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

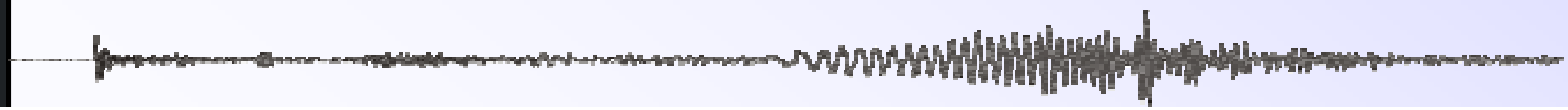
With contributions by Michael Ewald, Gilbert Brietzke, Markus Treml, Michael Thorne, Gunnar Jahnke, Johannes Ripperger

Slides at: http://www.geophysik.uni-muenchen.de/~igel/utrecht

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

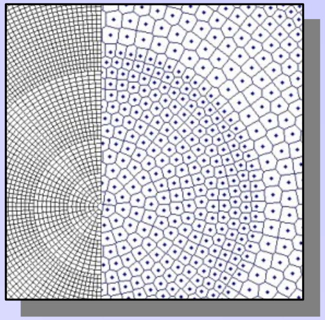
Elastic wave equations

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

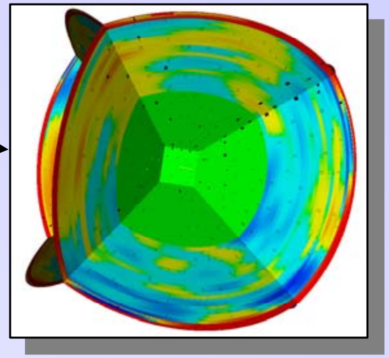
$$\sigma_{ij} = c_{ijkl} \varepsilon_{kl}$$

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

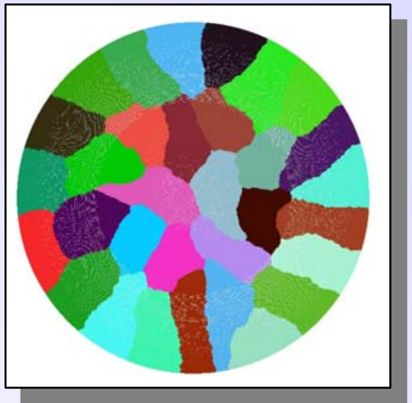
Grid



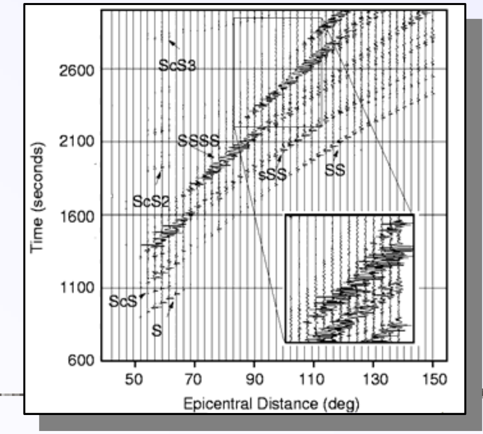
3D Model



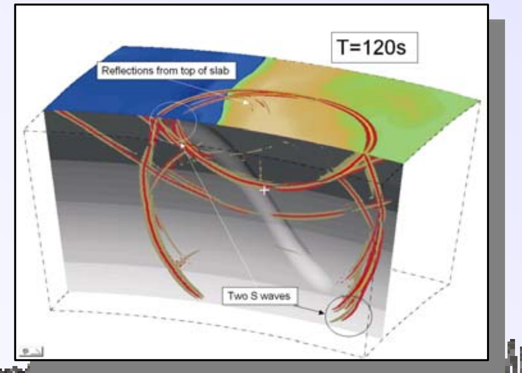
Parallelisation



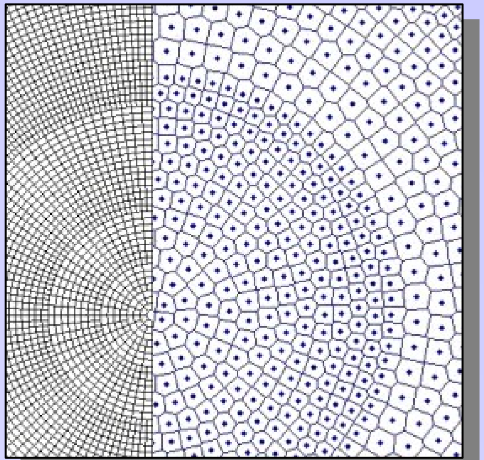
Synthetic seismograms



Simulation



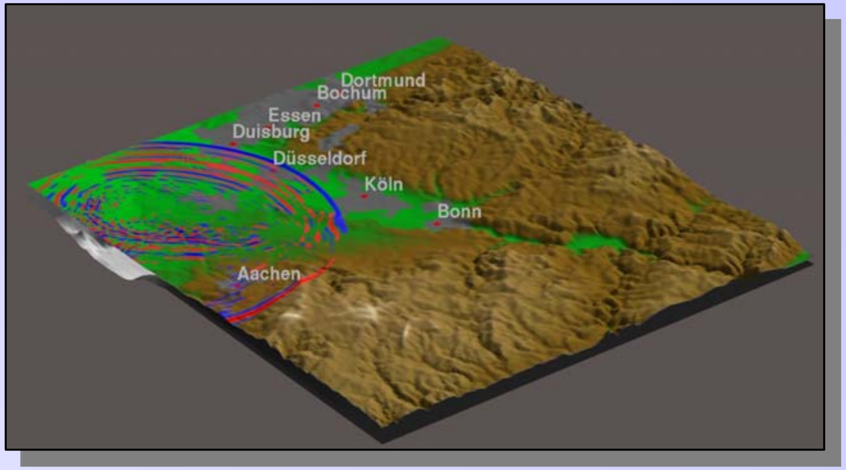
Numerical methods



- Finite Differences (high order, optimal operators)
- Pseudospectral methods (Chebyshev, Fourier, Lagrange)
- Unstructured grids (finite volumes, natural neighbours)
- Finite/spectral elements
- Parallelization using MPI (message passing interface)

-> for rupture problems special internal boundary conditions apply

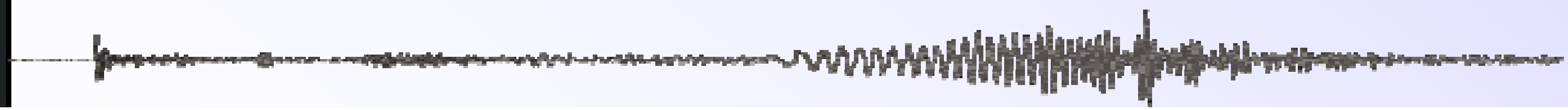
Typical model (grid) sizes



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

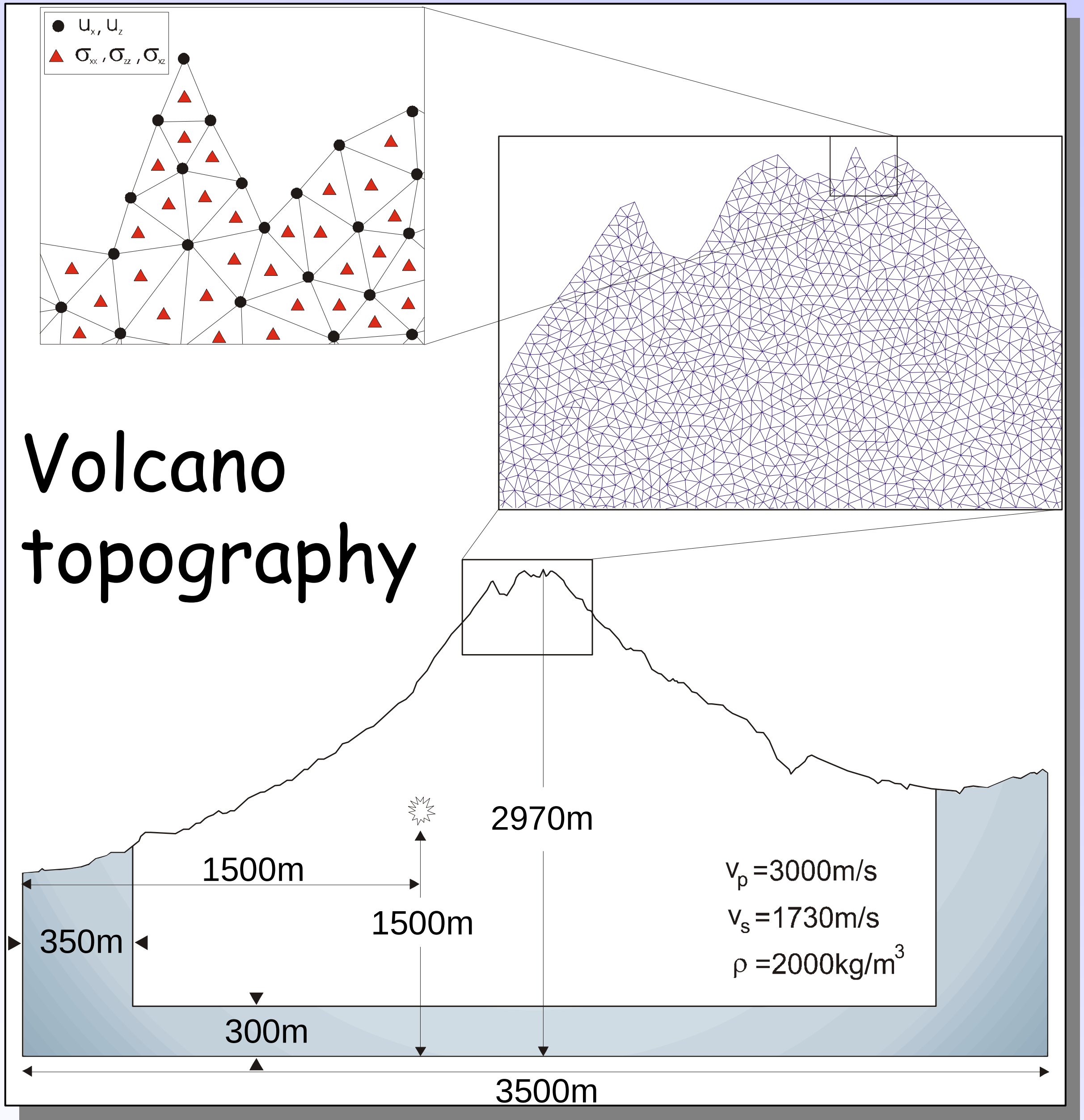


I - Volcano seismology

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?

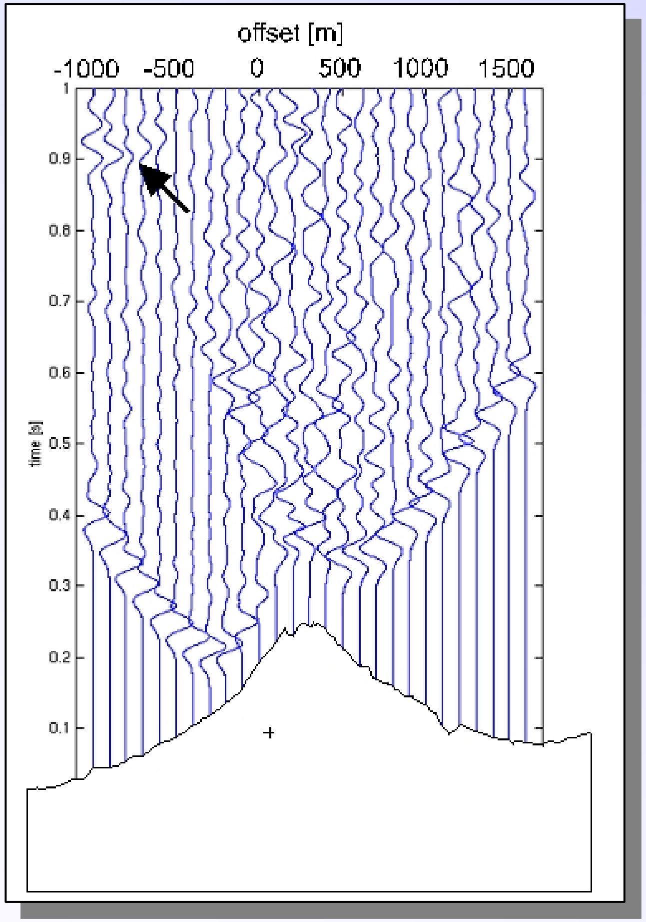
Disciplines:
- seismology – petrology - mineralogy – meteorology – material science – geology – physics – geochemistry

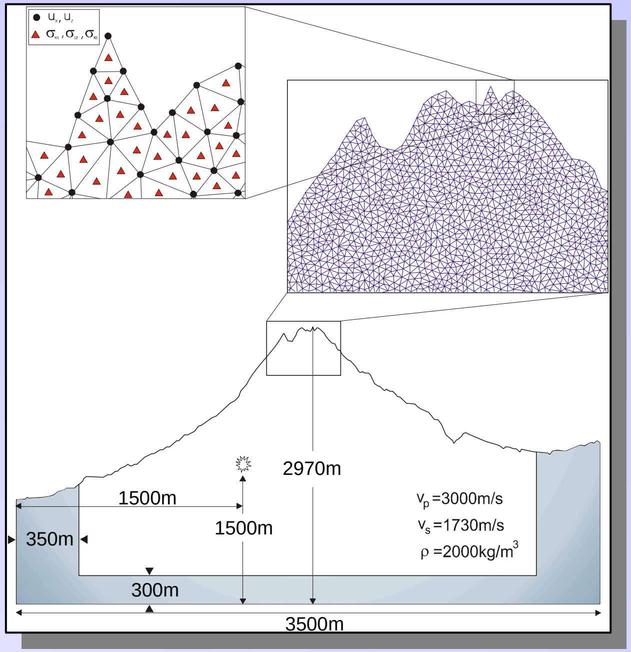
Supercomputing:
- 3D wave propagation, topography, scattering, source processes, tomography

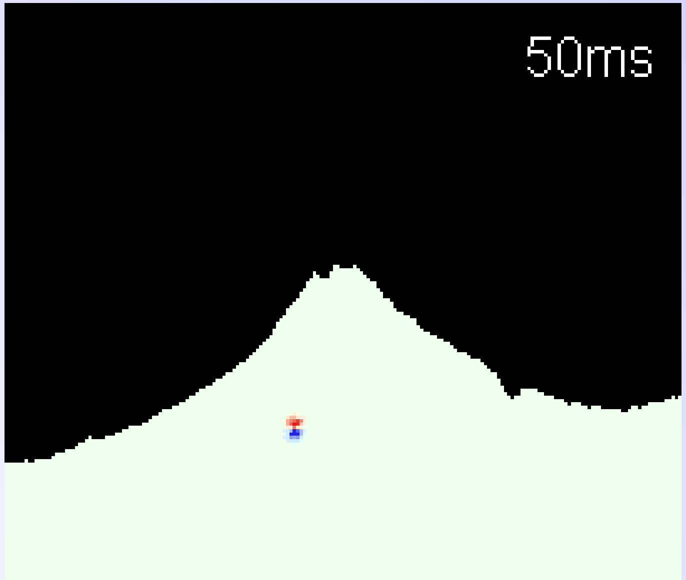


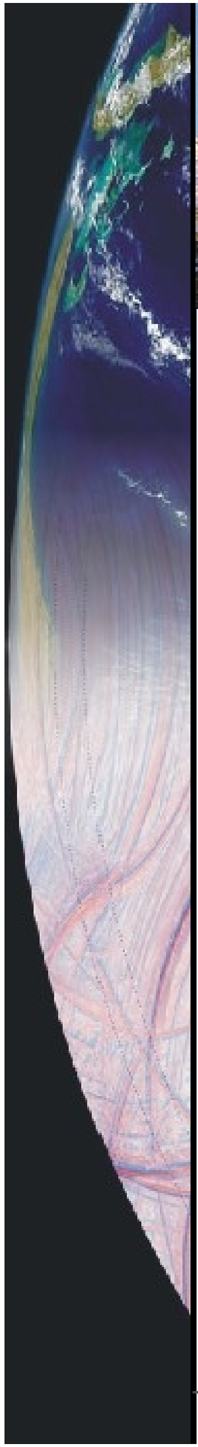
u_x, u_z
$\sigma_{xx}, \sigma_{zz}, \sigma_{xz}$
Volcano topography
2970m
1500m
1500m
350m
300m
3500m
v_p =3000m/s
v_s =1730m/s
ρ =2000kg/m^3

Volcano topography









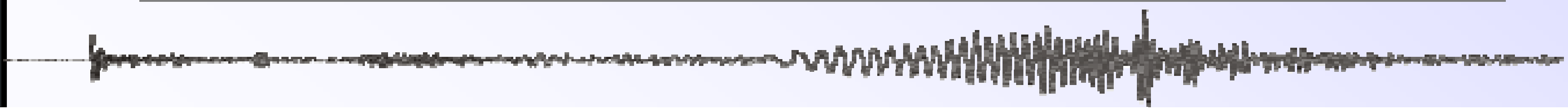
Summary
II - Volcano seismology

- 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:

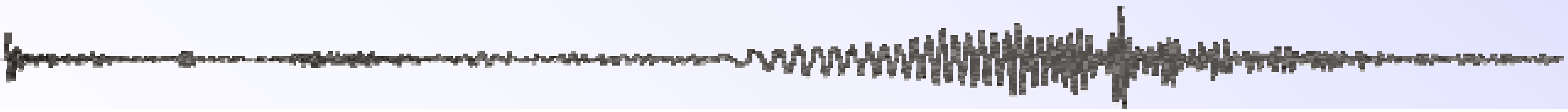
- What processes control the seismic rupture?
- What temporal and spatial scales are relevant (seismic cycle)?
- What means (experiments/simulations) are necessary to progress the field?

