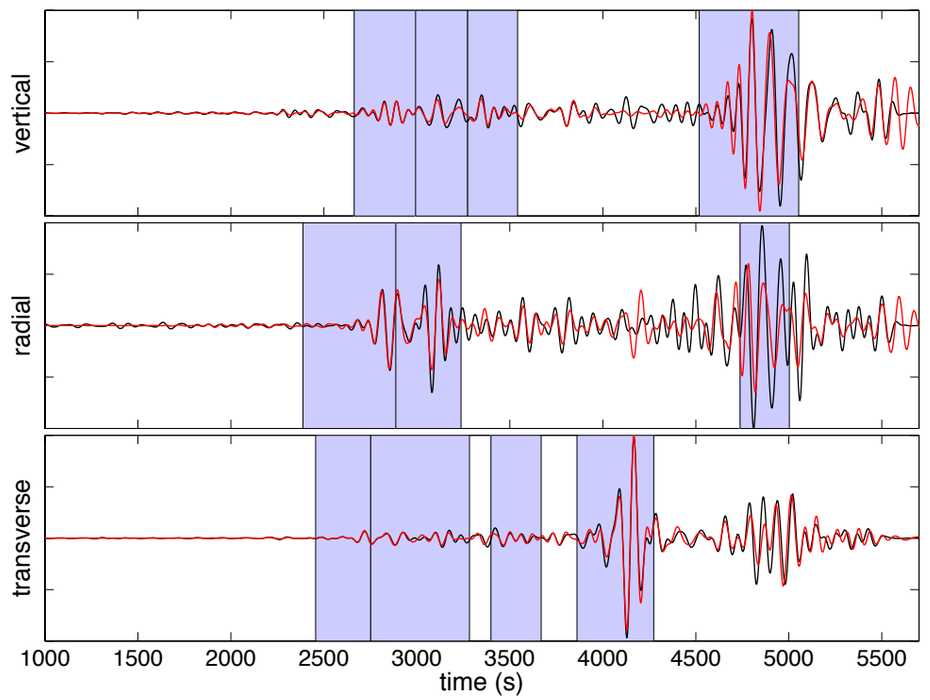
5) P-SV-Rayleigh on radial

6) SH-Love on transverse

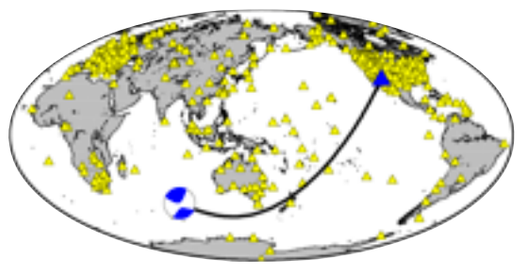
Data selection

2008, May 31, Mid-Indian Ridge event
Mw=6.4, depth=6.5 km





Station: 112A
Δ=165°



window selection:
FLEXWIN
(Maggi et al. 2009)

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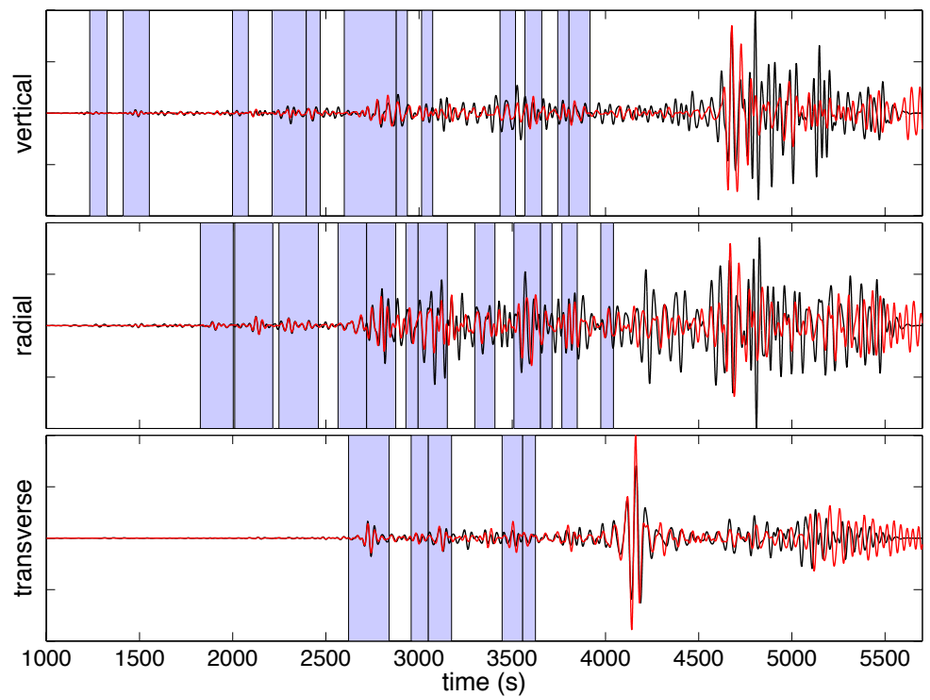

