Modeling and imaging based on acoustic or seismic waves: a combination of numerical modeling, high performance computing, and big data

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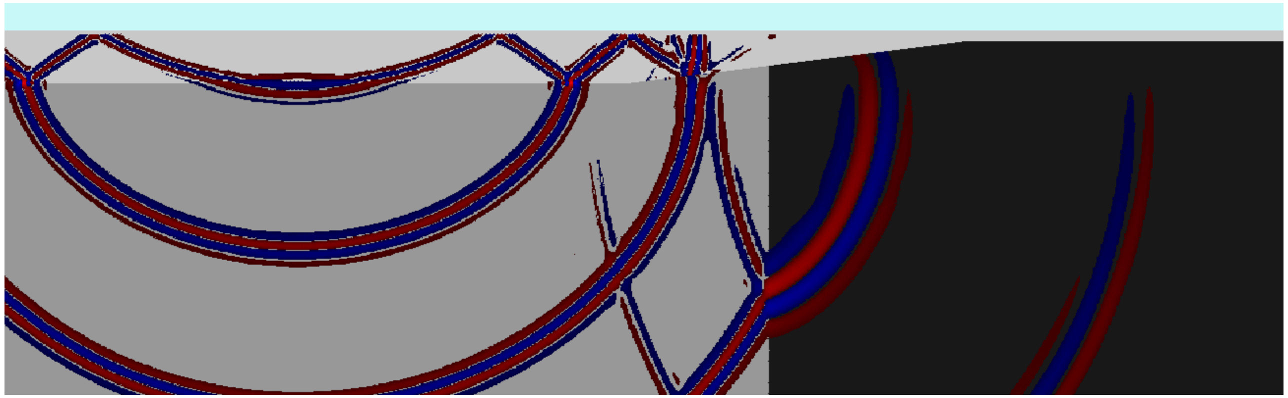
01 June 2017

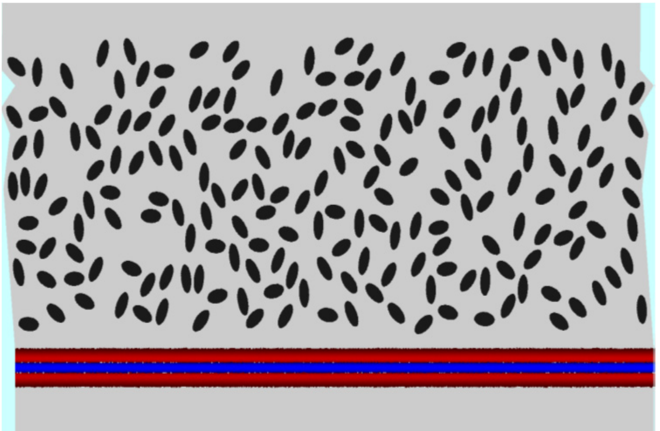
Application domains

Different application domains of acoustic full waveform numerical modeling

Earthquakes



Ocean acoustics



Non destructive testing

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:

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

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

+ attenuation (memory variables)

Equations of motion (fluid)

Differential or *strong* form in the time domain:

$$\rho\,\partial_t \mathbf{v} = -\nabla p \qquad \partial_t p = -\kappa\,\nabla\cdot\mathbf{v}$$

with κ the adiabatic bulk modulus.

We use a scalar potential of ρ * displacement:

$$\rho\mathbf{u} = \nabla\chi \qquad p = -\partial_t^2\chi$$

The integral or *weak* form is:

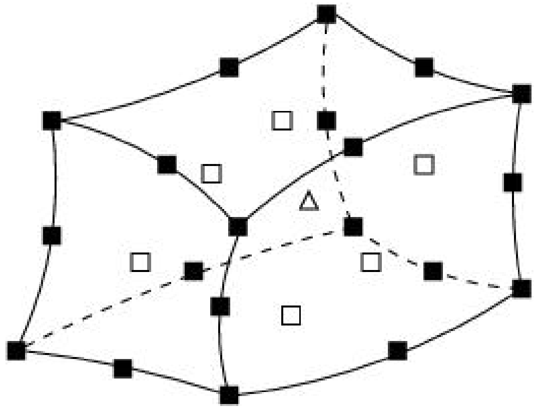
$$\int \kappa^{-1} w\,\partial_t^2\chi\,\mathrm{d}^3\mathbf{r} = -\int \rho^{-1}\nabla w\cdot\nabla\chi\,\mathrm{d}^3\mathbf{r}$$

$$+\int_{\mathrm{F-S}} w\,\hat{\mathbf{n}}\cdot\mathbf{v}\,\mathrm{d}^2\mathbf{r}$$

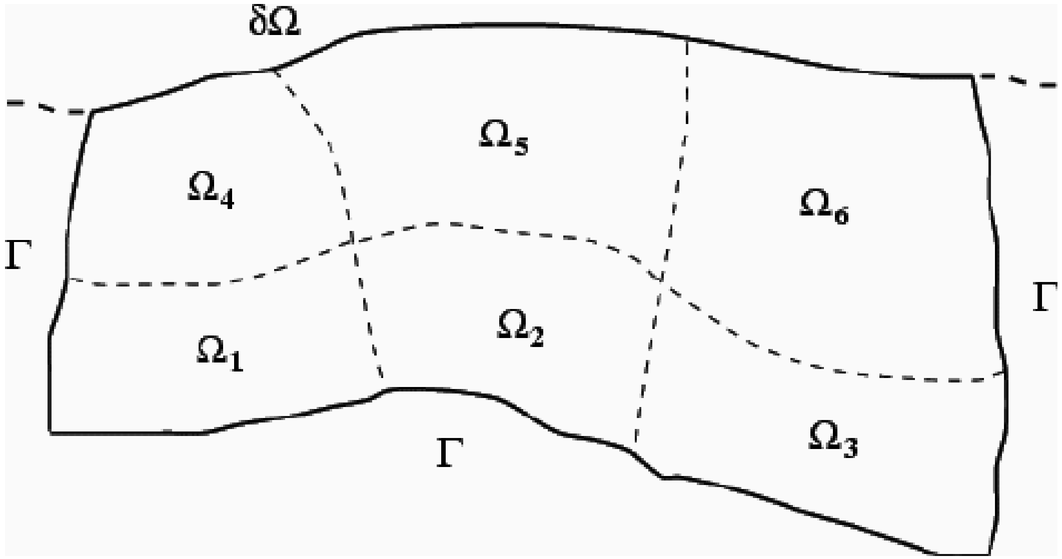
⇒ cheap (scalar potential)

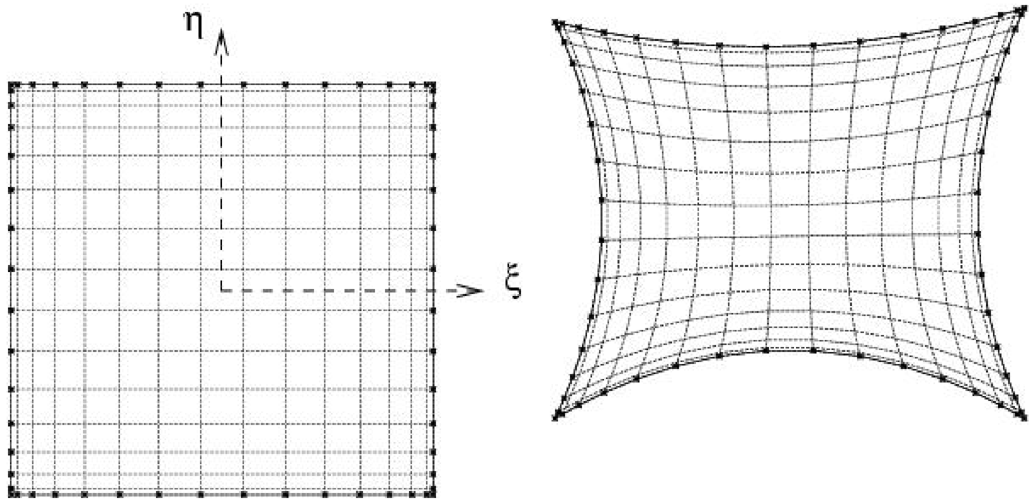
⇒ natural coupling with solid

Spectral-Element Method



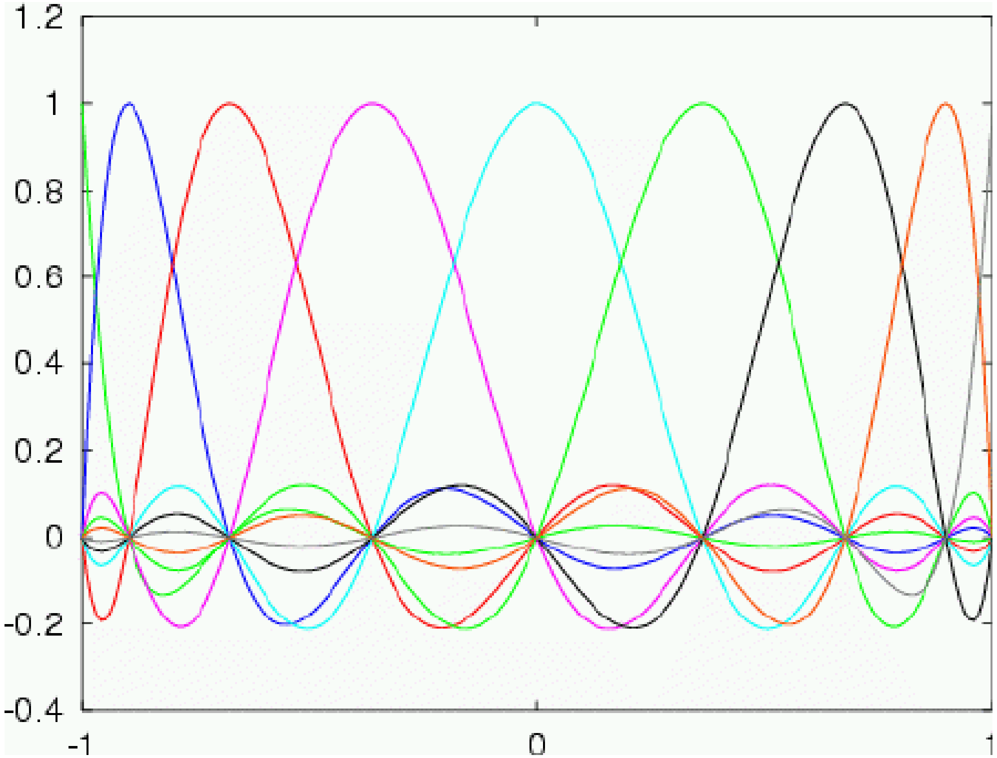
- Developed in Computational Fluid Dynamics (Patera 1984)
- Accuracy of a pseudospectral method, flexibility of a finite-element method
- Extended by Komatitsch and Tromp, Chaljub et al.
- Large curved “spectral” finite-elements with high-degree polynomial interpolation
- Mesh honors the main discontinuities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

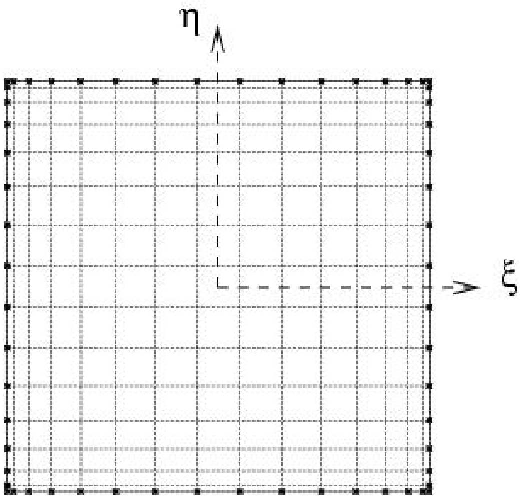


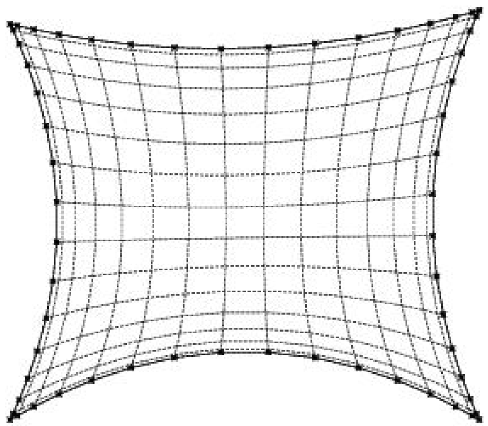


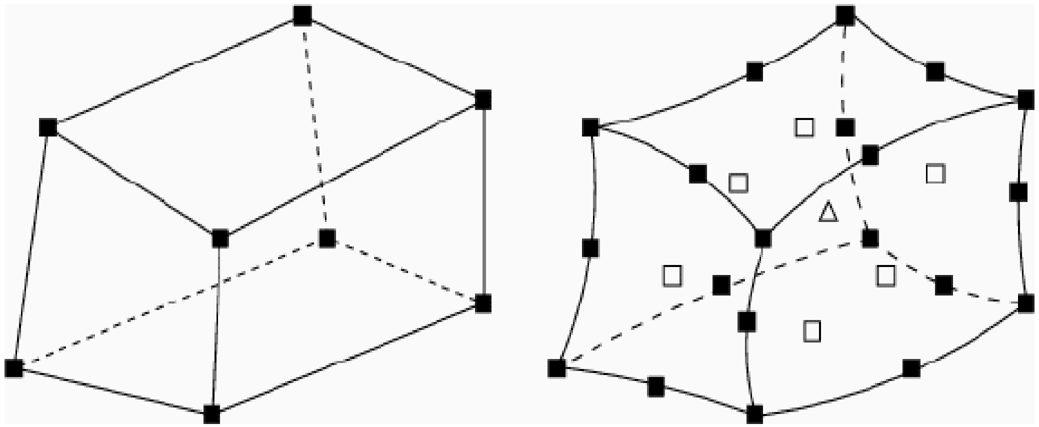
Finite elements

- High-degree pseudospectral finite elements
- N = 5 to 8 usually
- *Strictly* diagonal mass matrix
- No linear system to invert
- Fully explicit time scheme



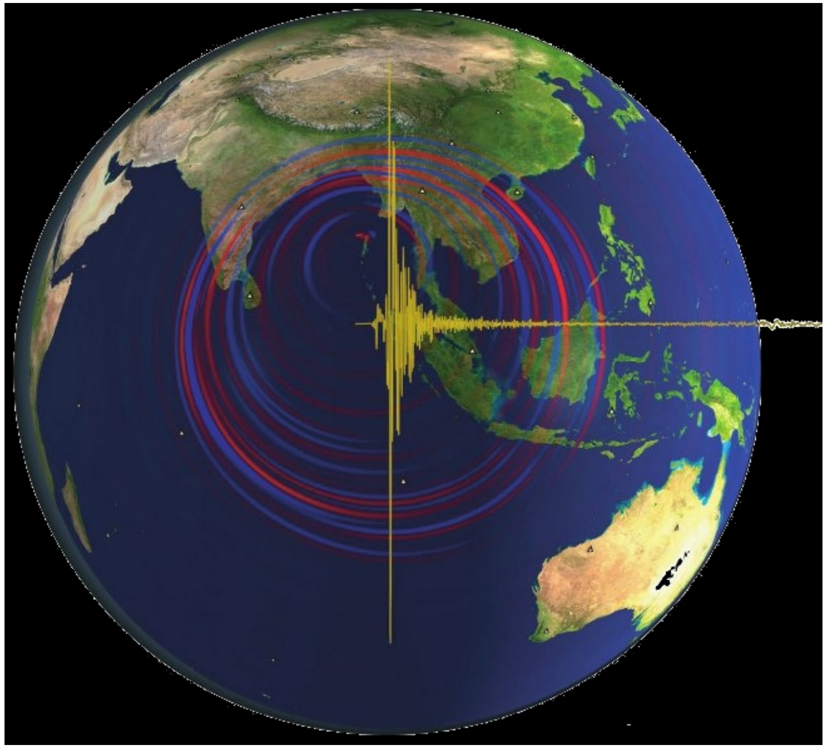






Our SPECFEM3D software package

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 v2)

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…

Earthquake hazard assessment

Use parallel computing to simulate earthquakes

Learn about structure of the Earth based upon seismic waves (tomography)

Produce seismic hazard maps (local/regional scale) e.g. Los Angeles, Tokyo, Mexico City, Seattle