Disciplines:

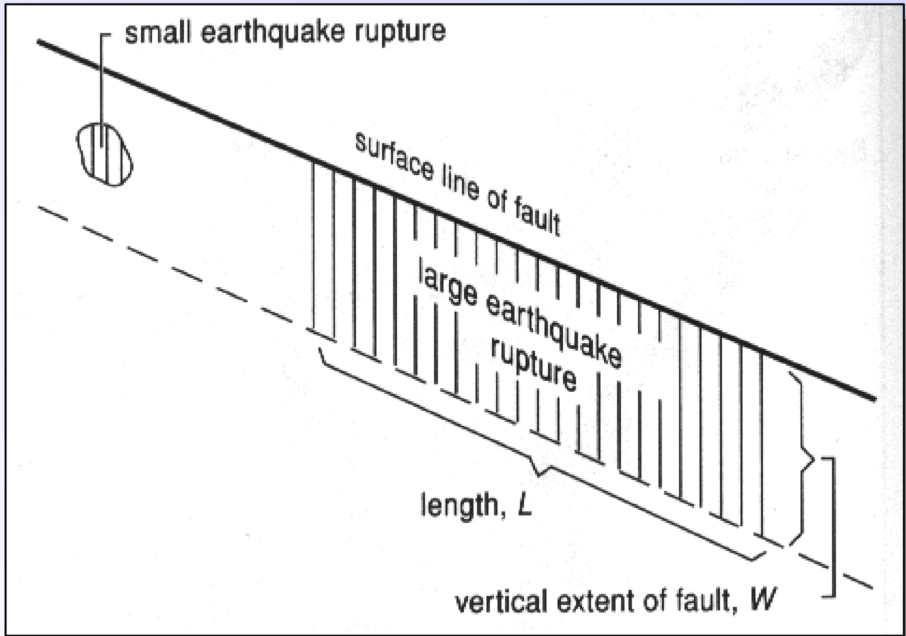
- seismology – mathematics – petrology – theoretical mechanics – rheology – hydrology – computational physics – statistical physics ...

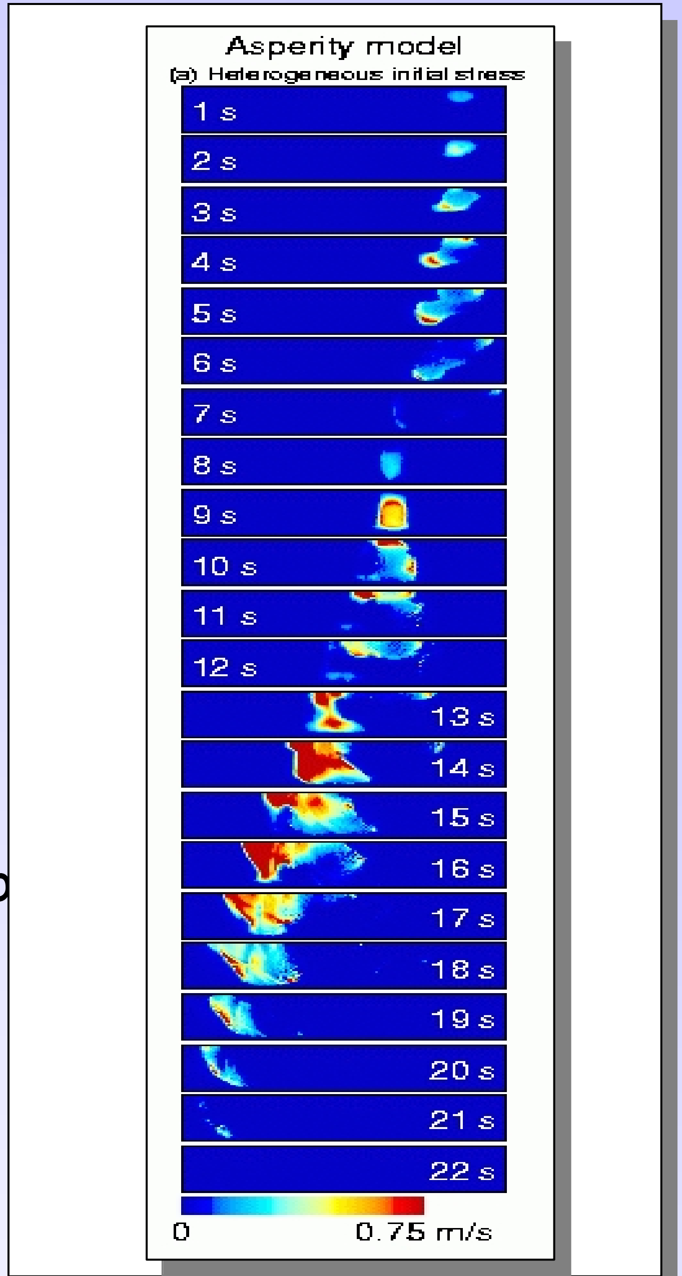
Supercomputing:

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



What is an earthquake?



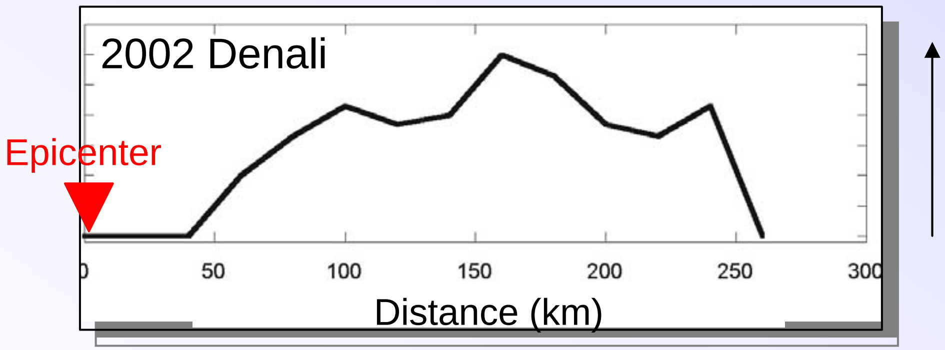


Source: K. Olsen

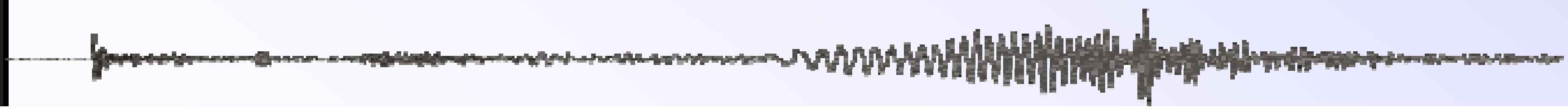
Two curious observations

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

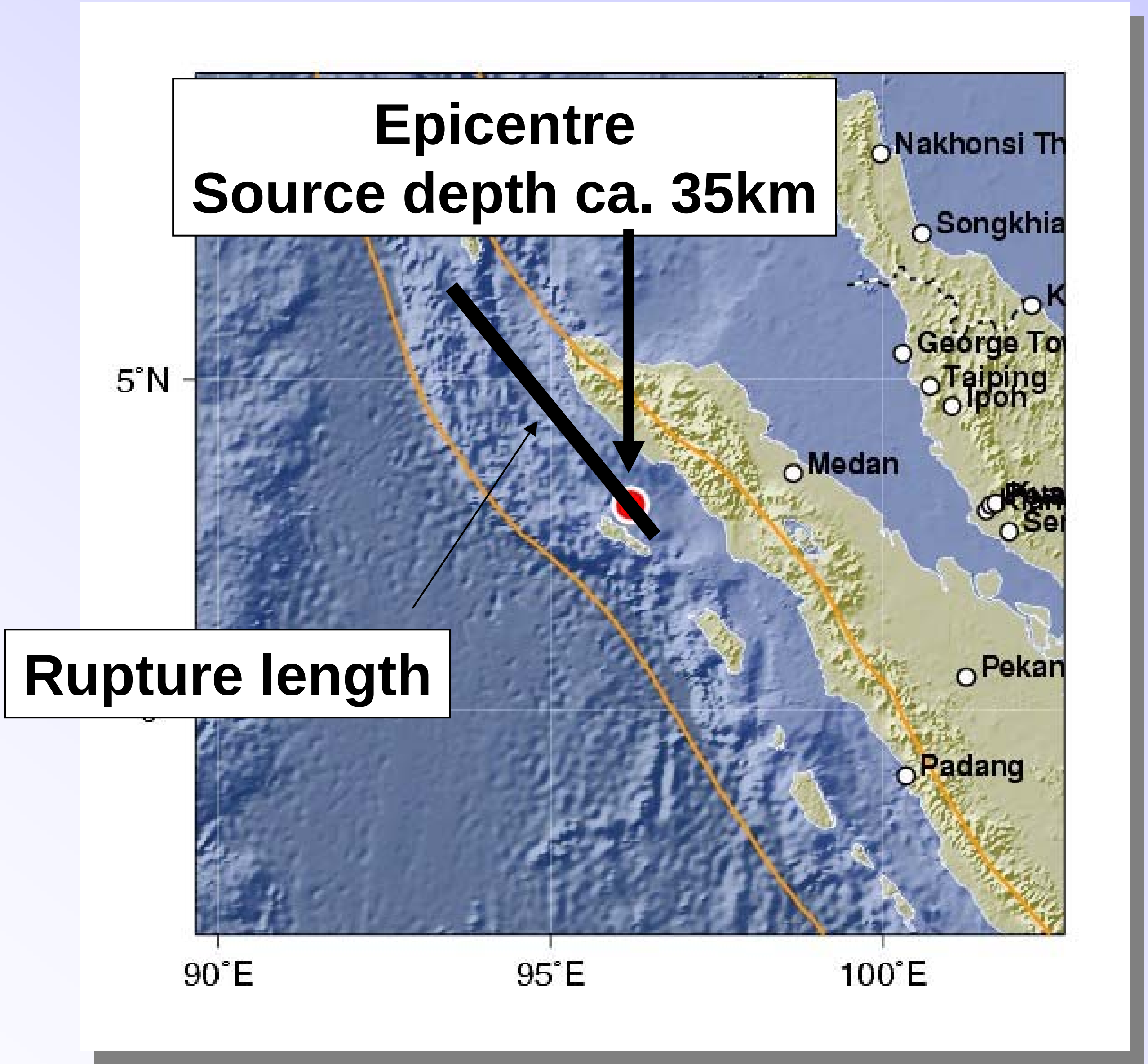
- The theory of crack propagation says that a rupture should propagate in both directions. We observe uni-lateral rupture for 80% of the large earthquakes.



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



26 Dec 2004 01:58:53MET



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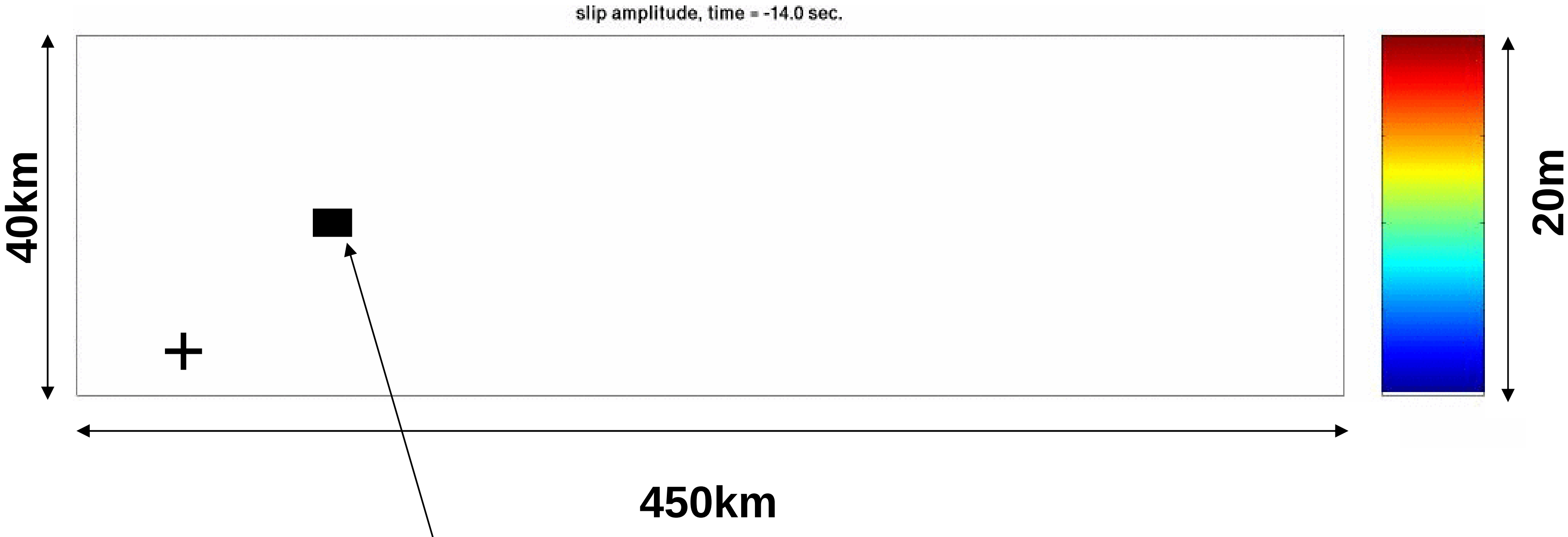
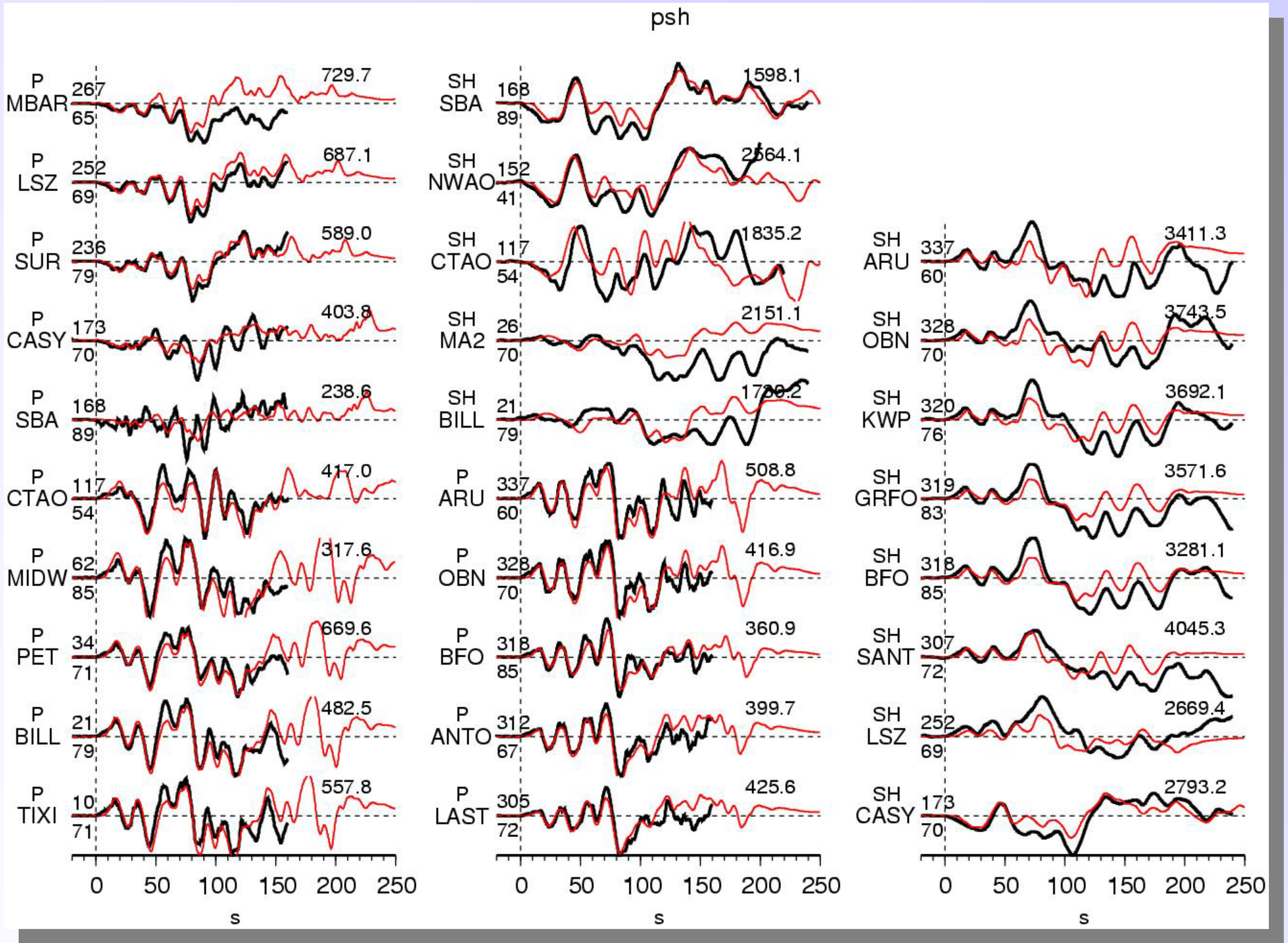
Sumatra rupture process

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



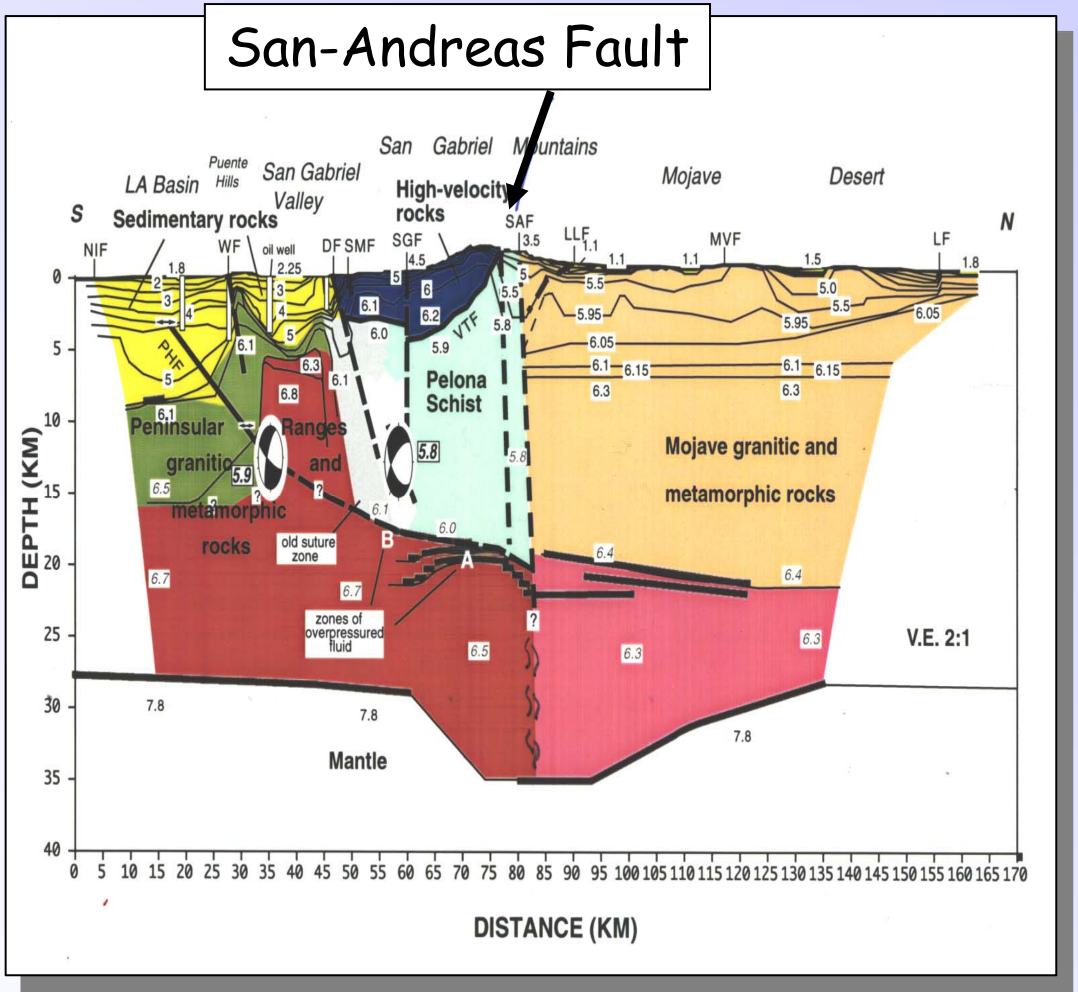
Largest conceivable rupture size in central Europe

