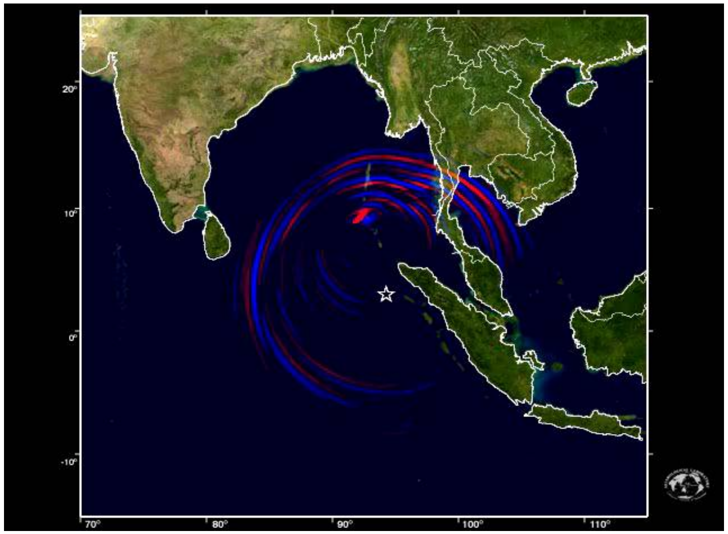
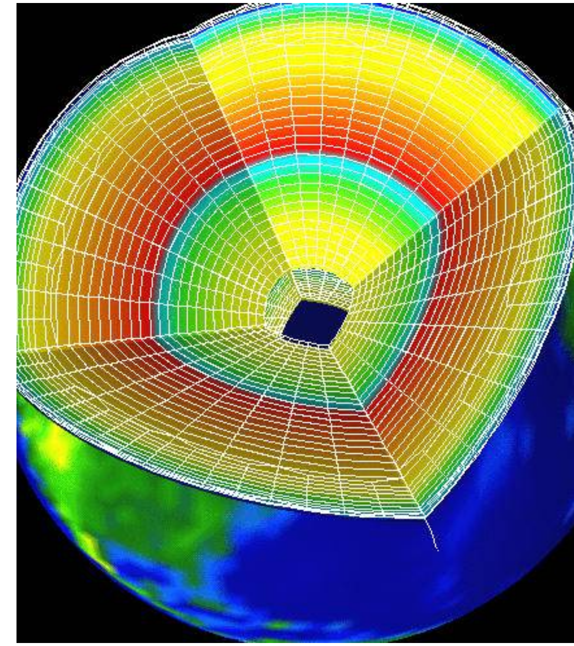
# SPECFEM3D

# SPECtral Finite Element Method in 3D

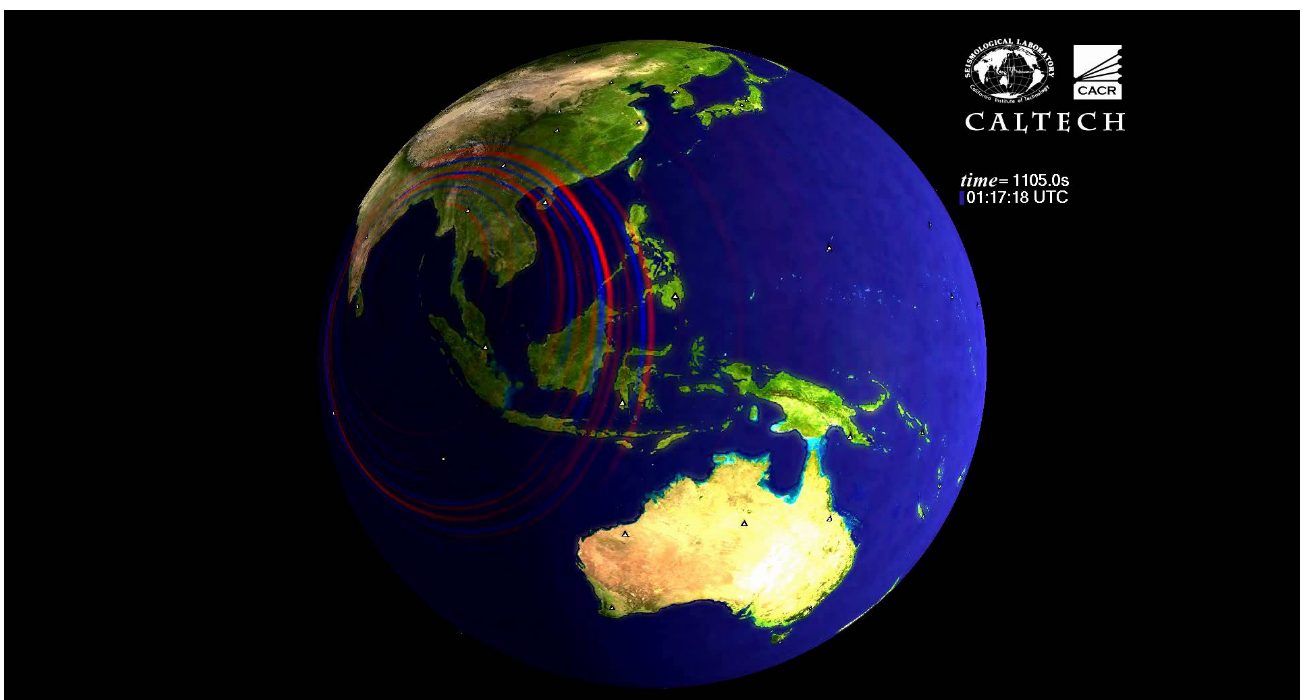
Seismic wave propagation
in 3D complex models

