Computational seismology: applications

Finite Differences

- Cartesian grids
  - Fault zone waves
  - Los Angeles Basin Earthquake scenarios (Olsen)

- Spherical grids
  - Global SH and P-SV wave propagation
  - Spherical sections – waves in subduction zones

Spectral Element Method

- Regular grids
  - Time reversal (Finite source inversion)
  - Full waveform inversion on a continental scale
- Irregular/unstructured grids
  - Soil-structure interaction
  - Earthquake scenarios
- Global wave propagation (Komatitsch and Tromp)

Discontinuous Galerkin Methods: WHY?

With studies by Jahnke, Fohrmann, Cochard, Käser, Fichtner, Stuppazzini, Ripperger, Nissen-Meyer, Kremers, Brietzke, a.o., (all LMU) as well as Olsen, Komatitsch, Tromp a.o.

What method should I use for a specific problem?

Numerical Methods

low-order vs. high order methods; FD, FE, SE, FV, DG, BE; global vs. local time stepping

Geometrical complexity, computational grids

regular, unstructured, adaptive meshes; conforming vs. non-conforming meshes; tetrahedral vs. hexahedral grids (combinations)

Parallelization

mesh partitioning, load balancing, optimization, multi-platform implementations, parallel scaling

Large data volume handling

post-processing, visualization, transfer and storage

Finite Differences

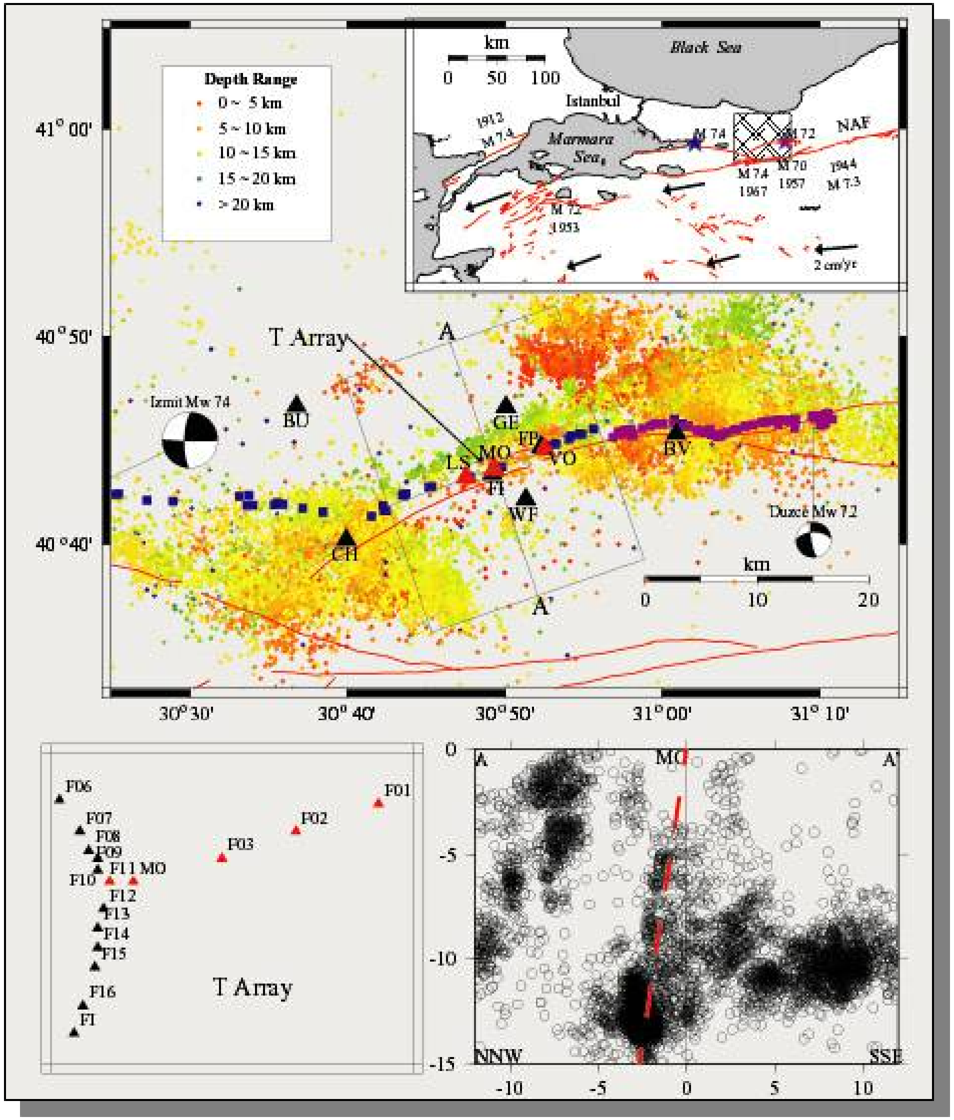
- FD approximations in space and time
- Simple to understand
- Compact codes
- Easy to parallelize
- Hard to get boundary conditions (free surface, absorbing) accurate
- „brute force“ approach

FD Cartesian Grids

FD – Fault zone wave propagation

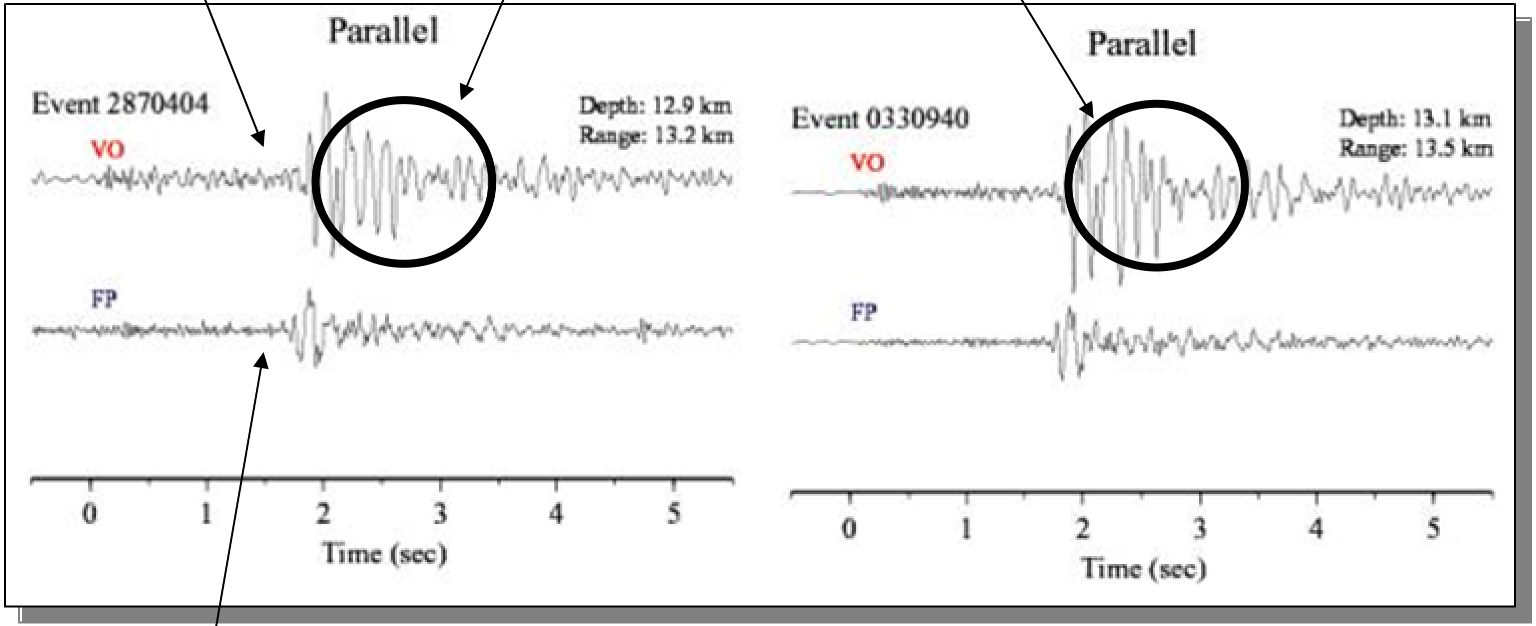
Aftershock recordings after the 1999 M7.4 Izmit earthquake

From:
Ben-Zion, Peng, Okaya, Seeber, Armbruster, Michael, Ozer, SSA2002



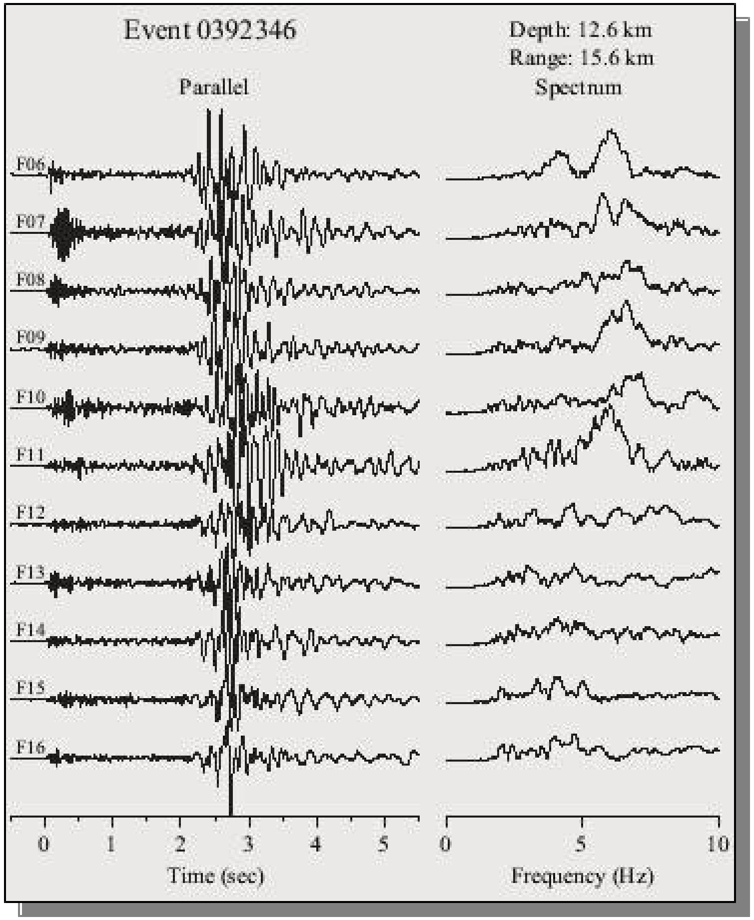
FZ trapped waves

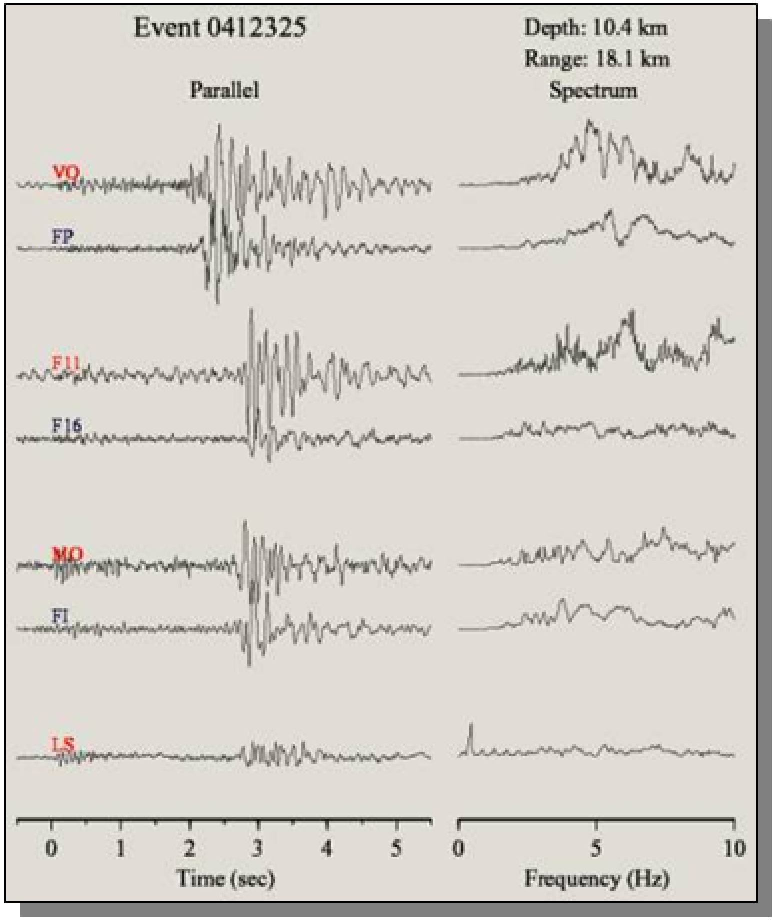
Near fault



At distance (about 300m) from fault

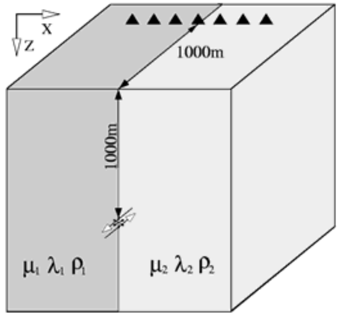
Observations across FZ





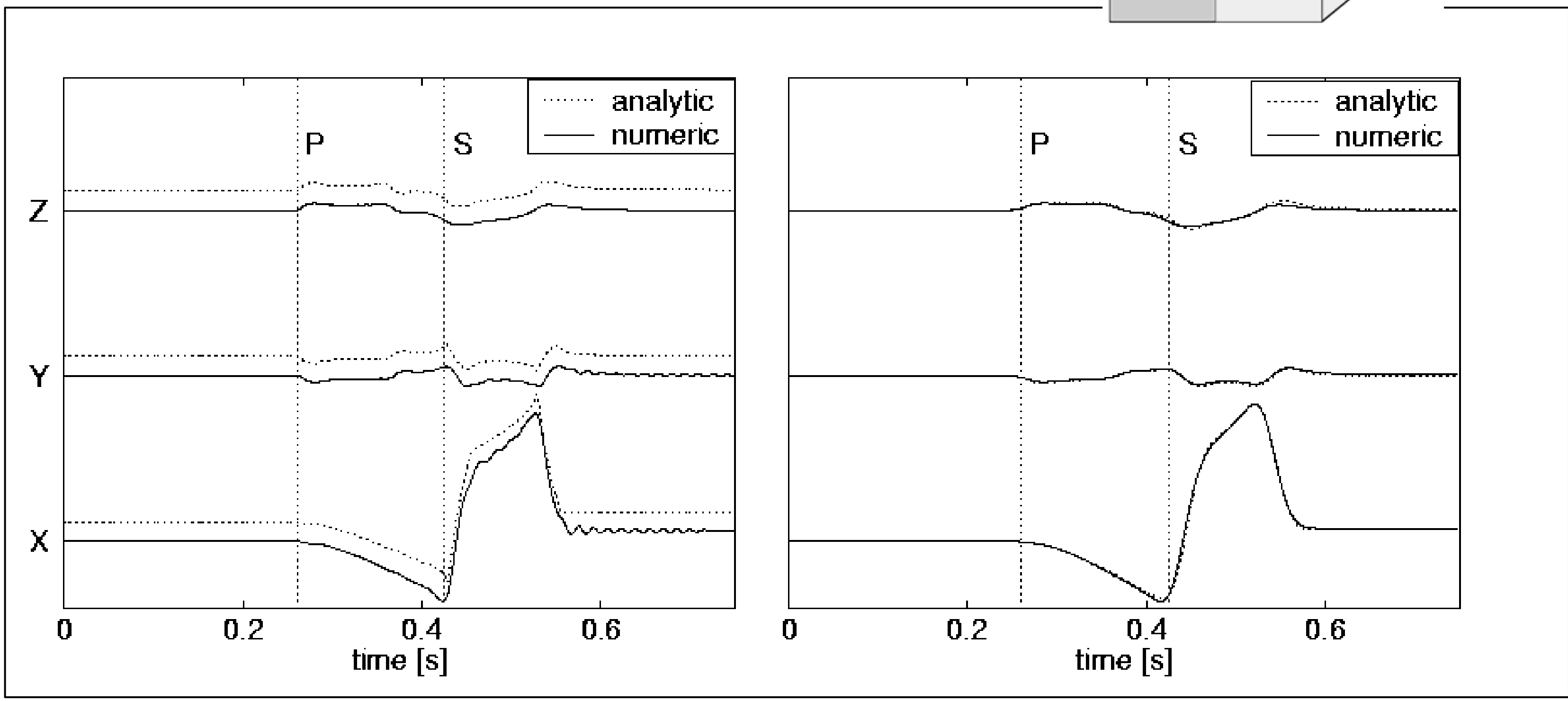
Benchmarking

Comparison of analytical solution (Ben-Zion, 1990) with staggered FD method



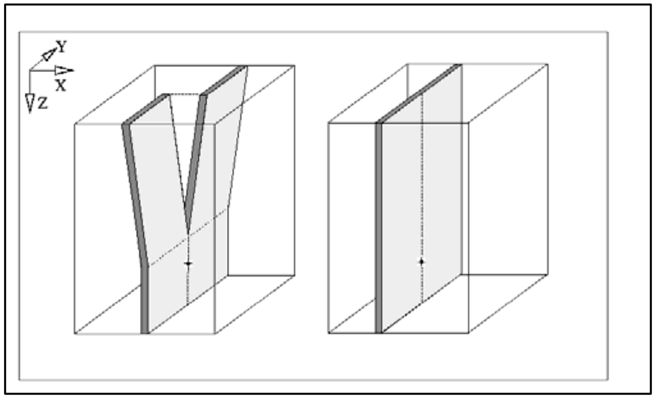
unfiltered

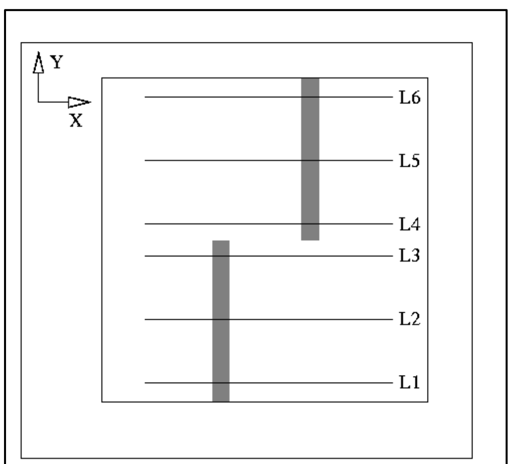
filtered

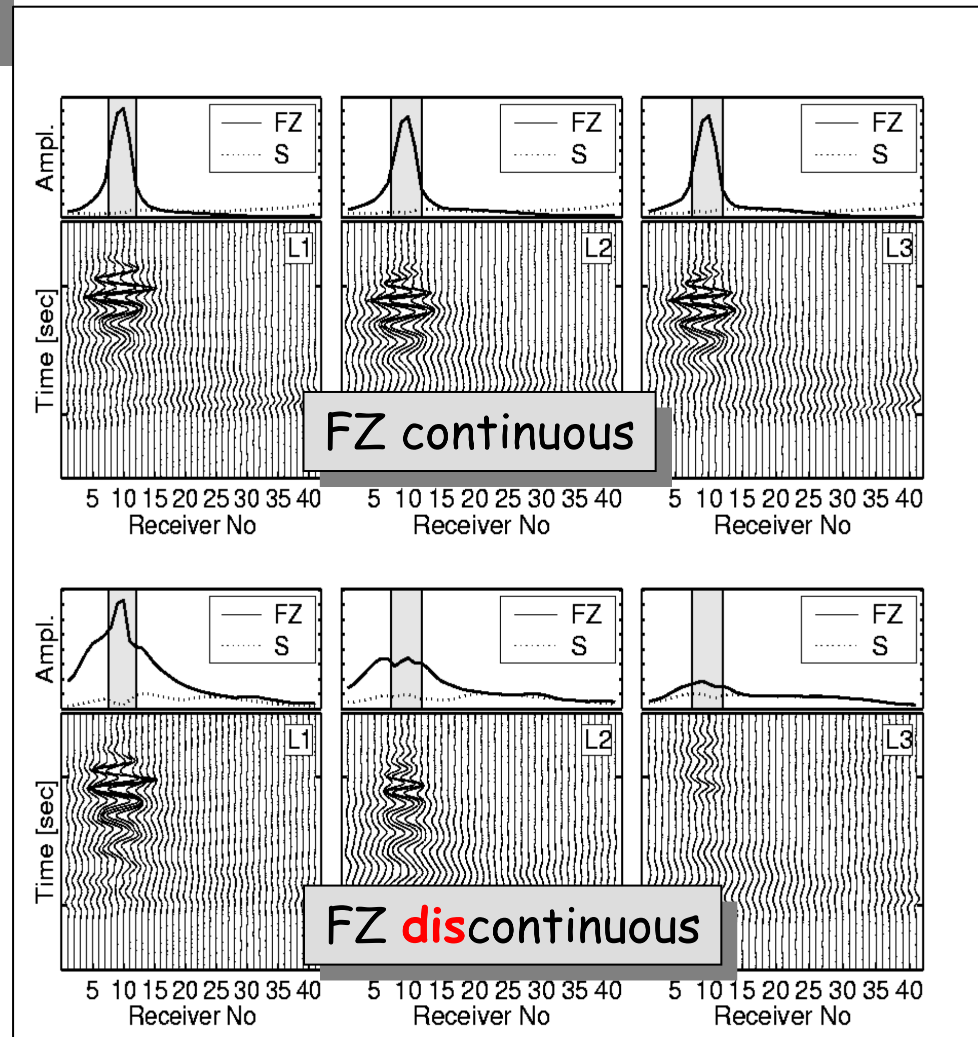


FZ discontinuities

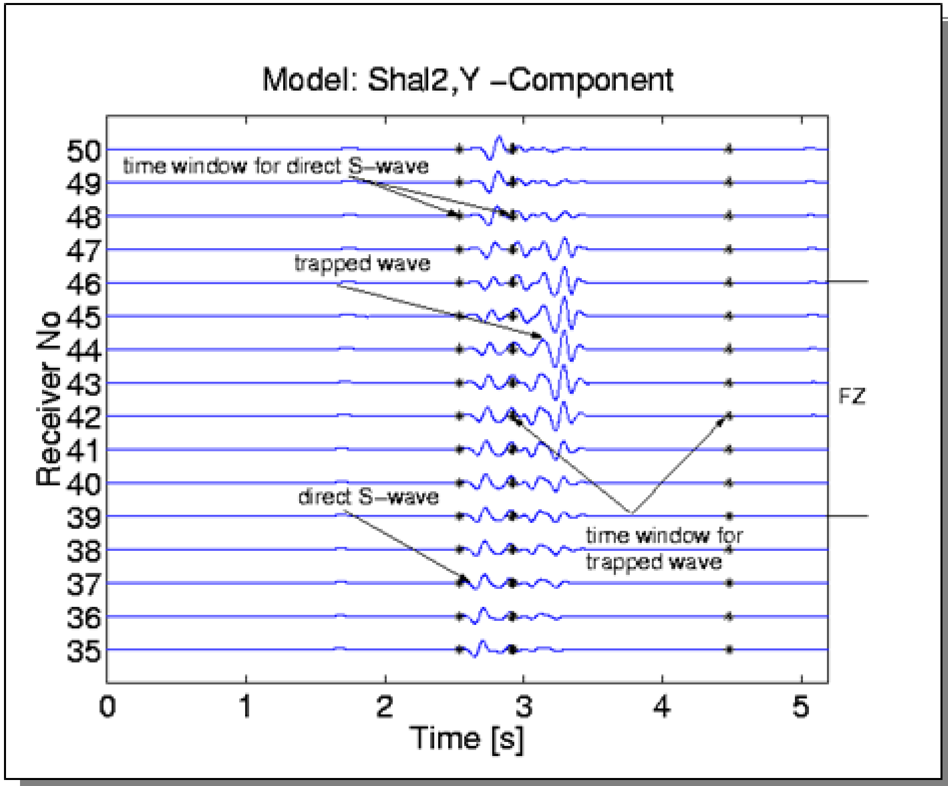
Is FZ continuous at depth?

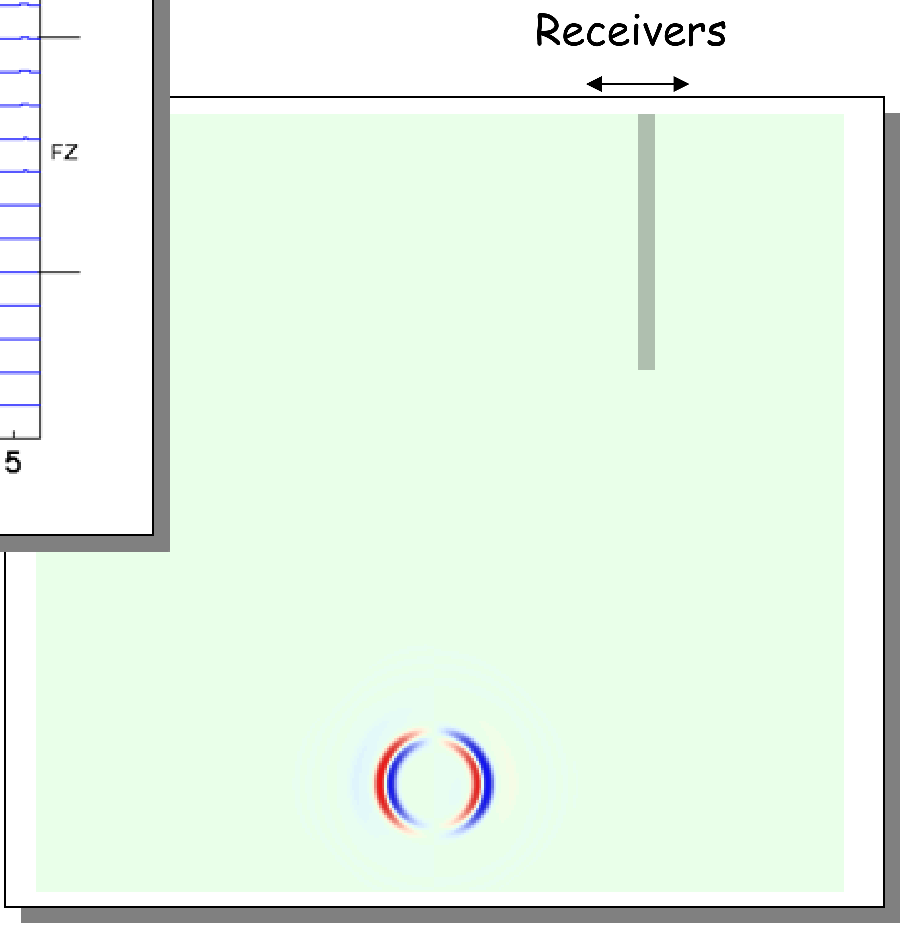






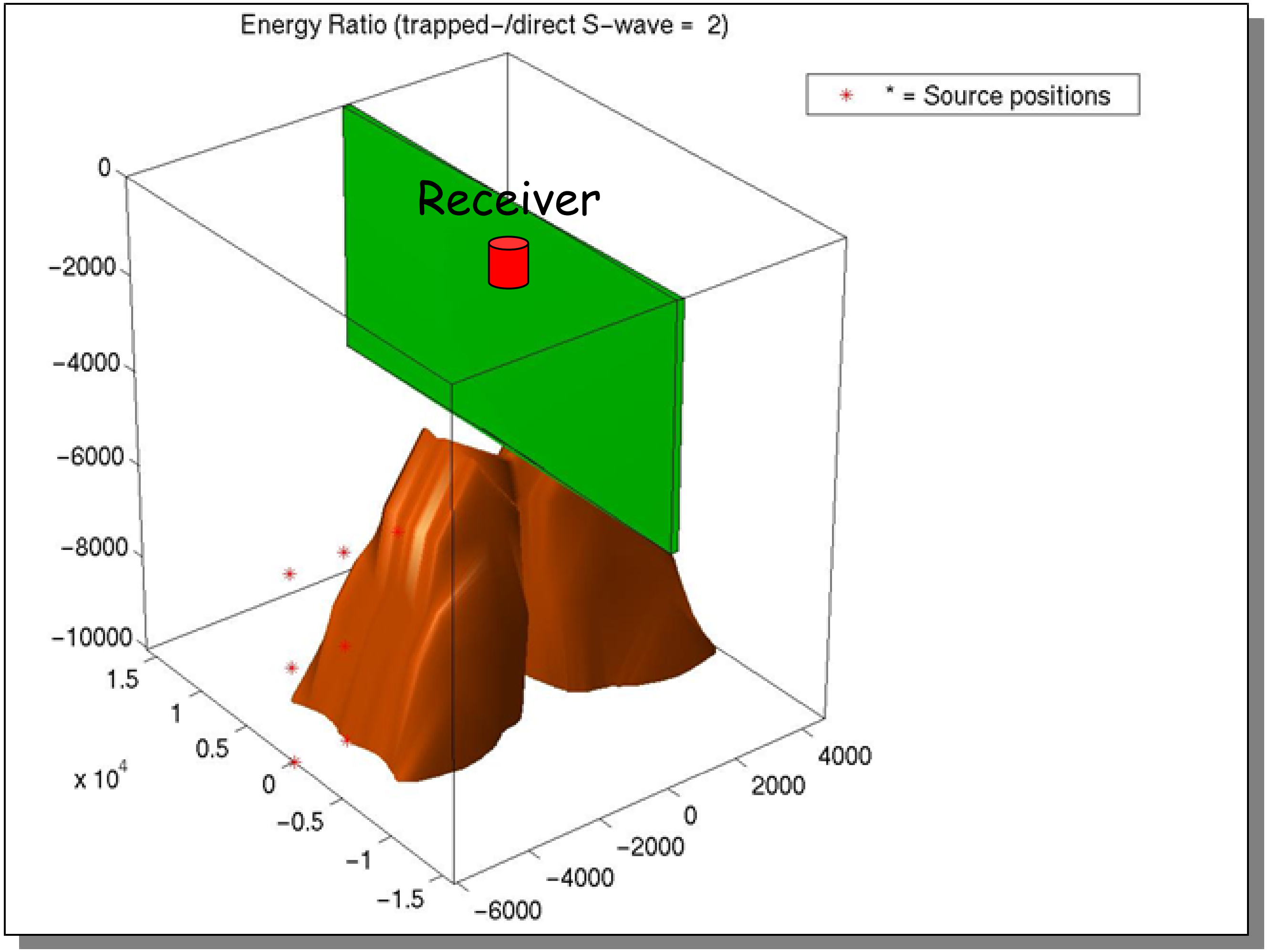
Shallow fault zones





Considerable FZ trapped wave energy generated.

