Tomography with the wave-equation across the scales

MASTERCLASS Jean Virieux

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Université Grenoble Alpes

Outline

Introduction

80's to 2010's - from dreams to reality

2010's to today - making this reality working accross the scales

And now: where are we heading?

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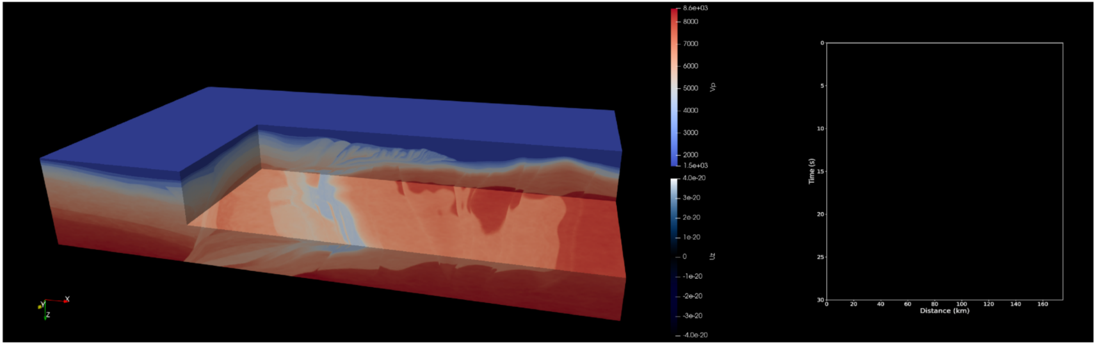
And now: where are we heading?

The complexity of real full wavefield



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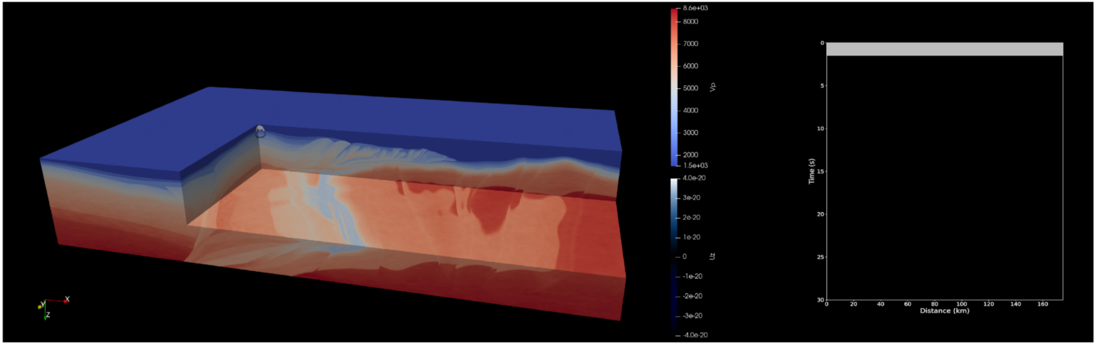

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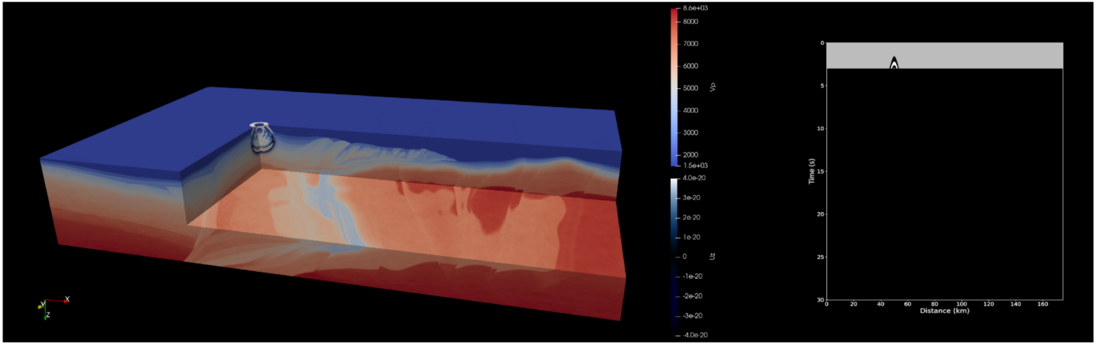

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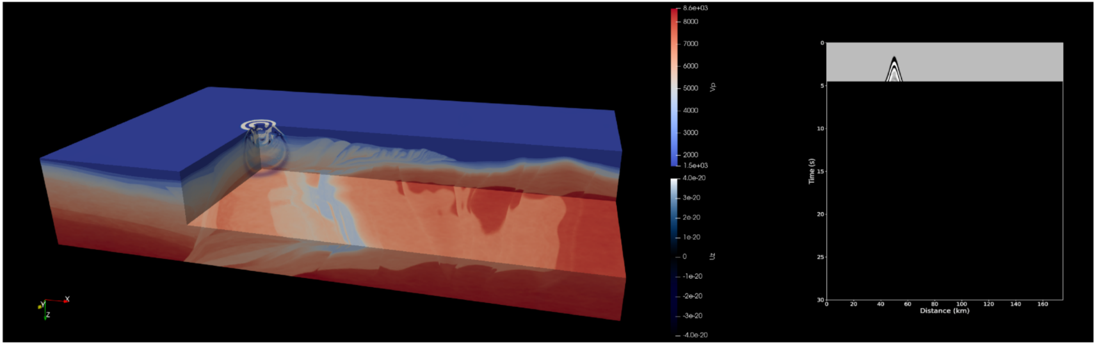

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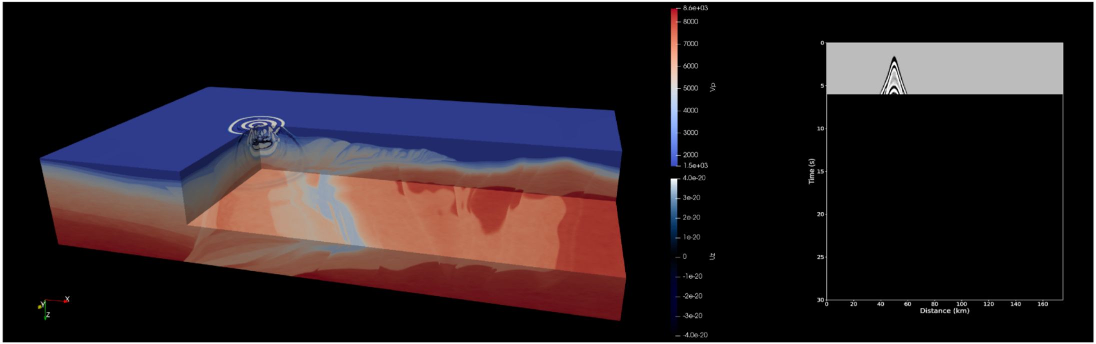