# Global scale



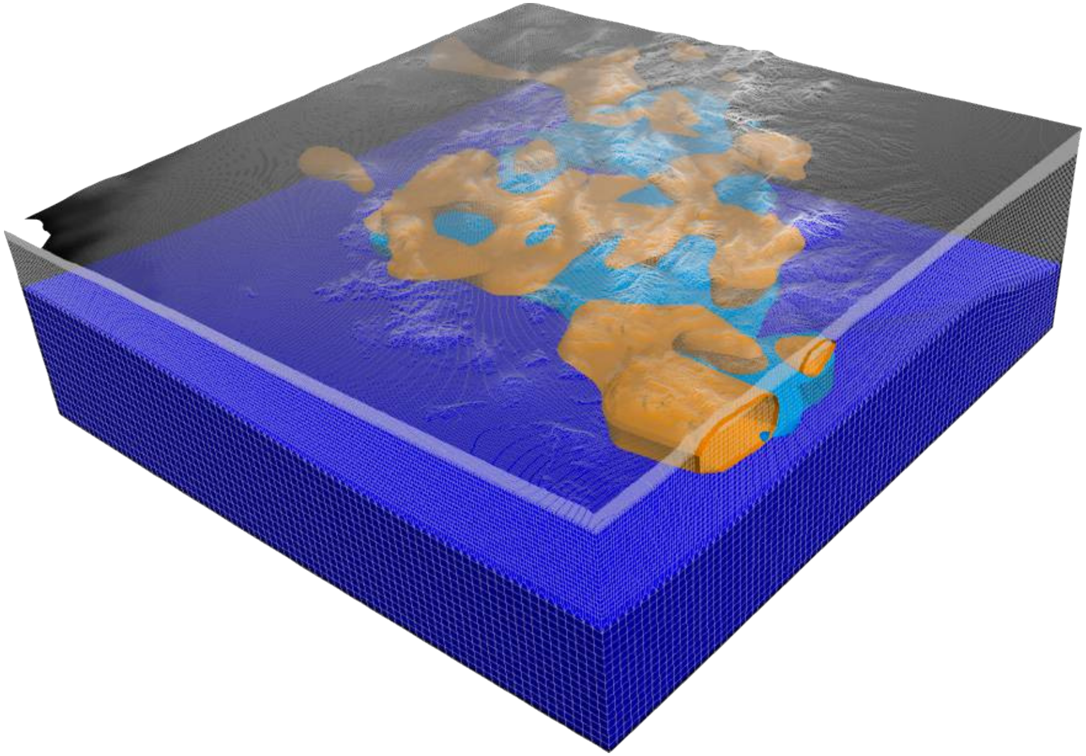



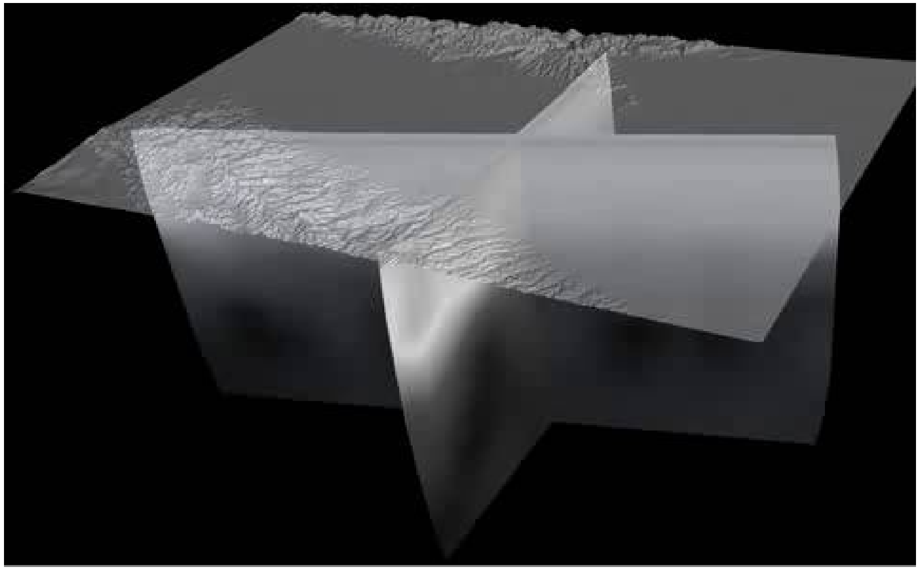
Sumatra 2004

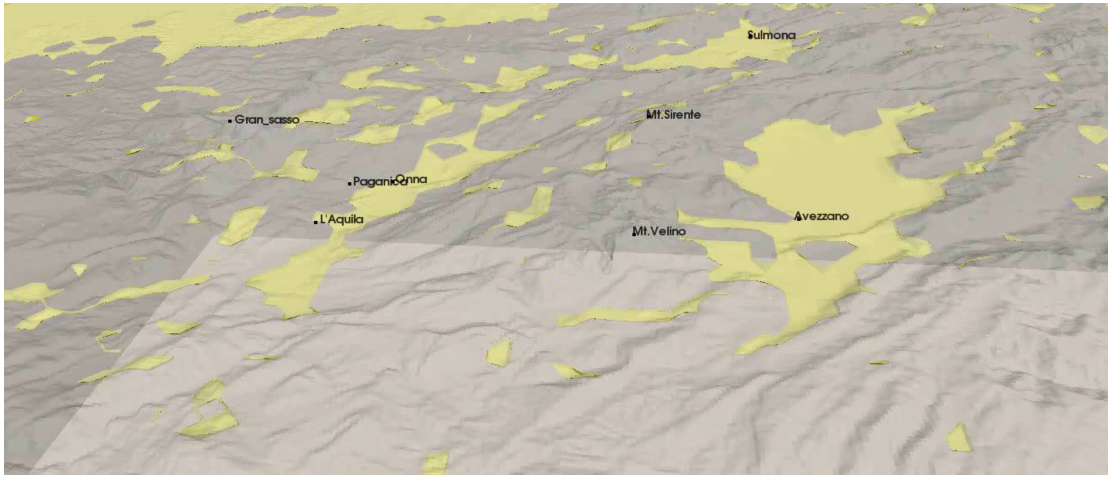



*(Komatitsch et al 2002)*

# Regional scale



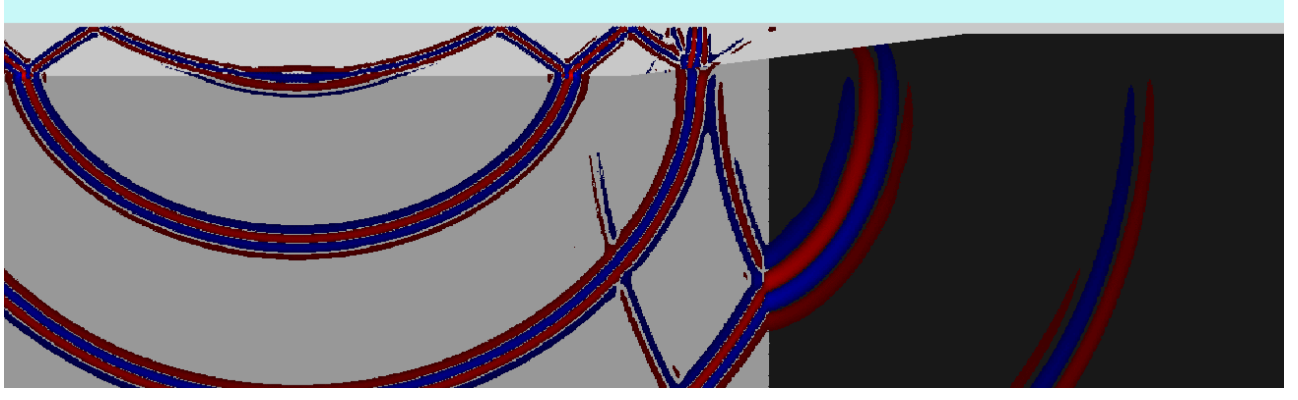




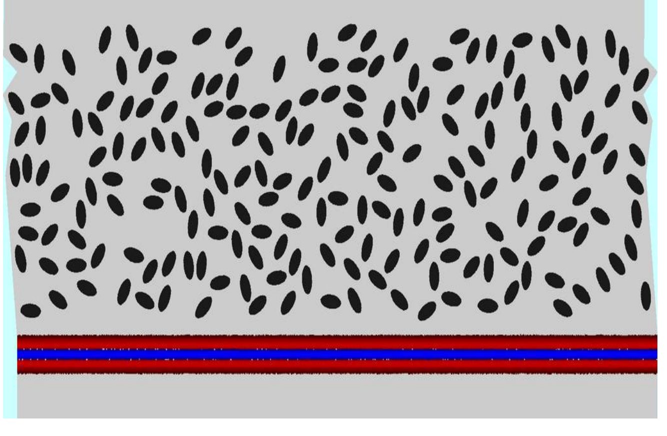

(Magnoni et al 2014)

# Application domains

Seismology



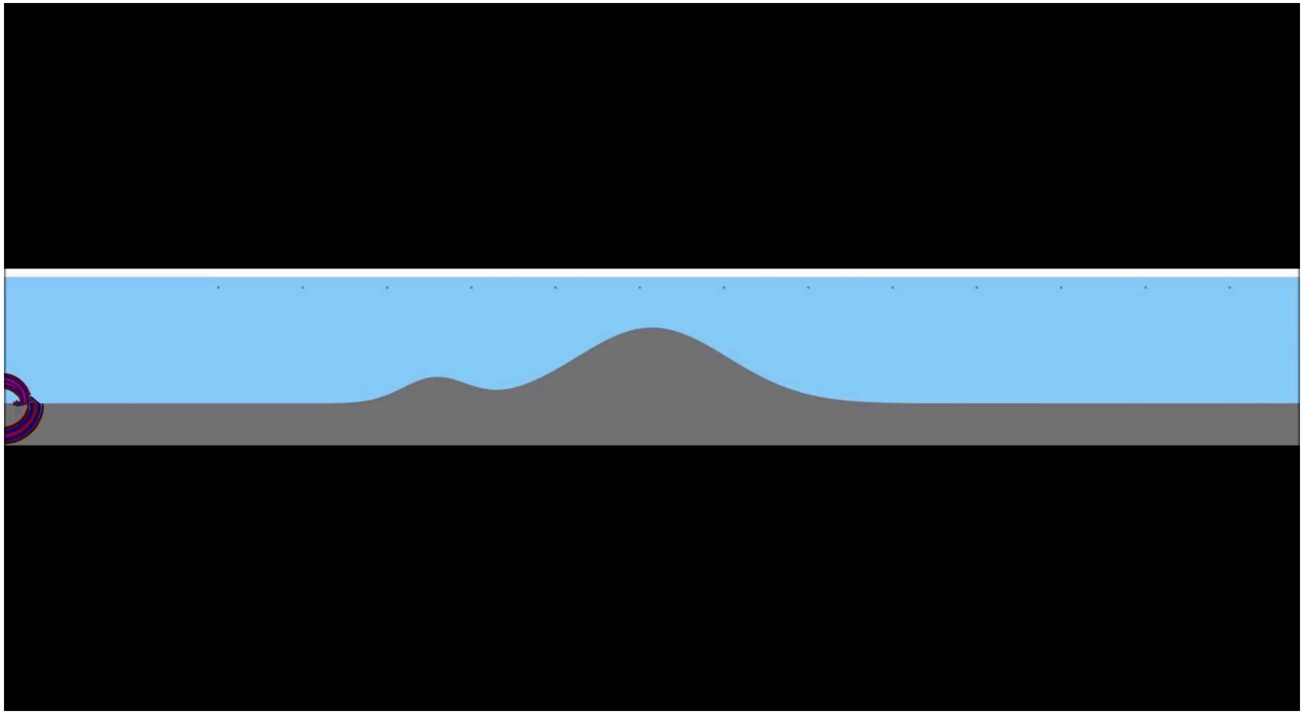
Ocean acoustics



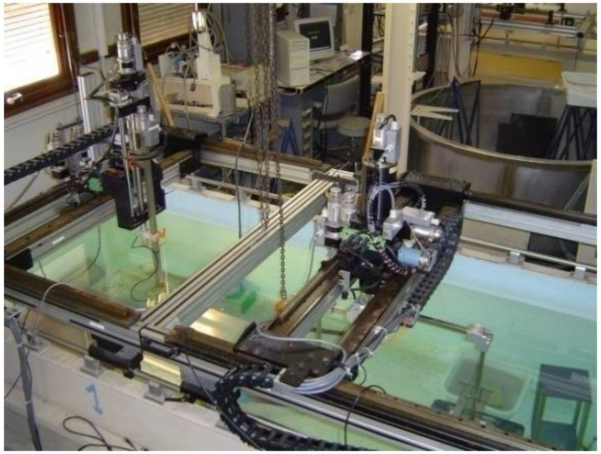
Non destructive testing

# Ocean acoustics

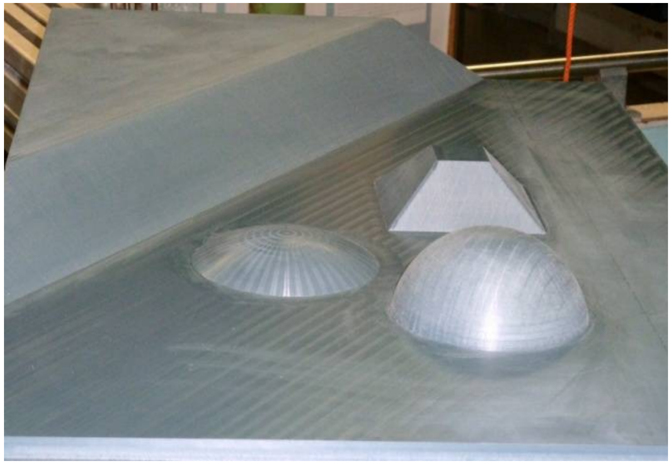
**Numerical simulation**



**Experiments performed in tanks**

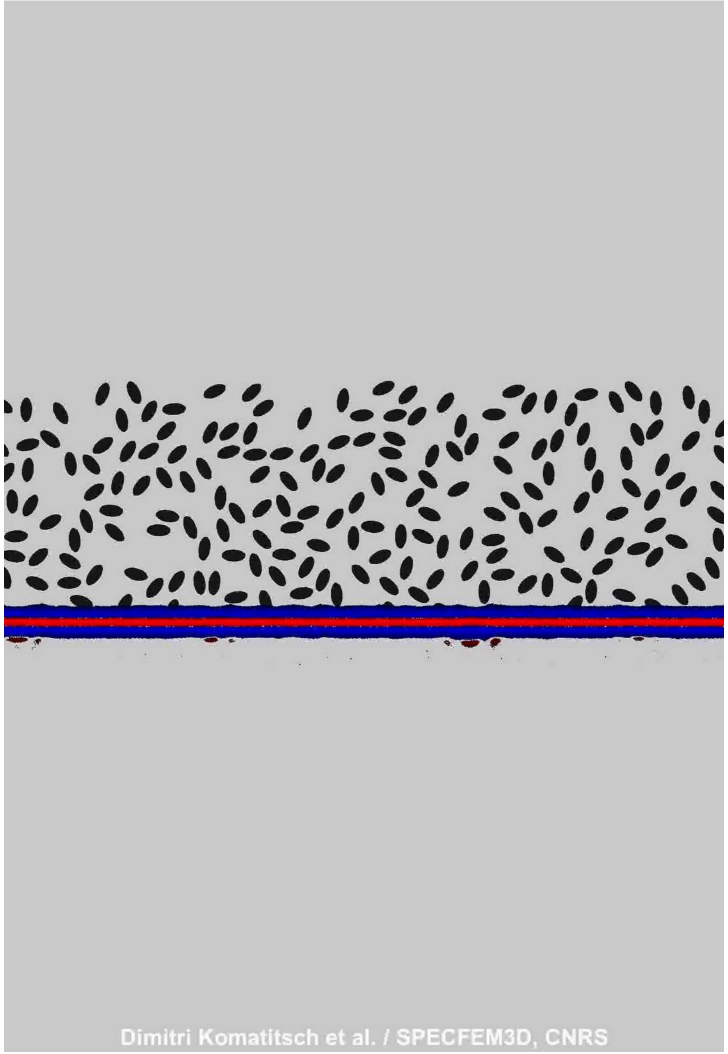


Experimental tanks in LMA (Marseille)



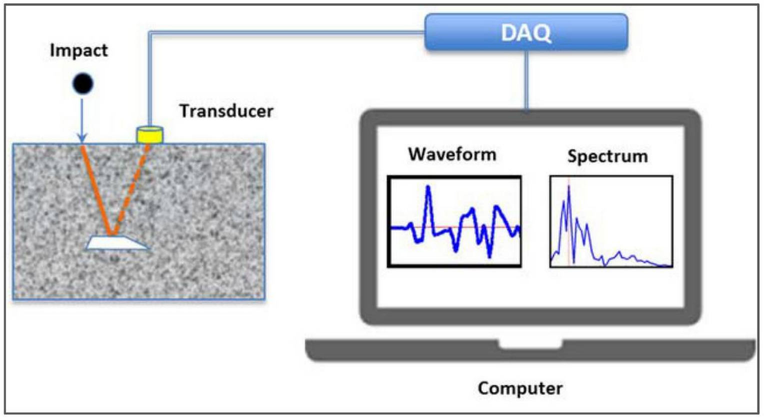
Objects with a complex shape

# Non destructive testing of materials



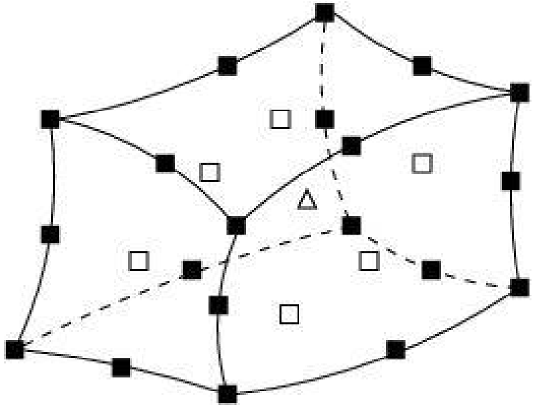

Currently : Physical modeling based on diffusion functions for objects of complex shape, cracks or multiple cavities in concrete, metals, or composite materials. Experiments on samples.

