Current challenges in seismology

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- Wave propagation: from lab to planetary scale

- Scientific challenges in seismology and the role of numerical simulations

  I   Volcano seismology
  II   Sources of seismic energy: Rupture processes
  III Earthquake scenarios: Ground motion after large earthquakes
  IV Global wave propagation: Earthquakes and the structure of the Earth's interior

- Outlook

With contributions by Michael Ewald, Gilbert Brietzke, Markus Treml, Michael Thorne, Gunnar Jahnke, Johannes Ripperger

Wave propagation on all scales

0.1m

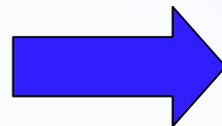- Lab scale, elastic properties, fracturing, porosity, anisotropy

10km

- Volcano seismology, reservoir modelling and inversion, marine seismics
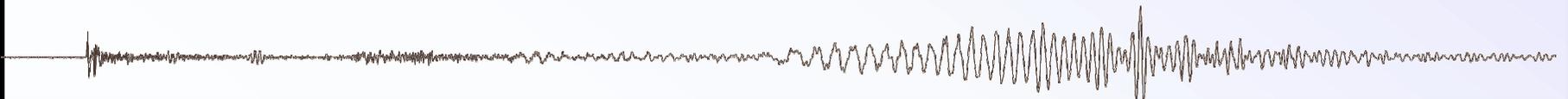
100-1000km

- Dynamic rupture propagation, earthquake scenario simulations

>1000km

- Continental and planetary scale, global wave propagation, deep earth imaging

Progress in those fields depends on advances in accurate calculations of wave propagation in heterogeneous 3D media

Theory vs. observations

- There is a wide gap between theoretical/numerical and observational seismology

- Computational power is now such that 3D numerical approaches to wave propagation could enter routine data fitting procedures (e.g. source or structural imaging) or monitoring

- The scientific value of 3D simulation data is continuously increasing (e.g. earthquake scenario simulations, global wave propagation)
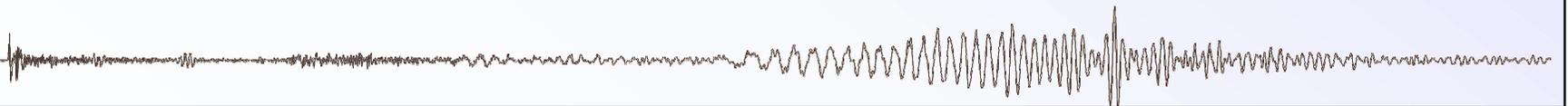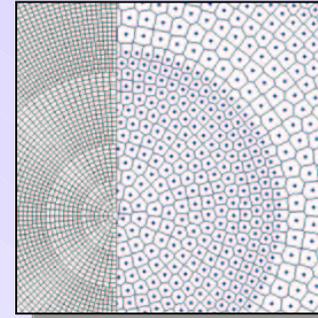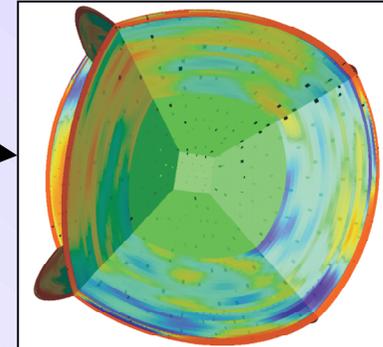
Numerical simulation of seismic wave propagation

Elastic wave equations

$$\rho \partial_t^2 u_i = \partial_j (\sigma_{ij} + M_{ij}) + f_i$$

$$\sigma_{ij} = c_{ijkl} \varepsilon_{kl}$$

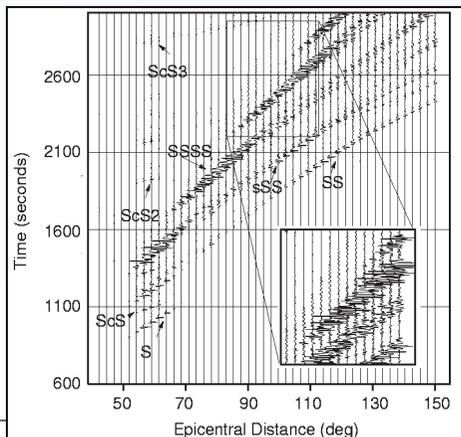$$\varepsilon_{kl} = 1/2(\partial_k u_l + \partial_l u_k)$$
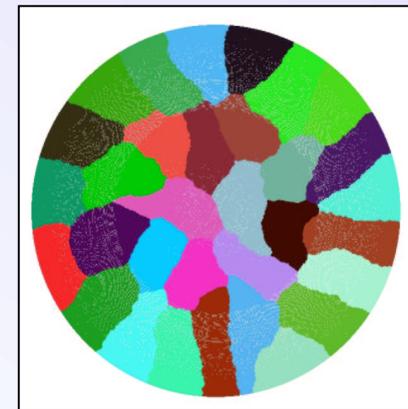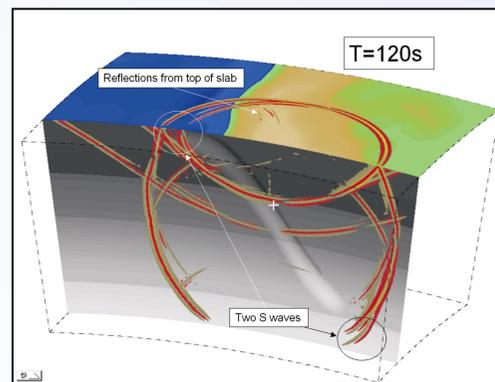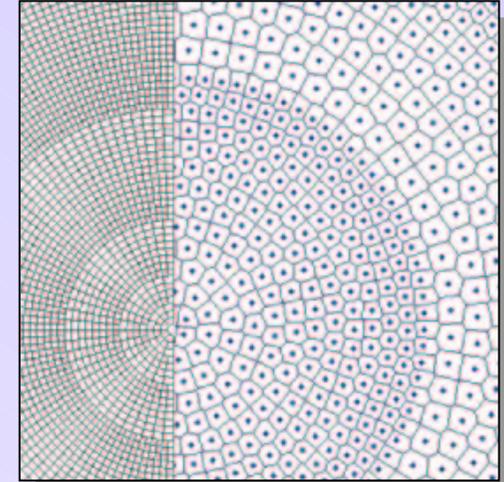
Grid

3D Model

Parallelisation

Synthetic seismograms

Simulation

Numerical methods

- Finite Differences (high order, *optimal* operators)

- Pseudospectral methods (Chebyshev)

- Unstructured grids (finite volumes, *natural neighbours*)

- Finite/spectral elements

- Parallelization using MPI (message passing interface)

-> for rupture problems special internal boundary conditions apply
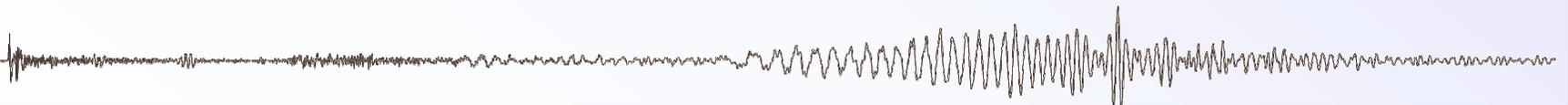
Typical model sizes
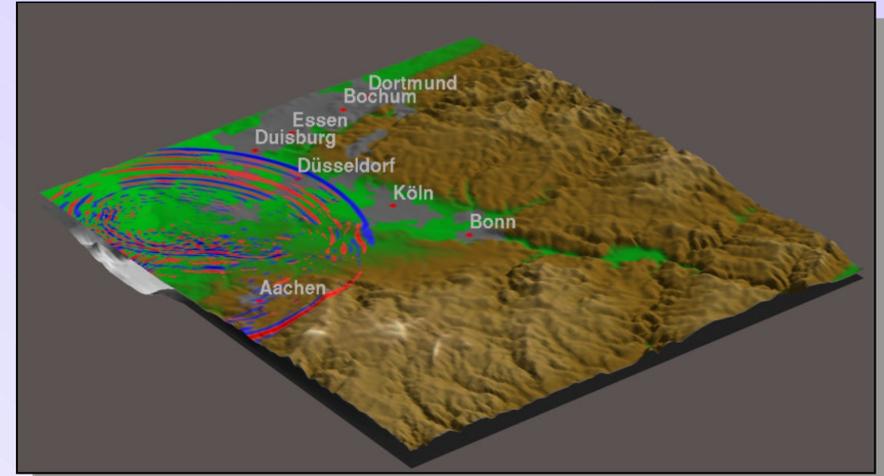
SIMULATION PARAMETERS	
Spatial discretization (km)	0.2
Temporal discretization (sec)	0.0198
Lowest S-wave velocity (km/sec)	1.4
Grid size (physical model)	$700 \times 800 \times 150 = 84 \cdot 10^6$
Grid size (computational model)	$800 \times 900 \times 200 = 144 \cdot 10^6$
Number of time steps	3034
Simulation time (sec)	60
Memory usage (GB)	24.0
Computation time (hours)	12

We simulate on Hitachi SR8000, LRZ- München, 1.5 TB RAM
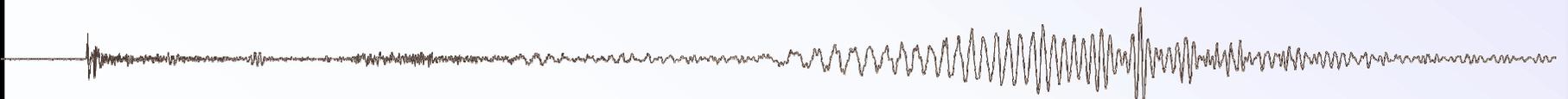
I - Volcano seismology

Scientific questions:
- What processes control eruptions?
- What are the sources of seismic energy?
- Can we estimate the inside structure of volcanoes?
- Can seismic observations help predict eruptions?

Disciplines:
- seismology – petrology - mineralogy – meteorology – material science – geology – physics – geochemistry
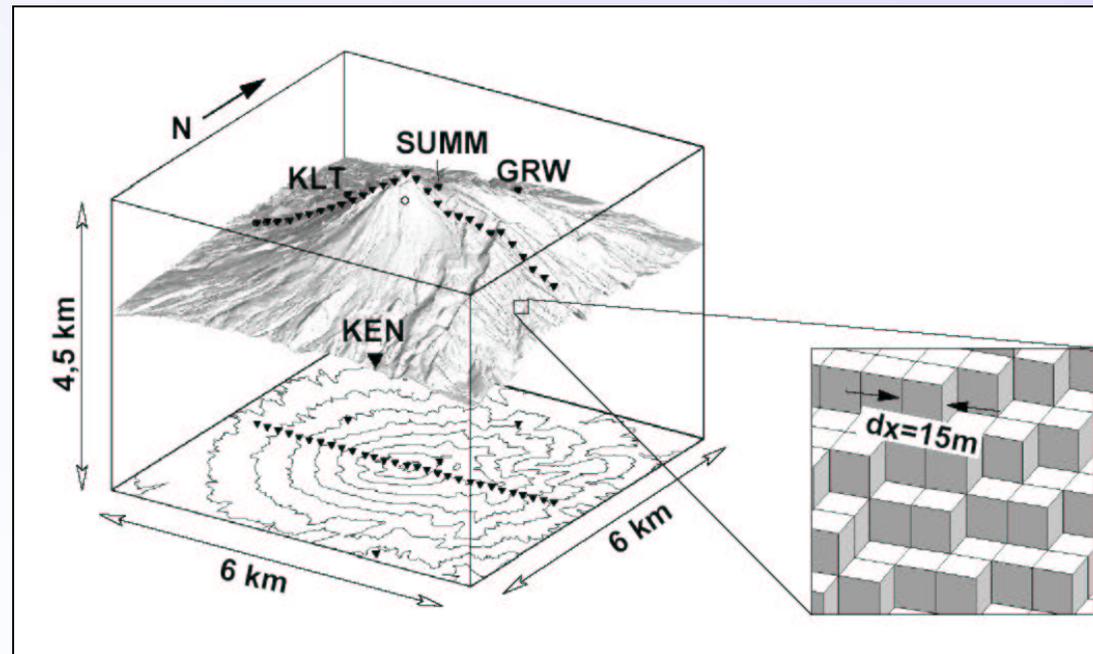
Supercomputing:
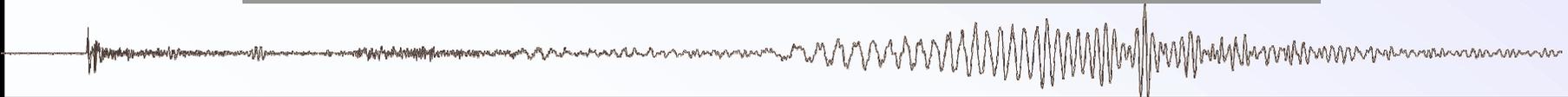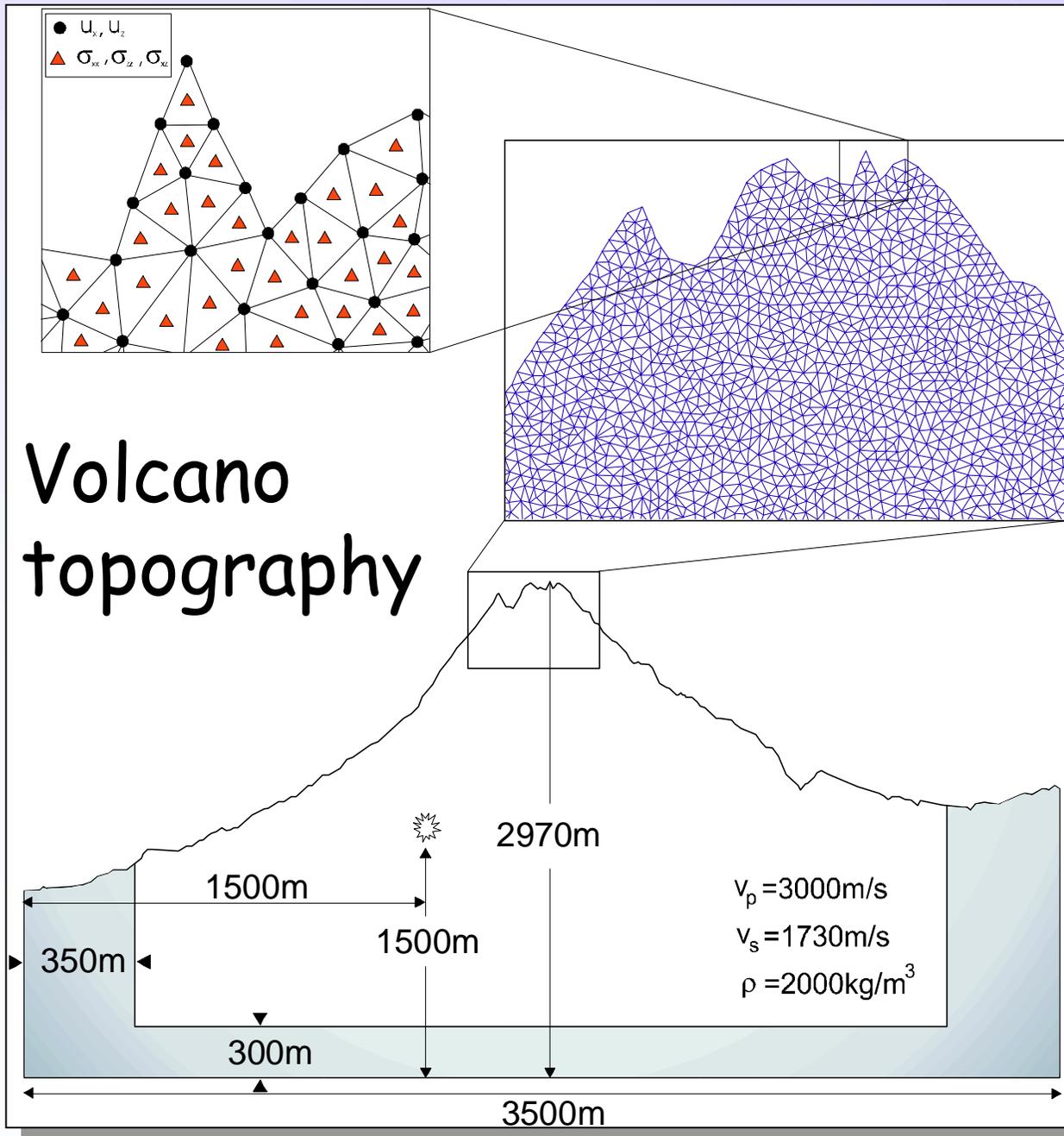- 3D wave propagation, topography, scattering, source processes, tomography

Merapi, Java   SIR-C/X-SAR Image (P-45750)
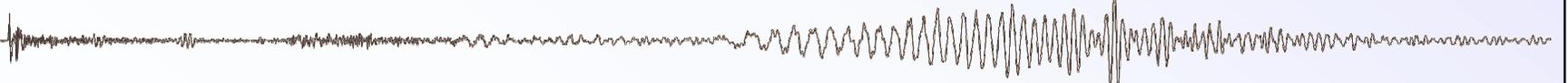
Volcano seismology
technical challenges

- Modelling free surfaces with very strong topography
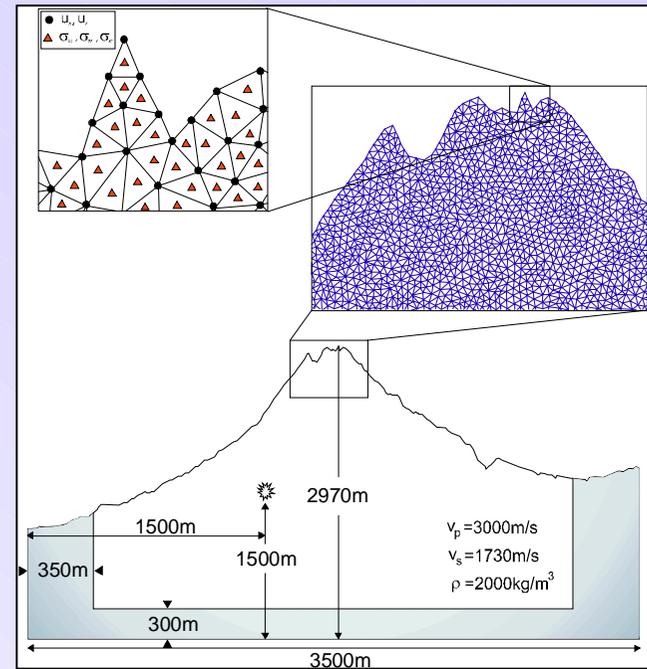- Highly heterogeneous structures
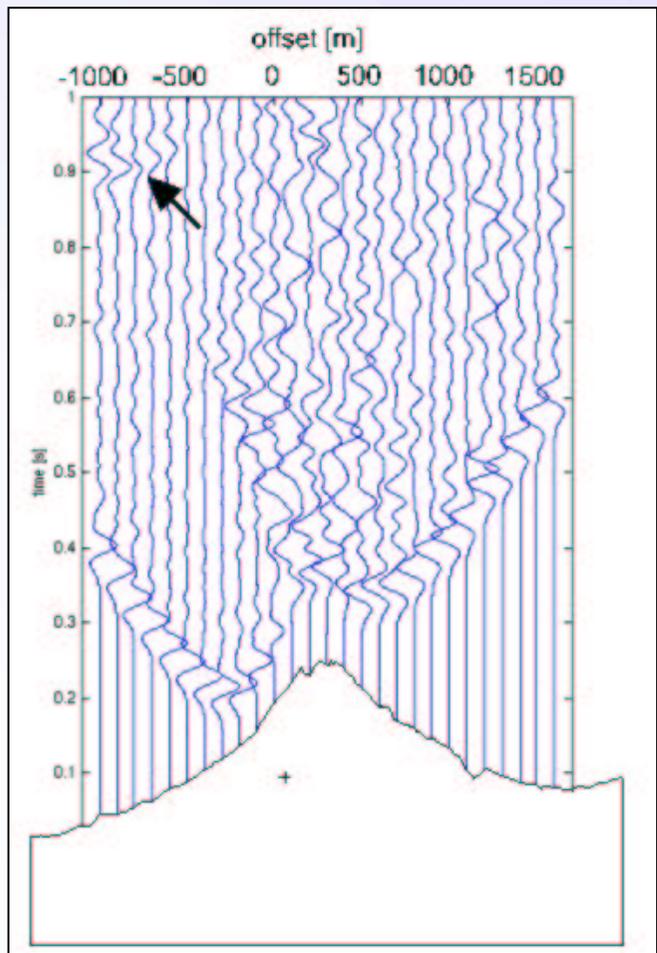- Complex source processes
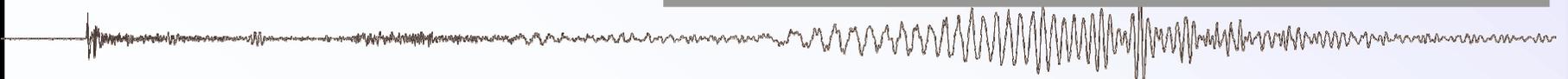- Surface sources (pyroclastic flows)