Volume that generates FZ waves



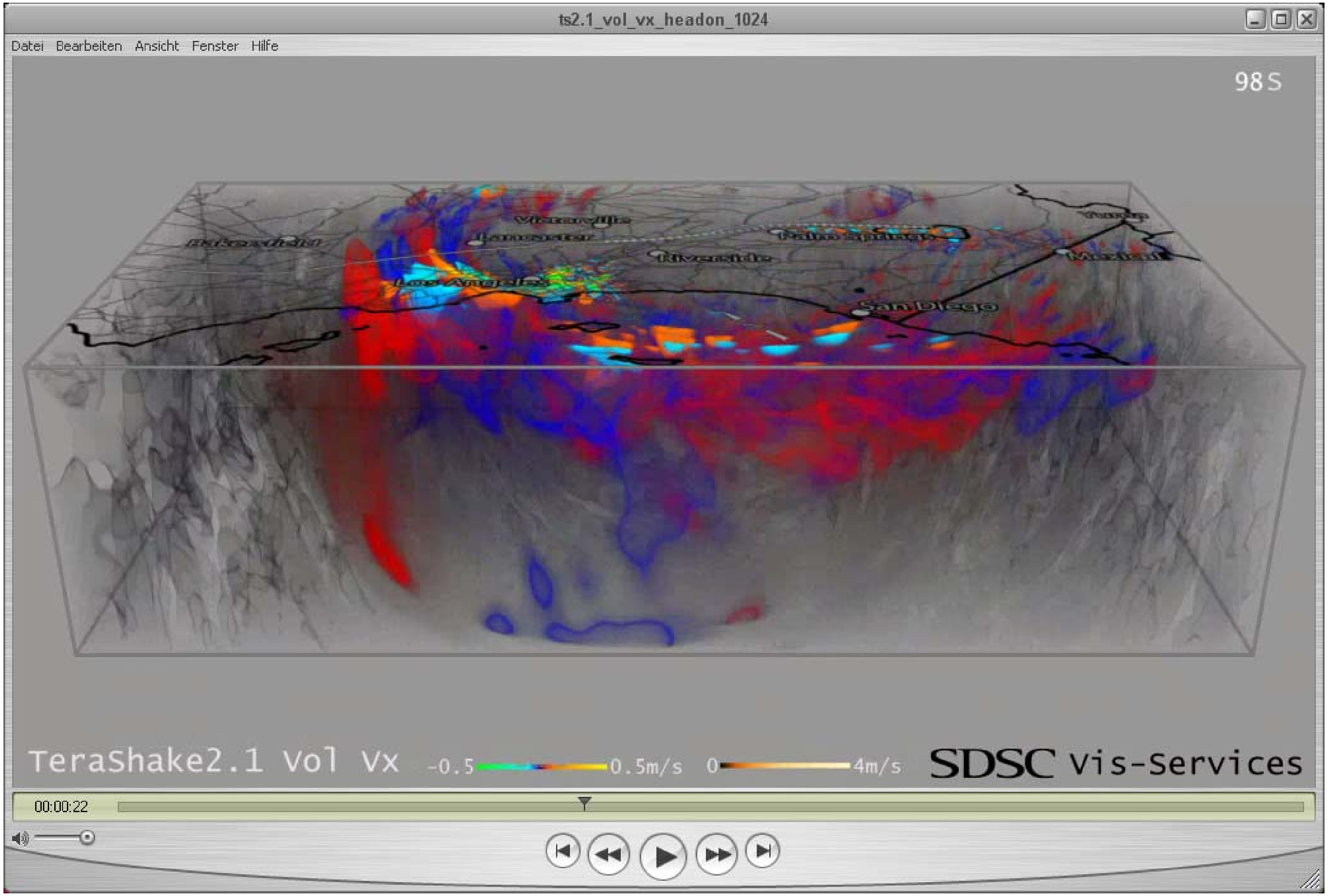
Fohrmann et al. 2002.

Earthquake scenarios based on FD

A number of stunning visualizations of earthquake scenarios can be found here (code by Kim Olsen, SDSU):

http://visservices.sdsc.edu/projects/scec/terashake/2.1/

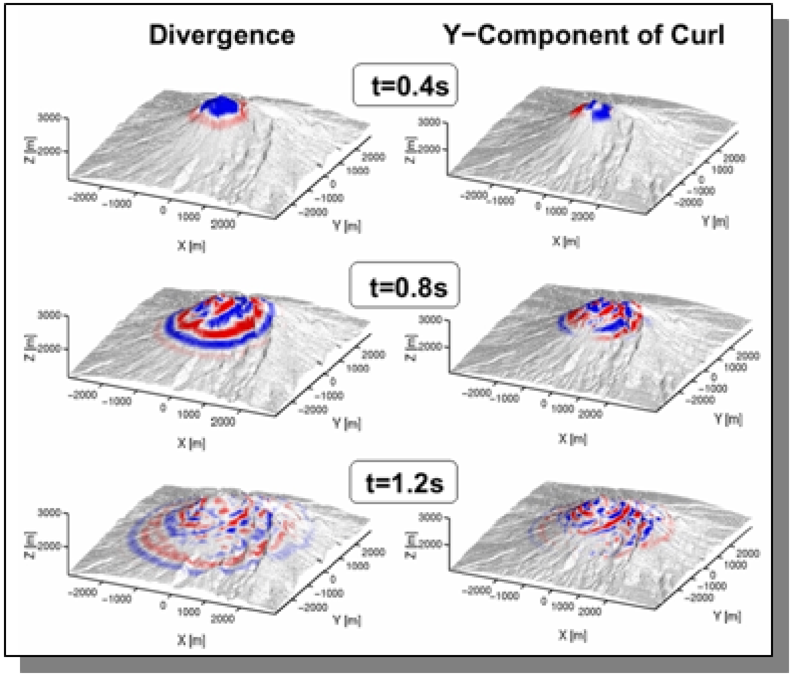
Earthquake scenarios Los Angeles



FD Cartesian Grids

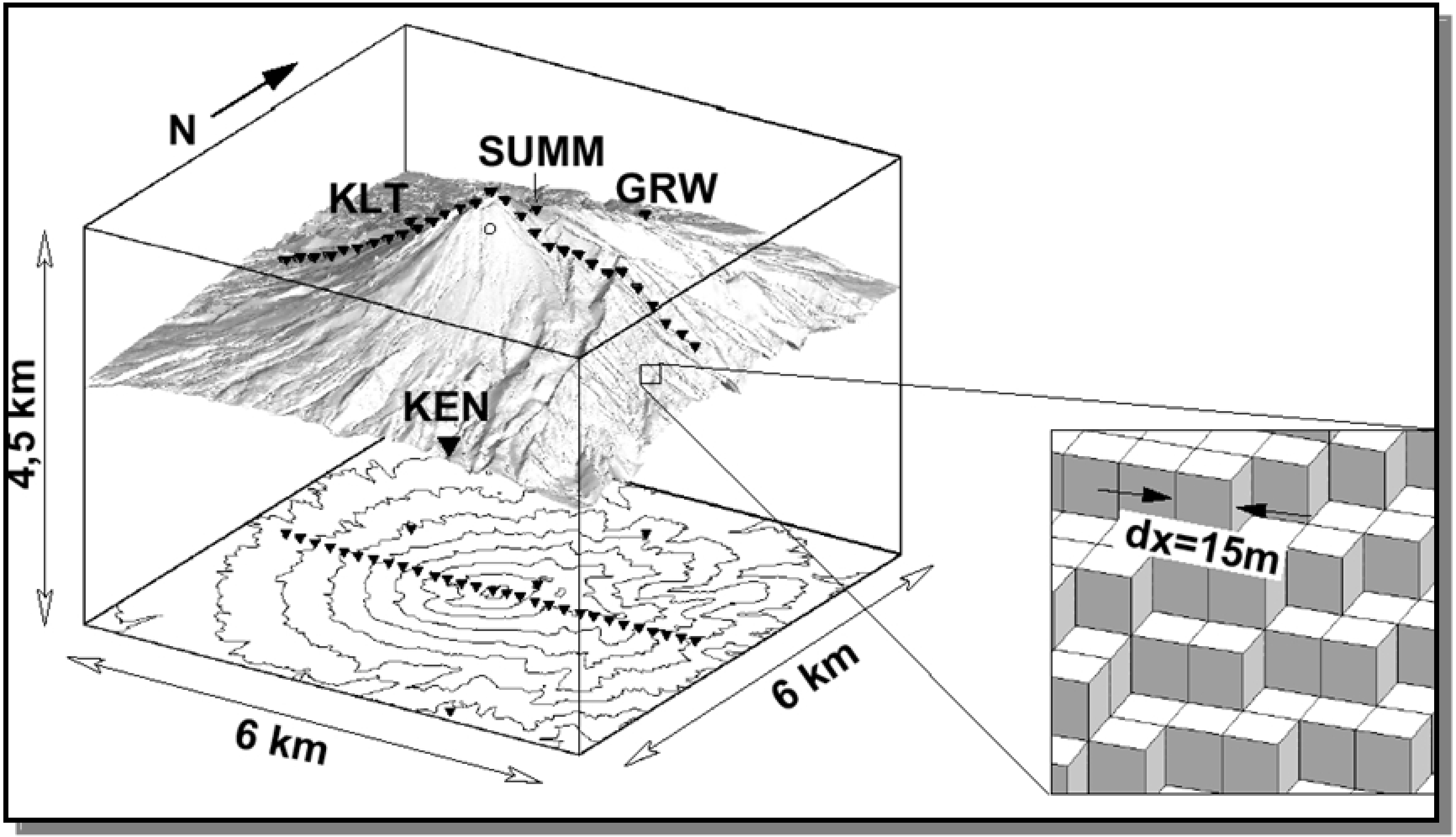
3-D with topography

Volcanoes

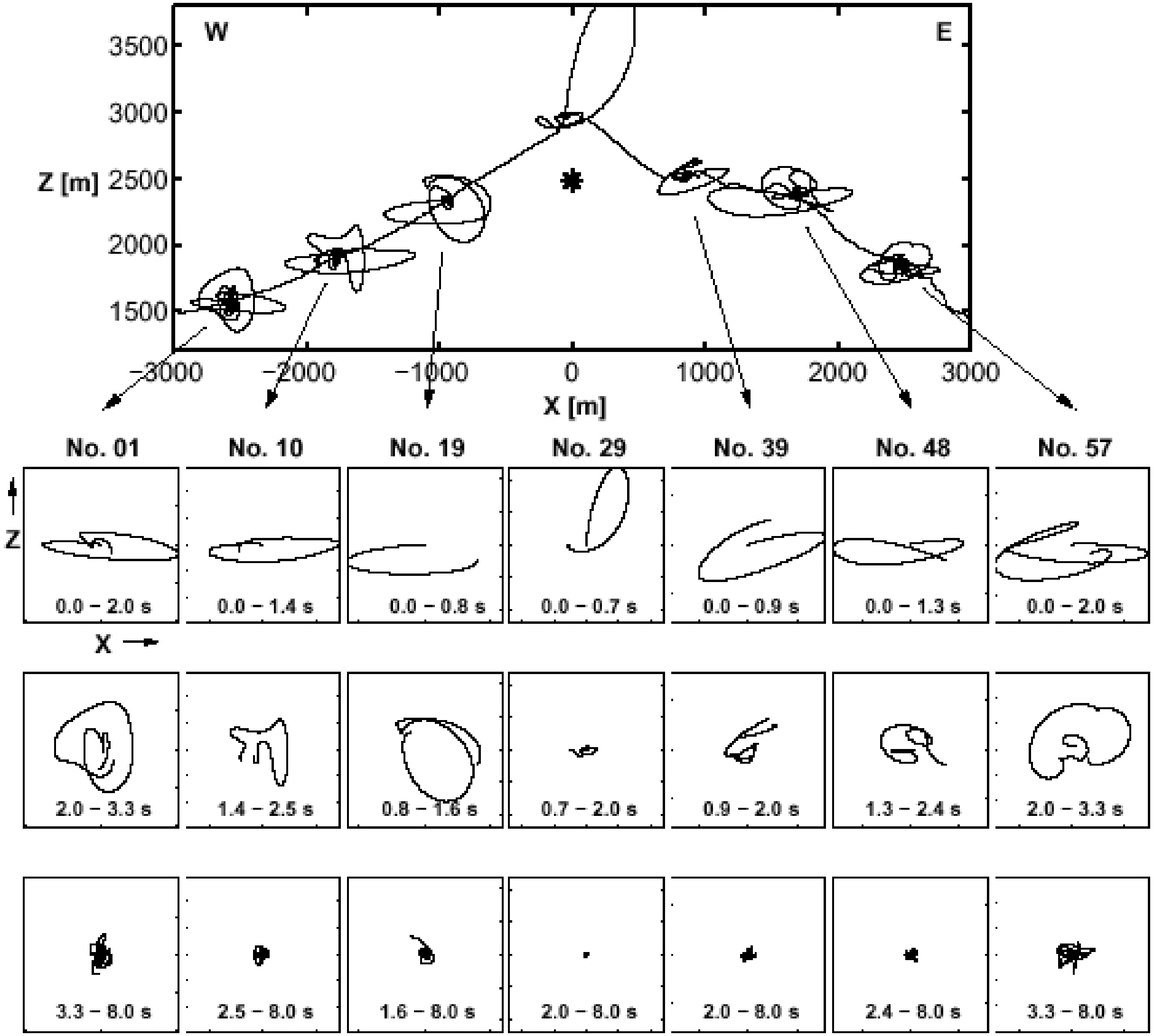


What is the contribution of topography to scattering?
Can we simulate the seismic signatures of pyroclastic flows?

Blocky topography



Particle Motions



FD Spherical Grids

axisymmetric

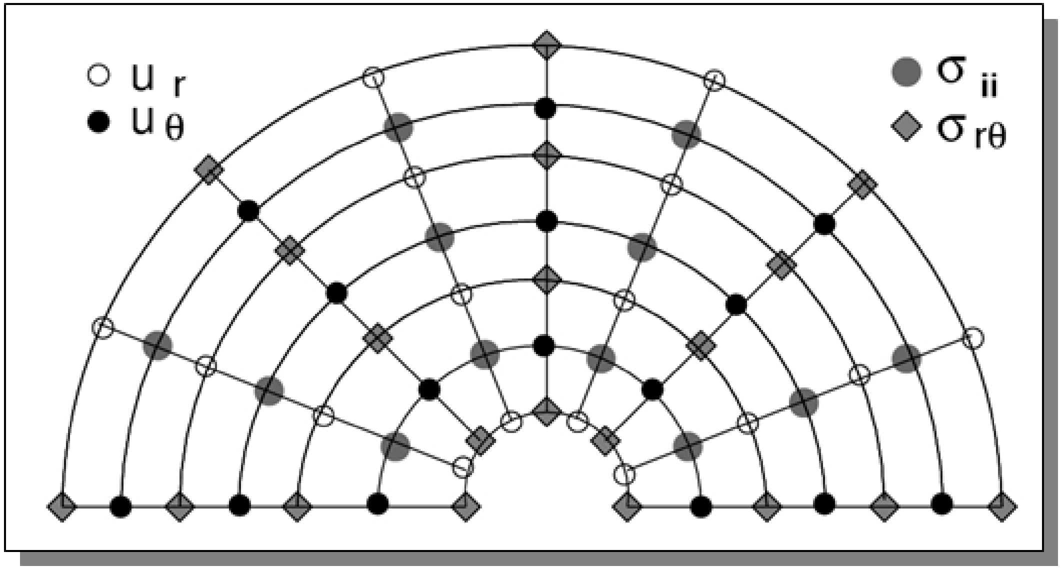
Waves in spherical coordinates

$$
\begin{aligned}
\rho\partial_t v_r &= \partial_r\sigma_{rr} + \frac{1}{r}\partial_\theta\sigma_{r\theta} + \boxed{\frac{1}{r\sin\theta}\partial_\varphi\sigma_{r\varphi}} \\
&\quad + \frac{1}{r}(2\sigma_{rr} - \sigma_{\theta\theta} - \sigma_{\varphi\varphi} + \sigma_{r\theta}\cot\theta) + f_r \\
\rho\partial_t v_\theta &= \partial_r\sigma_{r\theta} + \frac{1}{r}\partial_\theta\sigma_{\theta\theta} + \boxed{\frac{1}{r\sin\theta}\partial_\varphi\sigma_{\theta\varphi}} \\
&\quad + \frac{1}{r}((\sigma_{\theta\theta} - \sigma_{\varphi\varphi})\cot\theta + 3\sigma_{r\theta}) + f_\theta \\
\rho\partial_t v_\varphi &= \partial_r\sigma_{r\varphi} + \frac{1}{r}\partial_\theta\sigma_{\theta\varphi} + \boxed{\frac{1}{r\sin\theta}\partial_\varphi\sigma_{\varphi\varphi}} \\
&\quad + \frac{1}{r}((3\sigma_{r\varphi} + 2\sigma_{\theta\varphi}\cot\theta)) + f_\varphi
\end{aligned}
$$

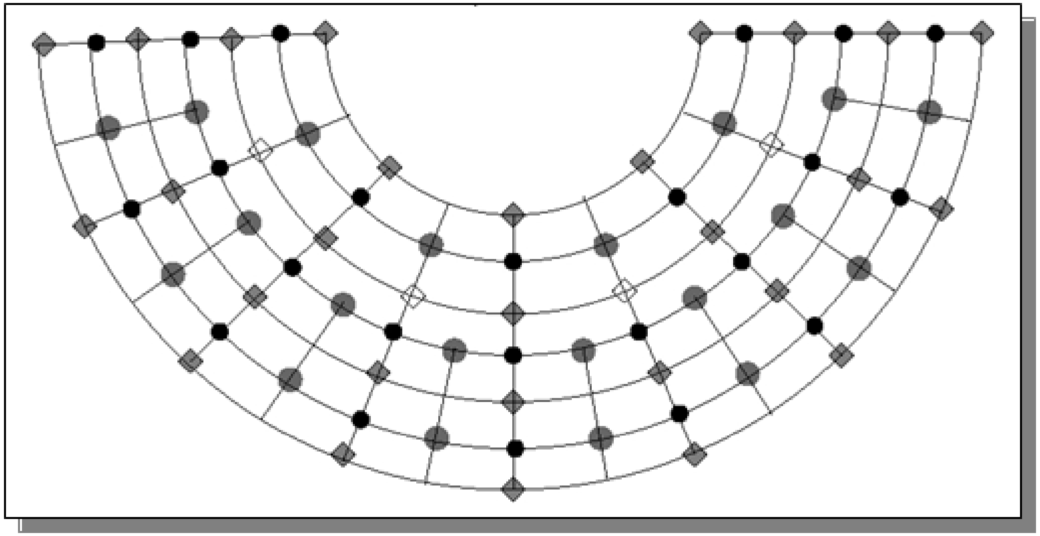
(.) = 0
Axisymmetric
Models

Equations of motion (velocity – stress)

Grids in spherical geometry



P-SV



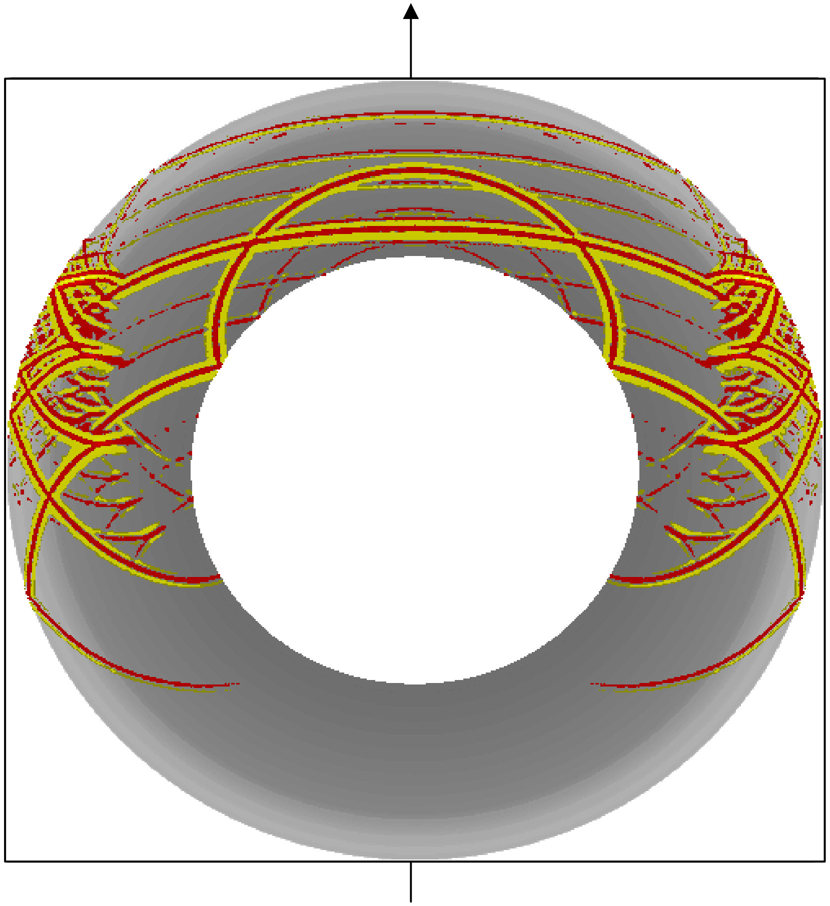
SH

SH wave propagation

Red and yellow denote positive and negative displacement

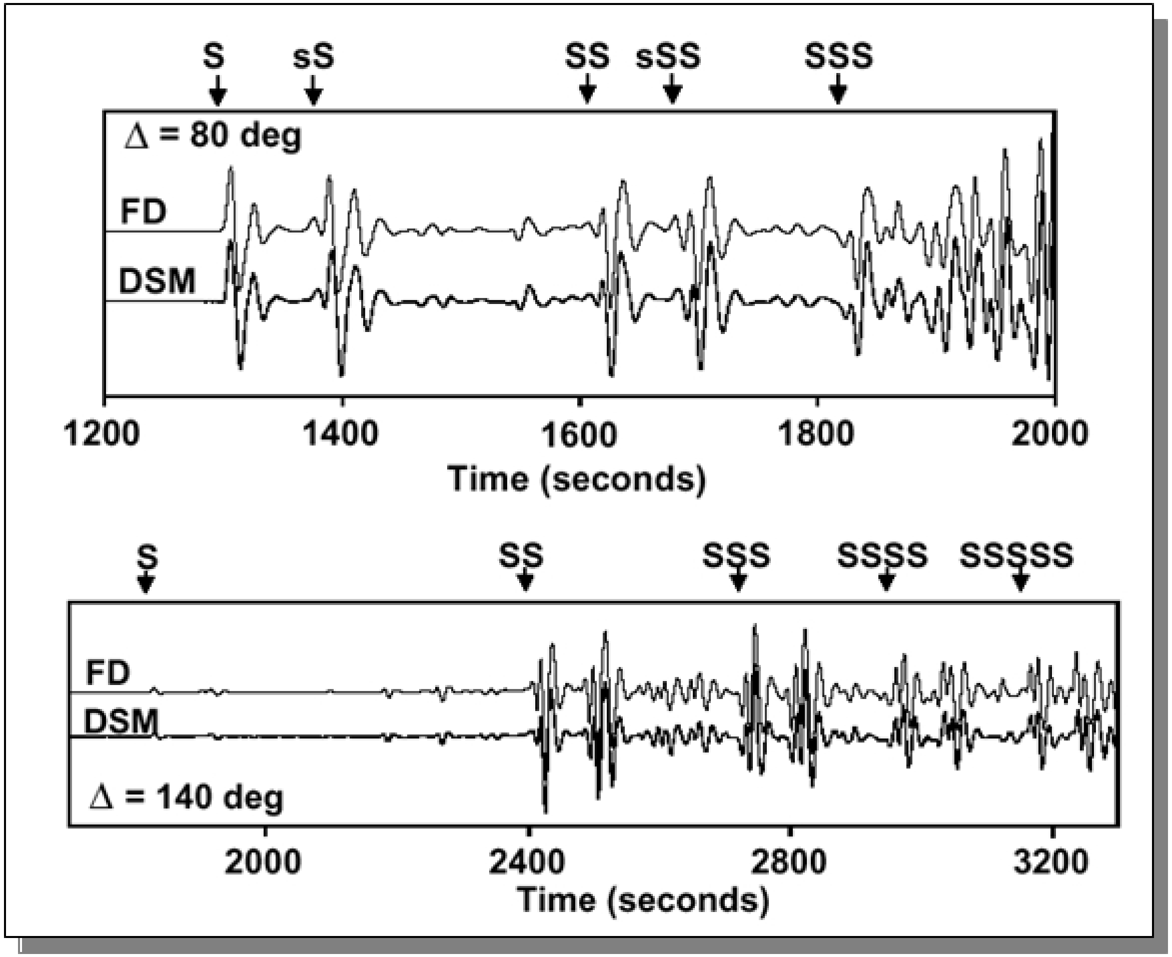
Wavefield for source at 600km depth.