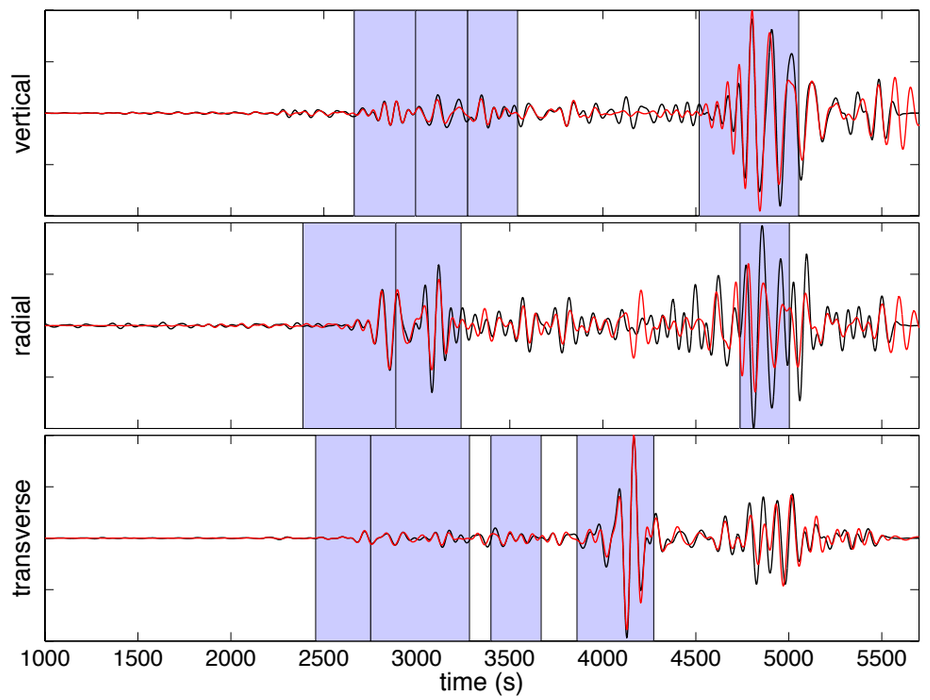

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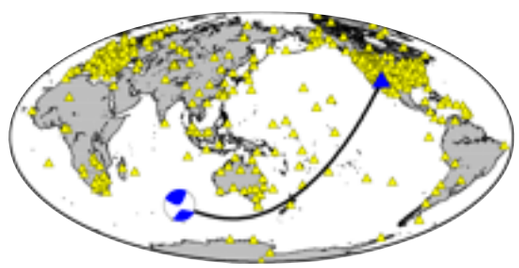