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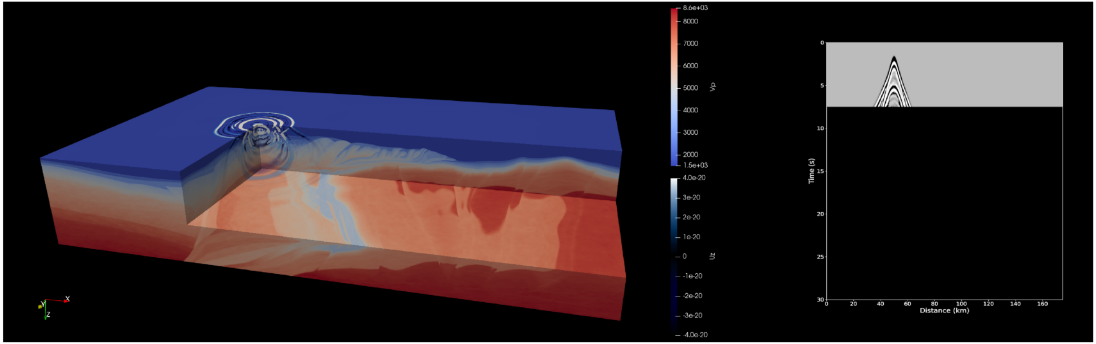

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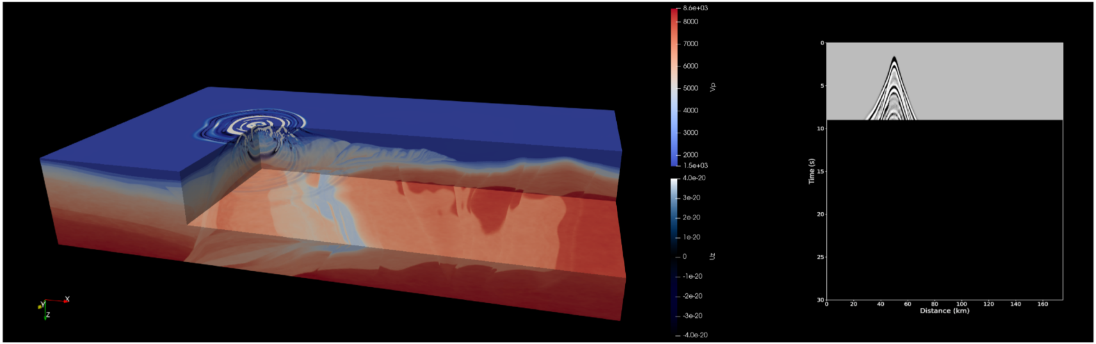

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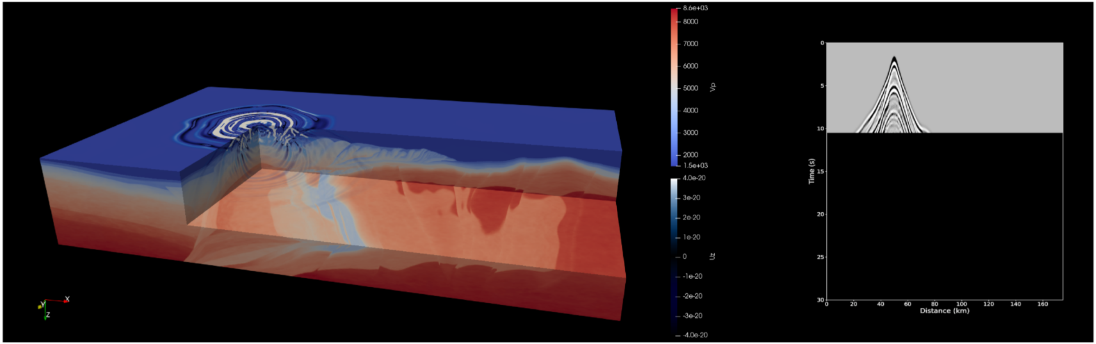

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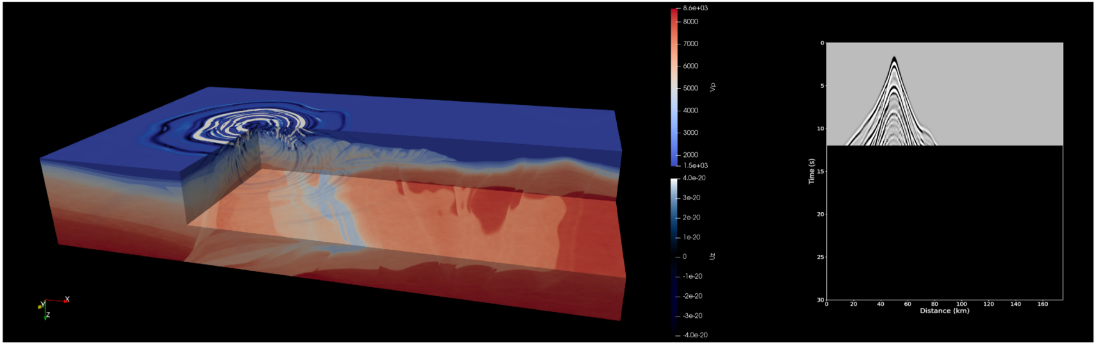