z.B. Igel und Weber, 1995
Chaljub und Tarantola, 1997



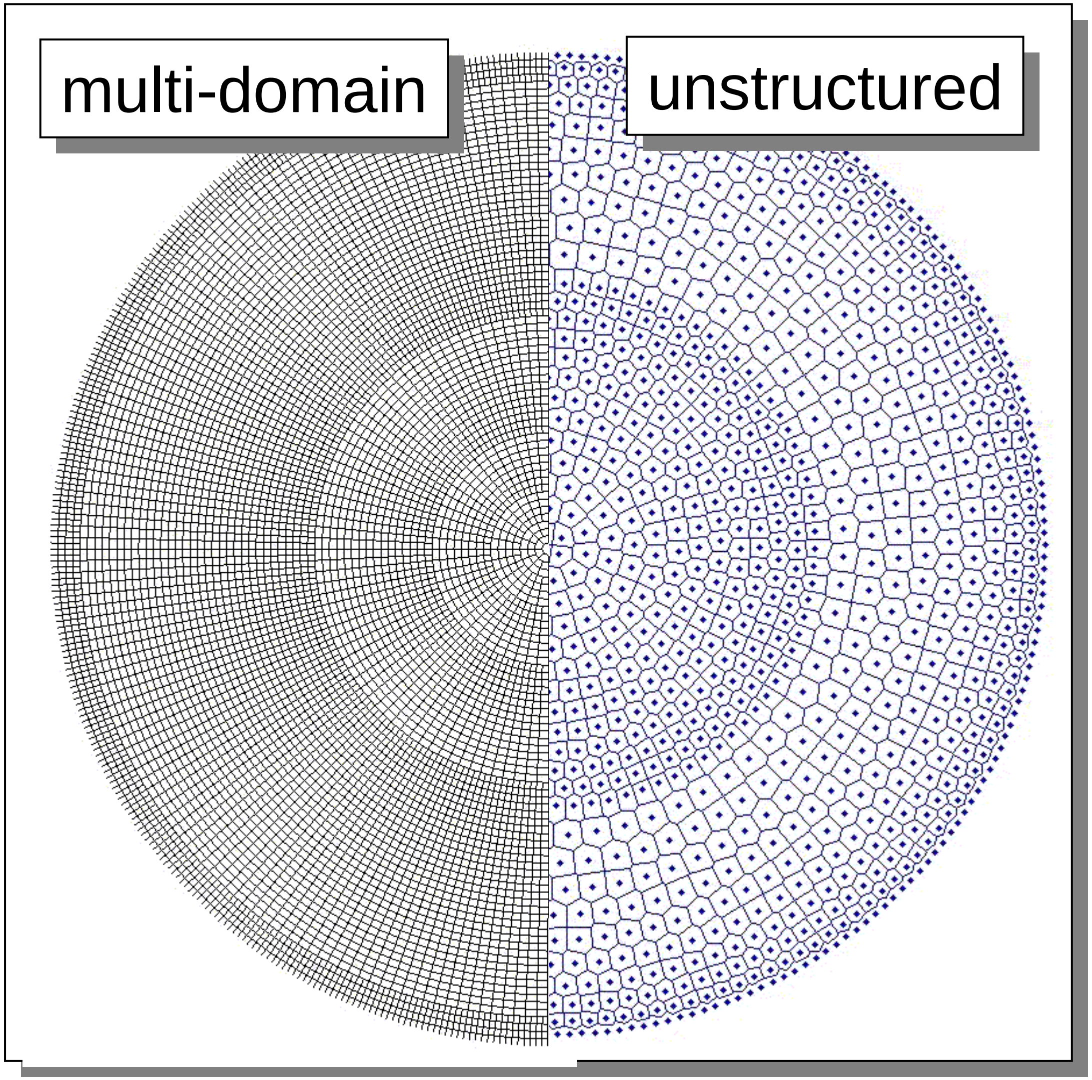
Symmetry axis

Benchmarking

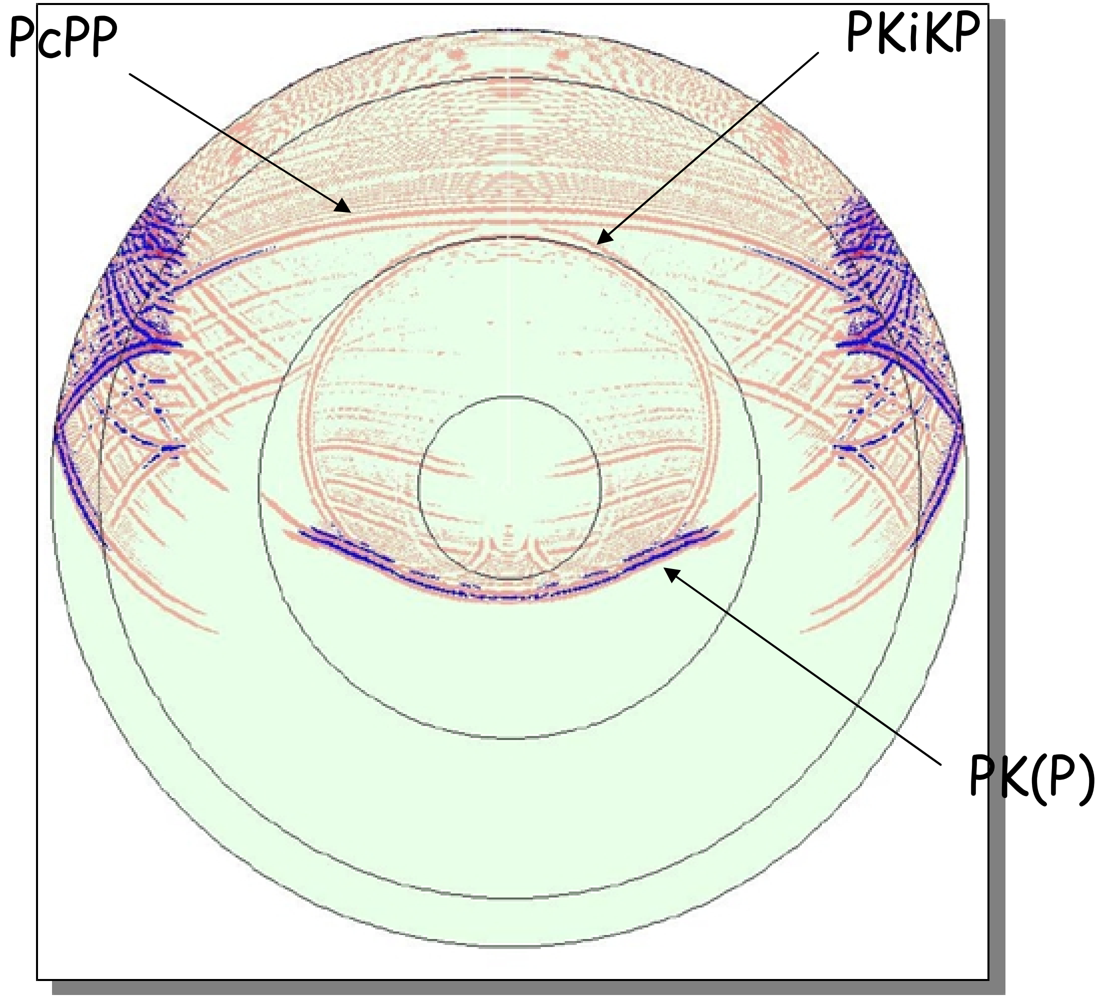


DSM: Direct solution method by Geller, Cummins, ...

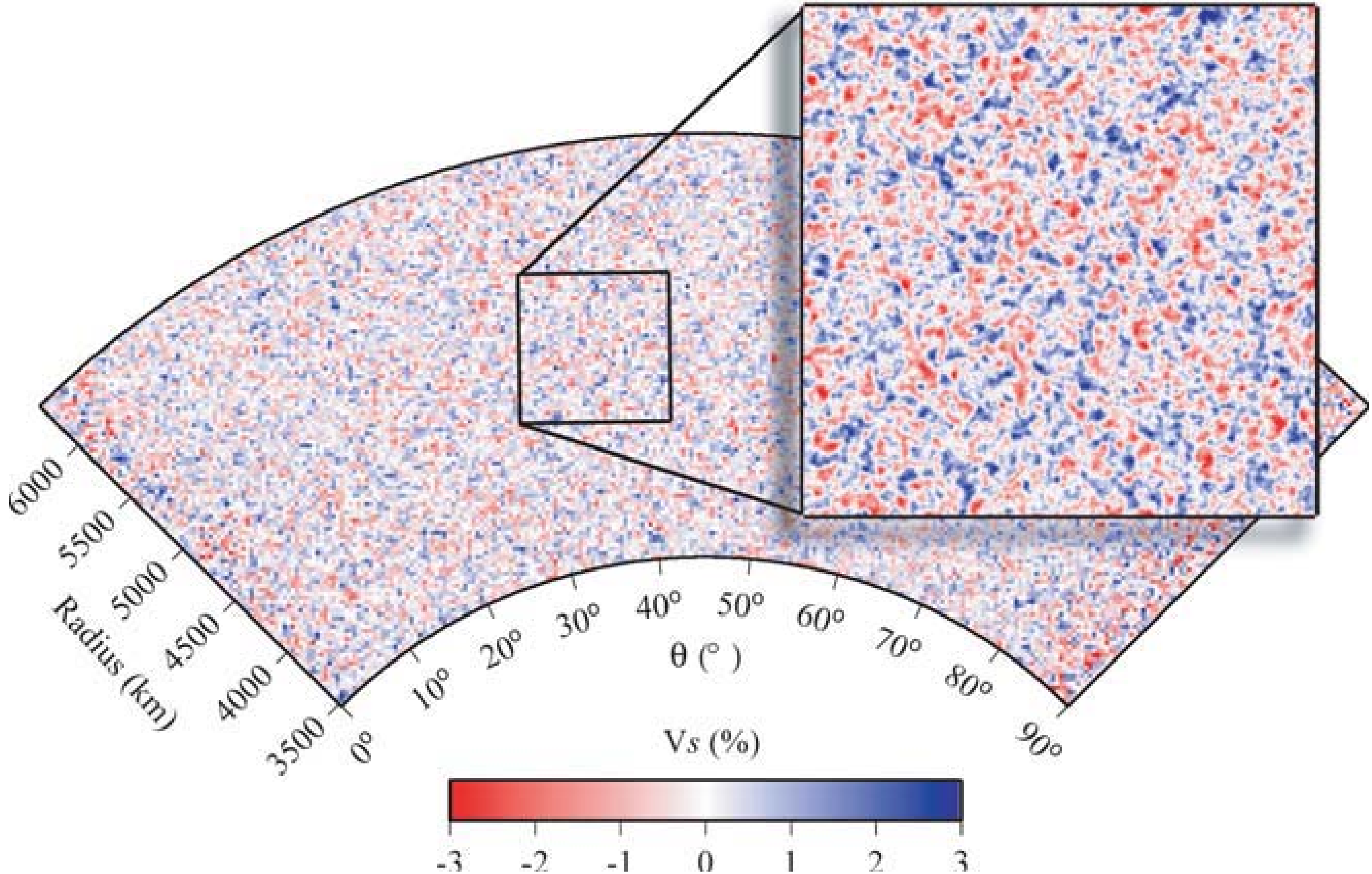
Towards 3-D global wave propagation



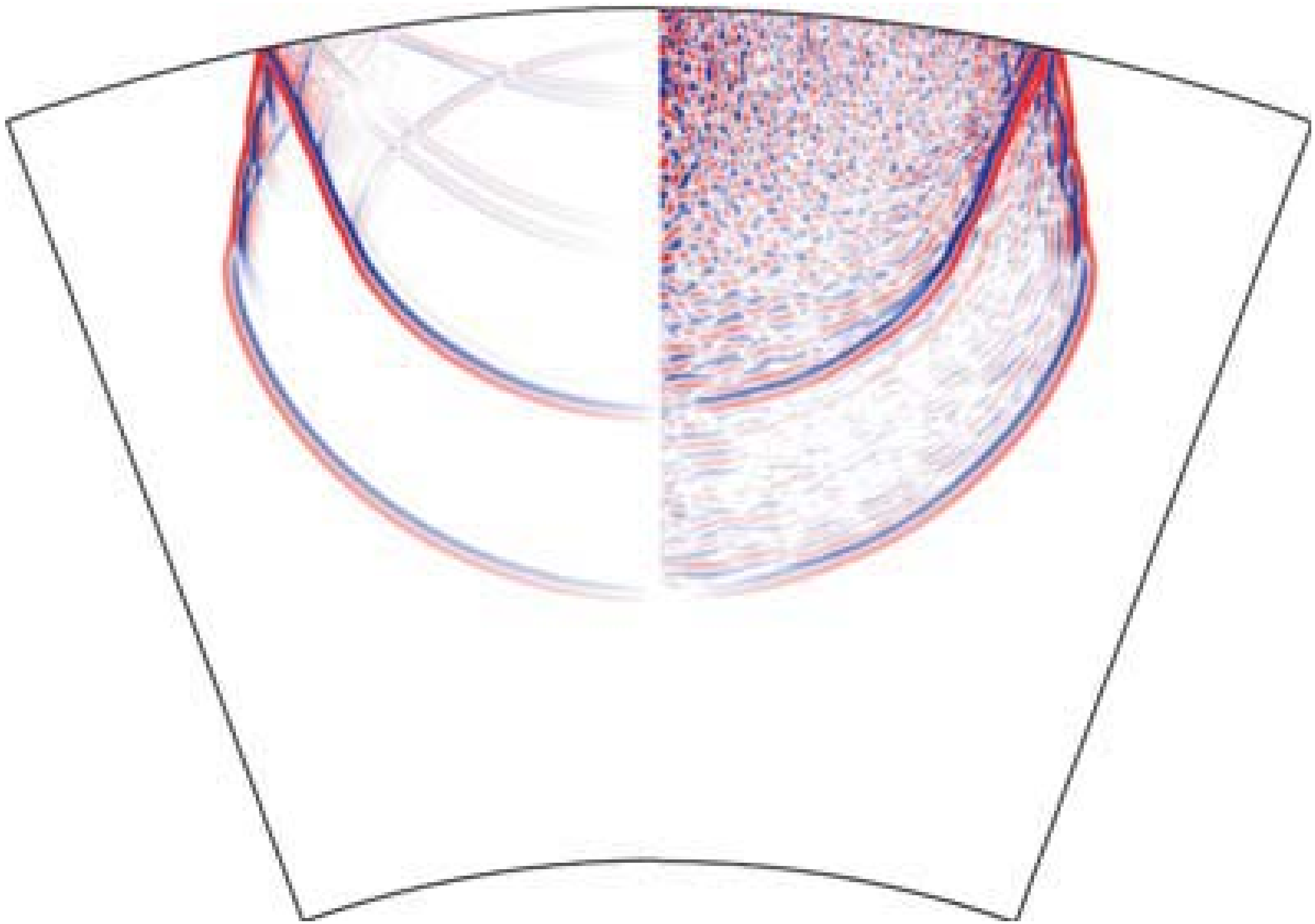
Global P-wave propagation



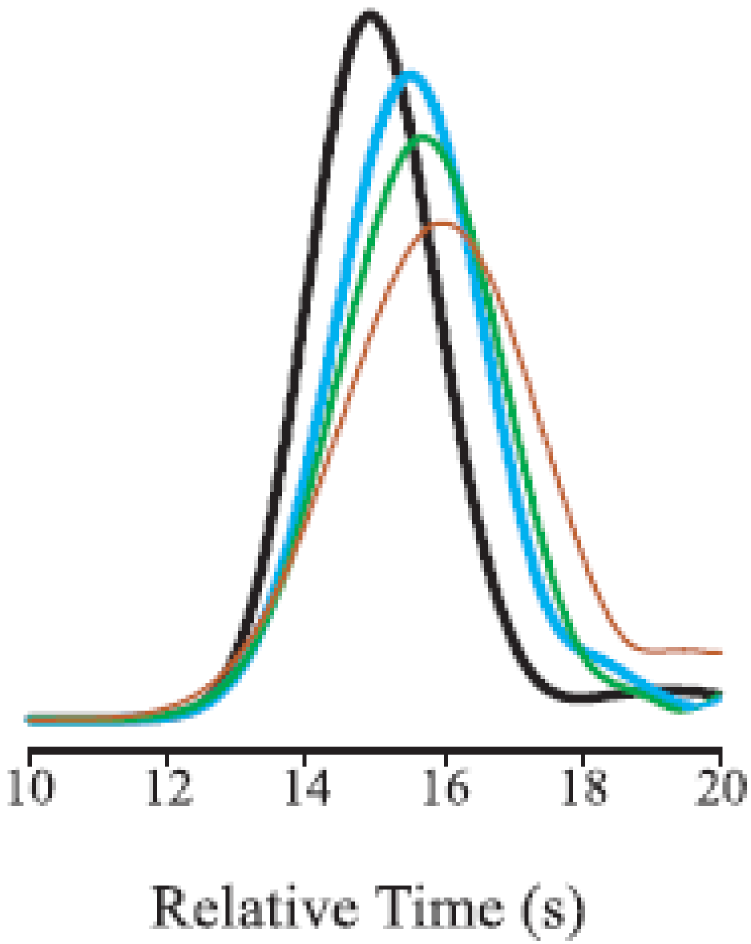
Waves through random mantle models

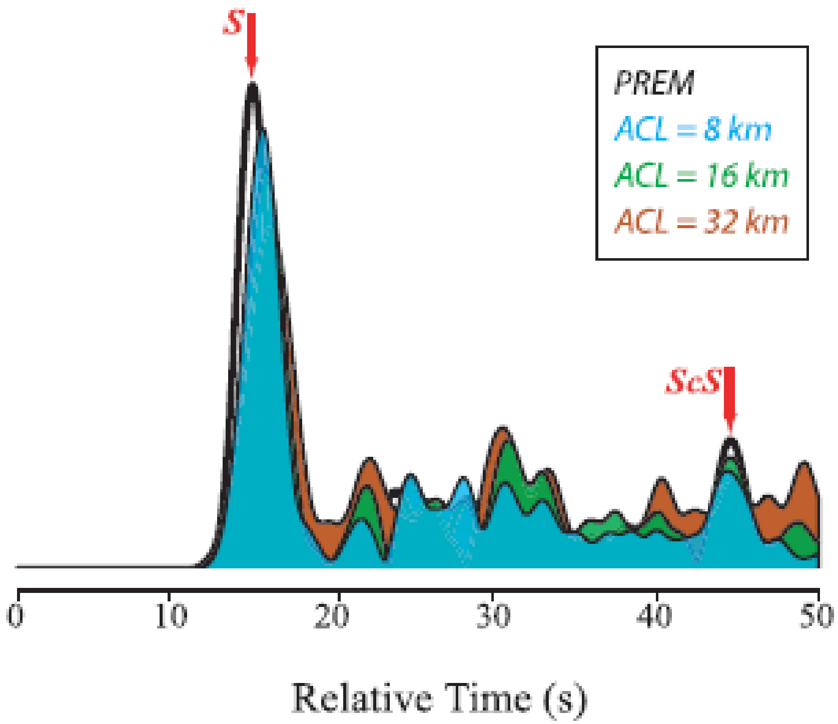


SH - Wave effects



Is the mantle faster than we think?