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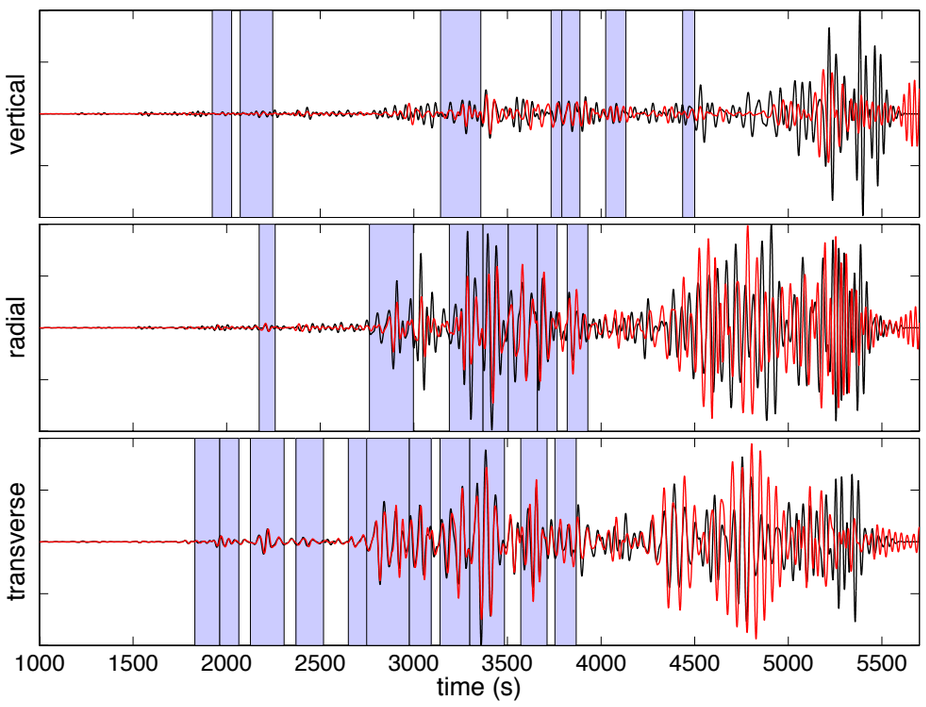
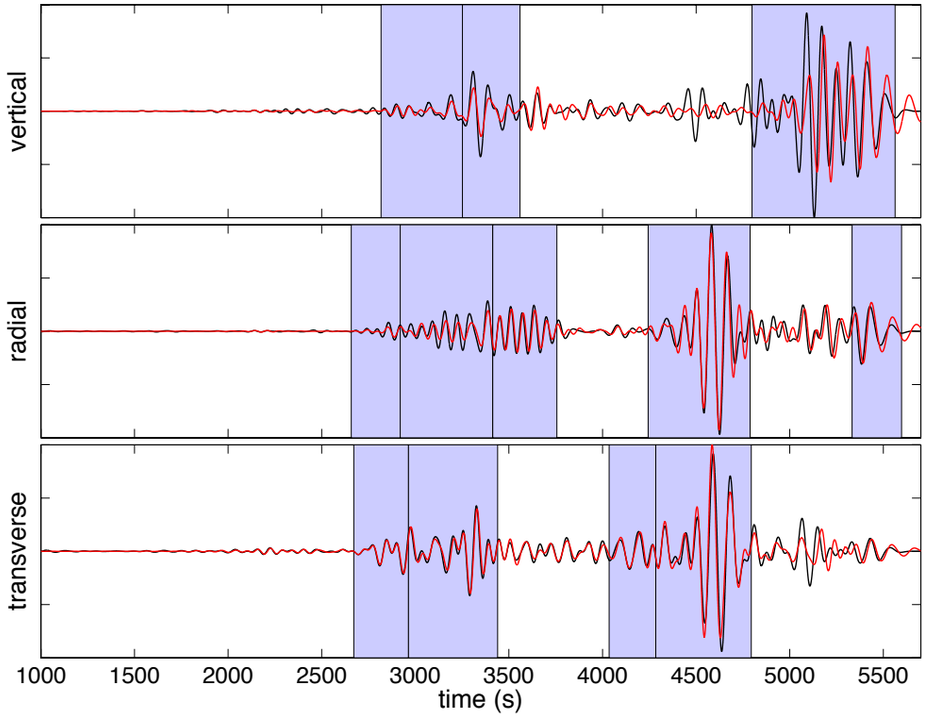
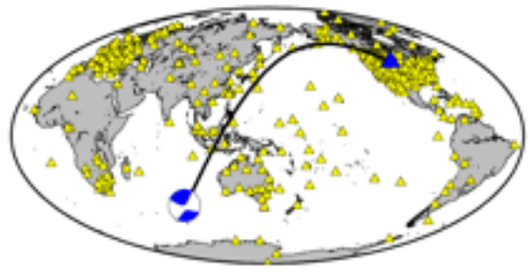
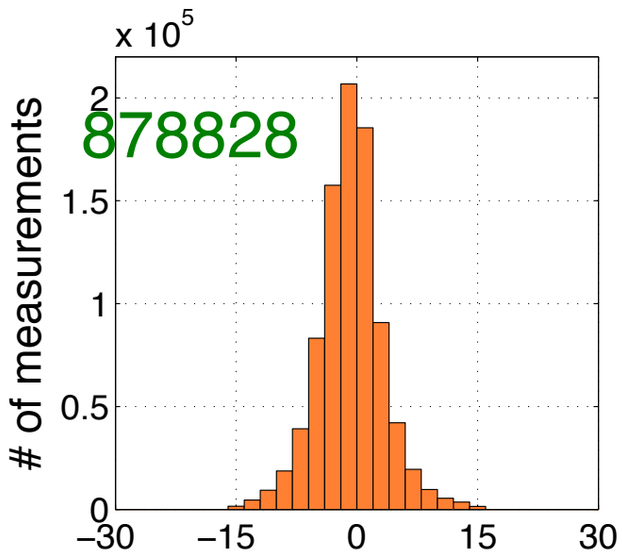
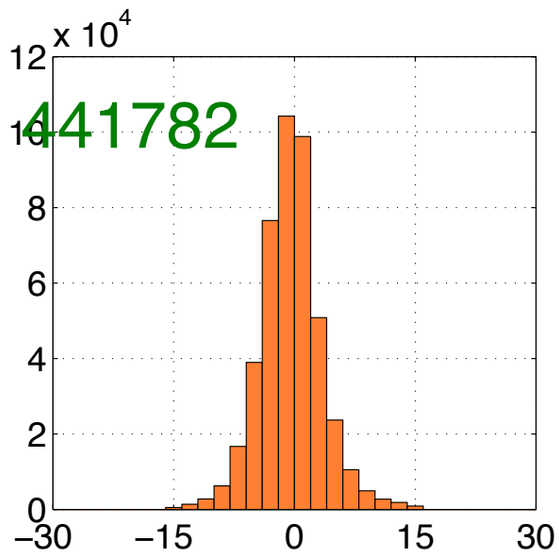
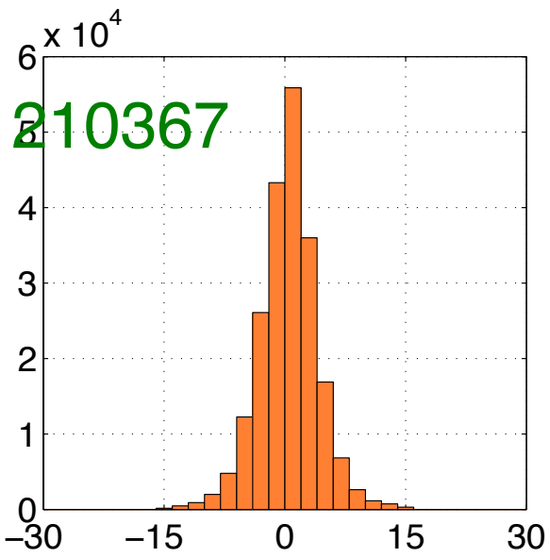
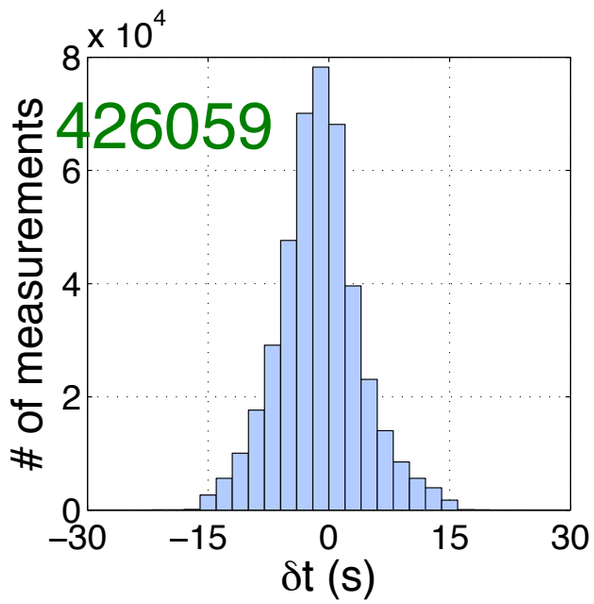
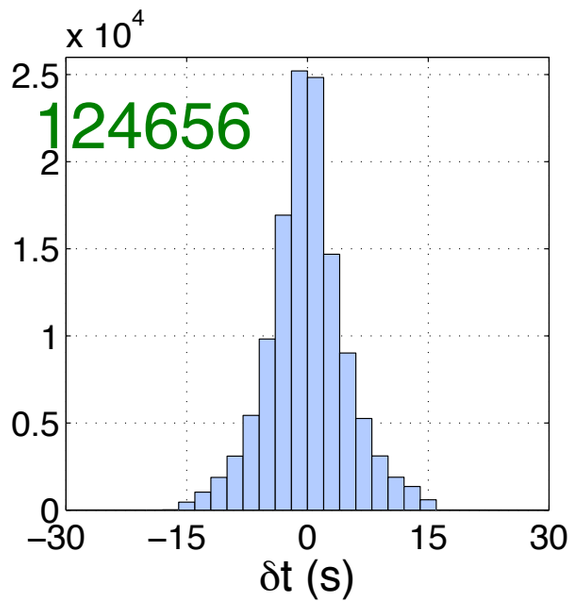
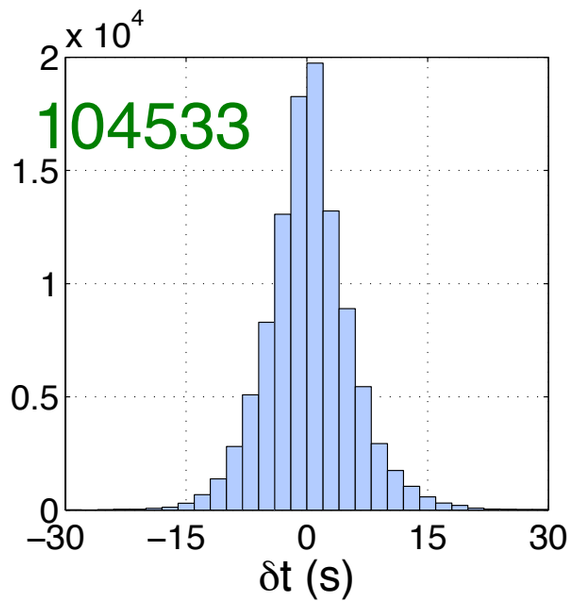