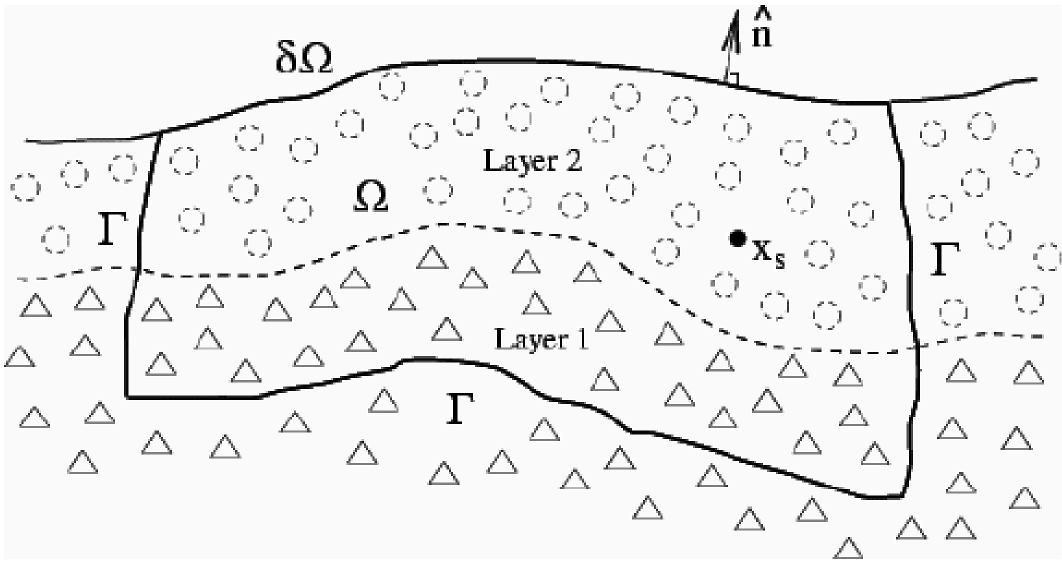
Reliable modeling of the “coda” part of the signal, which contains useful information on the medium.

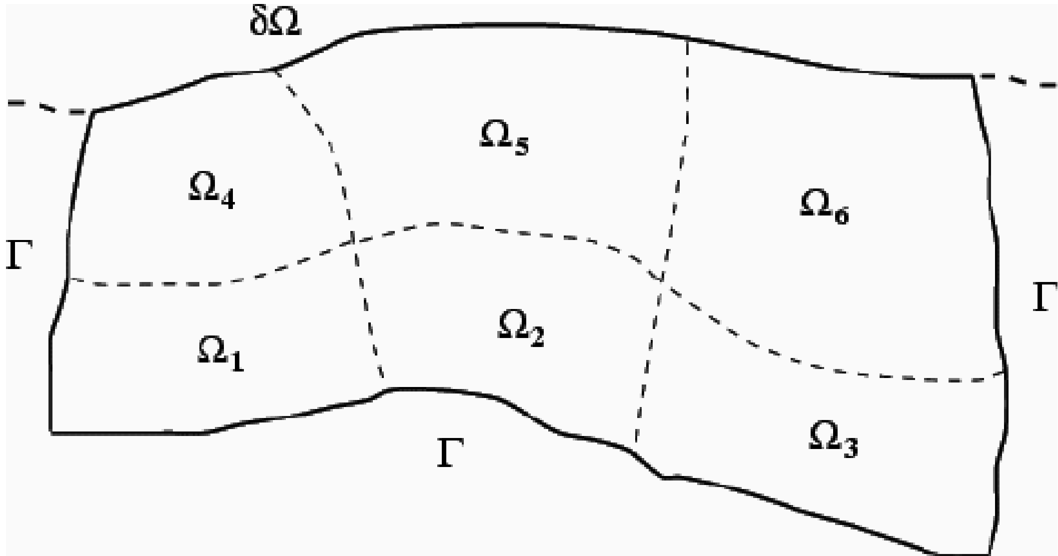


# Spectral-Element Method

- Developed in Computational Fluid Dynamics (Patera 1984)
- Accuracy of a pseudospectral method, flexibility of a finite-element method
- Extended by Komatitsch and Tromp, Chaljub et al., Capdeville et al.
- Large curved “spectral” finite-elements with high-degree polynomial interpolation
- Mesh honors the main discontinuities (velocity, density) and topography
- Very efficient on parallel computers, no linear system to invert (diagonal mass matrix)





# Equations of motion (solid)

Differential or *strong* form (e.g., finite differences):

$$\rho\,\partial_t^2 \mathbf{u} = \nabla \cdot \sigma + \mathbf{f}$$

We solve the integral or *weak* form in the time domain:

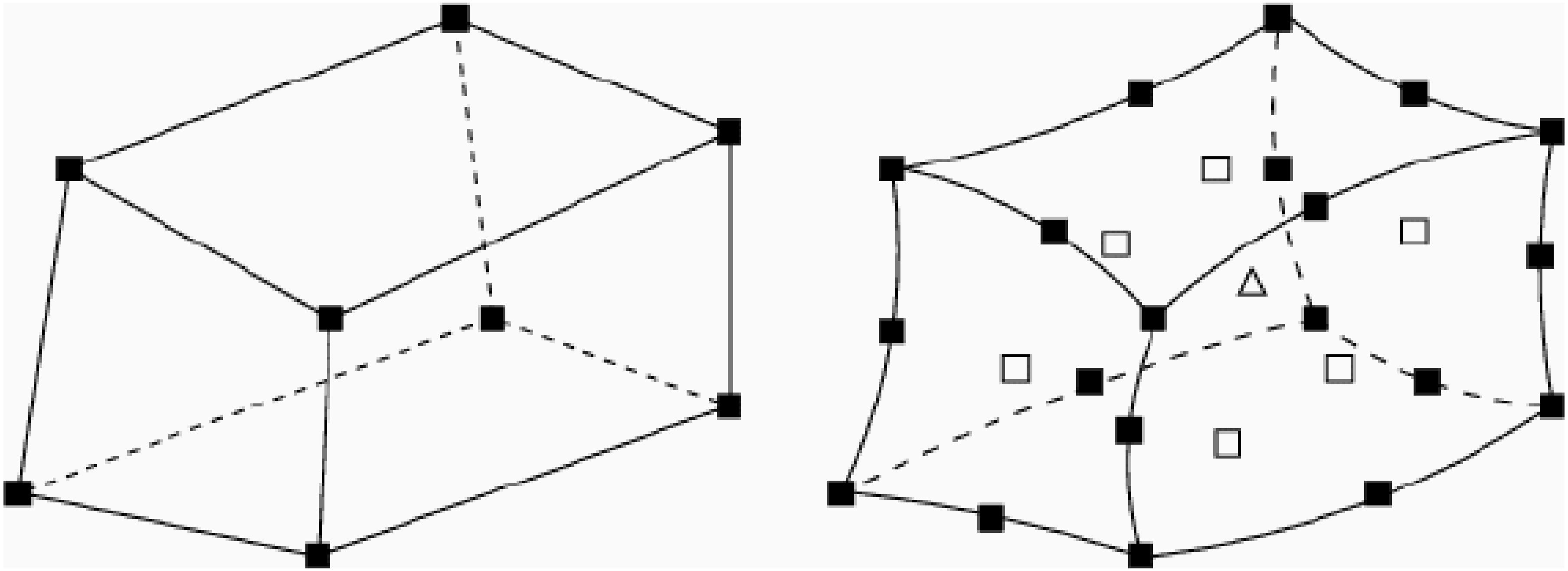
$$\int \rho\, \mathbf{w} \cdot \partial_t^2 \mathbf{u}\, \mathrm{d}^3\mathbf{r} = -\int \nabla \mathbf{w} : \sigma\, \mathrm{d}^3\mathbf{r}$$

$$+ \mathbf{M} : \nabla \mathbf{w}(\mathbf{r}_s)\, S(t) - \int_{F-S} \mathbf{w} \cdot \sigma \cdot \hat{\mathbf{n}}\, \mathrm{d}^2\mathbf{r}$$