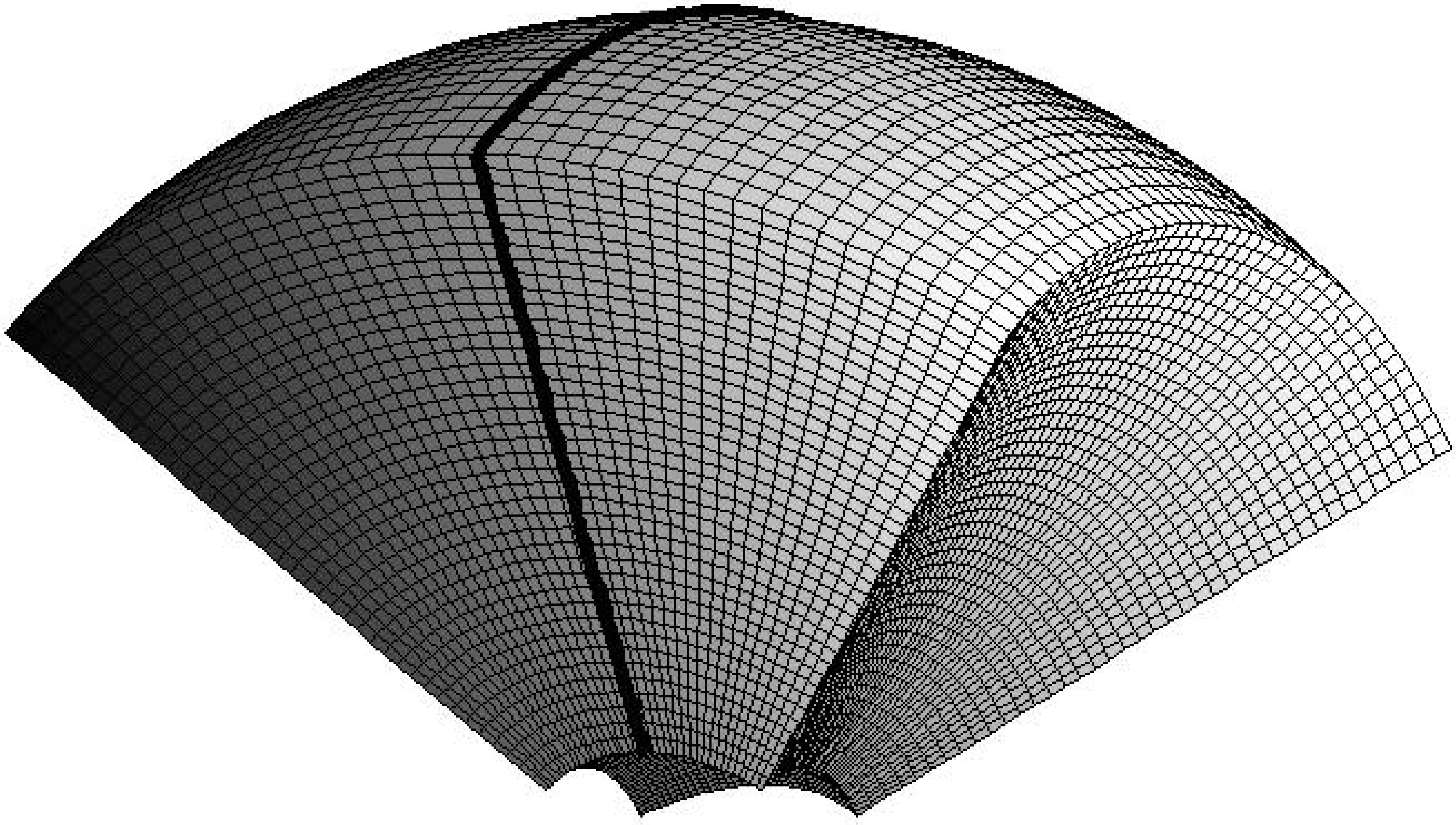


Jahnke, Thorne, Cochard, Igel, GJI, 2008

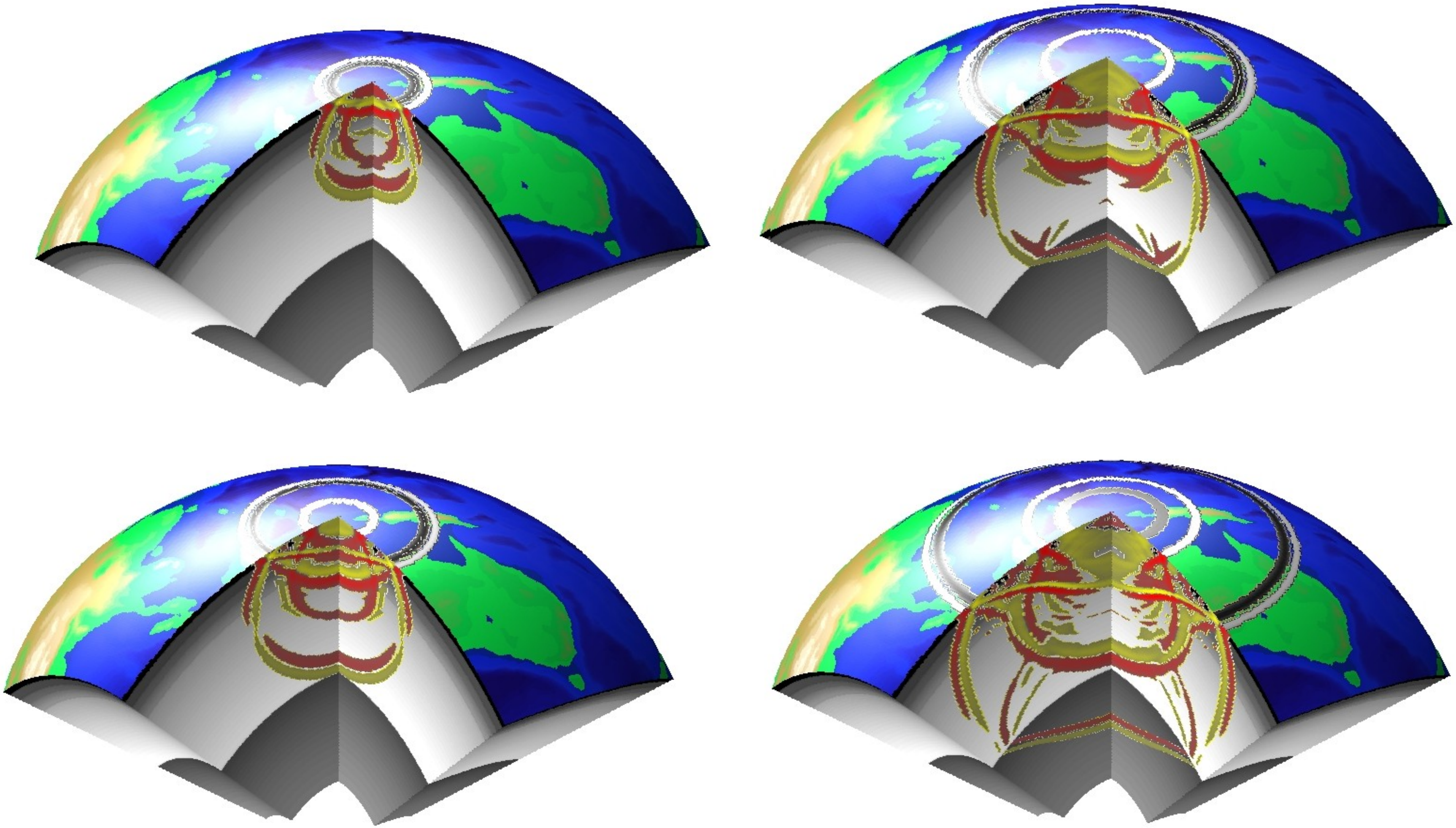
FD Spherical Grids

3-D sections

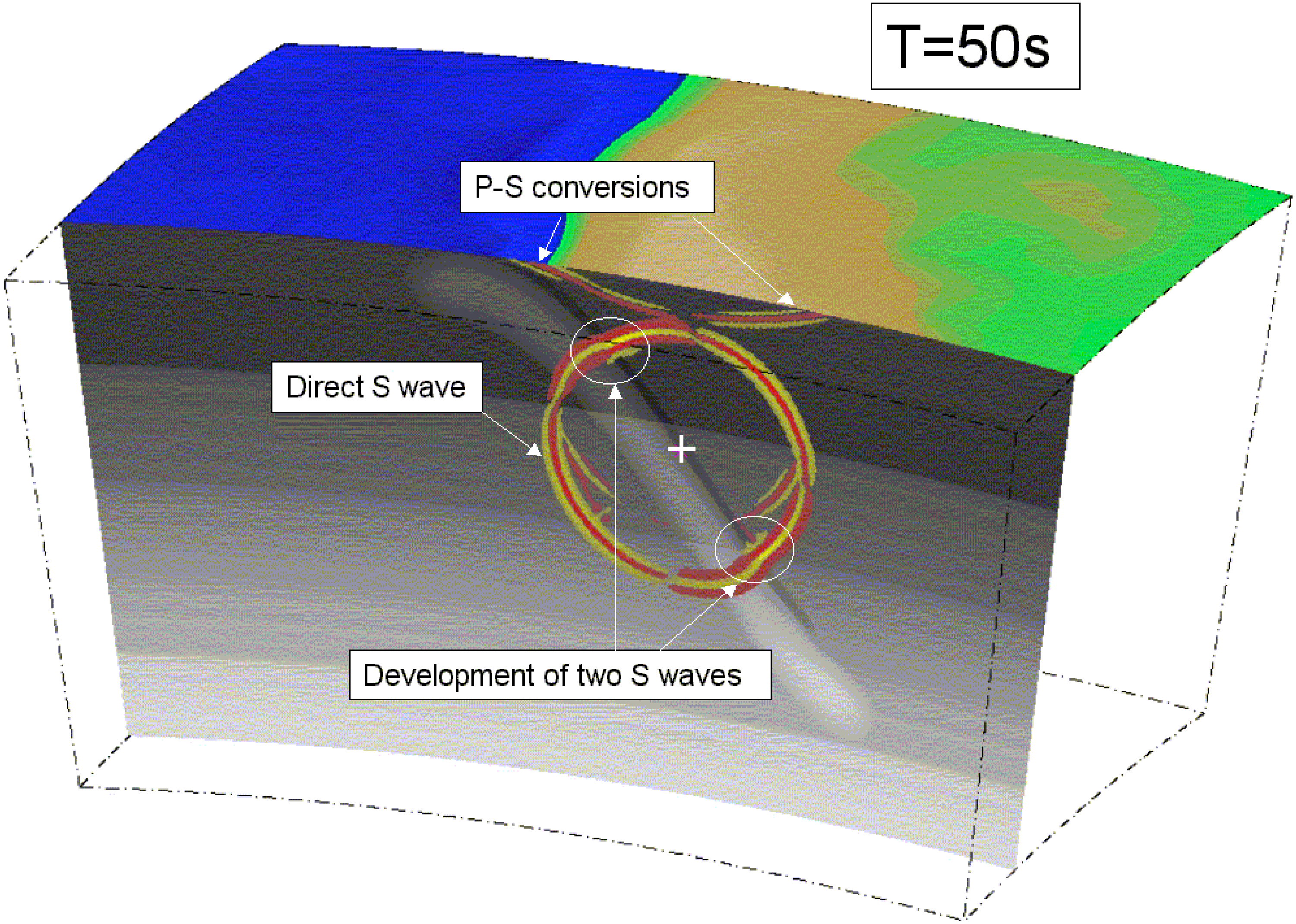
Spherical section – regular grid



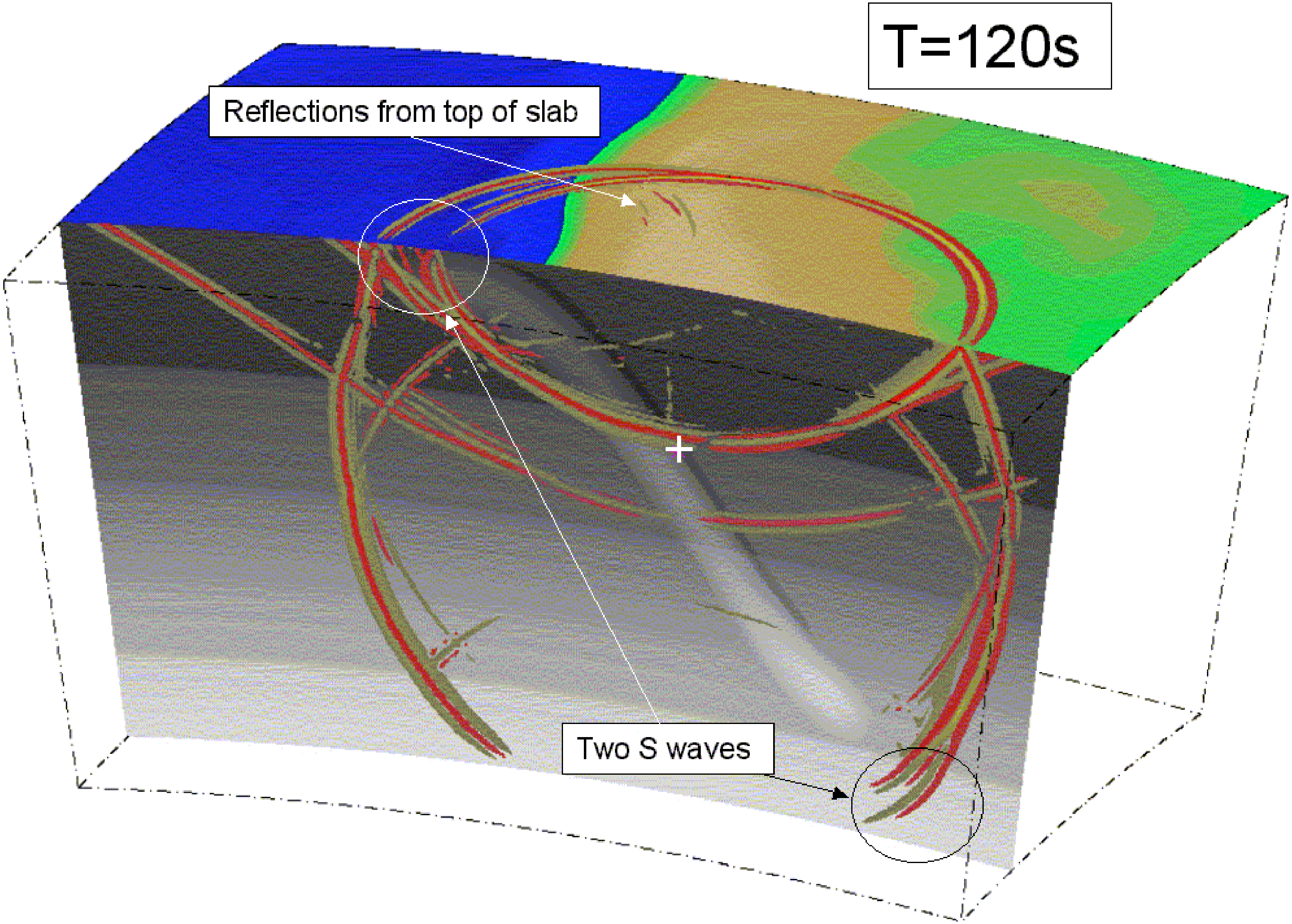
Waves in spherical sections



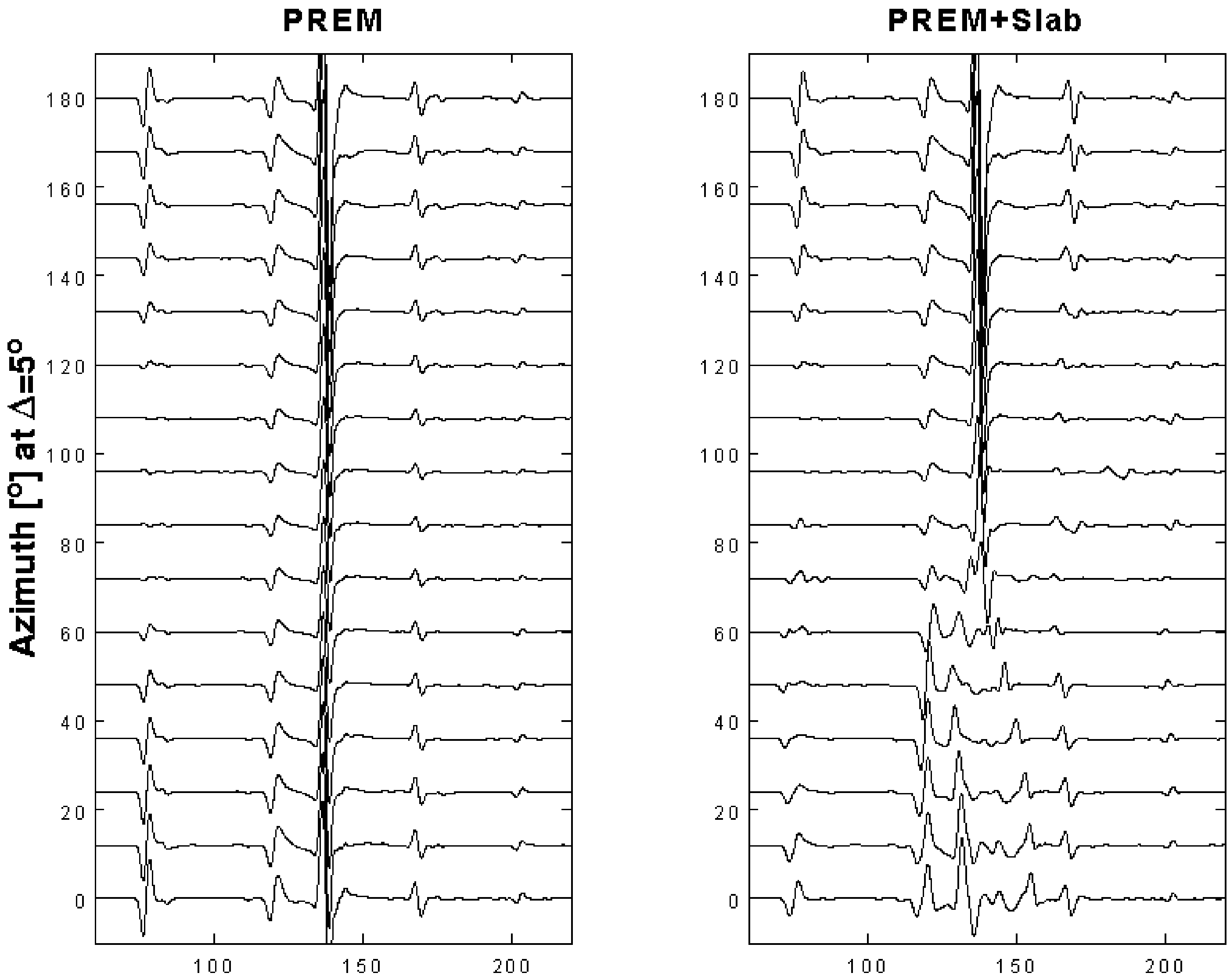
Subduction zones



Subduction zones



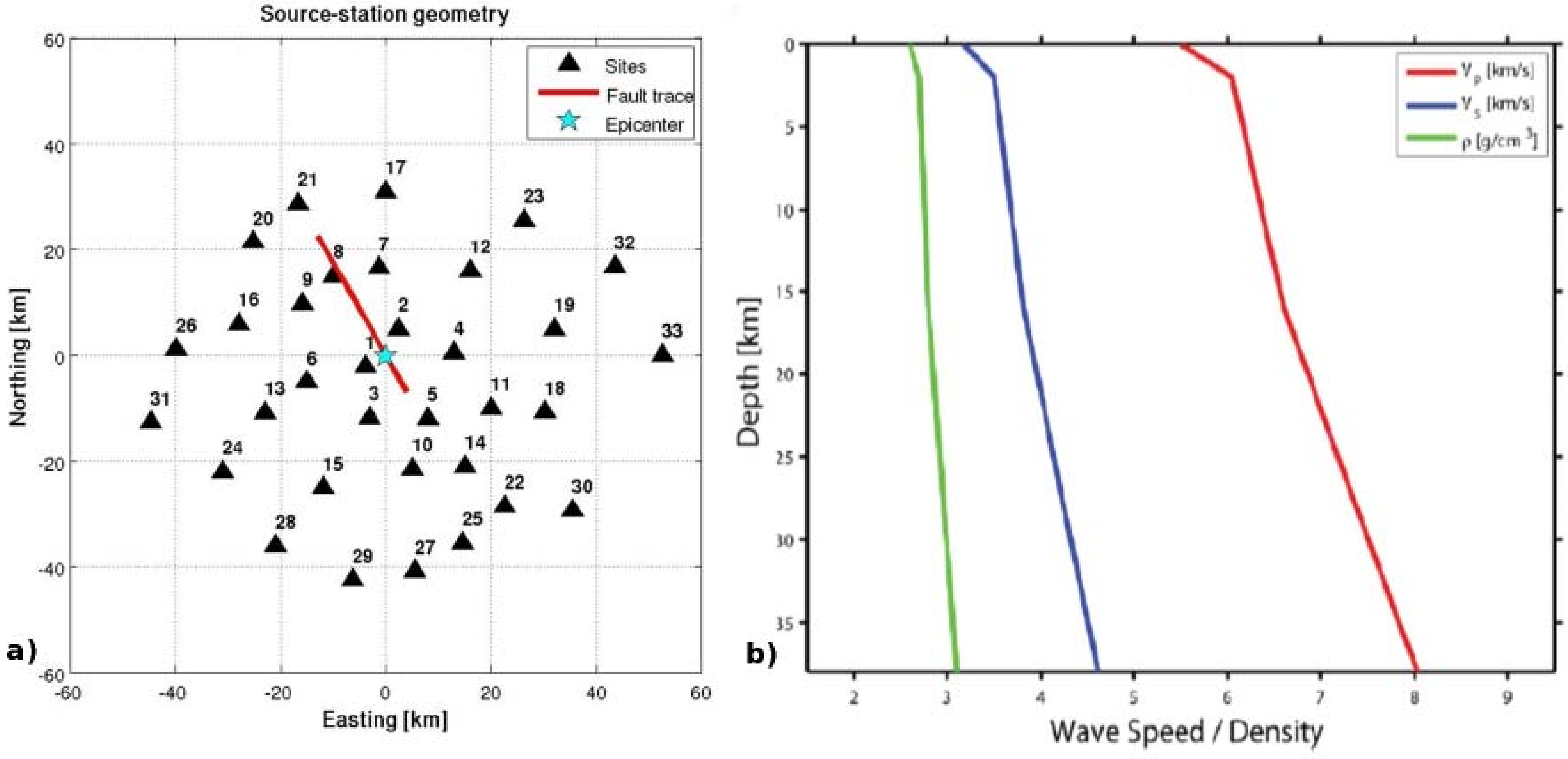
Can we observe such effects?