Theory (black) – Observations (red)
First 250 seconds

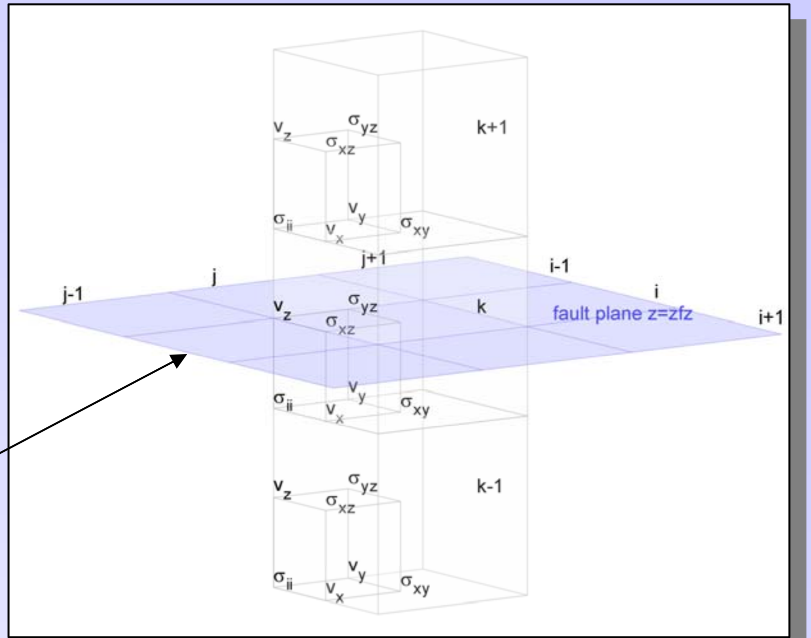


Possible explanation:

unilateral rupture – material interface



Dynamic Rupture in a 3D medium

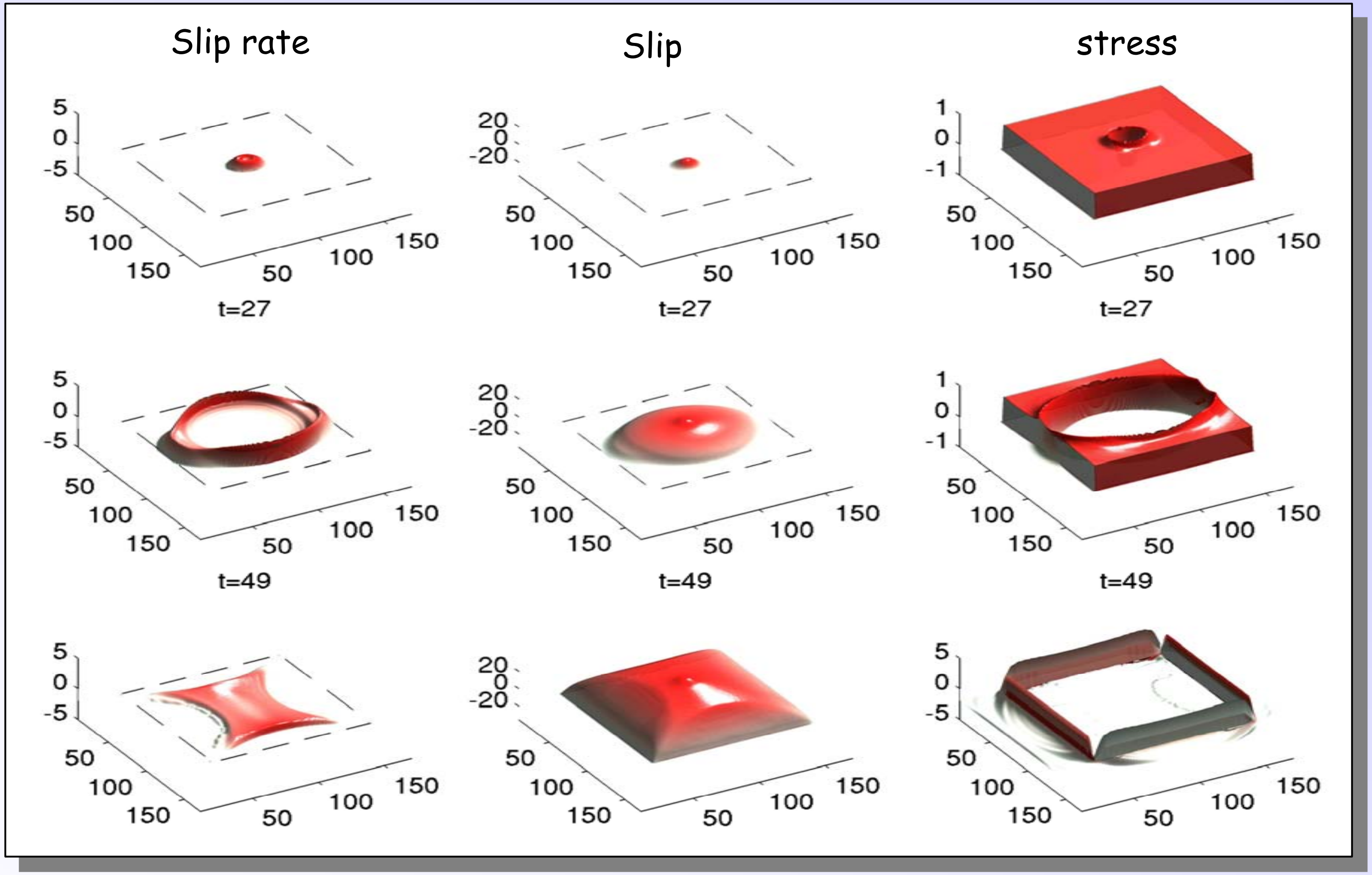


Fault surface

- 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)

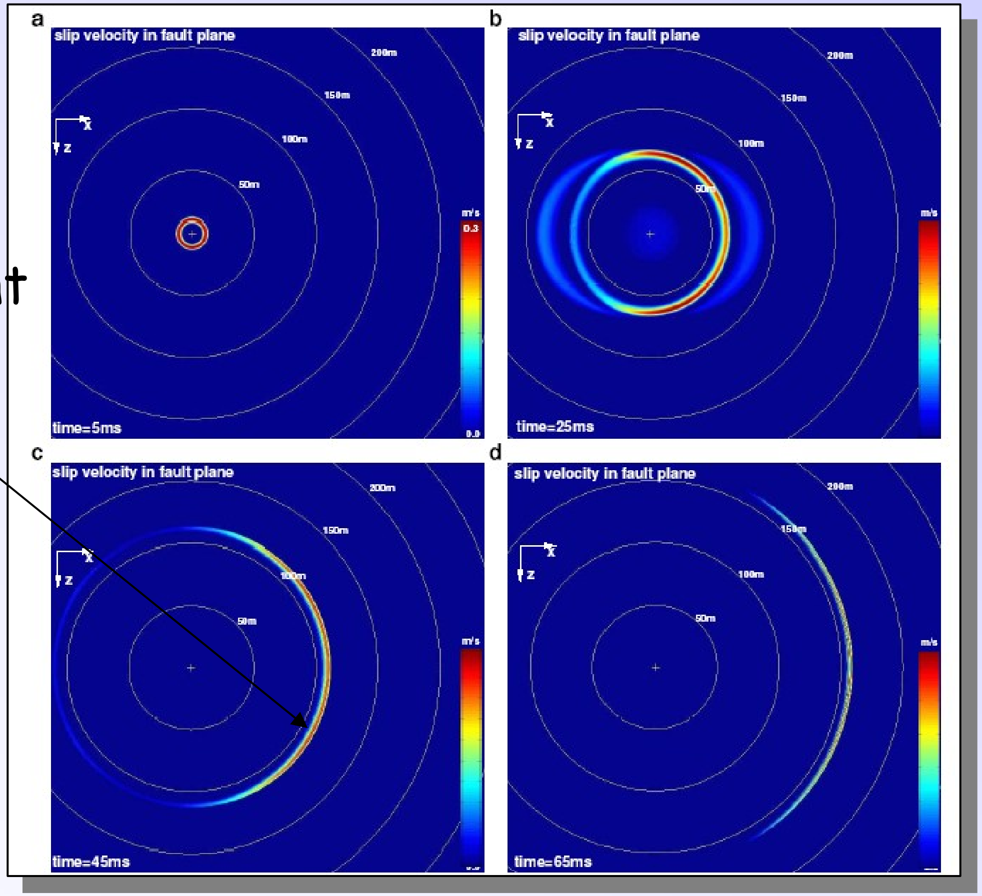
3D simulation of rupture

Time



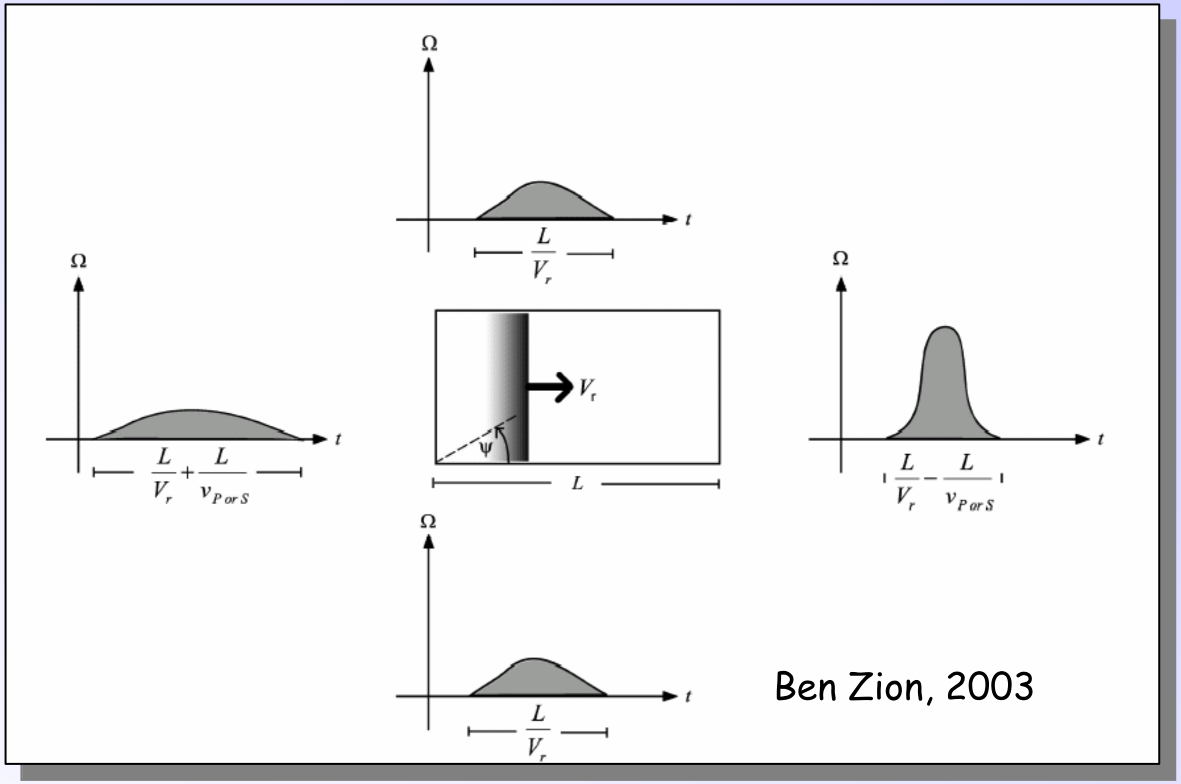
Pulse-like rupture at a material interface slip-rate as a function of time

Rupture front



Brietzke und Ben Zion, 2003

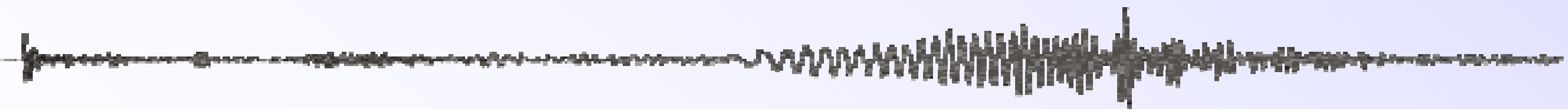
Directivity



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?)



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:

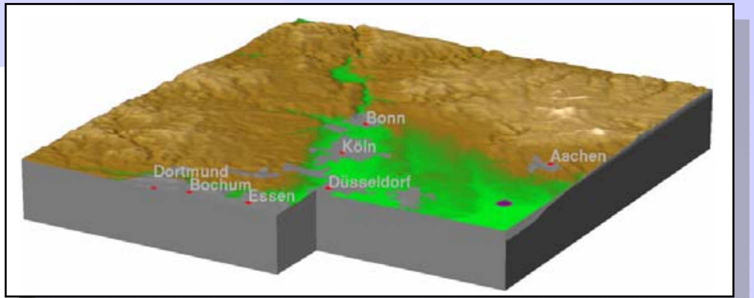
- Do we know the earthquake hazard of specific regions?
- Can we estimate the strong ground motions for specific earthquake scenarios?
- What information is necessary to make these estimates reliable?

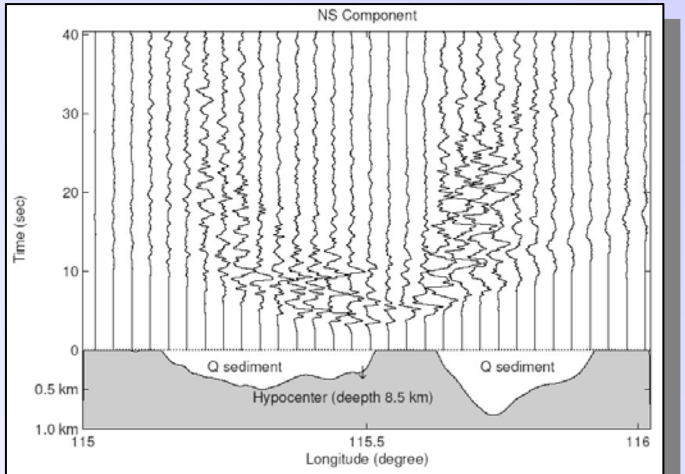
Dsiciplines:

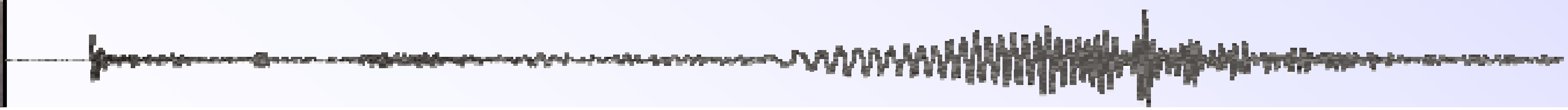
- seismology – earthquake engineering – geology – neotectonics (paleo-seismology) – geomorphology – geodesy ...