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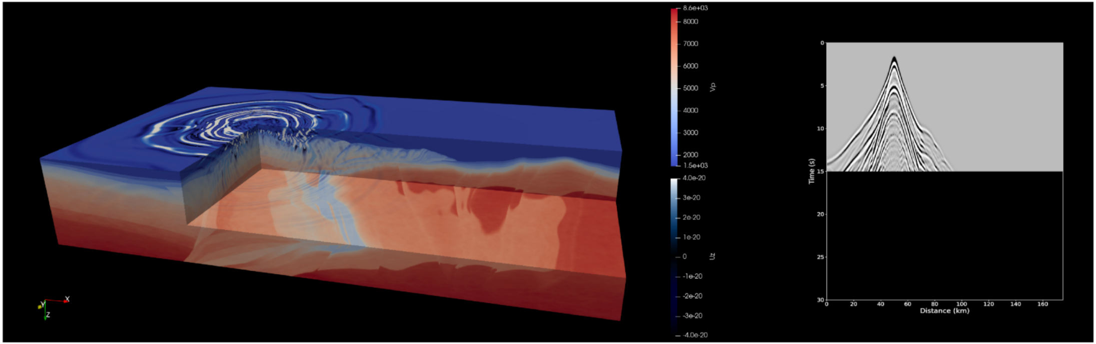

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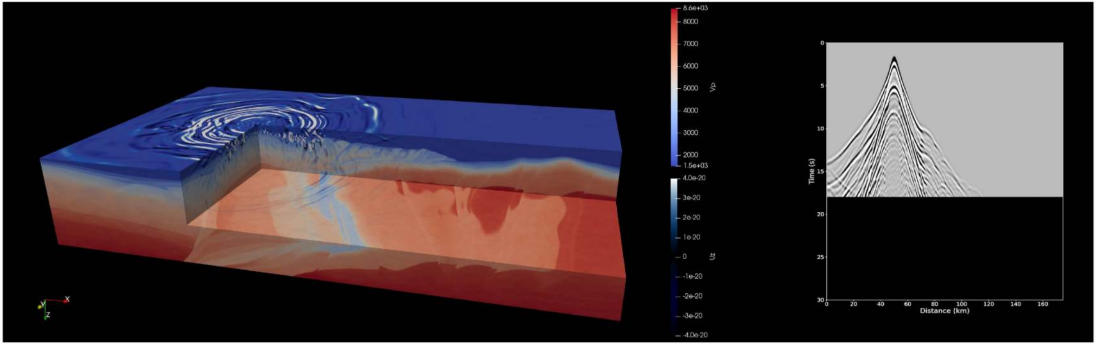

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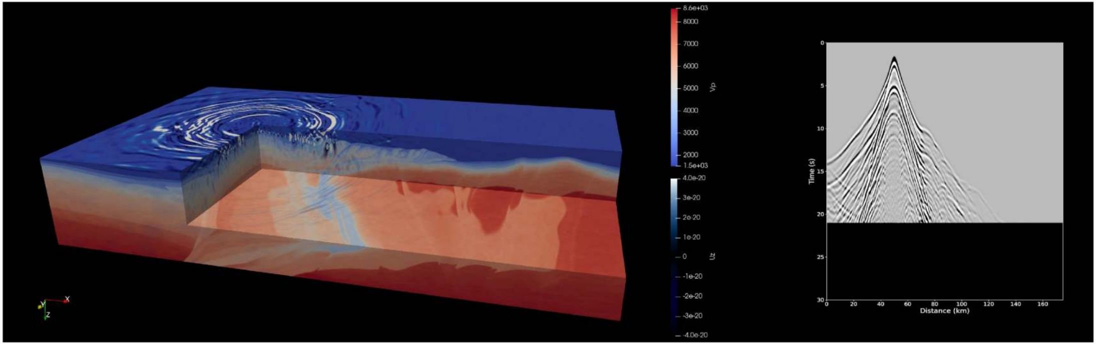

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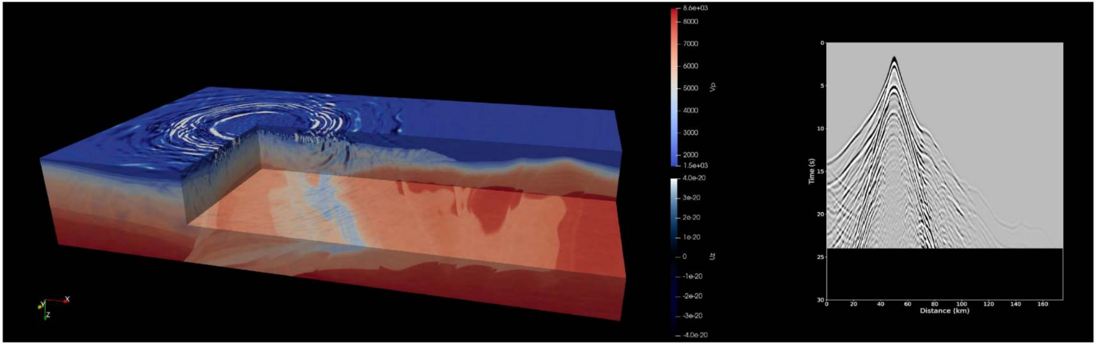

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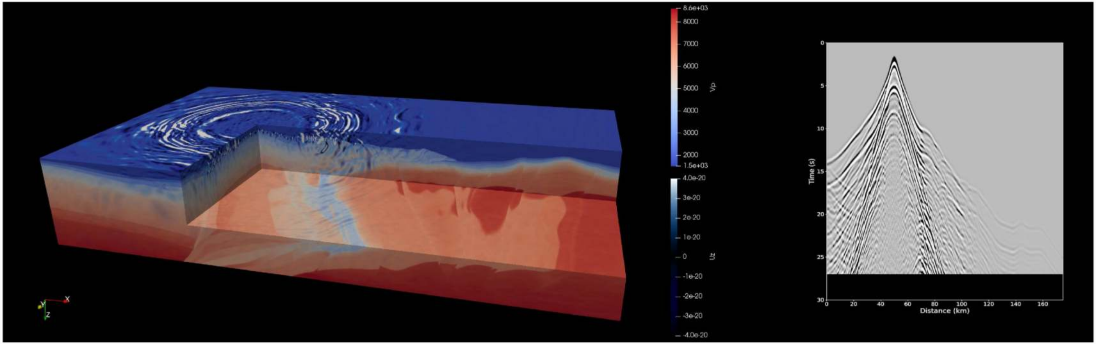