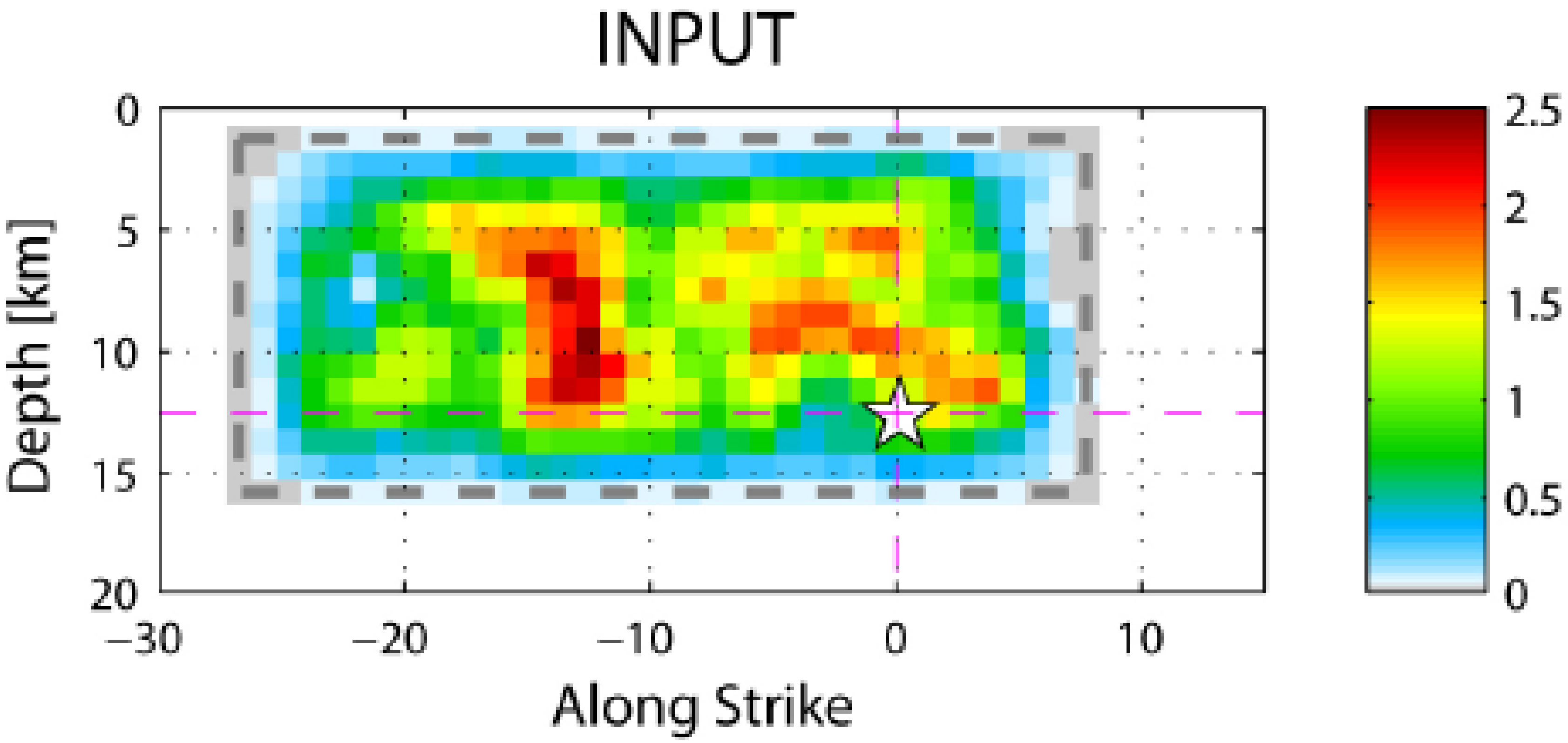
Spectral element method

Cartesian grids

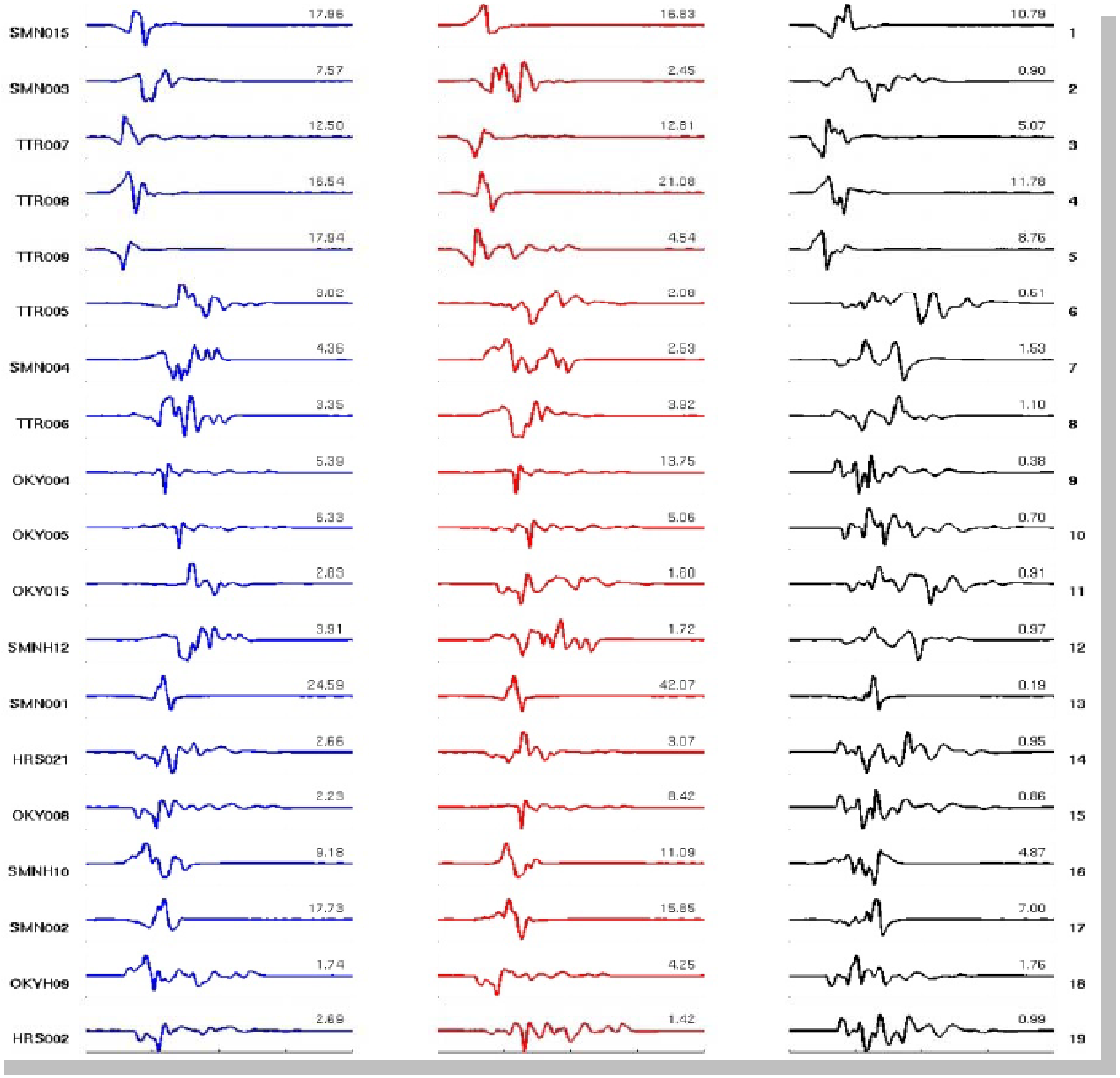
Synthethic experiment: source inversion



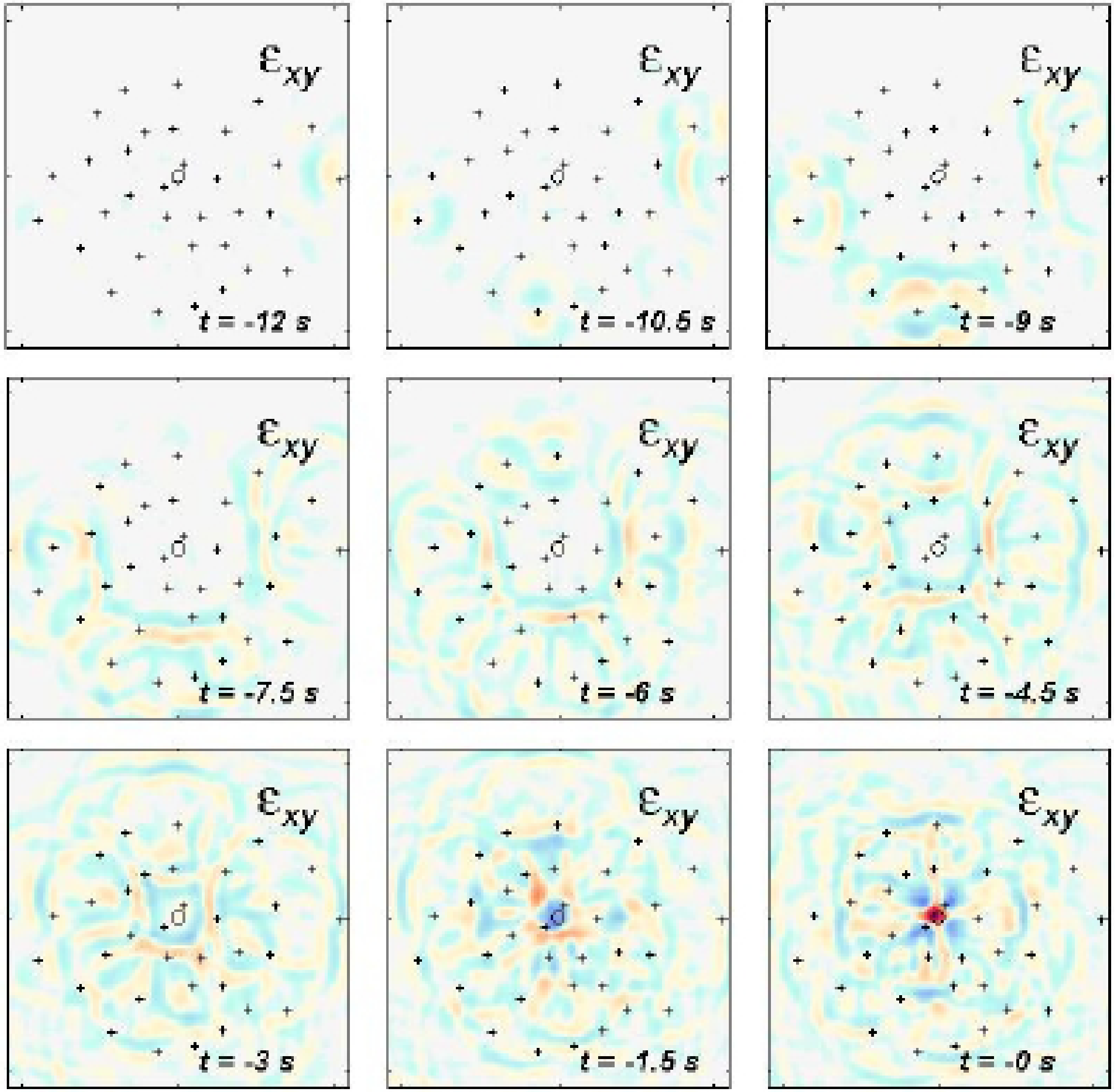
True source



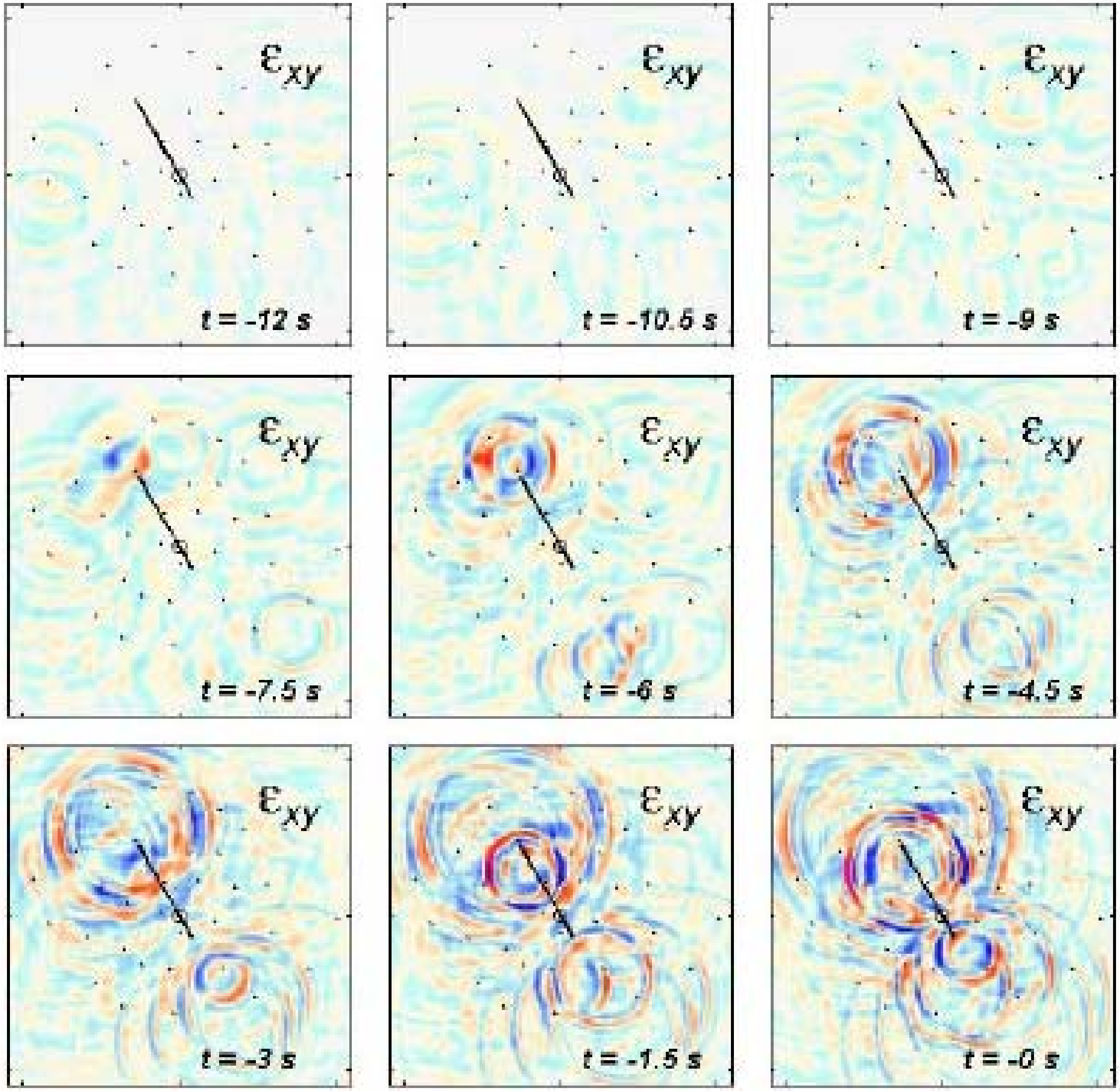
Seismograms



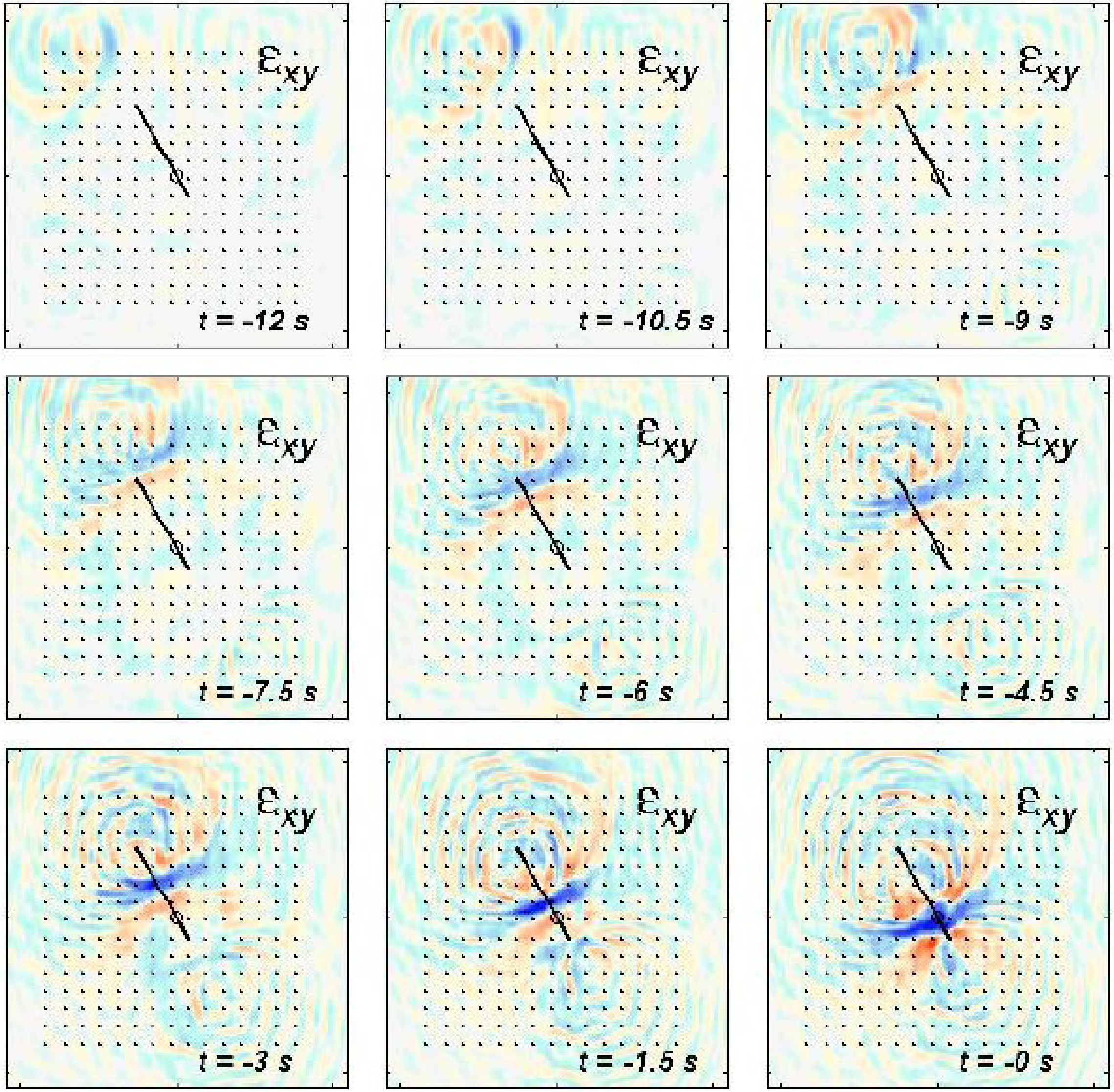
Time reversal – point source



Time reversal: real network

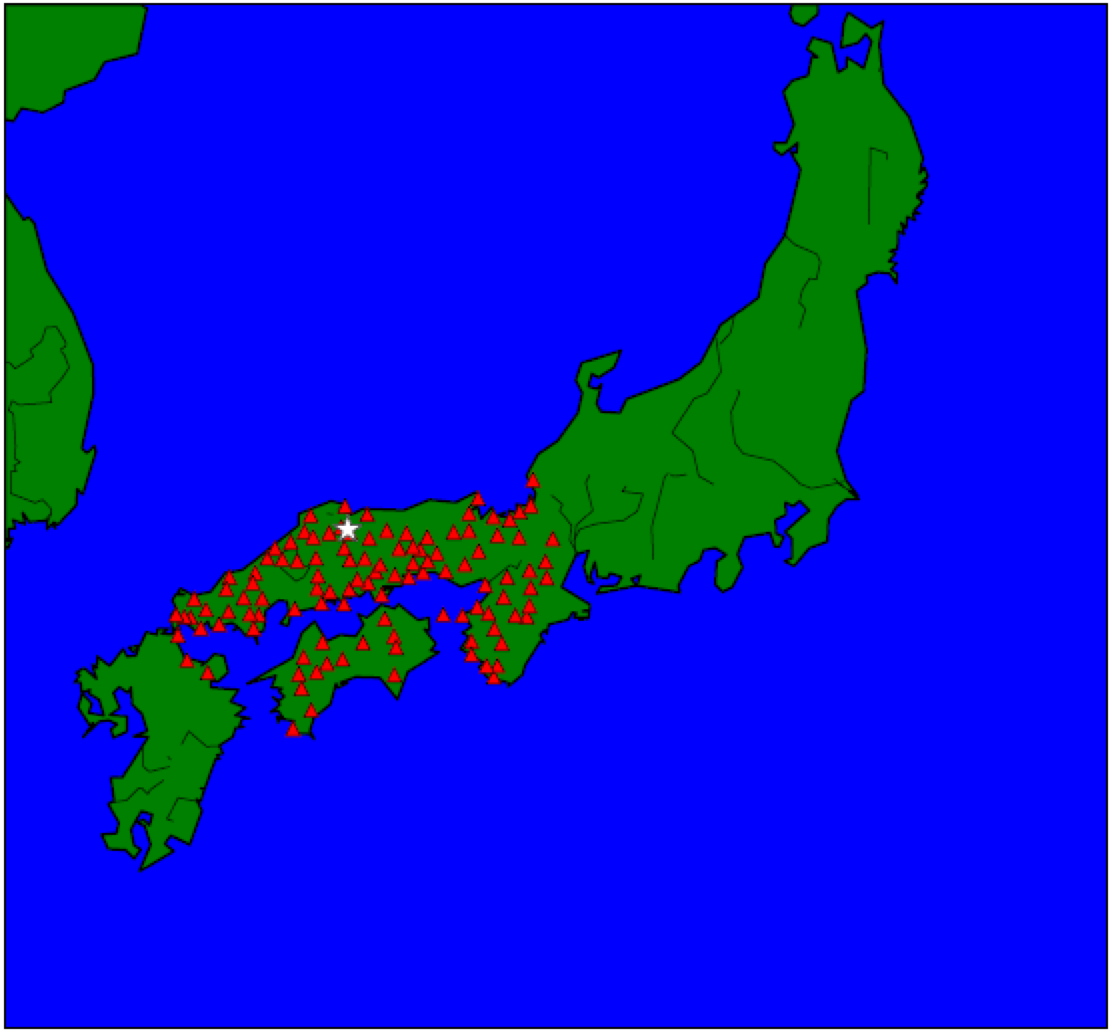


Time reversal: ideal network

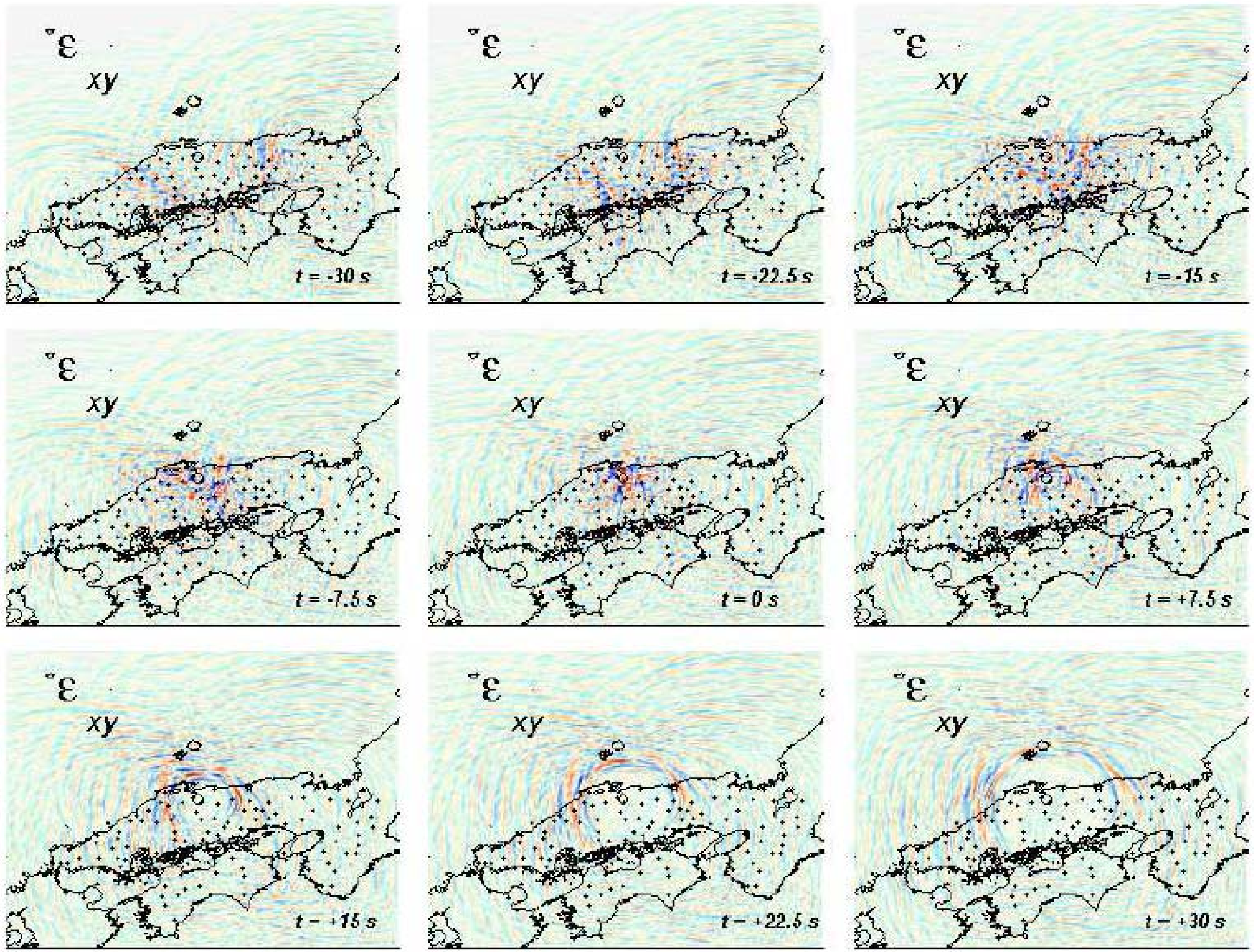


Real data: Tottori earthquake

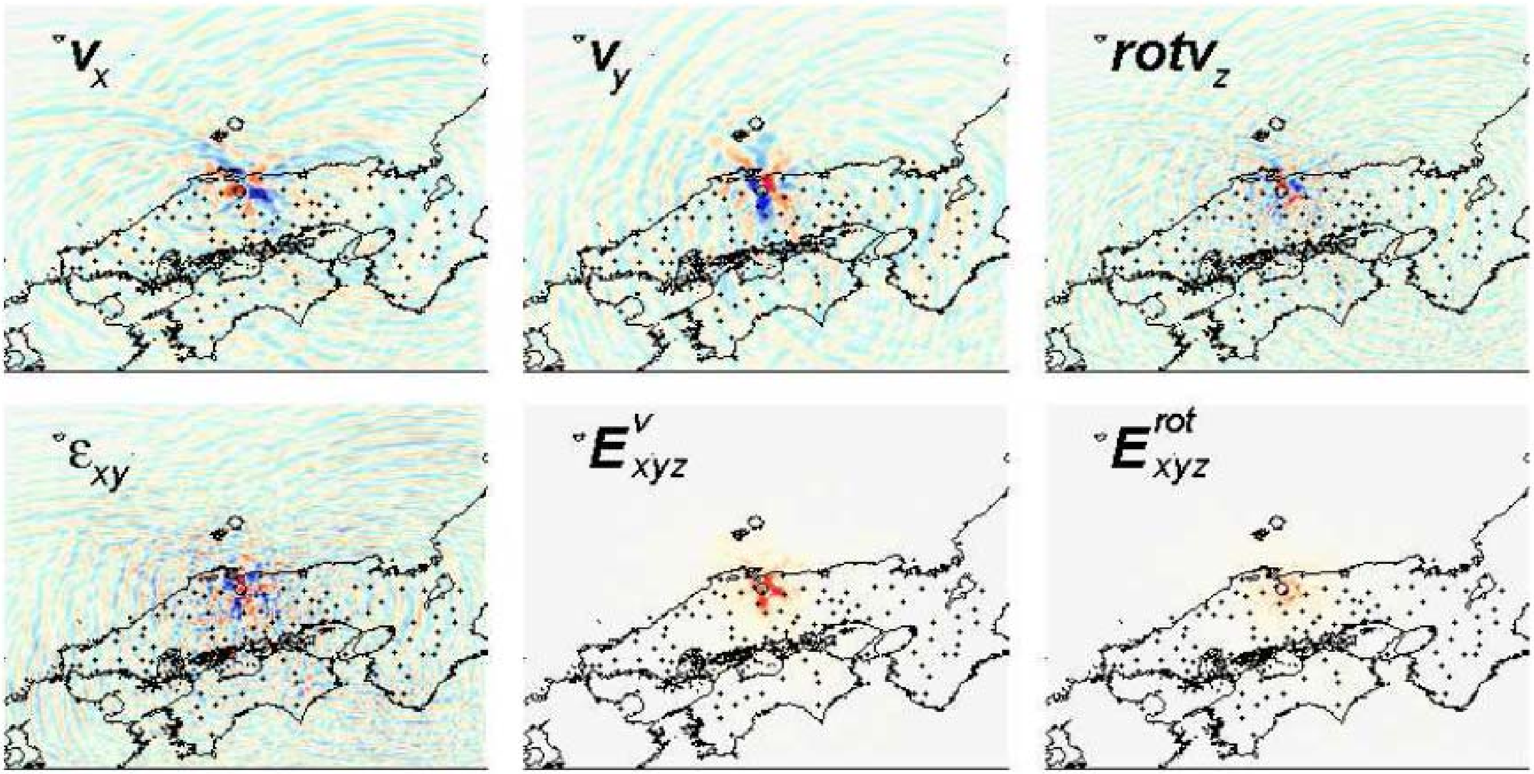
KiK-net station distribution



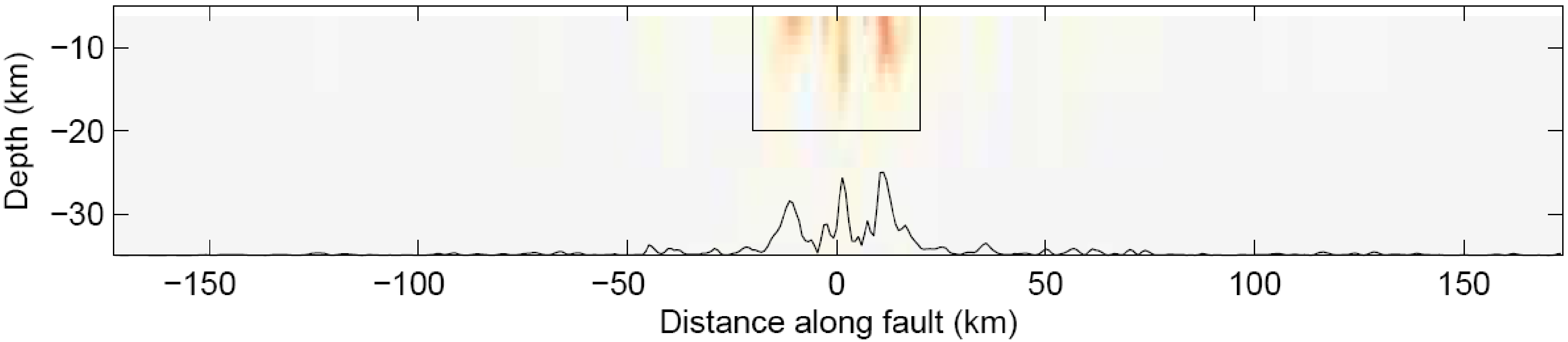
Reverse movie



Focus time

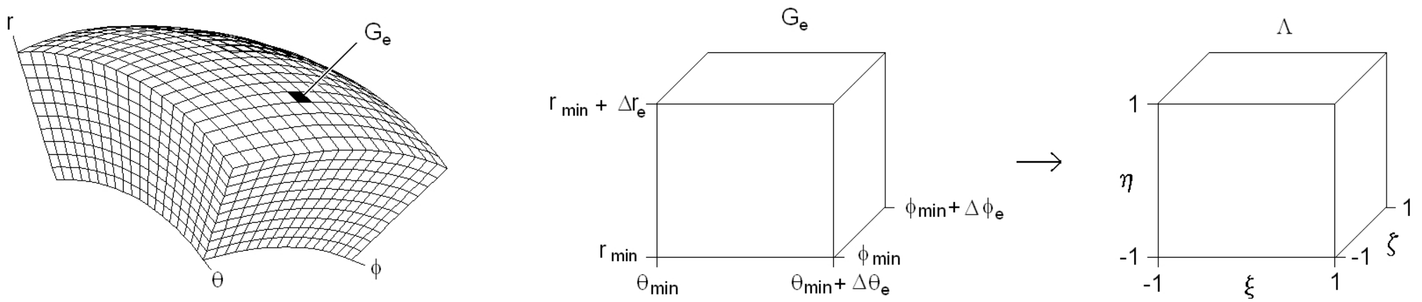


Projection on fault

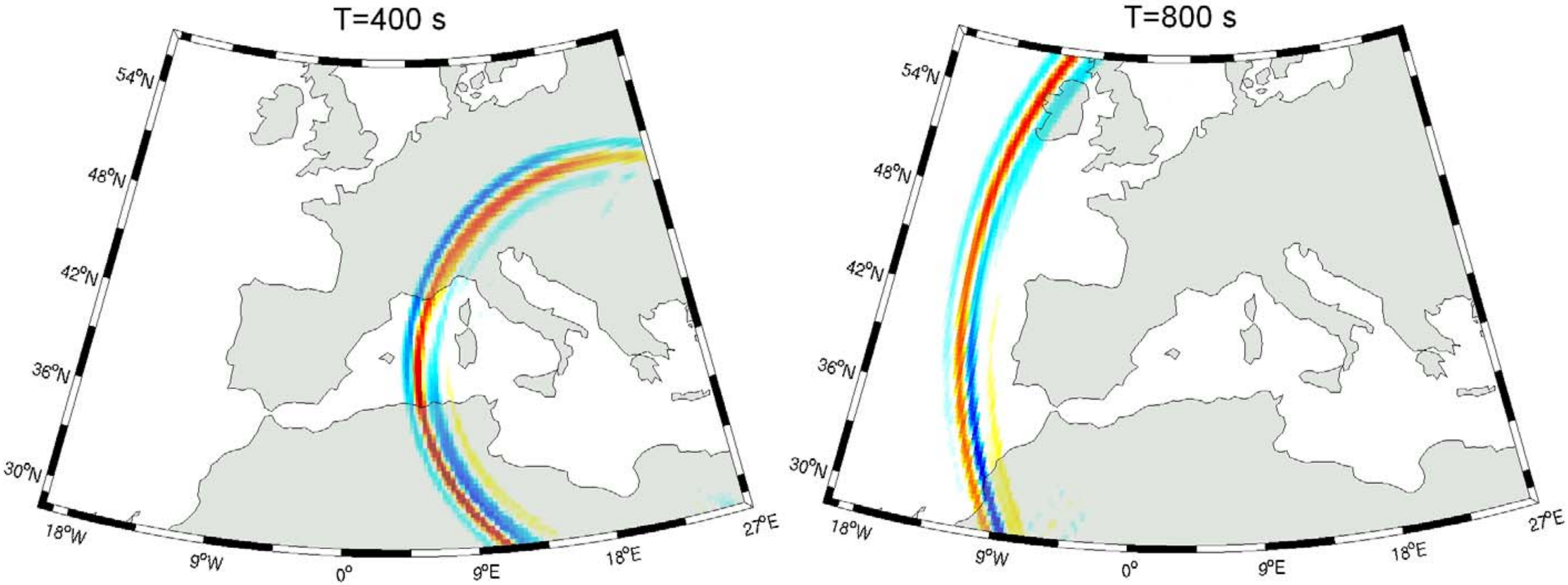


Spectral element method

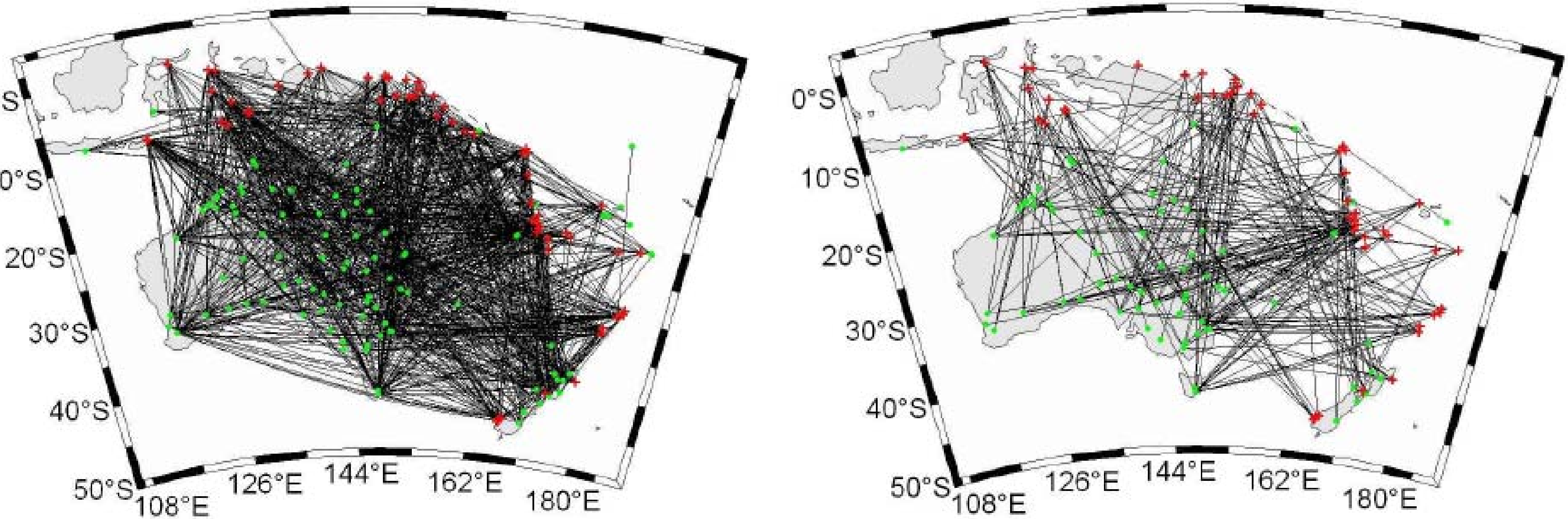
spherical regular grids

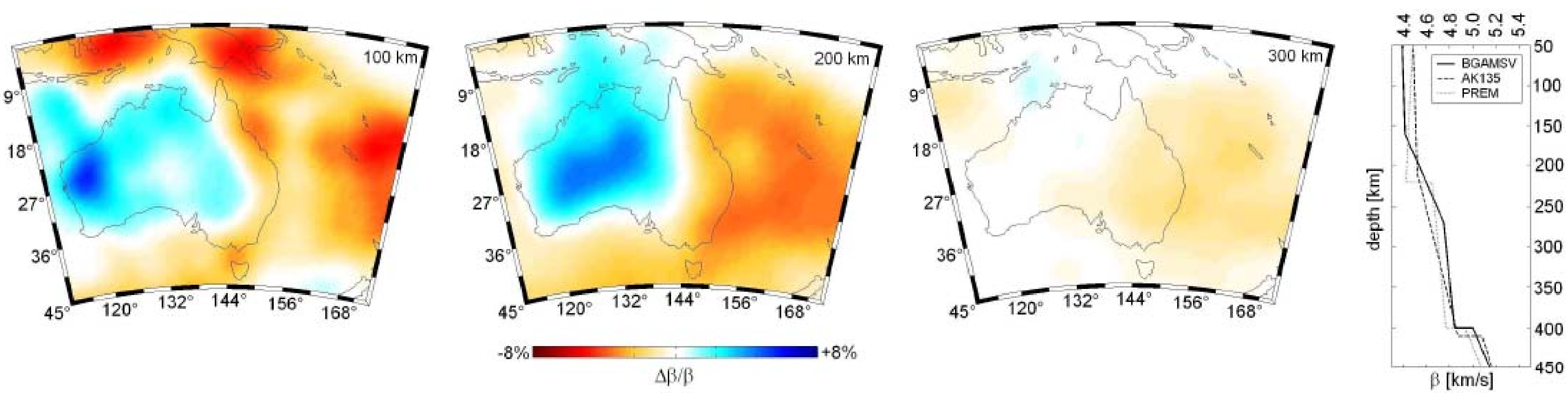


Simple example

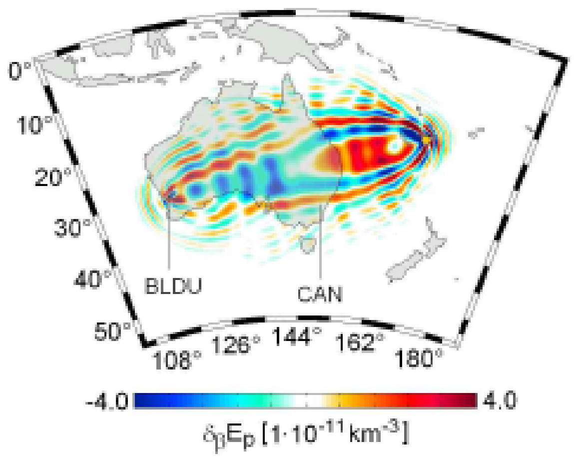