Supercomputing:

- Calculation of earthquake scenarios in frequency bands that are relevant for earthquake engineers (structural safety)







Taiwan M7.4 Earthquake 1999

Taiwan M7.4 Earthquake 1999

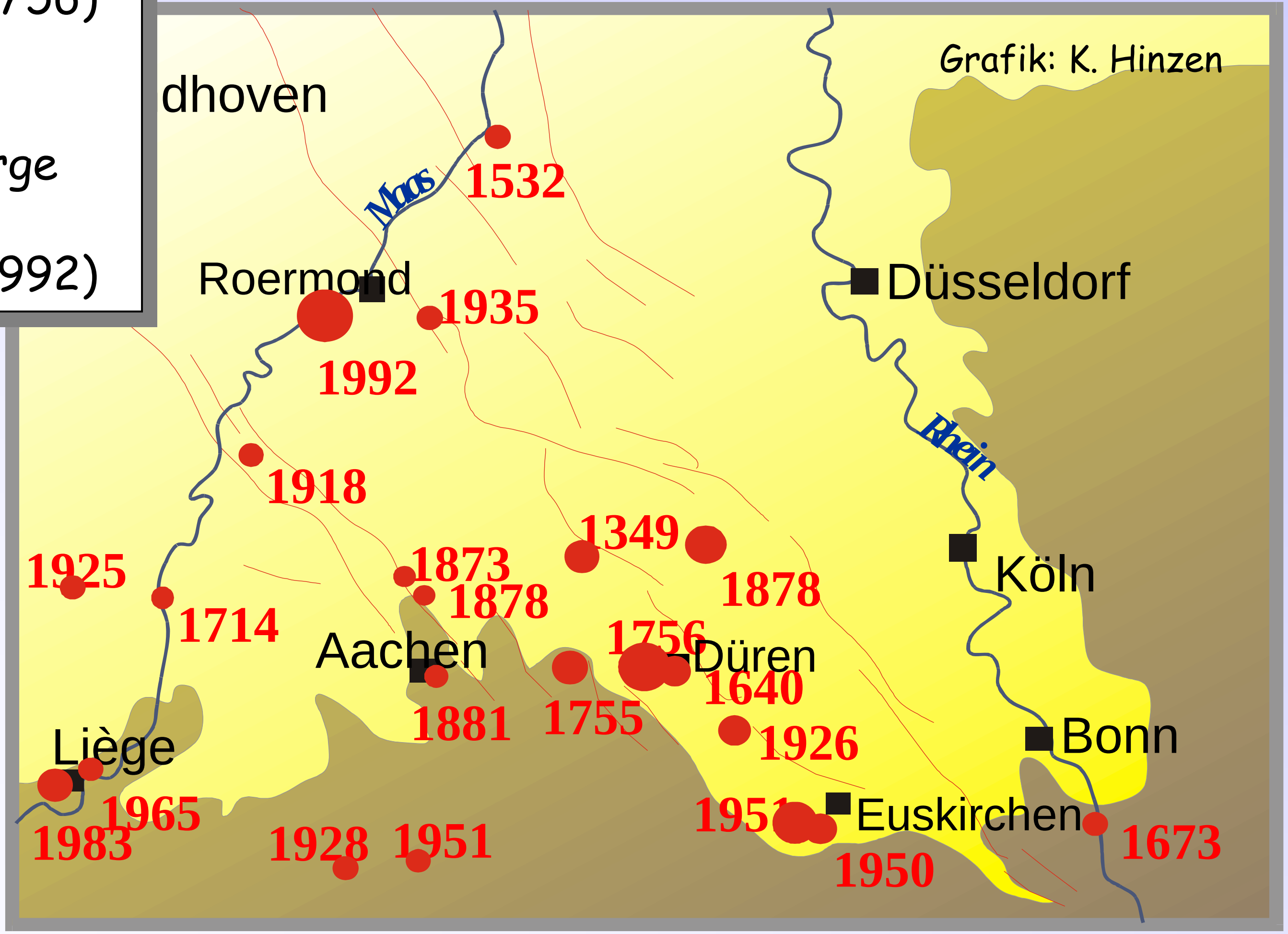
Cologne Basin Tectonics

Sediment basins may lead to large amplifications of ground motion

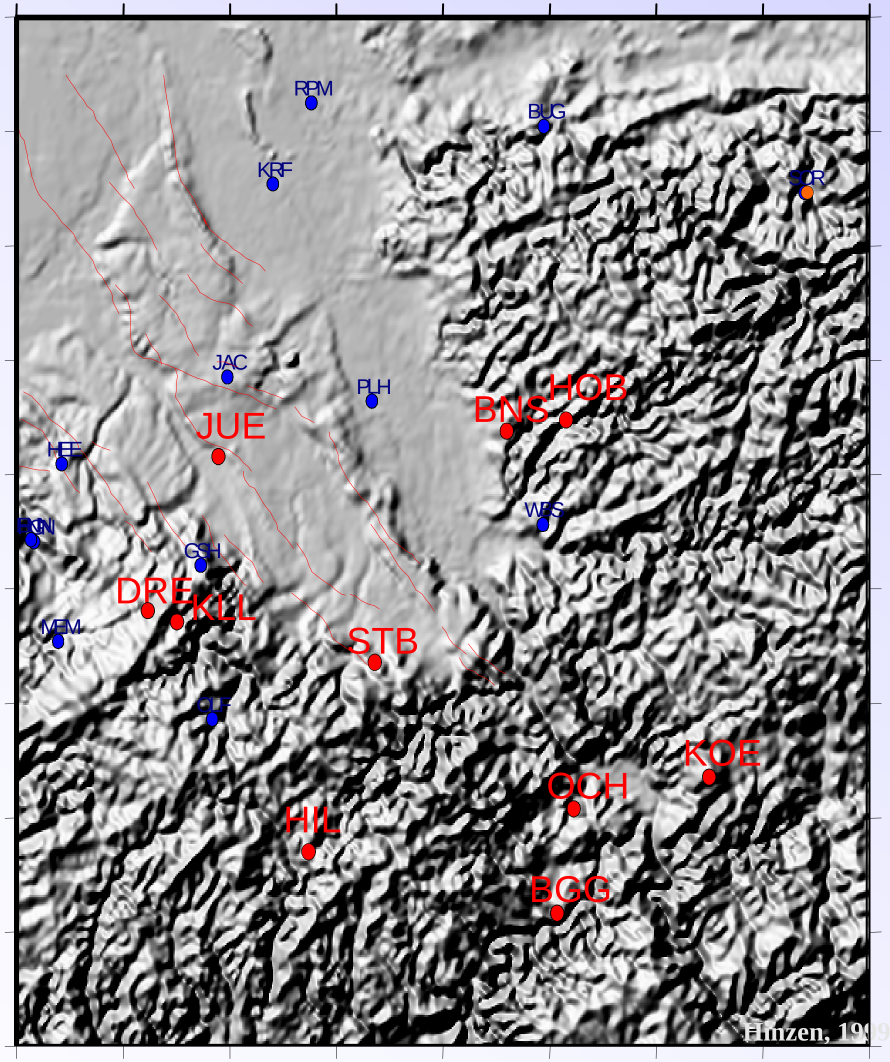
Earthquakes in the Cologne Basin

Largest event
M_L=6.4 (1756)

Latest large event
M_L=5.9 (1992)



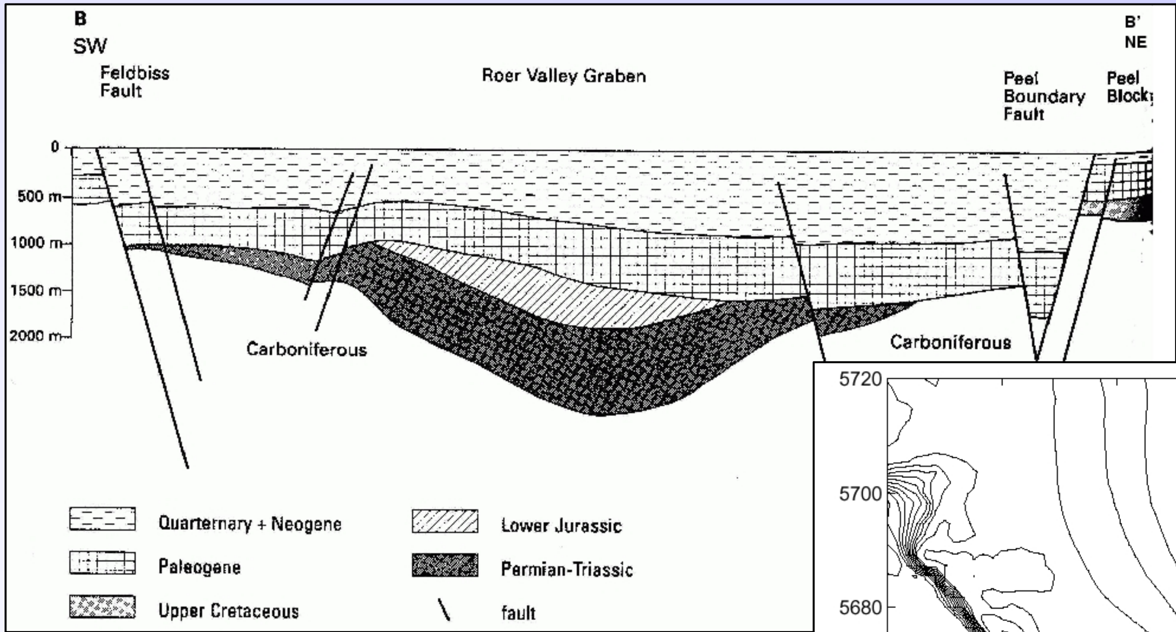
Known earthquake faults



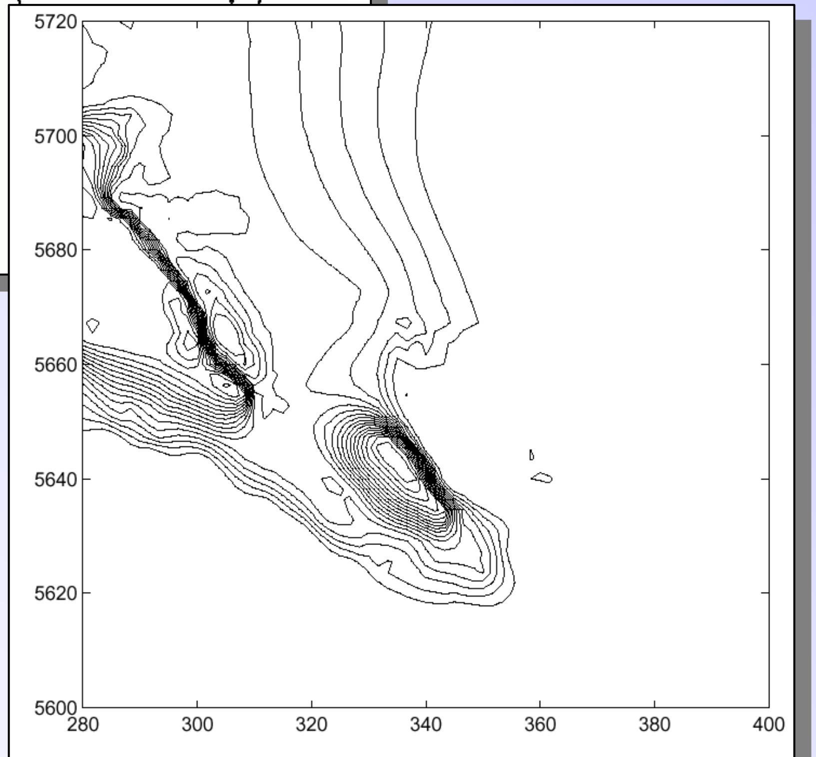
In paleoseismology and geology (neotectonics) one tries to recognize active faults and determines maximum rupture dimensions (-> magnitudes)

This allows in principle the calculation of potential earthquake scenarios.