2001 Gujarati (M 7.7) Earthquake, India

20,000 people killed
167,000 injured
≈ 339,000 buildings destroyed
783,000 buildings damaged

Earthquakes

6 April 2009
M_w 6.2 L'Aquila (Italy)

310 casualties
~ 1000 injured
~ 26000 homeless

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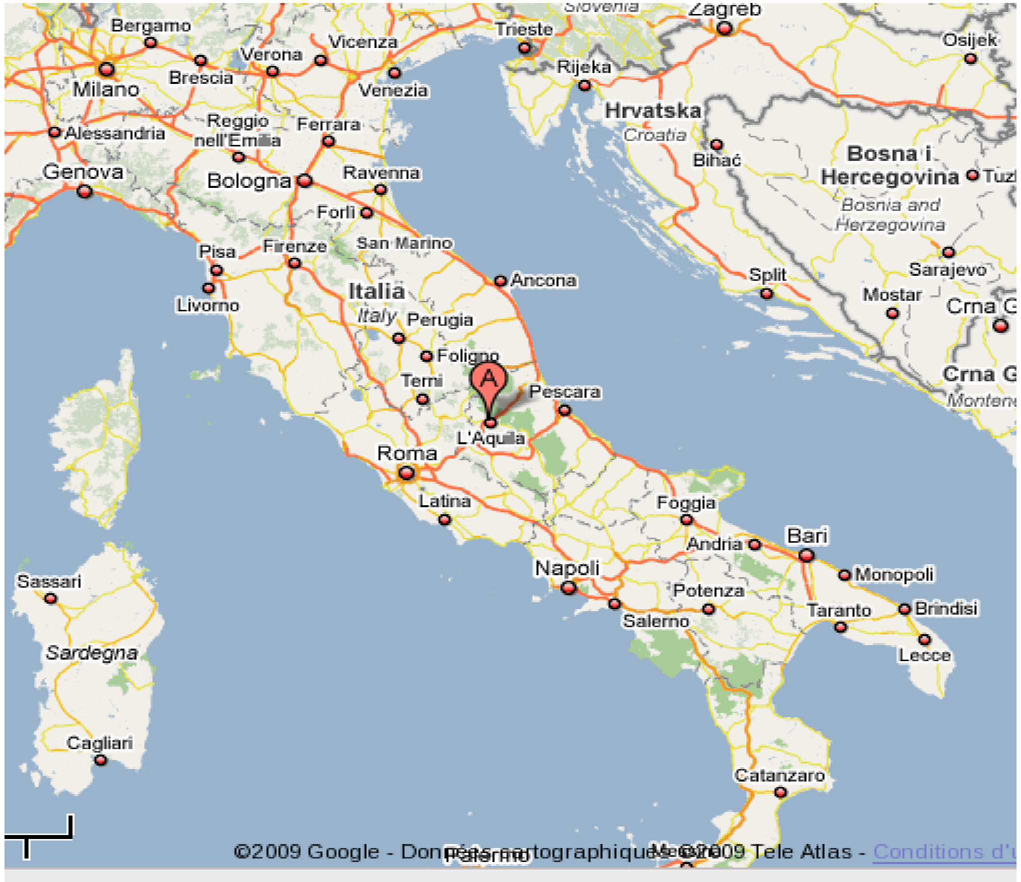
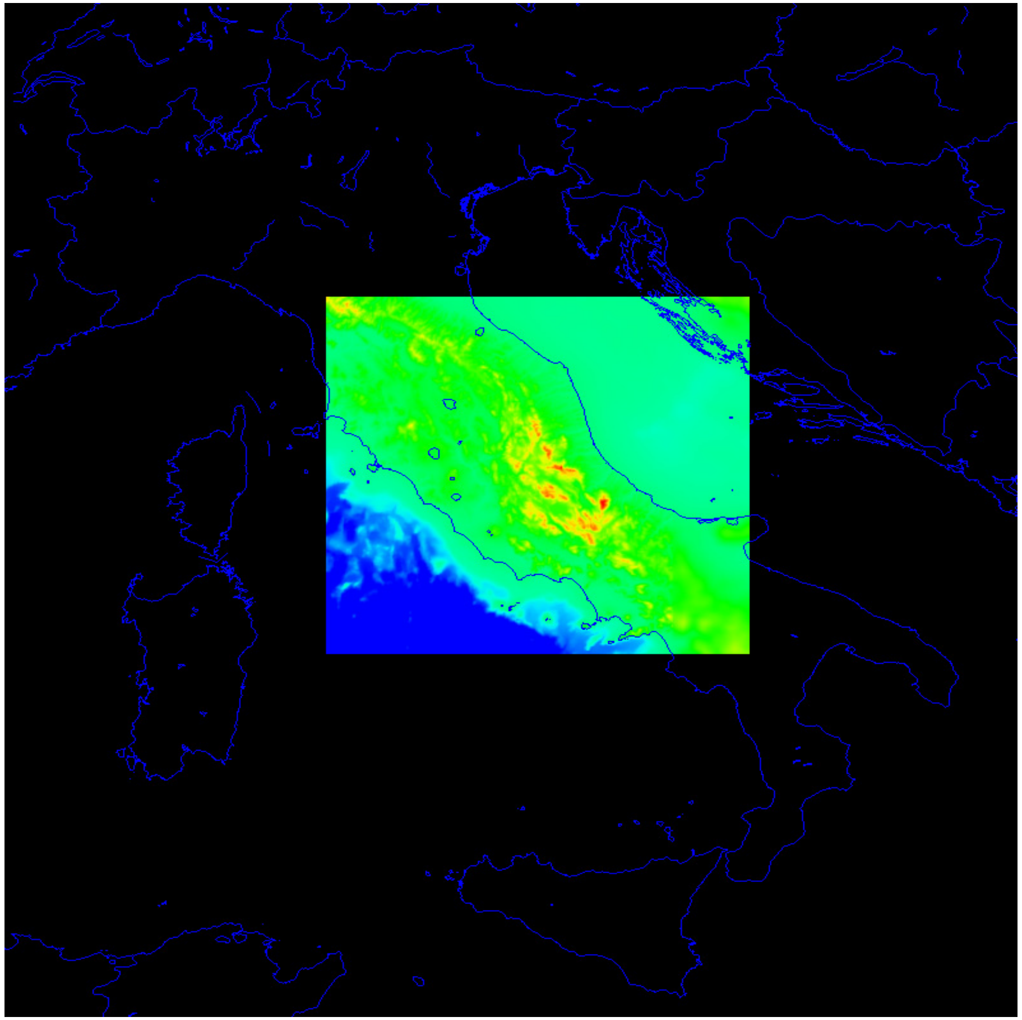
Collaboration with
Emanuele Casarotti and Federica Magnoni (INGV Roma, Italy)

L’Aquila, Italy, April 6, 2009 (Mw = 6.2)



Location of the epicenter
(© Google Maps)



Mesh defined on the
JADE supercomputer
on April 7, 2009

M_W 6.2 L'Aquila

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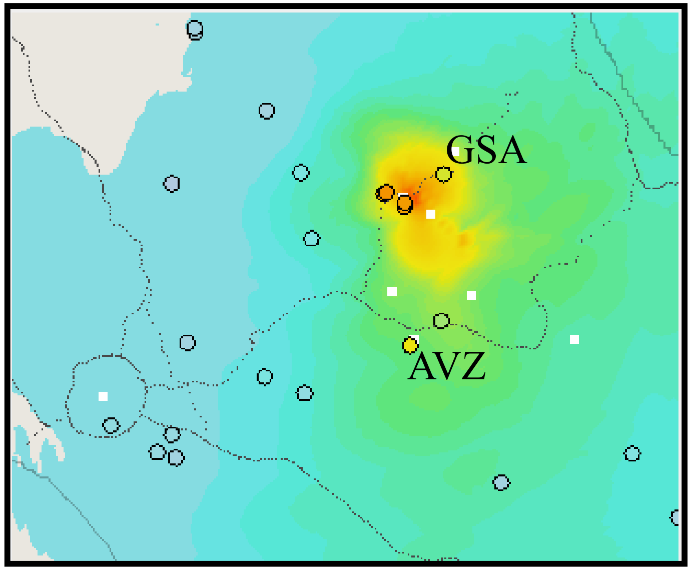
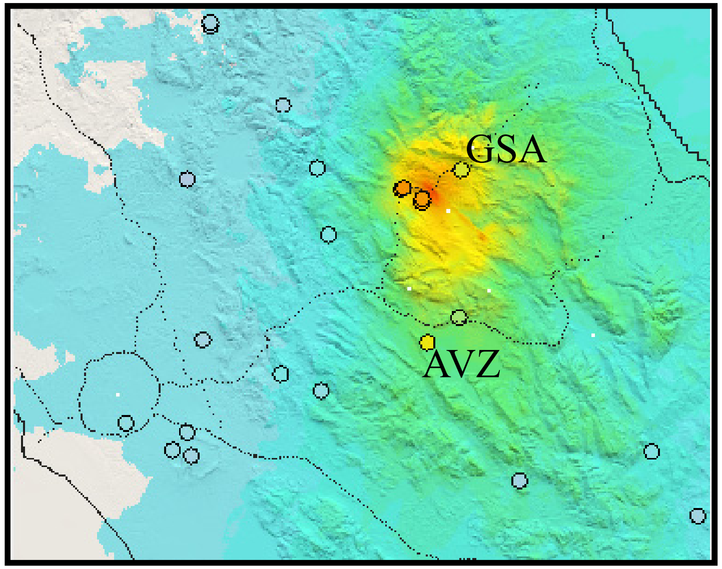
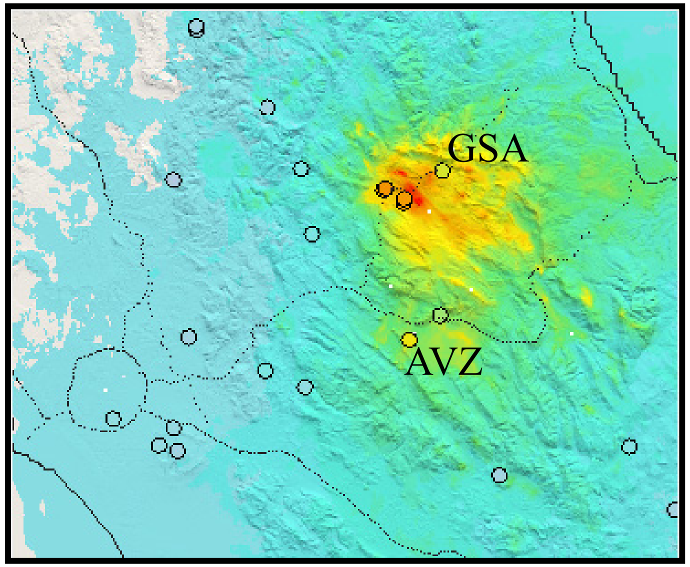
Scenario



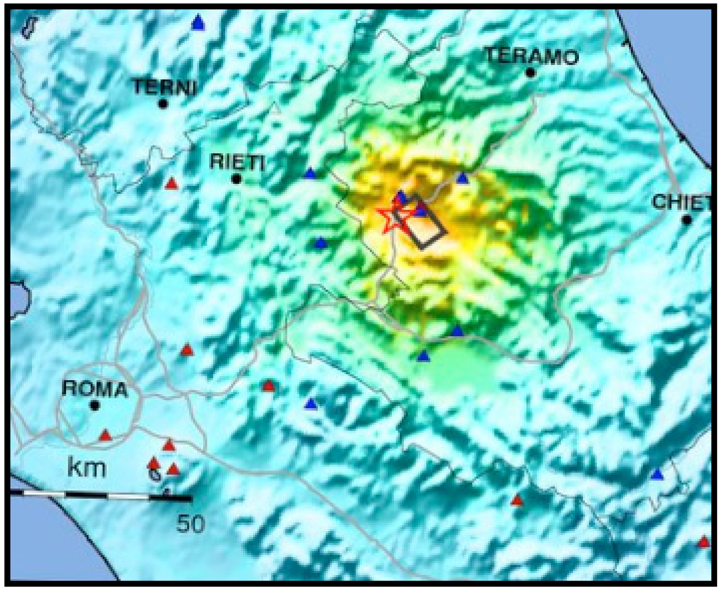
1D flat - max PGV 45 cm/s



1D w topo - max PGV 48 cm/s



3D - max PGV 74 cm/s



(Faenza et al., 2011)

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INGV ShakeMap : CENTRAL ITALY – AQUILANO

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.17	0.17–1.4	1.4–4.0	4.0–9	9–17	17–32	32–61	61–114	>114
PEAK VEL.(cm/s)	<0.12	0.12–1.1	1.1–3.4	3.4–8	8–16	16–31	31–59	59–115	>115
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Adjoint methods for tomography and imaging

Problem is self-adjoint, thus no need for automatic differentiation (AD, autodiff)

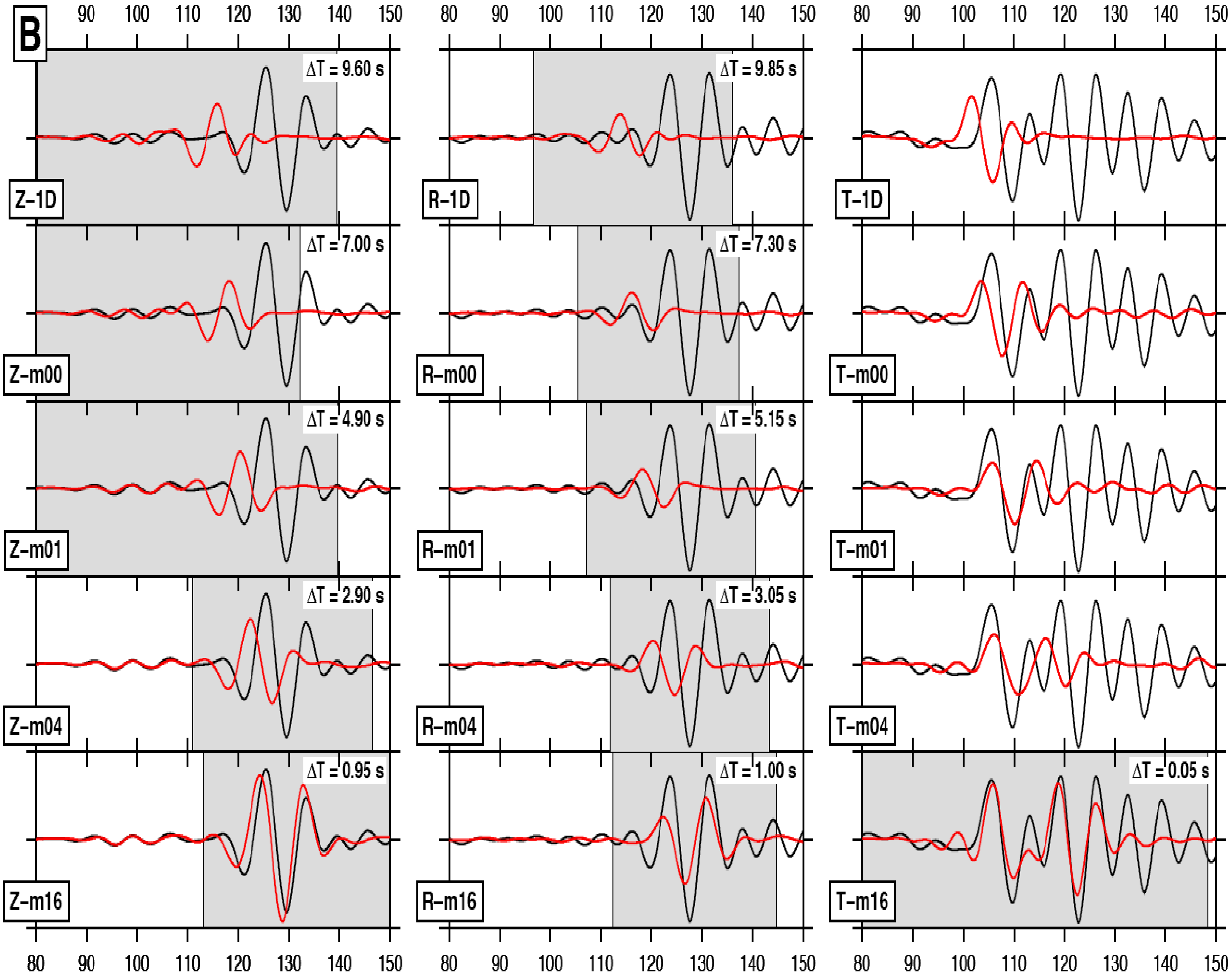
$$\chi_1(\mathbf{m}) = \frac{1}{2}\sum_{r=1}^{N_r}\int_0^T w_r(t)||\mathbf{s}(\mathbf{x}_r,t;\mathbf{m}) - \mathbf{d}(\mathbf{x}_r,t)||^2\,\mathrm{d}t,$$

$$\delta\chi_1 = \int_V [K_\rho(\mathbf{x})\,\delta\ln\rho(\mathbf{x}) + K_\mu(\mathbf{x})\,\delta\ln\mu(\mathbf{x}) + K_\kappa(\mathbf{x})\,\delta\ln\kappa(\mathbf{x})]\,\mathrm{d}^3\mathbf{x},$$

$$K_\kappa(\mathbf{x}) = -\int_0^T \kappa(\mathbf{x})\,[\nabla\cdot\mathbf{s}^\dagger(\mathbf{x},T-t)]\,[\nabla\cdot\mathbf{s}(\mathbf{x},t)]\,\mathrm{d}t,$$

Theory: A. Tarantola, Talagrand and Courtier.
'Banana-Donut' kernels (Tony Dahlen et al., Princeton)
Close to time reversal (Mathias Fink et al.) but not identical, thus interesting developments to do.