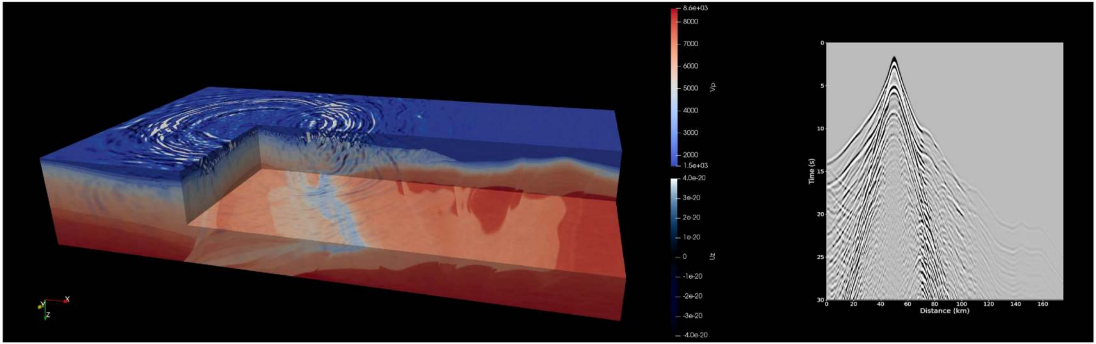
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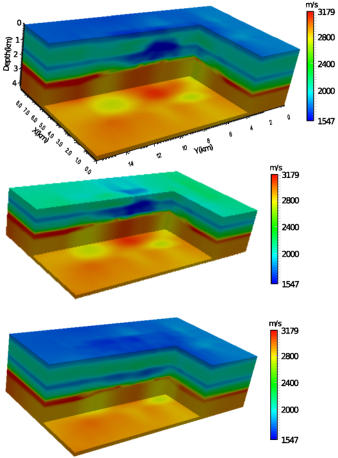
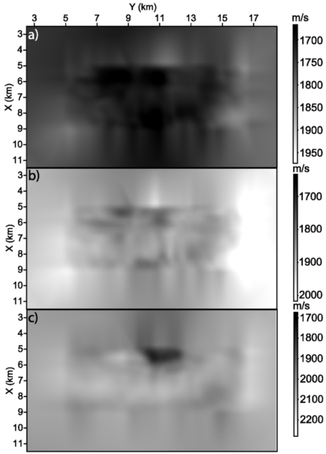
8000
7000
6000
5000
4000
3000
2000
1.5e+03
Vp
4.0e-20
3e-20
2e-20
1e-20
0
-1e-20
-2e-20
-3e-20
-4.0e-20
Uz
Time (s)
Distance (km)

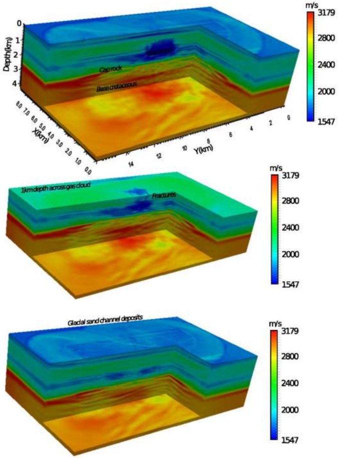
The interest of real full wavefield

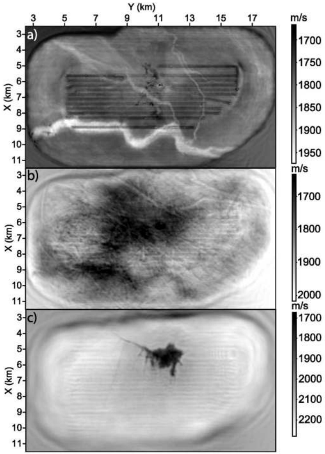




from Operto et al. (2015)

The interest of real full wavefield





from Operto et al. (2015)

Challenge of subsurface imaging for the XXIst century

Needs, lifestyle and the need for change: Energy and Materials

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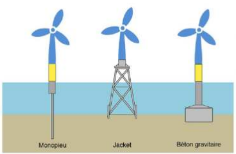
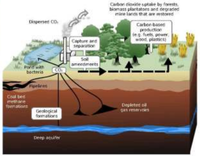
Changes in energy production: Energy, Materials, Storage





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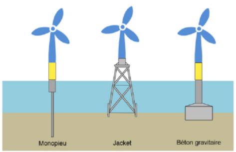
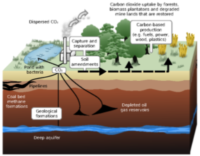
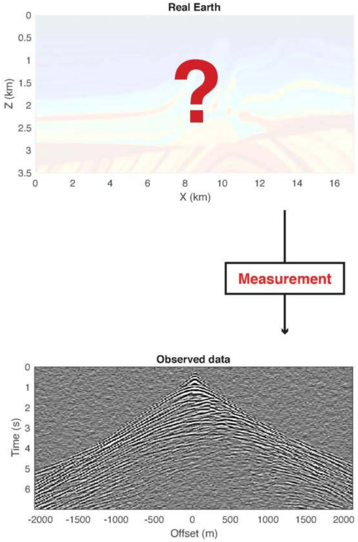


→ The (dynamic) knowledge of the Earth's crust is going to be a major challenge of this century

Full Waveform Inversion's principle



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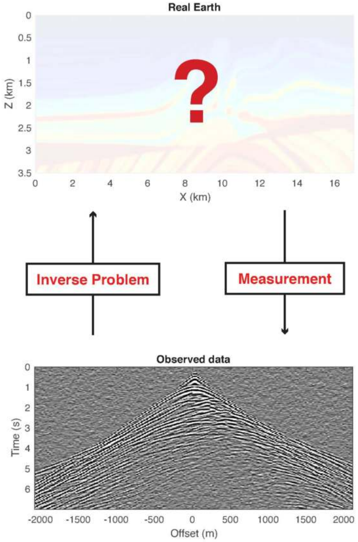

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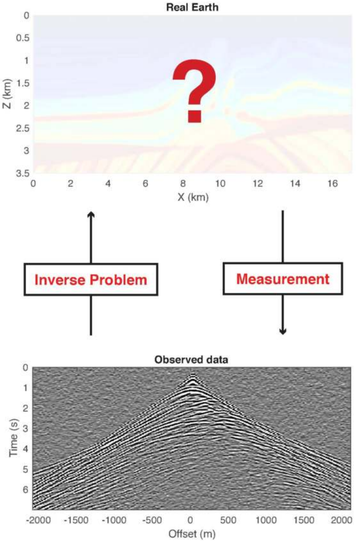