+ attenuation (memory variables) and ocean load

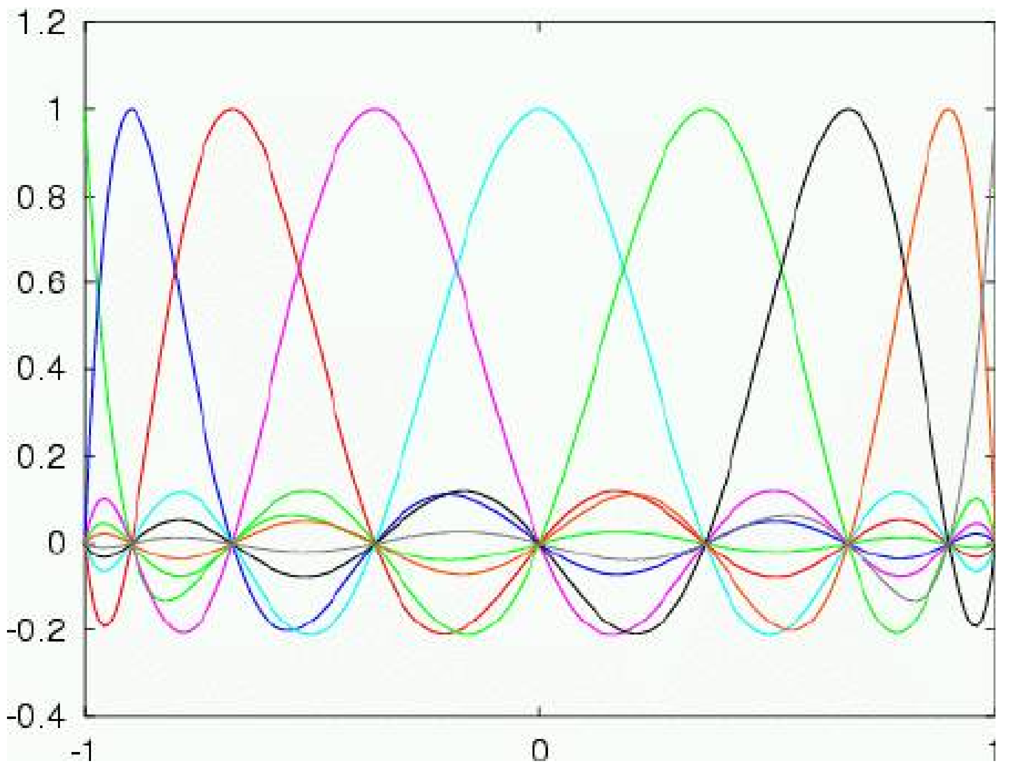
# Curved finite elements

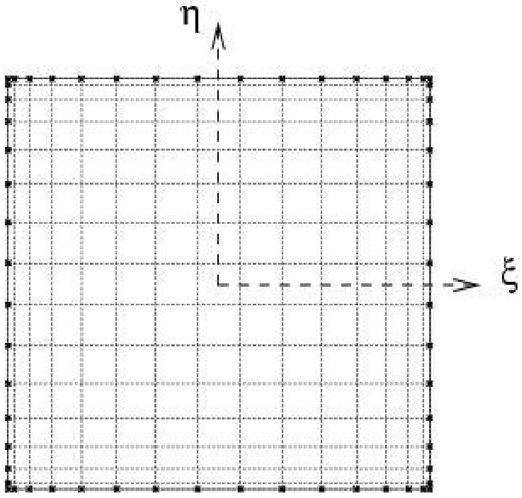
- Curved elements are mapped to unit cube
- Geometry is described by 27 control points

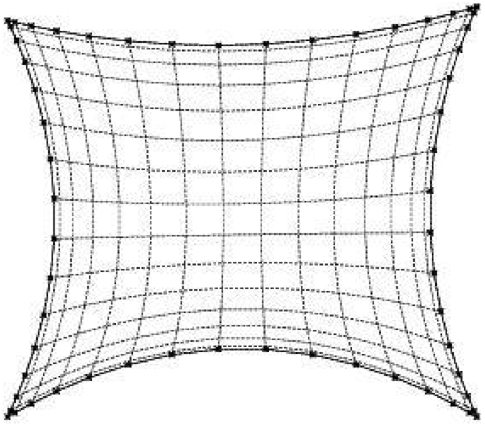


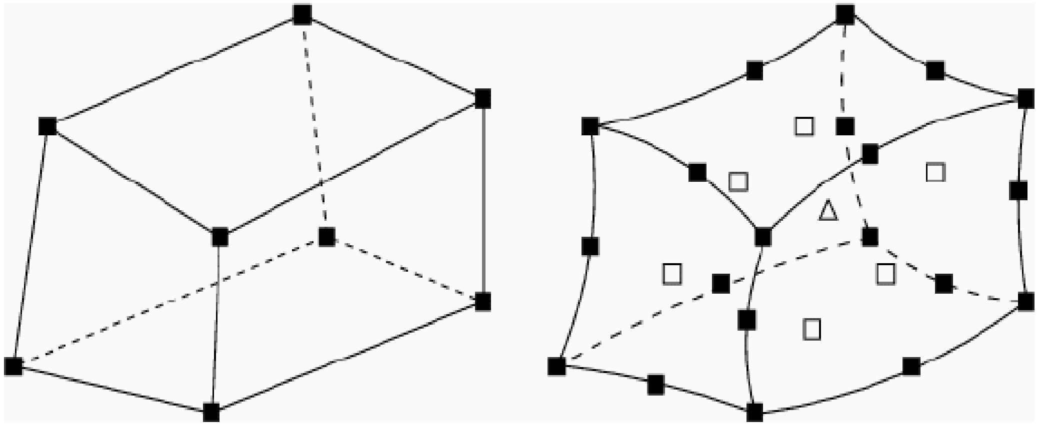
# Finite elements

- High-degree pseudospectral finite elements
- degree N = 4 to 7 usually
- *Strictly* diagonal mass matrix
- No linear system to invert
- Fully explicit time scheme