Idea: apply this to tomography of the full Earth (current ANR / NSF contract with Princeton University, USA), and in acoustic tomography: ocean acoustics, non destructive testing.



Princeton, USA

L-BFGS method

- Iterative Gauss-Newton algorithm

$$m_{k+1} = m_k + \underbrace{(G_k^t G_k + C_m^{-1})^{-1} \nabla J(m_k)}_{\delta m_k}$$

- L-BFGS (Low-memory Broyden–Fletcher–Goldfarb–Shanno):

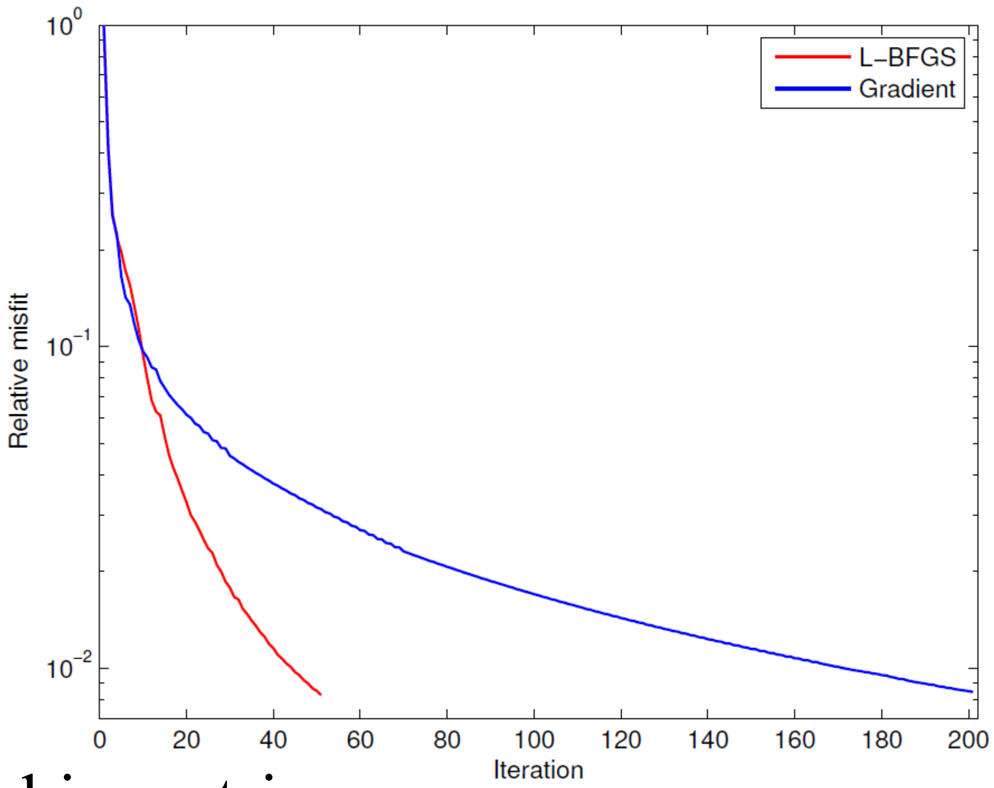
  Approximate

  $$\delta m_k$$

  from:

  $$m_{k-1}, m_{k-2}, m_{k-3}, \ldots, m_0$$

  $$\nabla J(m_{k-1}), \nabla J(m_{k-2}), \ldots, \nabla J(m_0)$$



→ no need to invert or even build a big matrix

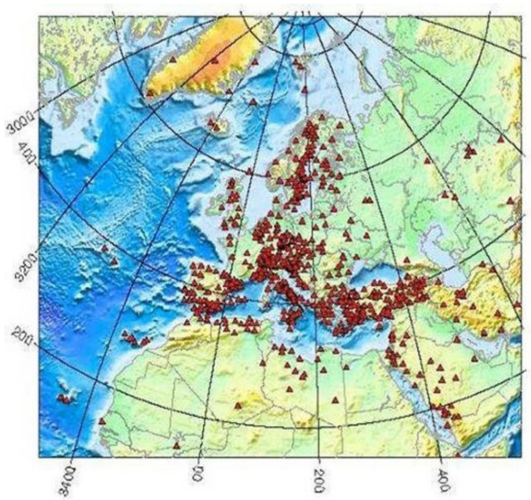
Réseaux denses d’enregistrement

Des réseaux denses d’enregistrement impliquent du “big data” pour la tomographie.

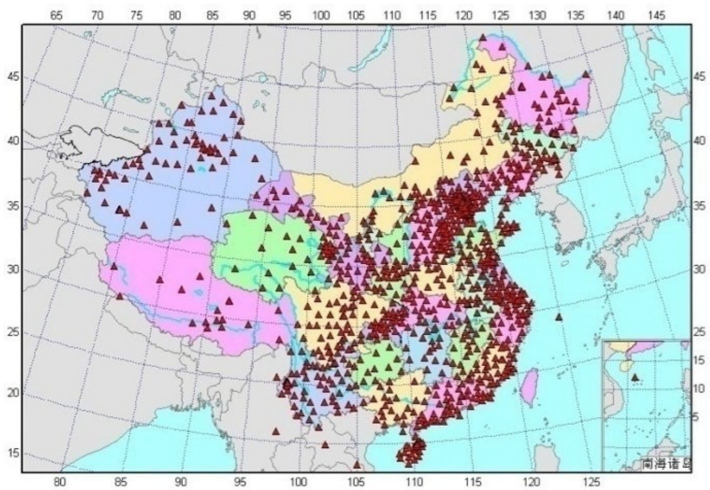
Ceci va conduire à de bien meilleures images en tomographie et imagerie (ici, de la Terre).

Cela veut dire que l’on a besoin de HPDA (High-Performance Data Analysis) et non plus simplement de HPC (High-Performance Computing).

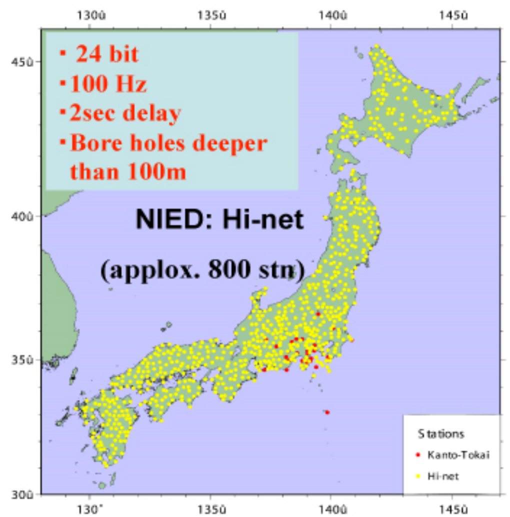
[web.mst.edu]



[www.geo.uib.no]



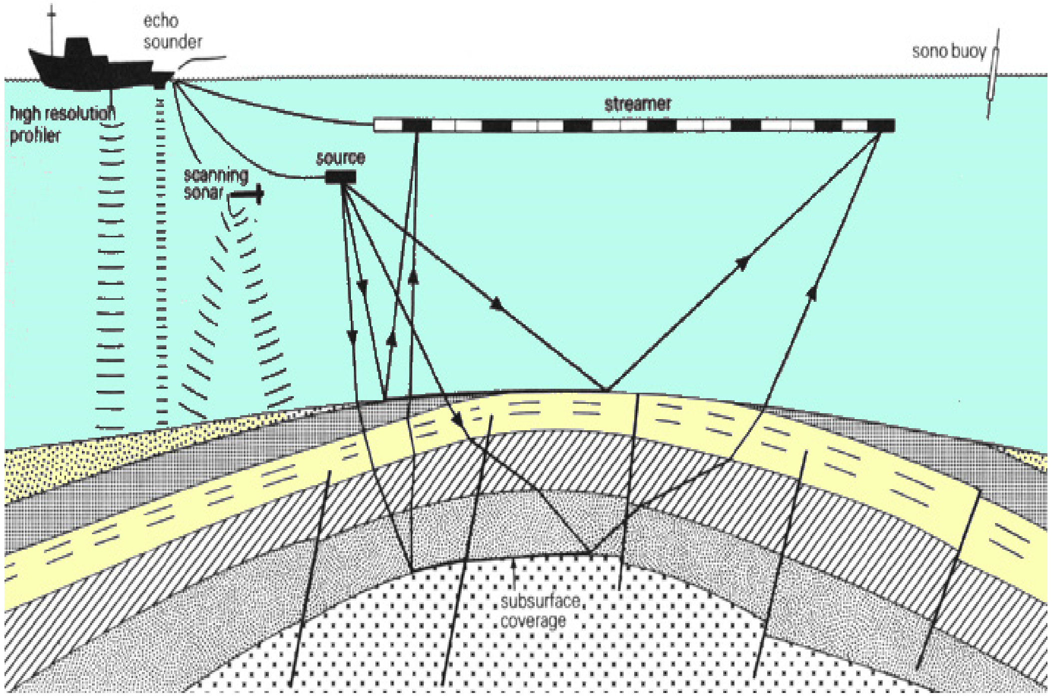
[data.earthquake.cn]



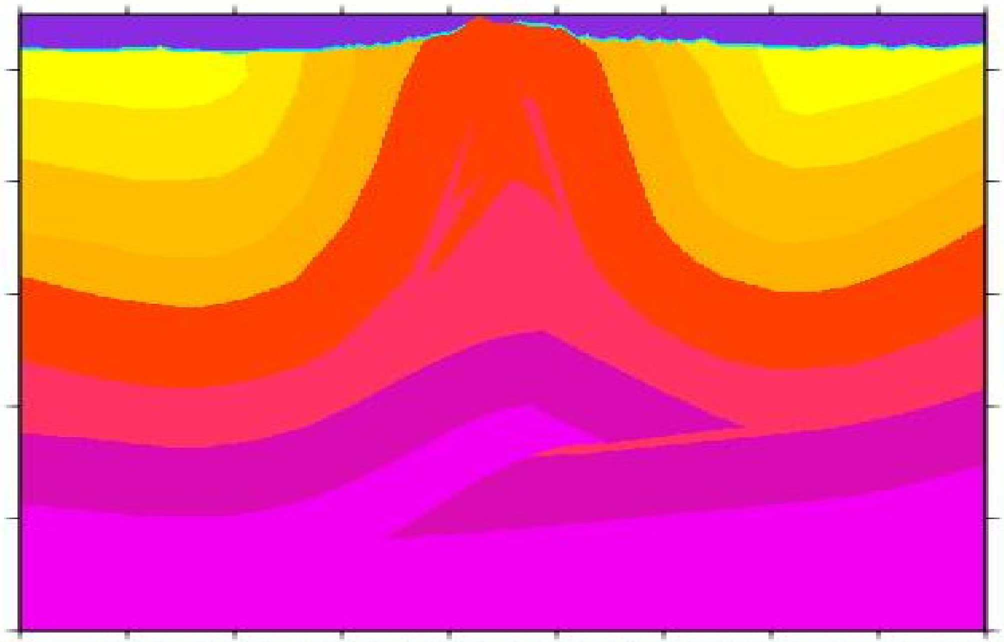
[drh.edm.bosai.go.jp]

Oil industry applications

TOTAL S.A.



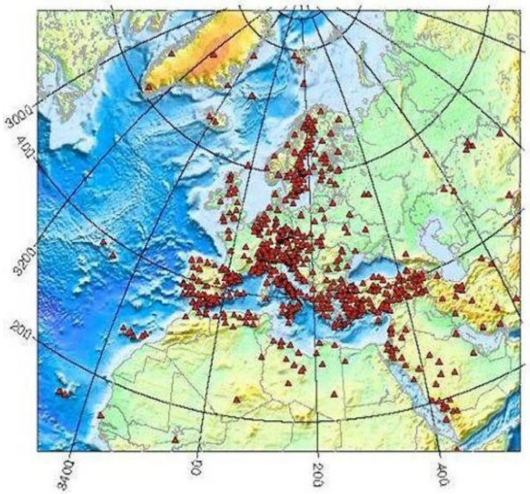
Offshore



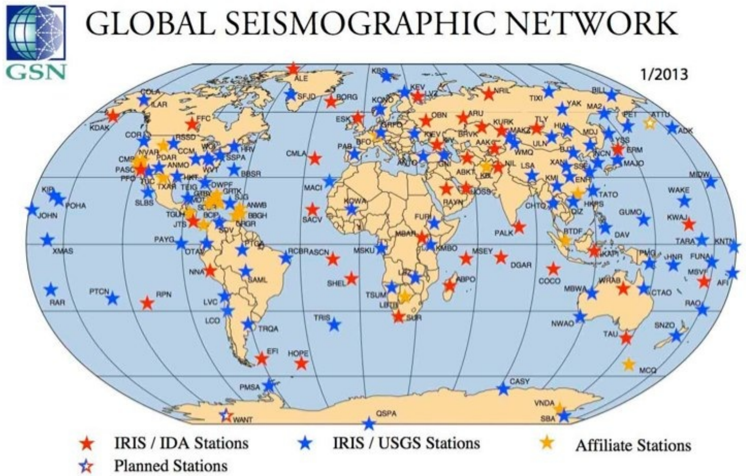
In foothill regions

- Elastic wave propagation in complex 3D structures,
- Often fluid / solid problems: many oil fields are located offshore (deep offshore, or shallower).
- Anisotropic rocks, geological faults, cracks, bathymetry / topography…
- Thin weathered zone / layer at the surface $\Rightarrow$ model dispersive surface waves.