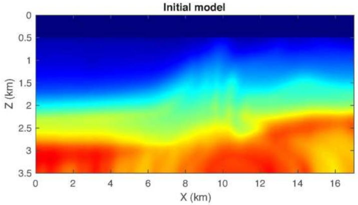

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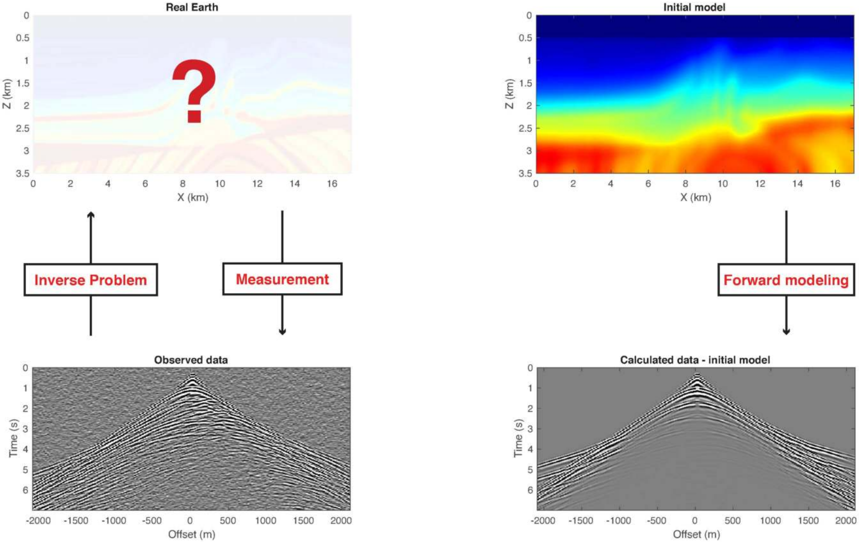

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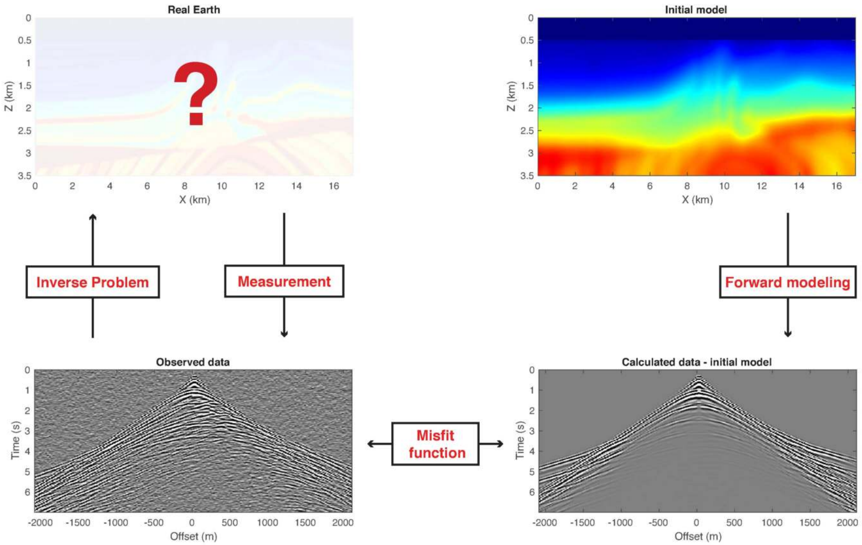

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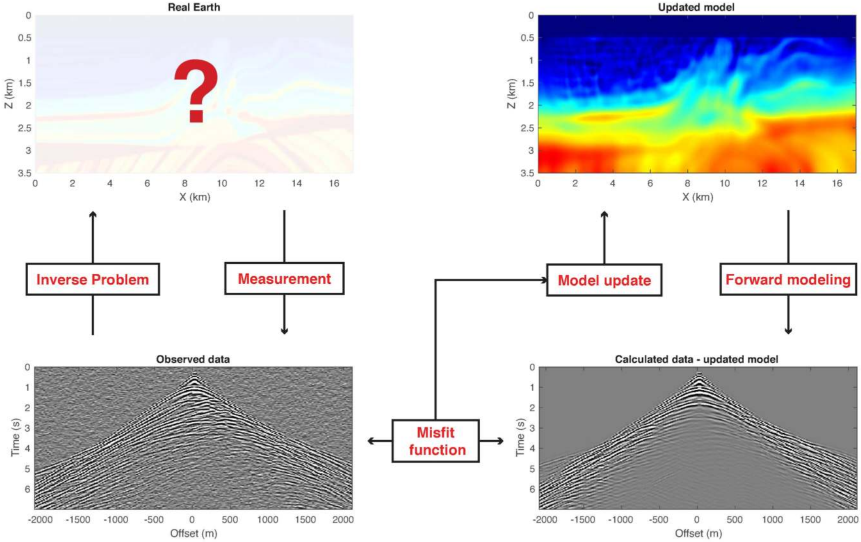

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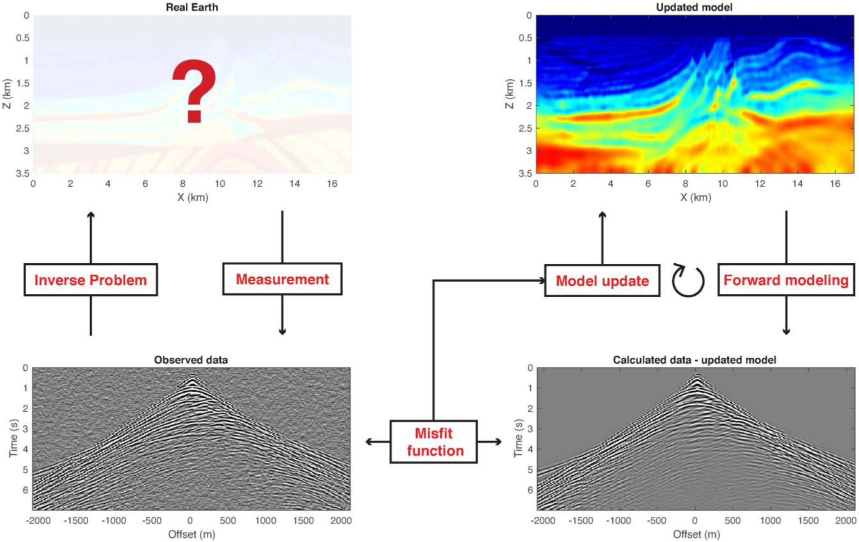