Station: RSSD
Δ=175°

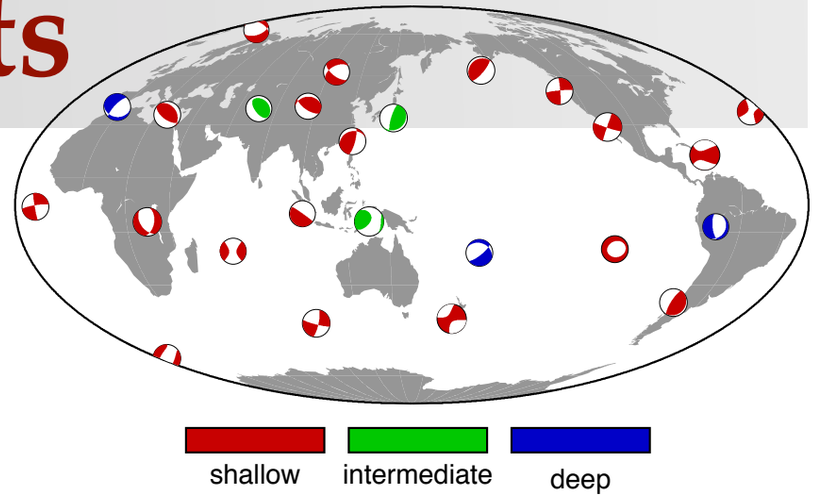


Cross-correlation time-shifts

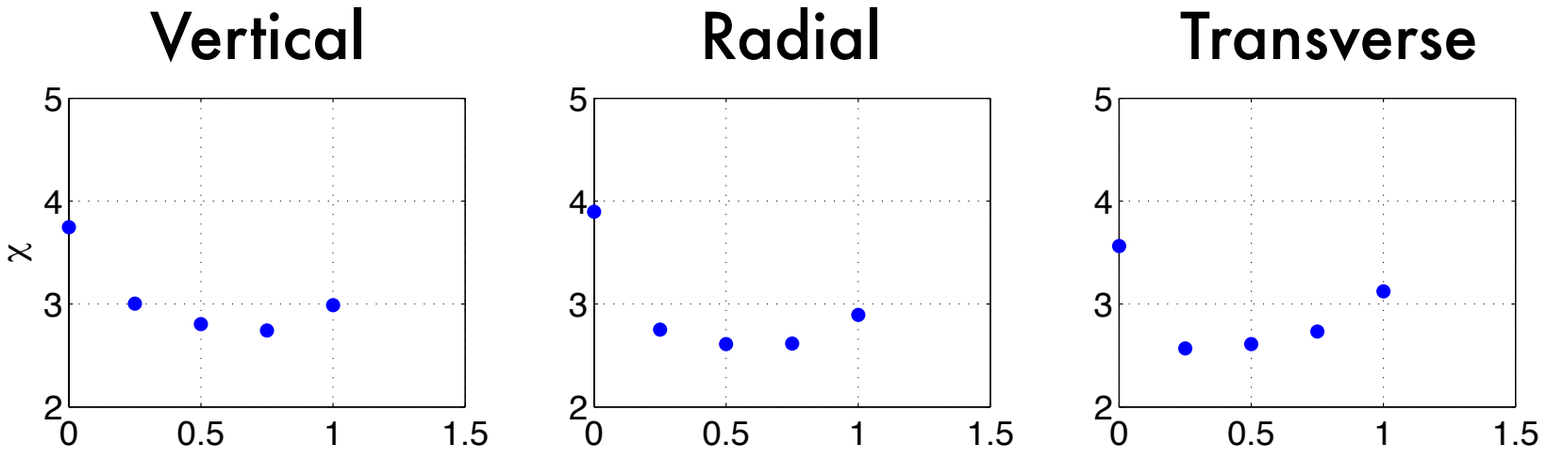
	vertical	radial	transverse
27 - 60 s			
60 - 120 s			