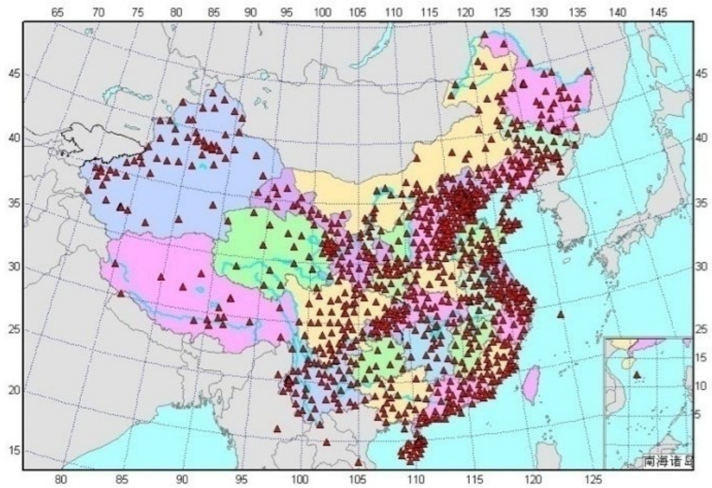
"Big Data" in seismology:



www.geo.uib.no



www.iris.edu



data.earthquake.cn

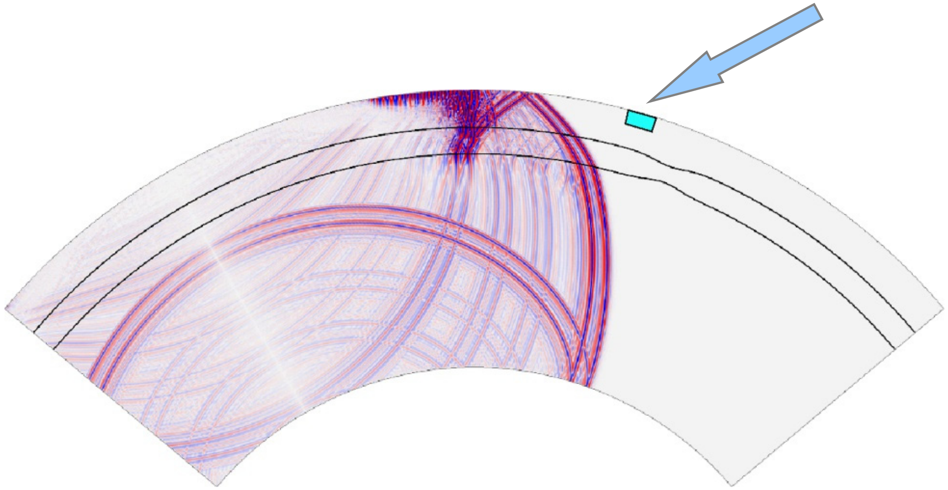
and in the oil and gas industry:

3D marine surveys can involve 5,000 shots and 50,000 receivers:

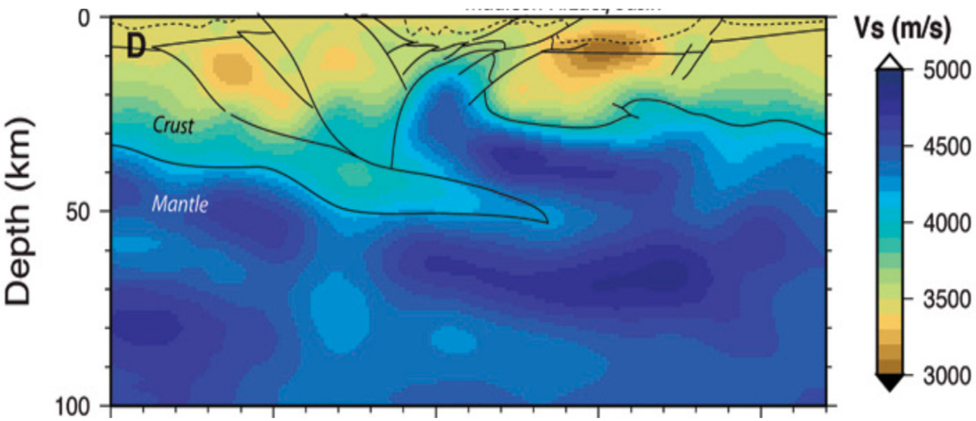
- Petabytes of data
- Need for « big data » tools
- High-Performance Data Analysis (HPDA) rather than pure HPC

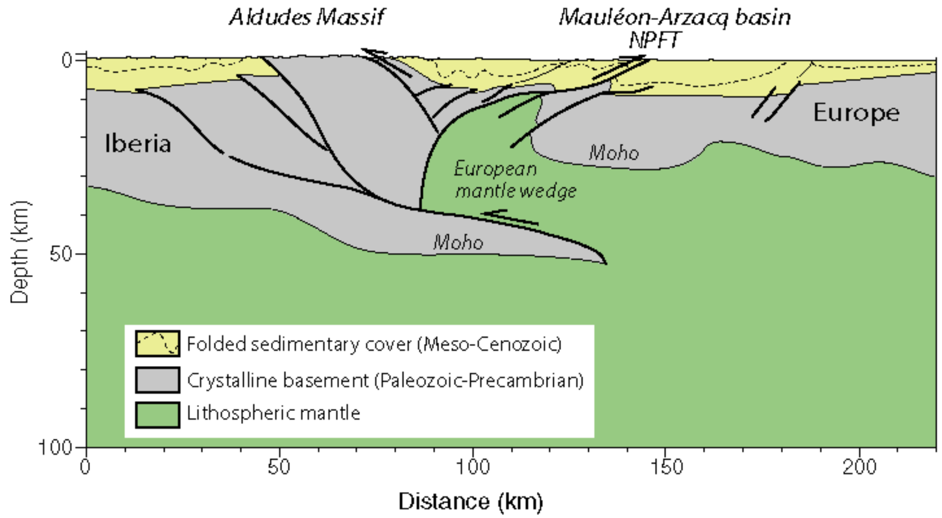
Projet industriel pétrolier « OROGEN »

Imagerie sismique très haute résolution



Techniques d'imagerie adaptées



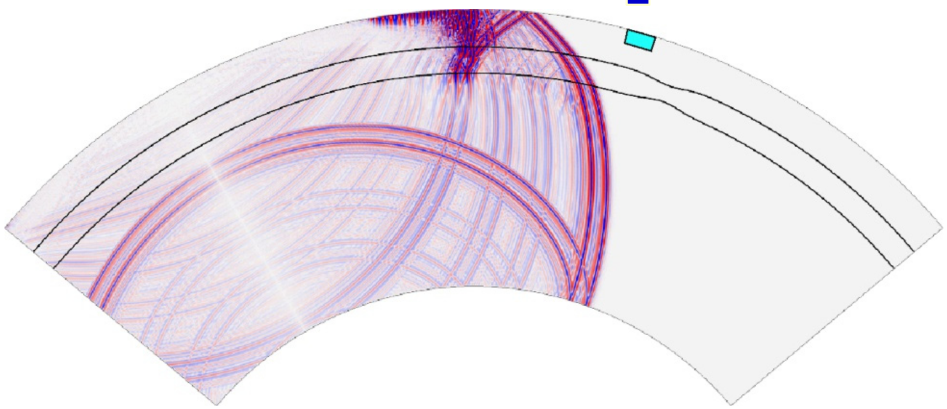


Les ondes sismiques venant de toute la terre éclairent et permettent d'imager une structure géologique donnée (ici les Pyrénées).

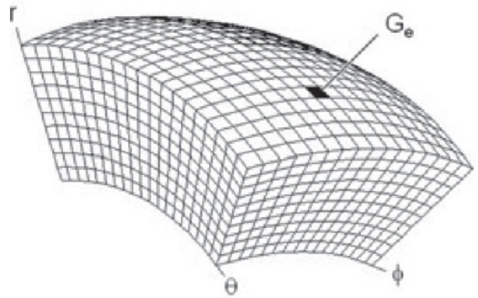
Plus haute résolution jamais atteinte, grâce au calcul haute performance.

A hybrid approach: Coupling global and regional propagations

A hybrid technique for 3-D waveform modeling and inversion of high frequency teleseismic body waves



Global propagation
Spherically symmetric Earth model



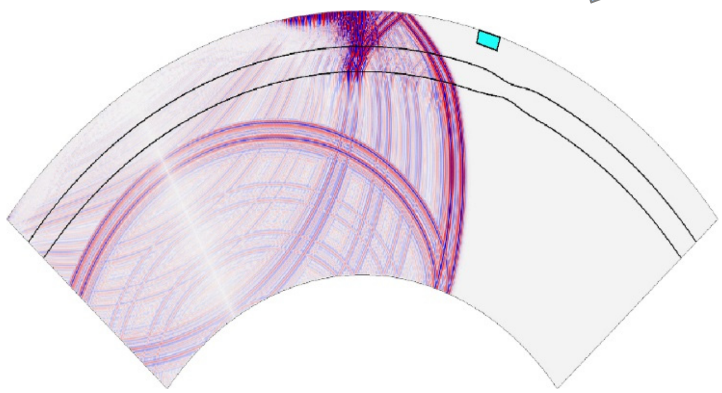
Regional propagation
3-D spherical shell

S. Chevrot, V. Monteiller, D. Komatitsch & N. Fuji
Geophysical Journal International, 2014

Local inversion based on coupling with teleseismic wave propagation

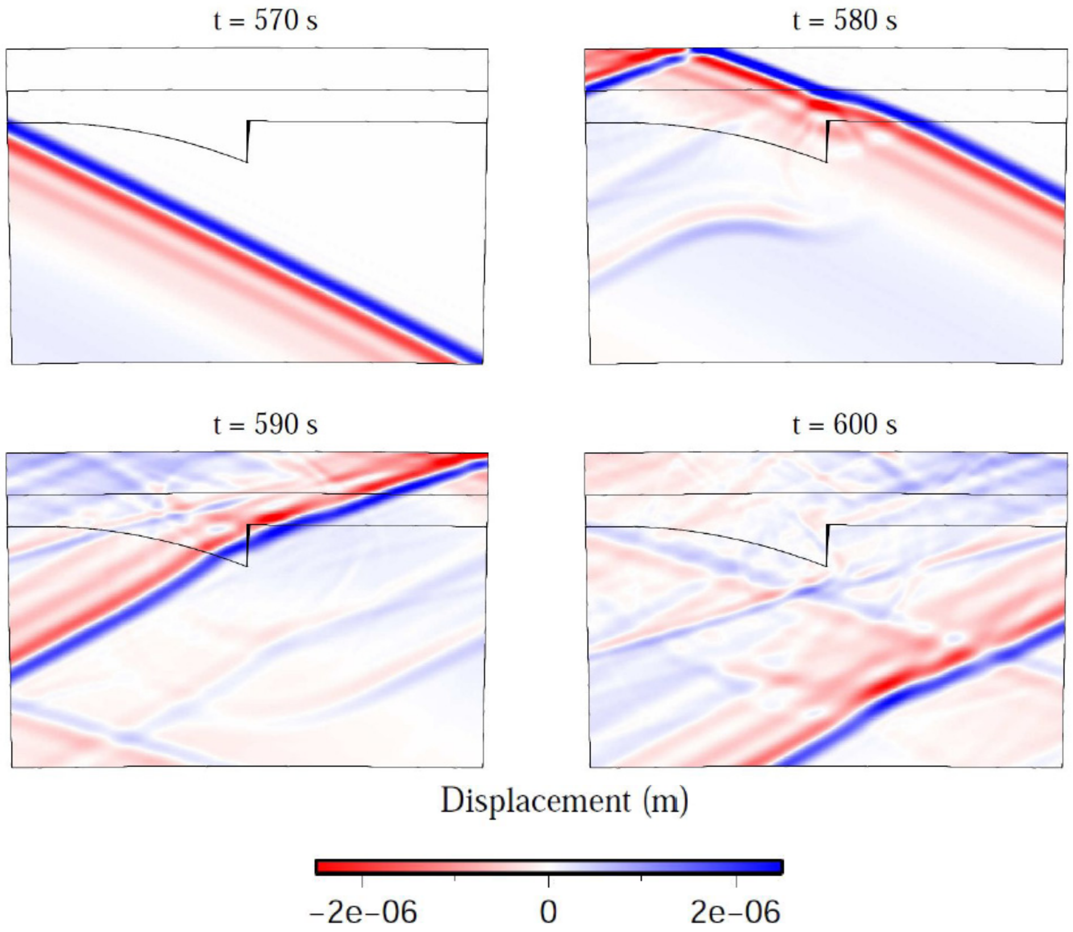
***Monteiller** et al, GJI 2013*

3D mesh box



1D, 2.5D or 3D model outside

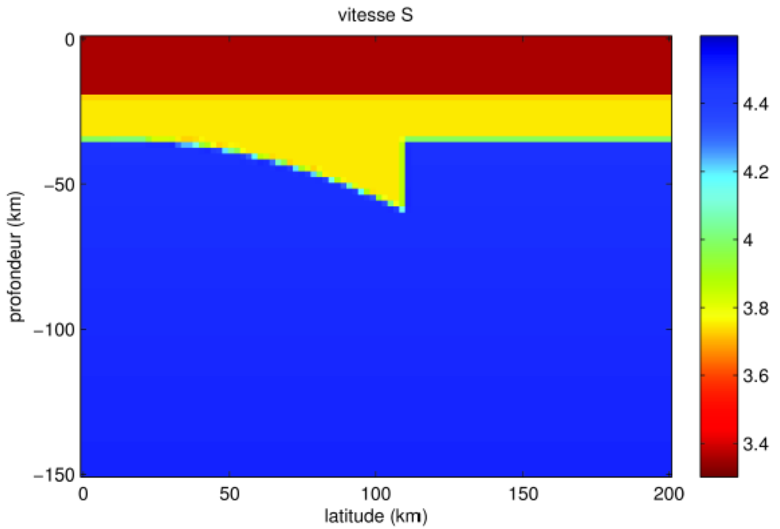
computed e.g. based on DSM, GEMINI, AxiSEM or even SPECFEM3D_GLOBE itself

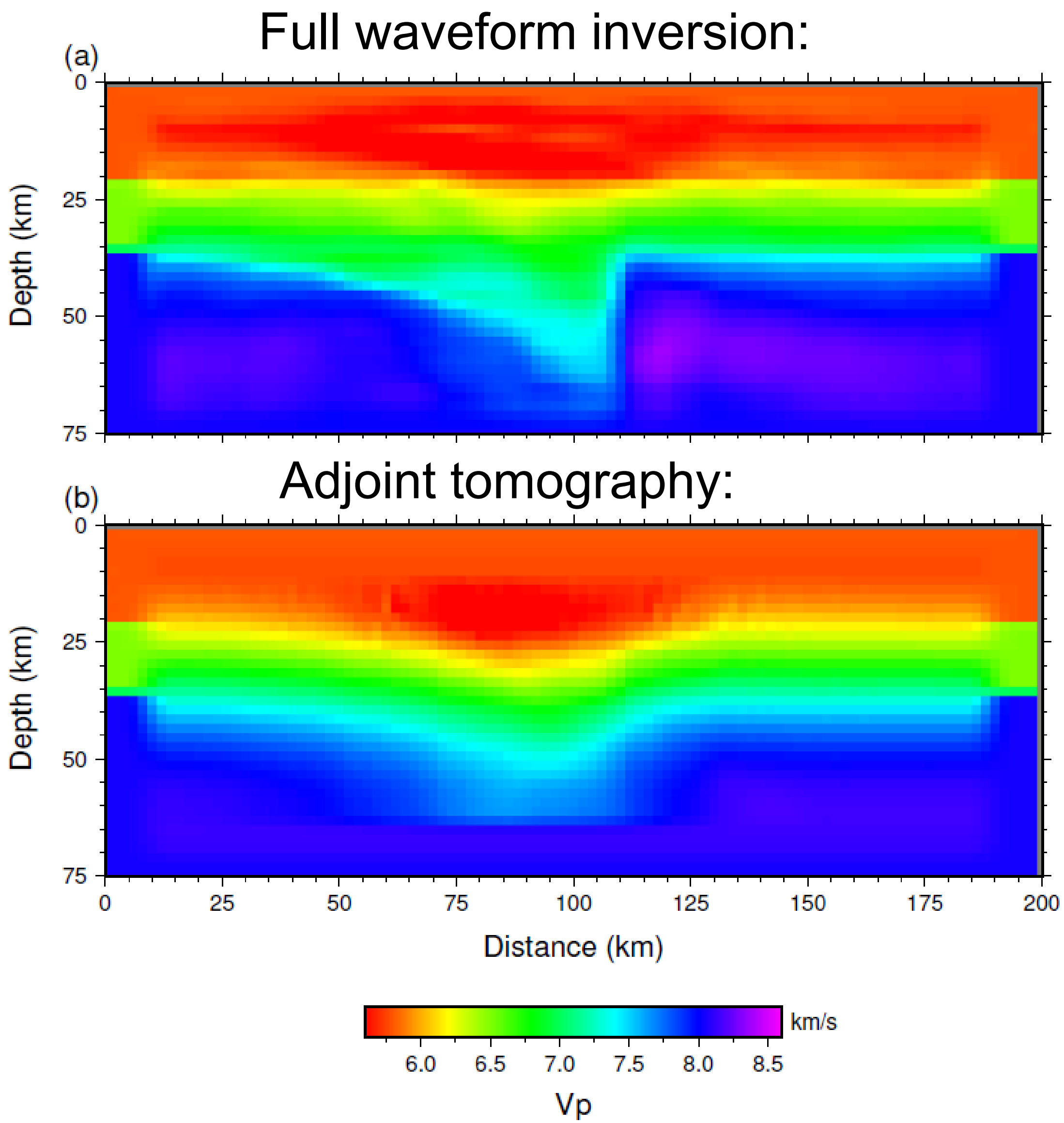


Full 3D wave propagation inside the box
at the regional scale based on spectral elements

Coupling of both methods for full waveform inversion at high frequency (down to 1 second)