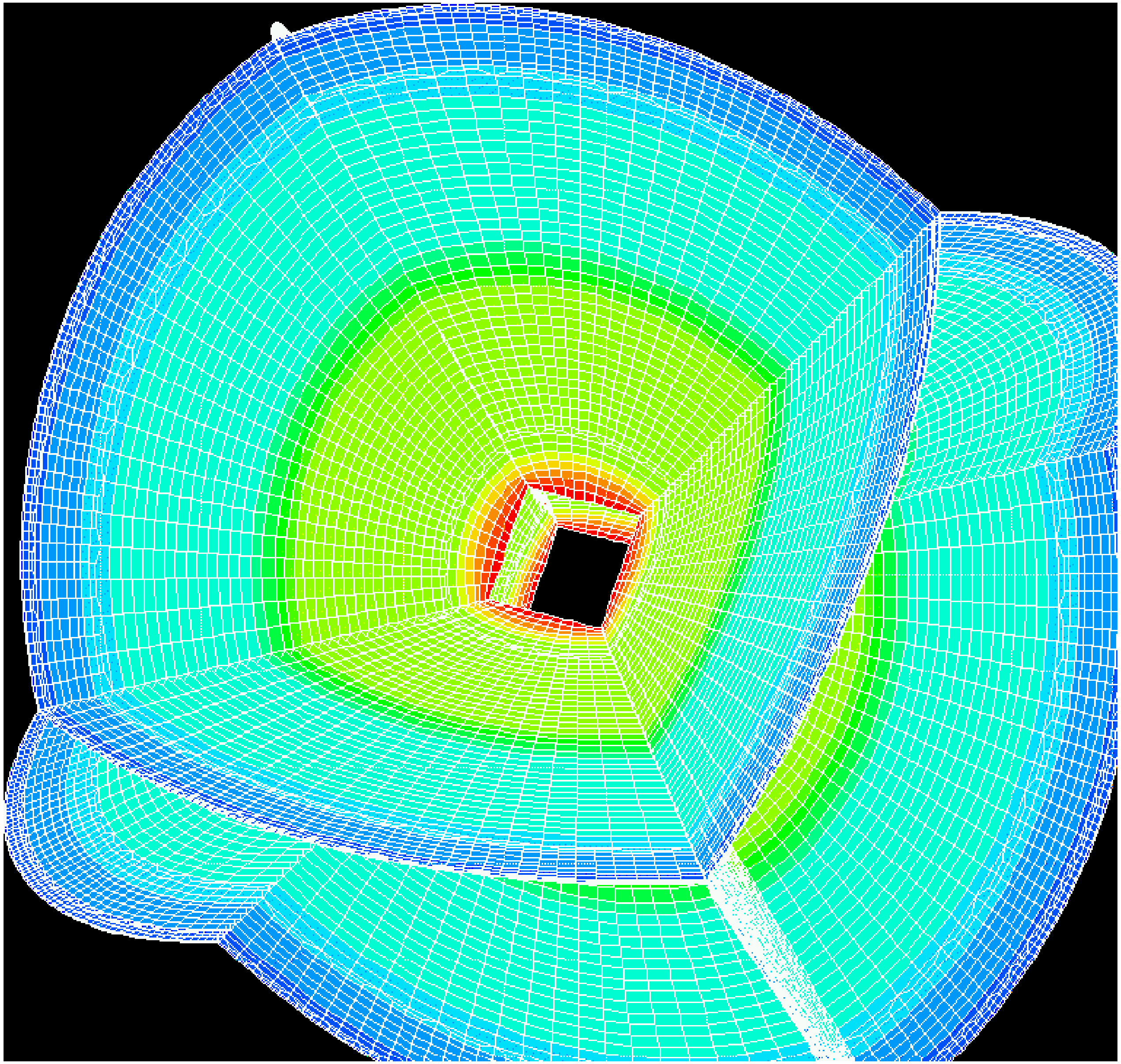


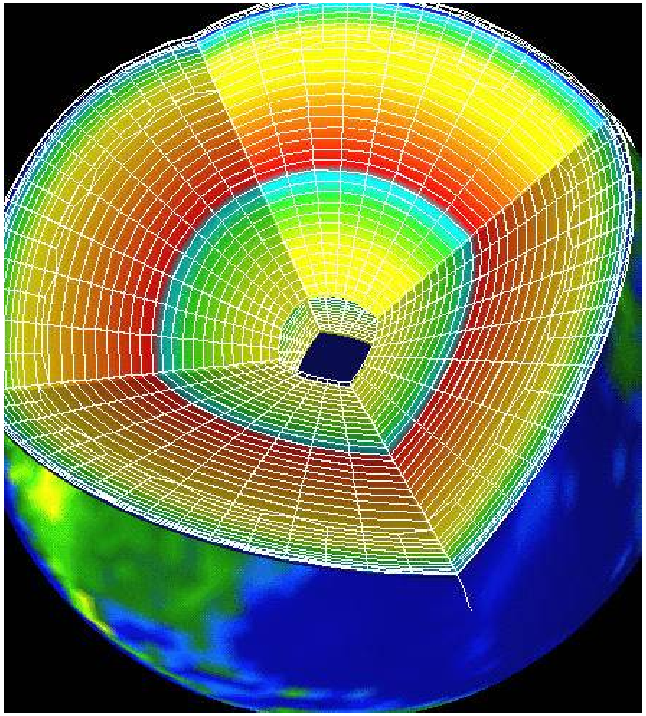



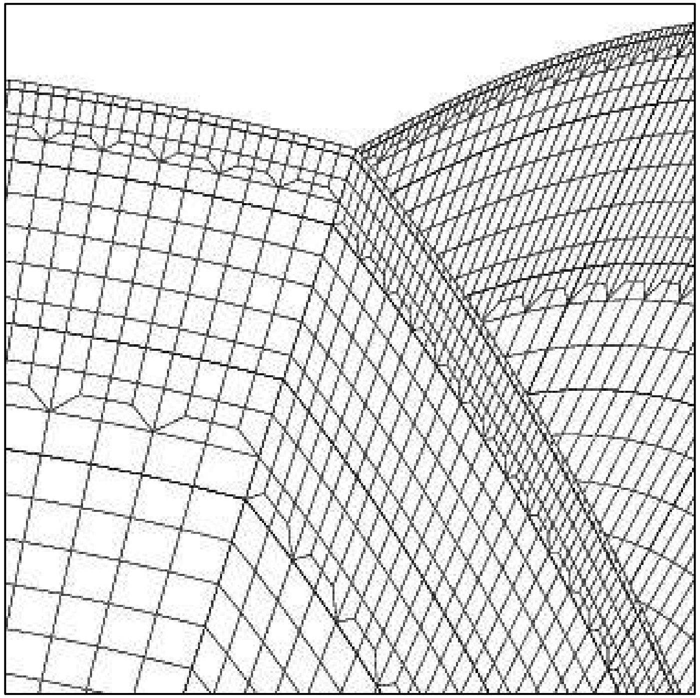





# Global scale Mesh

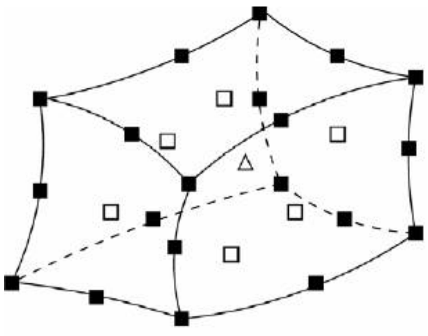


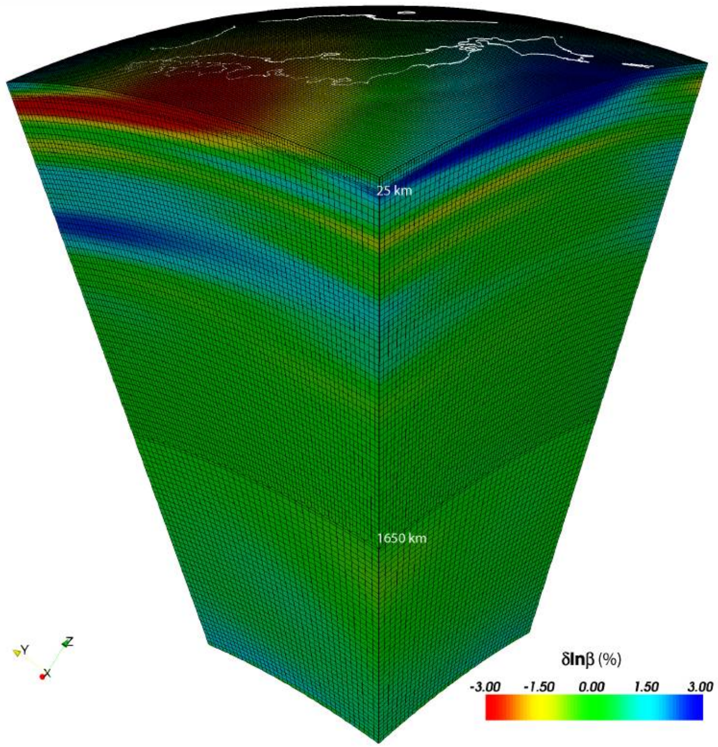


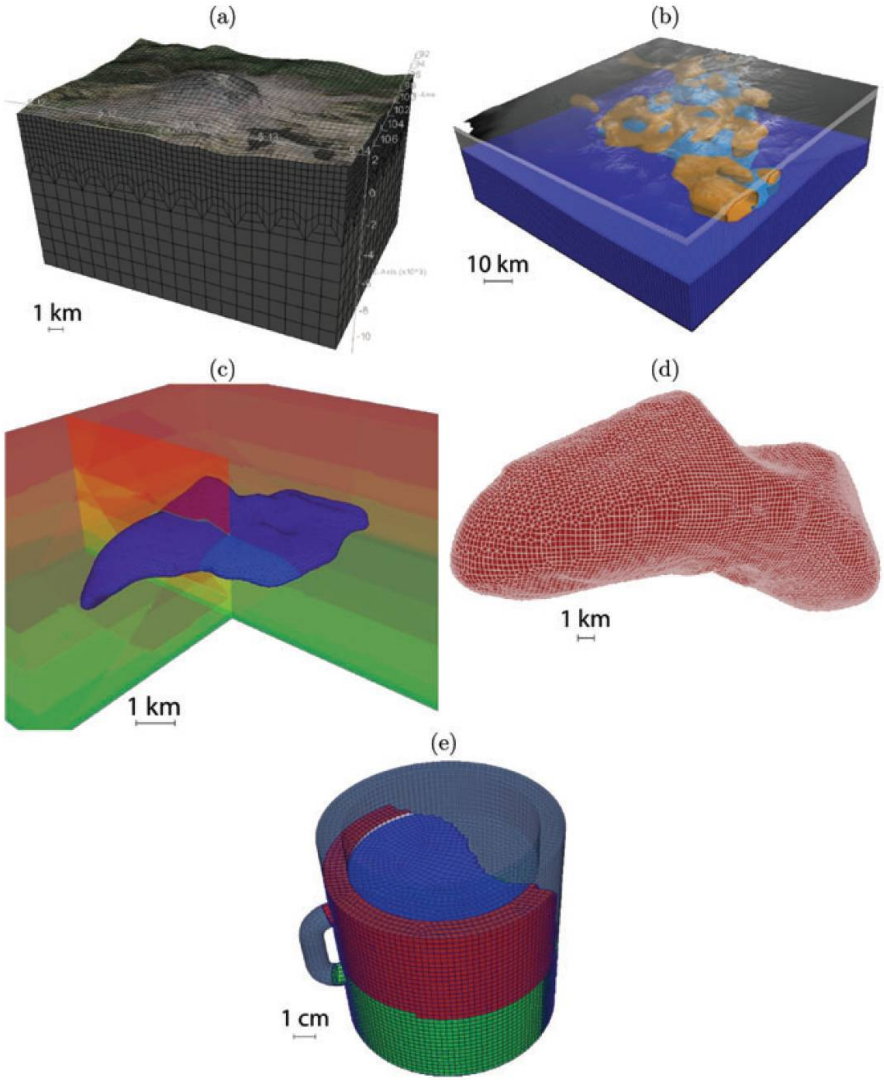


# SPECFEM3D : spectral element method for 3D wave simulation

## *Hexahedral Meshes*

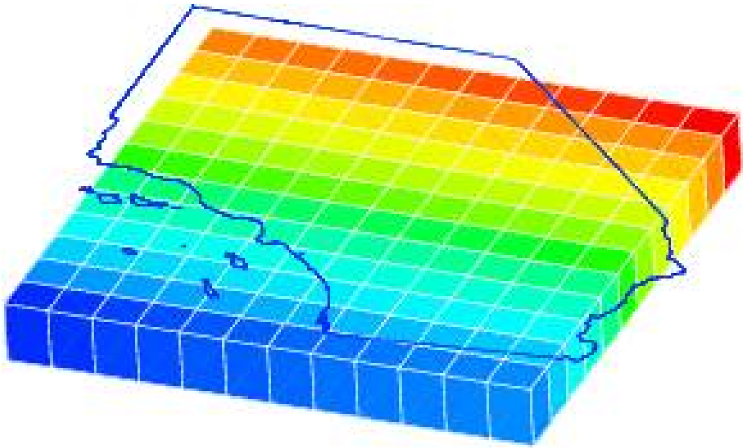


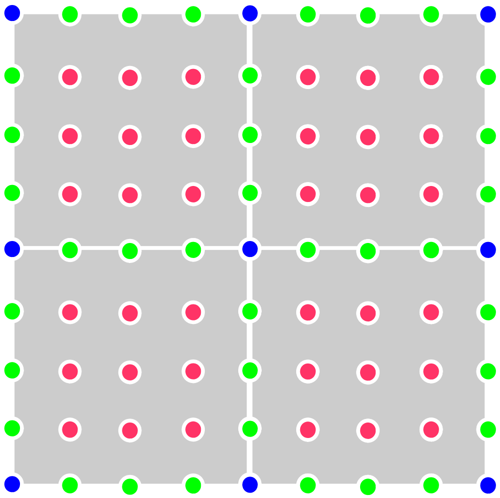



*(Peter et al., 2011)*

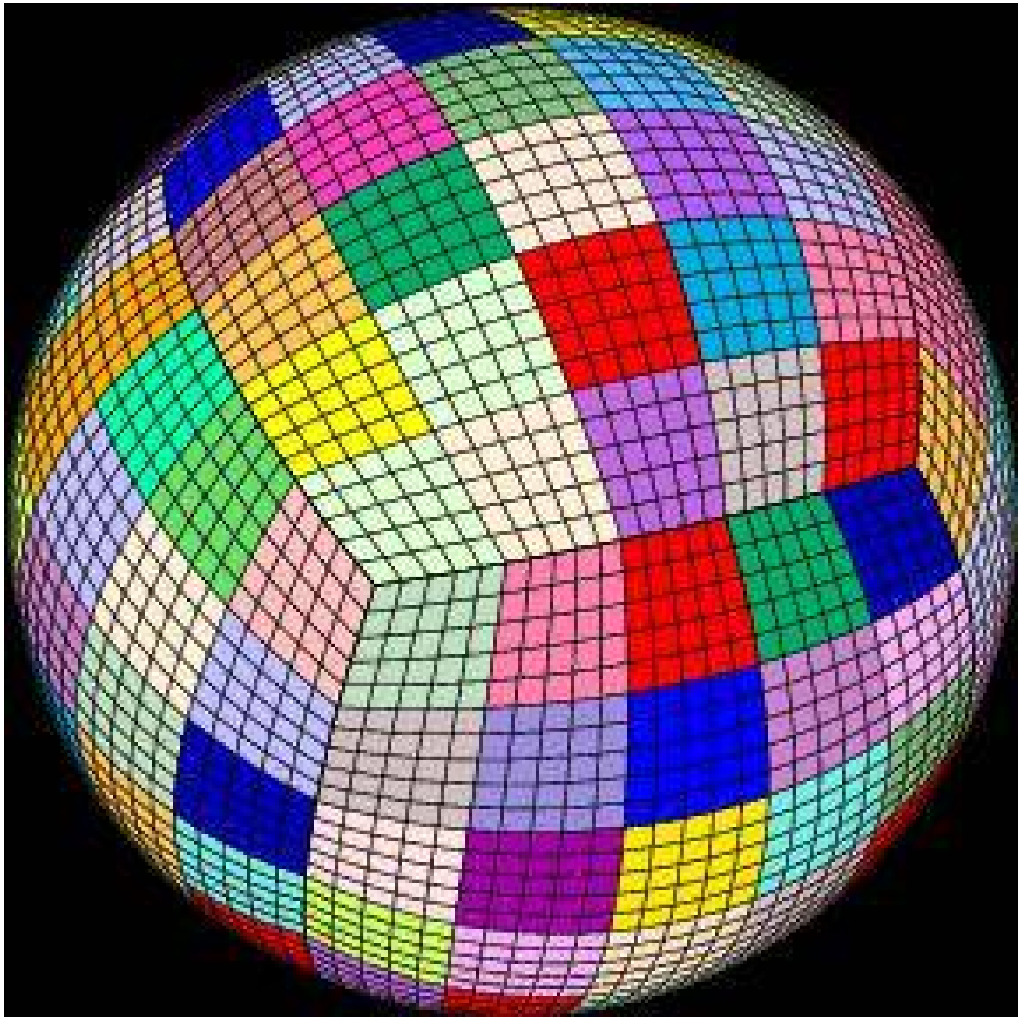
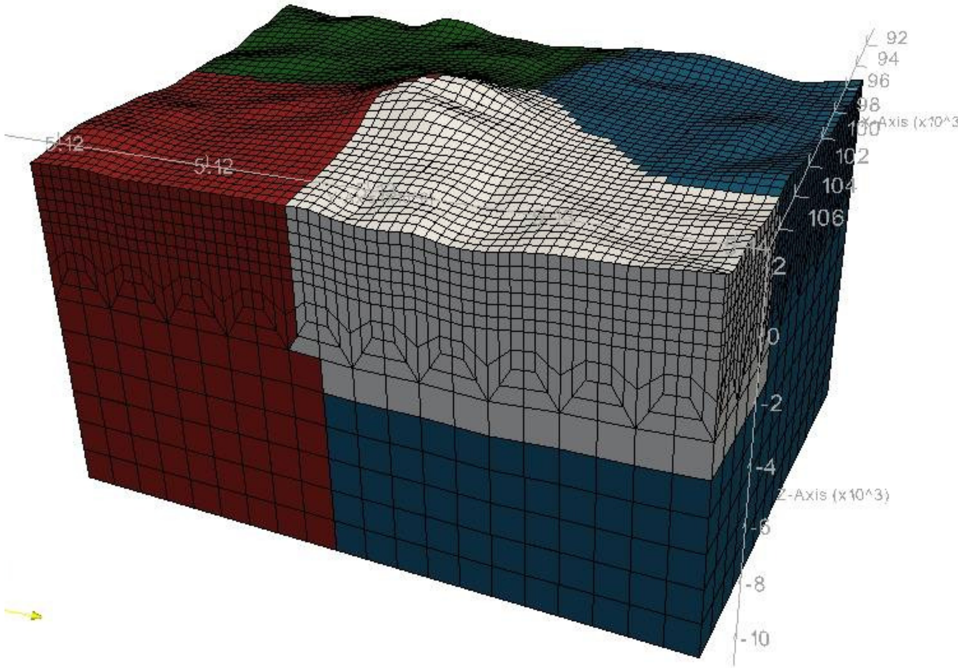
# High-performance computing