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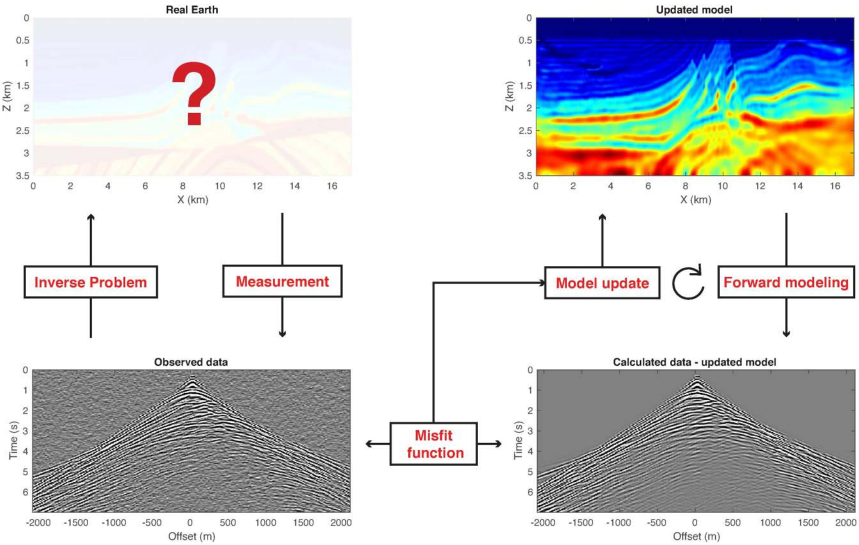

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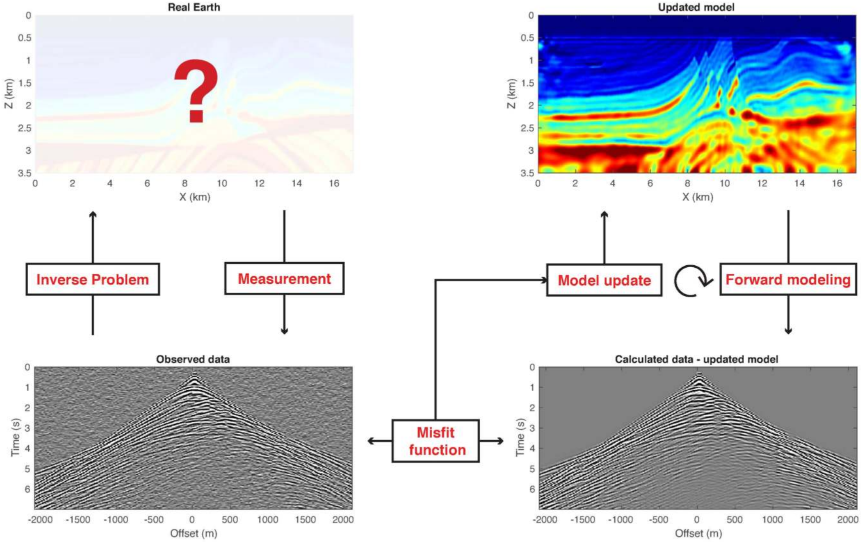

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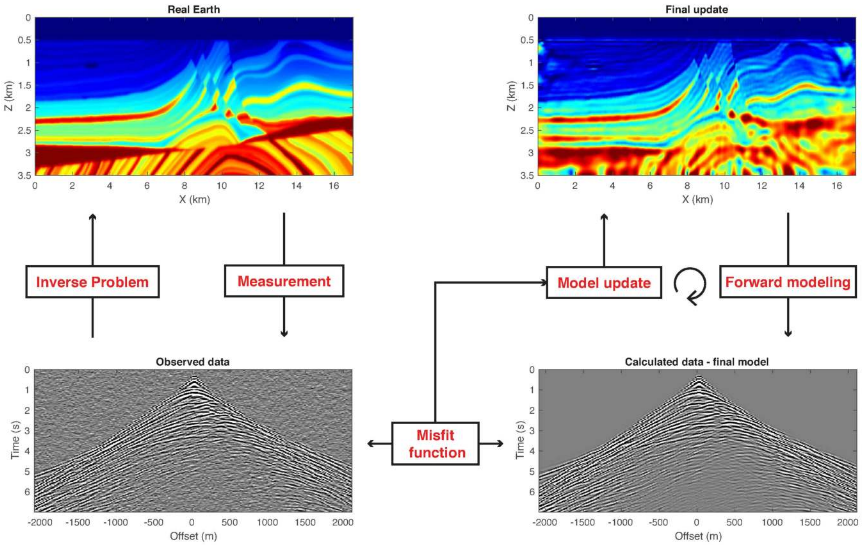

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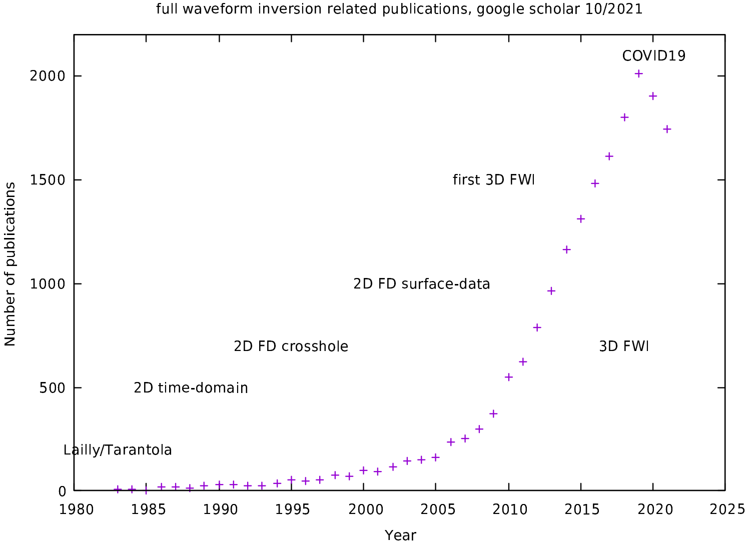
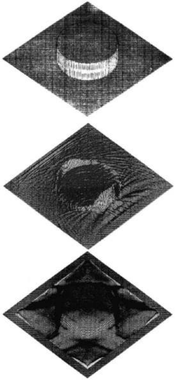
Interest in the literature

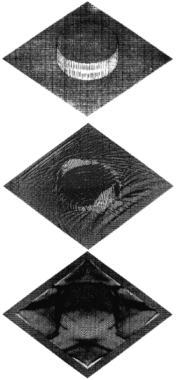


80's and 90's - from concept to success, through hopelessness

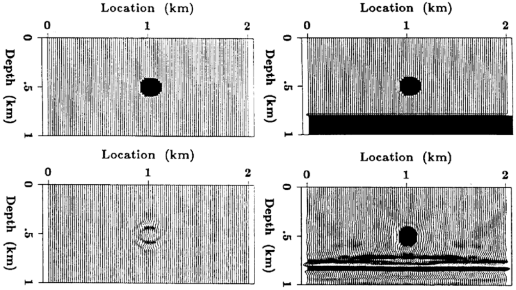


Gauthier et al. (1986)

- 80's: understanding of the concept.