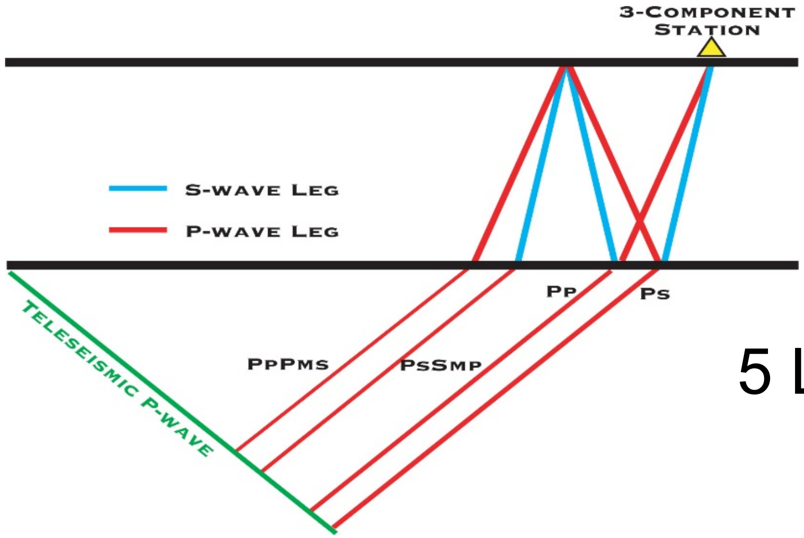
Synthetic full waveform inversion example





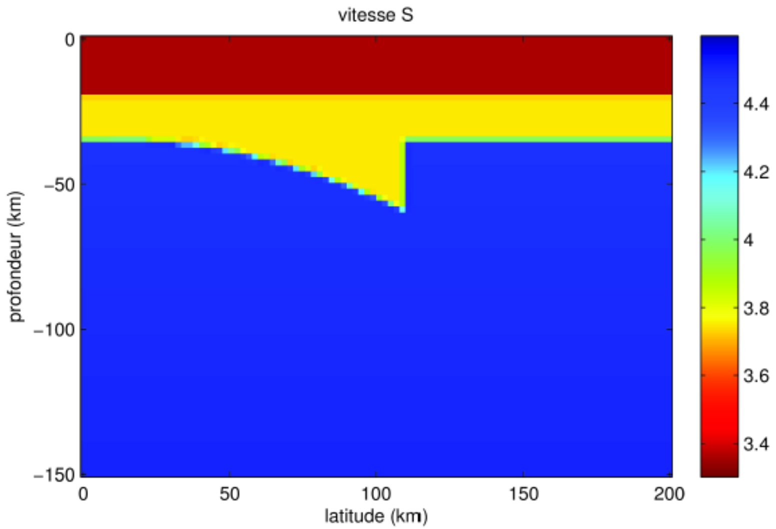
Full waveform modeling :

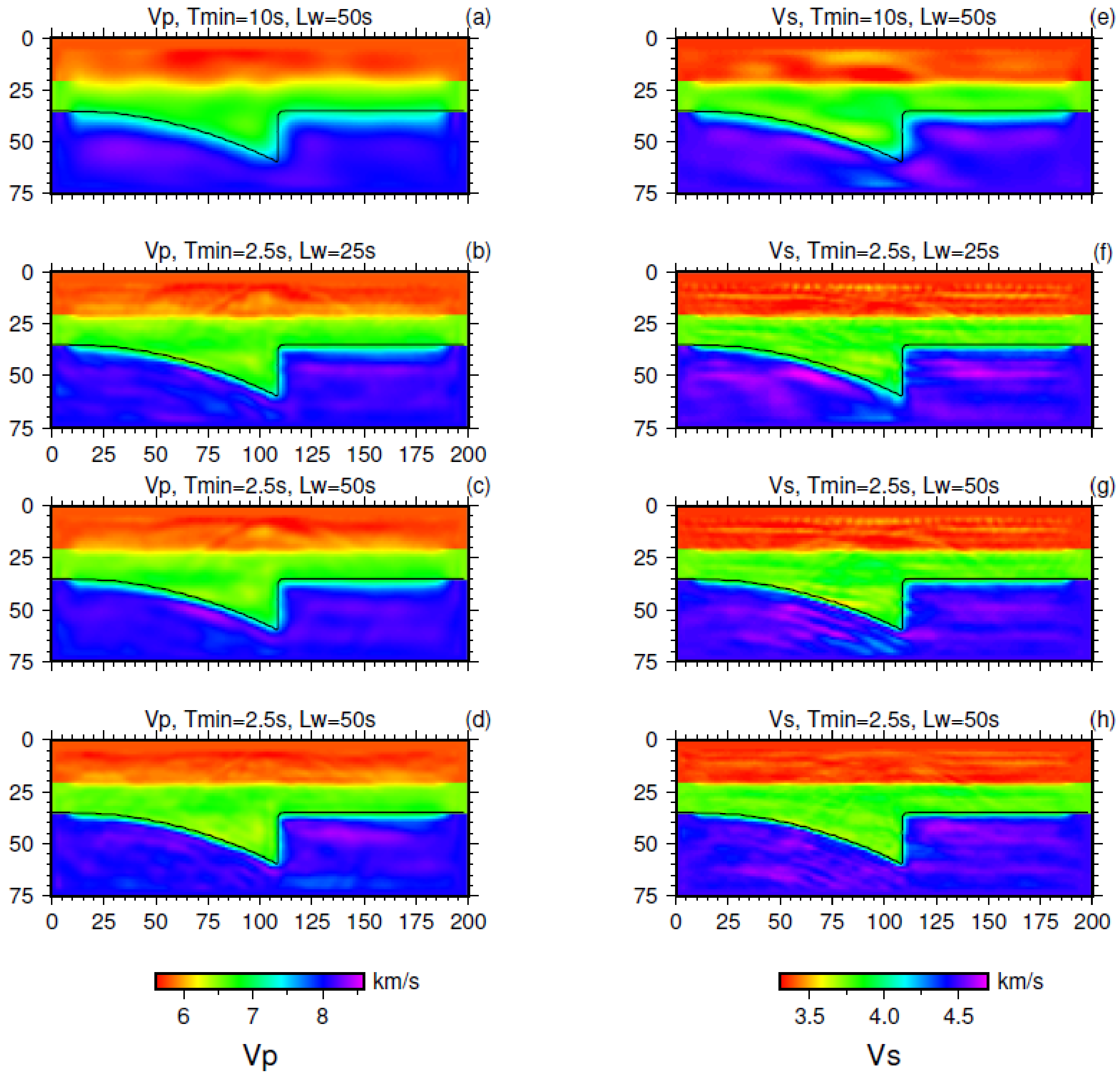
- Direct P wave
- Converted waves



5 L-BFGS iterations of full waveform inversion vs. 15 iterations of adjoint tomography

Synthetic full waveform inversion example





Full waveform modeling :

- Direct P wave
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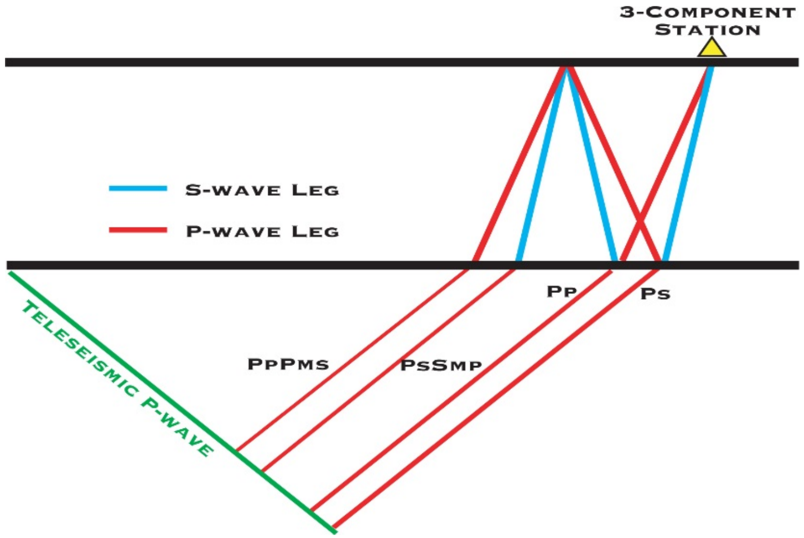
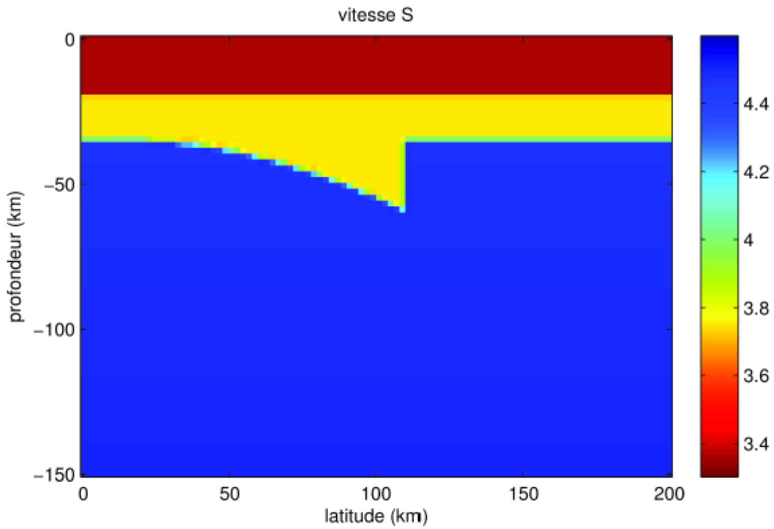
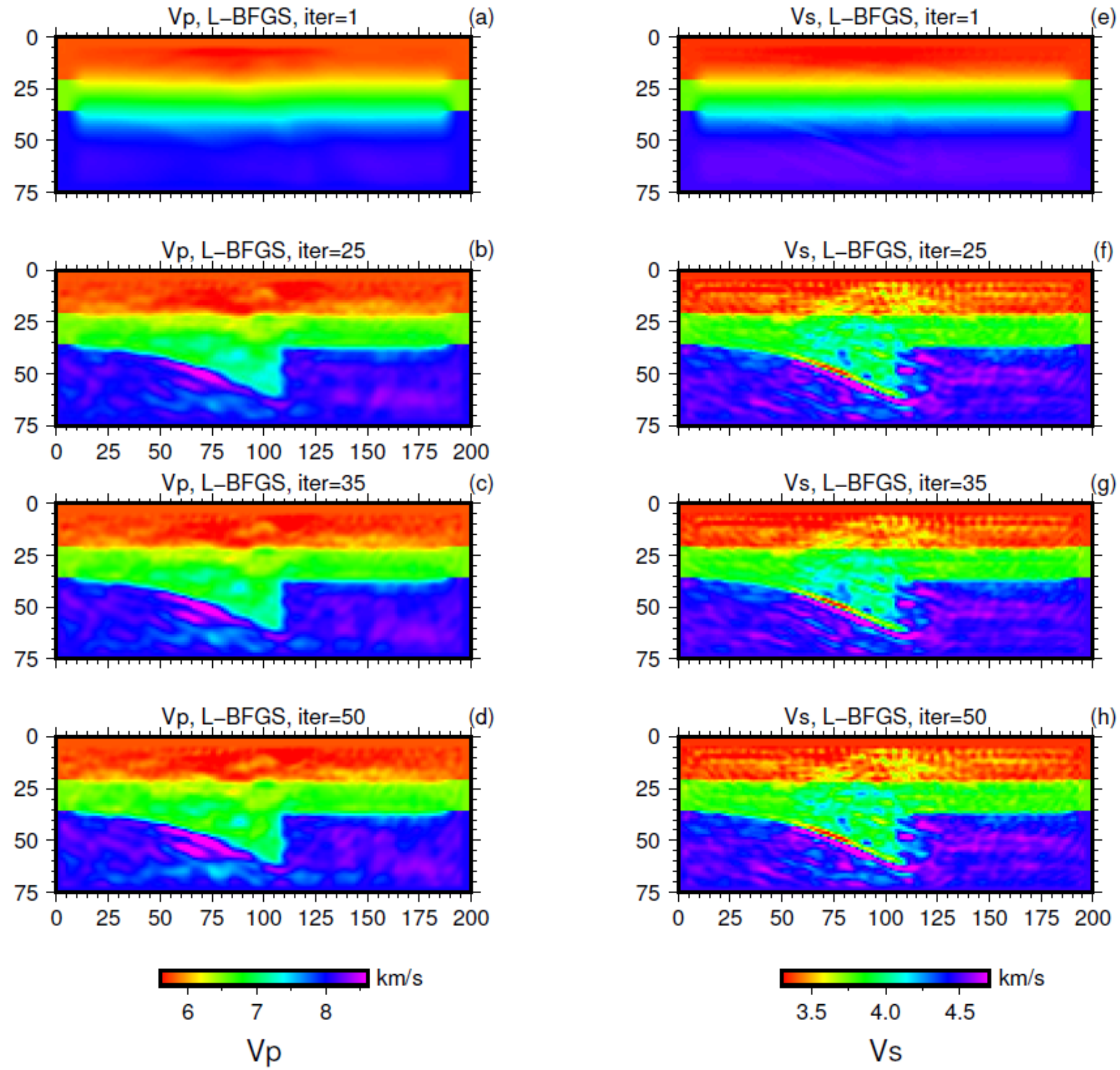


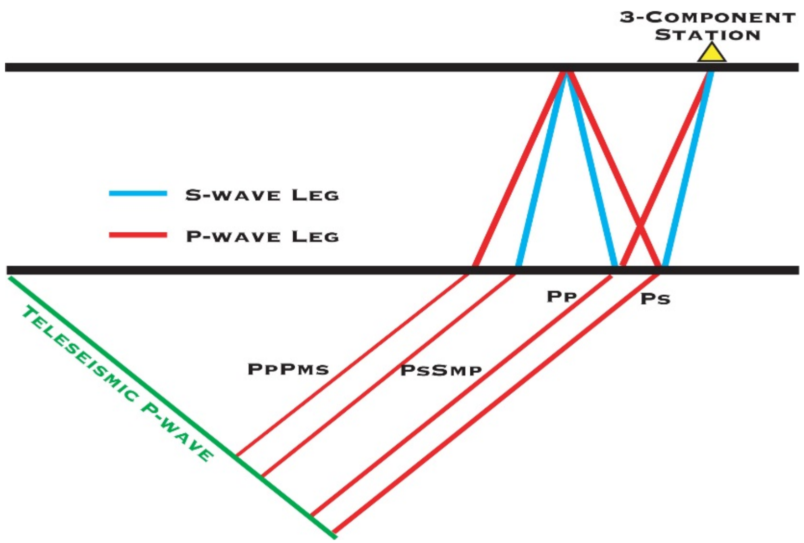
With hierarchical frequency content

Synthetic full waveform inversion example



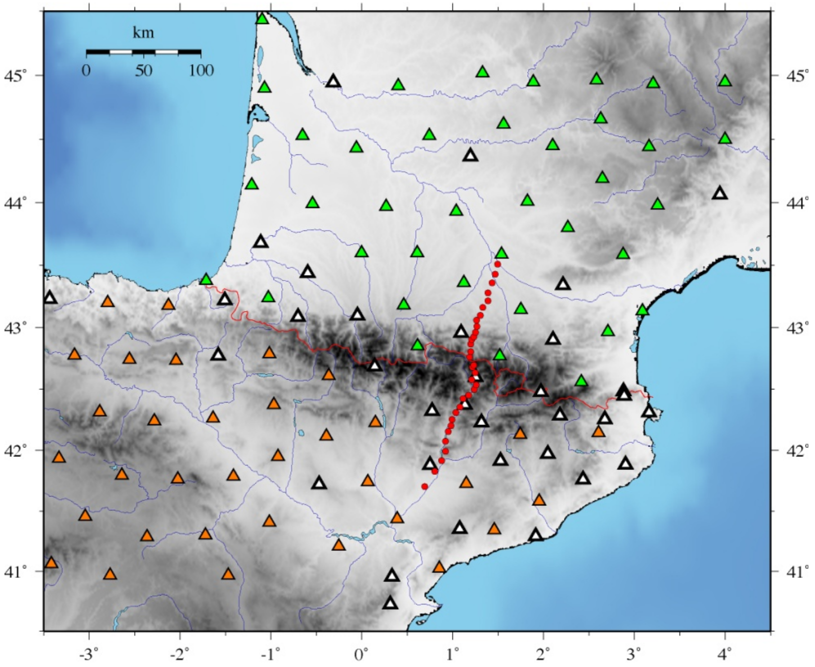


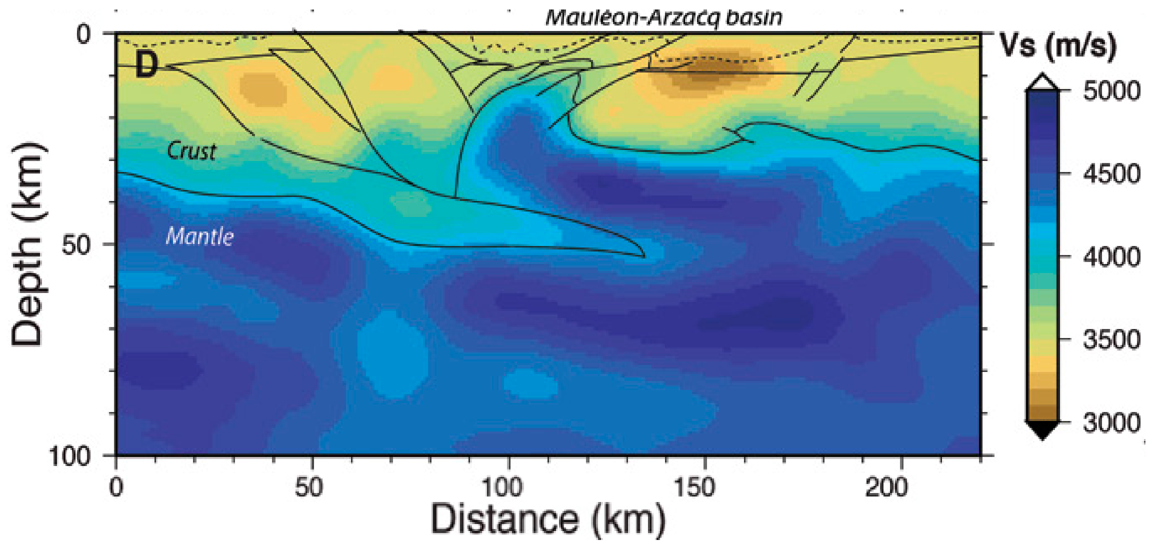
Full waveform modeling :
- Direct P wave
- Converted waves