Sediment structure

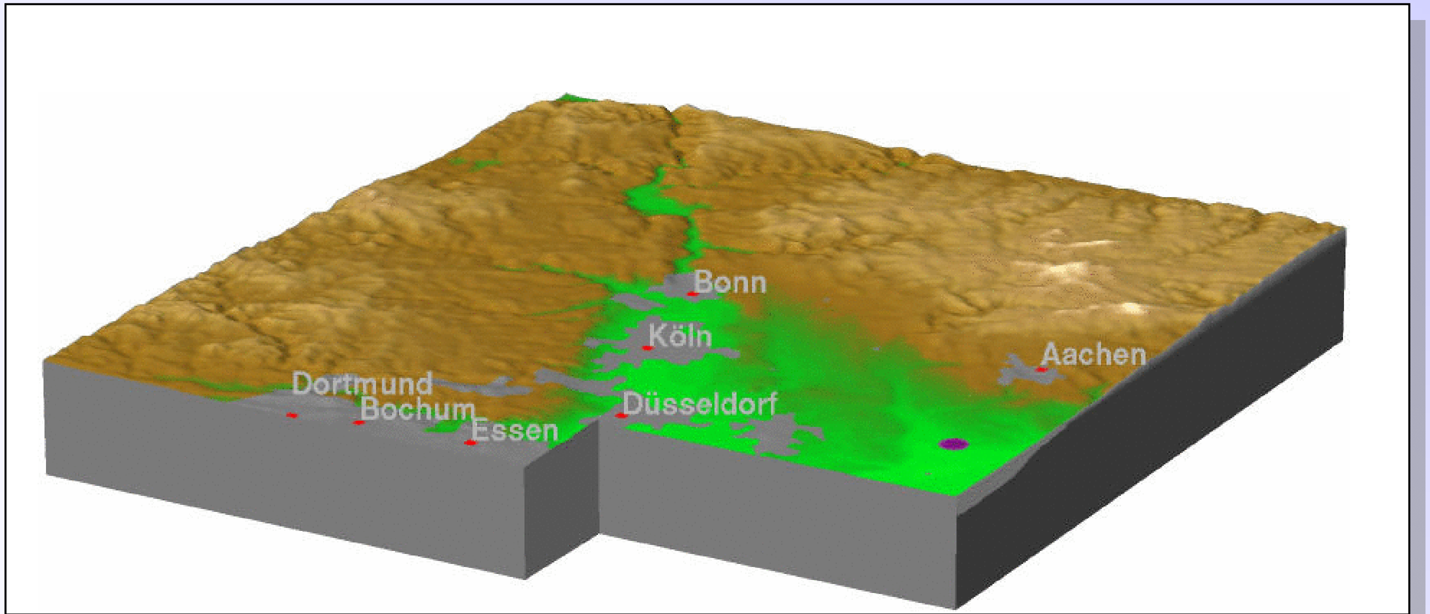


Basement topography

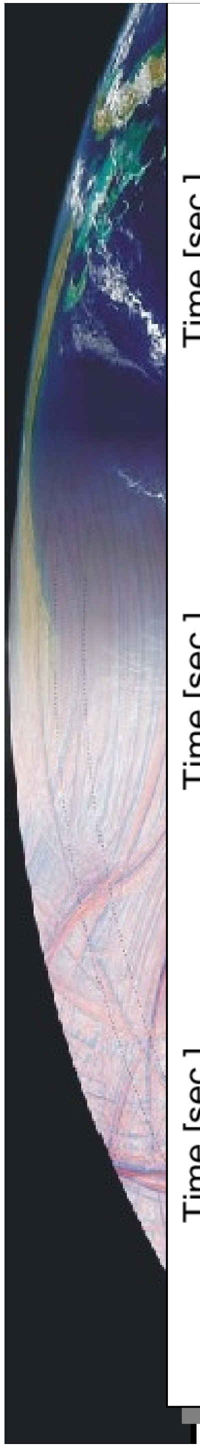


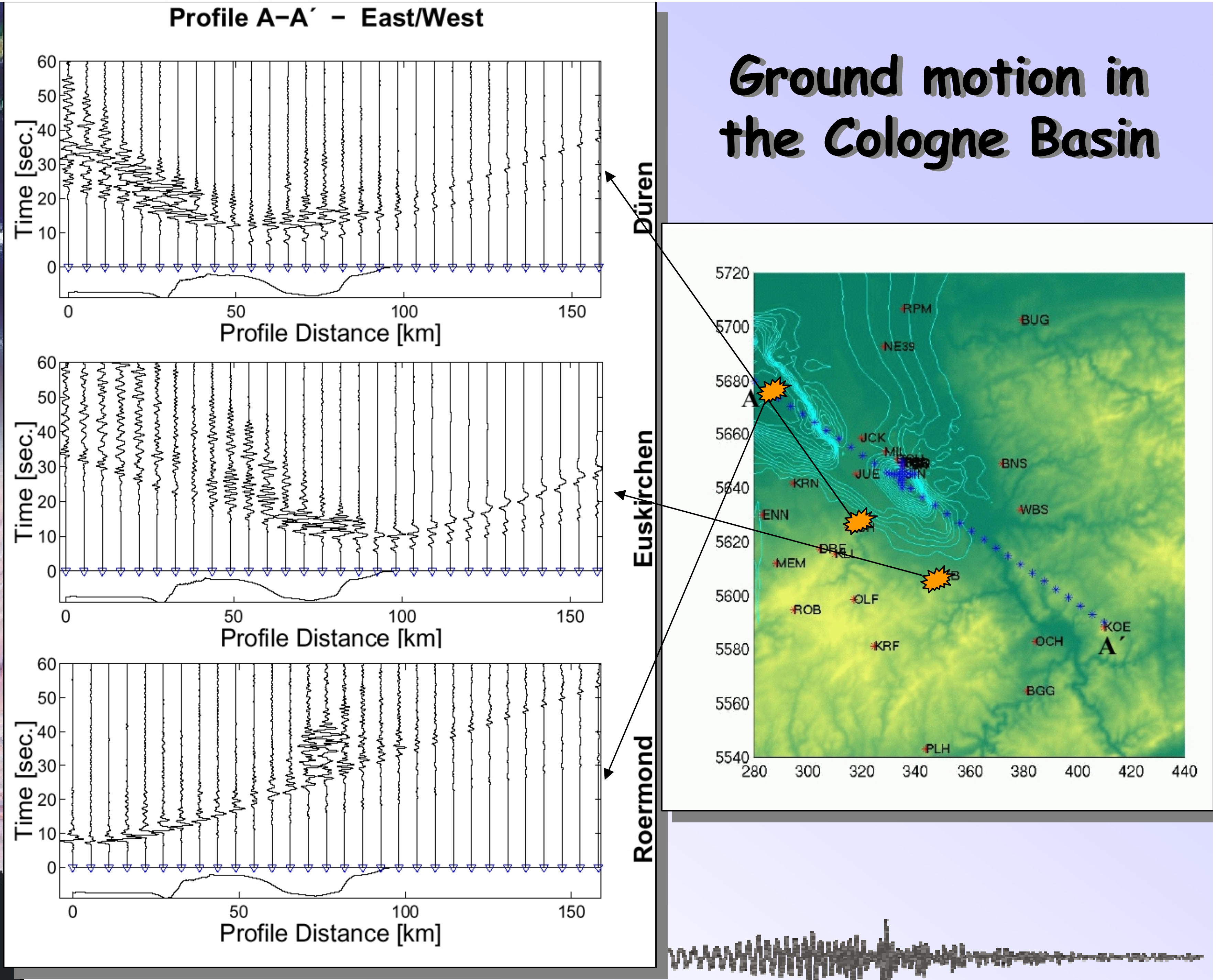
Earthquake scenarios

Roermond – earthquake M5.9, 1992



Ground motion in the Cologne Basin

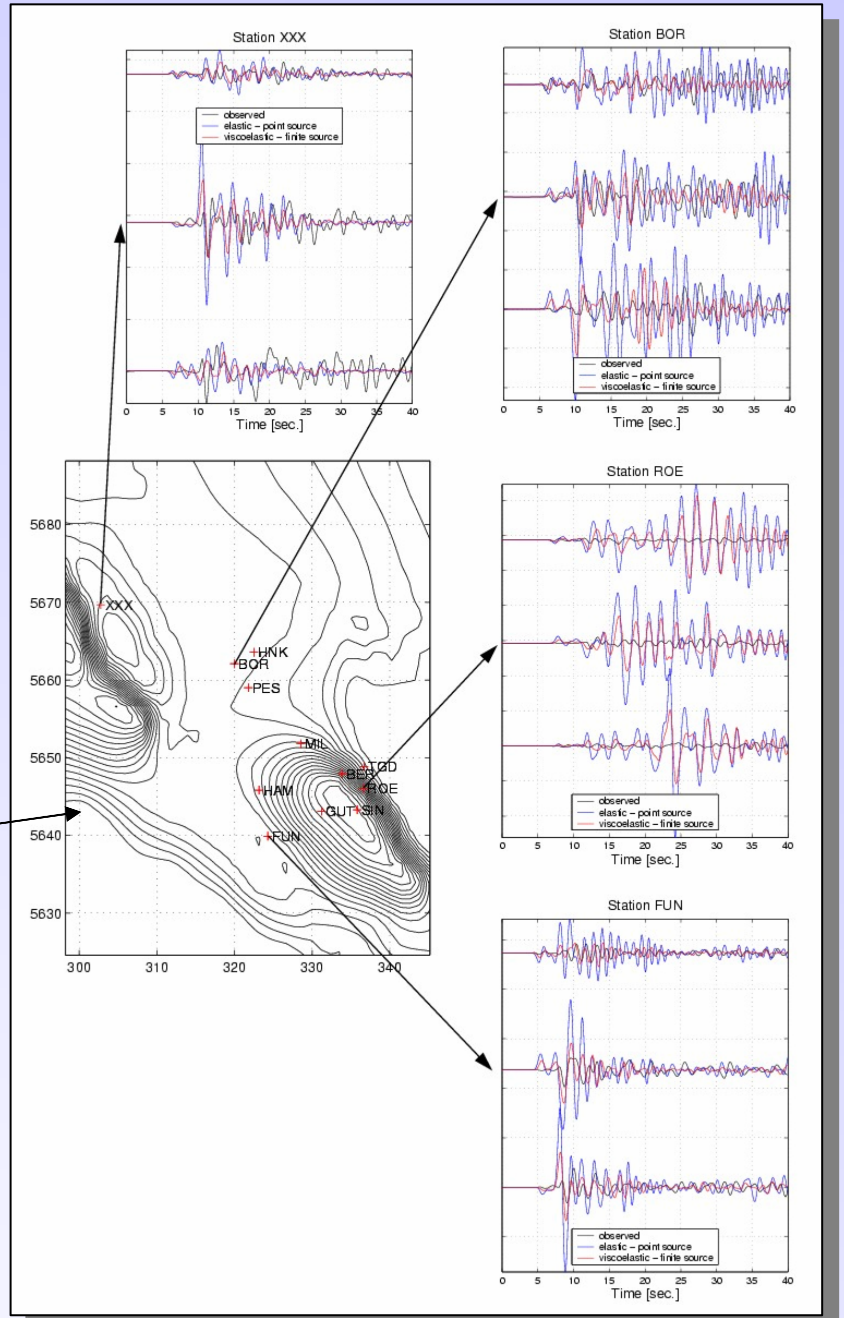




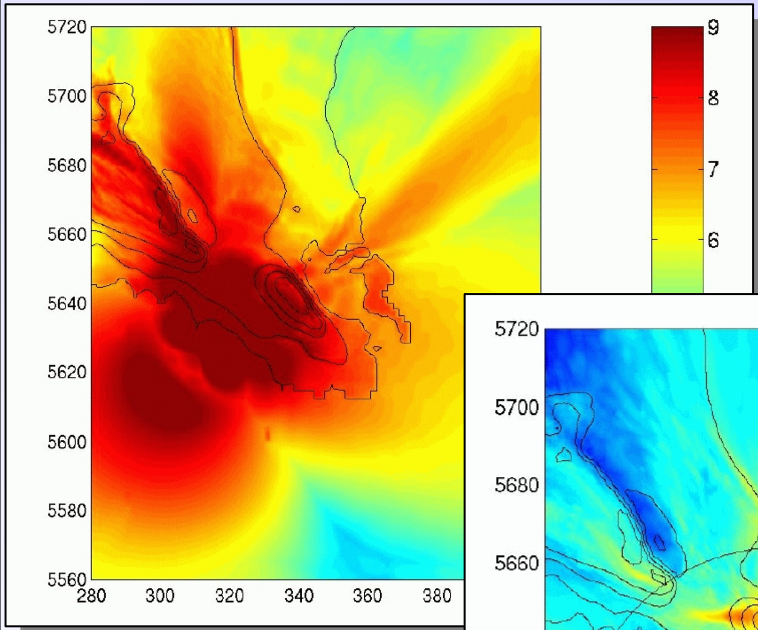
Earthquake scenarios

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

Cologne Basin topography

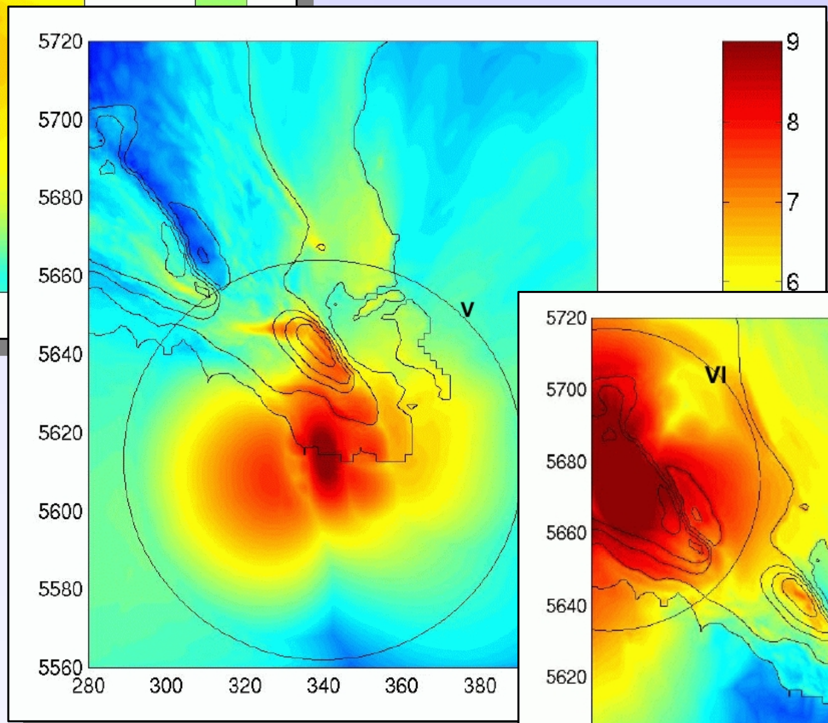


Seismic intensities (Mercalli scale)

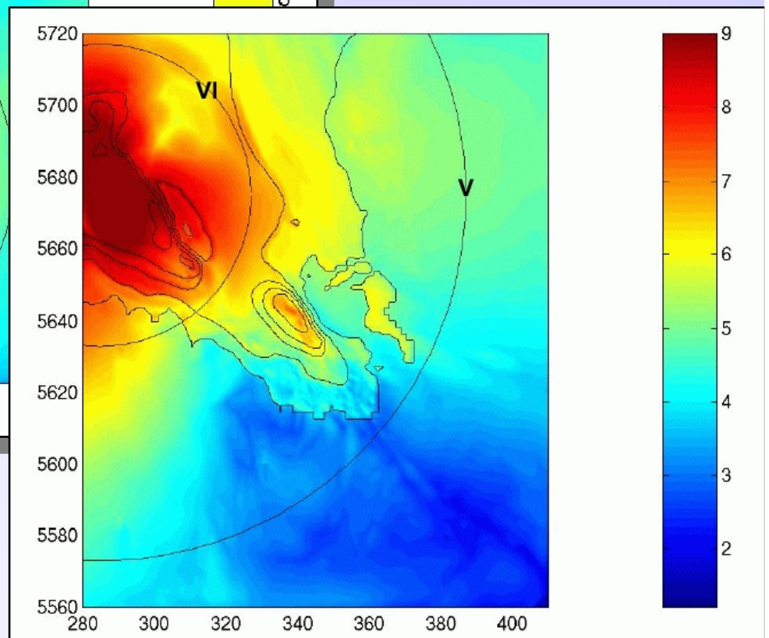


Euskirchen

Dueren

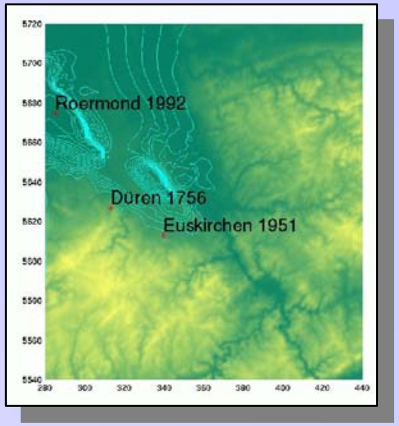


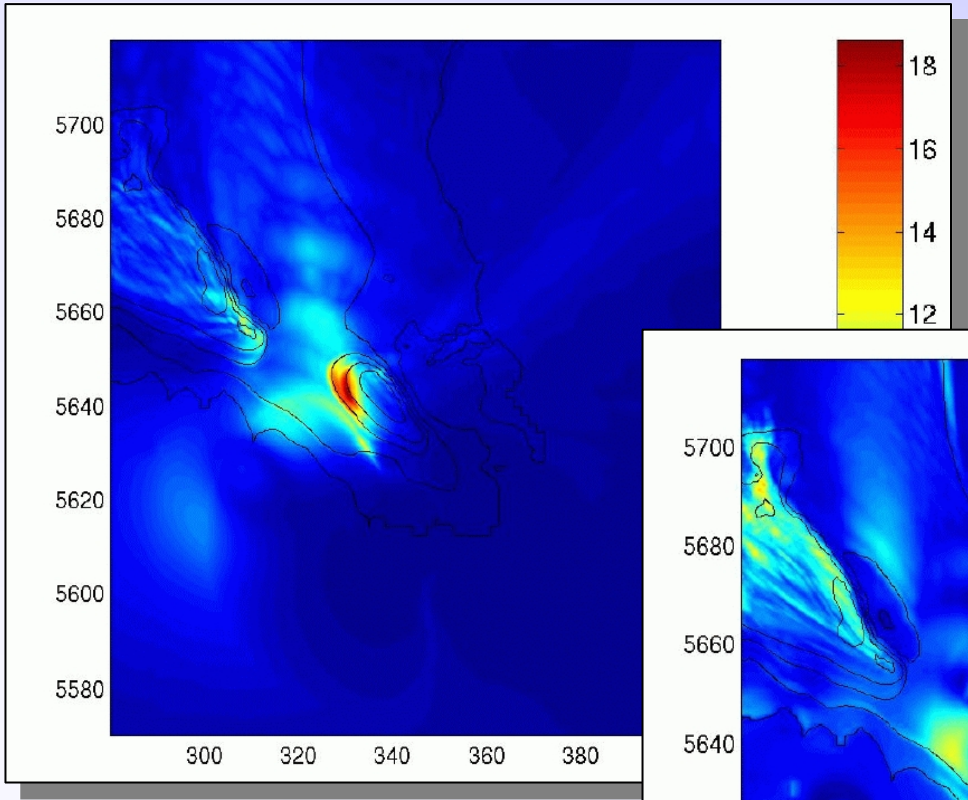
Roermond



The intensities are calculated from peak ground velocities

Amplification through 3D model





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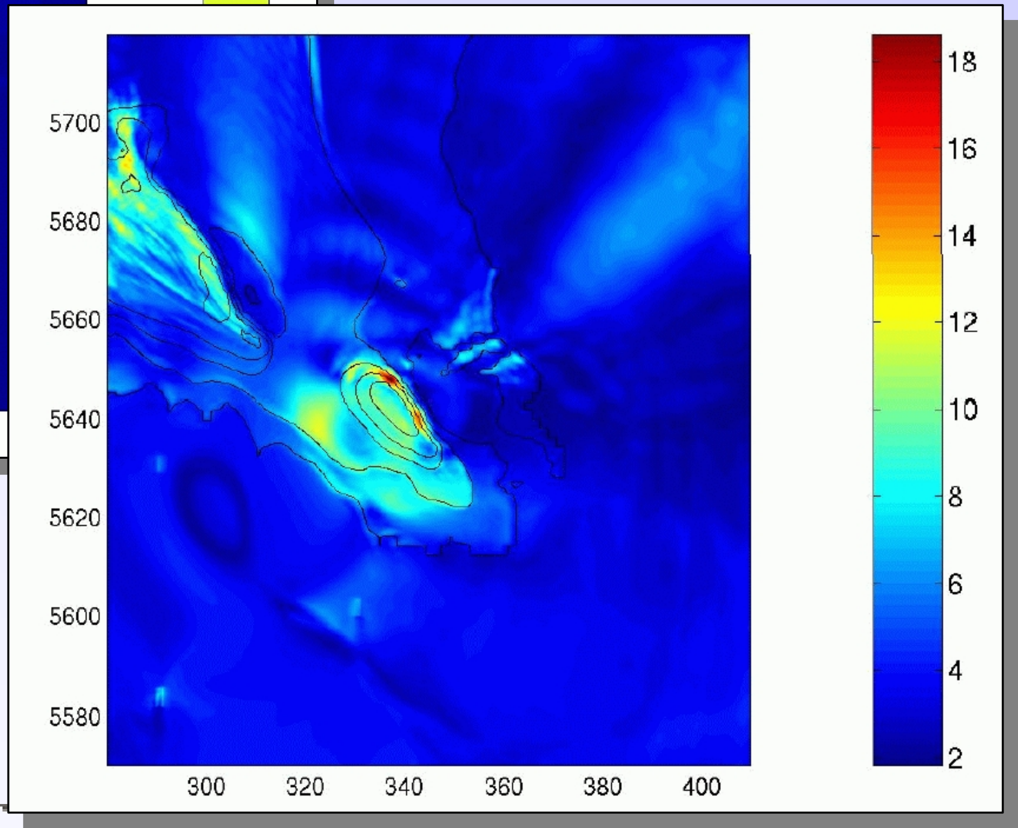
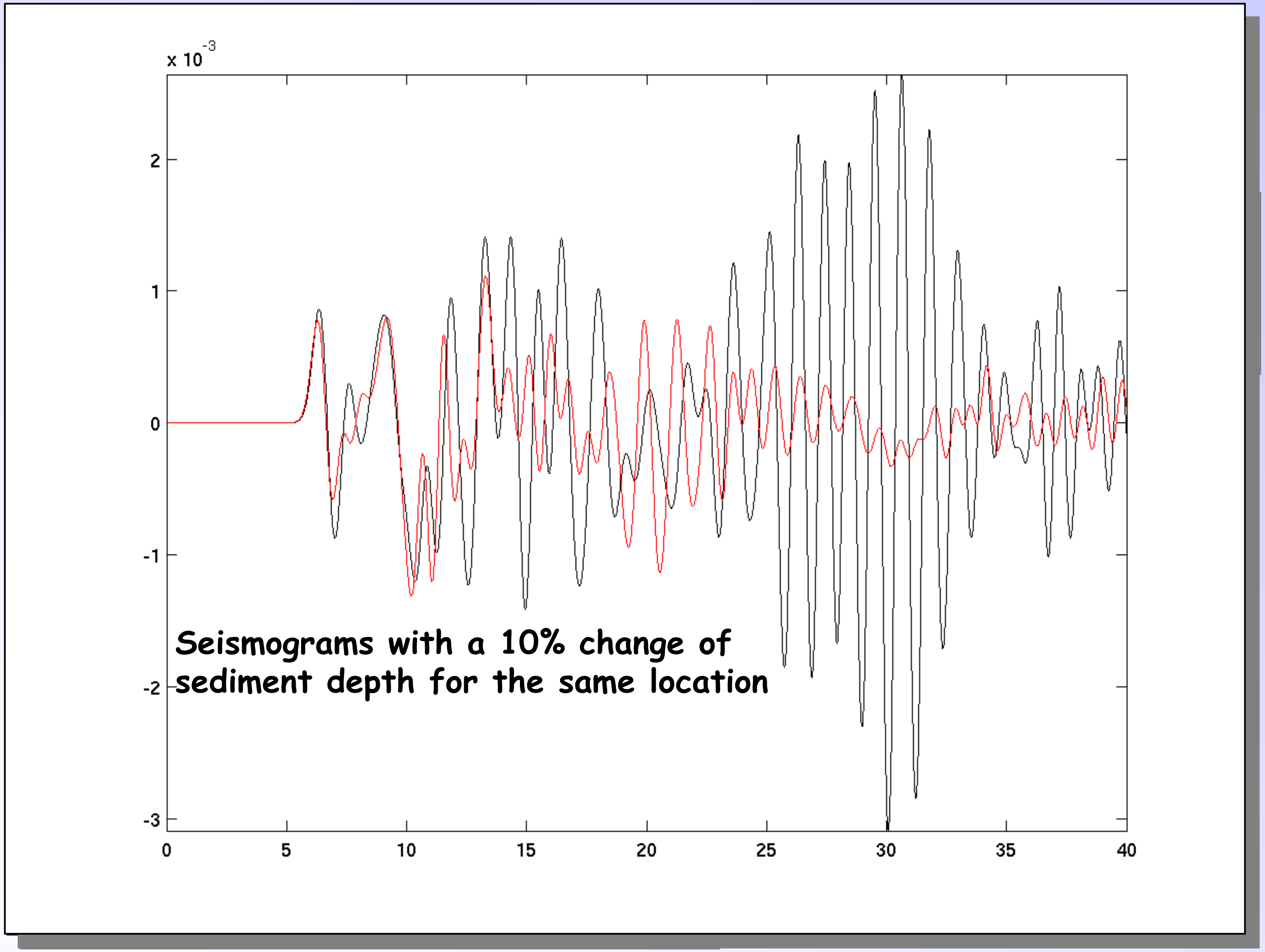
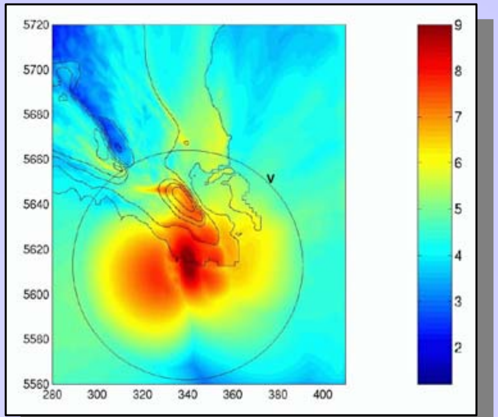


Euskirchen

What can we do with the uncertainties in the crustal structure?