~2.2 million measurements

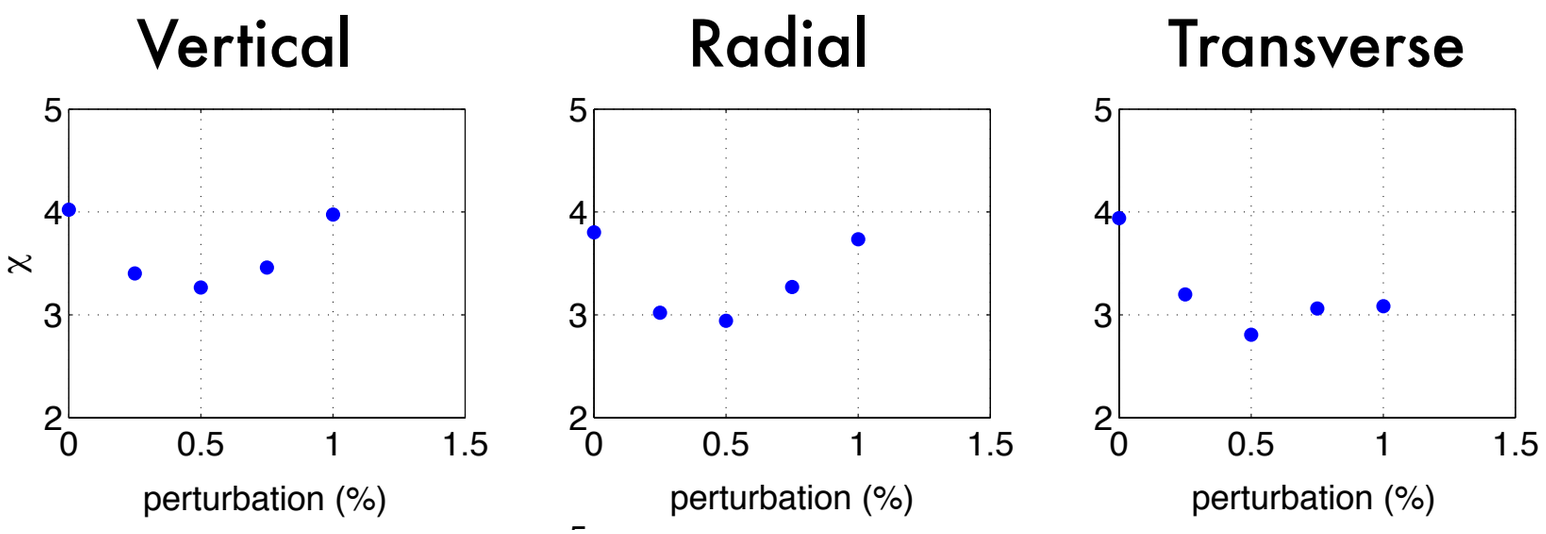
Line search with 24 test events



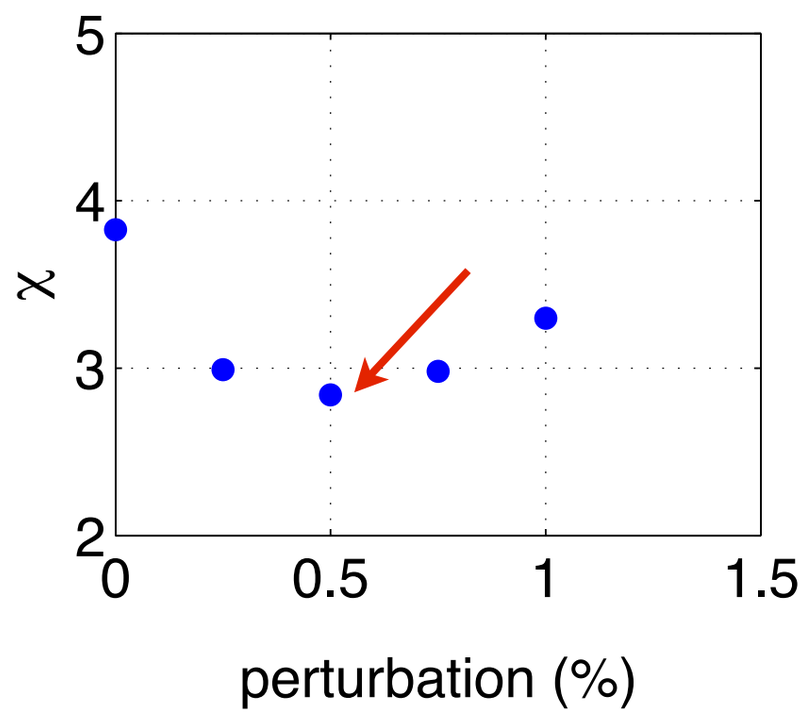
27 - 60 s



60 - 120 s



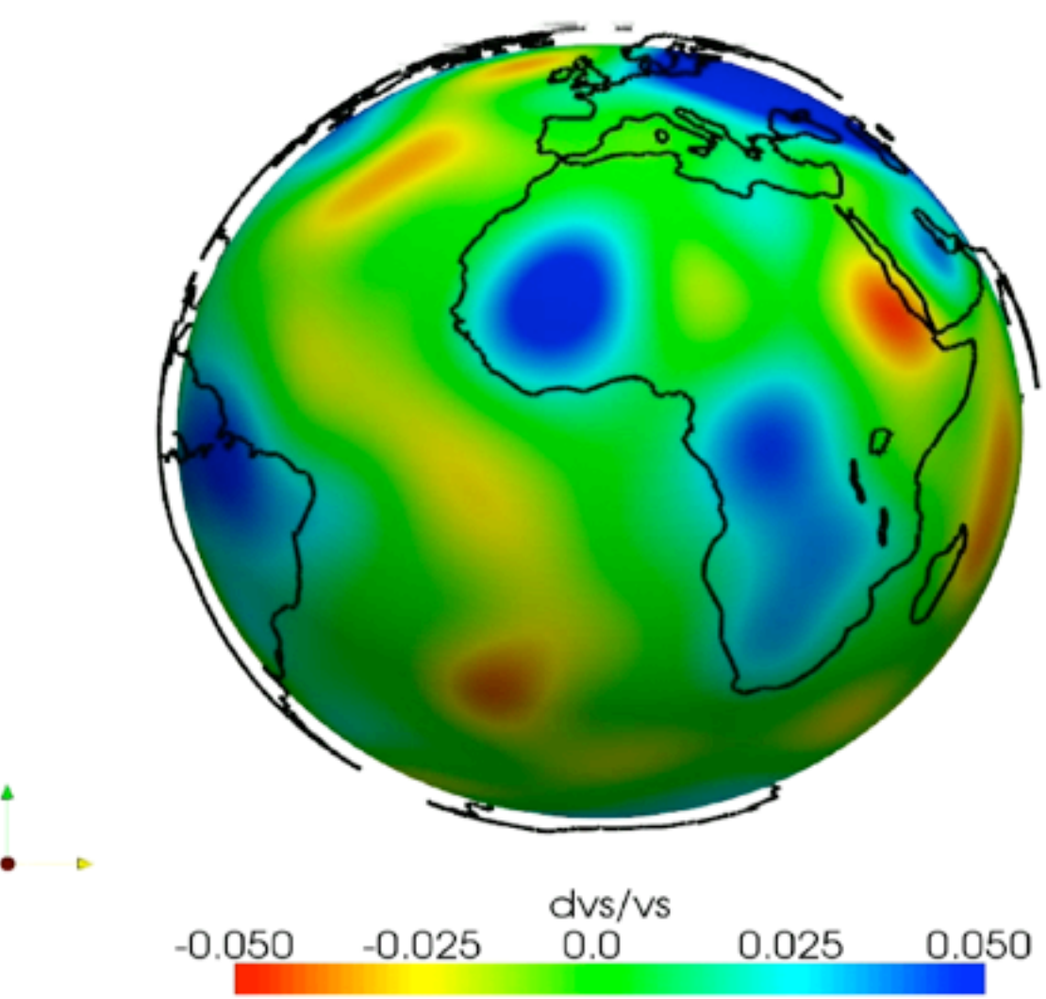
Total misfit

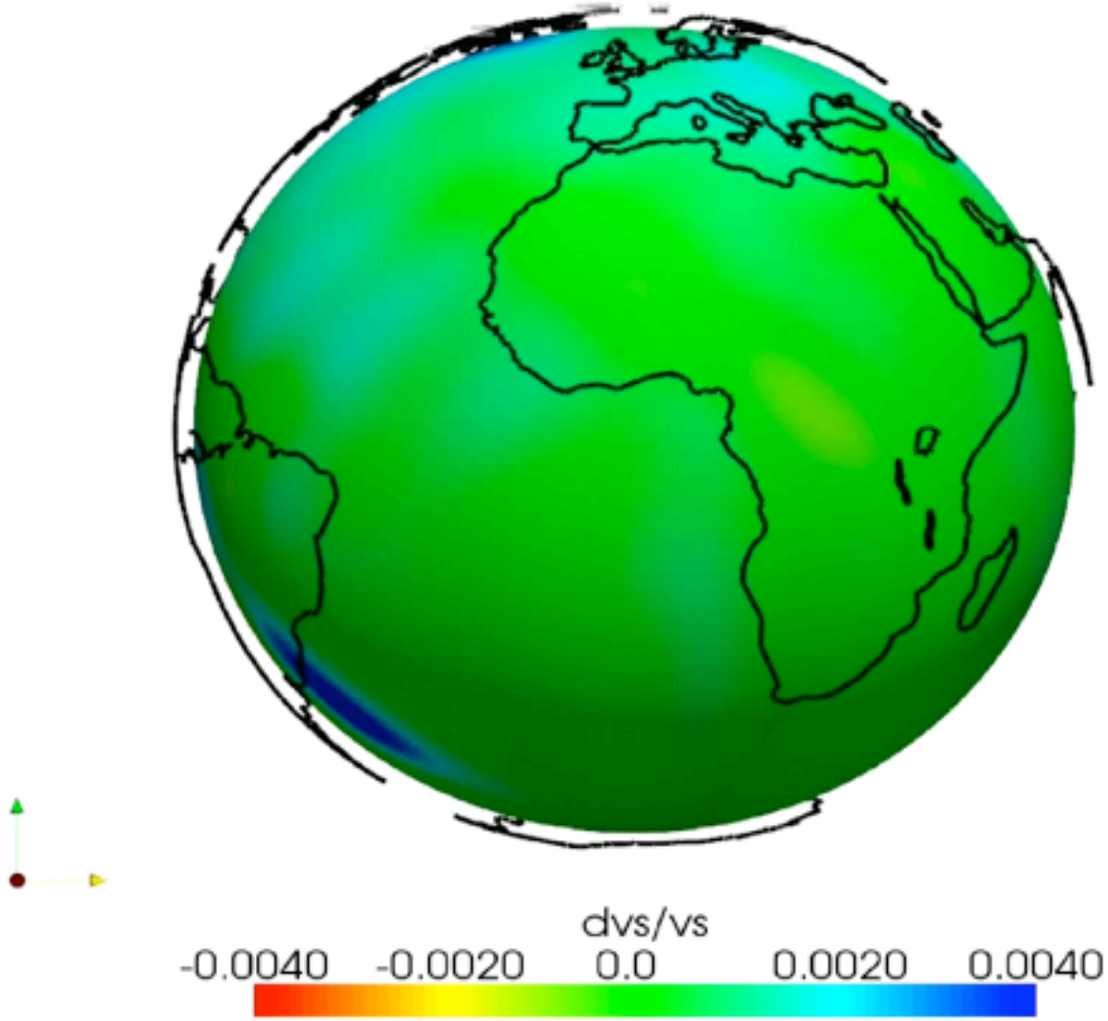


M00 - 1DREF

M01 - M00

150 km