Gauthier et al. (1986)



Mora (1989)

- 80’s: understanding of the concept. Short-offset data only → FWI as a non-linear migration, but already seen the interest of “transmissions”

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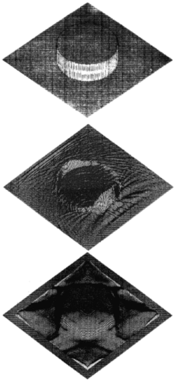
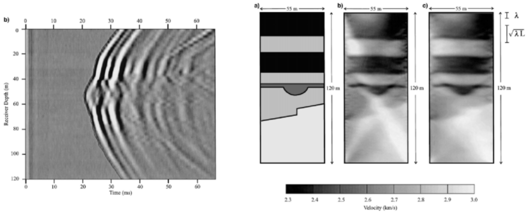


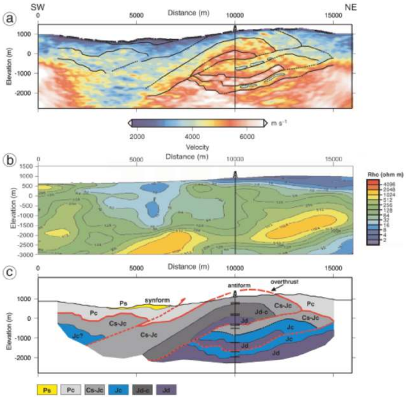
Gauthier et al. (1986)



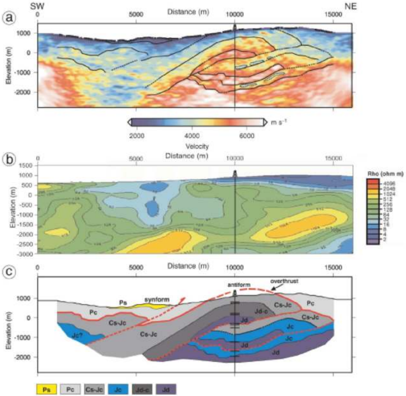
Pratt (1999)

- 80's: understanding of the concept. Short-offset data only → FWI as a non-linear migration, but already seen the interest of "transmissions"
- In the 90's: reinvestigation of FWI in the 90's by Pratt's group, for cross-well data (in 2D frequency-domain) → success thanks to transmissions (and cheaper HPC cost)

2000's - 2D pioneering applications from surface data



Ravaut et al. (2004)



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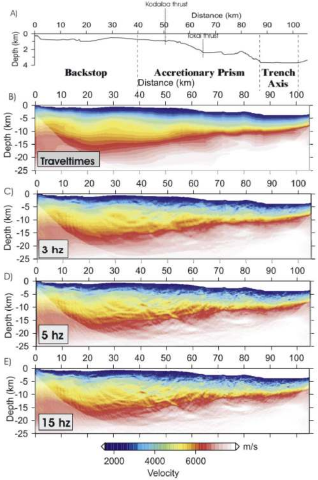
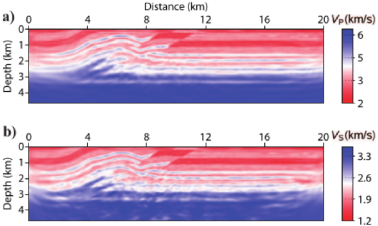
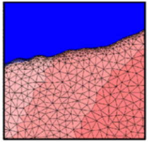
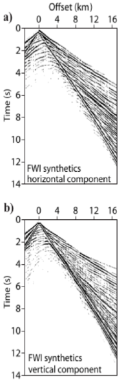


Operto et al. (2006)



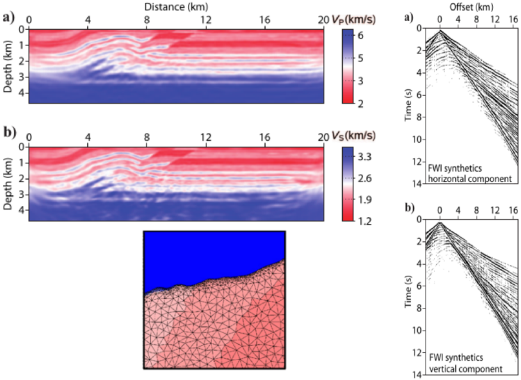




Gélis et al. (2007); Brossier et al. (2009)

- wish to consider more complex physics (with more sofisticated numerical schemes): anisotropy, elasticity, ...

2000's - toward more complex physics



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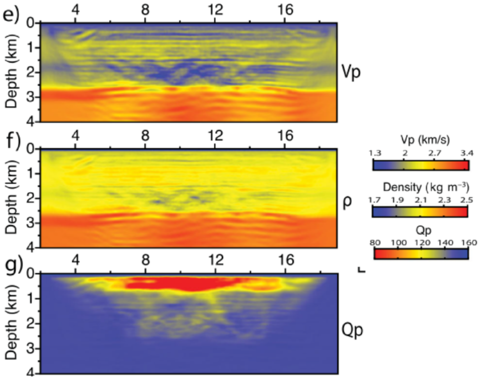

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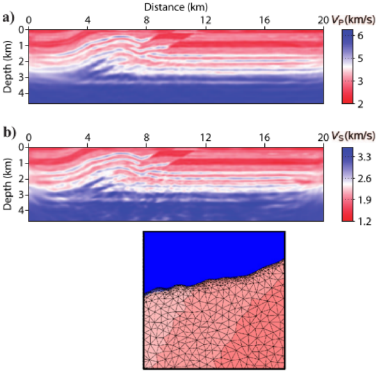