Ray coverage – initial model

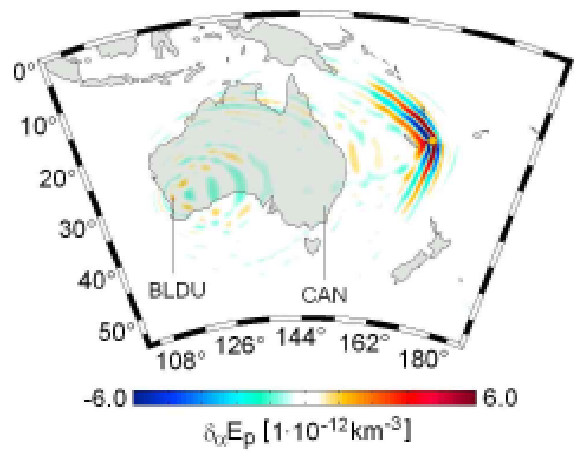




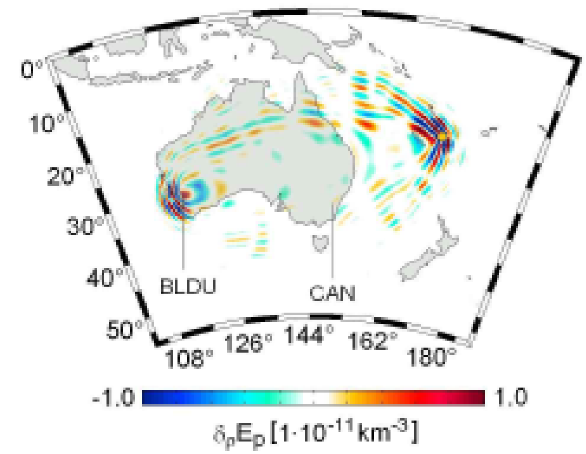
Sensitivity kernels



S velocity

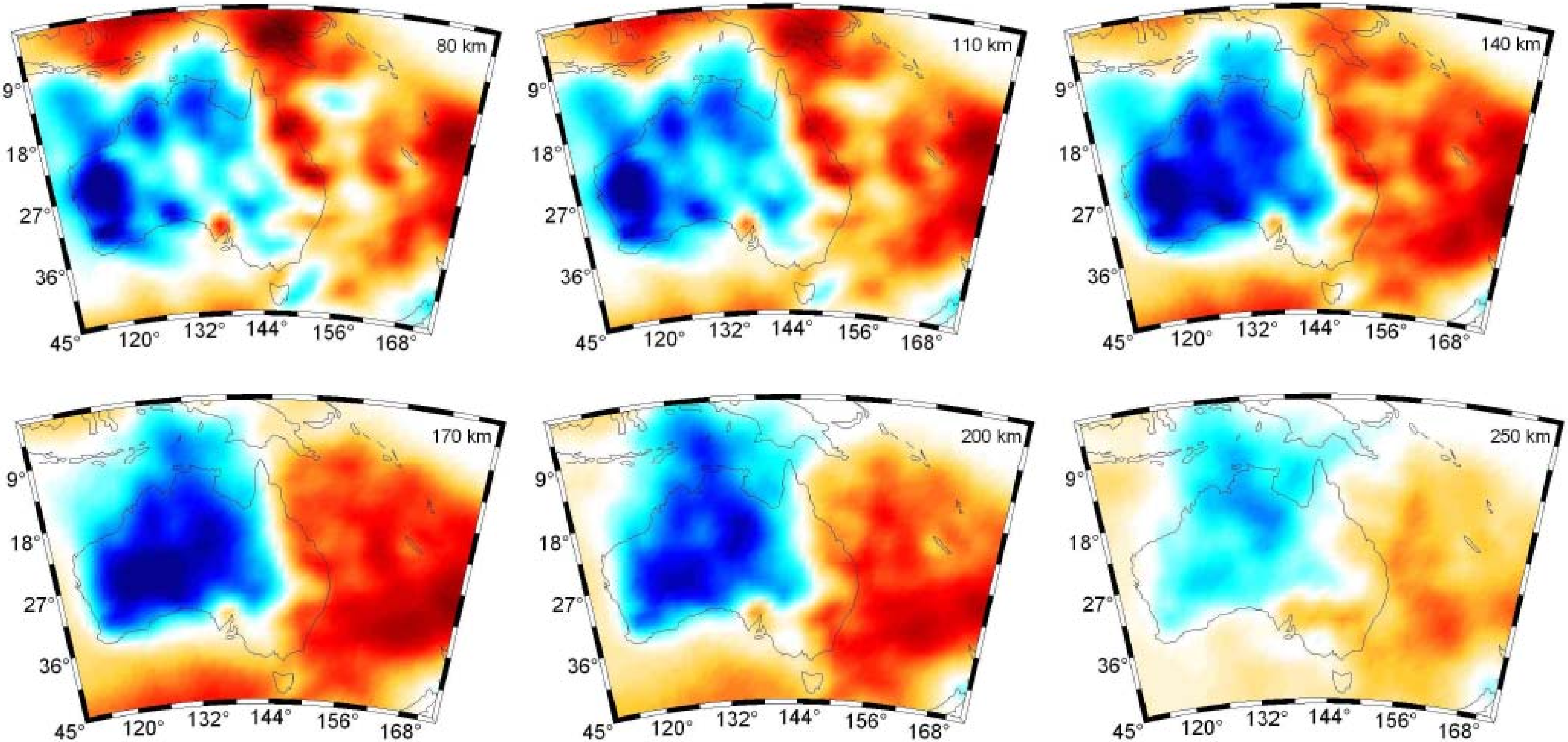


P velocity

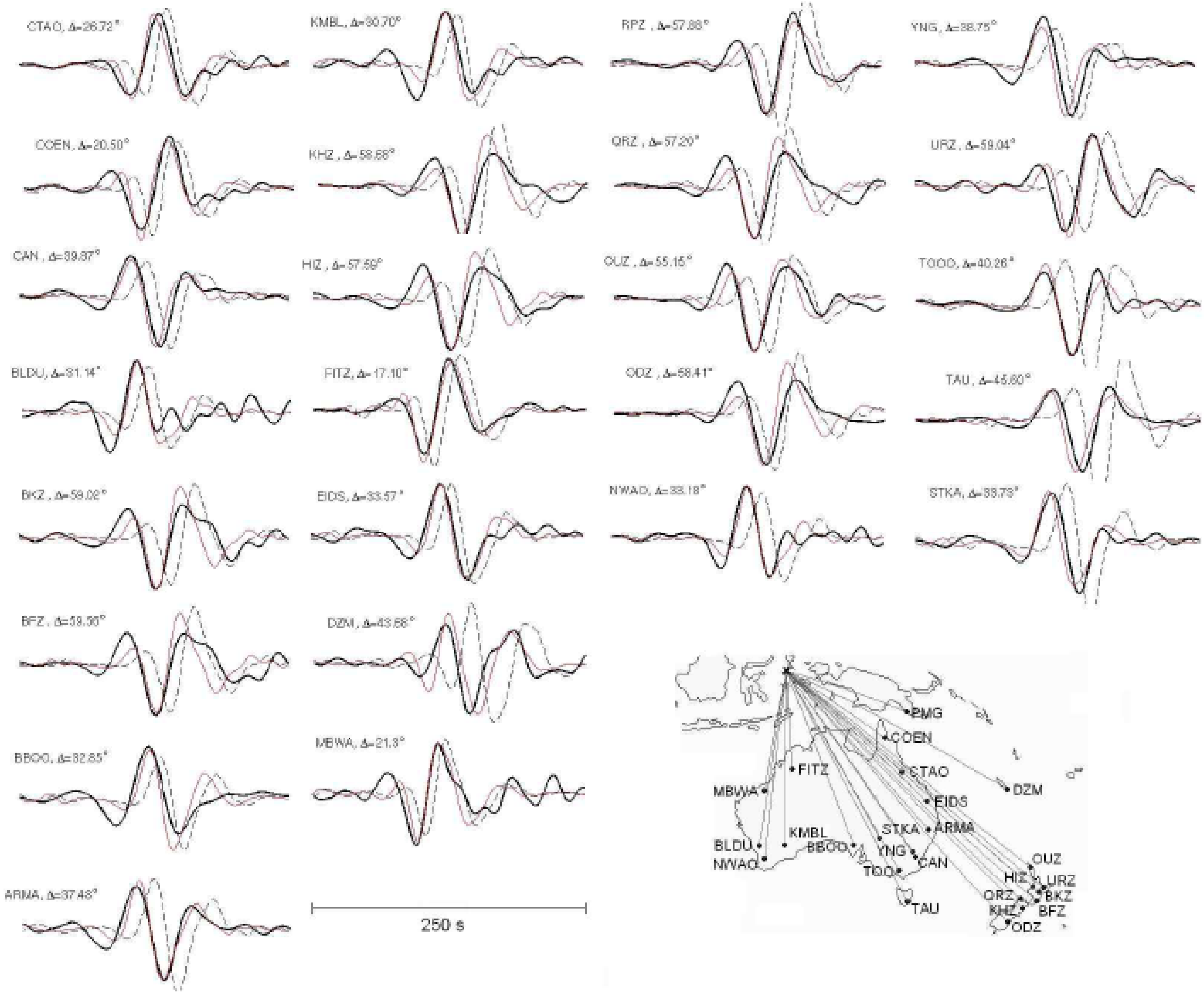


Density

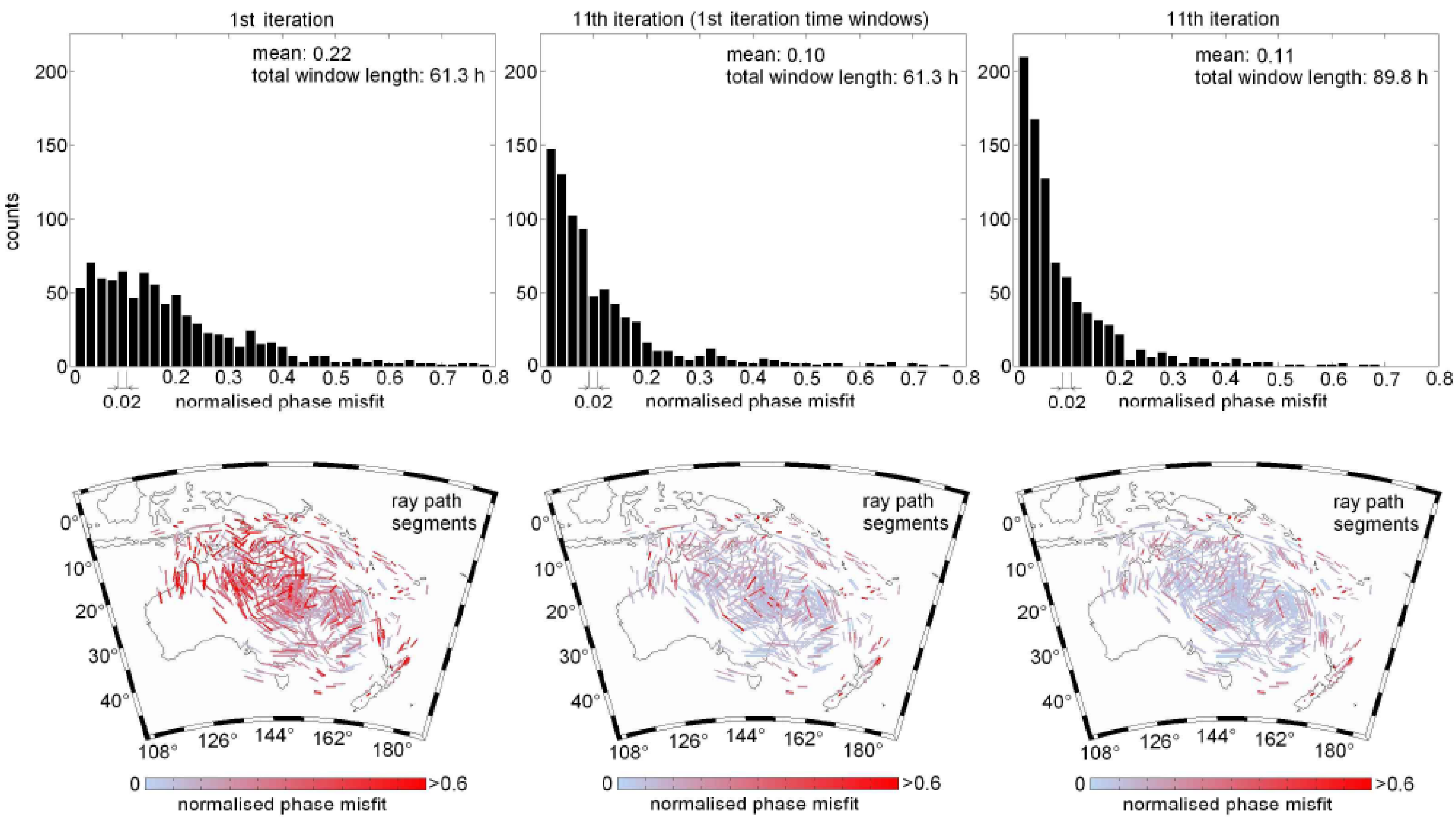
Final model


80 km
110 km
140 km
170 km
200 km
250 km
9°
18°
27°
36°
45°
120°
132°
144°
156°
168°

Before - After

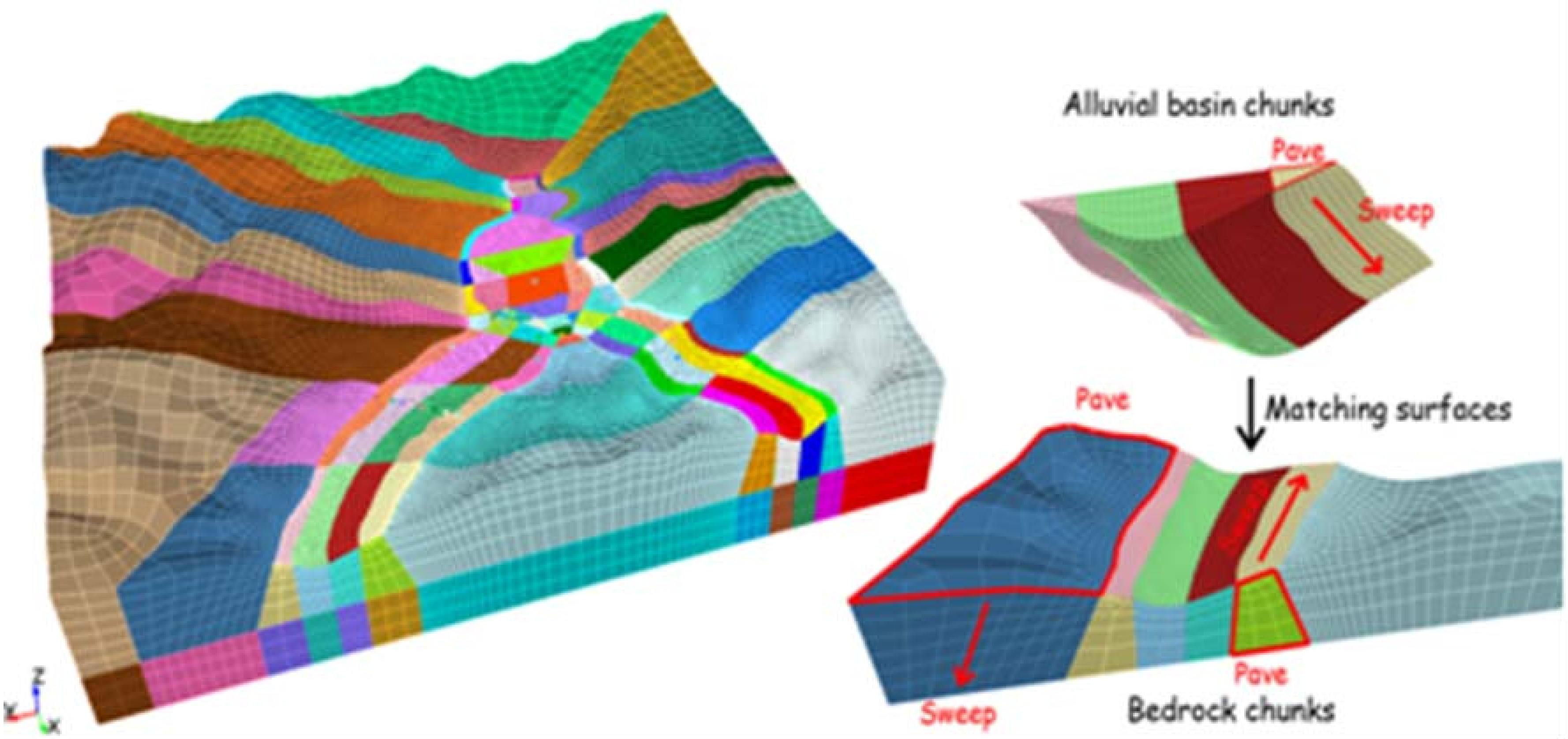


Improvement

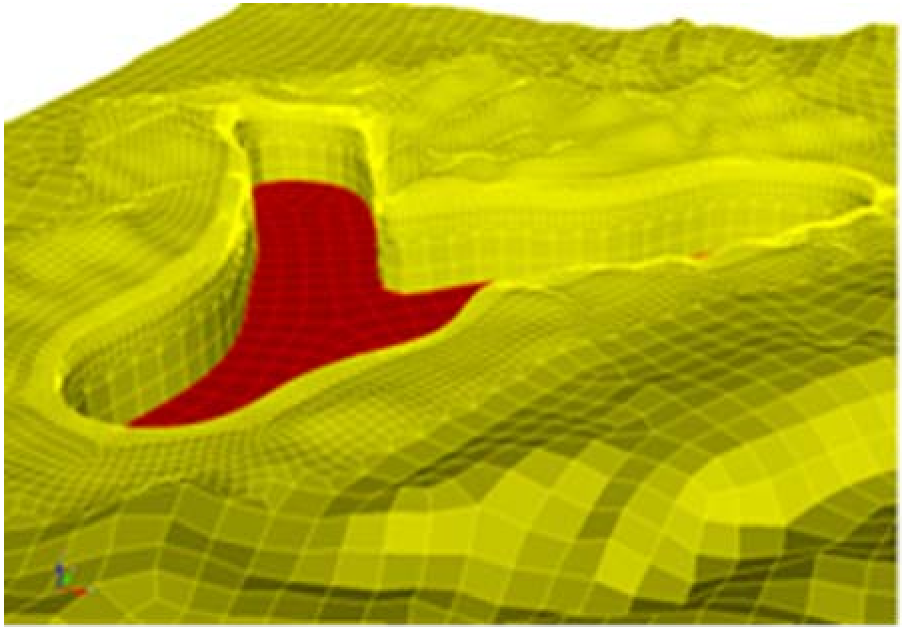


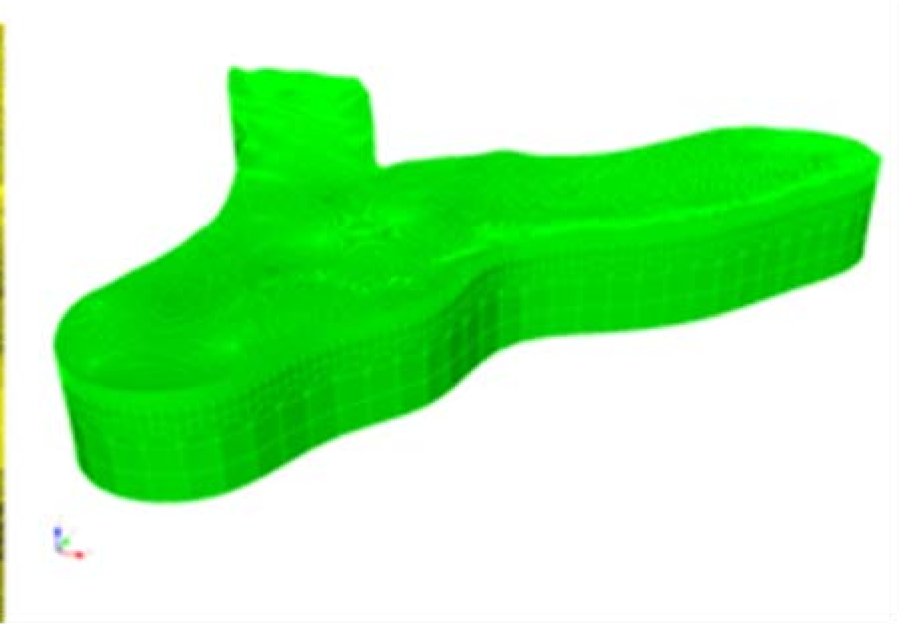
Spectral element method

Unstructured grids

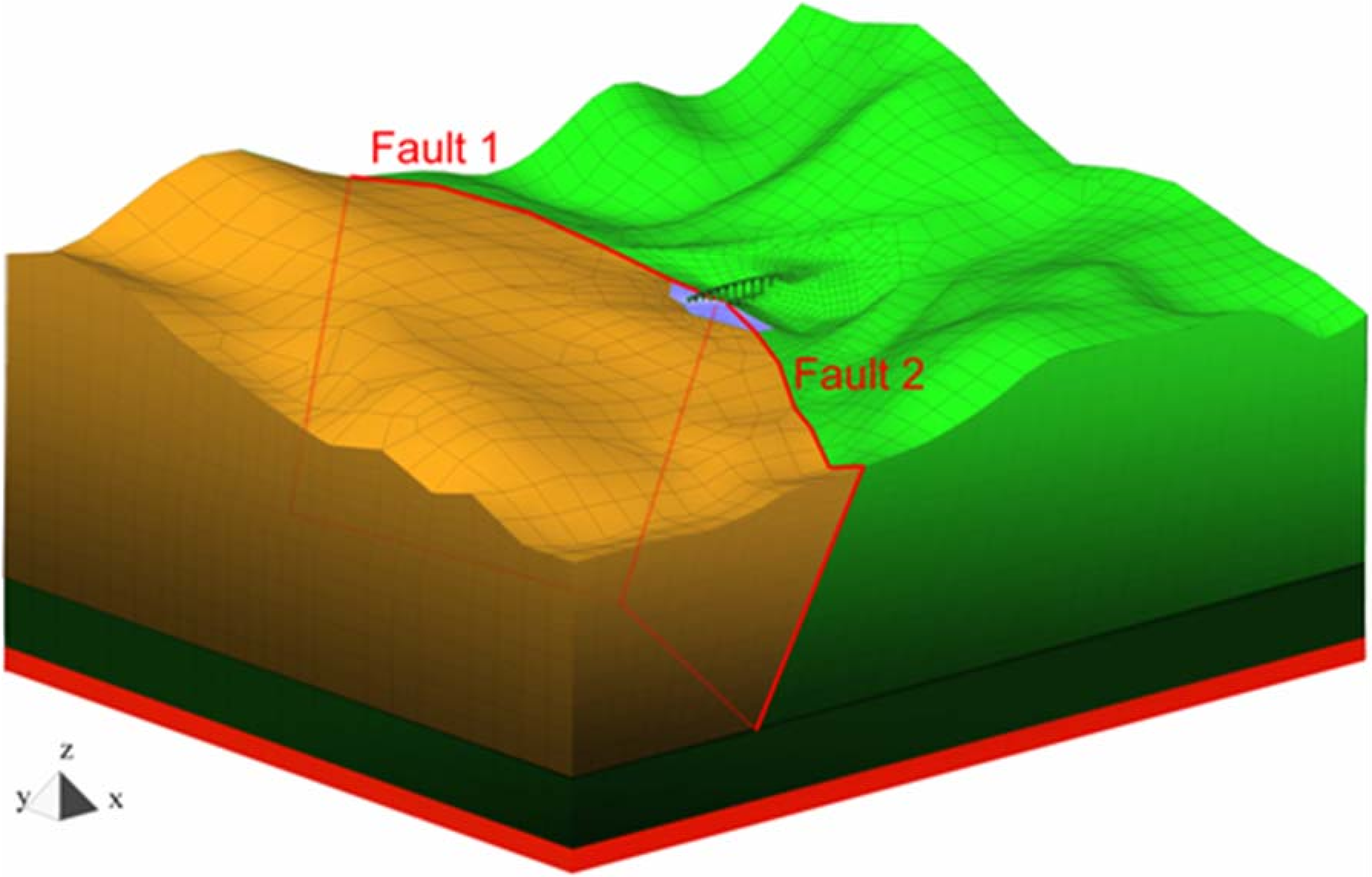

Alluvial basin chunks
Pave
Sweep
Pave
Matching surfaces
Pave
Sweep
Bedrock chunks

Grenoble basin

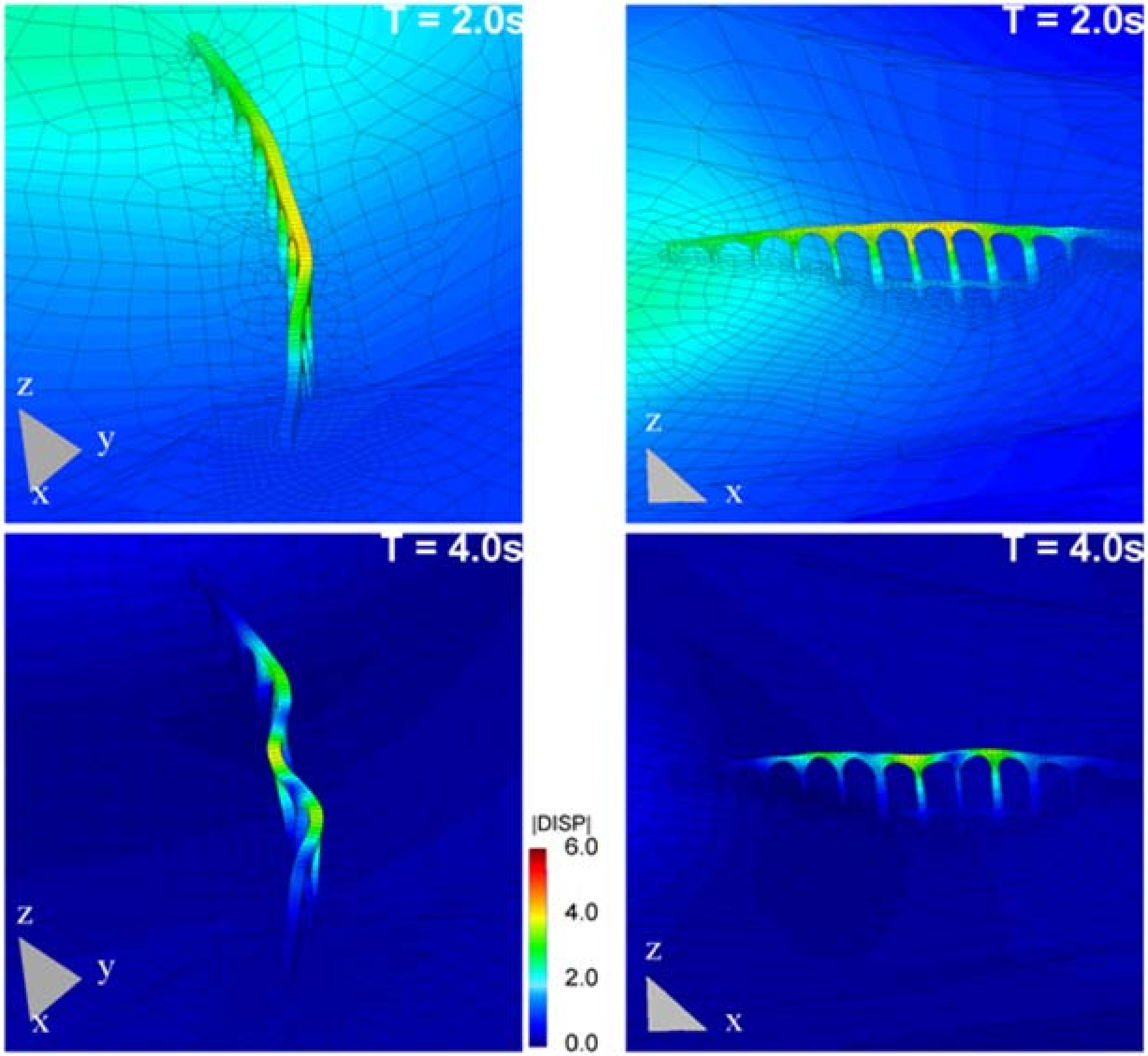




The bridge



Soil – structure interaction

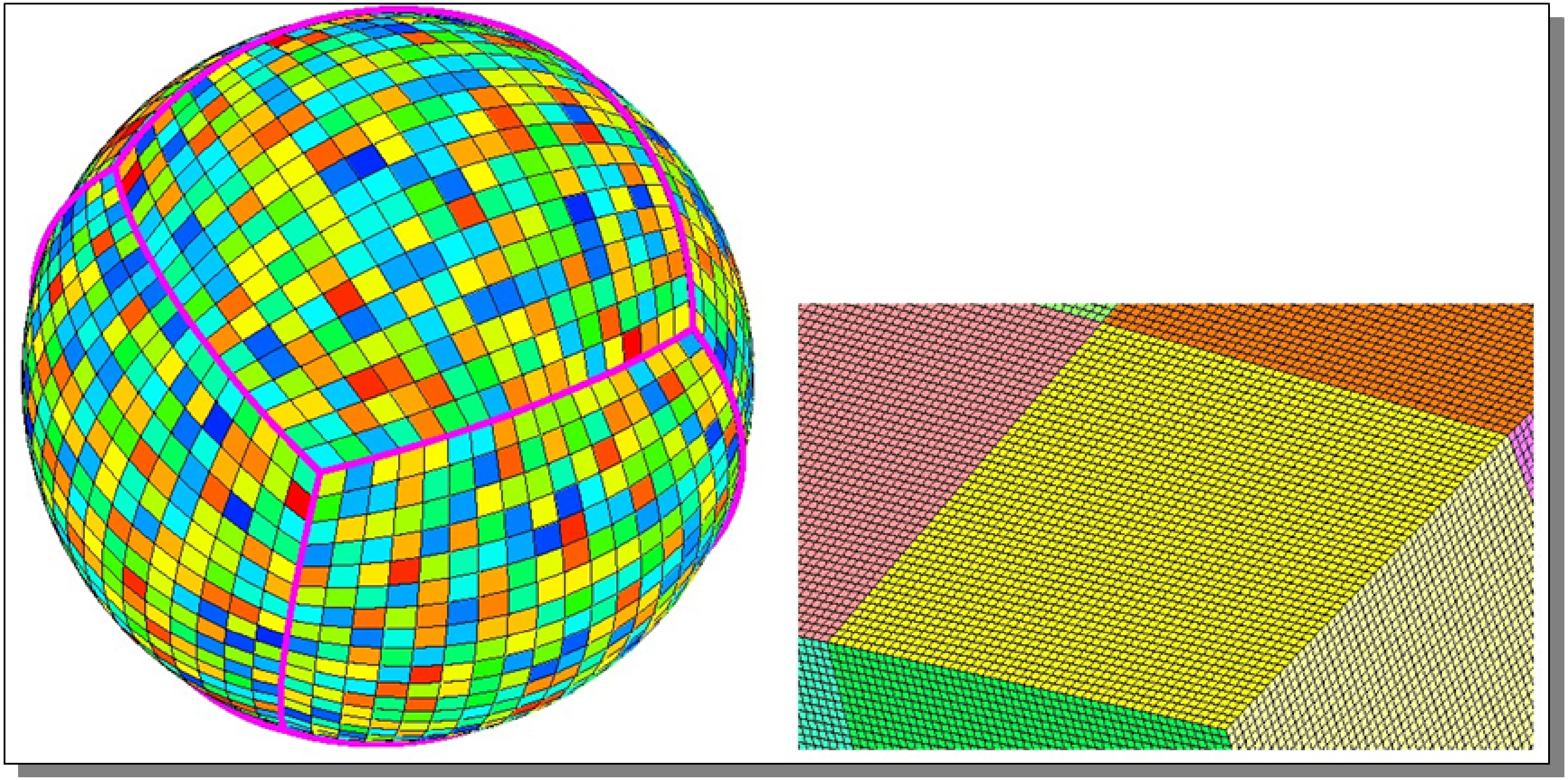


Spectral element method

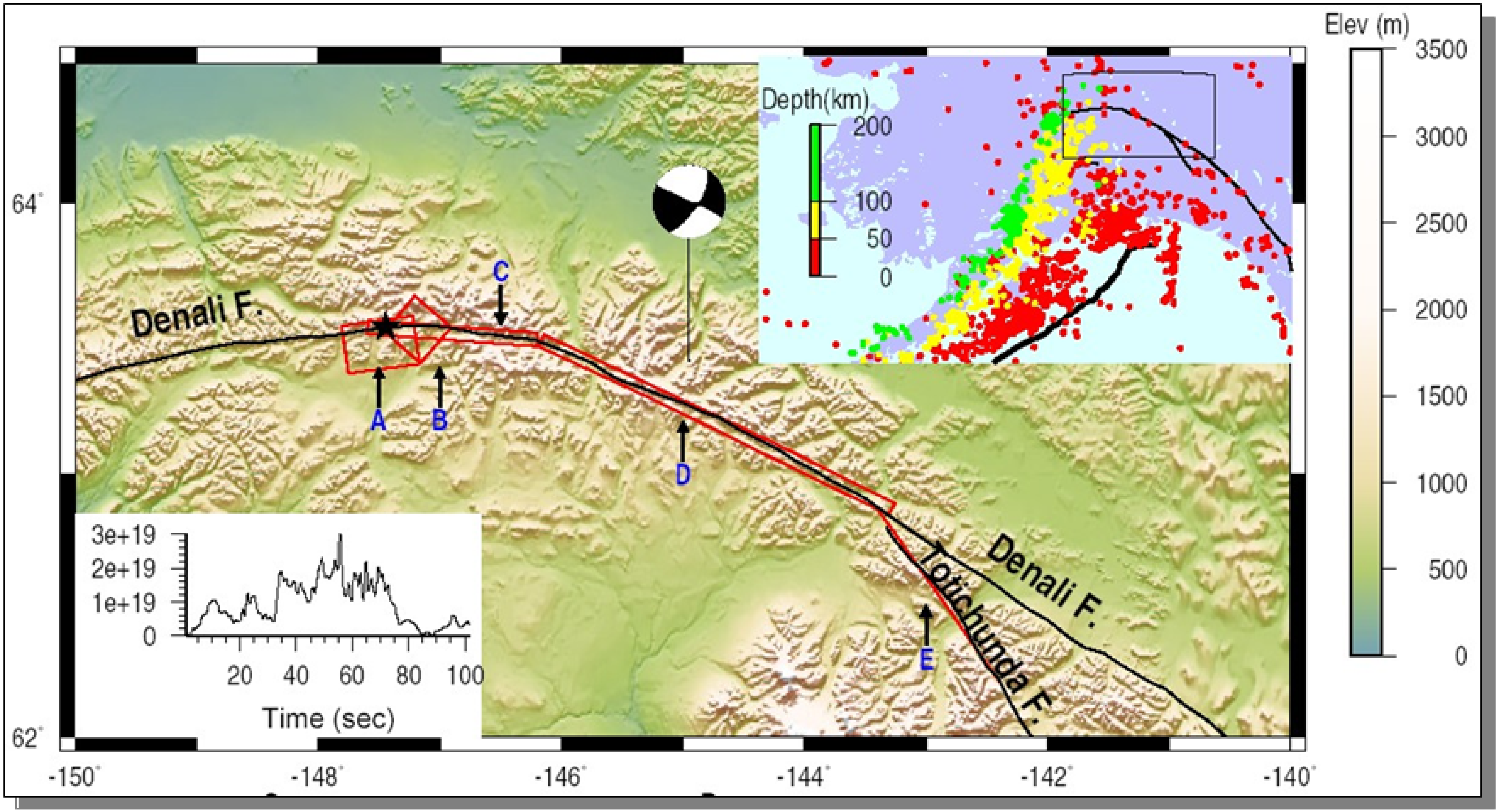
Global wave propagation

(Komatitsch and Tromp)