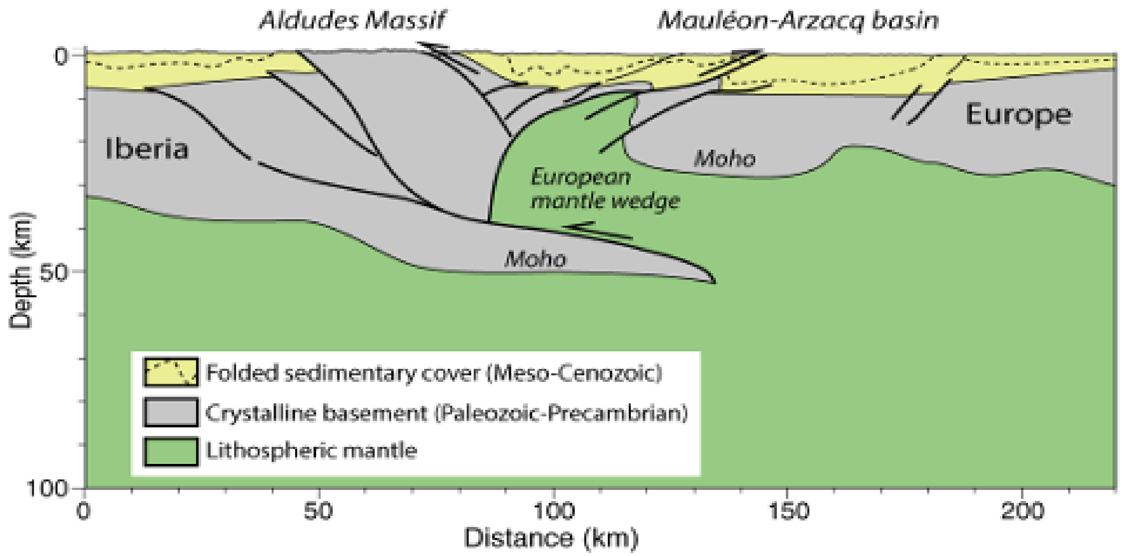


Without hierarchical frequency content
→ not good (Pratt et al. 1998)

Imaging the Pyrénées Mountains





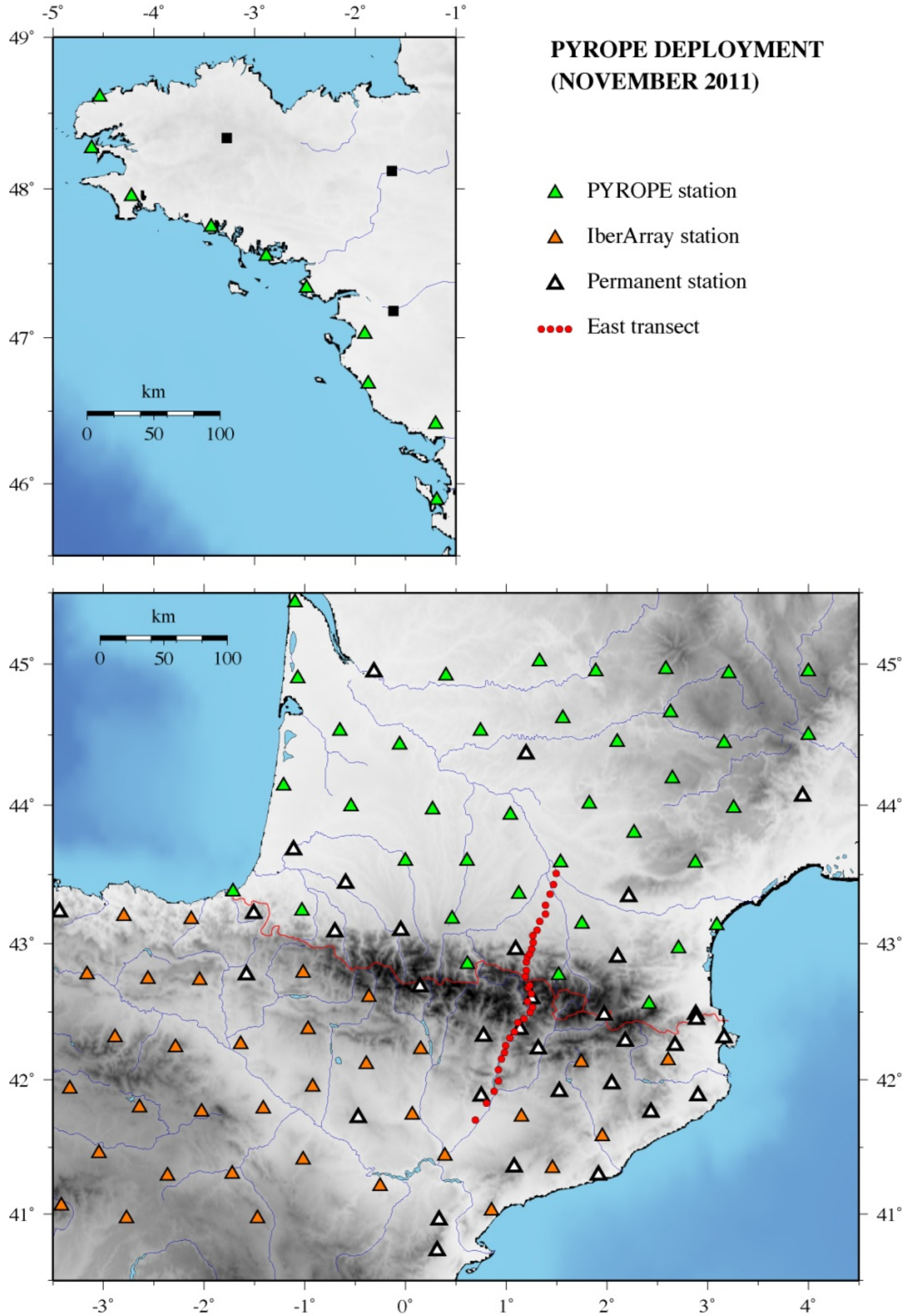


- ➢ Drastically-improved quality of the images thanks to the high frequencies involved

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

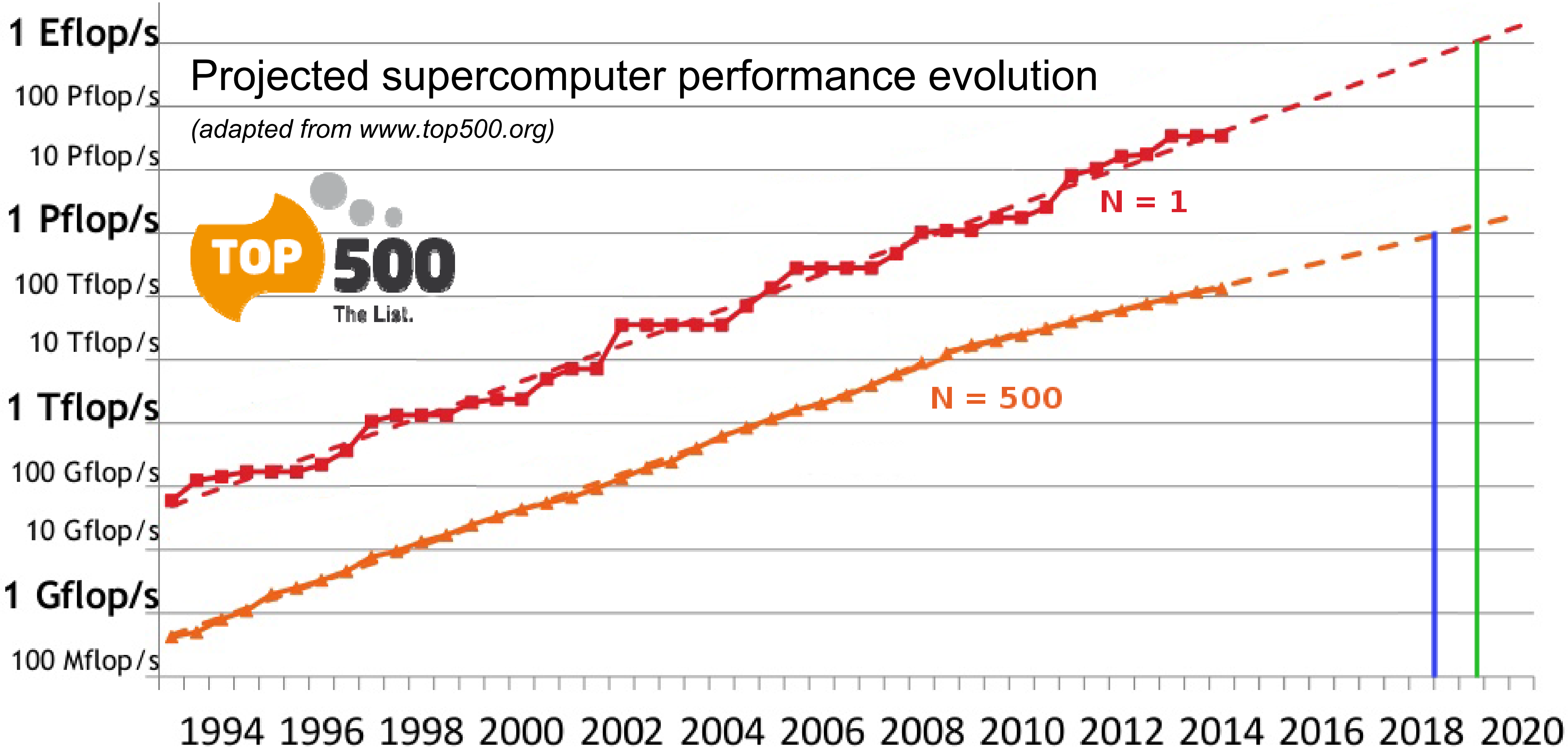
Wang et al., Geology, vol. 44, p. 475-478 (2016).

The PYROPE experiment



- French/Spanish initiative, supported by the French ANR
- ~150 temporary + 50 permanent BB stations
- Interstation spacing ~ 60 km
- Dense transects across the Pyrénées

About the path to exaflops



- End of 2018 for exaflop/s, end of 2017 for petaflop/s easily everywhere, around 2027 for exaflop/s easily everywhere (?)
- For SPECFEM3D it is increasingly needed to perform a very large number (thousands!) of medium-size runs (500 to 2000 cores), rather than a single, very large grand-challenge run; this comes from solving imaging problems iteratively rather than a single forward problem once.

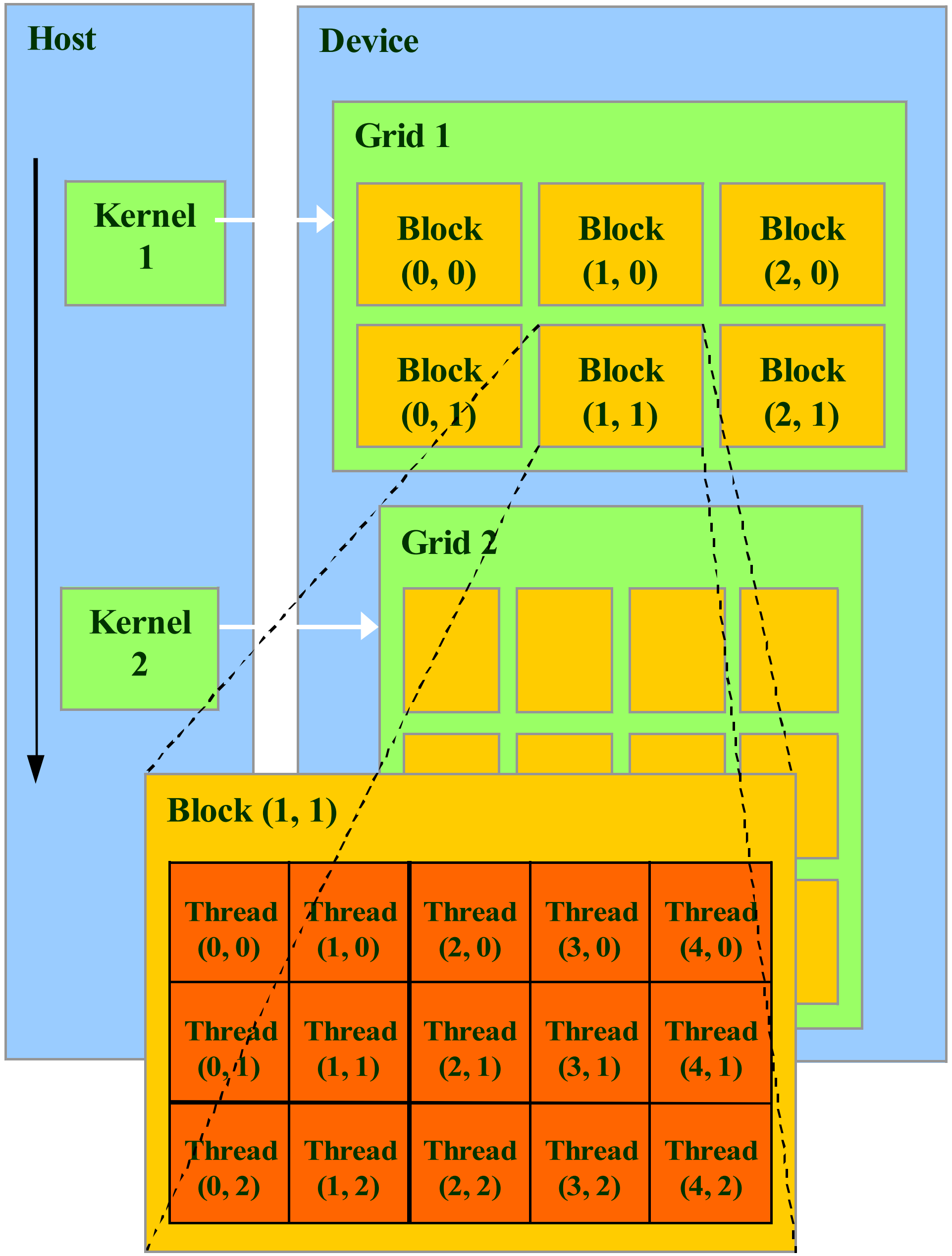
The path to exaflops and beyond

Nomenclature:

- petaflop/s 10^{15} (current, since 2009)
- exaflop/s 10^{18} (end of 2018)
- zettaflop/s 10^{21} ($\approx$ 2027?)
- yottaflop/s 10^{24} ($\approx$ 2036??)