Ripperger, Igel, Wassermann, 2004

Volcano topography

Legend:
- ● u_x, u_z
- ▲ σ_{xx}, σ_{zz}, σ_{xz}

2970m

1500m

1500m

350m

300m

3500m

$v_p = 3000\text{m/s}$

$v_s = 1730\text{m/s}$

$\rho = 2000\text{kg/m}^3$

Volcano topography
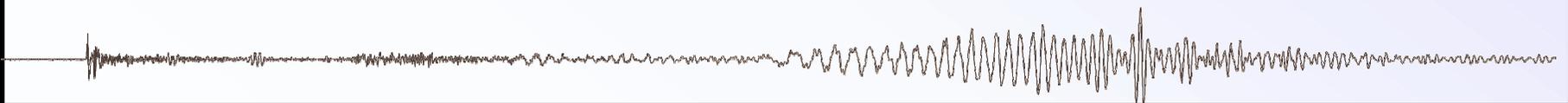
Volcano seismology

Topographic vs. internal scattering
Dome growth – summit sources
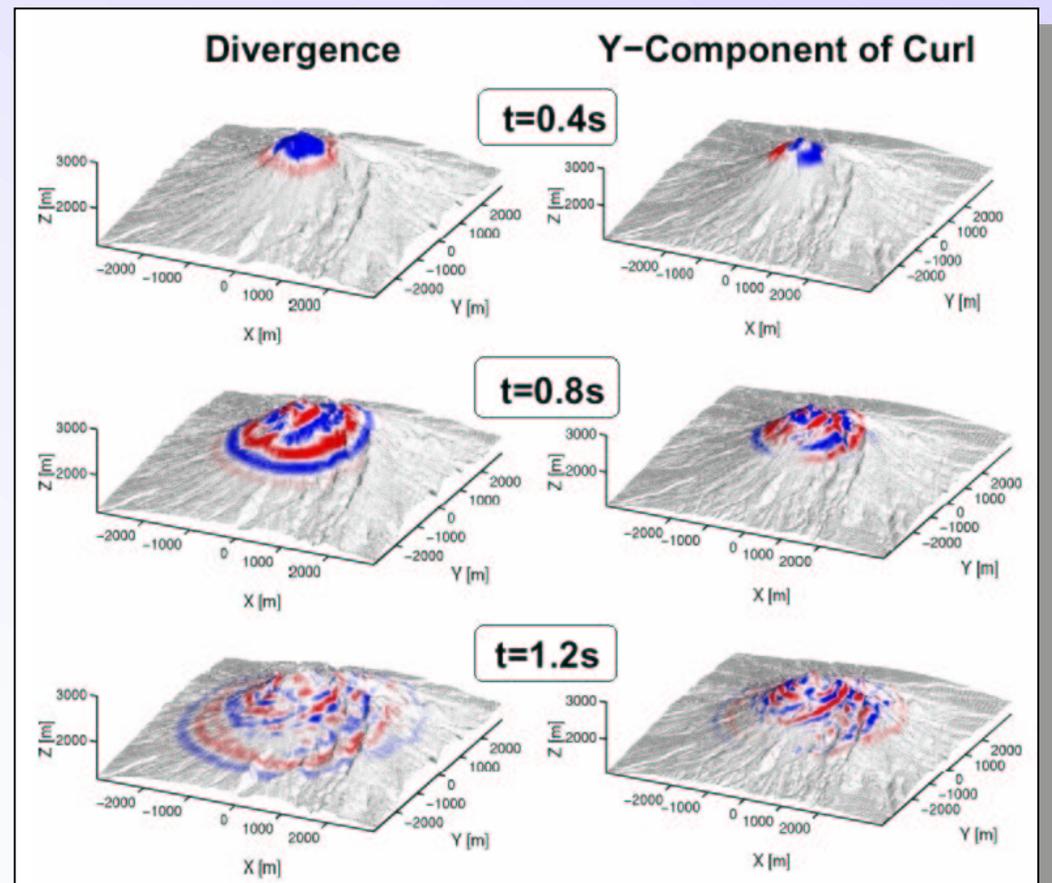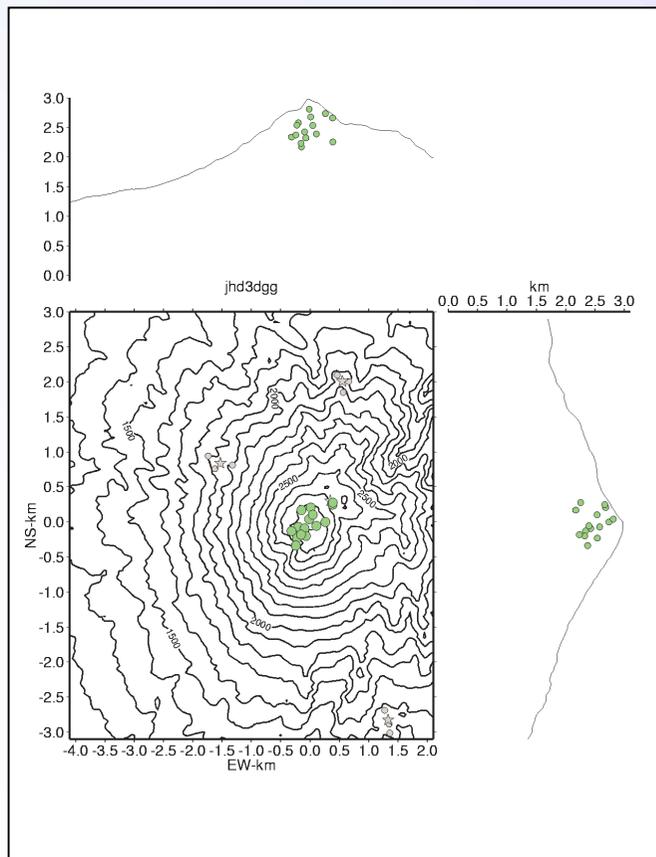
Volcano seismology
particle motion

Neglecting topography leads to errors in the imaging of source properties (moments, type, depth, etc.)
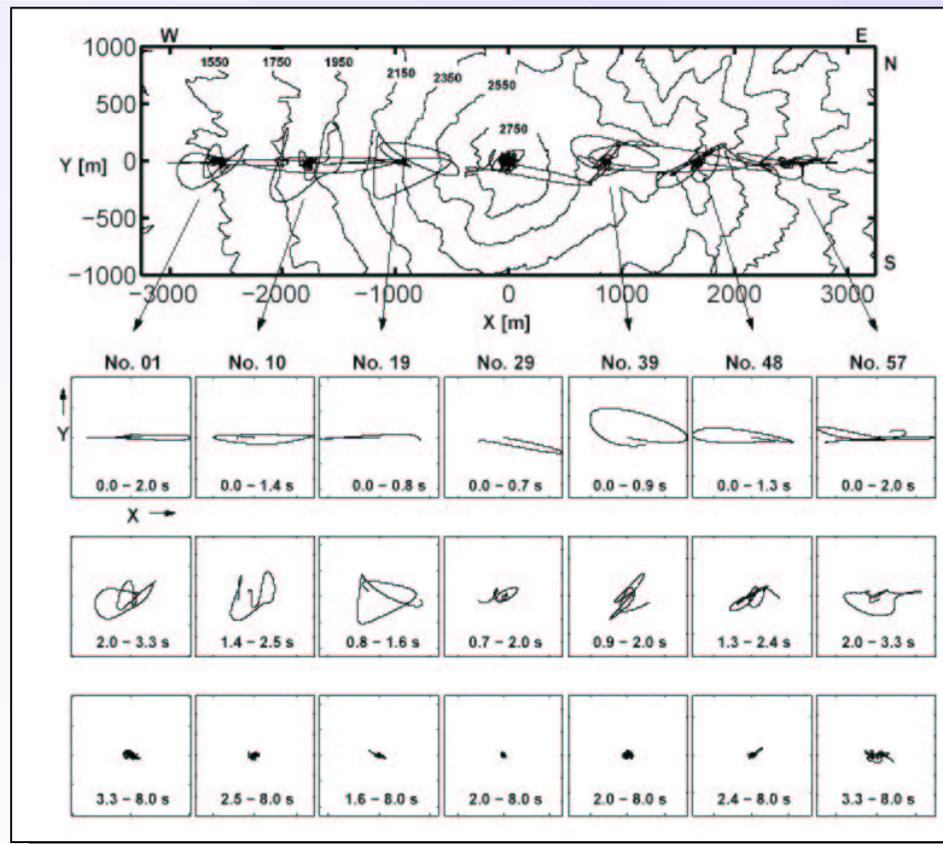
Summary
II – Volcano seismology

- Observations of seismic waves is an important part of a volcano monitoring system

- Volcanoes are a seismologist's nightmare (strongly heterogeneous media, strong topography) ...

- We are only beginning to be able to model waves through realistic volcano structures

- The ultimate goal is to understand the observed seismograms in terms of (time-dependent) processes happening in the magma chambers

II – Earthquake rupture

Scientific questions:
- What processes control the seismic rupture?
- What temporal and spatial scales are relevant (seismic cycle)?
- What means (experiments/simulations) are necessary to progress the field?

Disciplines:
- seismology – mathematics – petrology – theoretical mechanics – rheology – hydrology – computational physics – statistical physics ...

Supercomputing:
- Phenomenological studies of rupture processes varying rupture criteria, 3D simulations of rupture and wave propagation

What is an earthquake?

small earthquake rupture

surface line of fault

large earthquake rupture

length, L

vertical extent of fault, W

Asperity model
(a) Heterogeneous initial stress

1 s
2 s
3 s
4 s
5 s
6 s
7 s
8 s
9 s
10 s
11 s
12 s
13 s
14 s
15 s
16 s
17 s
18 s
19 s
20 s
21 s
22 s

0   0.75 m/s
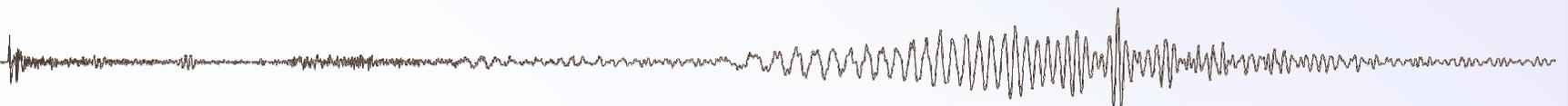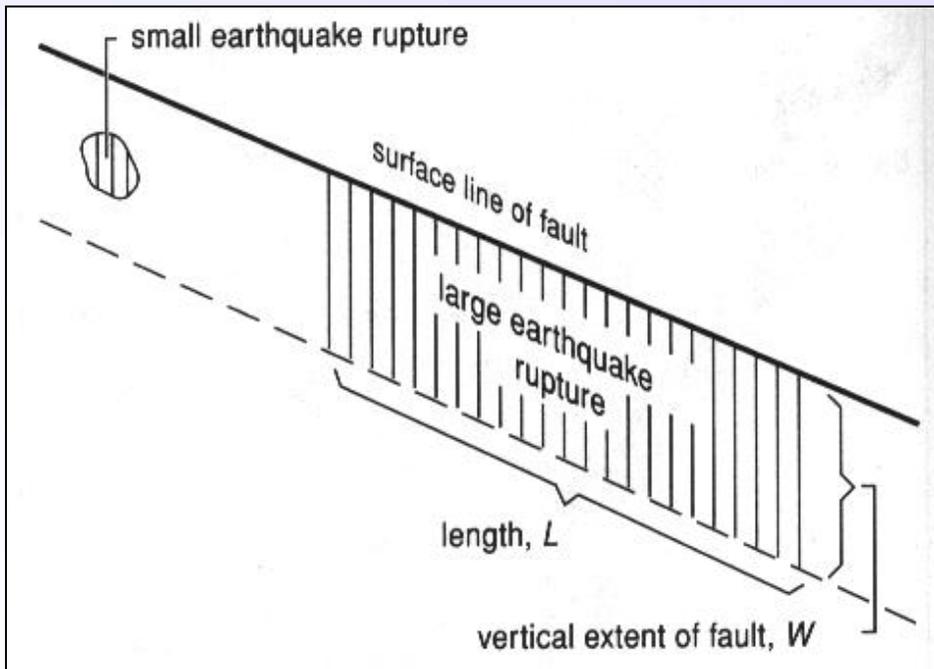
Source: K. Olsen
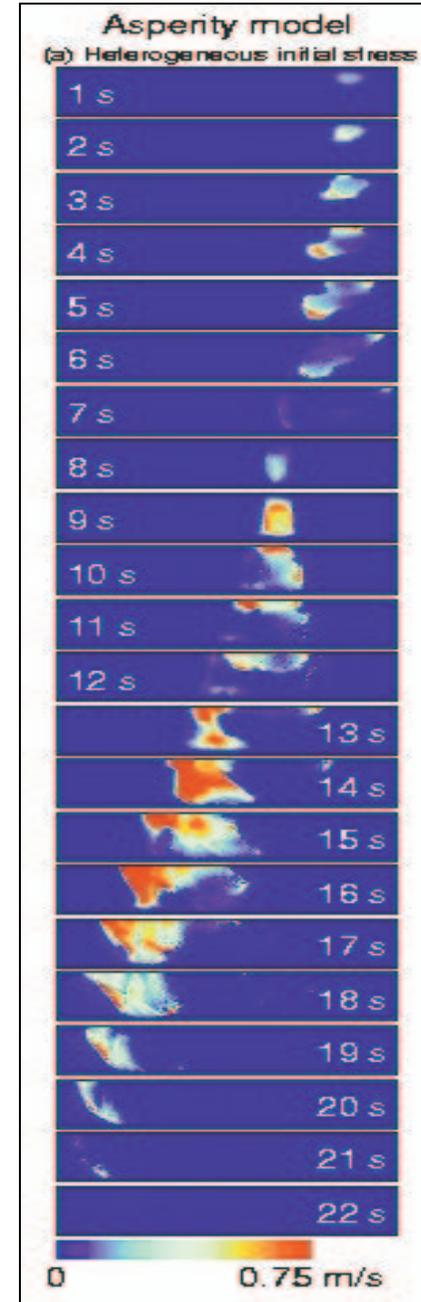
Two curious observations

- The heat-flow paradoxon
  During an earthquake an enormous amount og heat should be generated -> it's not observed.

- The theory of crack propagation says that a rupture should propagate in both directions. We observe uni-lateral rupture for 80% of the large earthquakes.

2002 Denali

Epicenter

Distance (km)
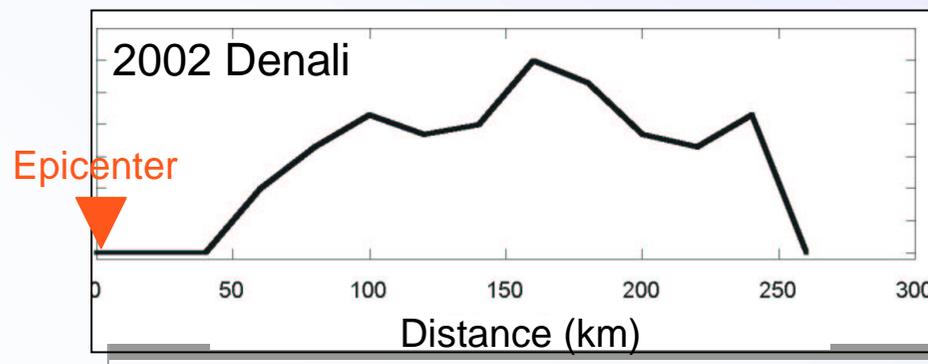
Slip at the surface after the earthquake along the fault (max 10m)

26 DEC 2004 01:58:53MET

Epicentre
Source depth ca. 35km

Rupture length
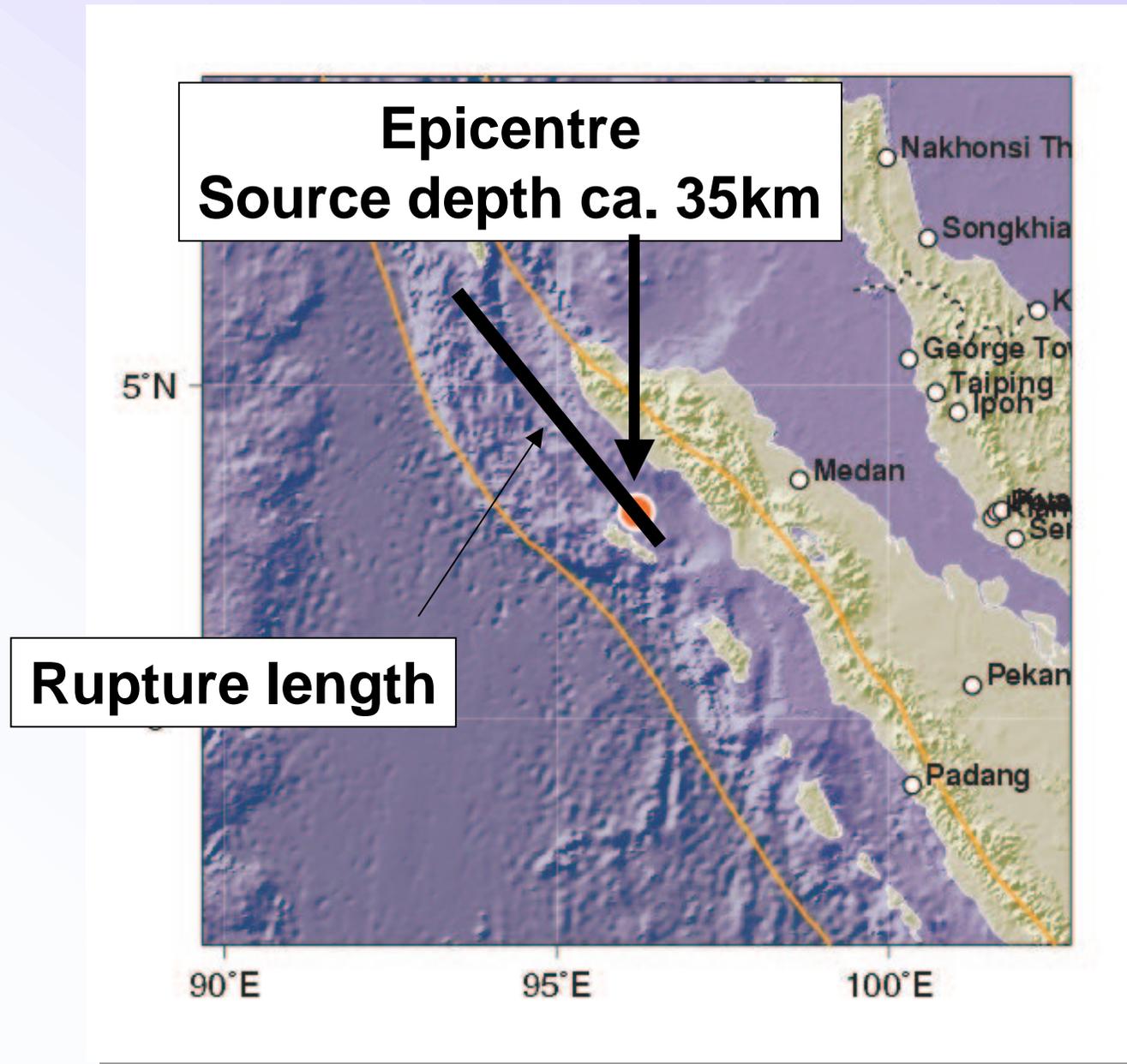
26 Dec 2004 01:58:53MET

Sumatra rupture process
results immediately after the rupture
(Data from Ji Chen, CalTech)