Summary
III- Earthquake scenarios

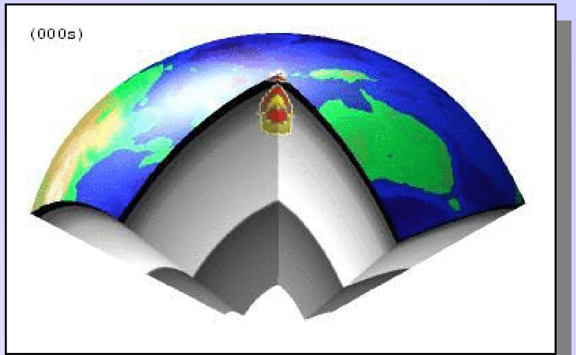
- There are considerable uncertainties in estimating strong ground motion for earthquake scenarios (3D structure, source behavior)
- With the concept of “Green’s functions” a large number of earthquake scenarios could be simulated and some of the uncertainties accounted for

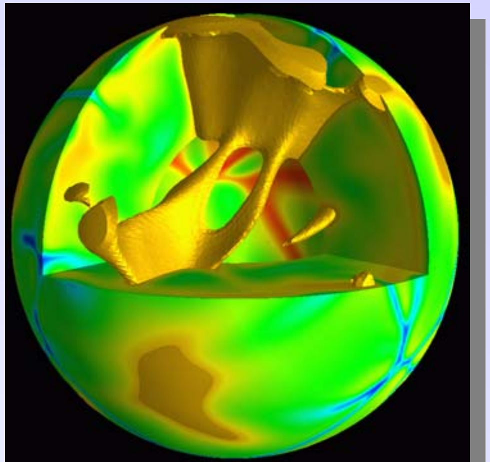
IV – Global seismology

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

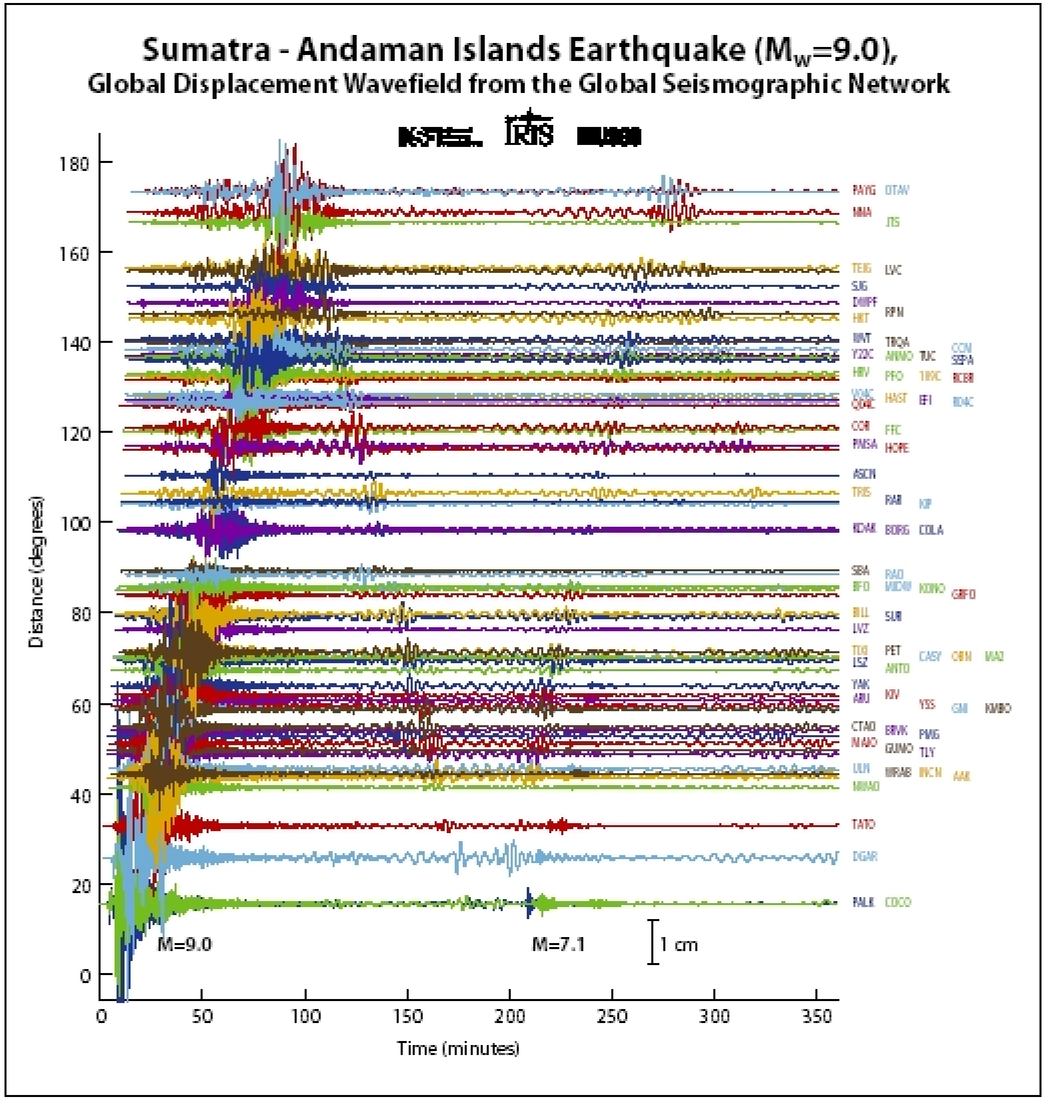
Supercomputing:
- Towards simulation and inversion of the globally observed wave field using 3D modelling tools





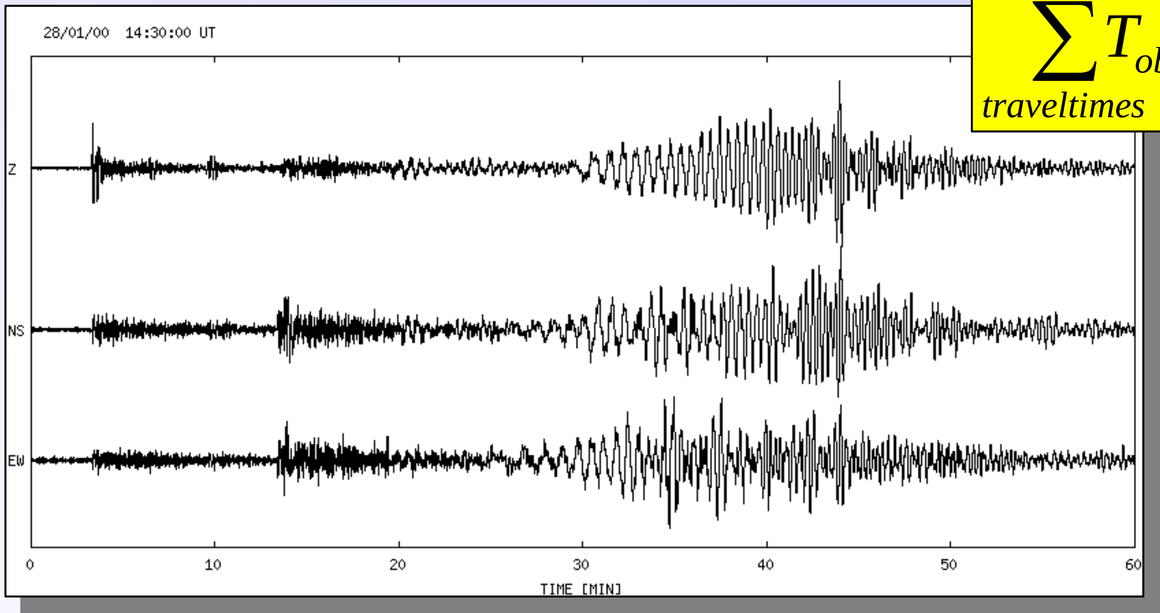
From: P. Bunge

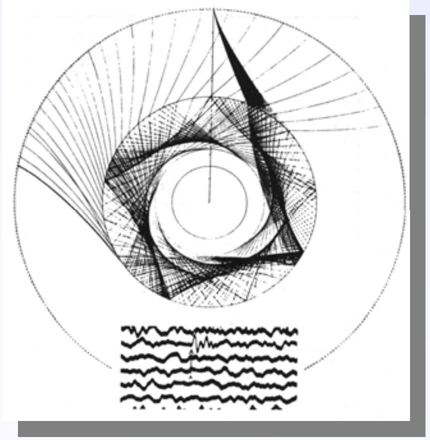
Global wave propagation

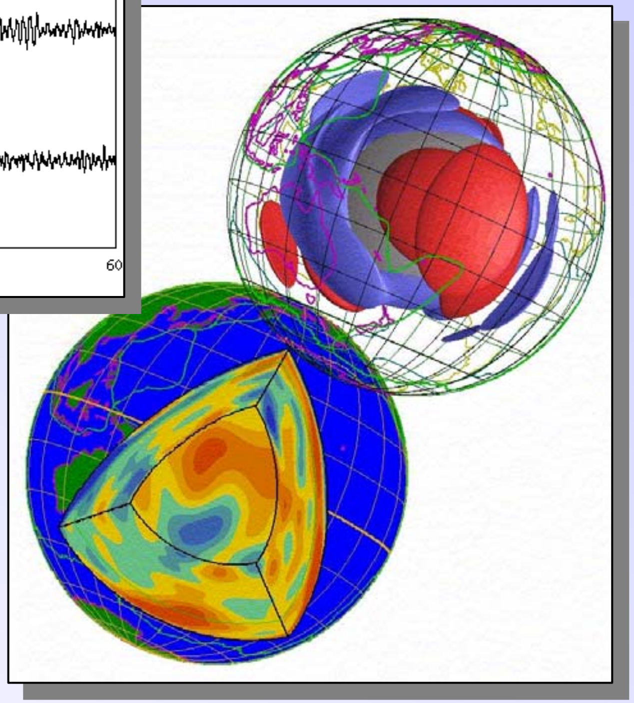


Seismic tomography and the structure of the Earth's deep interior

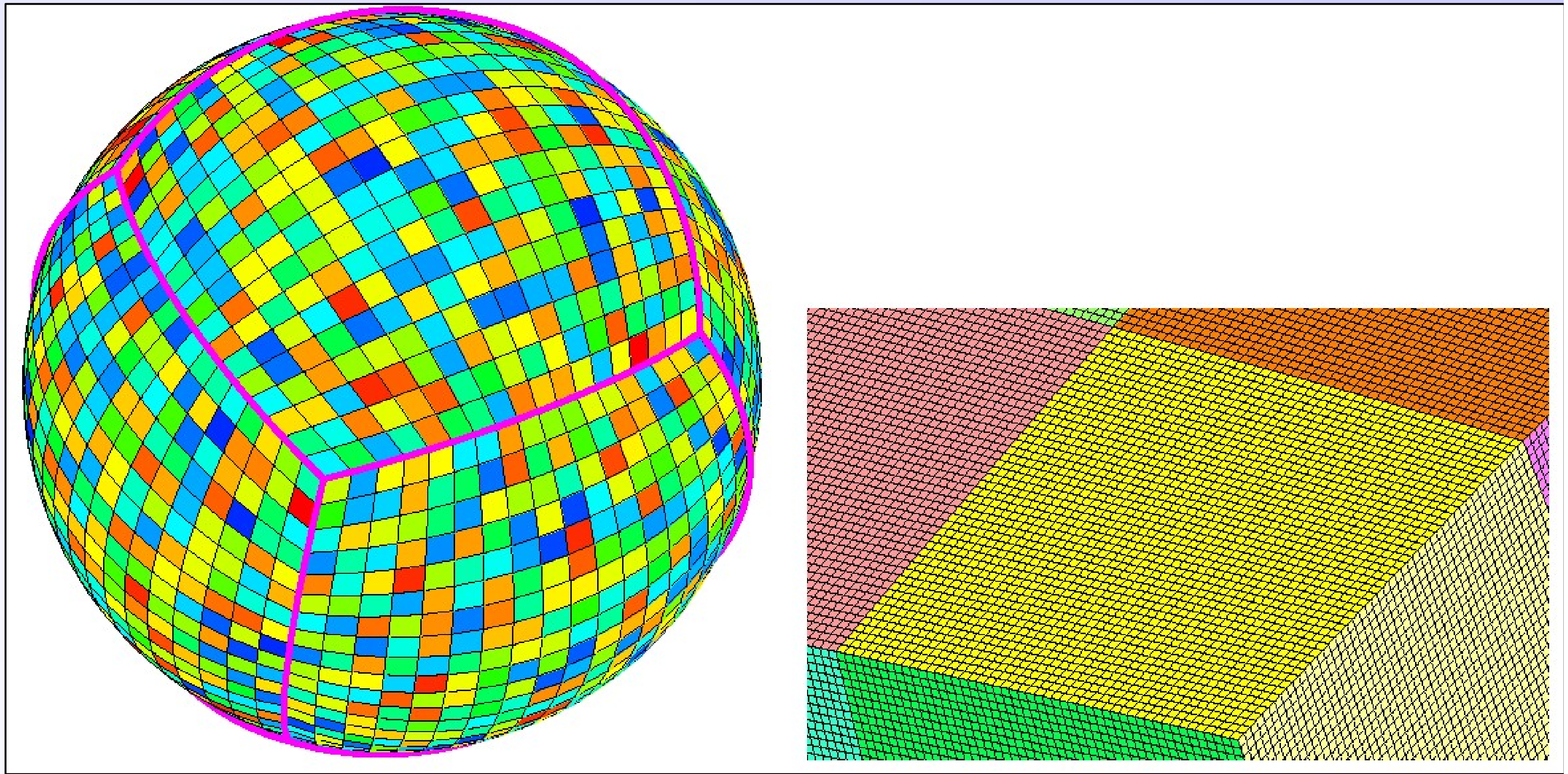
$$\sum_{traveltimes} T_{obs} - T_{theory}(m) = Min!$$