Flop/s: number of floating-point operations that the computer performs per second.

GPU graphics cards



Why are they so powerful for scientific computing?

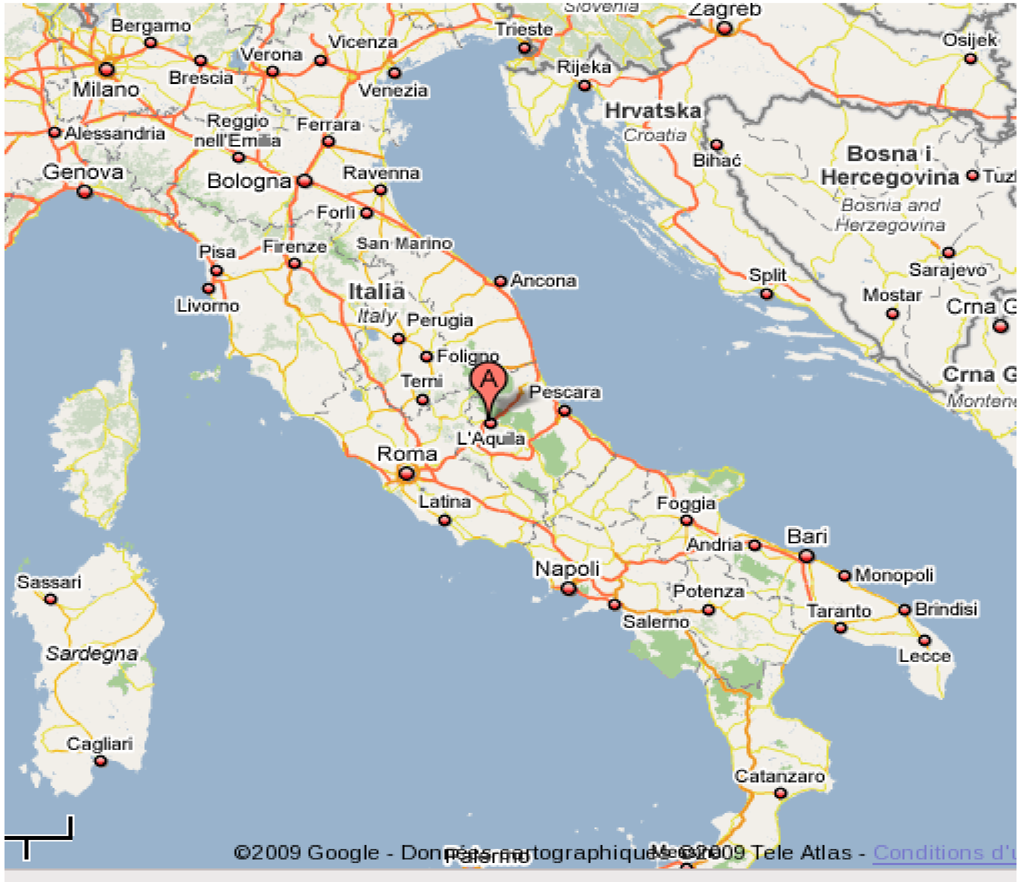
Massive lightweight multithreading.

Collaboration with D. Peter (ETH Zürich), P. Messmer (NVIDIA), D. Göddeke (Dortmund, Germany)

Our PRACE European project

PRACE project with INGV Roma (E. Casarotti, F. Magnoni, D. Melini, A. Michelini) + Princeton University, USA (J. Tromp) + University of Fairbanks, Alaska (C. Tape) to image the Italian lithosphere: 40 million core hours on CURIE (PRACE / TGCC, France)

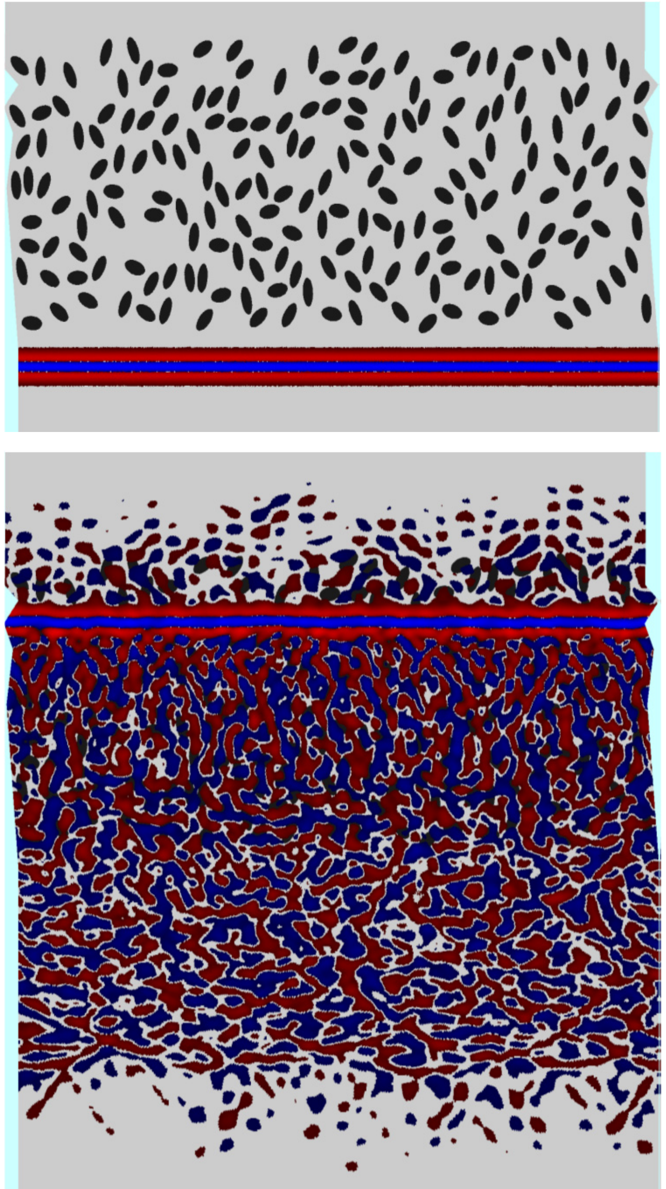
“IMAGINE_IT: 3D full-wave tomographic IMAGINg of the Entire ITalian lithosphere”



Istituto Nazionale di Geofisica e Vulcanologia

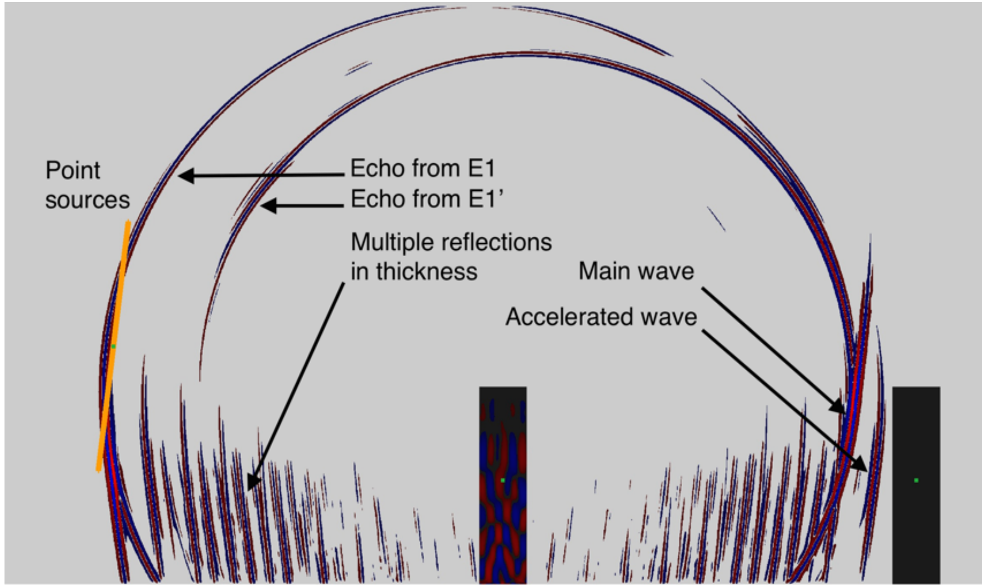
cnrs

Projets EDF et CEA en contrôle non destructif



Propagation et contrôle dans du béton (avec EDF).

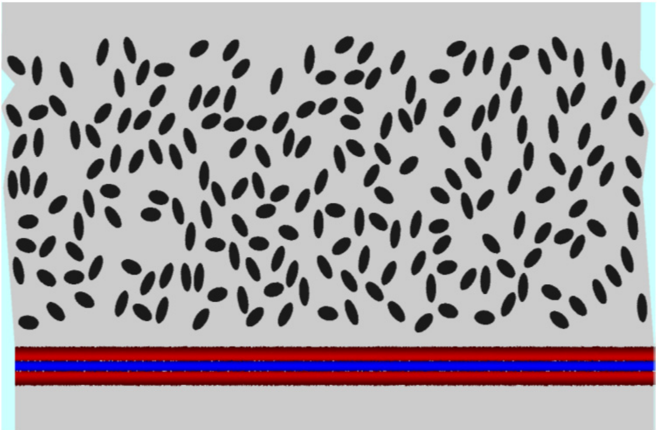
La modélisation numérique permet d'étudier facilement différents modèles de chanfreins pour les tubes de sortie du sodium chaud.

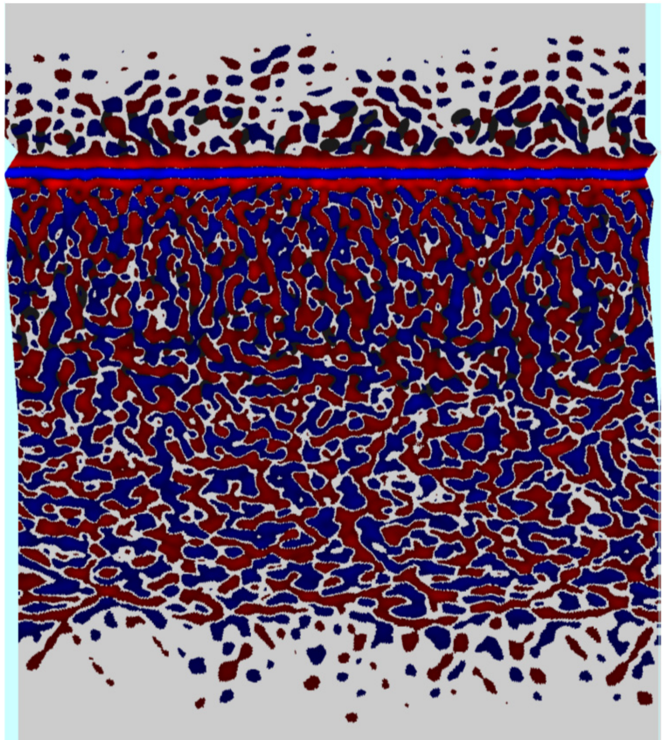


Propagation et contrôle dans du sodium liquide (avec le CEA).

La modélisation numérique permet d'aller au-delà des fonctions de diffusion usuelles, aussi d'étudier la zone interfaciale de transition (ITZ).

Non destructive testing of materials





Collaboration with Non Destructive Testing Lab in Marseille.

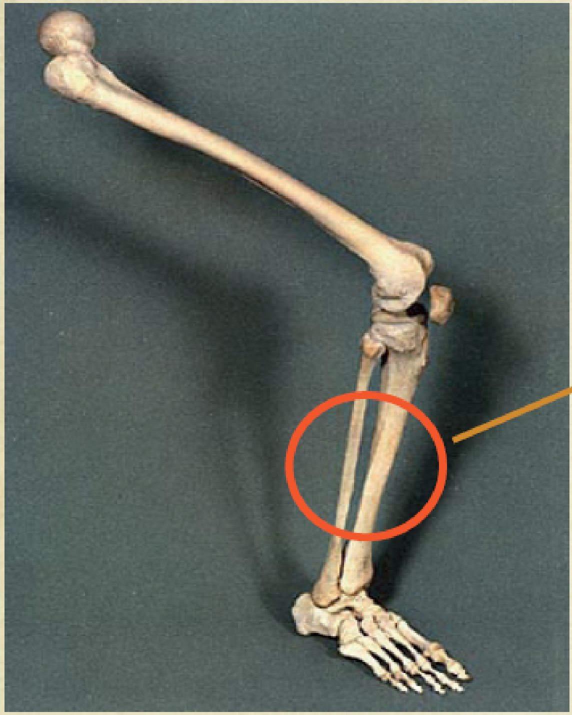
Currently: Physical modeling based on diffusion functions for objects of complex shape, cracks or multiple cavities in concrete, metals, or composite materials. Experiments on samples.

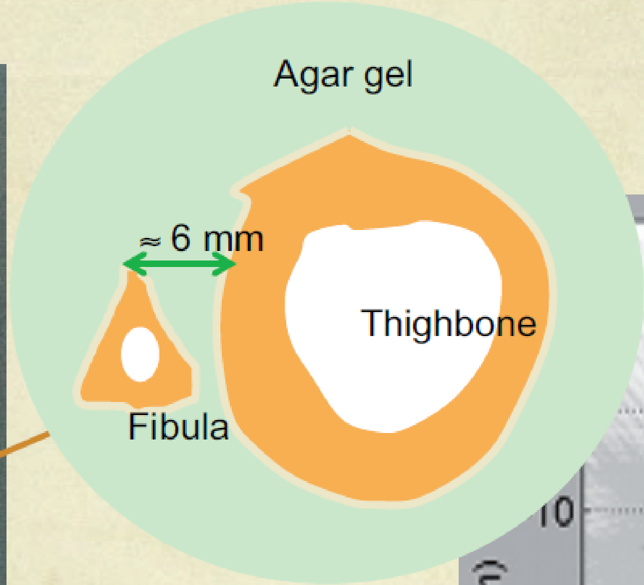
Very accurate calculations without homogenization can validate (or not) these diffusion functions and extend them beyond their domain of validity.

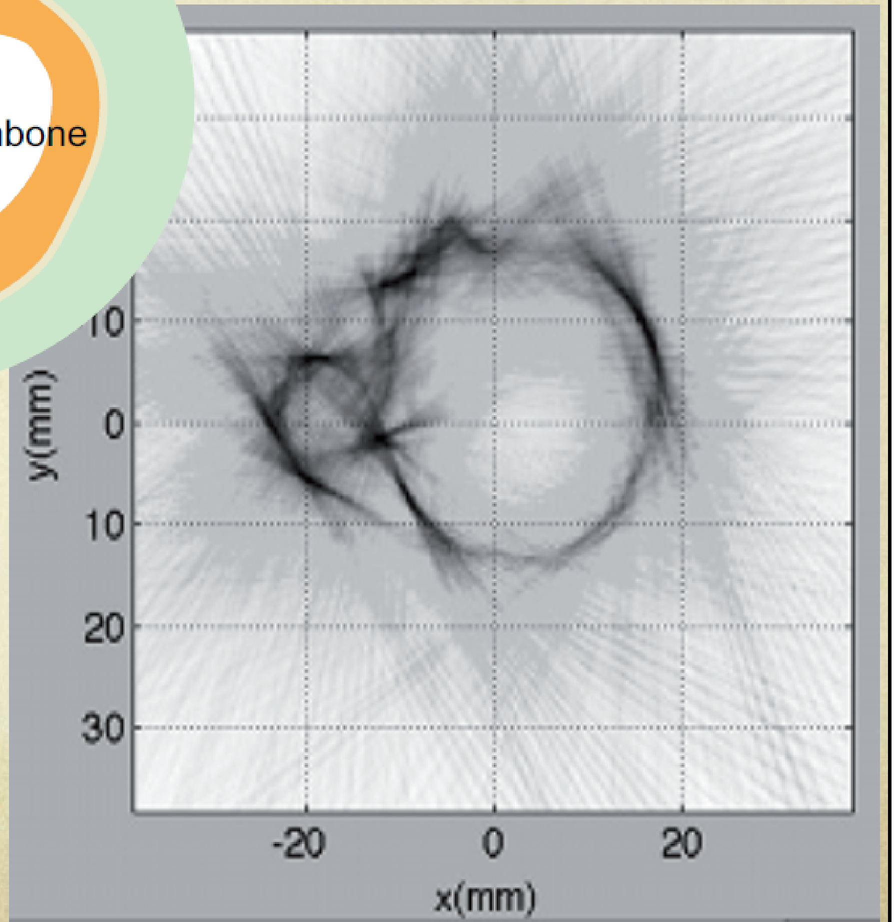
Reliable modeling of the "coda" part of the signal, which contains useful information on the medium.