40km

20m

450km

Largest conceivable rupture size in central Europe
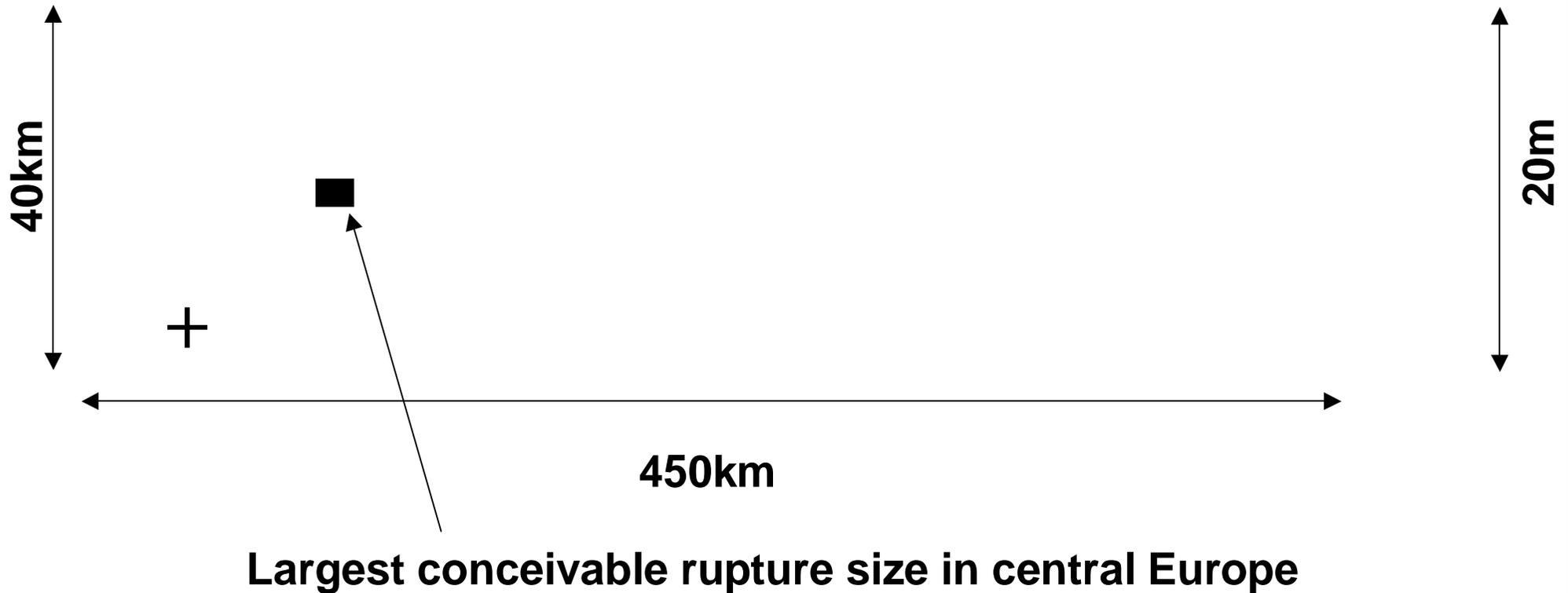
Theory – Observations
First 250 seconds
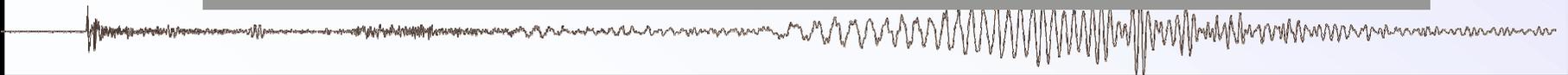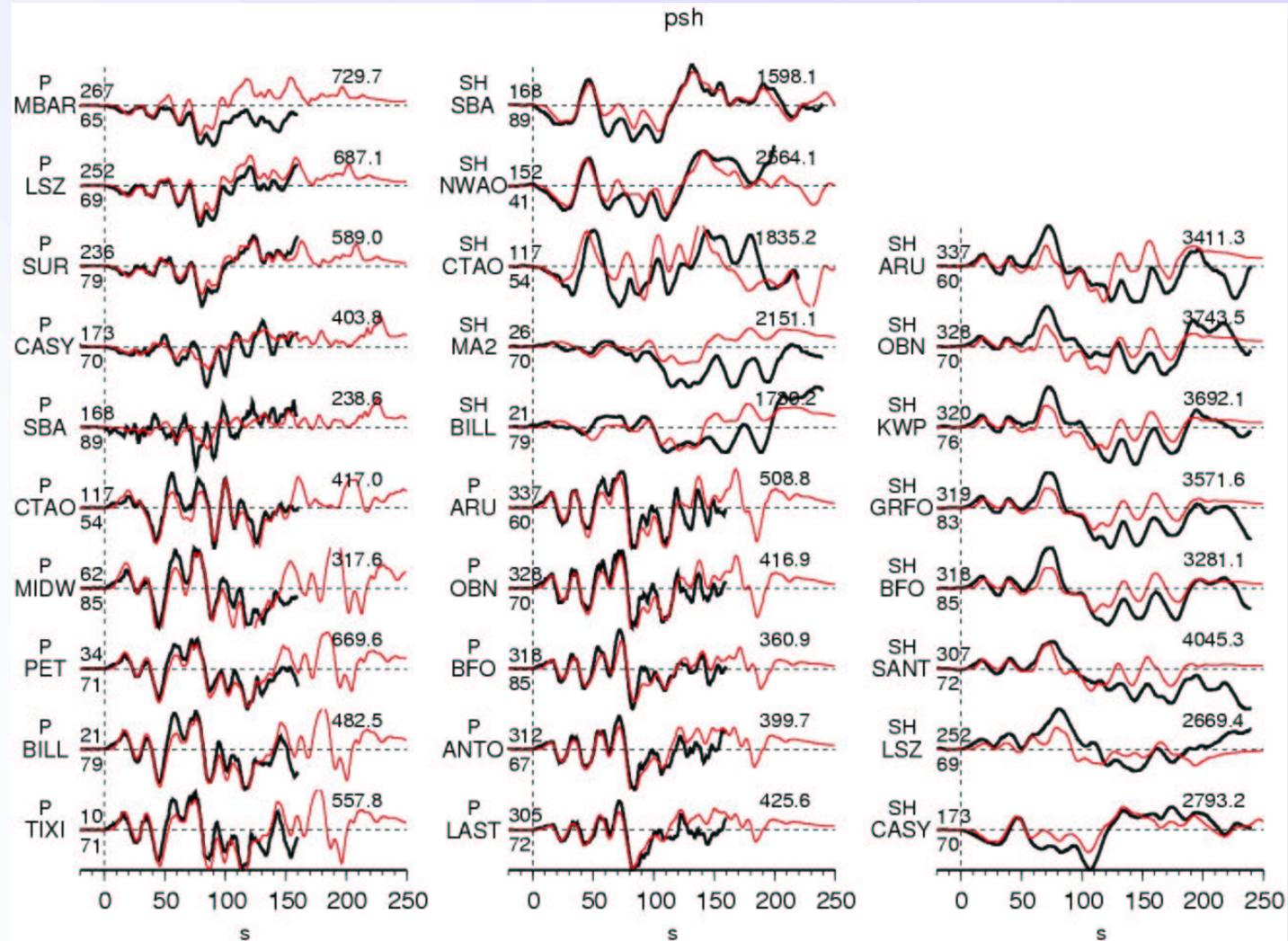
Possible explanation:
unilateral rupture – material interface
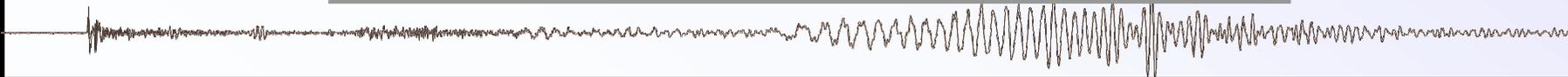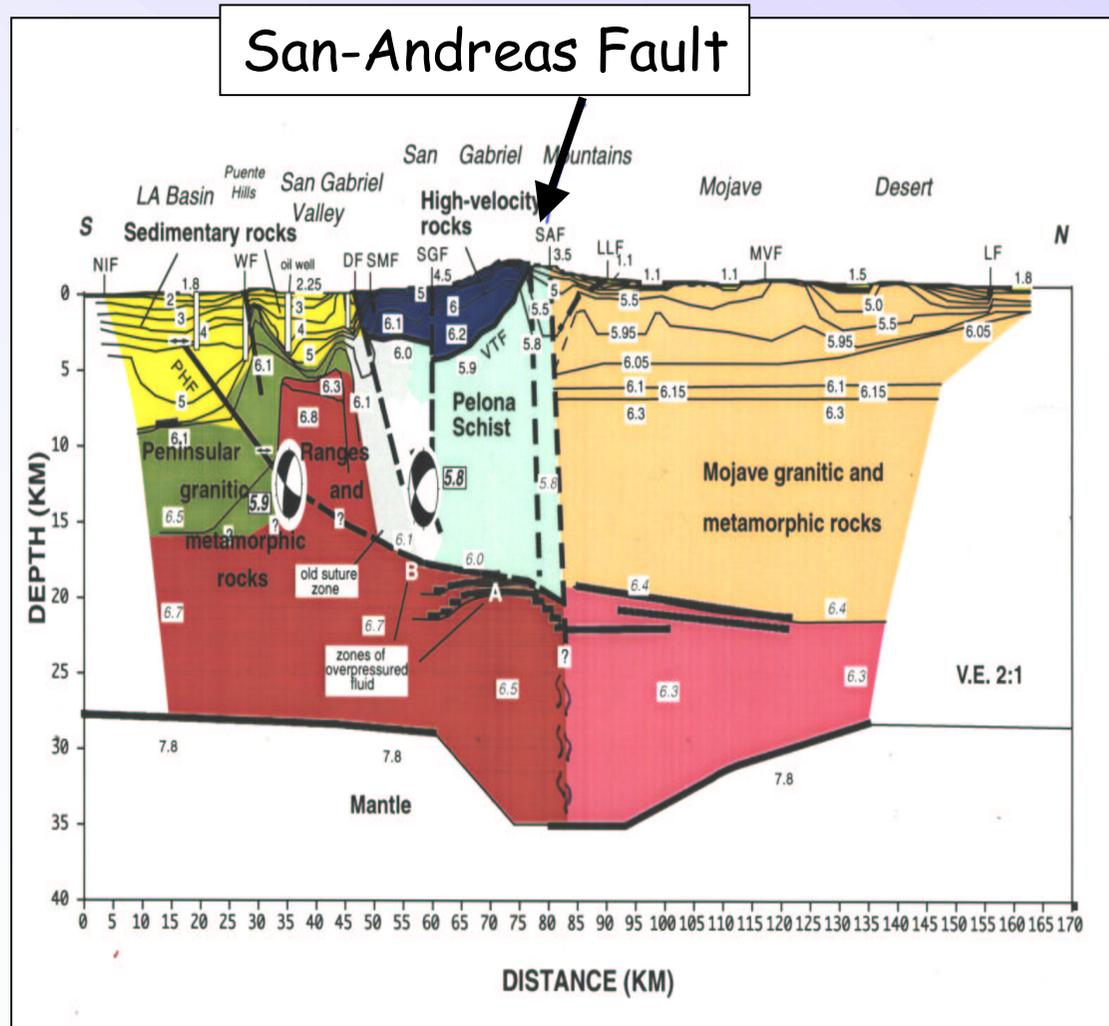
Dynamic Rupture in a 3D medium

Fault surface
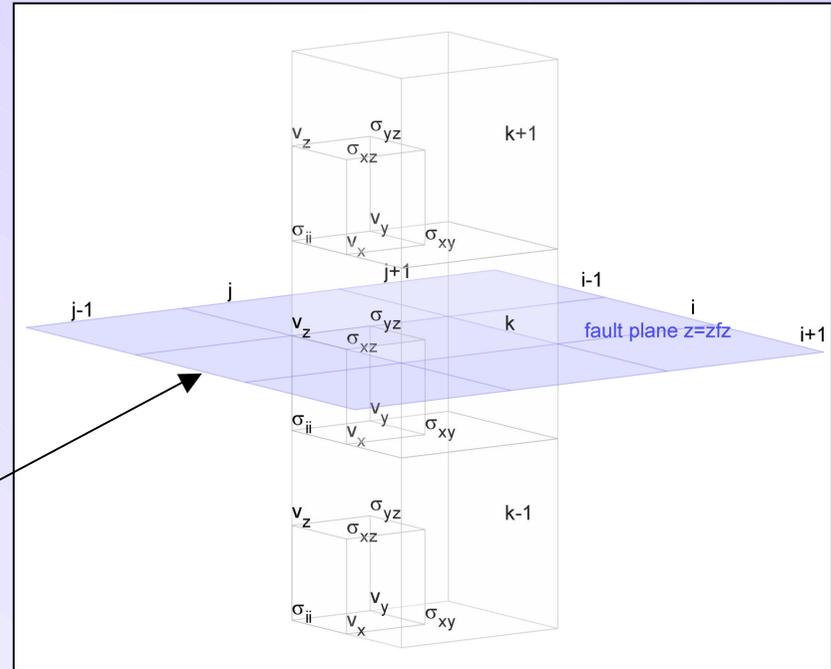
- The rupture starts after a threshold stress is surpassed

- A frictional boundary condition (e.g., *rate-and-state-dependent friction law*) determines the motions of the fracture surfaces

- Depending on the frictional behavior rupture is favored or not (*velocity weakening, slip weakening*)

- Actual rupture behavior is not known before simulation (**dynamic rupture** vs. kinematic rupture)
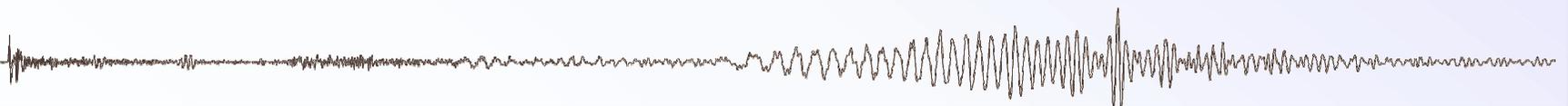
3D simulation of rupture
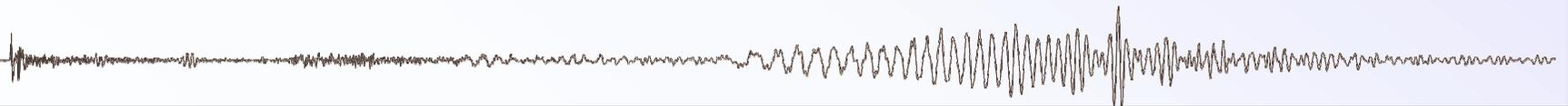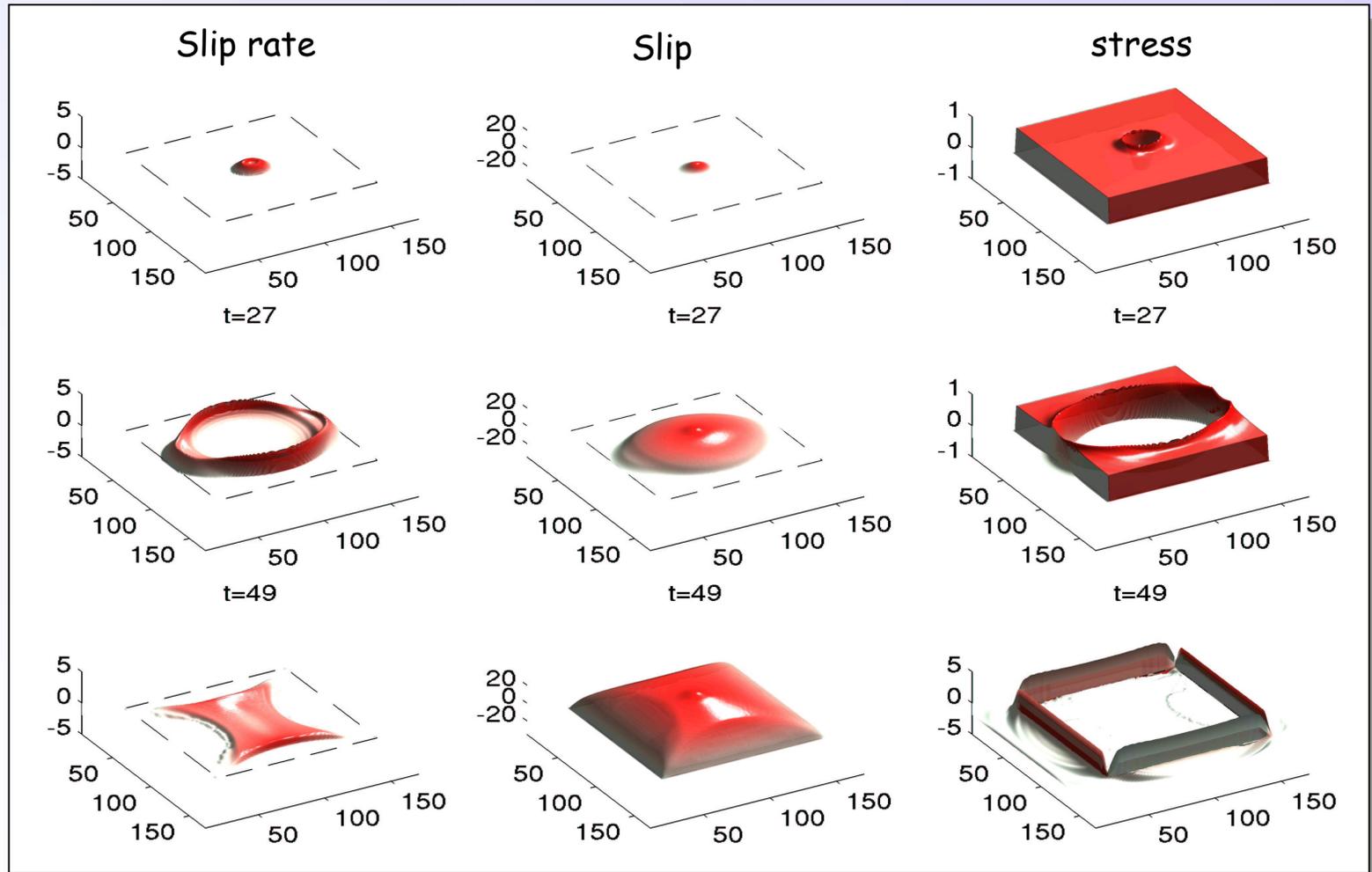
Pulse-like rupture at a material interface
slip-rate as a function of time

Rupture front
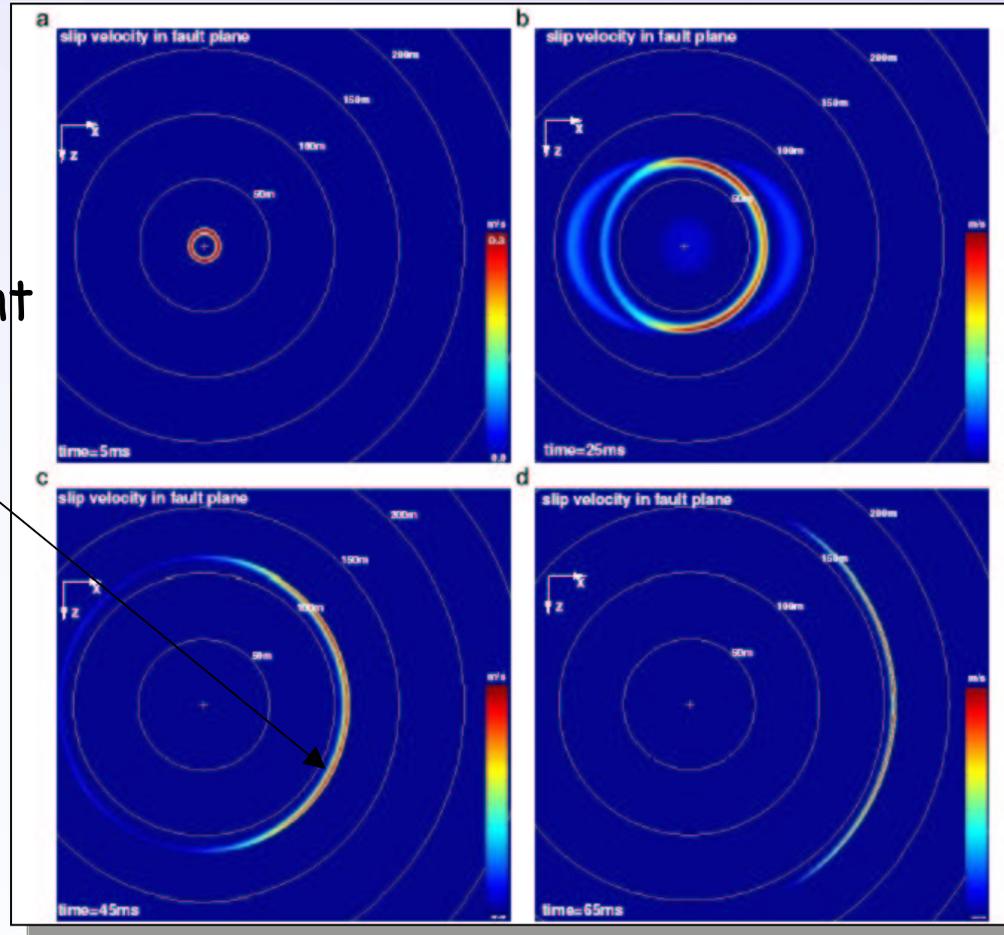
Brietzke und Ben Zion, 2003

Directivity

Ben Zion, 2003
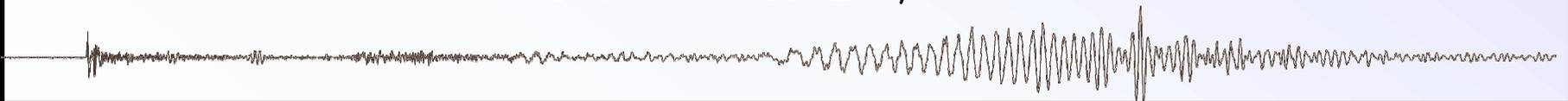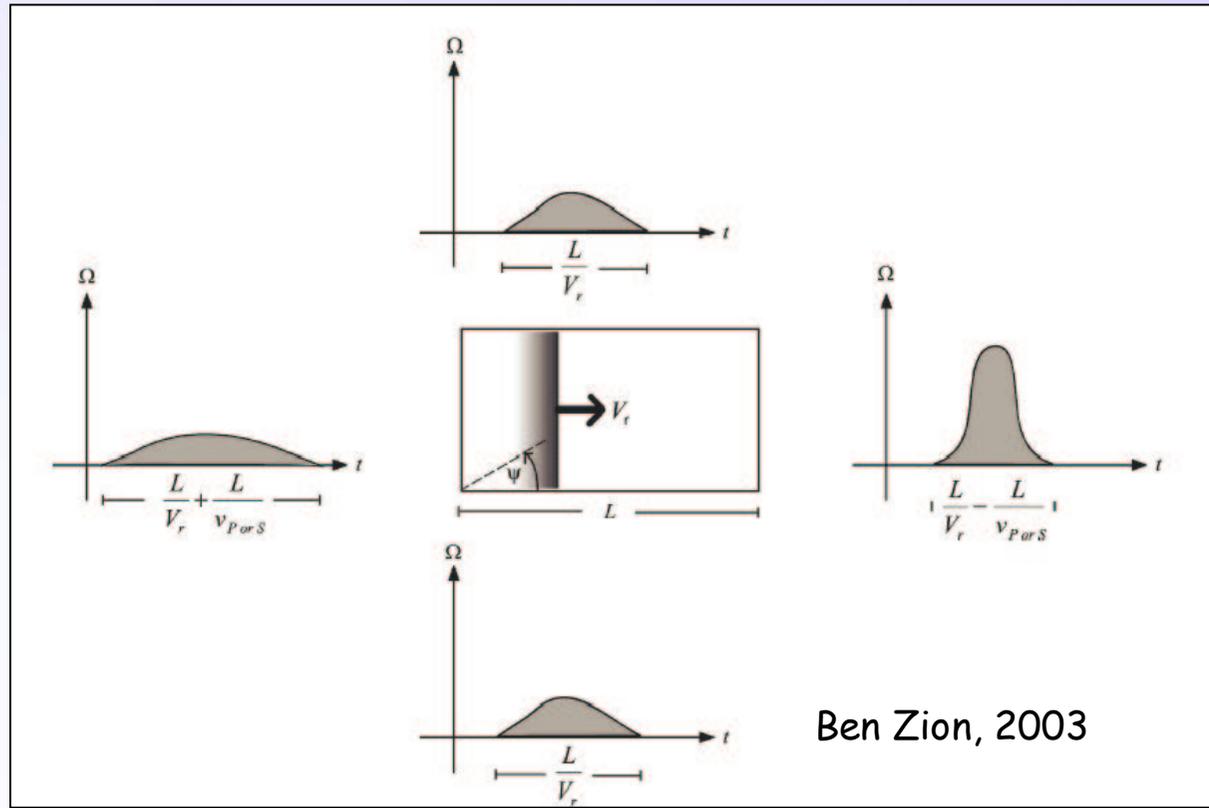
Rupture direction has consequences for seismic hazard: Doppler-effect may lead to enhanced shaking in the direction of rupture
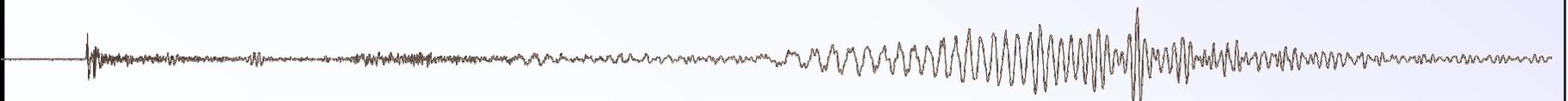
Rupture at material interfaces

- ... material interfaces are preferred locations of rupture, i.e., ruptures may migrate towards them ...