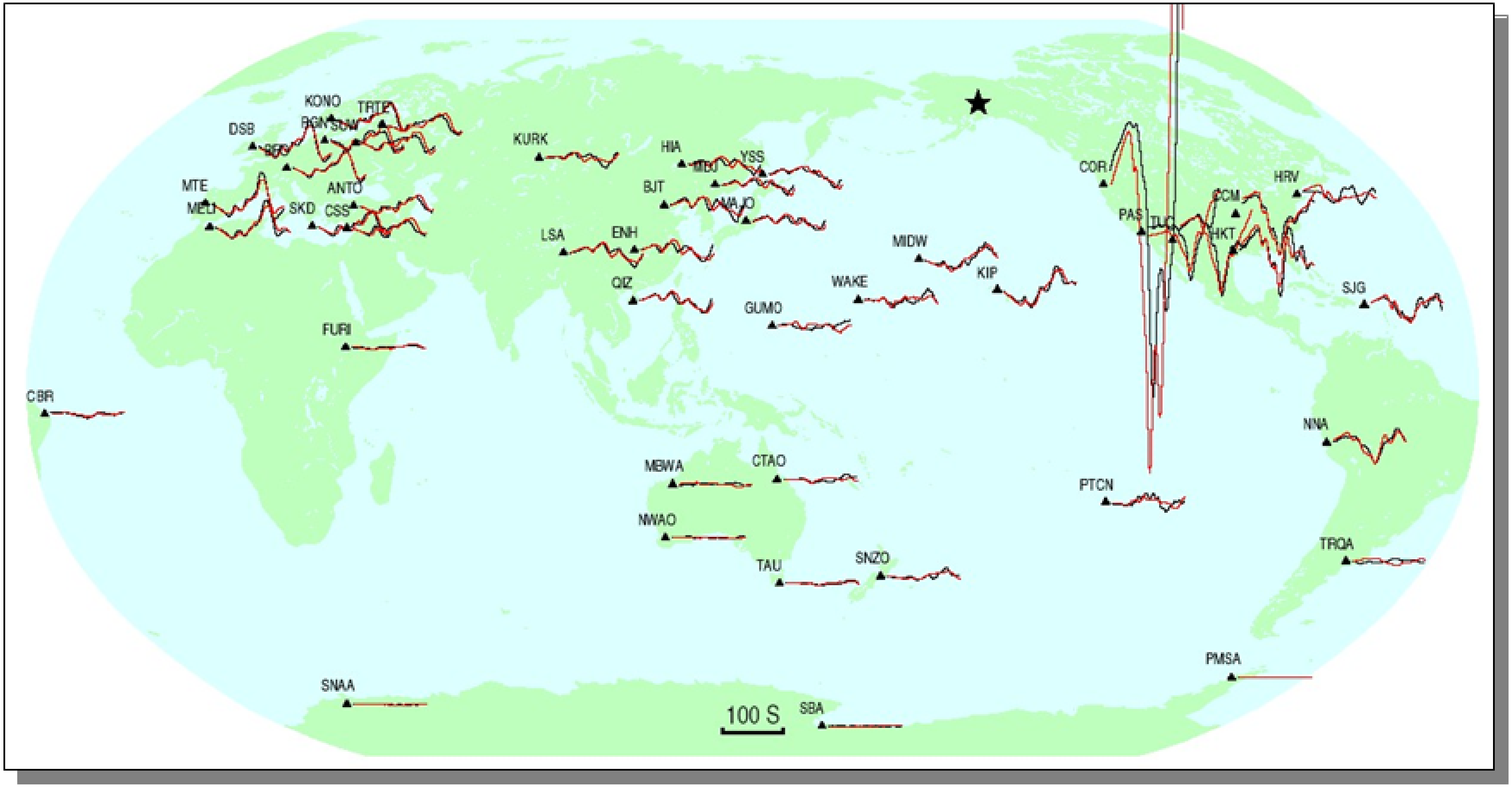
Cubed Sphere



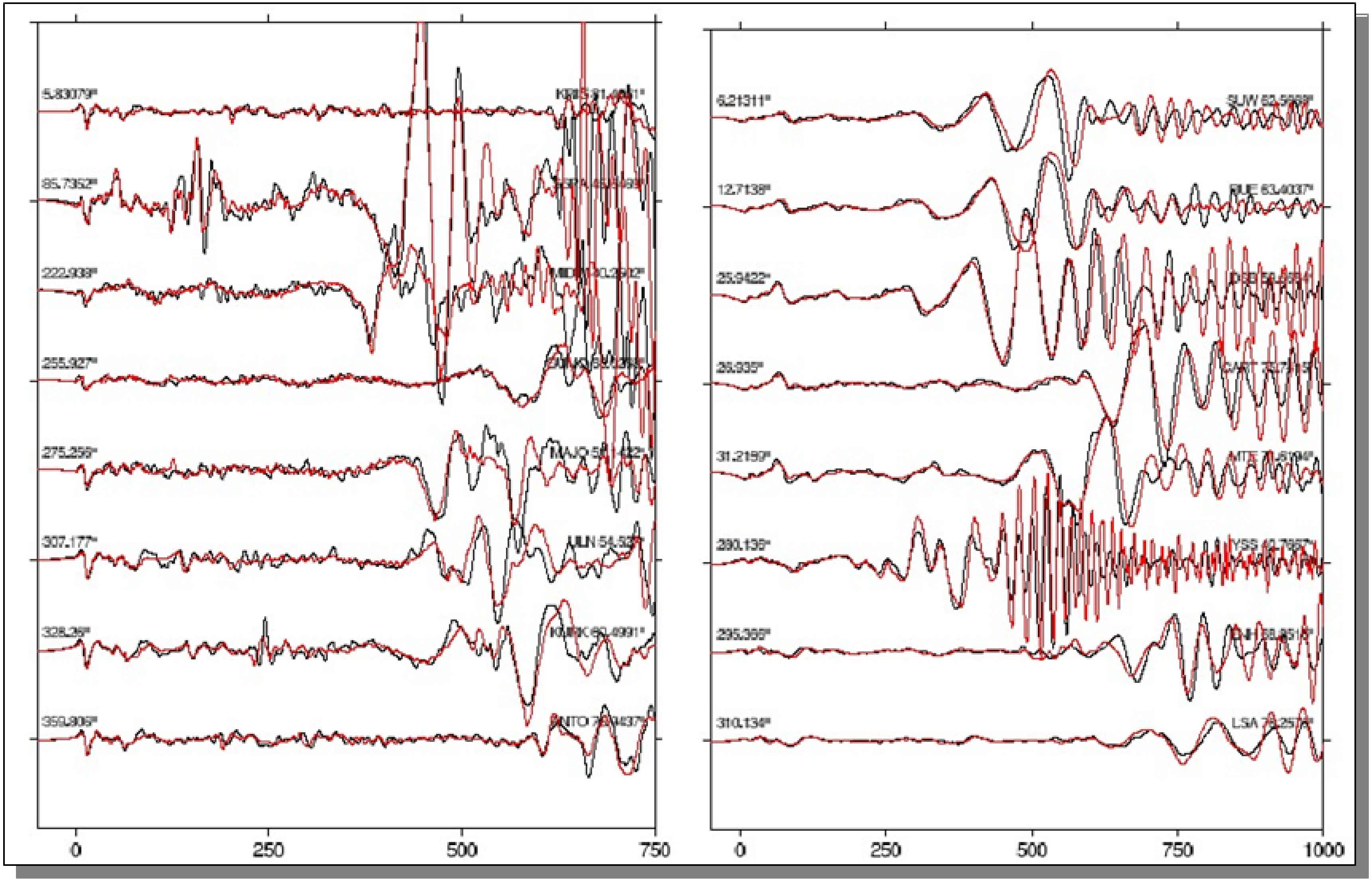
Alaska, Denali, M 7.9, 2002



Observations - Synthetics



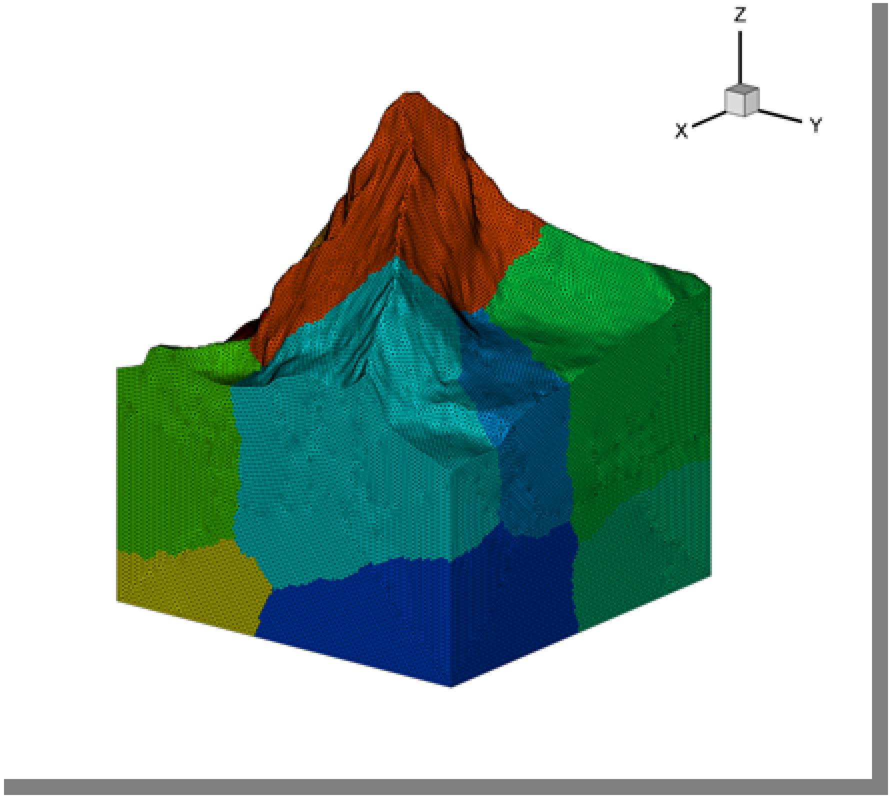
Observations - Synthetics

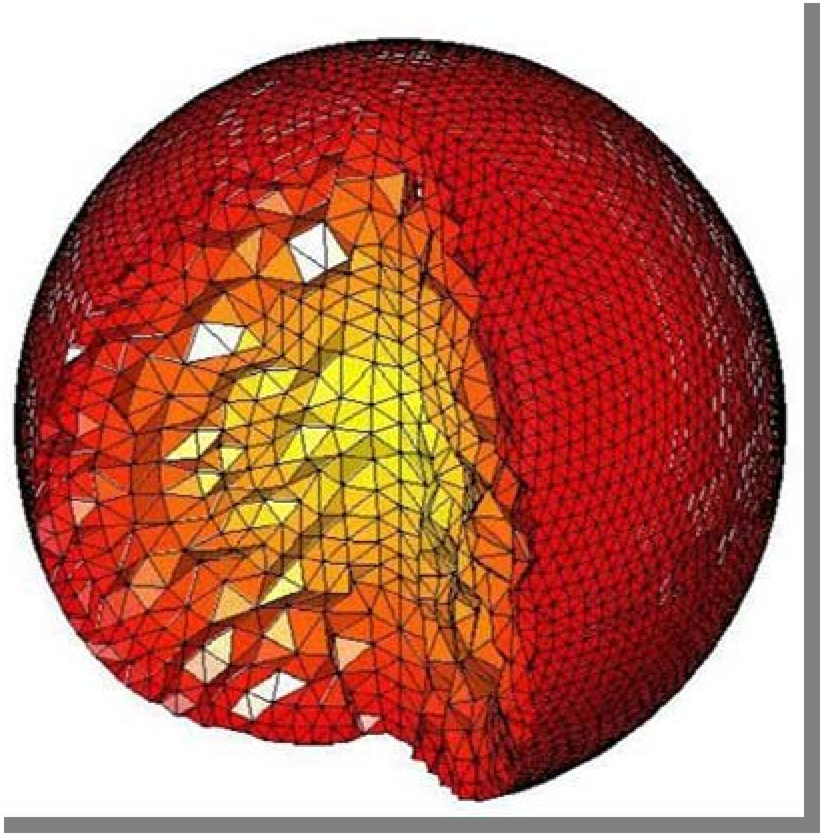


Discontinuous Galerkin

Why (the hell) do we need another method?

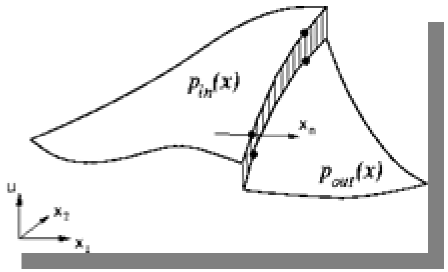
Waves on unstructured grids? *tetrahedral*

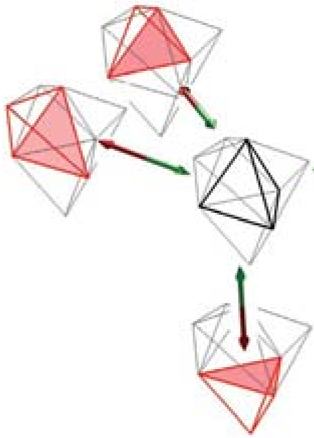




Arbirtrarily high-orDER - Discontinuous Galerkin

- Combination of a **discontinuous Galerkin method** with ADER time integration
- Piecewise polynomial approximation combined with fluxes across elements (**finite volumes**)
- **Time integration as accurate as spatial approximation**, applicable also to strongly irregular meshes (not so usually for FD, FE, SE)
- Method developed in **aero-acoustics** and **computational fluid dynamics**
- The scheme is entirely local, no large matrix inversion -> **efficient parallelization**
- **Drawback**: Algorithms on tetrahedral grids **slower** than spectral element schemes on hexahedra

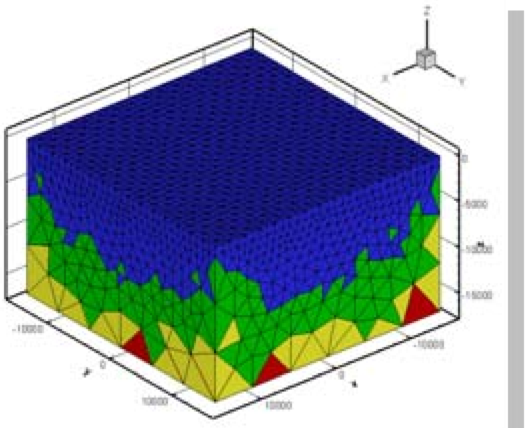




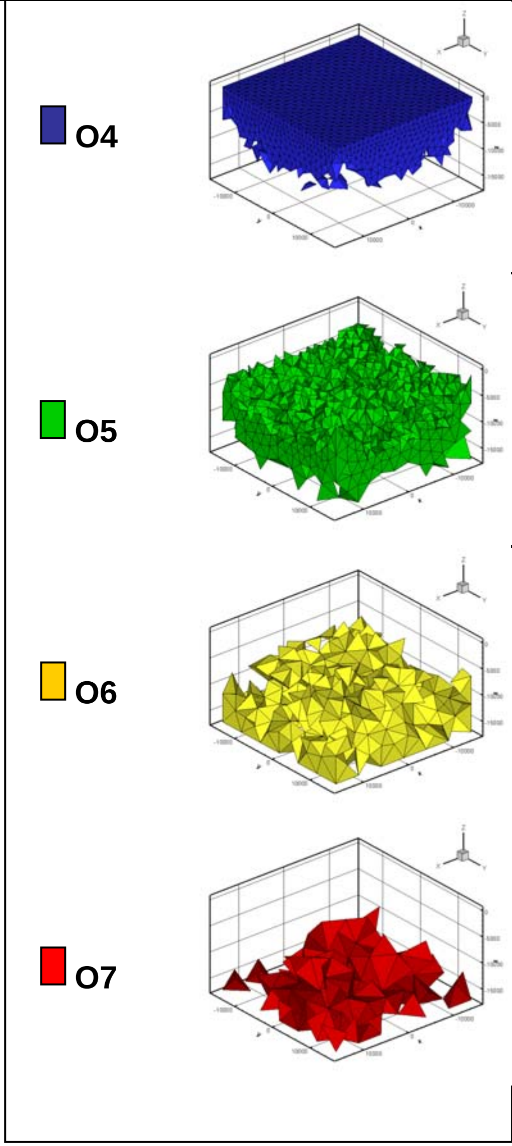
Several articles in Geophys. J. Int., Geophysics, a.o. by Käser, Dumbser, de la Puente, and co-workers

P - adaptivity

- Use high precision (i.e., high-order polynomials) only where necessary
- High precision where cells are large (high velocities)
- Low precision where cells are small (because of structural heterogeneities)



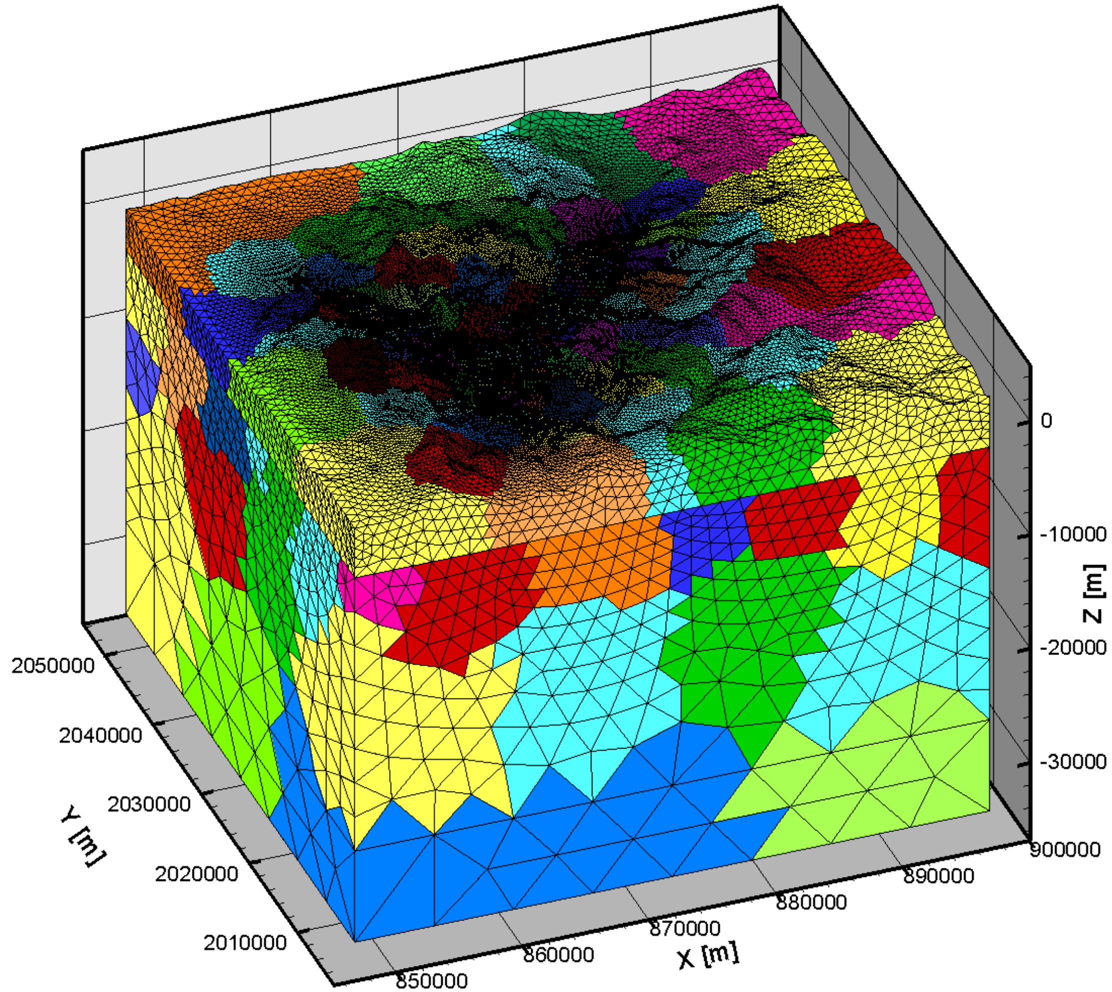
Dumbser, Käser and Toro, GJI, 2007



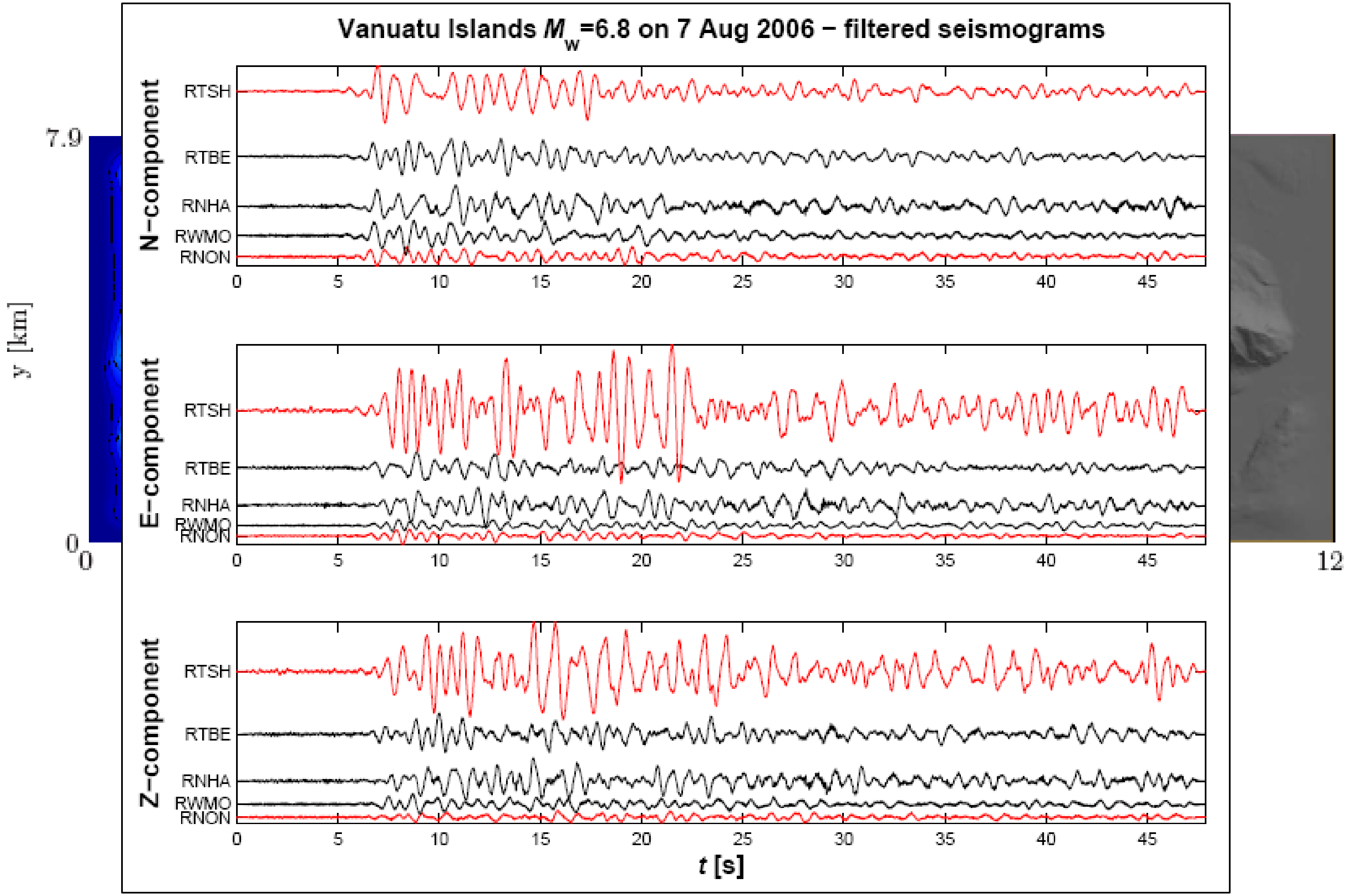
Käser et al. (2006)