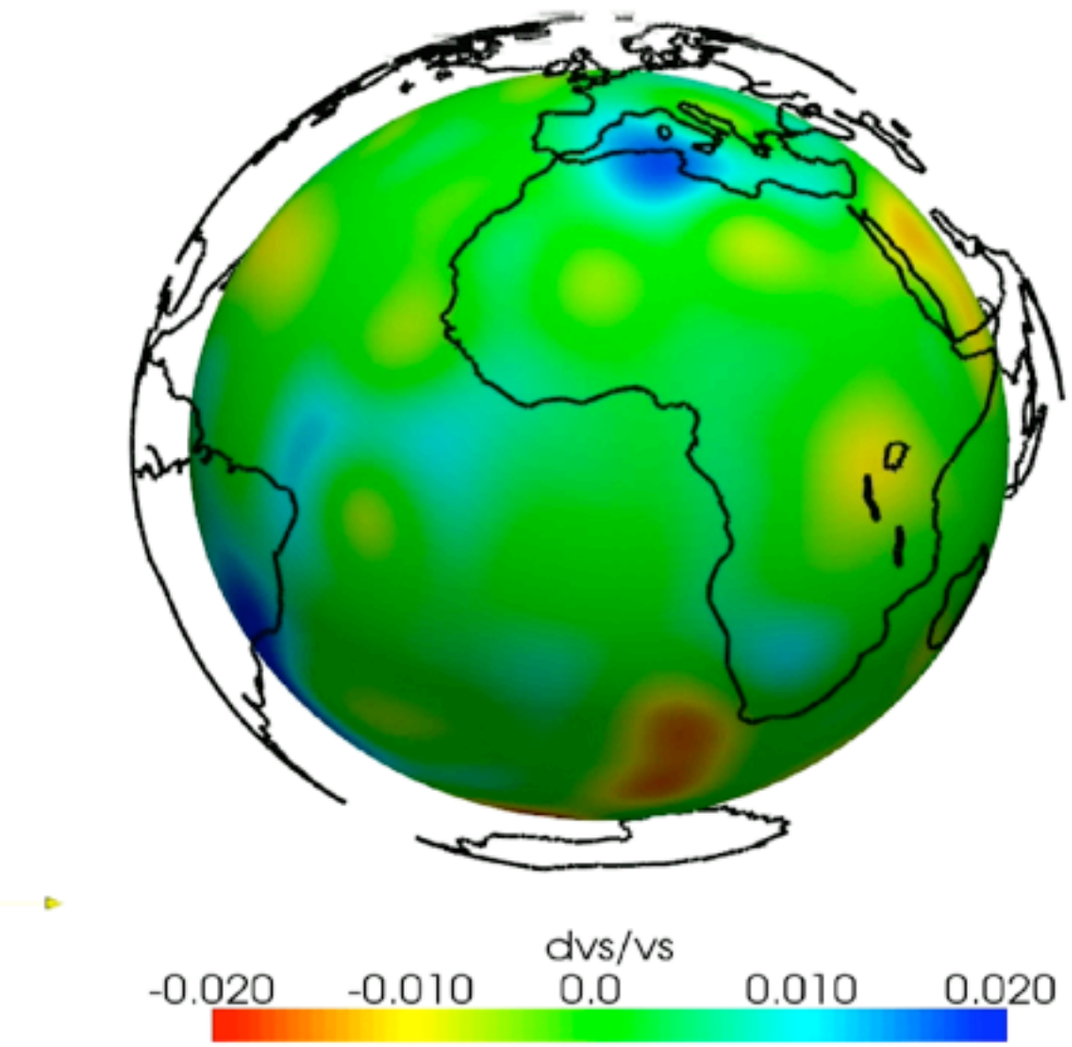


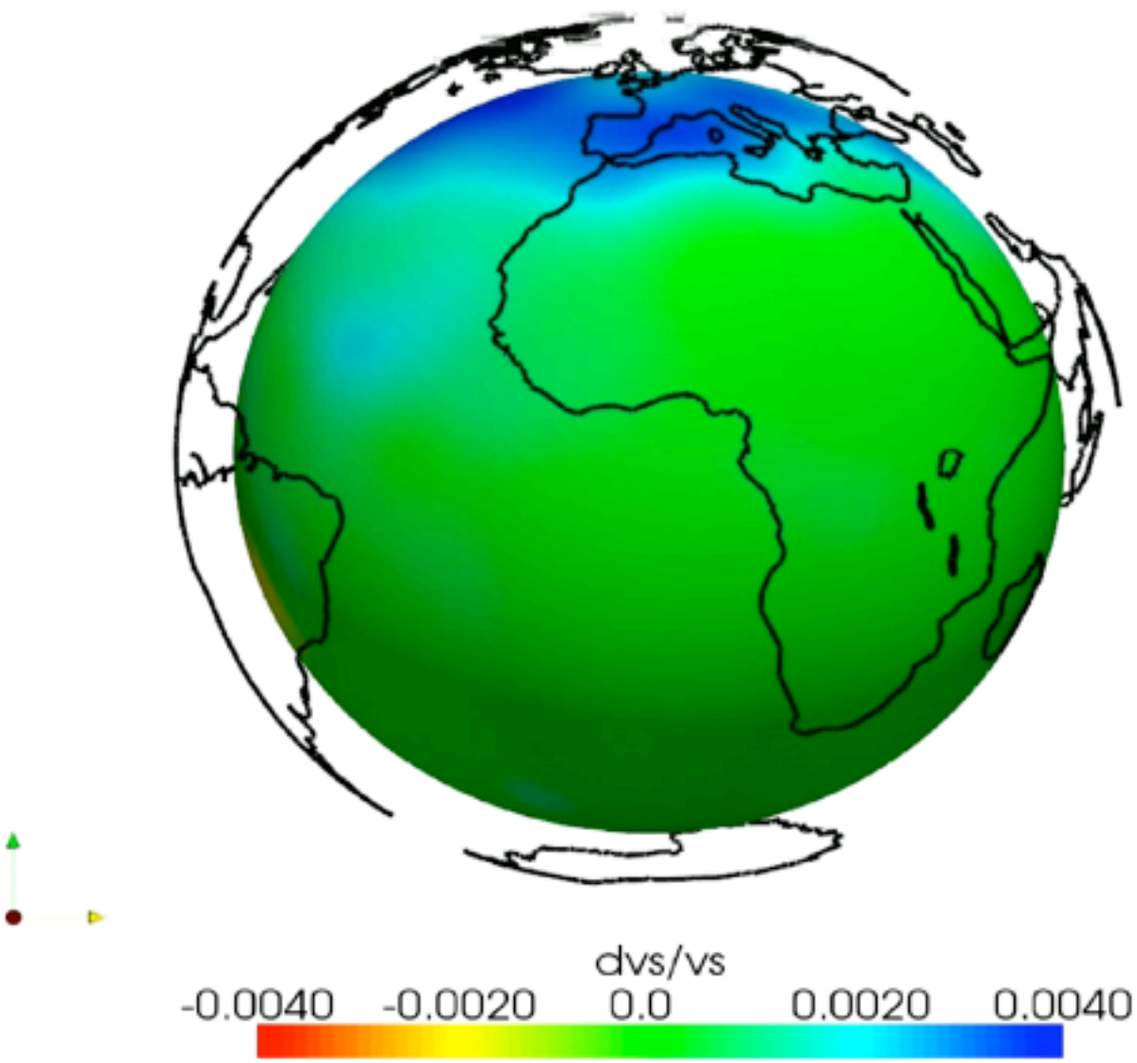


M00 - 1DREF

M01 - M00

660 km

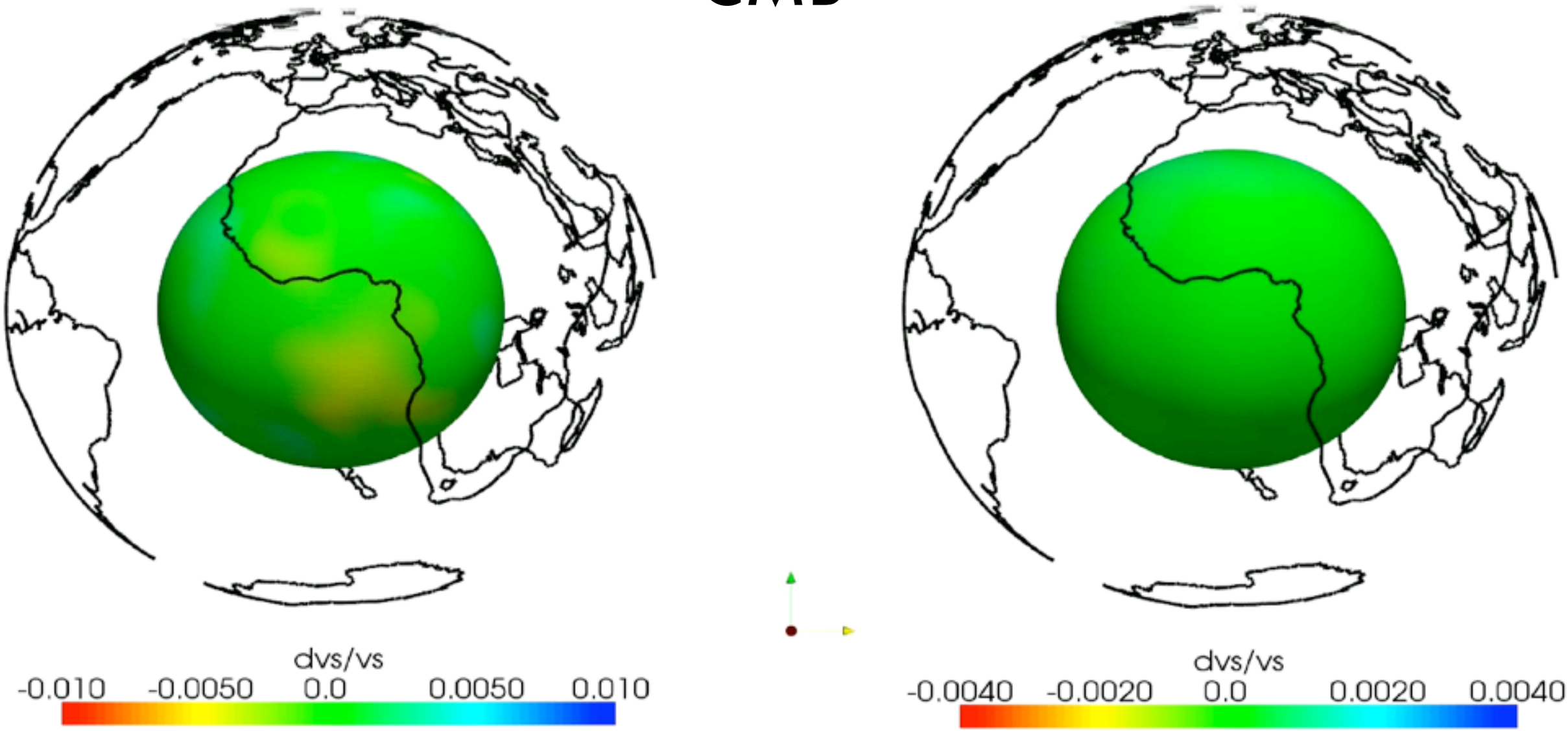




M00 - 1DREF

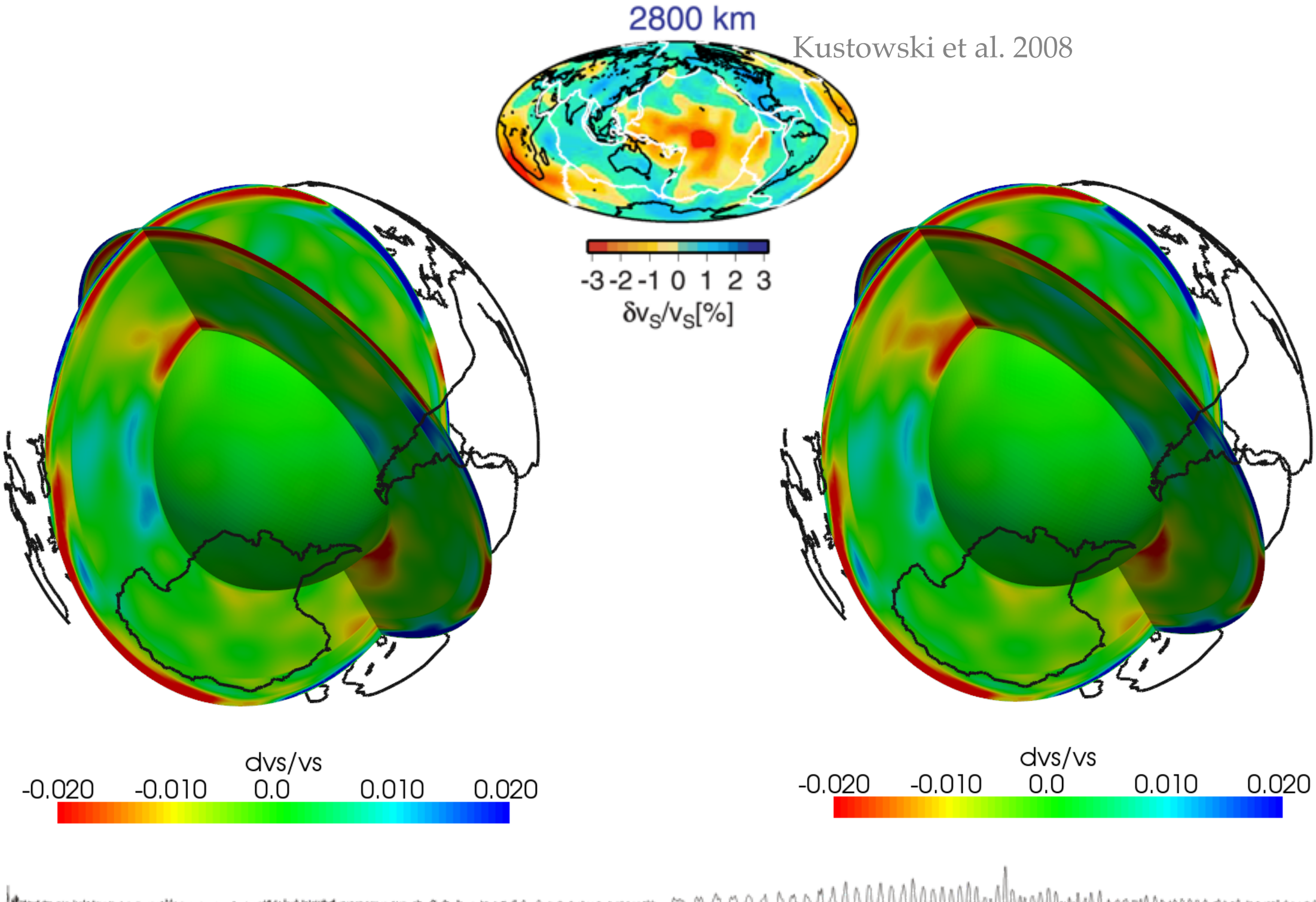
M01 - M00

CMB



M00 - 1DREF

M01 - 1DREF



Challenges

- Computational requirements