- ... possible explanation of the heat-flow paradoxon as normal stresses are dynamically reduced -> less friction -> less heat

- ... predominantly uni-lateral rupture through dynamic weakening and strengthening in the different rupture directions ...

- .. yet, there are considerable uncertainties as to the frictional phenomena during rupture (zero friction?)

Punchbowl fault
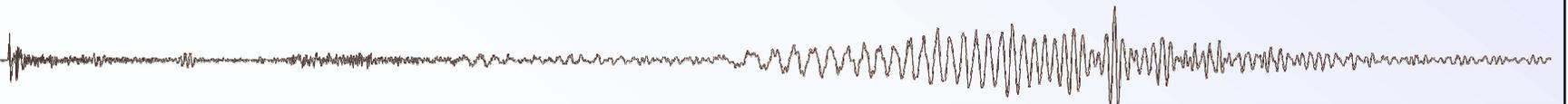
Summary
II – Rupture processes

- The earthquake rupture process is still poorly understood

- We are lacking direct observations close to the fault that ruptures (-> SAFOD project!)

- Rupture at material interfaces may explain some of the observations

- 3D simulations of wave propagation and rupture may help to constrain the physical processes involved

III - Earthquake hazard and risk

Scientific problems:
- Do we know the earthquake hazard of specific regions?
- Can we estimate the strong ground motions for specific earthquake scenarios?
- What information is necessary to make these estimates reliable?

Disziplinen:
- seismology – earthquake engineering – geology – neotectonics (paleo-seismology) – geomorphology – geodesy ...

Supercomputing:
- Calculation of earthquake scenarios in frequency bands that are relevant for earthquake engineers (structural safety)
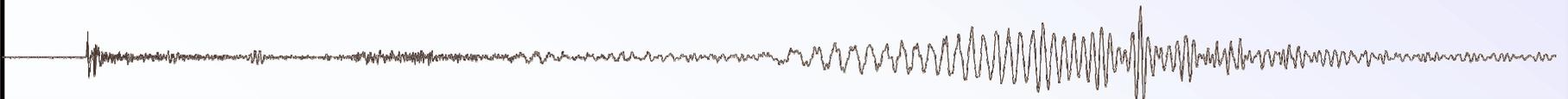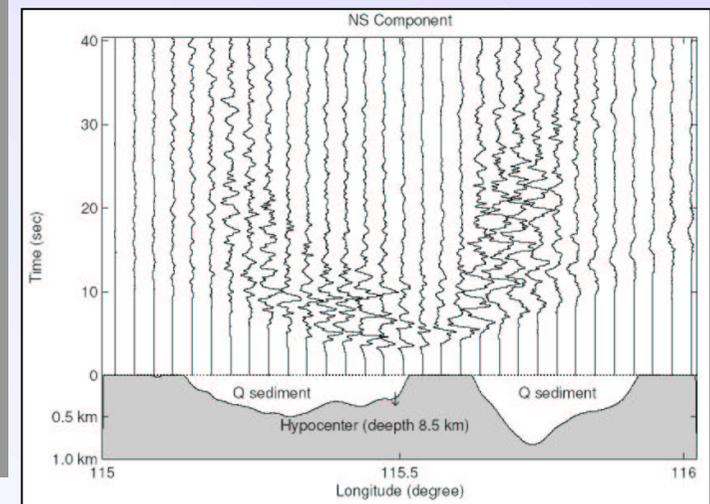
Taiwan M7.4 Erdbeben 1999
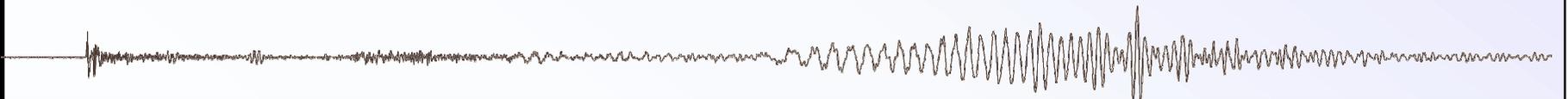
Taiwan M7.4 Erdbeben 1999

Cologne Basin Tectonics

Rheinisches Schiefergebirge

Rheintal

Ville

Erft-Scholle

Rur-Scholle
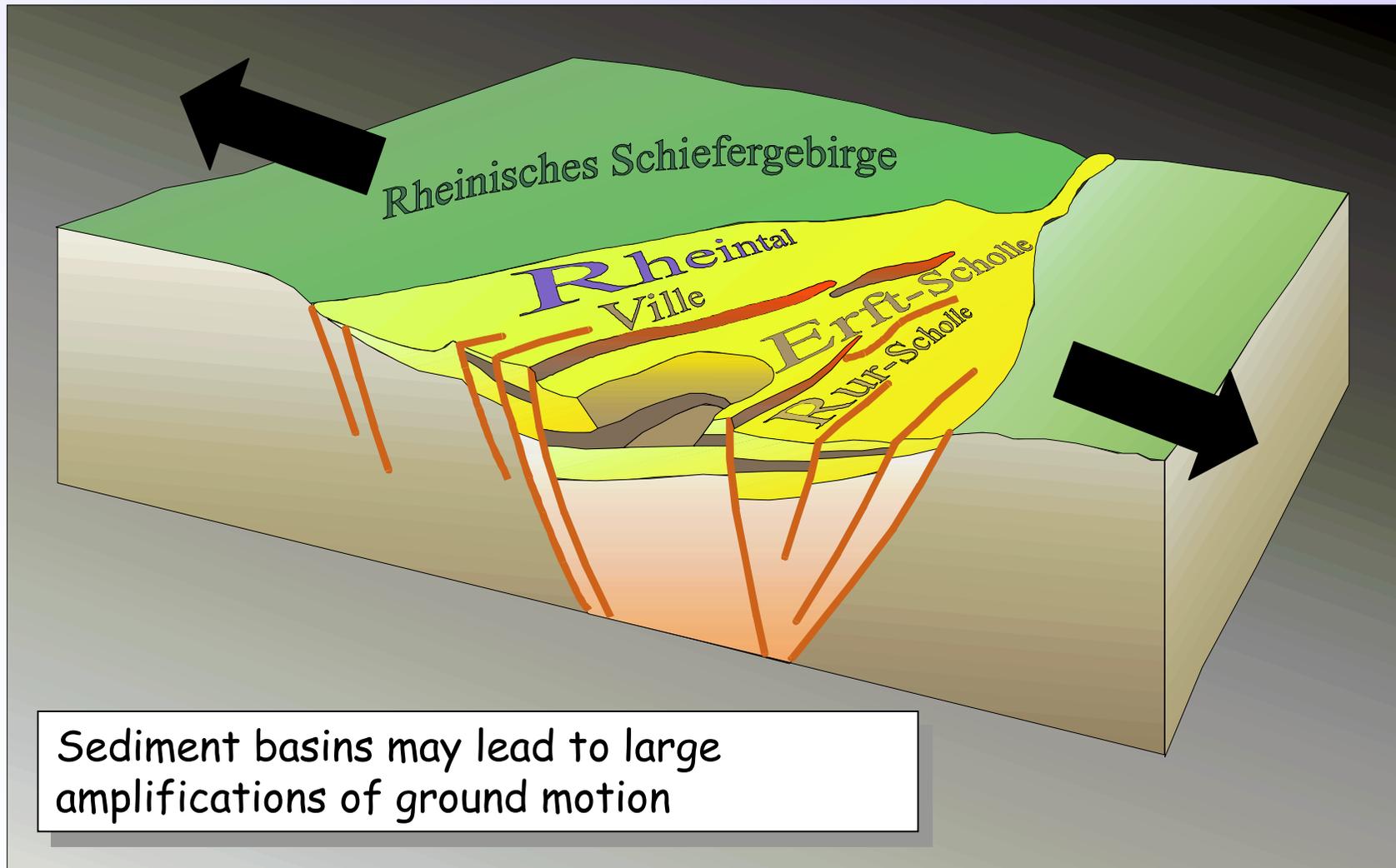
Sediment basins may lead to large amplifications of ground motion
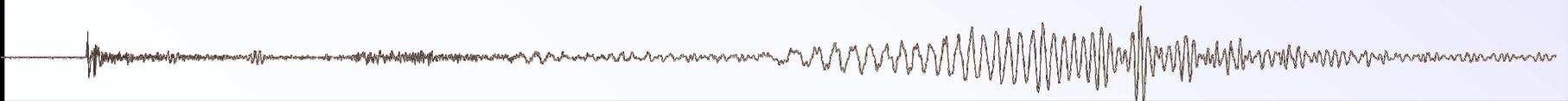
Earthquakes in the Cologne Basin

Largest event
M_L=6.4 (1756)

Latest large event
M_L=5.9 (1992)

Grafik: K. Hinzen
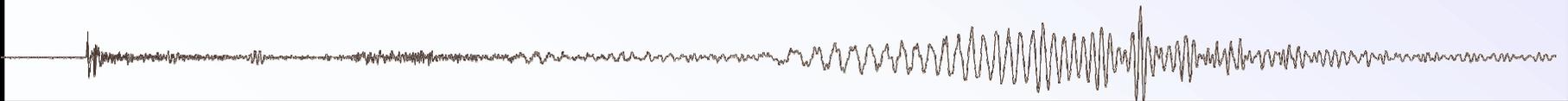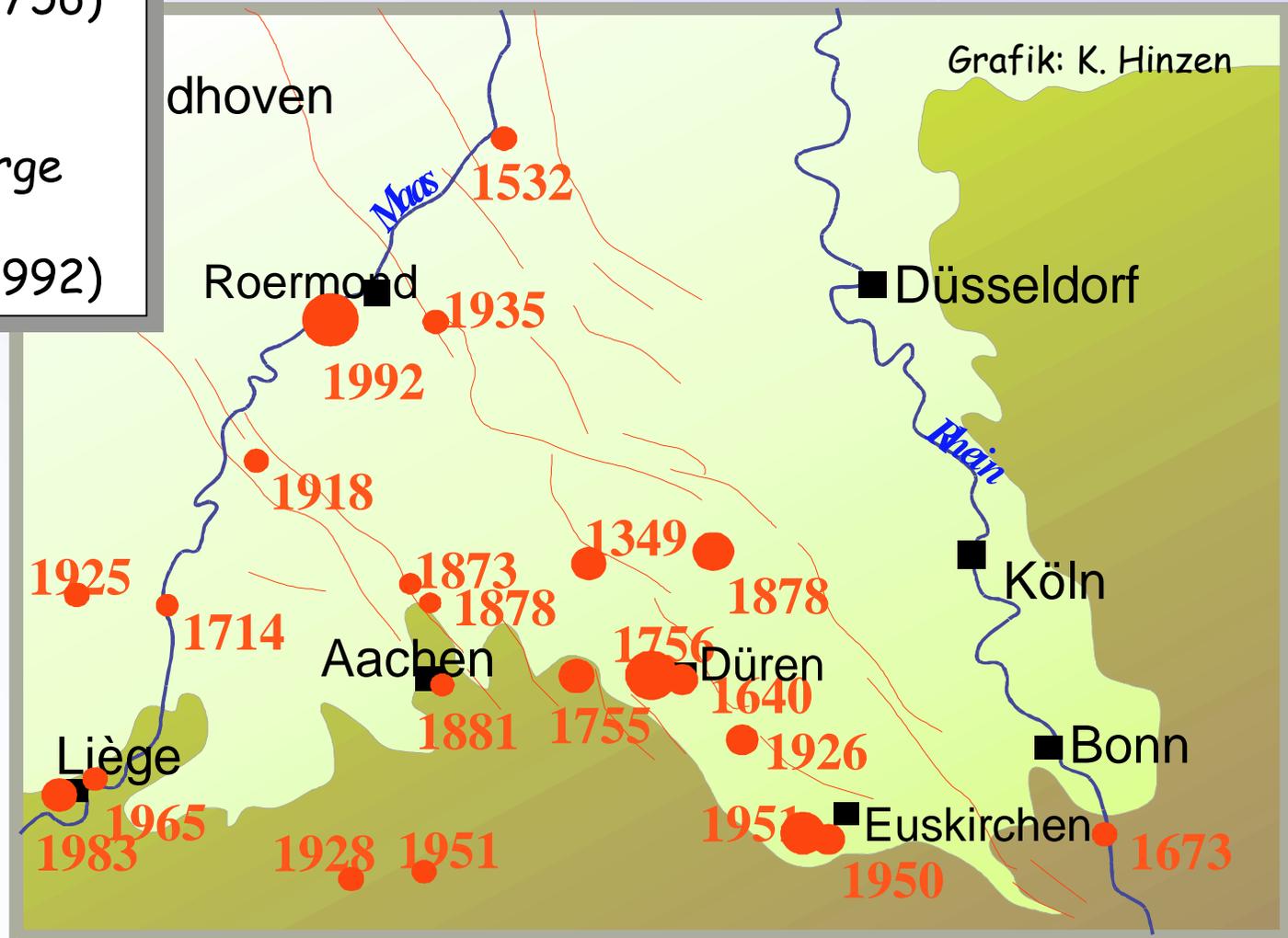
Known earthquake faults
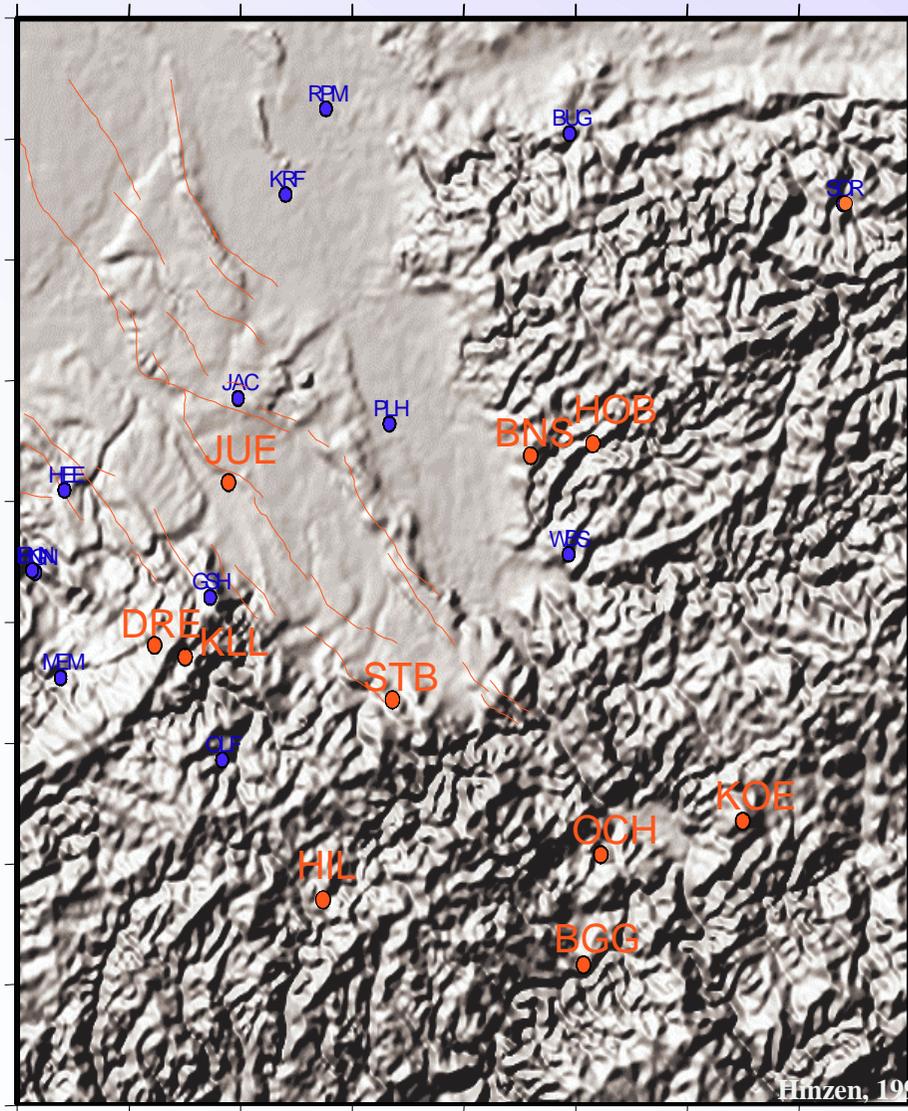
In paleoseismology and geology (neotectonics) one tries to recognize active faults and determines maximum rupture dimensions (-> magnitudes)