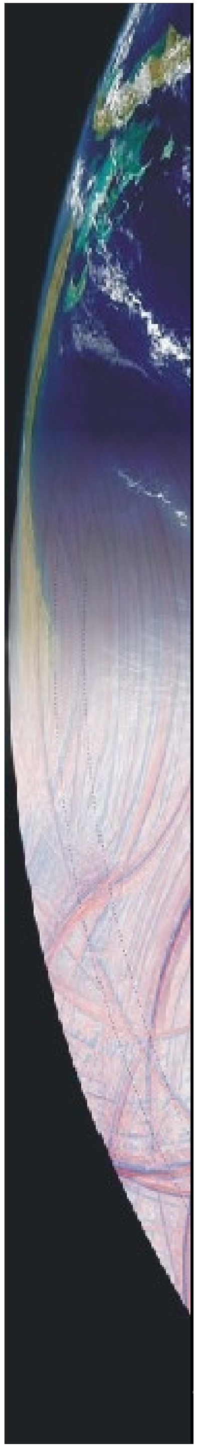




Spherical earth – *Cubed Sphere*
Discretization

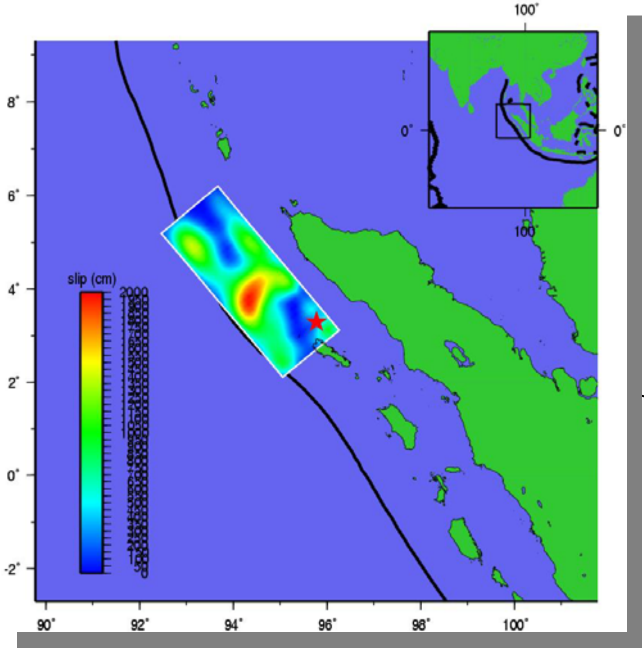


Tsuboi, Tromp, Komatitsch, 2003

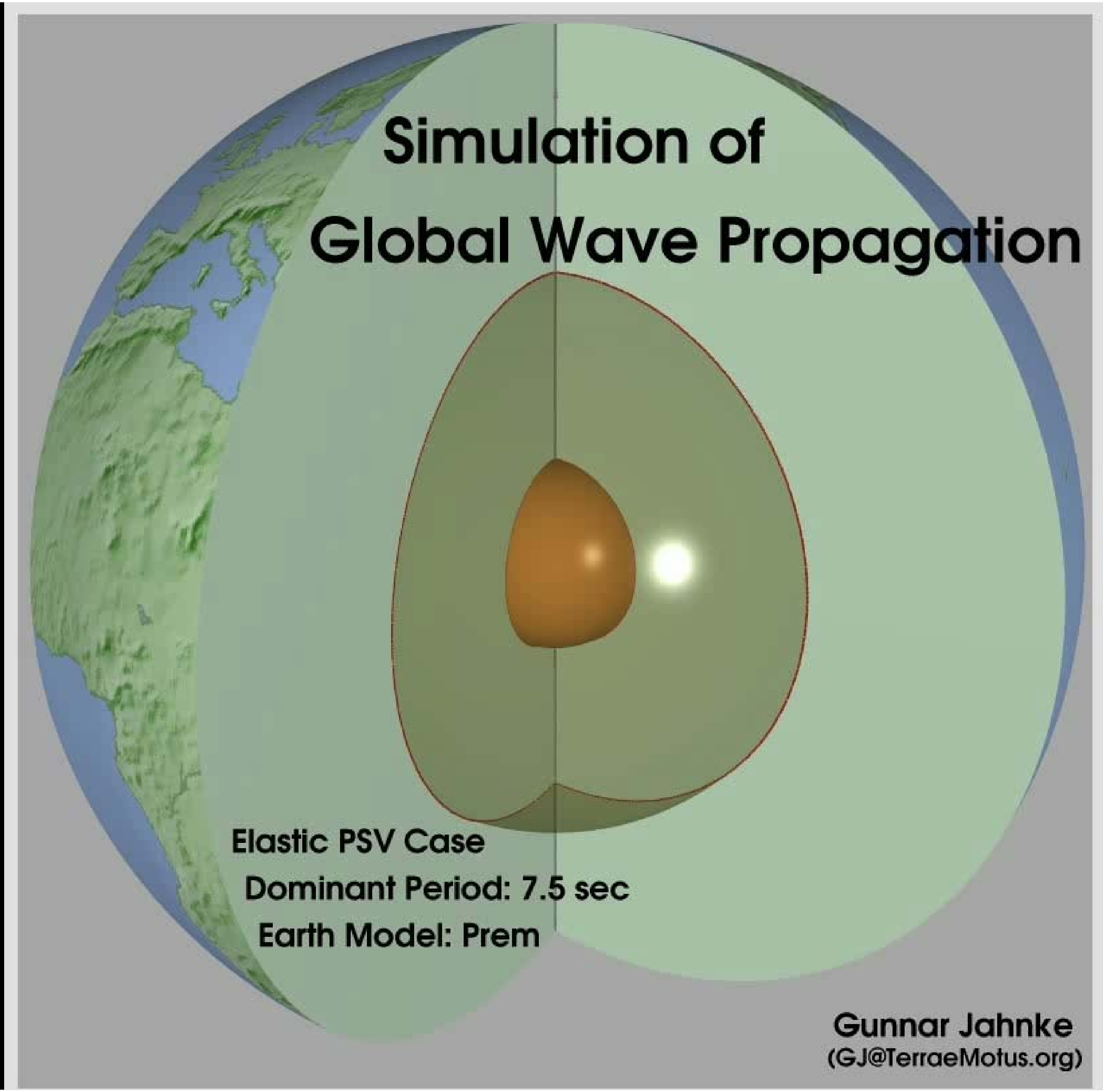


26 Dec 2004 01:58:53MET

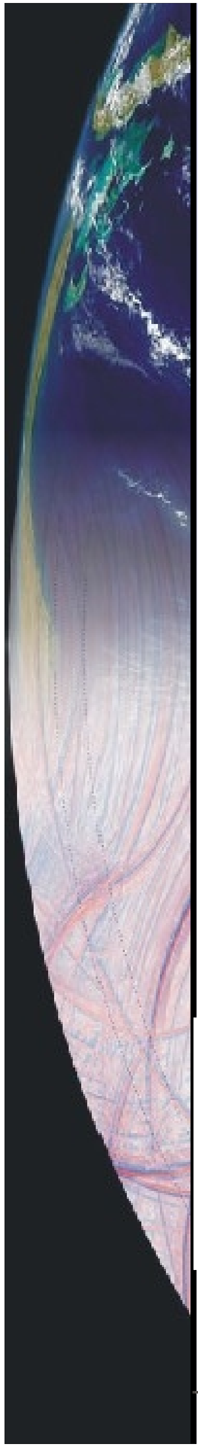
3D simulation - Sumatra event

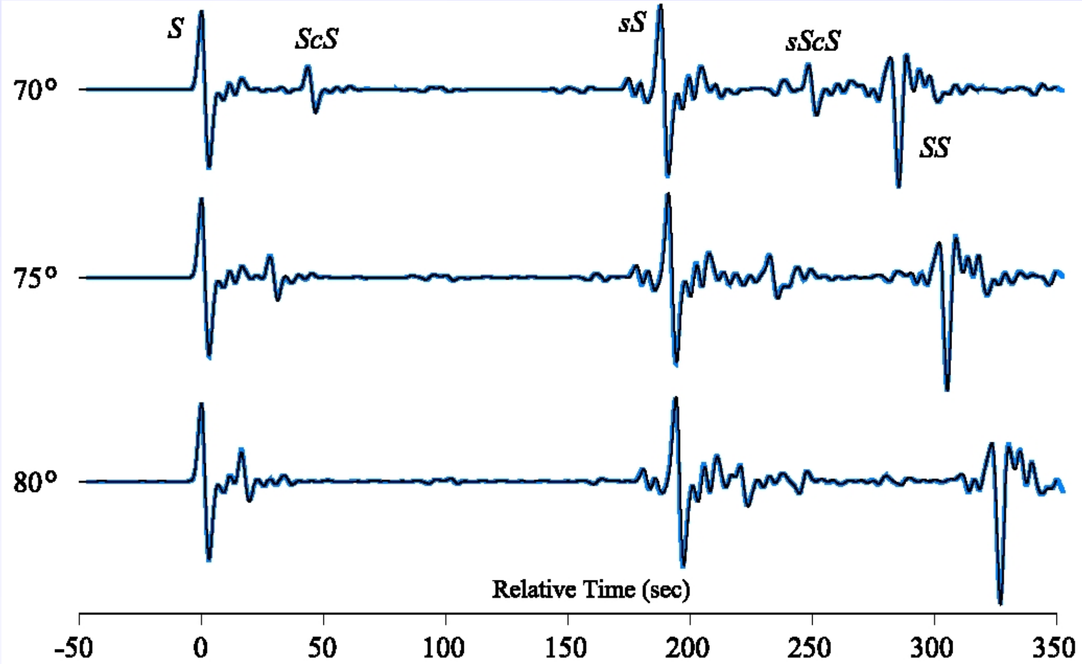


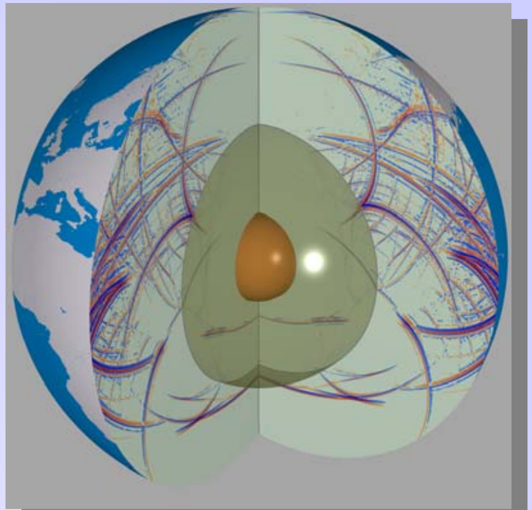
Finite source model
<20s periods
3D tomographic model
Spectral element method

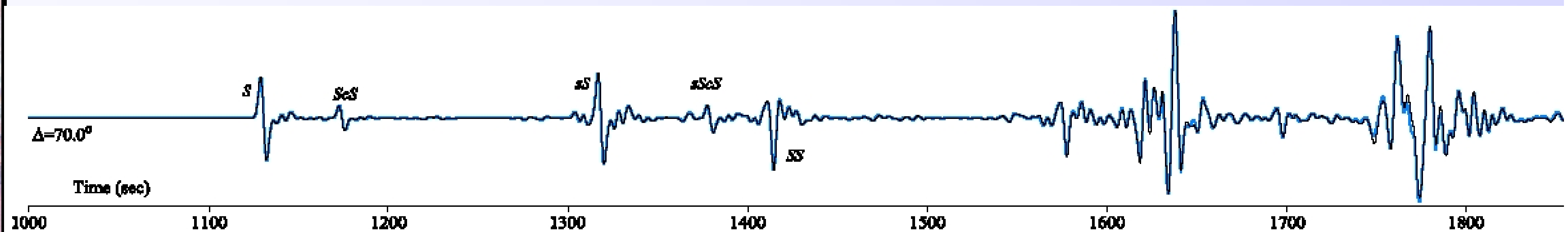

Simulation of
Global Wave Propagation
Elastic PSV Case
Dominant Period: 7.5 sec
Earth Model: Prem
Gunnar Jahnke
(GJ@TerraeMotus.org)