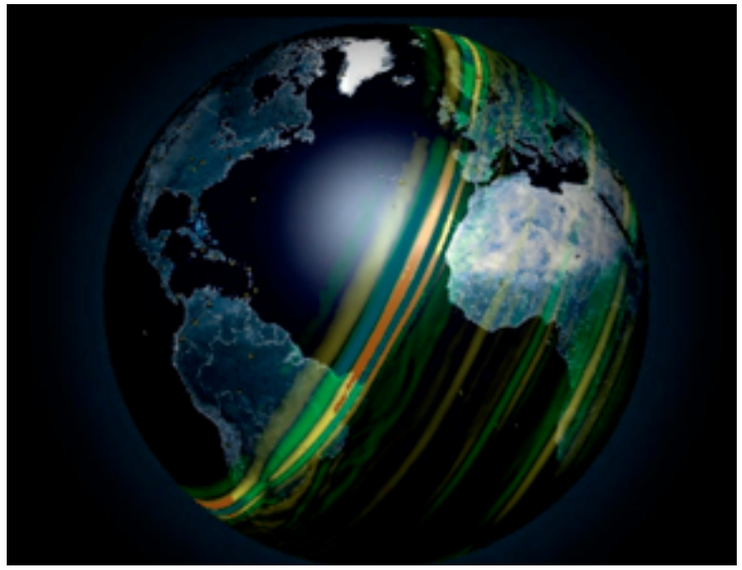
CPU hours	1 event	1 iteration (255 events)	20 iterations
forward + adjoint	3000	765,000	15,300,000

- Data processing - manual quality check
- Uneven distribution of source and receivers - Balance in gradient

Remedies

- More computational resources!
- Speeding up the forward/adjoint simulations: GPU computing
- Increasing data: using more earthquakes!

- First slide global wave propagation picture: April 12, 2012 Gulf of California Earthquake (Mw = 7, depth = 14 km) (global.shakemovie.princeton.edu).



- Master slide seismogram is from SPICE presentation template (www.spice-rtn.org).