This allows in principle the calculation of potential earthquake scenarios.
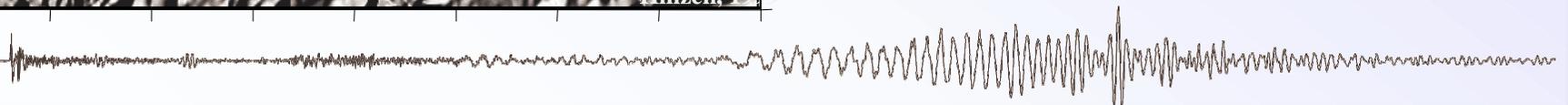
Sediment structure
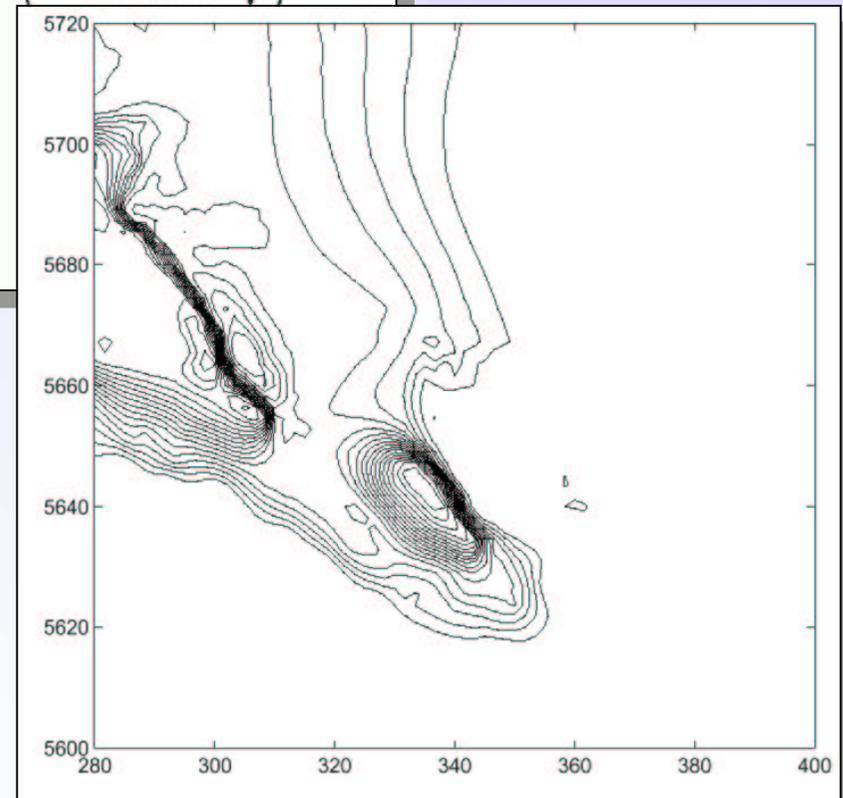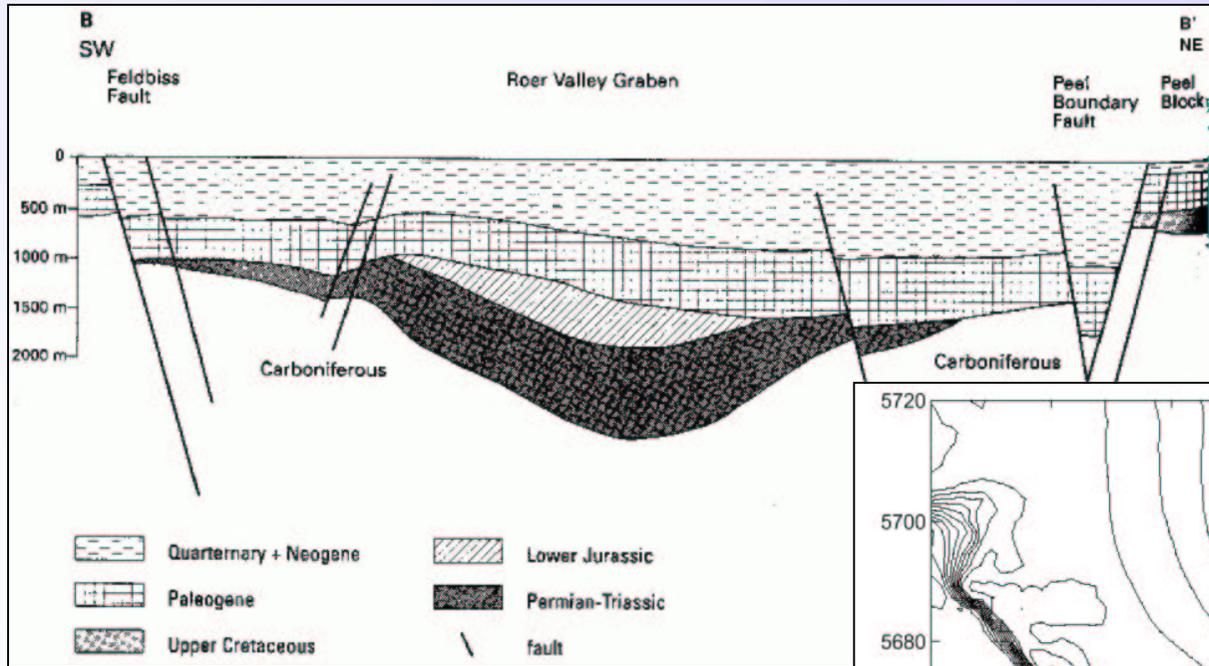
Basement topography
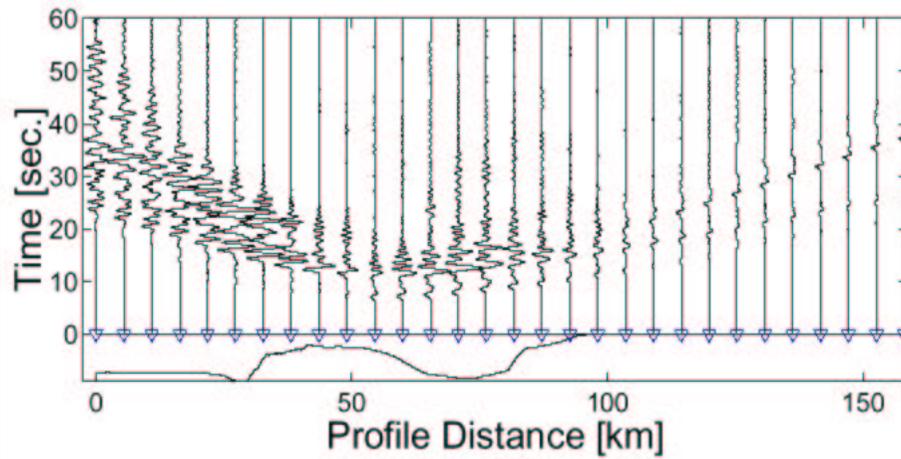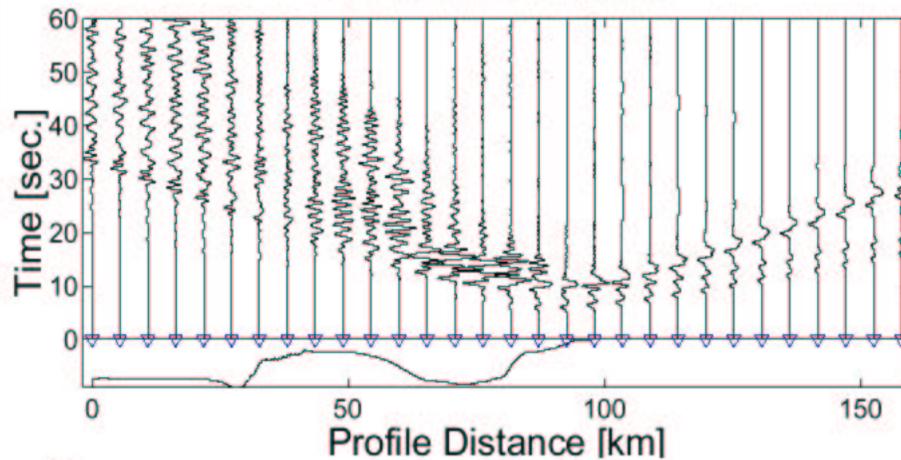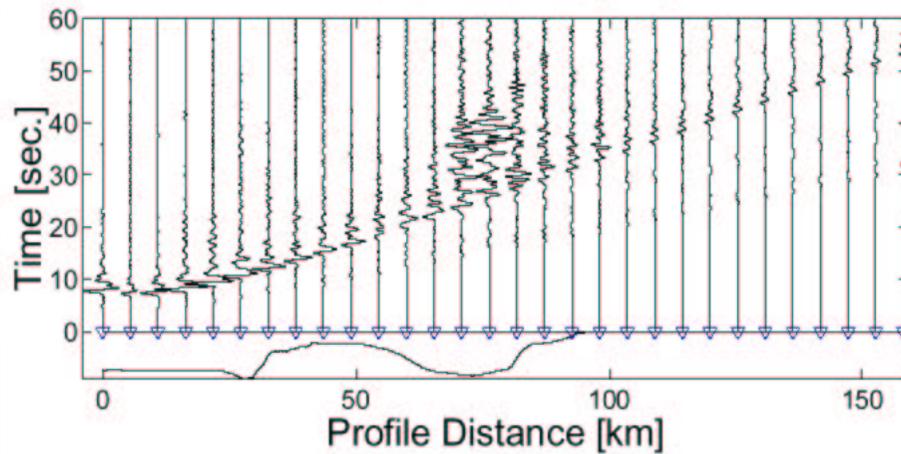
Ground motion in the Cologne Basin
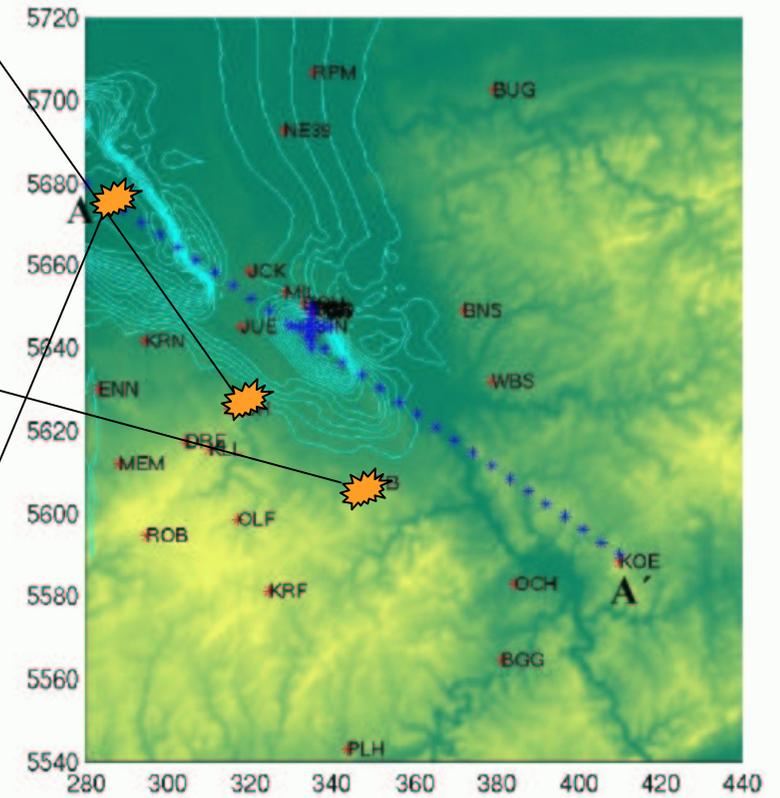
Earthquake scenarios

Comparison with observations
M4.9, July 2002
Cologne Basin, Germany

Cologne Basin topography
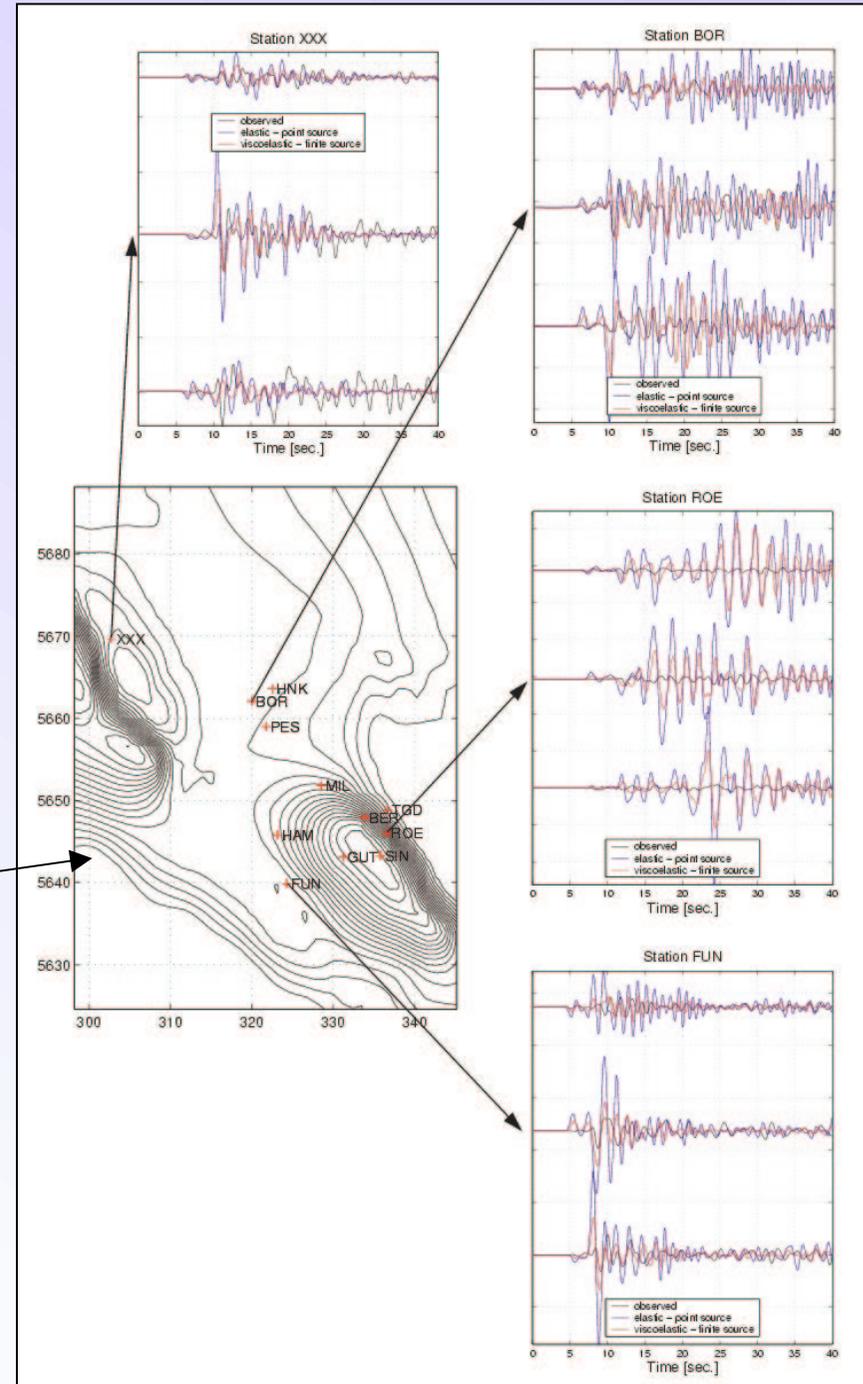
Seismic intensities
(Mercalli scale)

Dueren
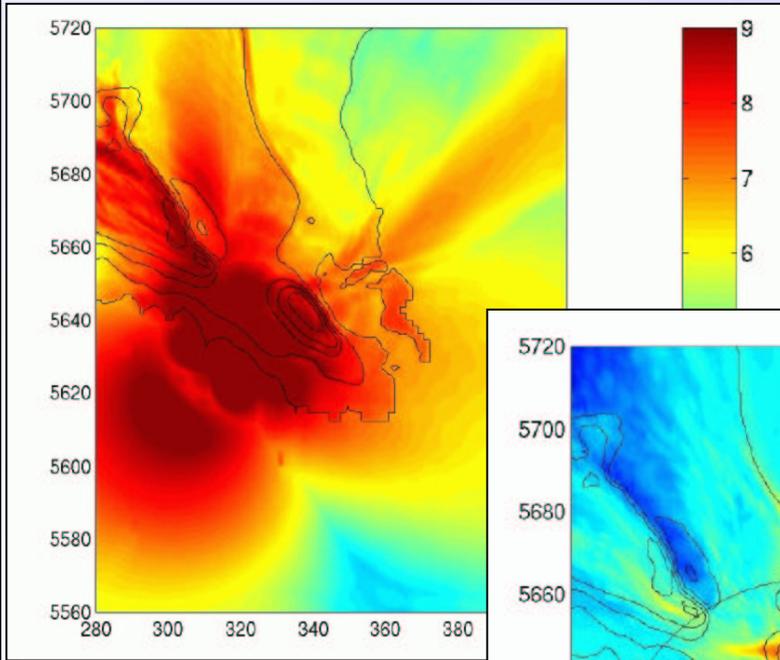
Roermond
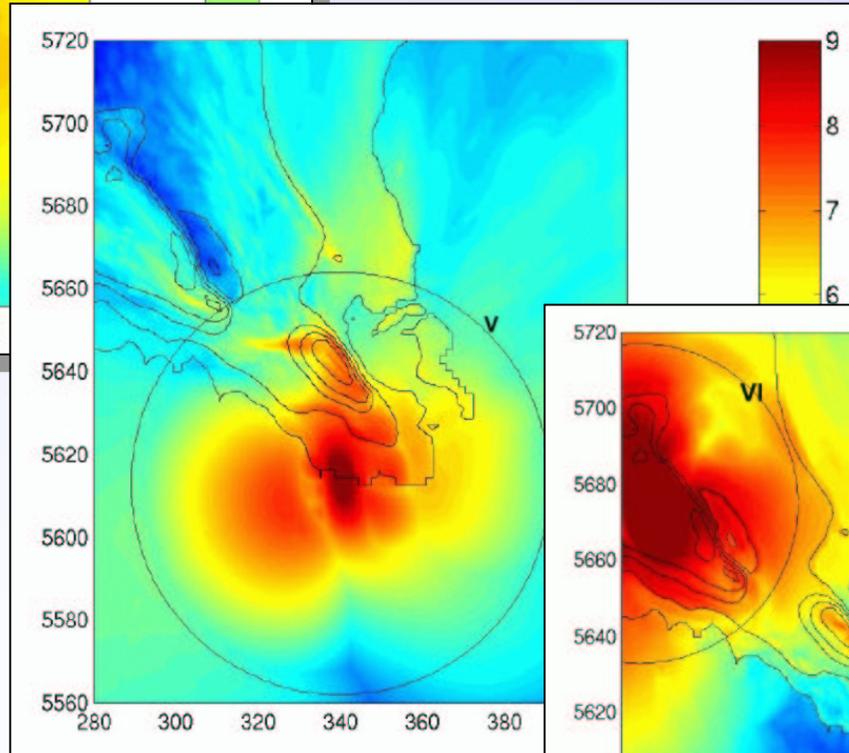
Euskirchen
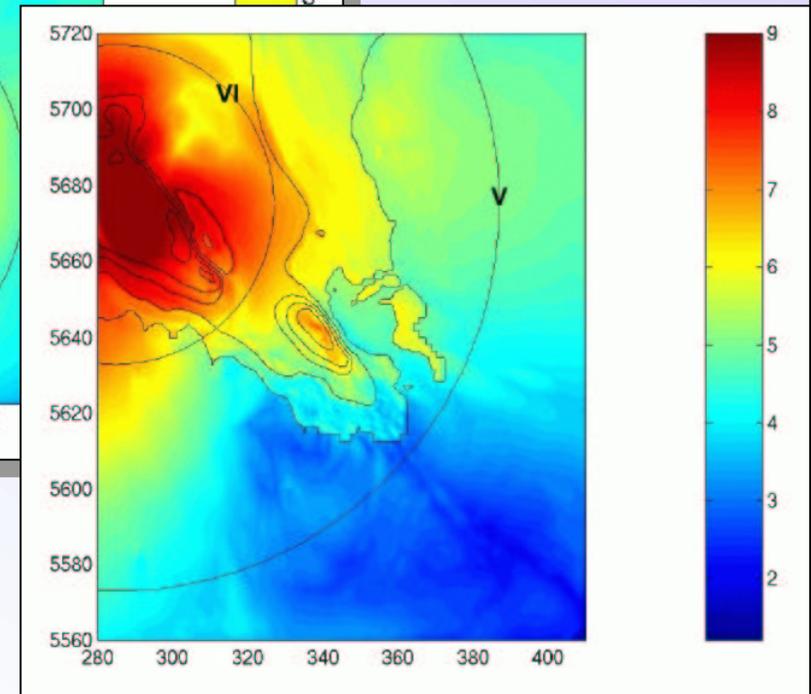
The intensities are calculated from peak ground velocities
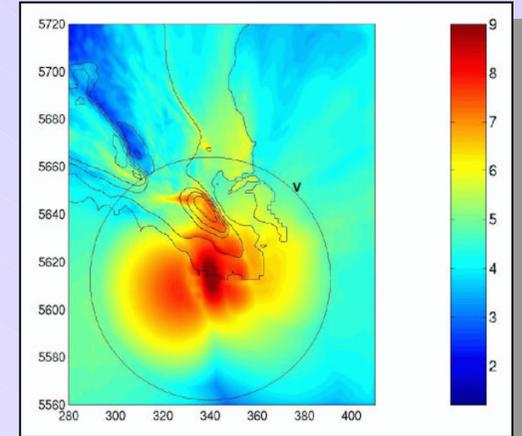
Amplification through 3D model
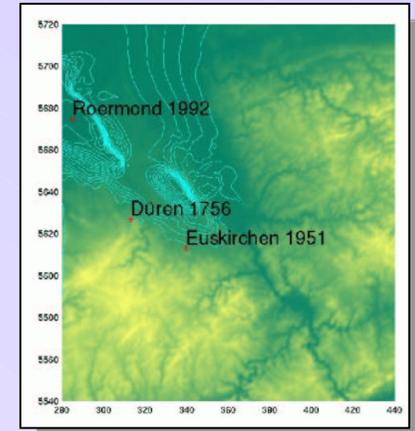
Dueren
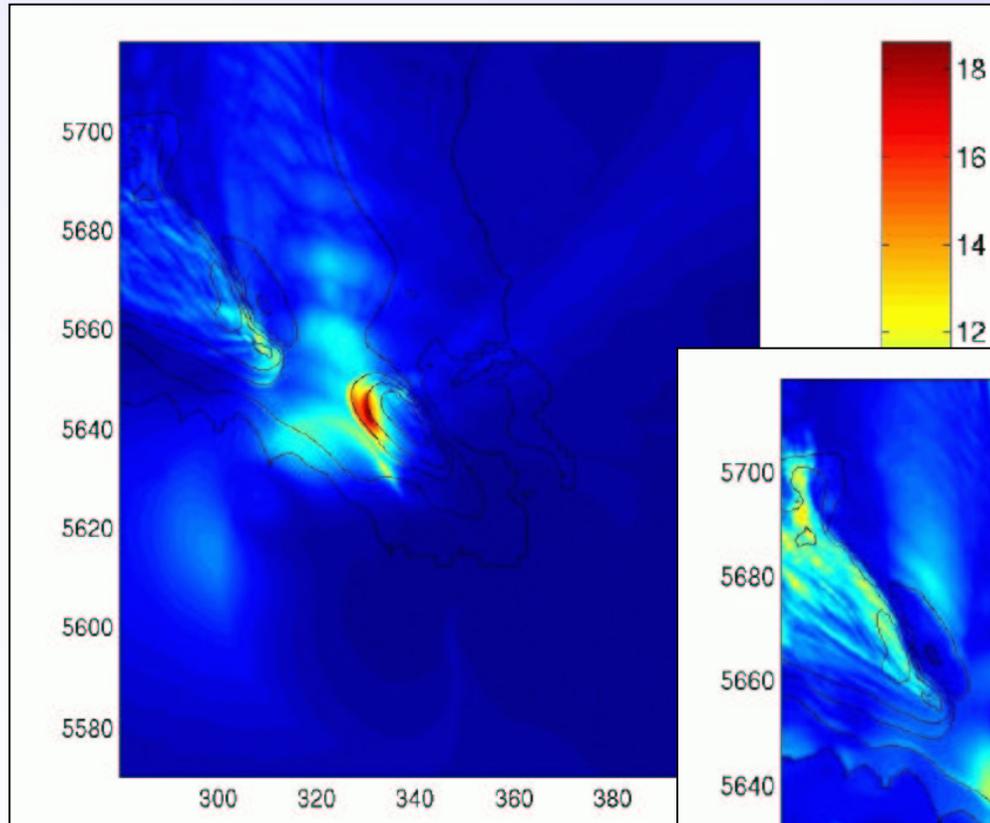
Euskirchen
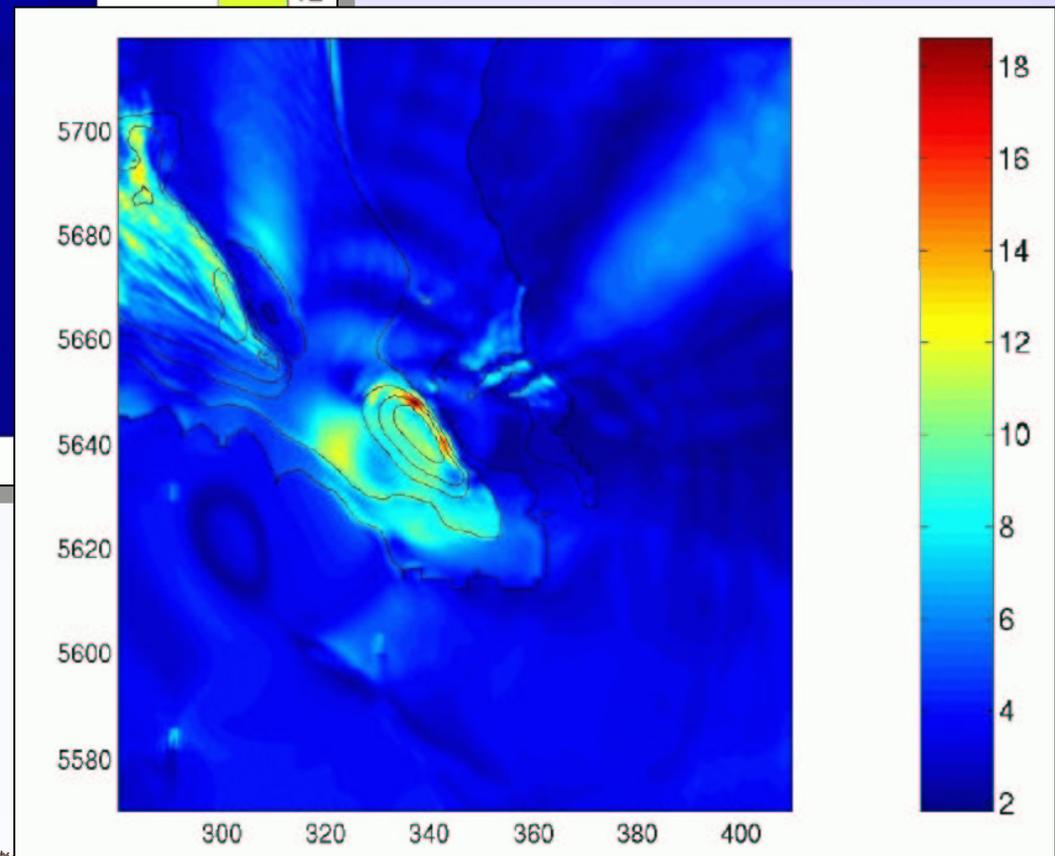
What can we do with the uncertainties in the crustal structure?