Parallel calculations
based on non-blocking message passing (MPI),
overlapping communication with calculations.

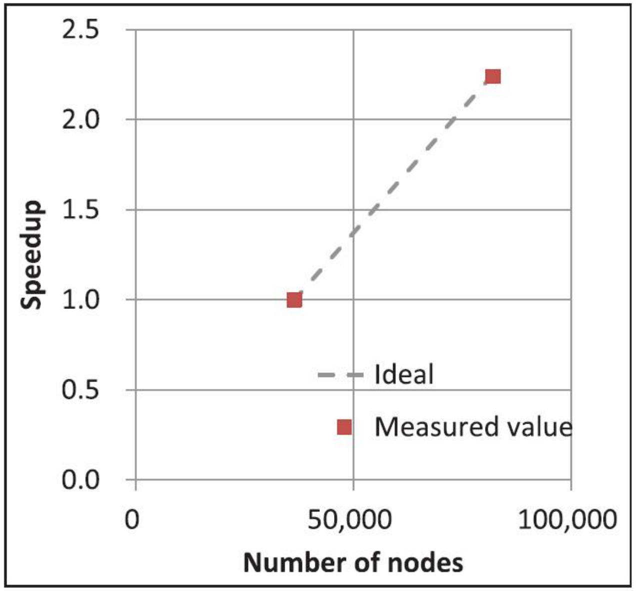

# MPI Implementation

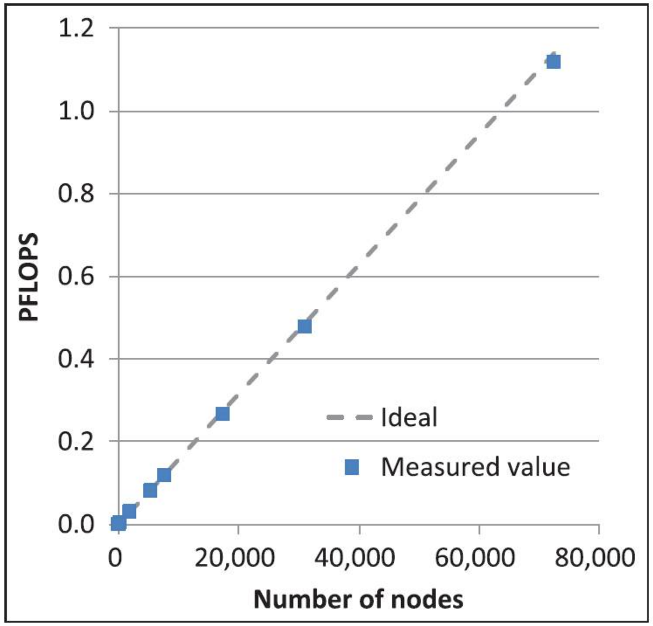

- One slice per processor – non-blocking MPI  communications
- Hybrid MPI/openMP parallelization (CPU)

# Global scale simulation on K computer (Japan)

- Simulation : 1.2 s period on
  82 134 nodes
  657 077 cores
- 82 134 MPI processes
  8 openMP thread / MPI process
- Mesh : 10 billions elements
  1.8 trillion degree-of-freedom



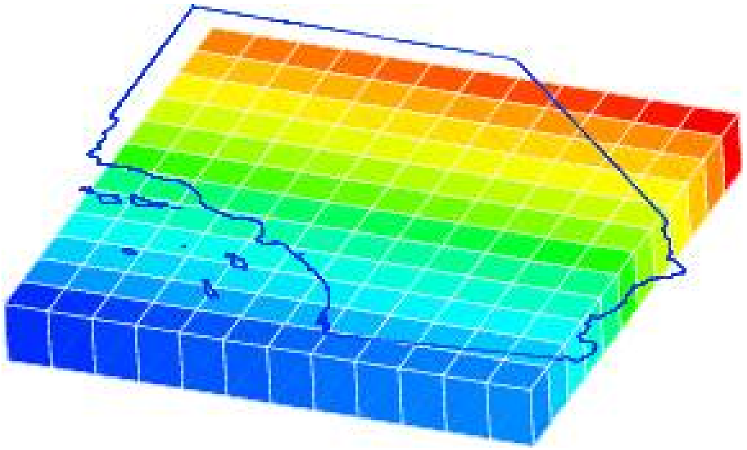

strong scaling

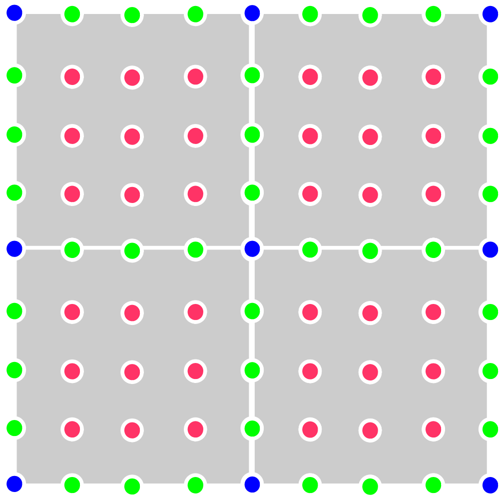



Weak scaling

(*Tsuboi et al., 2016*)

# High-performance & GPU computing





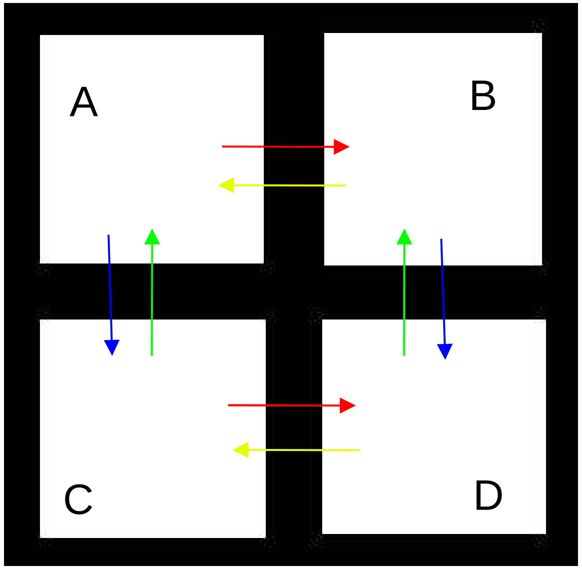
Parallel calculations based on non-blocking message passing (MPI), overlapping communication with calculations.



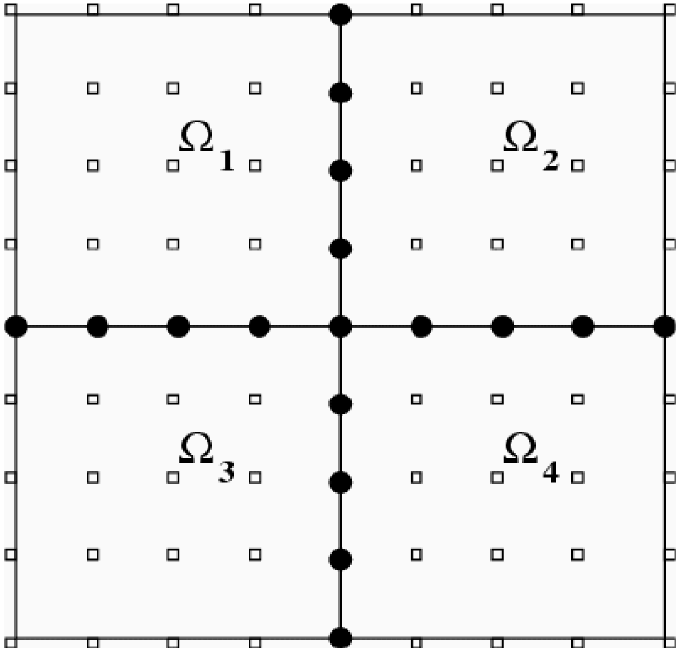
GPU cards:
Why are they so powerful for scientific computing?
Compute all pixels simultaneously, massive multithreading.

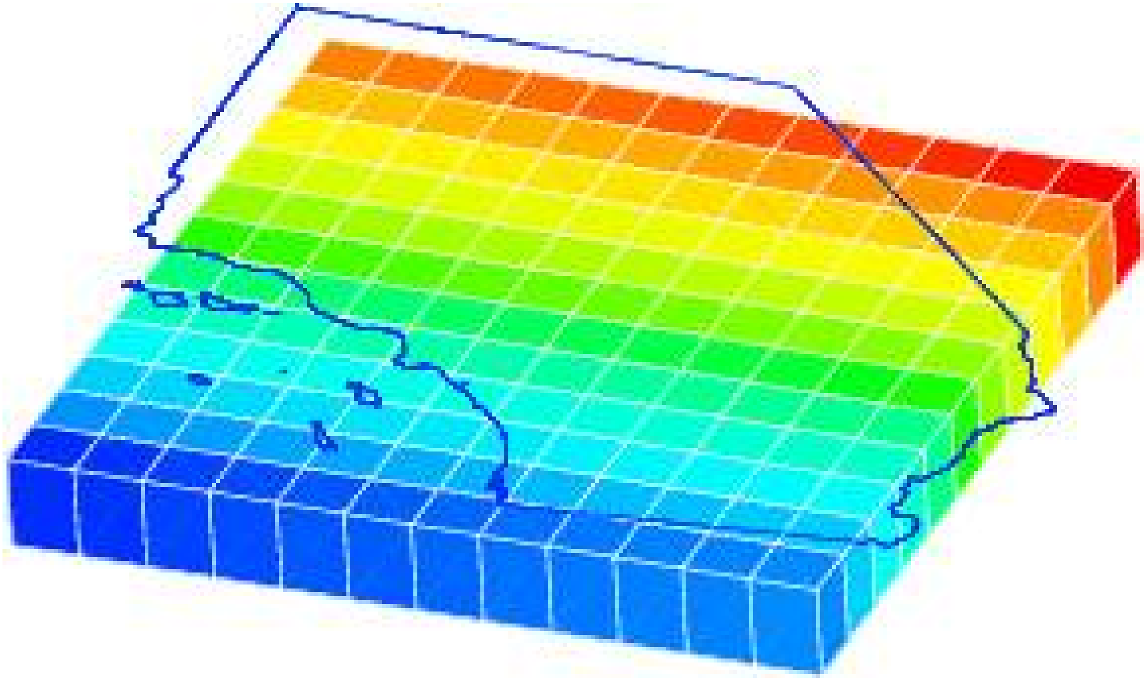
⇒ GPU computing: code is complex to rewrite, but large speedup can be obtained (but it is difficult to define speedup).