Mesh Partitioning and Parallel Computing
the problem of load blancing

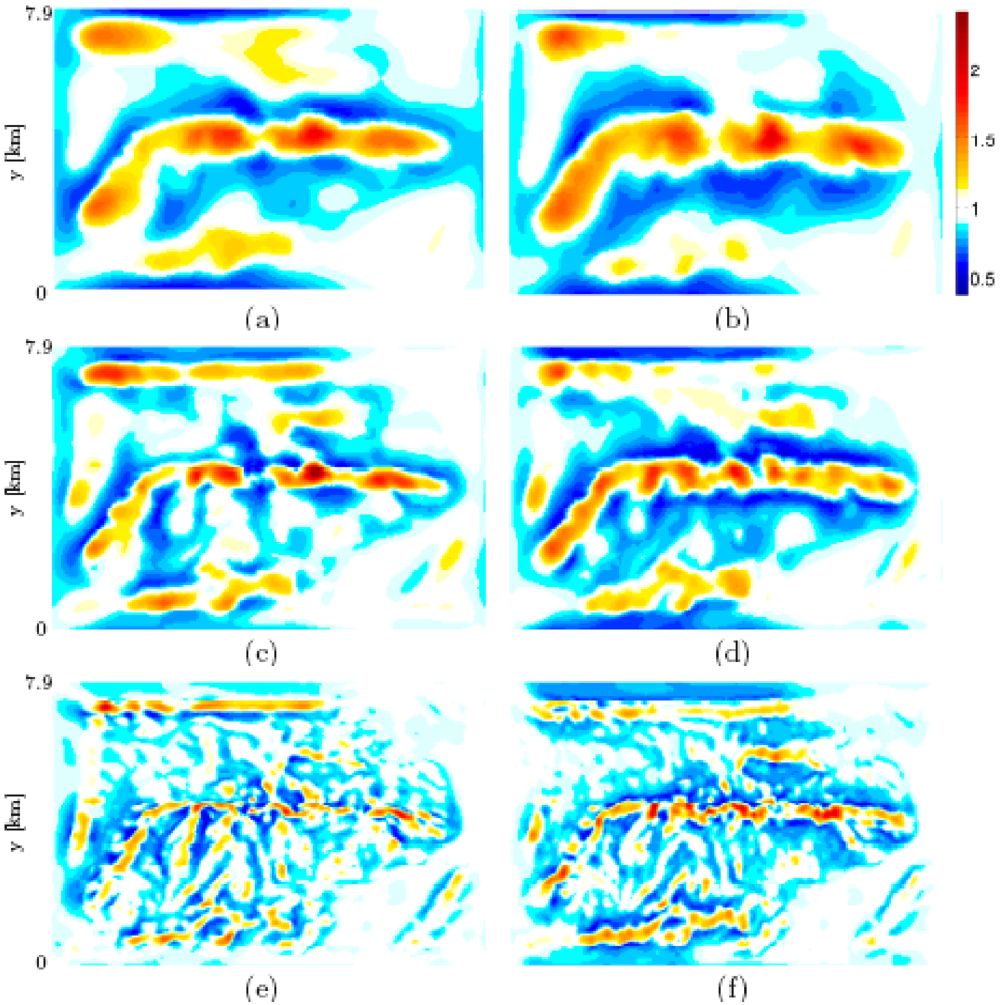
Same color means same processor

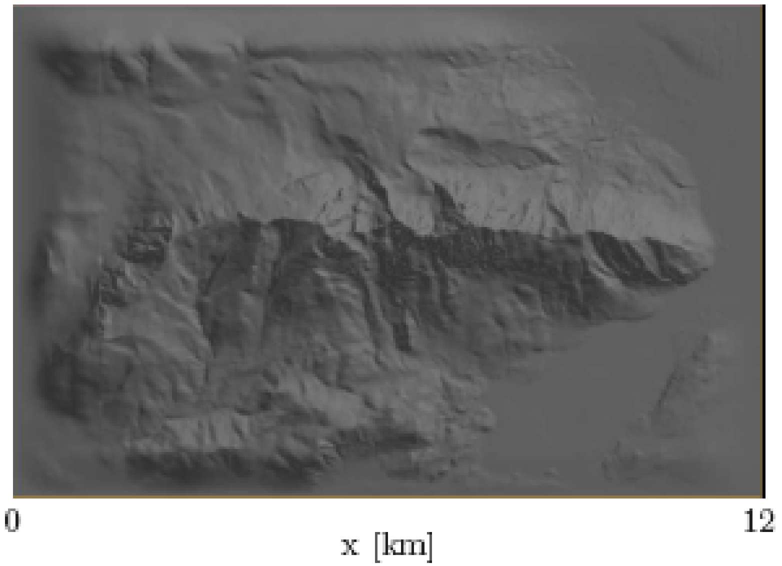


Topographic effects

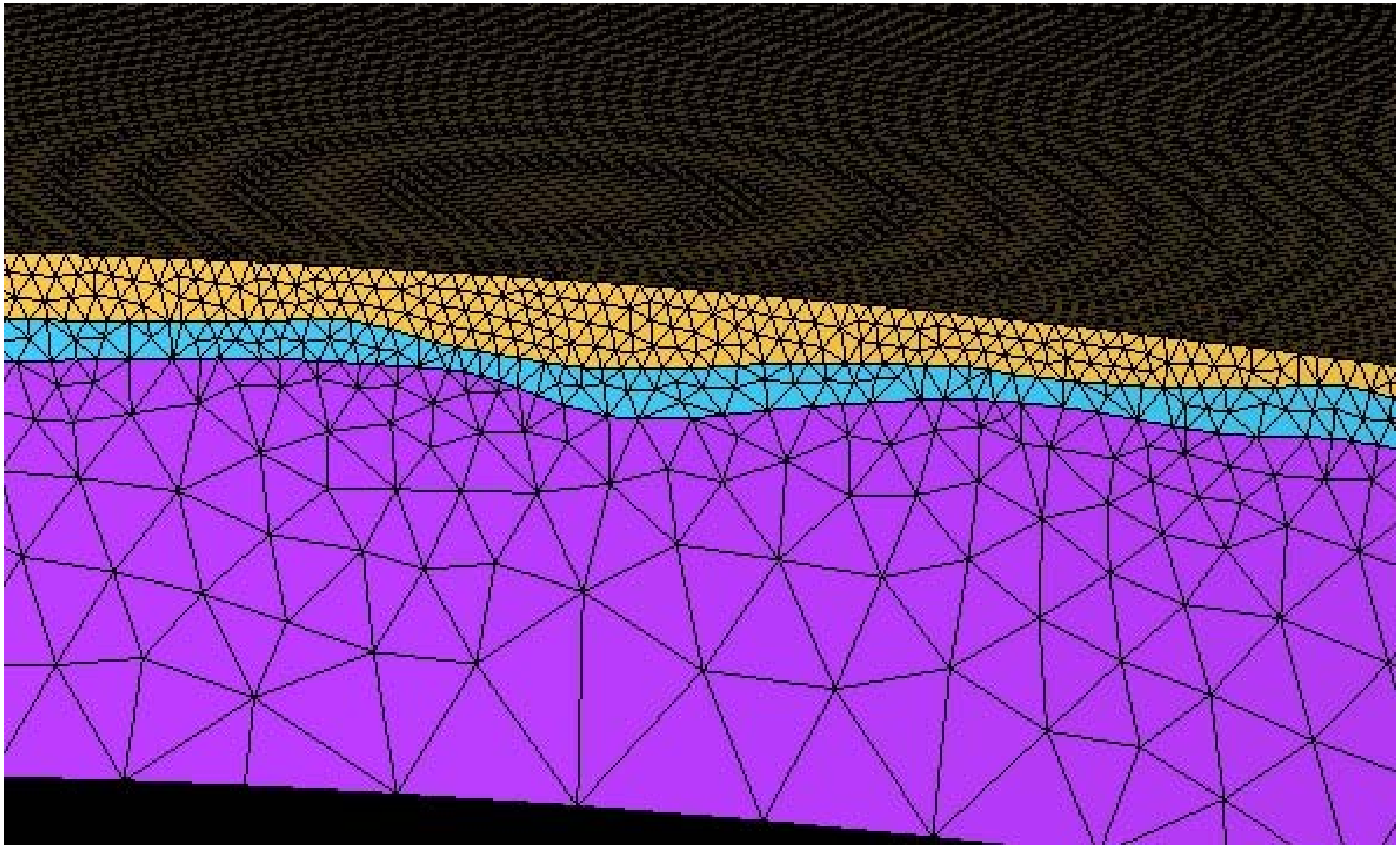


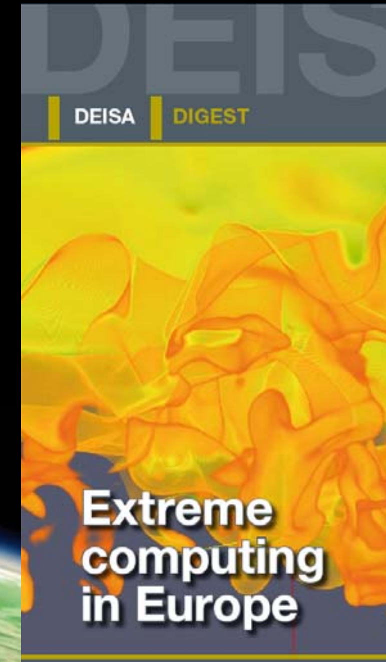
Topographic Effects





Regional and Global Wave Propagation
crust, crust, crust!





Earthquake scenarios for Europe

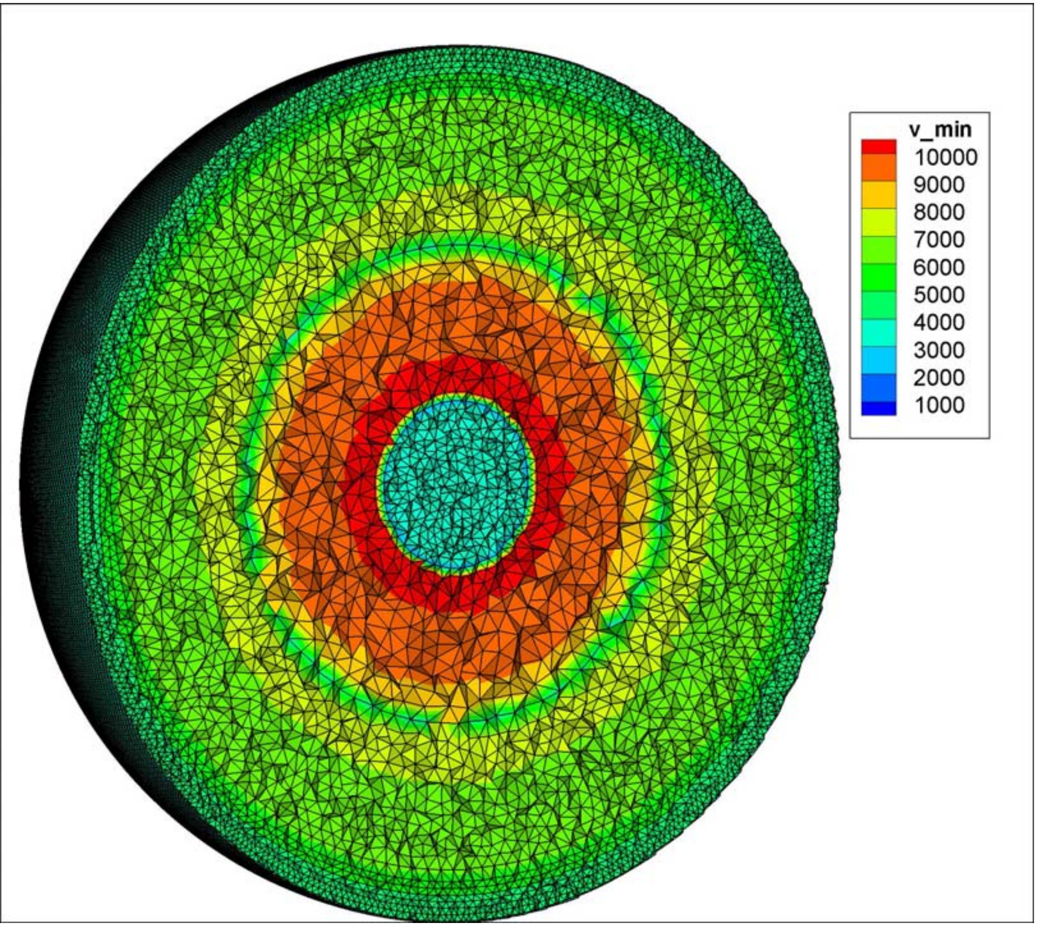
Sanna Pyysalo

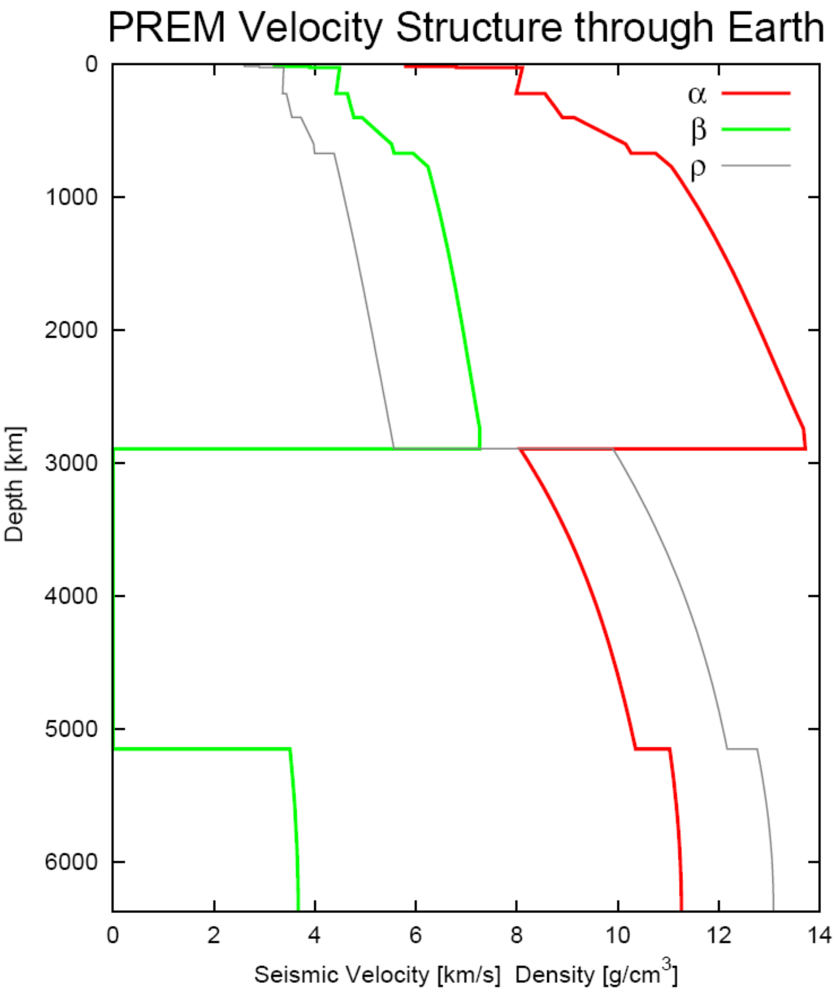
Seismic hazards and ground motion amplitudes will be better estimated in the future thanks to the EuQuake project. Its research results were achieved using supercomputing resources offered by DEISA. The project started in June 2008 and ended in August 2009.

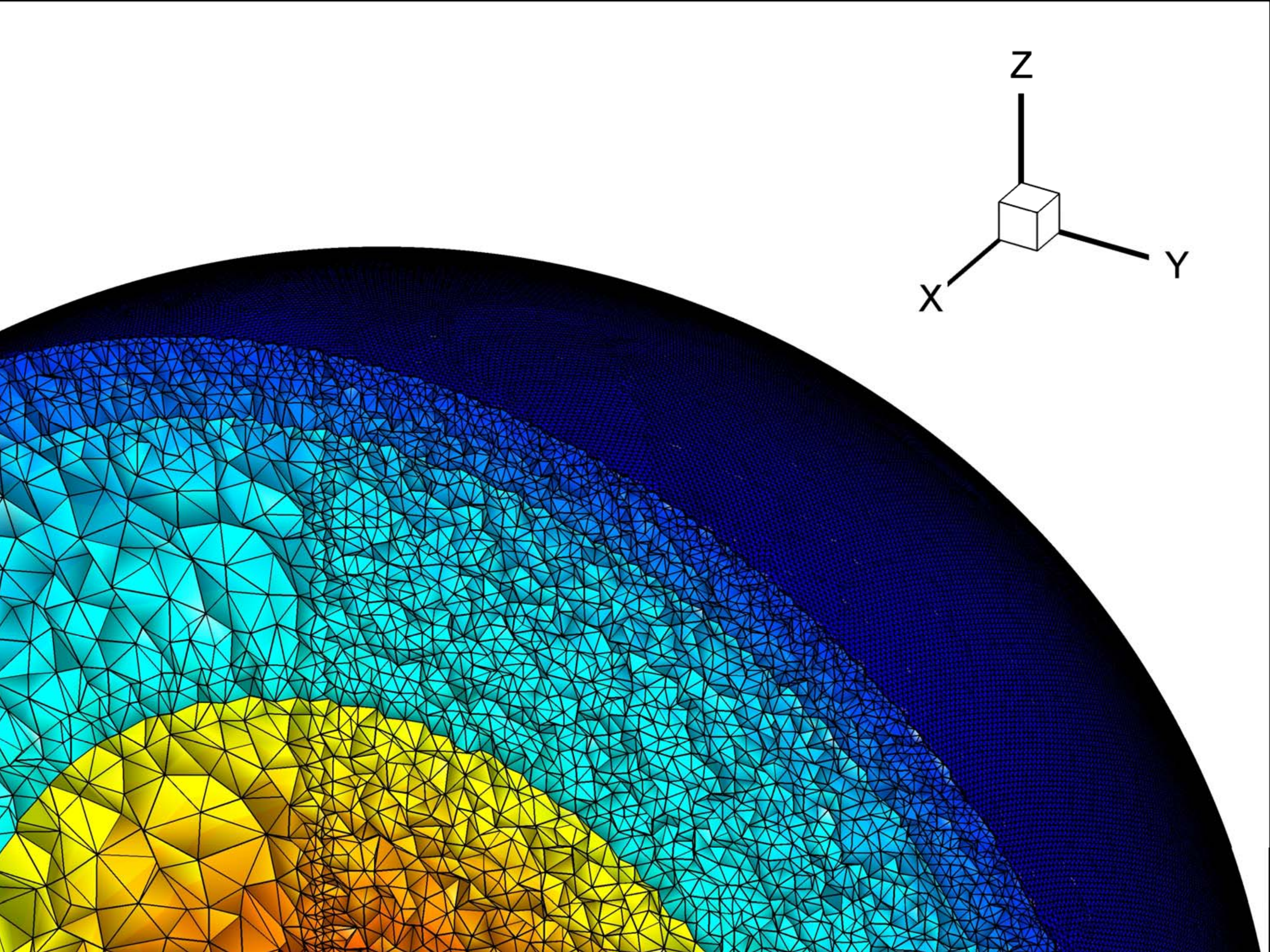
Global wave propagation

… keeping the number of points per wavelength constant …

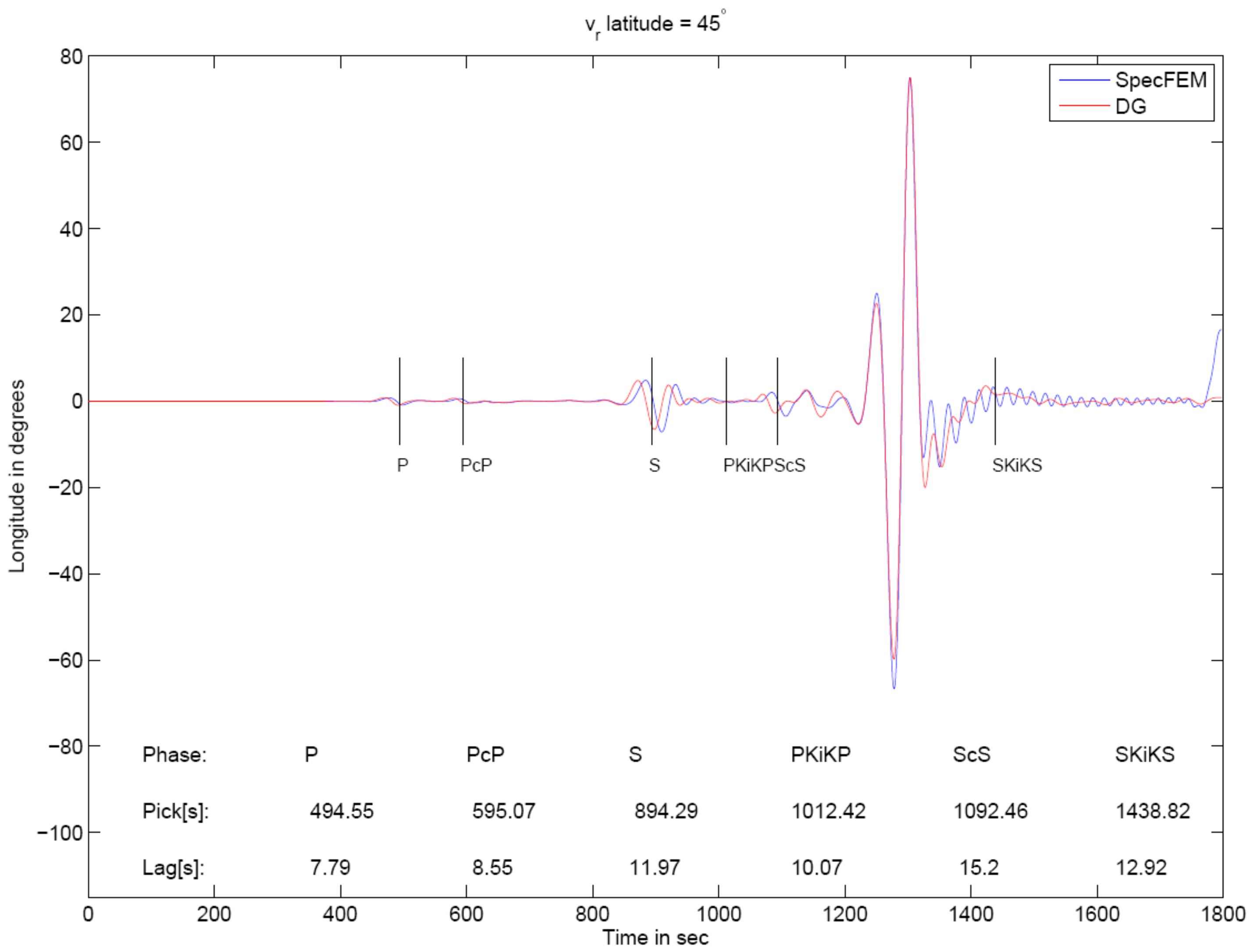
Minimum occurring wave speed



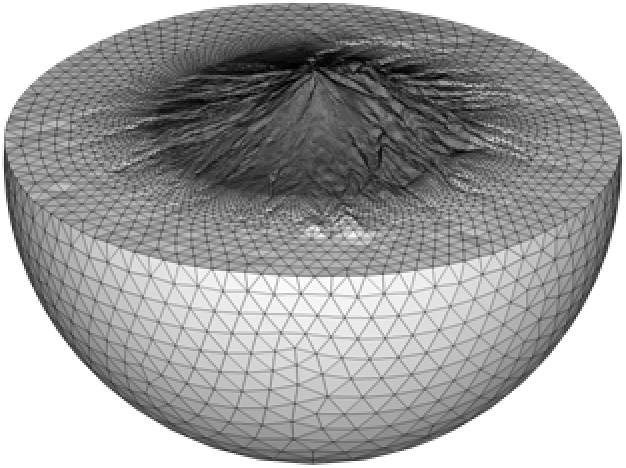


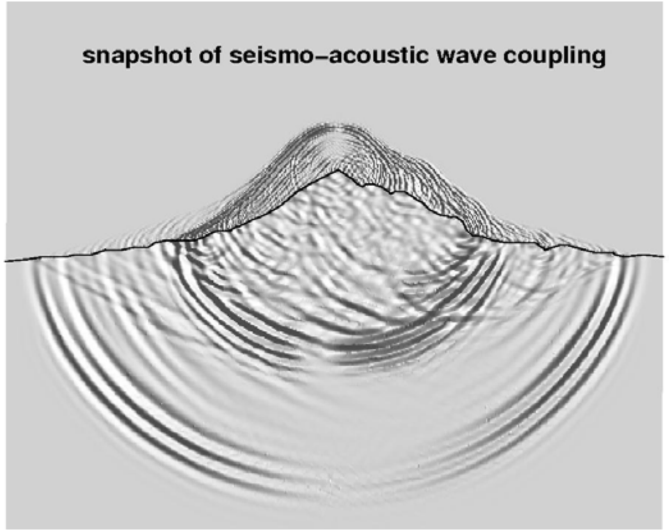

Z
Y
X

Benchmarking DG vs. SE

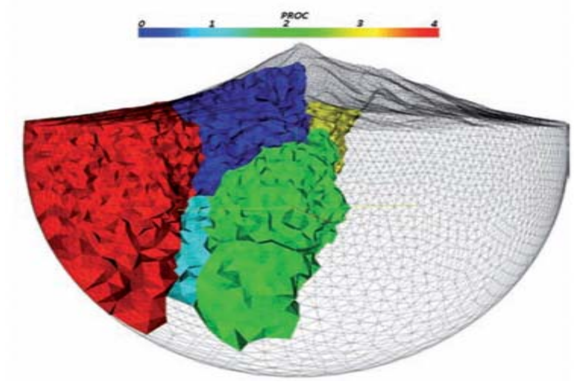


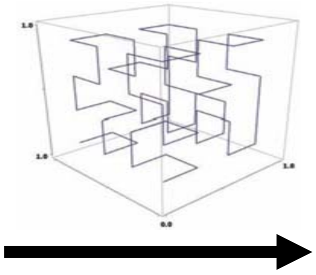
The sound of volcanoes

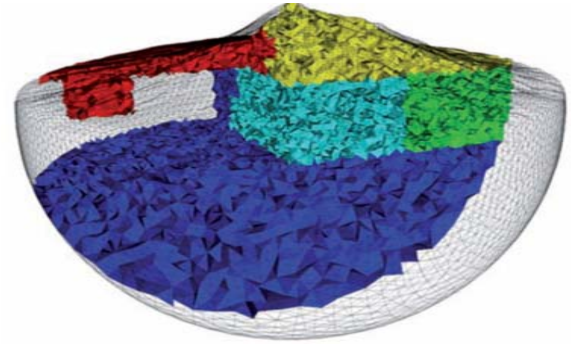




Eruption, 15. Juni, 2006

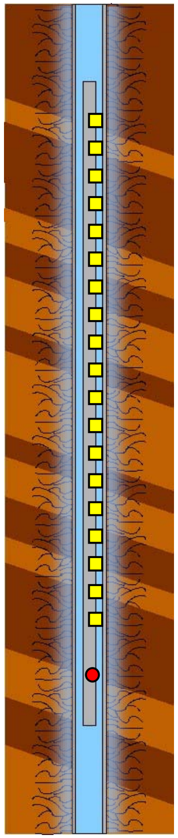


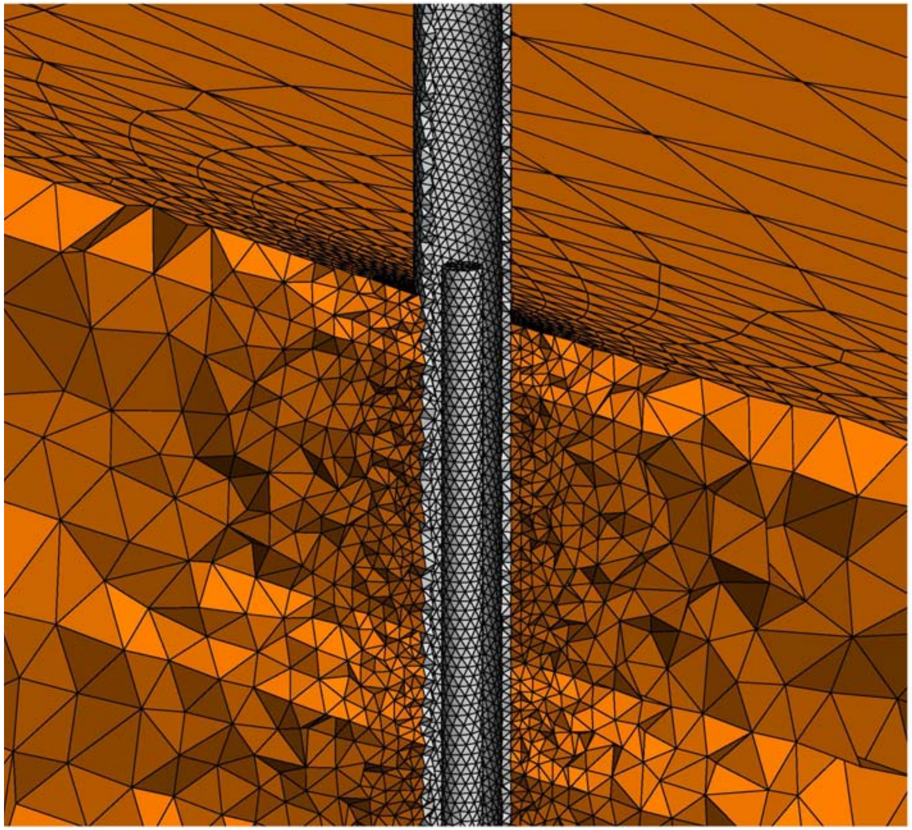


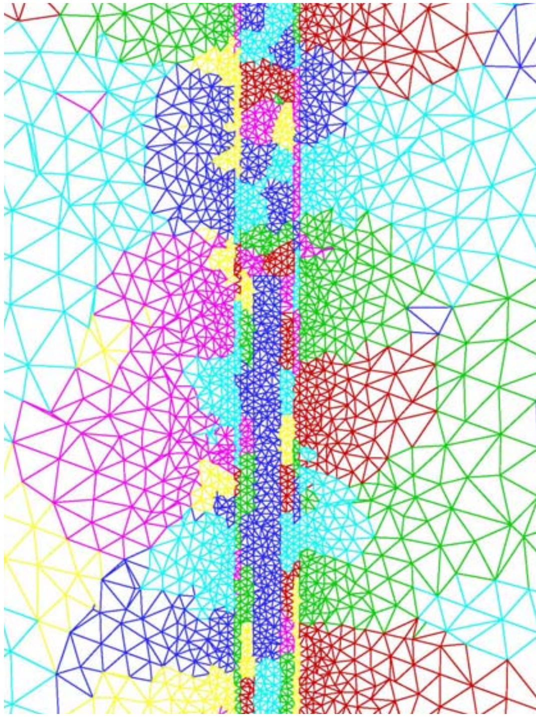


Reservoir applications

(Schlumberger Doll Rese







task: model also steel casing!

Summary

- Computational 3-D wave propagation finds is now applications in almost all fields of Earth sciences
- There is not ONE method that works best for all problems
- Making codes work on large computers will be more and more a challenge
- The most promising methods for the coming years seems FD (still), SE, and DG