Seismograms with a 10% change of sediment depth for the same location
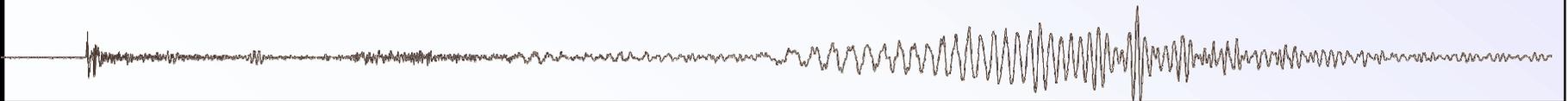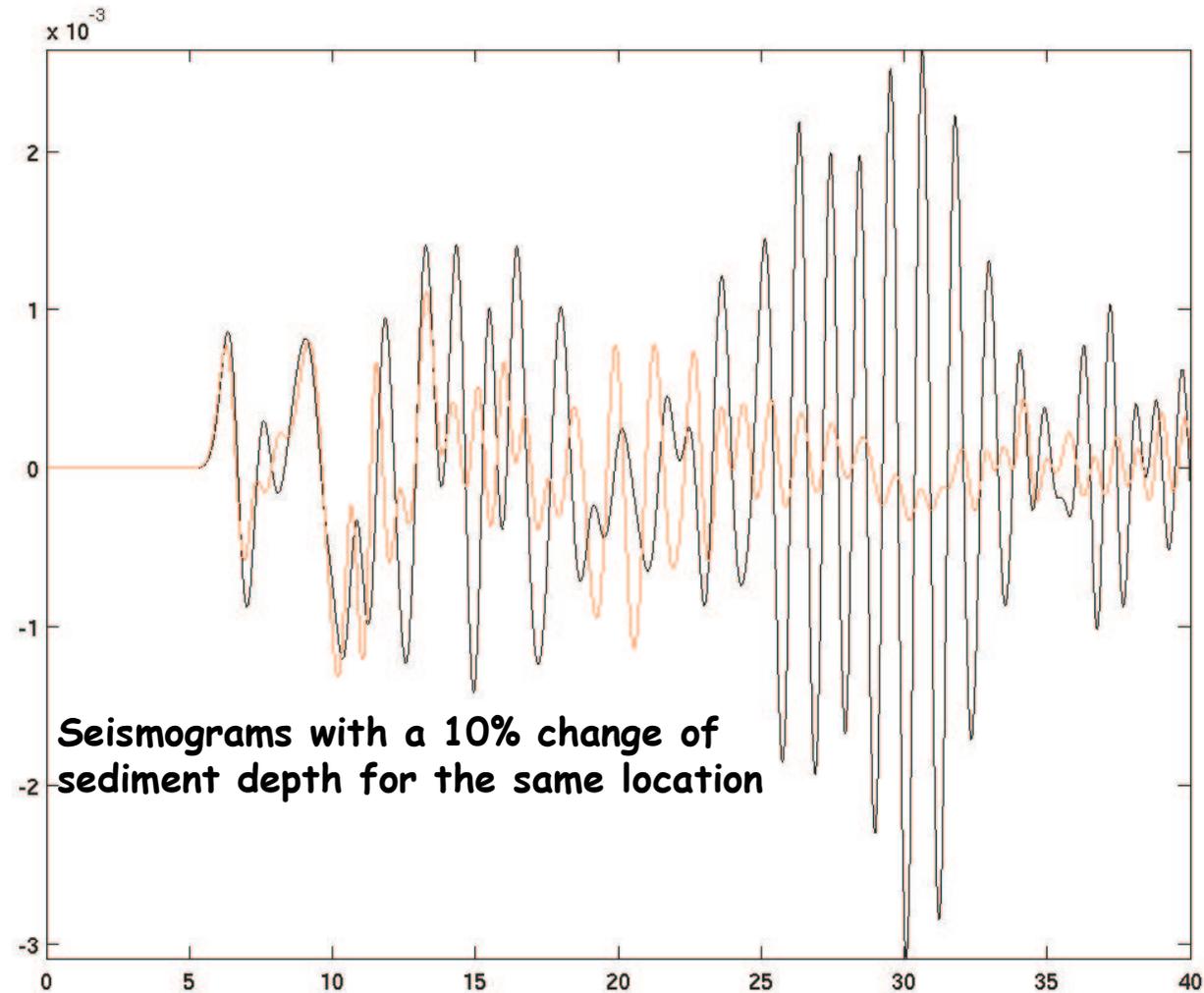
Summary
III- Earthquake scenarios

- There are considerable uncertainties in estimating strong ground motion for earthquake scenarios (3D structure, source behavior)

- With the concept of "Green's functions" a large number of earthquake scenarios could be simulated and some of the uncertainties accounted for
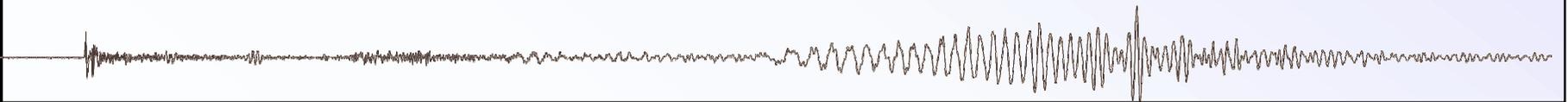
IV – Global seismology

Scientific questions:

- How do 3D structures inside our planet relate to its dynamic behavior (mantle convection)?
- What is the role of the major structural discontinuities (670km, core-mantle boundary, etc.)
- Where do plumes originate?

Disciplines:

- seismology – geodynamics – geochemistry – fluid dynamcis – cristallography – geodesy – geology - paleomagnetics

Supercomputing:

- Towards simulation and inversion of the globally observed wave field using 3D modelling tools
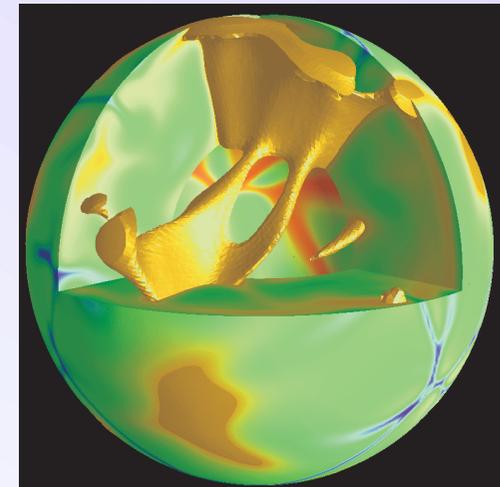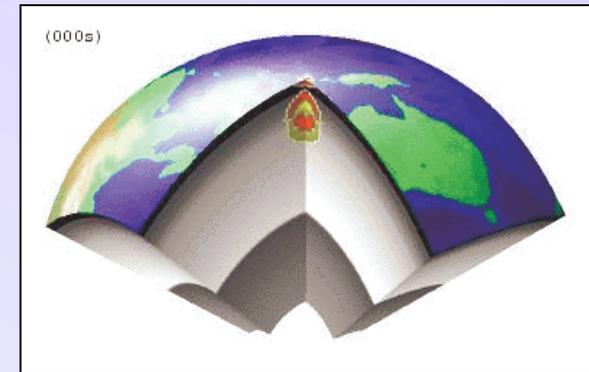
From: P. Bunge

Global wave propagation

Sumatra - Andaman Islands Earthquake (Mw=9.0), Global Displacement Wavefield from the Global Seismographic Network
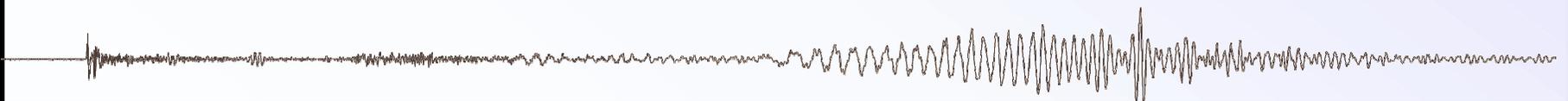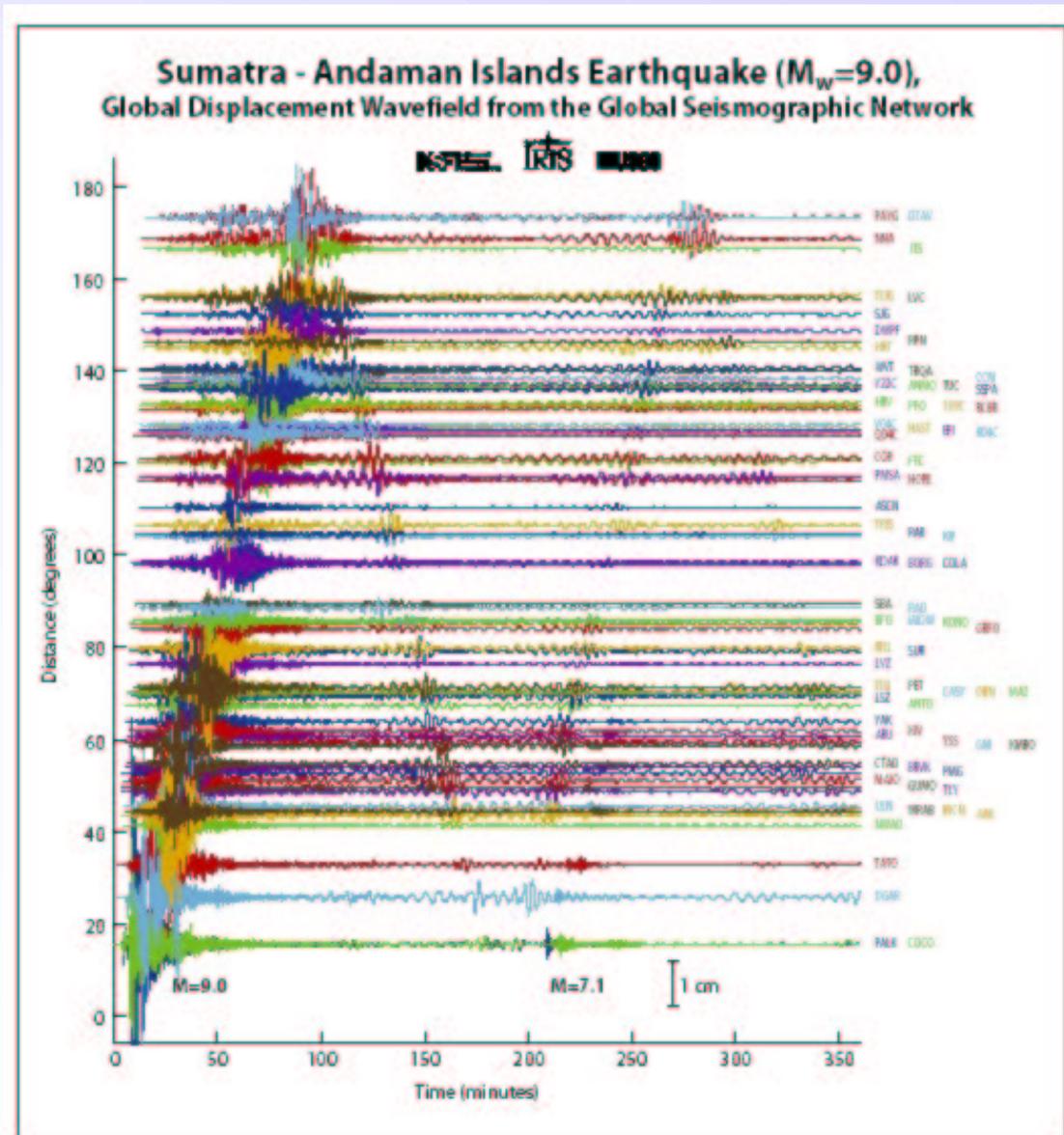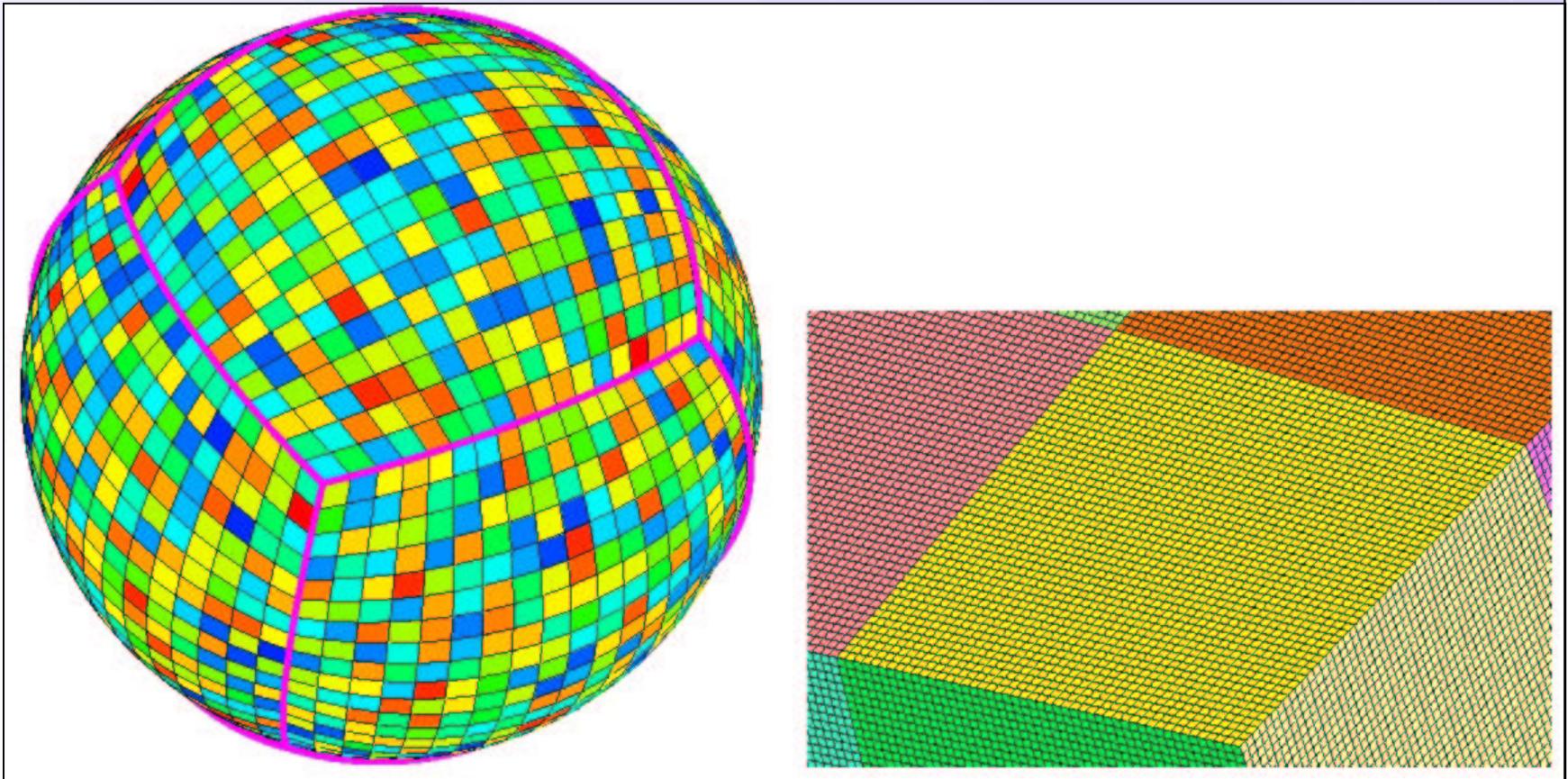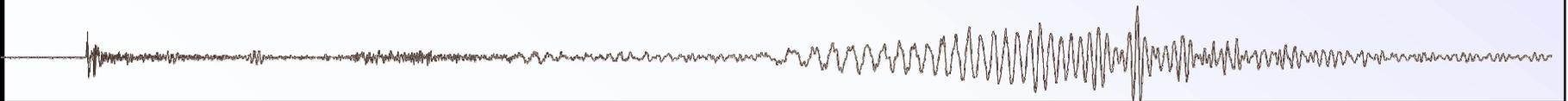
Seismic tomography and the structure of the Earth's deep interior