# CUDA + MPI

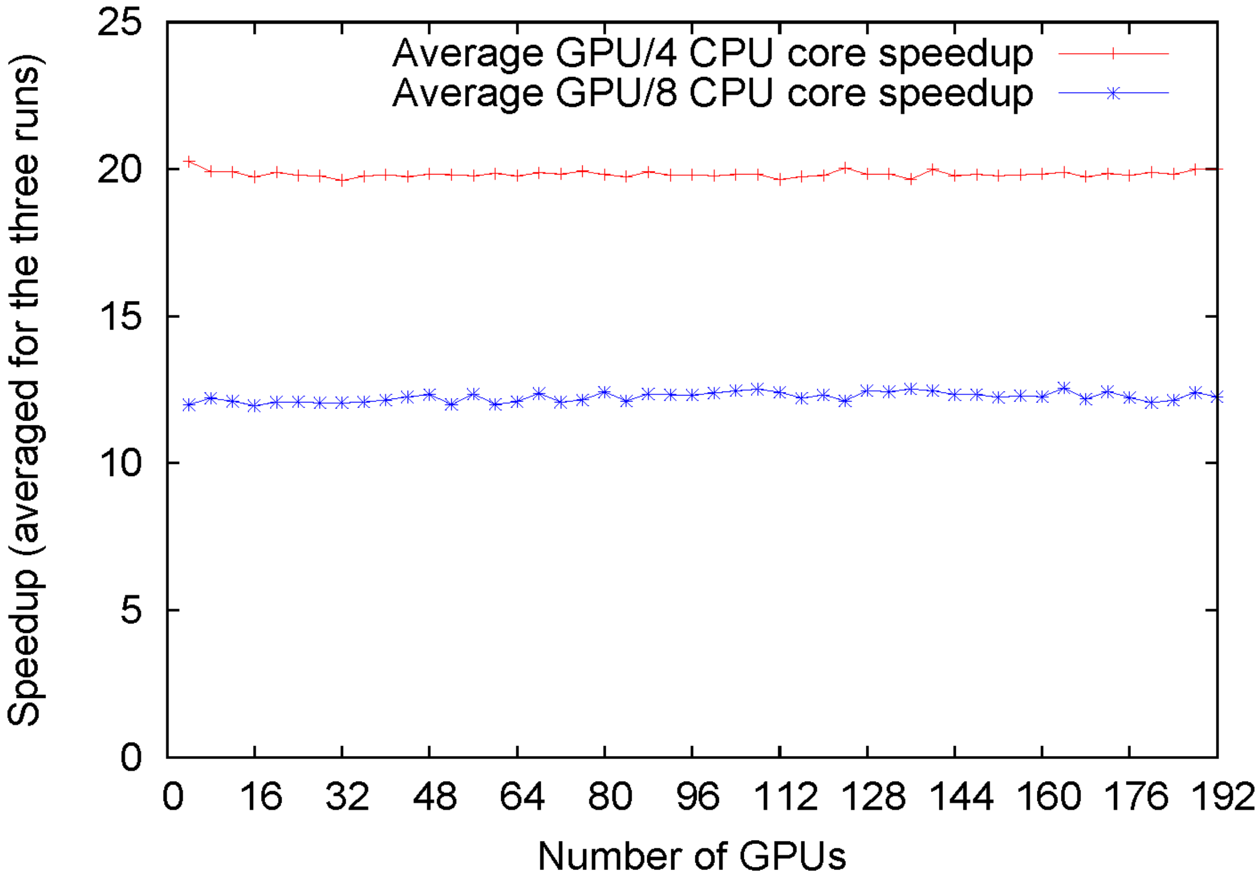



communication scheme
(non-blocking MPI)



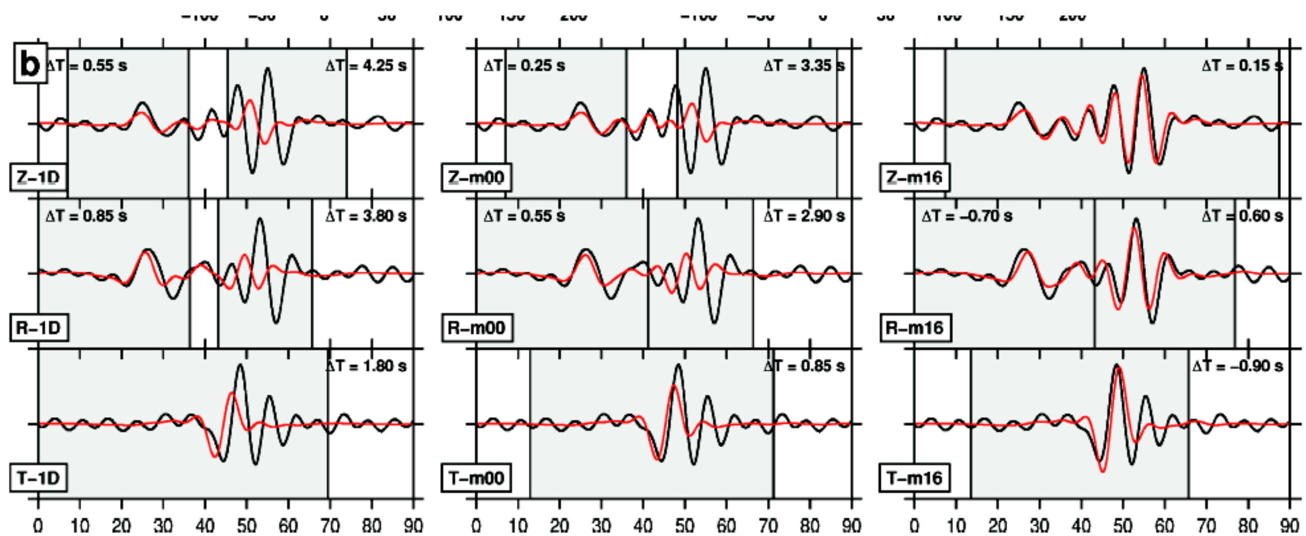
# Multi-GPU weak scaling

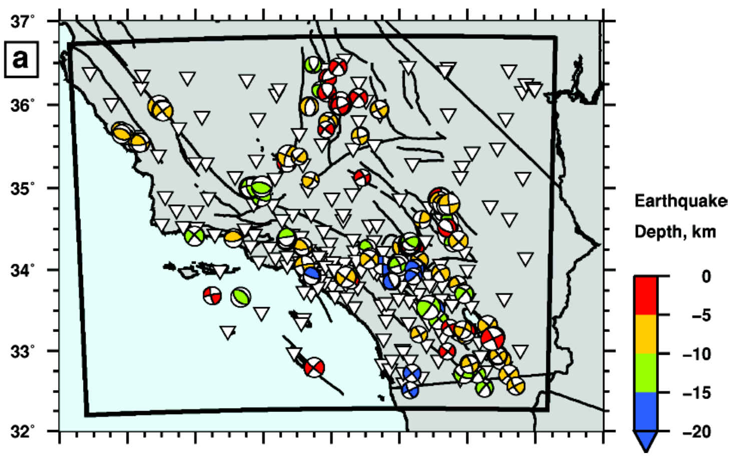


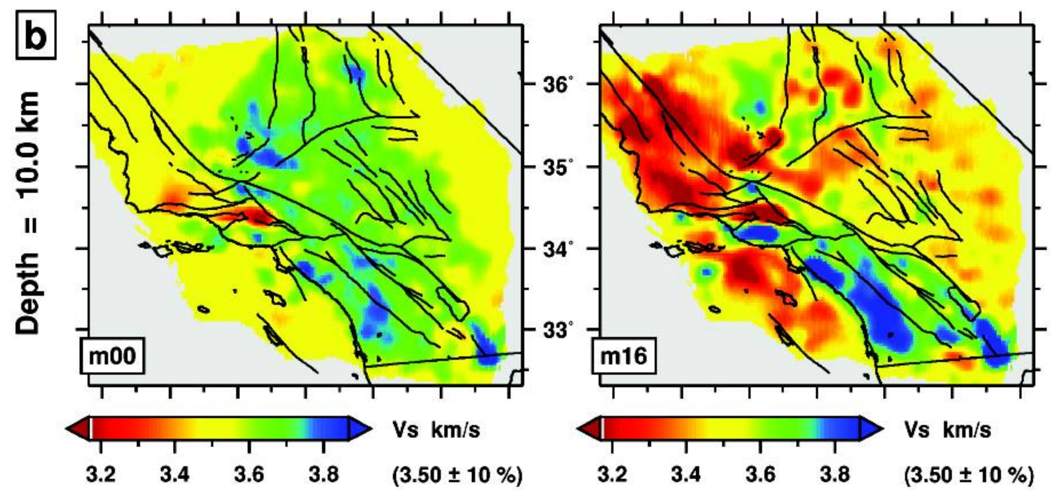

High-frequency ocean acoustics, inverse problems in seismology, acoustic tomography, reverse-time migration in seismics: high resolution needed, and/or large iterative problems to solve.