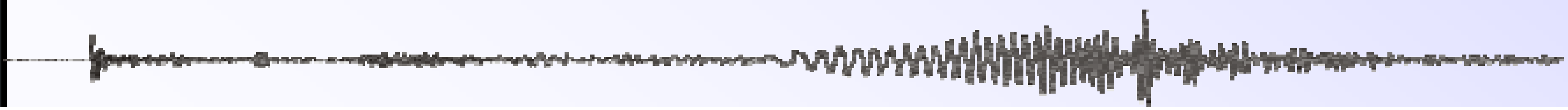
Theoretical seismograms - verification



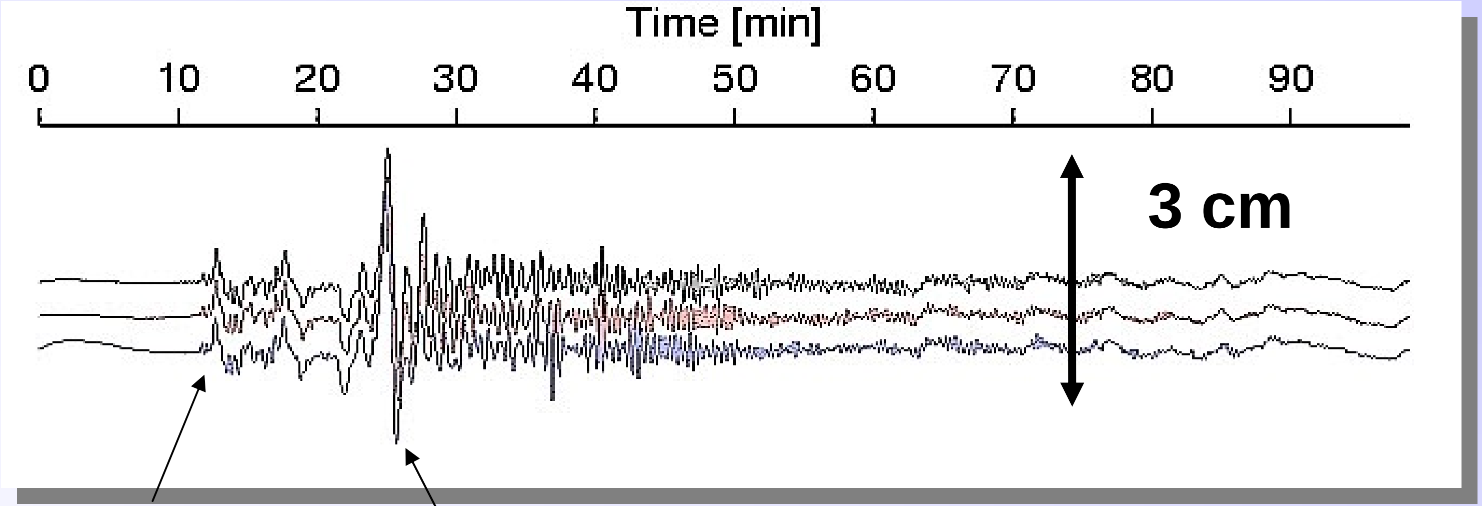






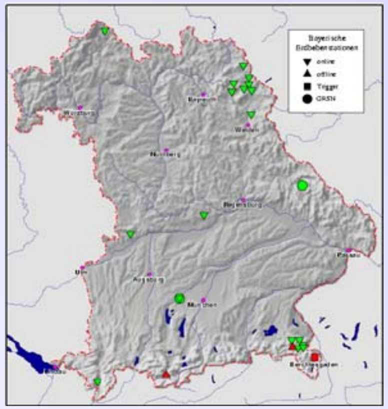


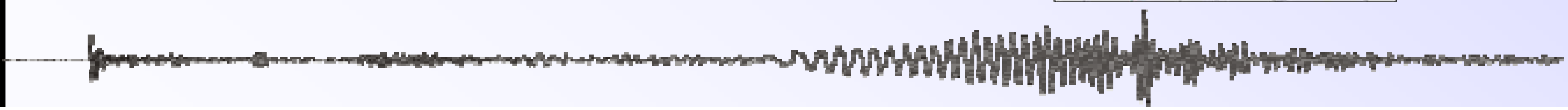
Sumatra quake - Observations



Shear waves

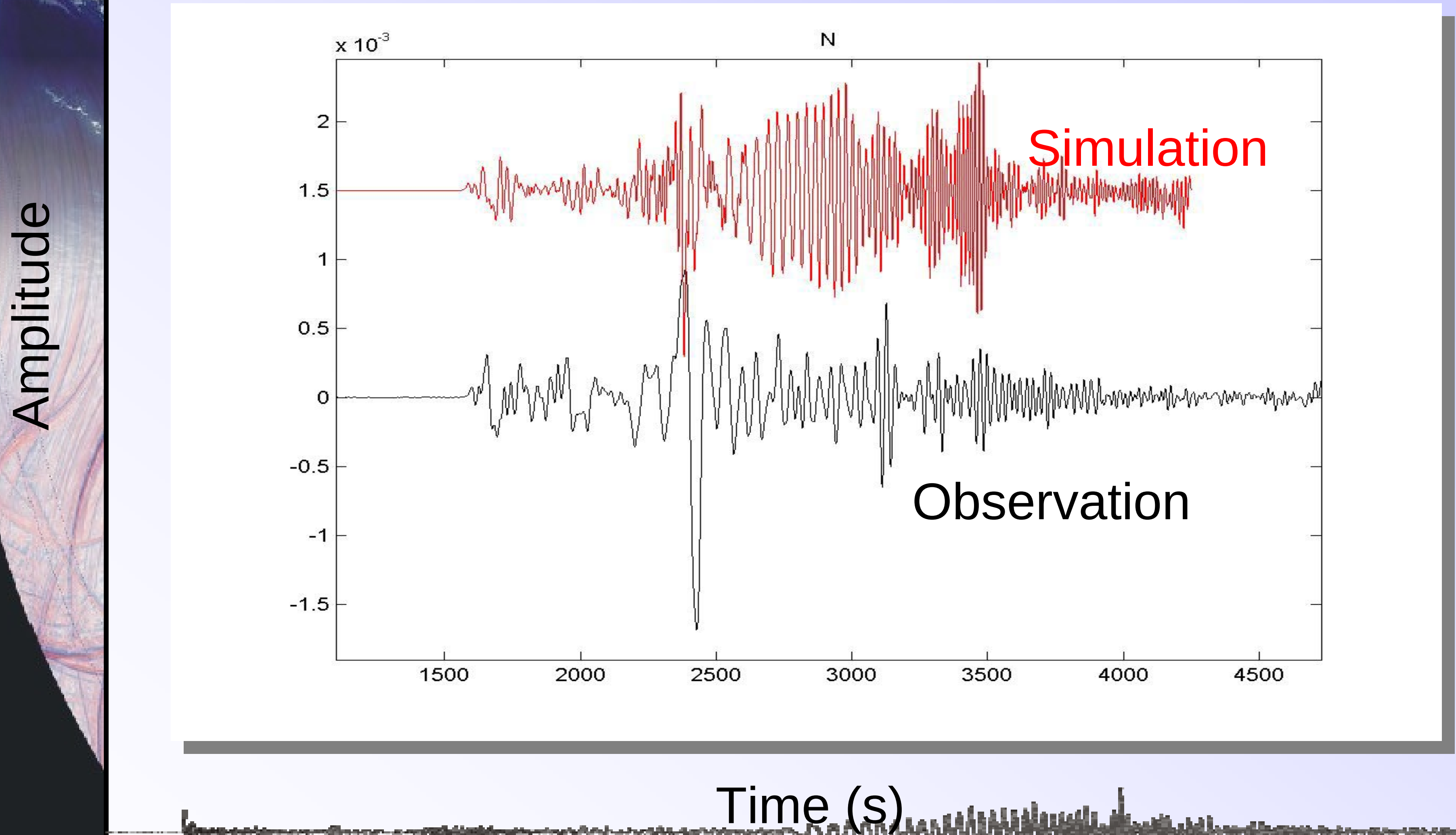
Surface waves
Love-waves





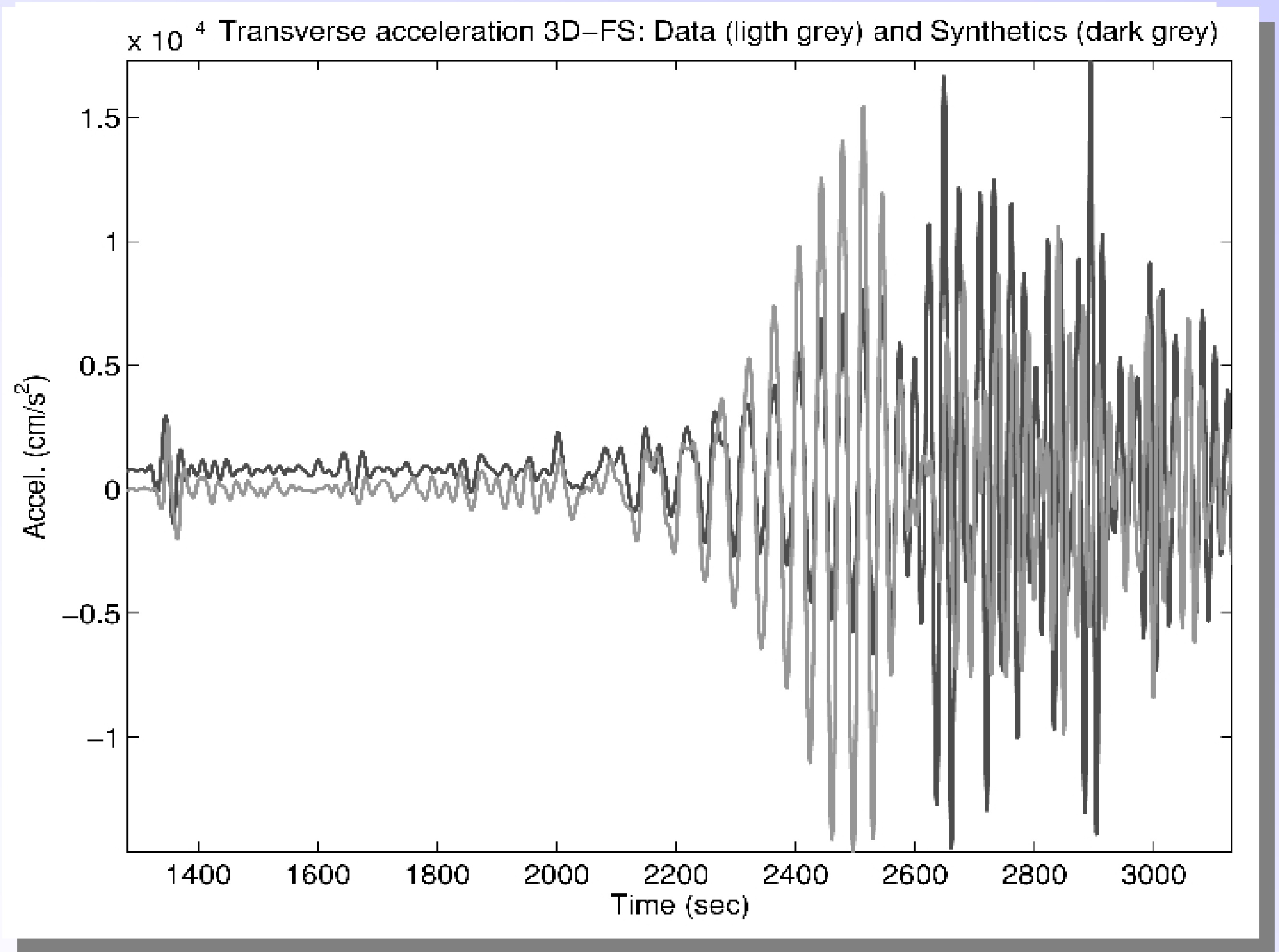
Sumatra quake

Theory vs. observation

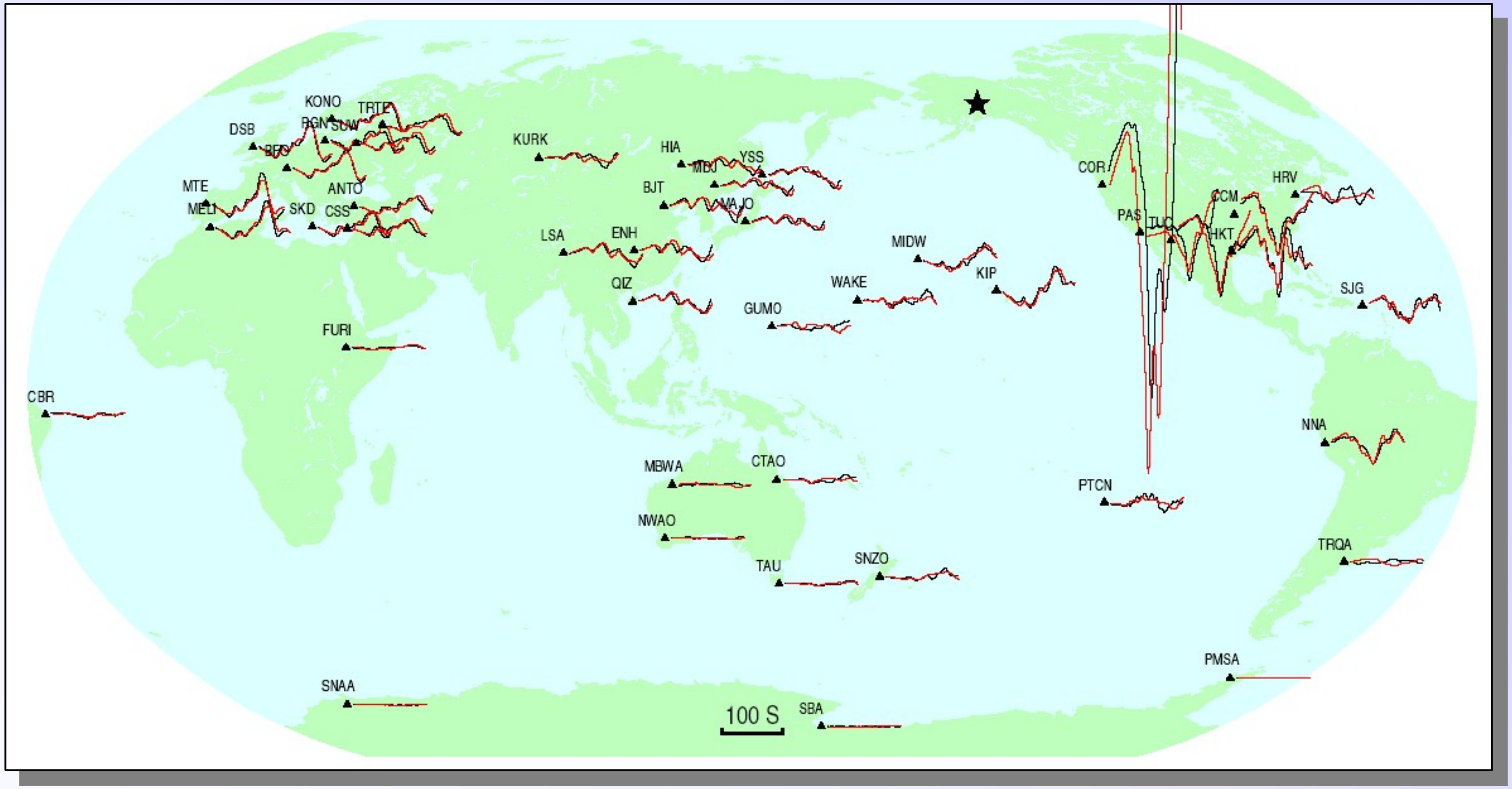


Tokachi-oki, M8.3

September 25, 2003

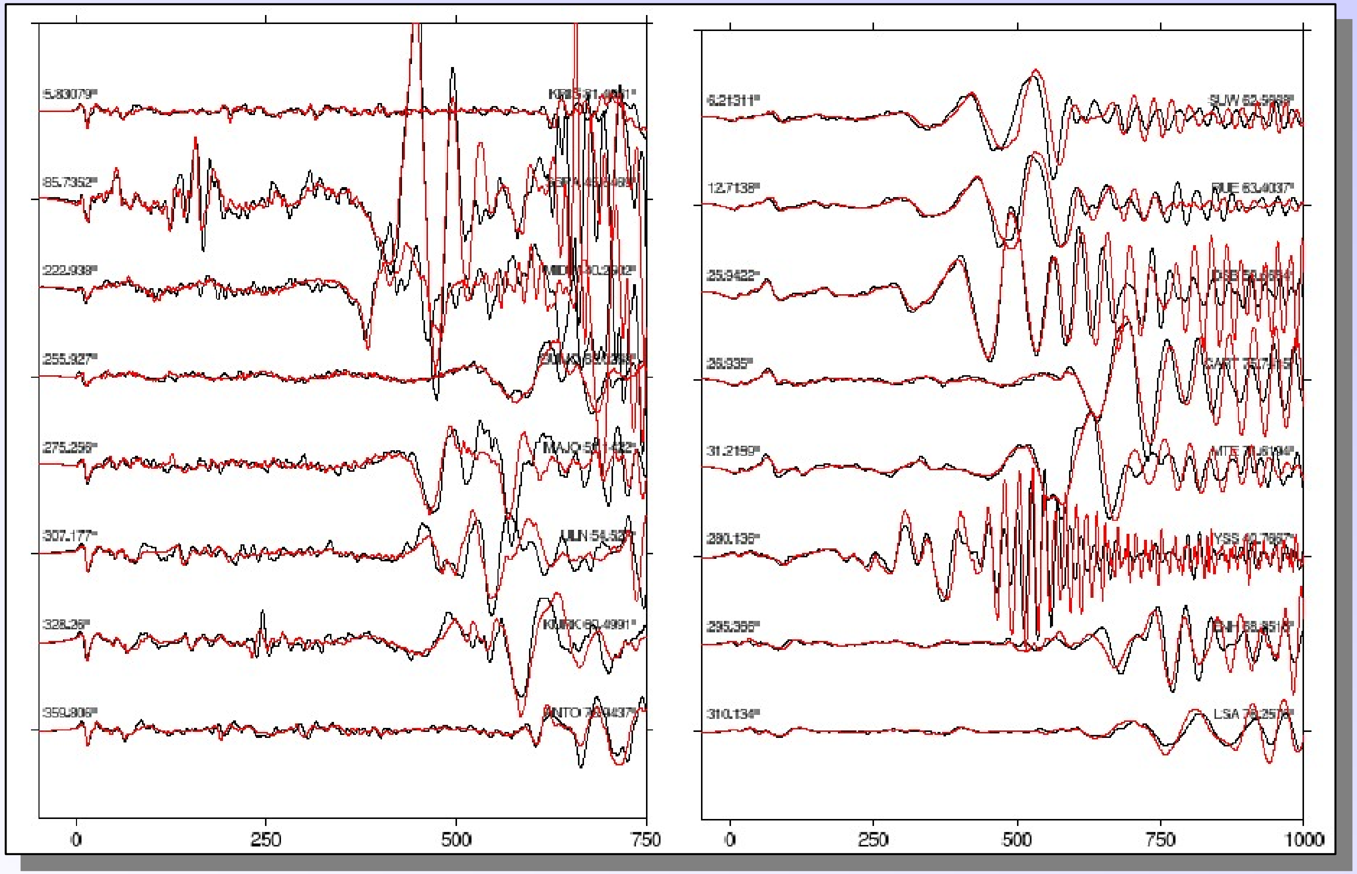


Global observations
Alaska, M7.9, November 2002



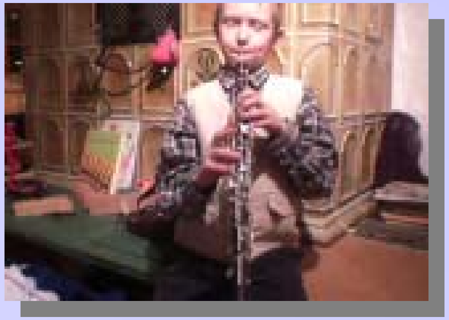
Tsuboi, Tromp, Komatitsch, 2003

Global observations
Alaska, M7.9, November 2002
observations (black) – simulations (red)

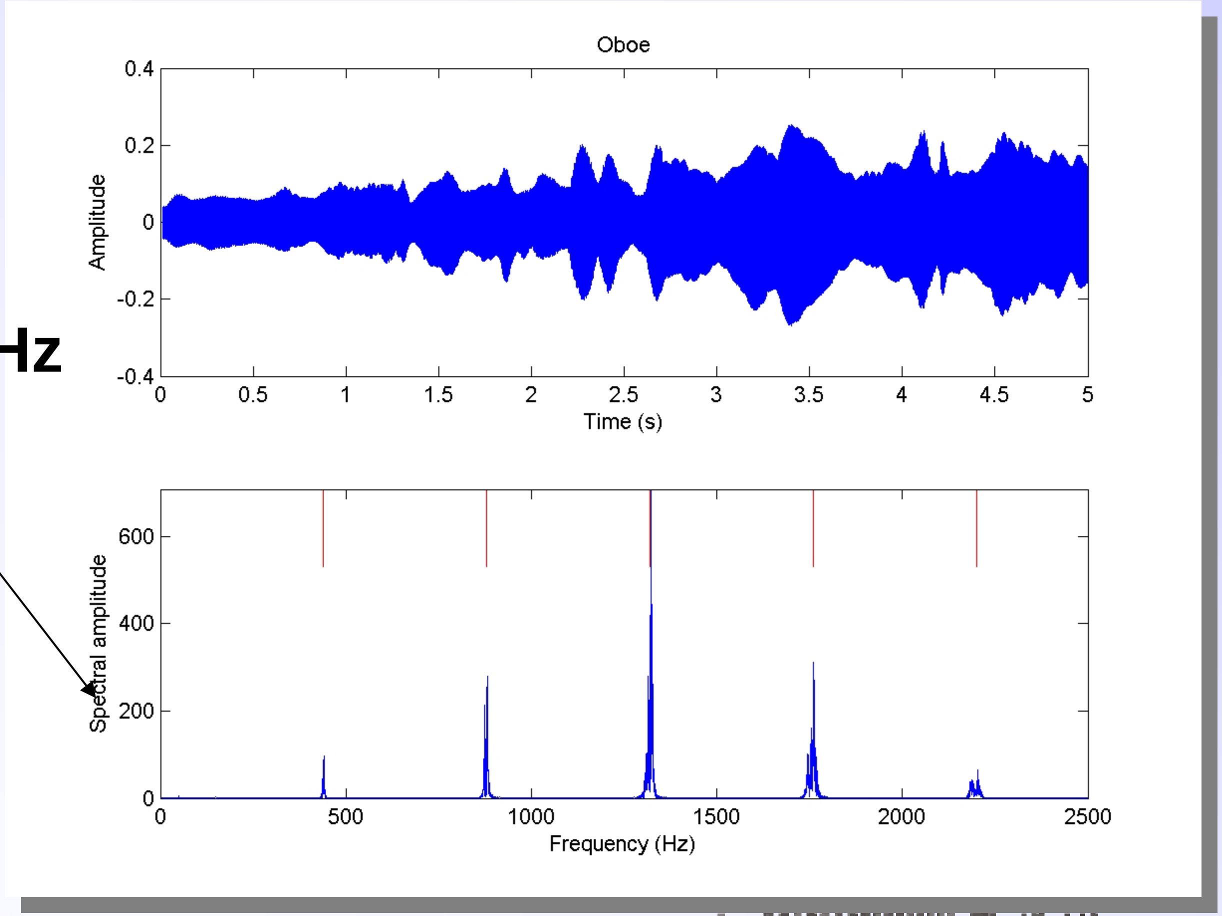


Tsuboi, Tromp, Komatitsch, 2003

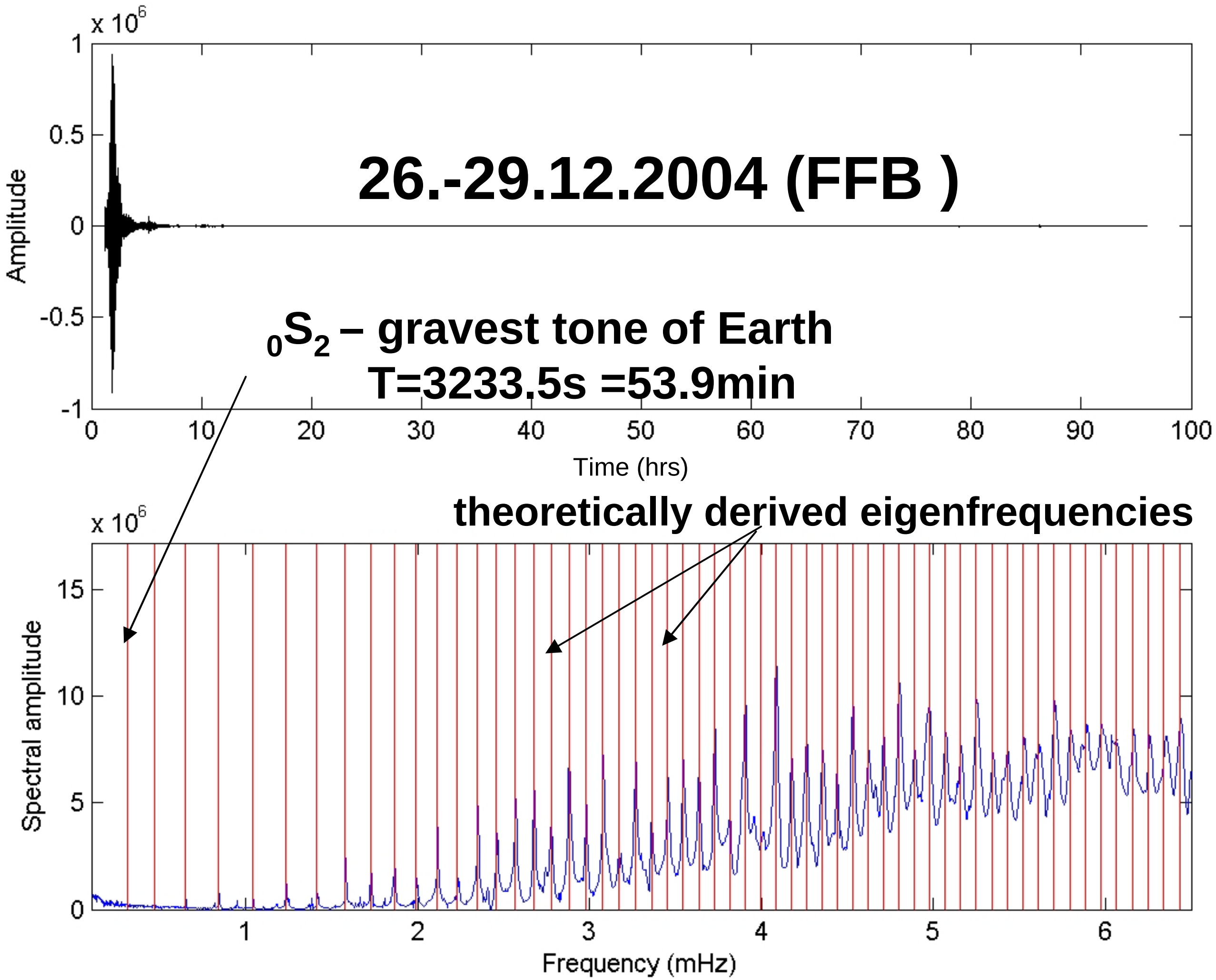
Sound of an instrument



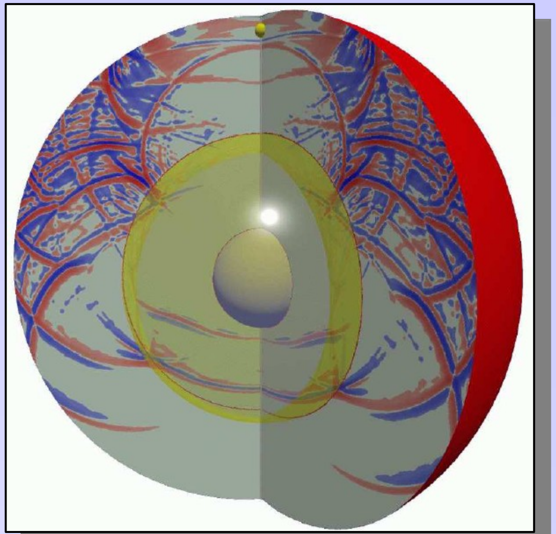
a' - 440Hz



Instrument Earth



Summary
IV- Global seismology



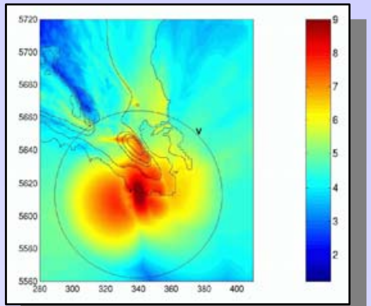
- 3D wave propagation for models on a planetary scale is now possible
- These methods will be used in the near future to obtain a sharper image of the structure inside the Earth
- There are still many open questions about the dynamics of the Earth's deep interior, seismology can – at least – provide an image of the state of the Earth's convective system now … but we need higher resolution!

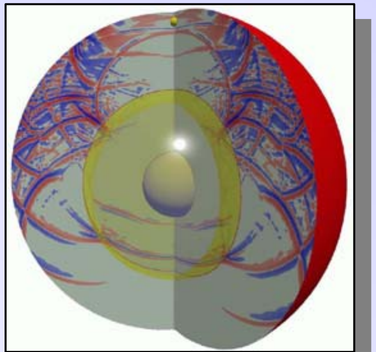
Outlook

- 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





Slides at: http://www.geophysik.uni-muenchen.de/~igel/utrecht