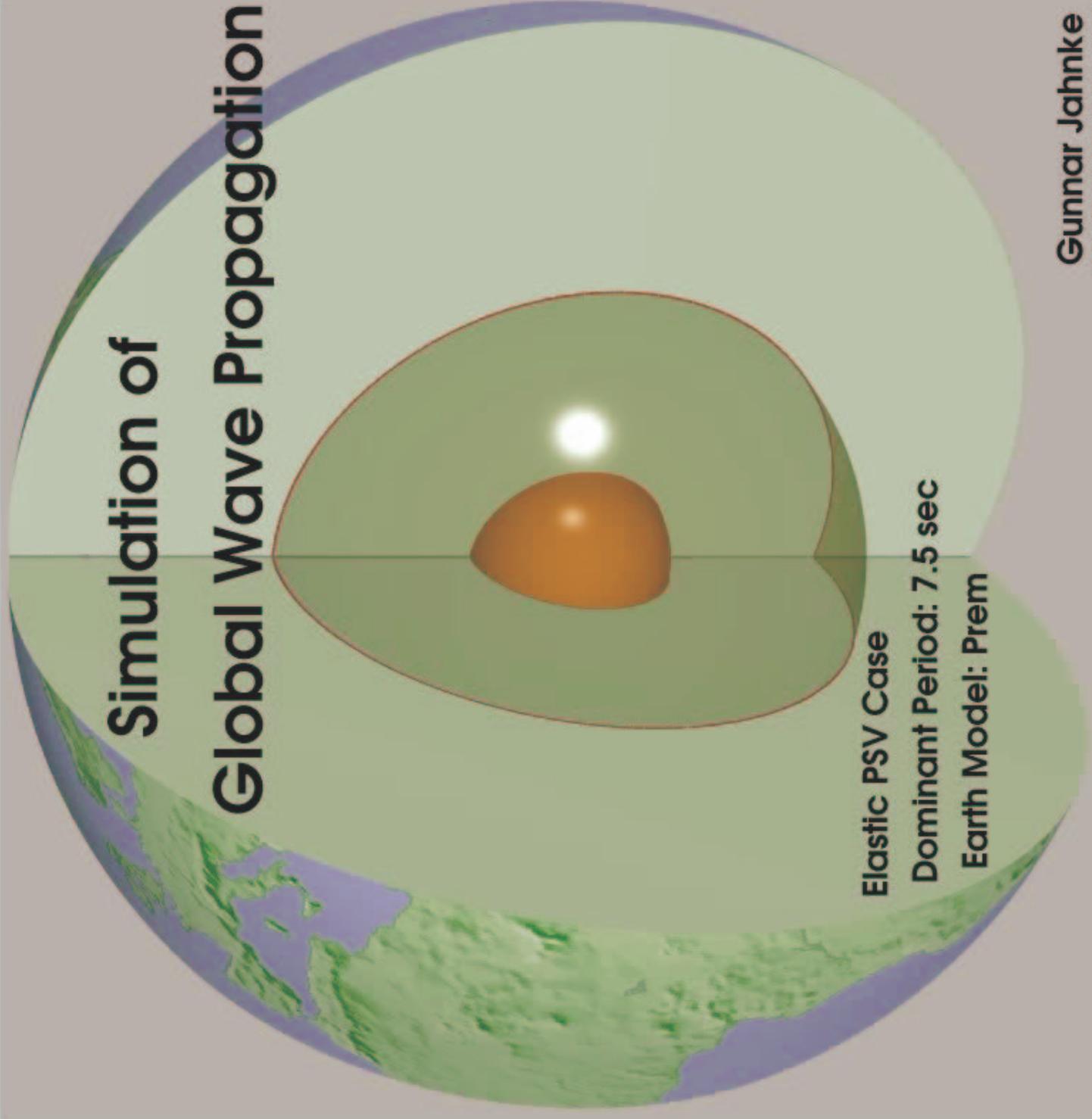$$\sum_{traveltimes} T_{obs} - T_{theory}(m) = Min!$$
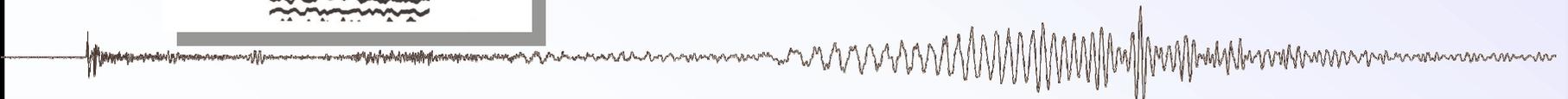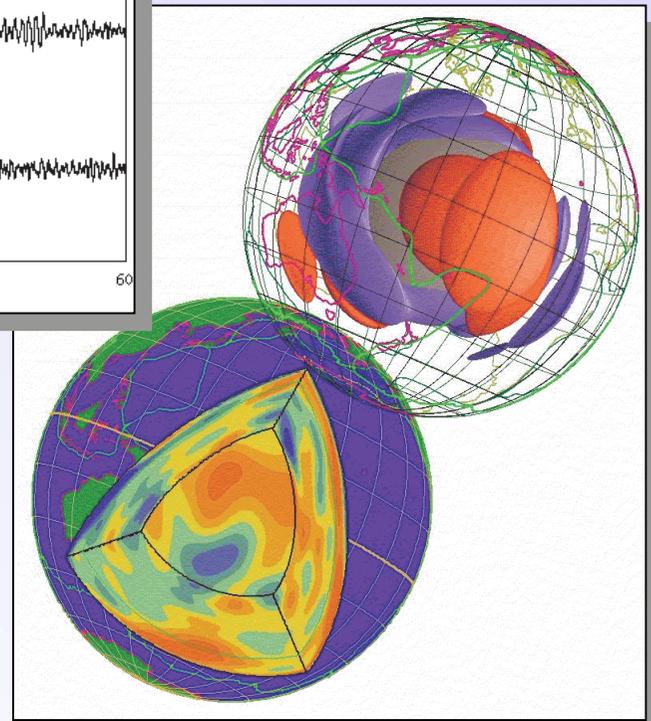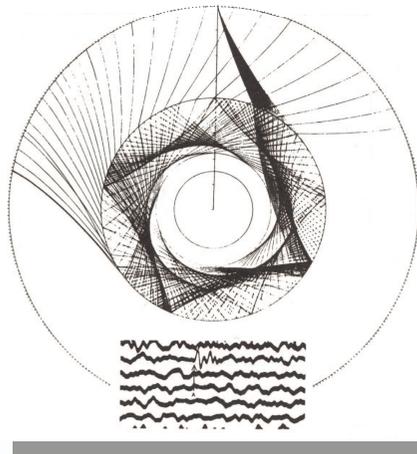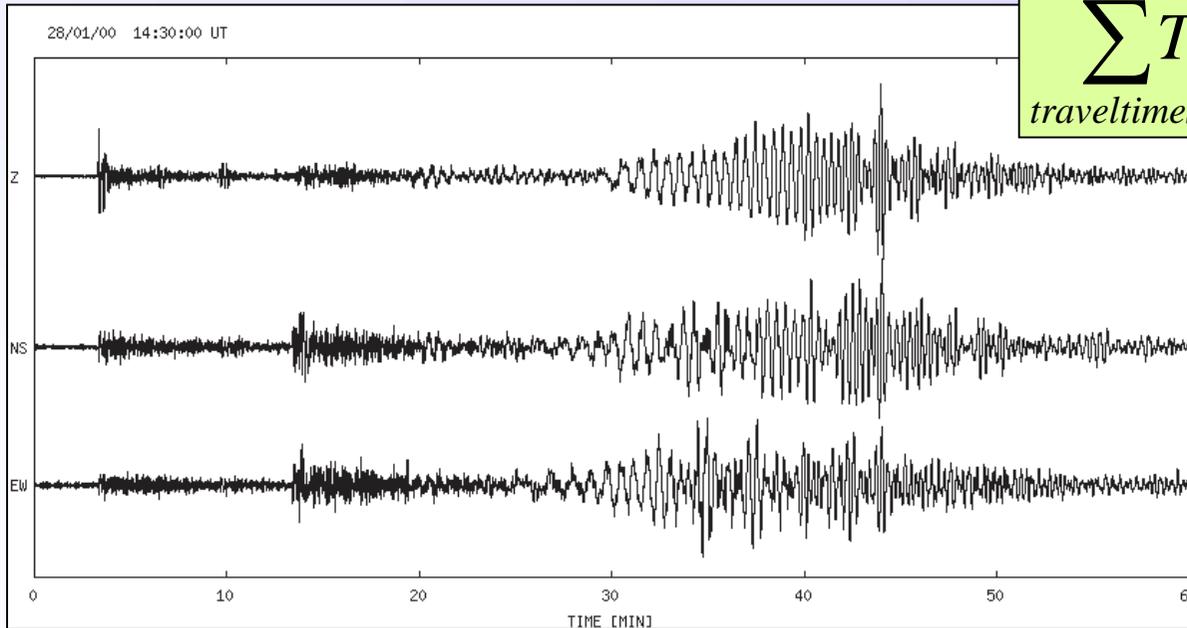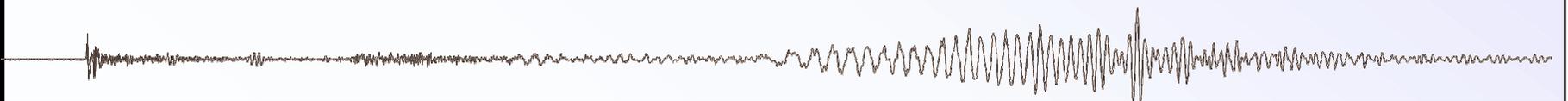
Spherical earth – *Cubed Sphere*
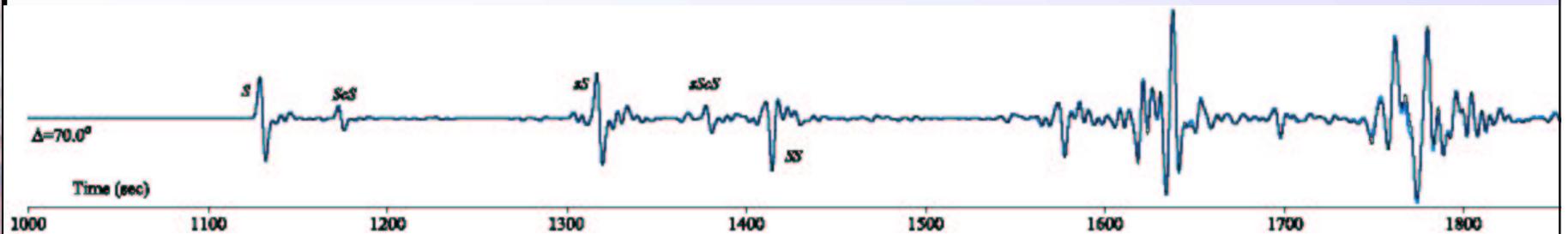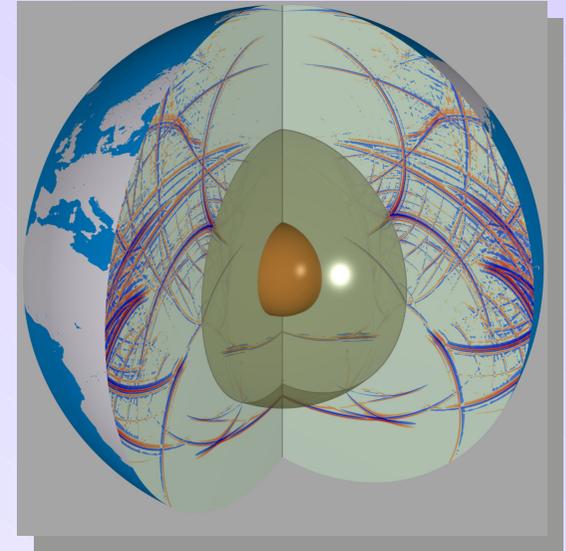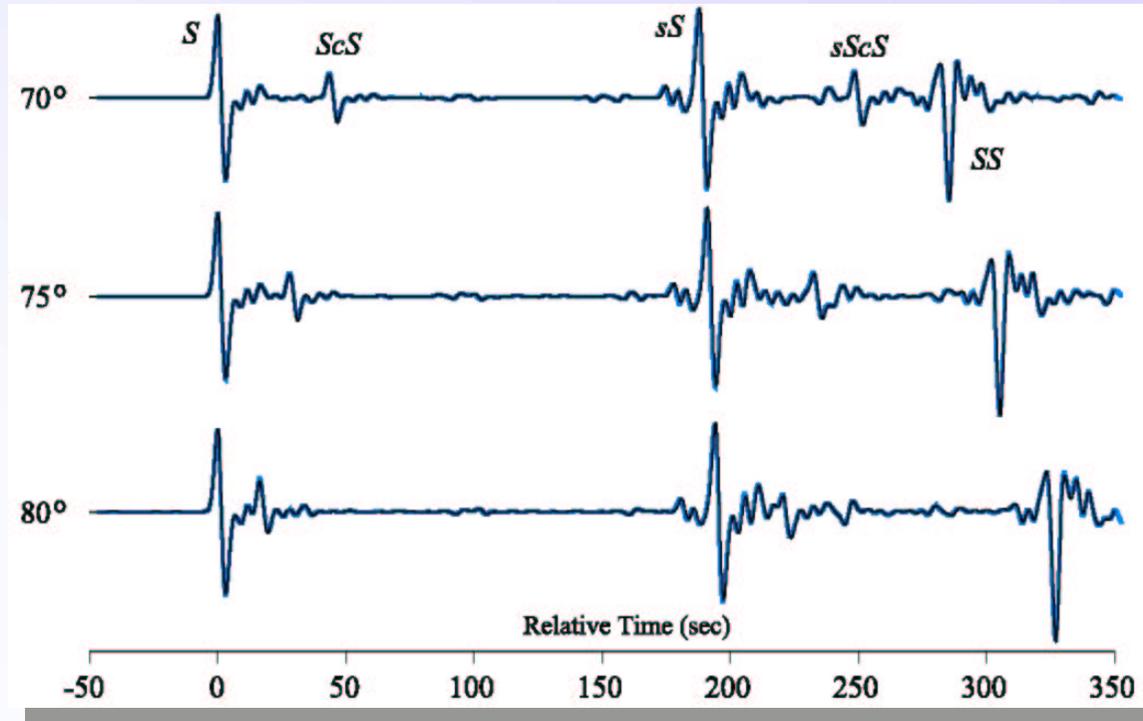## Discretization

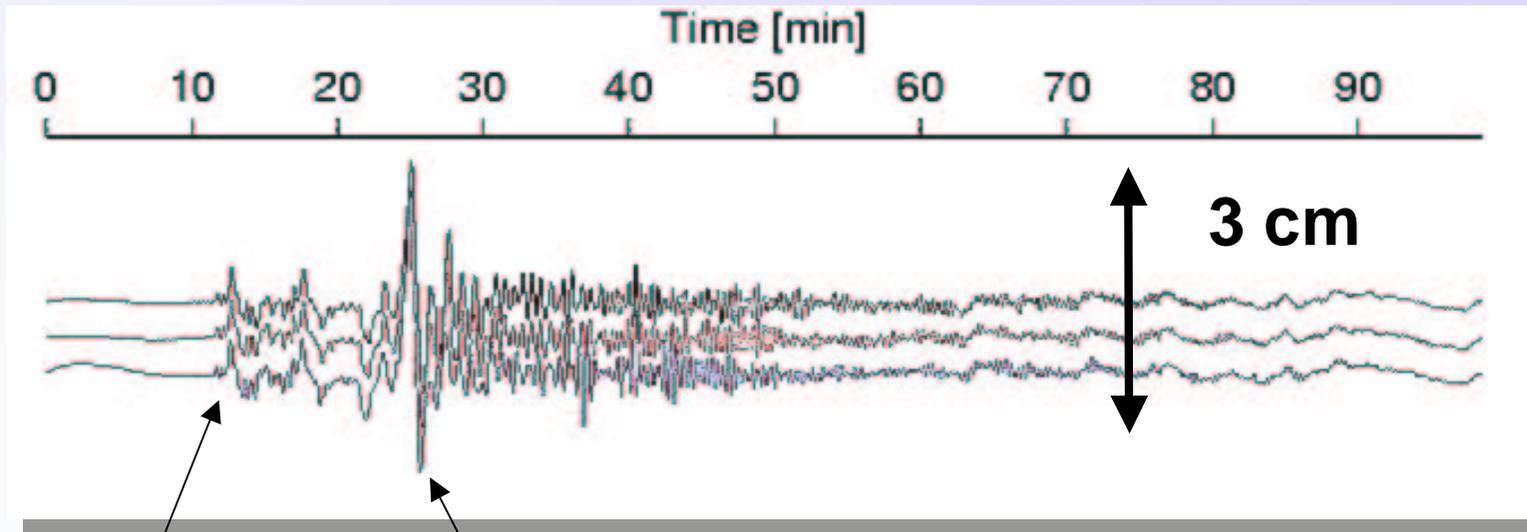Tsuboi, Tromp, Komatitsch, 2003

Simulation of
Global Wave Propagation

Elastic PSV Case
Dominant Period: 7.5 sec
Earth Model: Prem

Gunnar Jahnke
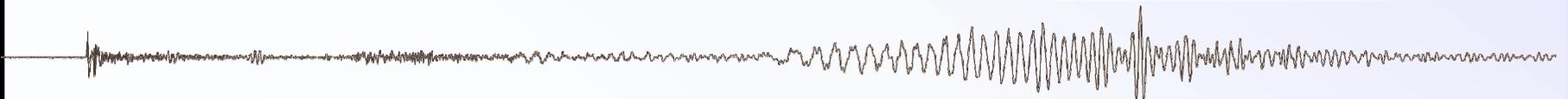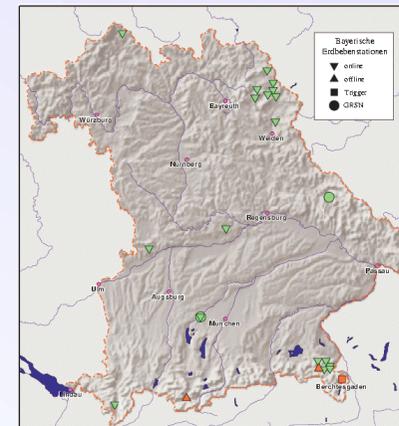(GJ@TerraeMotus.org)