Pour l'imagerie médicale

Cas difficiles : les os en paire !

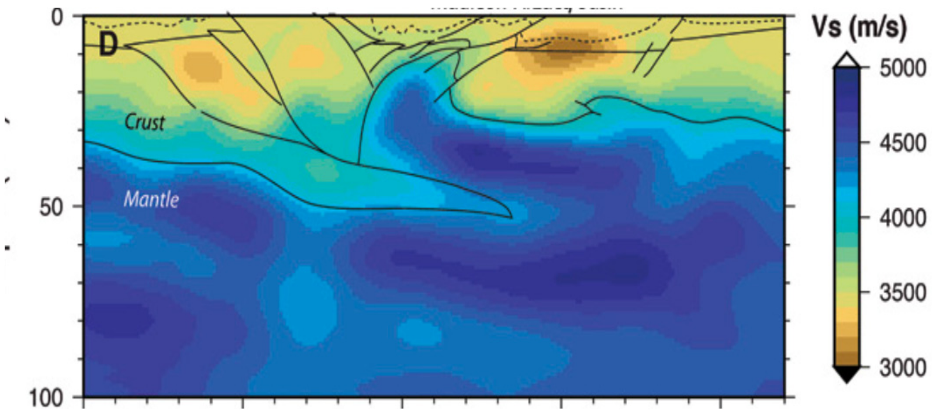


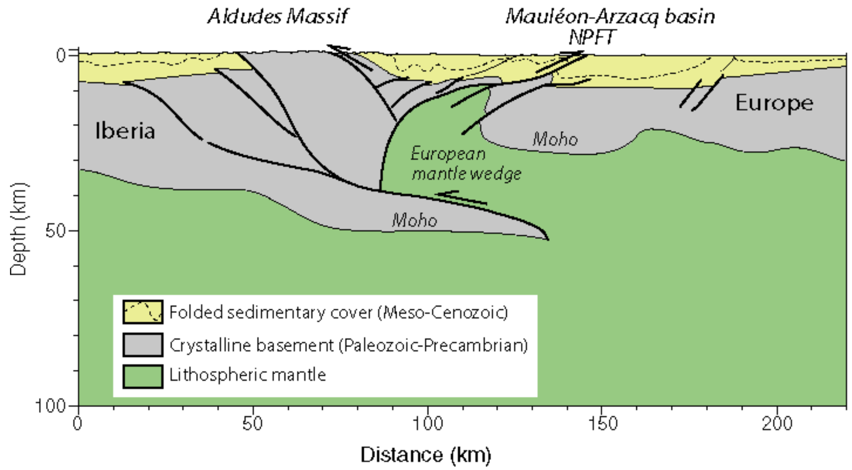




Par Philippe Lasaygues,
CNRS, mars 2014.

Exemple de projet en imagerie médicale





Imagerie sismique

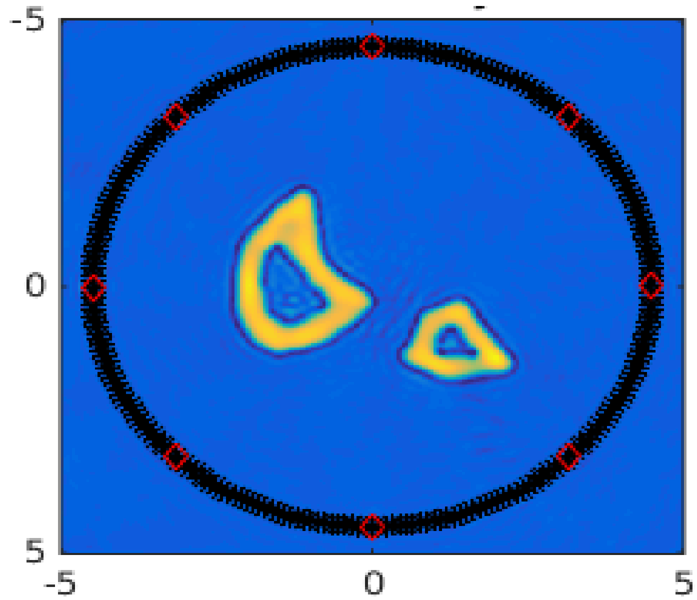


Image d'une paire tibia-péroné reconstruite par FWI sur données synthétiques.

Imagerie médicale

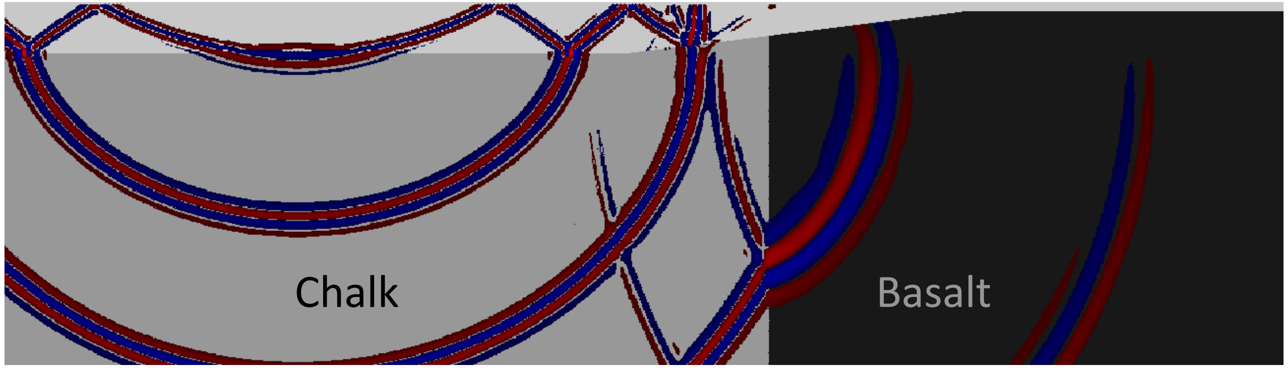
Liens avec notre équipe « Ultrasons médicaux », qui a de très belles données + expertise.

Nouvelles contraintes : l'inversion doit être rapide,
faibles vitesses des ondes de cisaillement, position des récepteurs très différente.

Ocean acoustics

Numerical simulation

Collaboration with Paul Cristini.

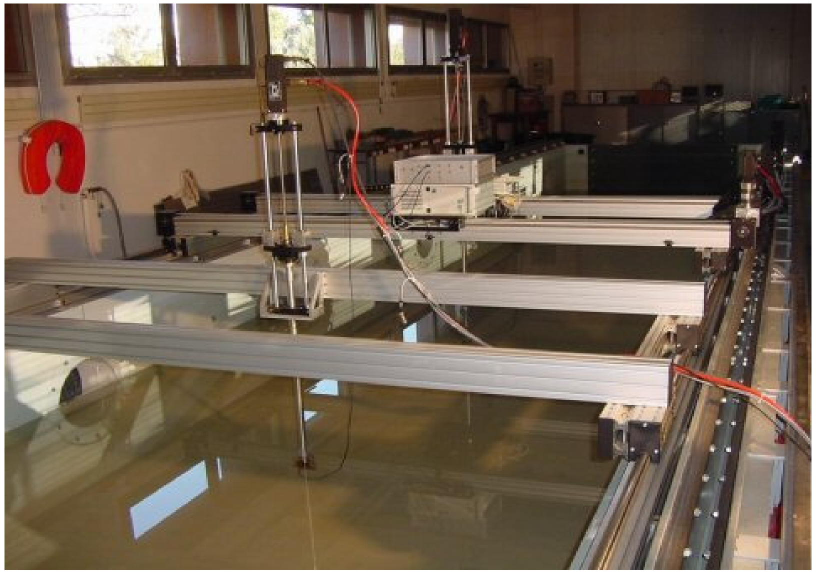


Wave propagation across an impedance discontinuity.

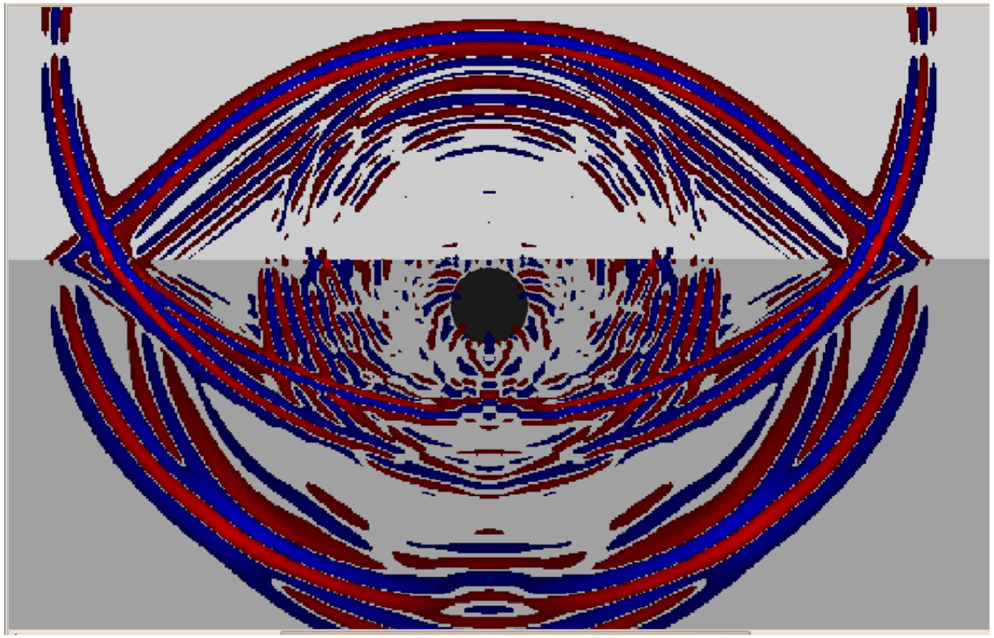
Influence on interface waves.

Going beyond usual approximations (parabolic).

Experiments performed in tanks



Experimental tanks in Marseille

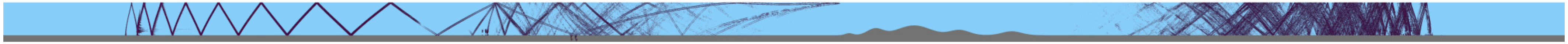


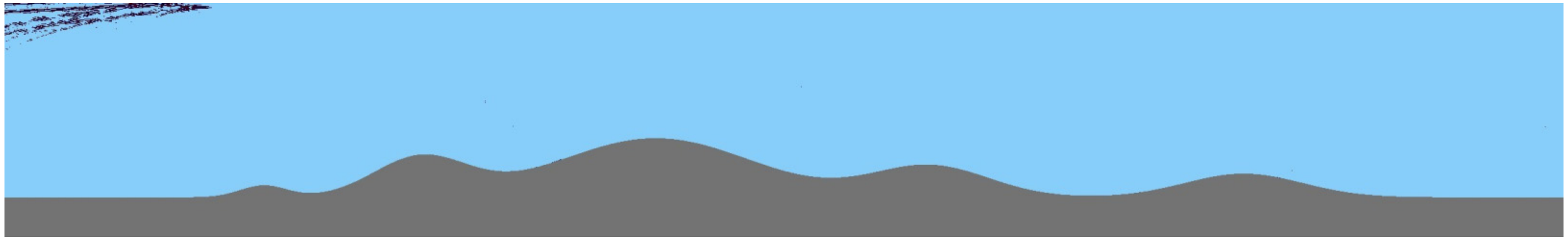
Experiments in known environment / setup

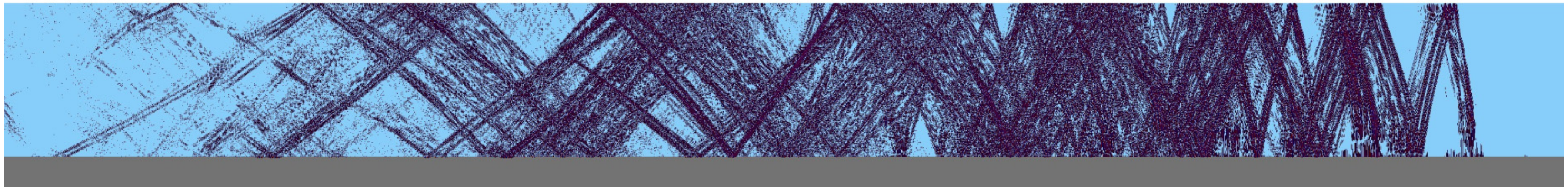
Perform experimental benchmarks

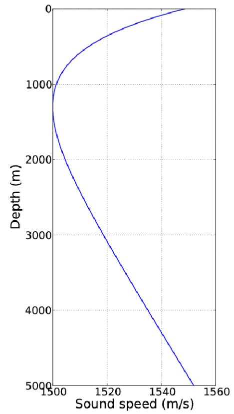
Ocean acoustics and monitoring

Numerical simulation Wave propagation across seamounts, earthquake T waves…

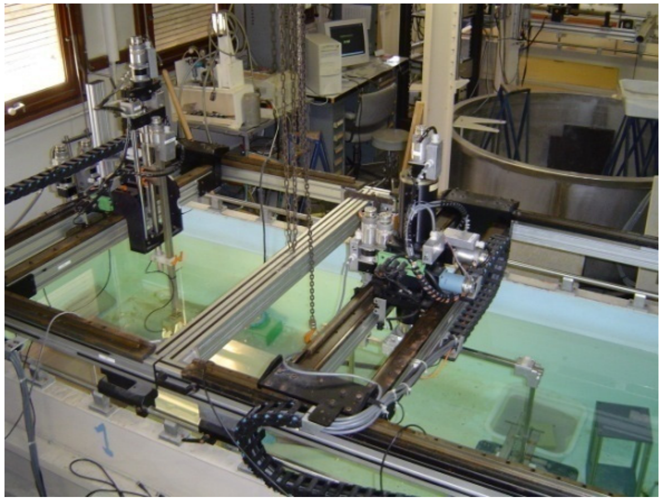




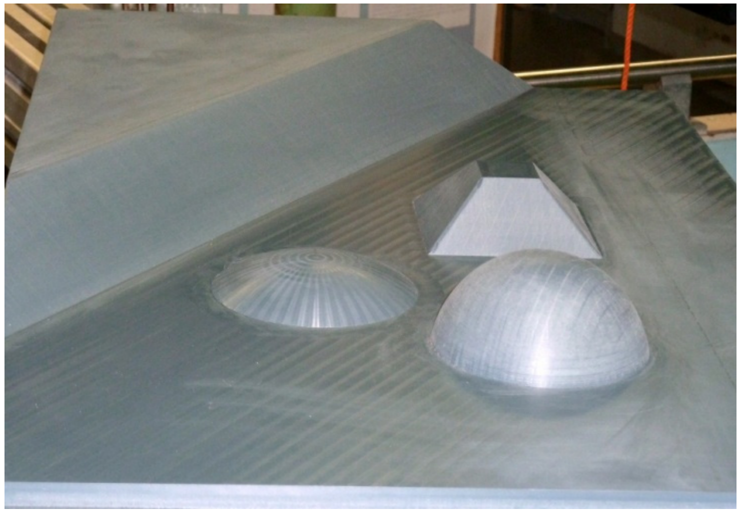




Experiments performed in tanks



Experimental tanks in Marseille



Objects with a complex shape

Conclusions and future work

- On modern computers, large 3D full-waveform forward modeling problems can be solved at high resolution in the time domain for acoustic / elastic / viscoelastic / poroelastic / seismic waves
- Inverse (adjoint) tomography / imaging problems can also be studied, although the cost is still high
- Useful in different industries in addition to academia: oil and gas, medical imaging, ocean acoustics / sonars, non destructive testing (concrete, composite media, fractures, cracks)
- Hybrid (GPU) computing is useful to solve inverse problems in seismic wave propagation and imaging
- PRACE project with INGV Roma to image the Italian lithosphere: 40 million core hours on a petaflop machine
- Some future trends: high-frequency ocean acoustics, tomography of buried objects, wavelet compression

Acknowledgements and funding

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