*(Komatitsch et al., 2010)*

# Regional scale adjoint tomography

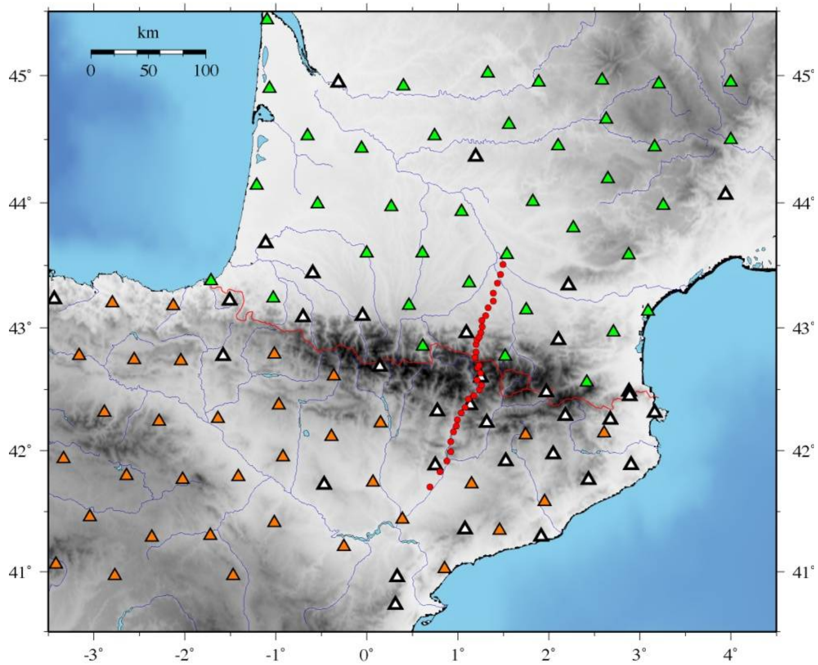


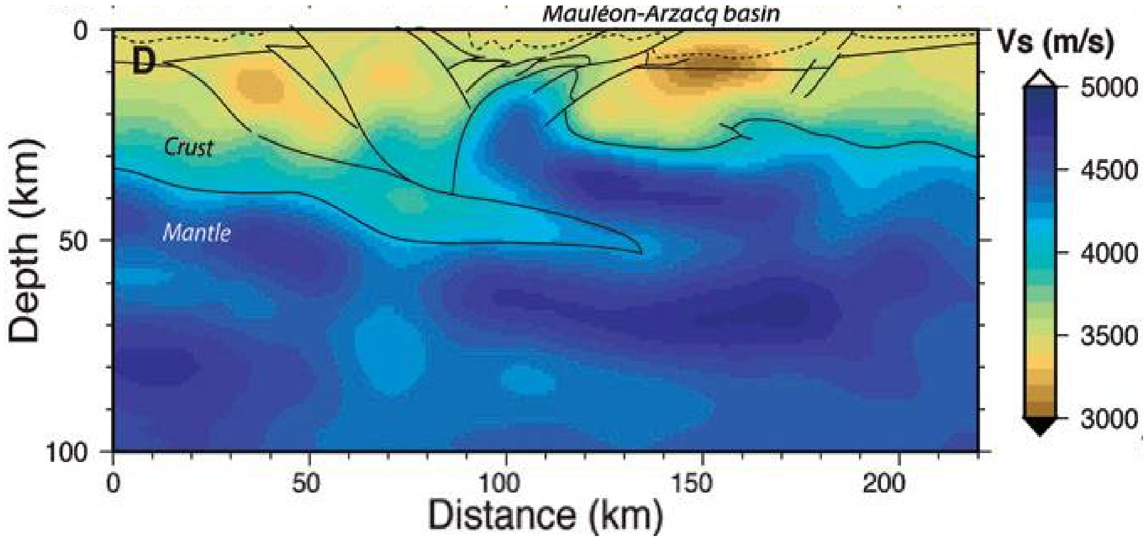



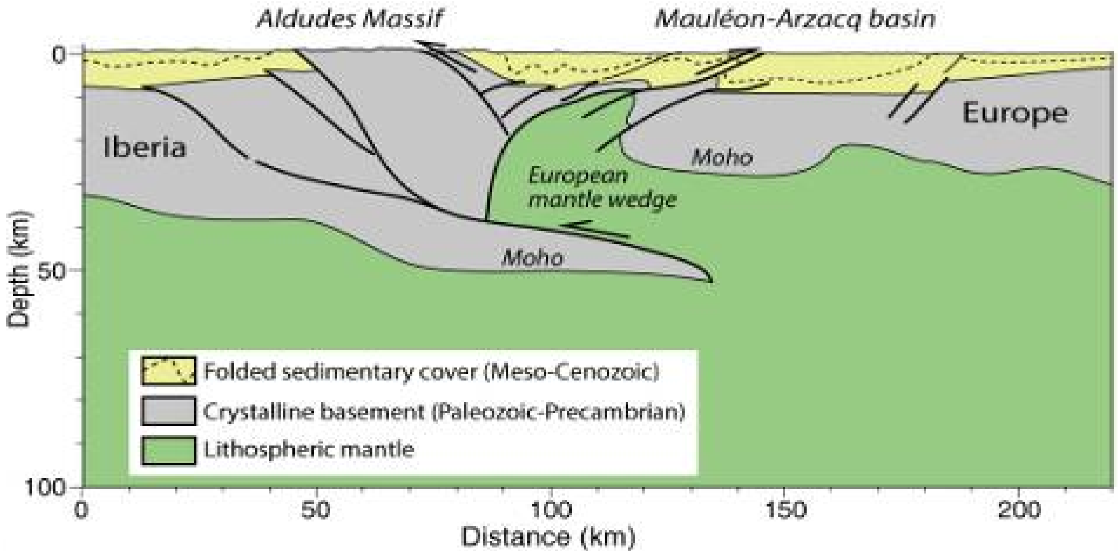




*(Tape et al., 2010)*

# Imaging the Pyrénées Mountains





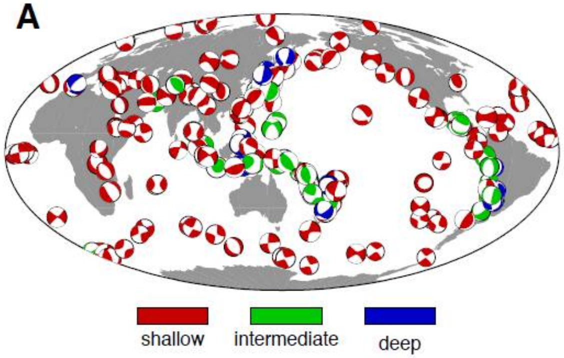



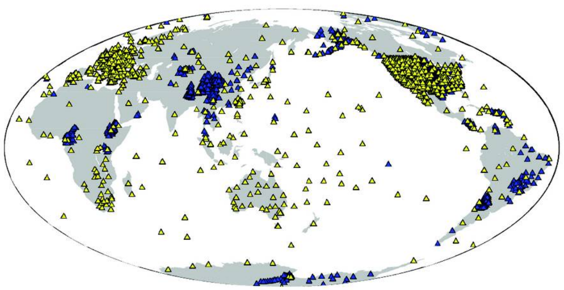

- Drastically-improved quality of the images thanks to the high frequencies involved

- This results in a much more precise and therefore much more interesting geological interpretation (how the Earth formed and keeps evolving)

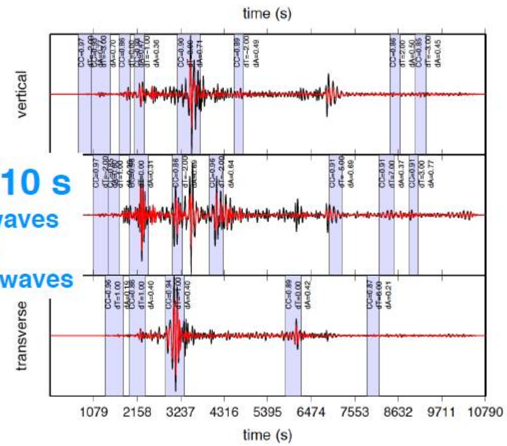
*(Wang et al., 2016).*

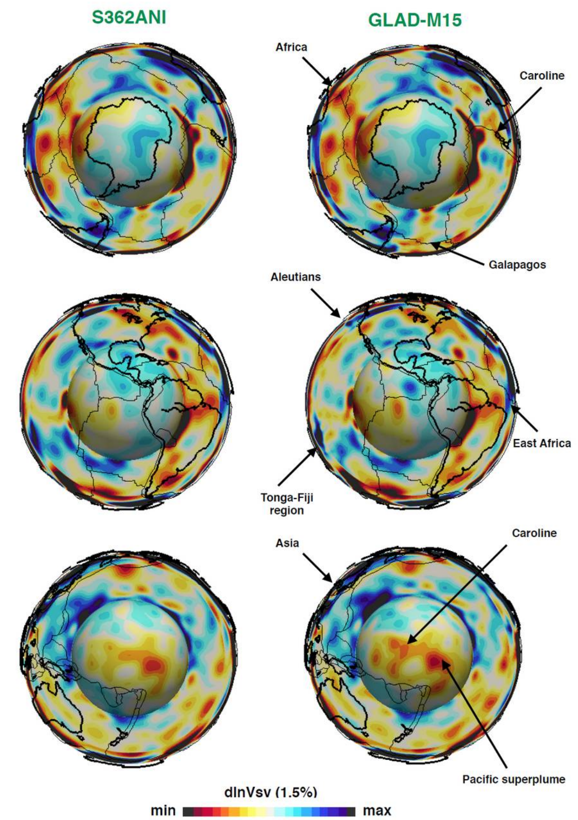
# Global Adjoint Tomography



45 - 110 s
body waves
+
surface waves



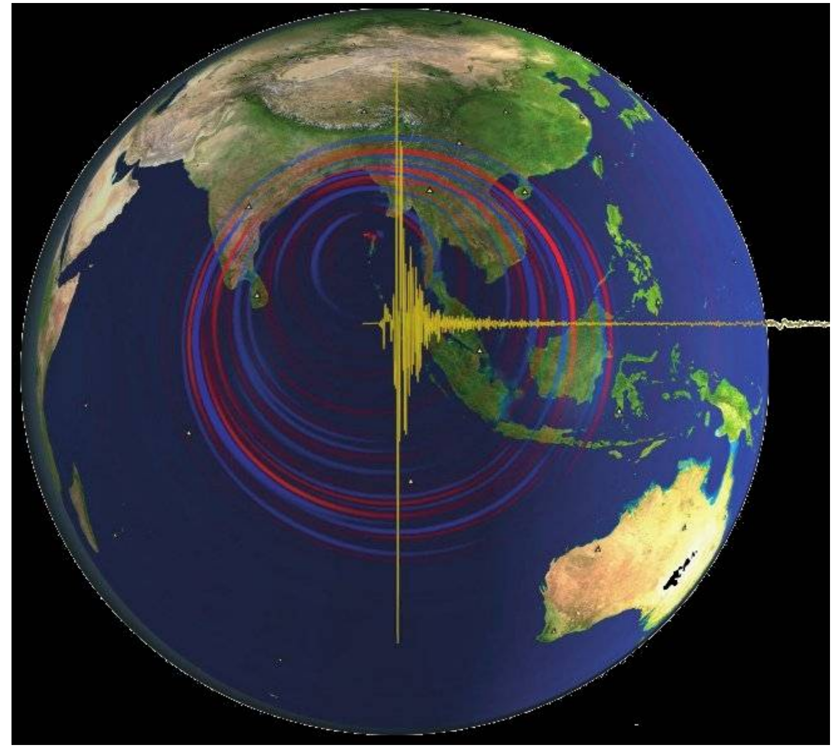




(Bozdag et al., 2016)

# SPECFEM3D software package

https://github.com/geodynamics/specfem3d

User download map



**Goal**: model acoustic / elastic / viscoelastic / poroelastic / seismic wave propagation in in non destructive testing, in ocean acoustics, in the Earth (earthquakes, oil industry)…

The SPECFEM3D source code is open (GNU GPL v3)

Initially Komatitsch and Vilotte at IPG Paris (France), mostly developed by Dimitri Komatitsch and Jeroen Tromp at Harvard University, then Caltech, Princeton (USA) and CNRS (France) since 1996.

Improved with INRIA and University of Pau (France), ETH Zürich and University of Basel (Switzerland), the Barcelona Supercomputing Center (Spain), NVIDIA…