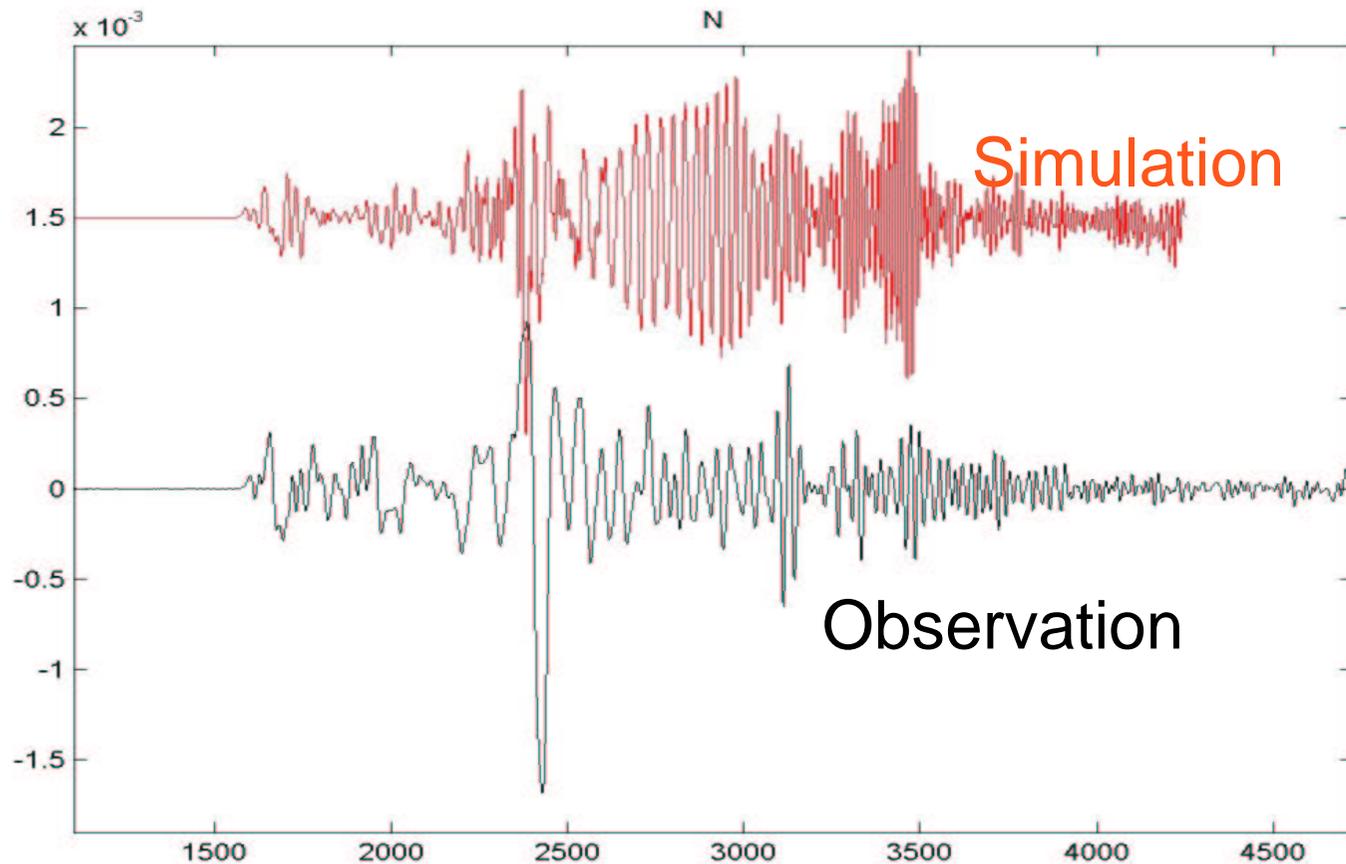# Theoretical seismograms - verification

Sumatra quake - Observations

Sumatra quake

Theory vs. observation

Tokachi-oki, M8.3
September 25, 2003

x 10⁴ Transverse acceleration 3D-FS: Data (ligth grey) and Synthetics (dark grey)
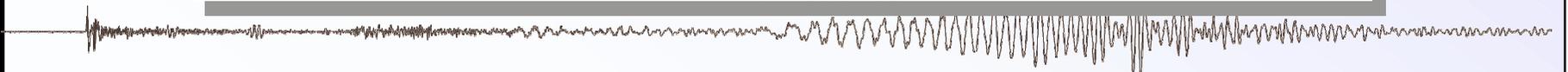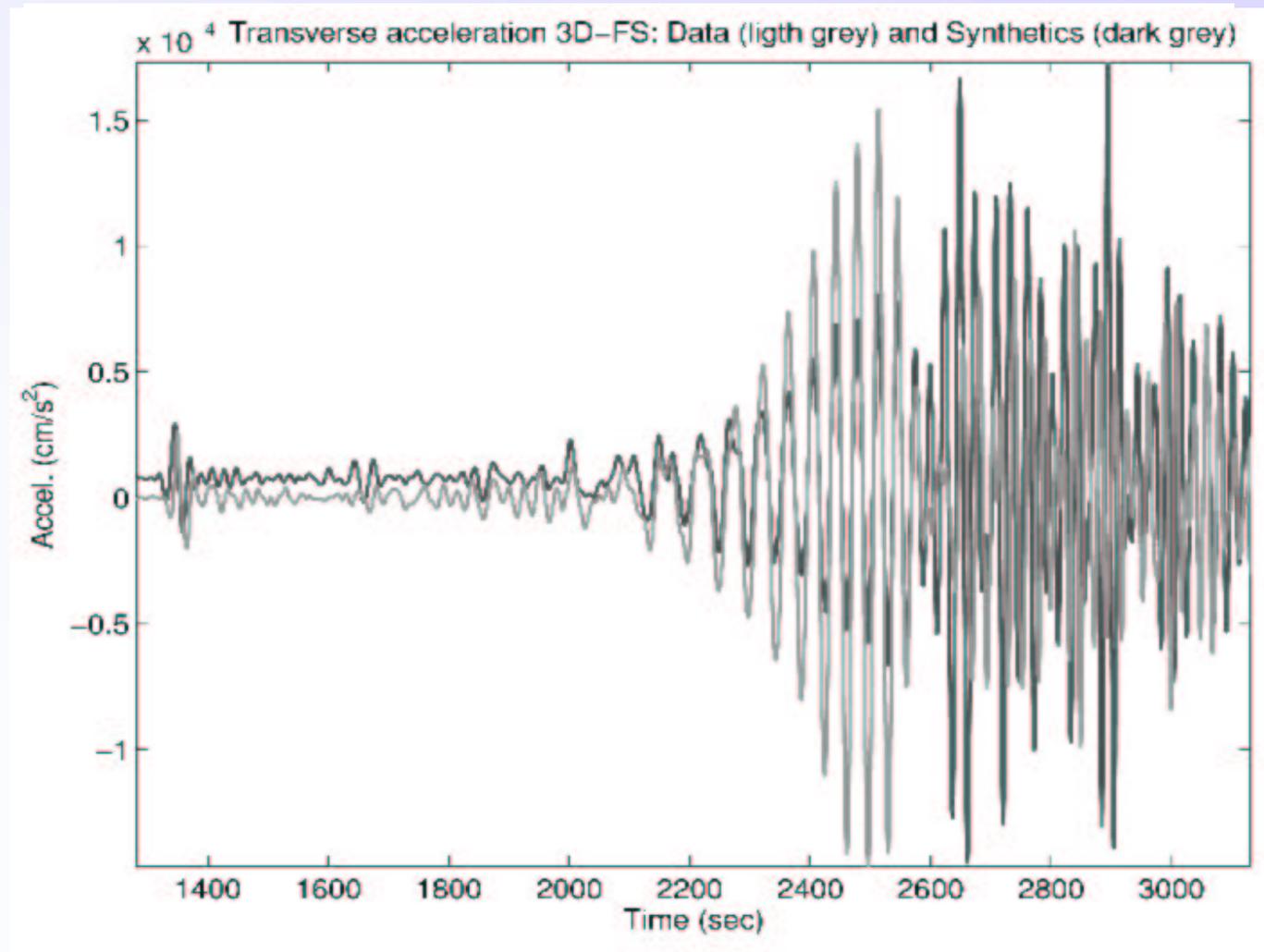
Global observations
Alaska, M7.9, November 2002
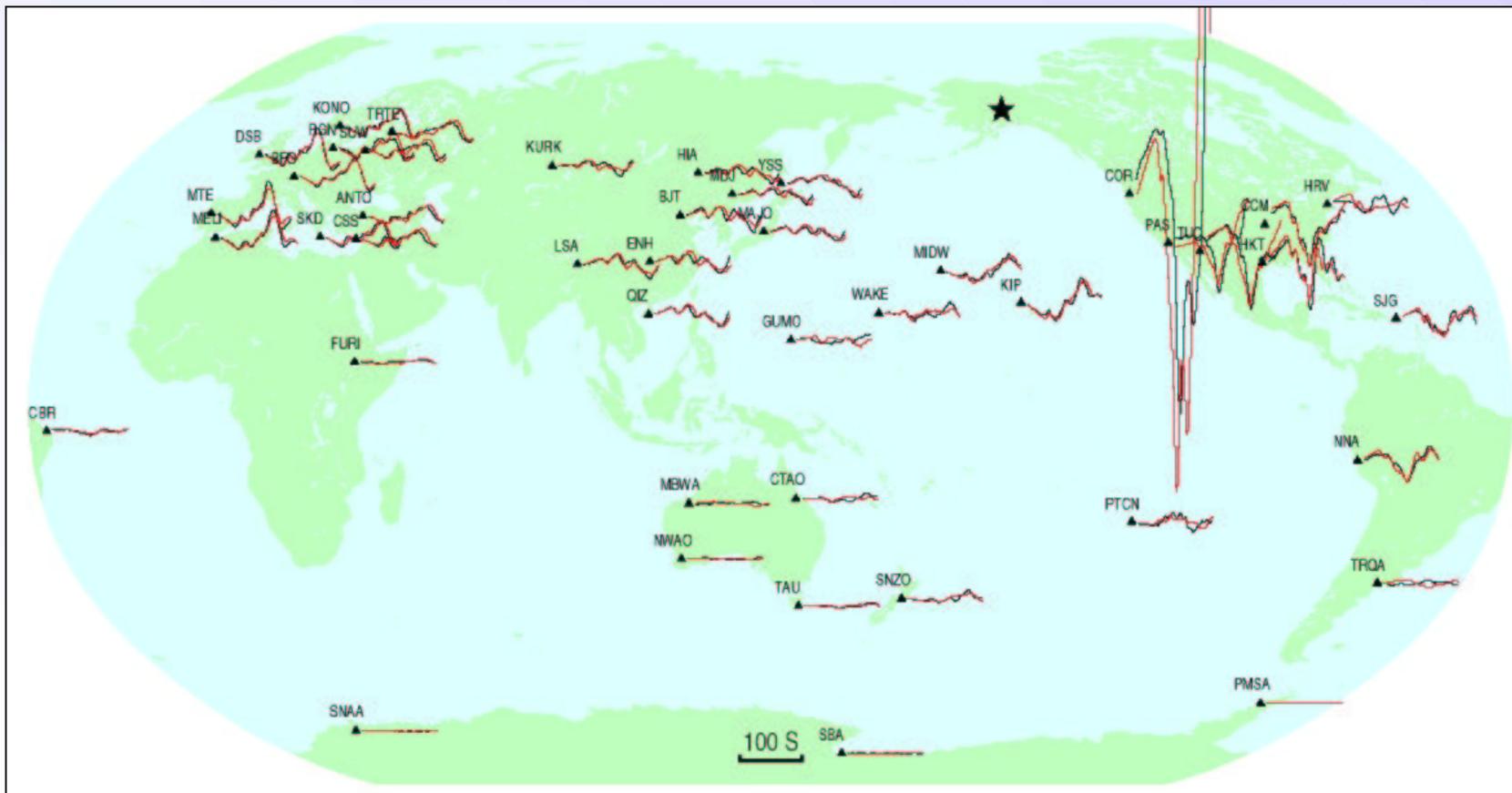
Tsuboi, Tromp, Komatitsch, 2003
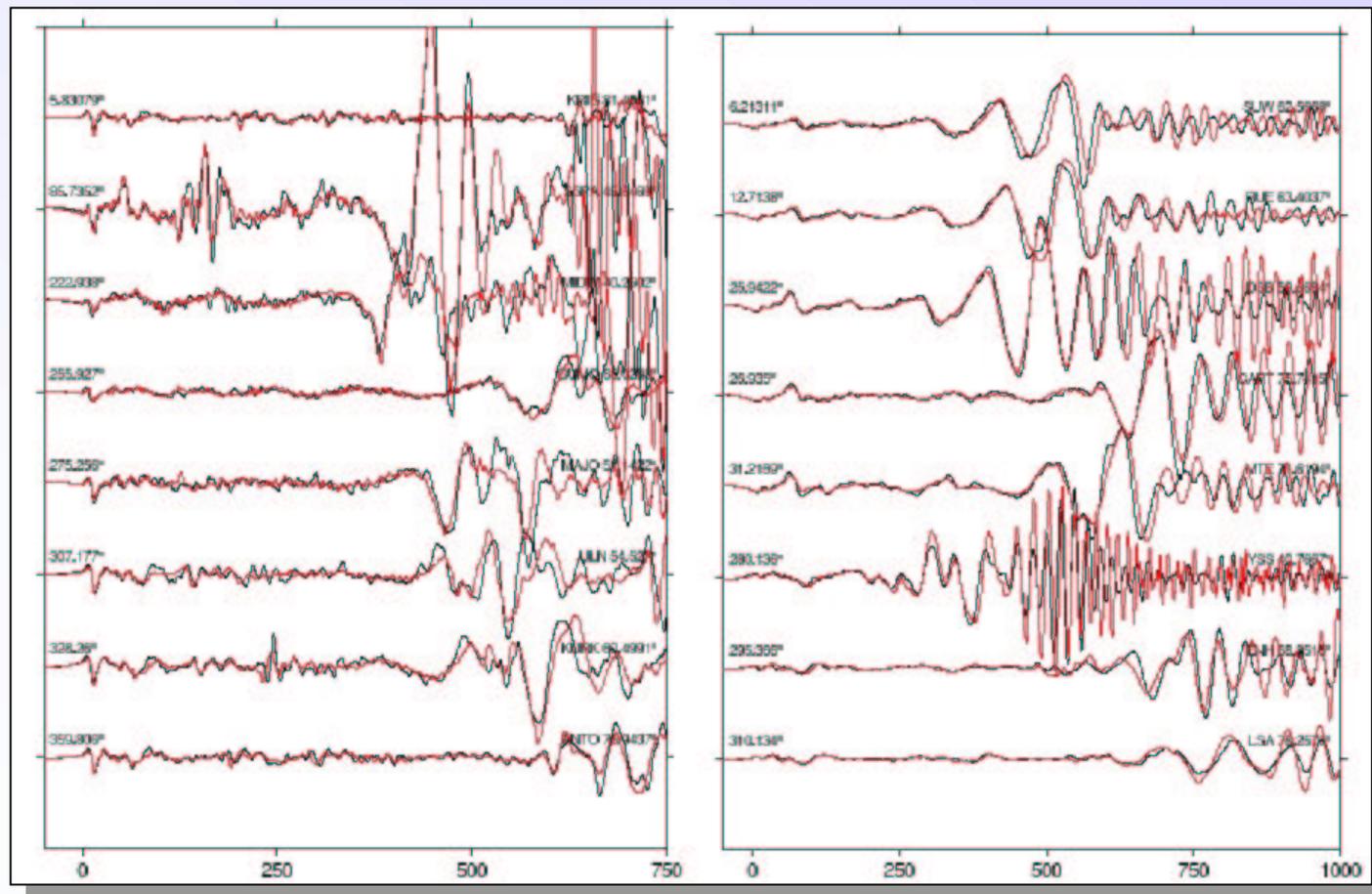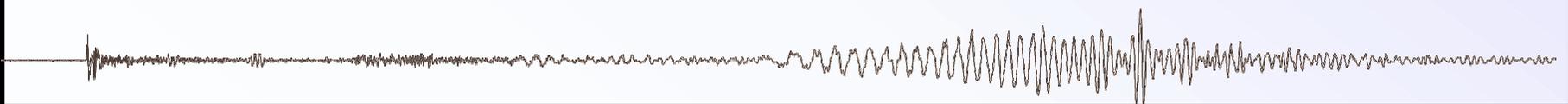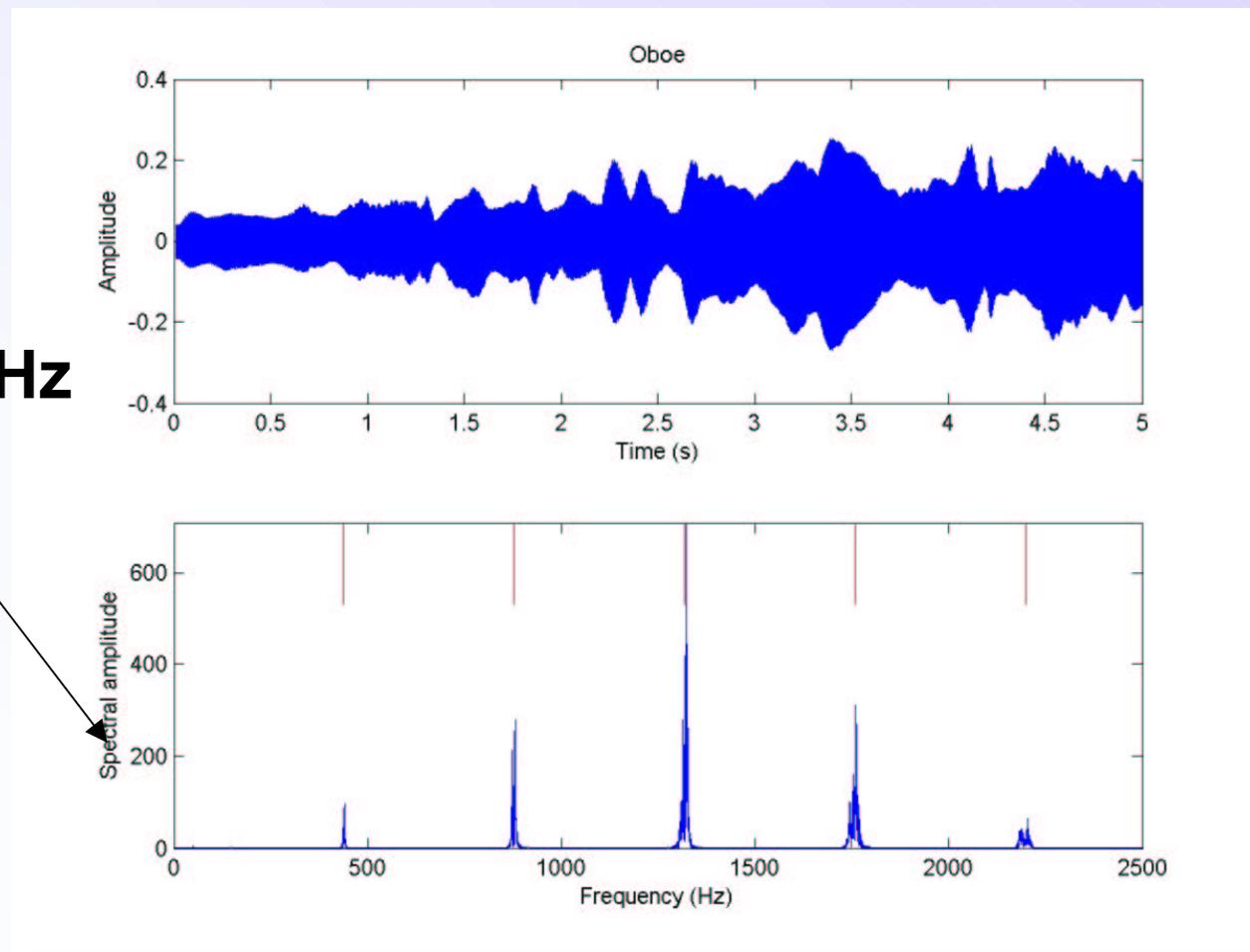
Global observations
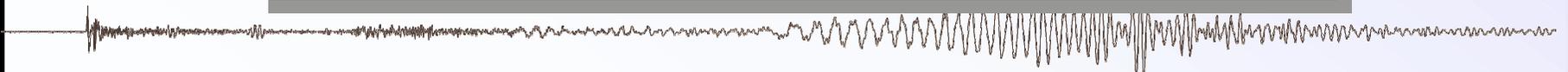# Alaska, M7.9, November 2002
observations (black) – simulations (red)

Tsuboi, Tromp, Komatitsch, 2003

Sound of an instrument
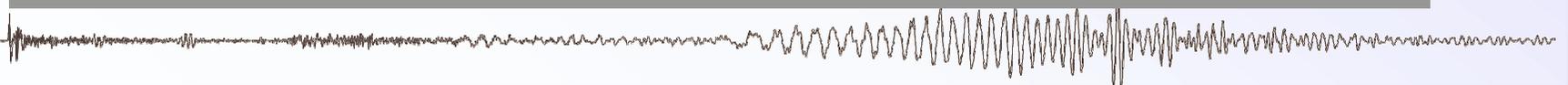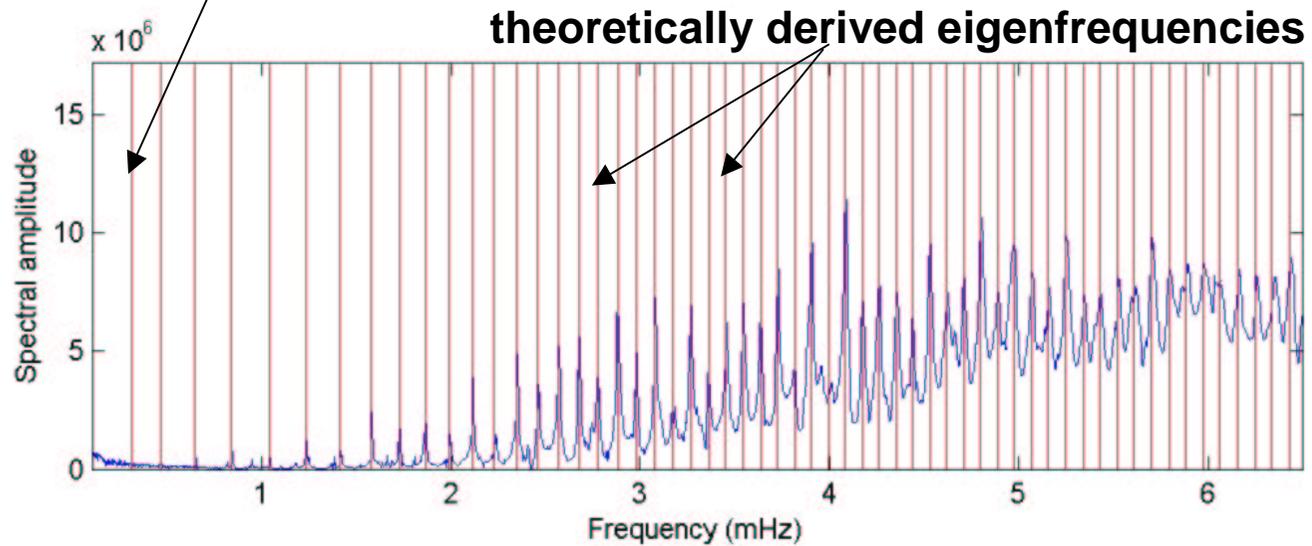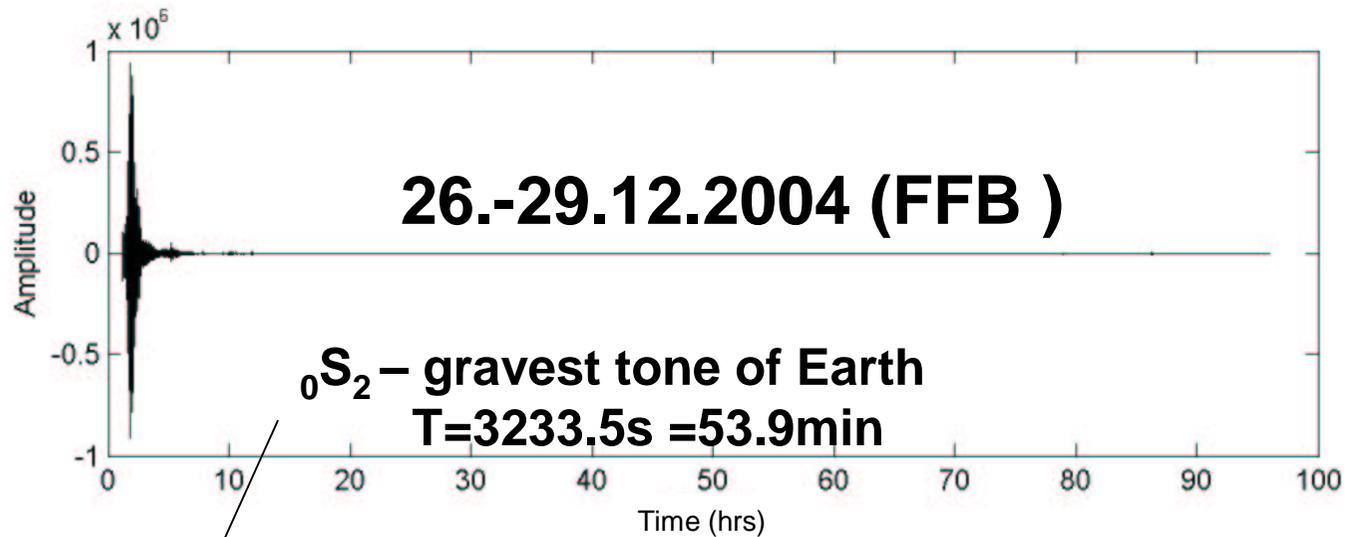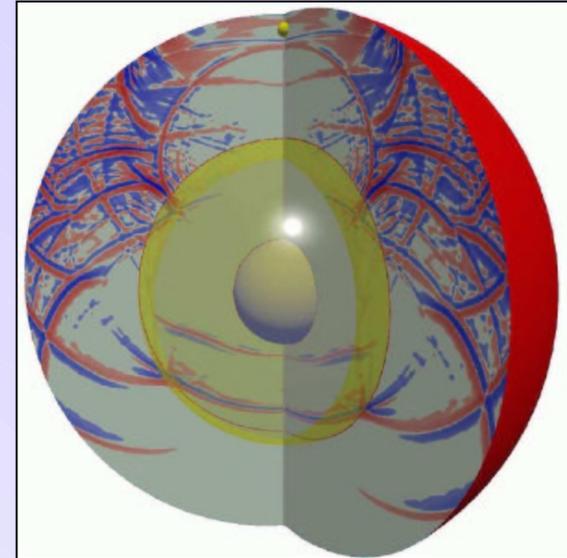
a' - 440Hz

Instrument Earth

26.-29.12.2004 (FFB)

$_0S_2$ – gravest tone of Earth
T=3233.5s =53.9min

theoretically derived eigenfrequencies

Summary
IV- Global seismology

- 3D wave propagation for models on a planetary scale is now possible

- These methods will be used in the near future to obtain a sharper image of the structure inside the Earth

- There are still many open questions about the dynamics of the Earth's deep interior, seismology can – at least – provide an image of the state of the Earth's convective system now

Outlook

- What shall we do with the gigantic amount of synthetic data that we create in addition to observations?

- How can our modelling/simulation tools help the observers in Earth sciences?

- How can we involve students in these developments?

... some of these issues are currently dealt with in our EU network SPICE with UoU as partner (Prof. J. Trampert) ...

www.spice-rtn.org