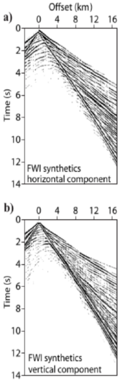

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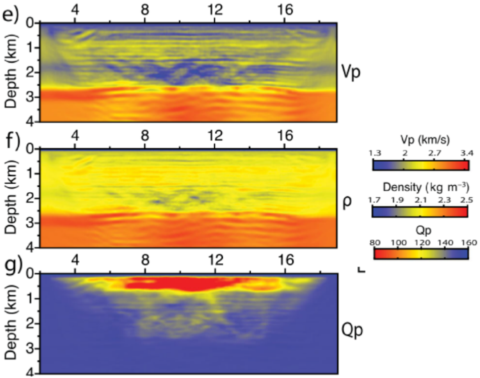

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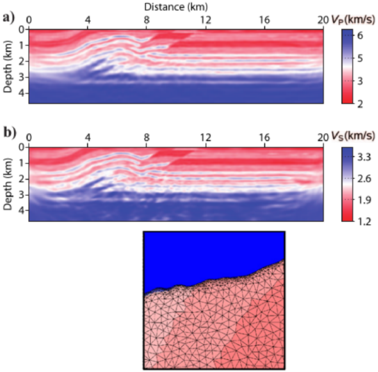

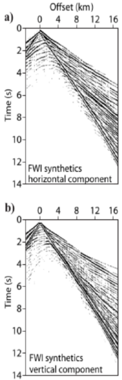

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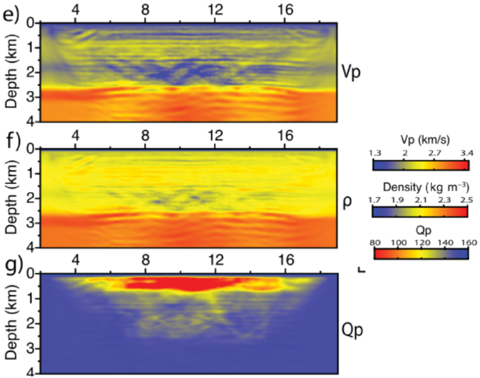

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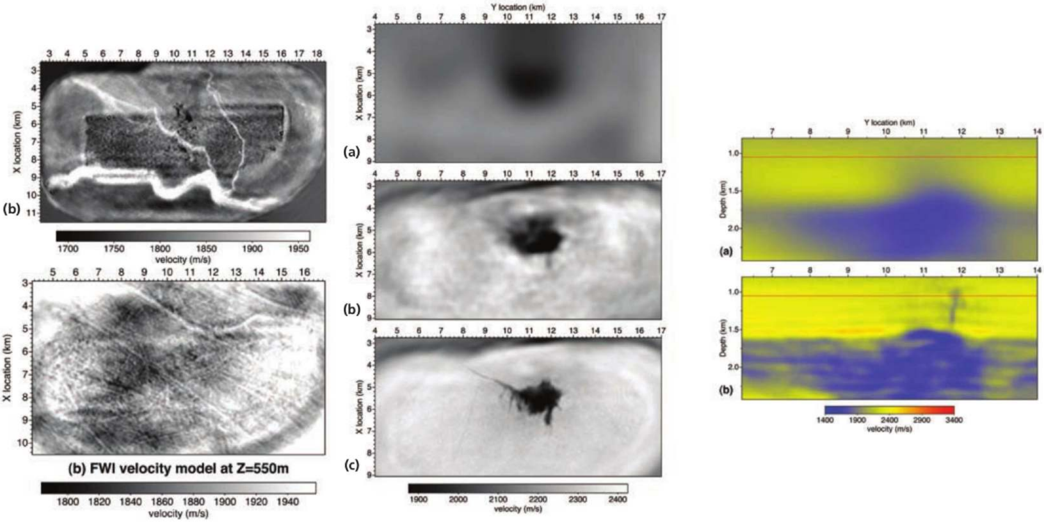
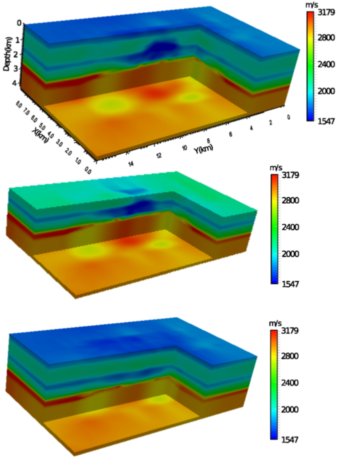
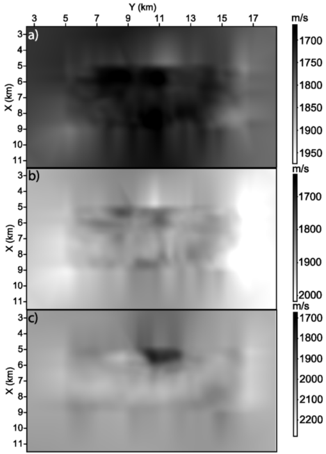
2010 - the first real FWI in 3D

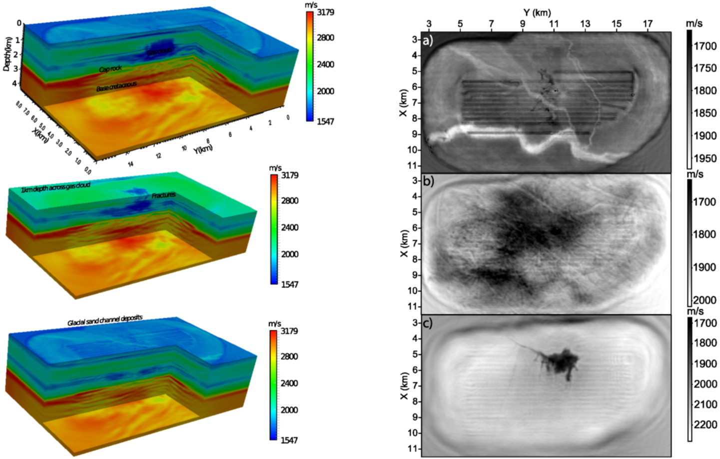


Sirgue et al. (2010), from BP on the Valhall 3D OBC data





from Operto et al. (2015) on the Valhall 3D OBC data, in the frequency domain with attenuation and anisotropy



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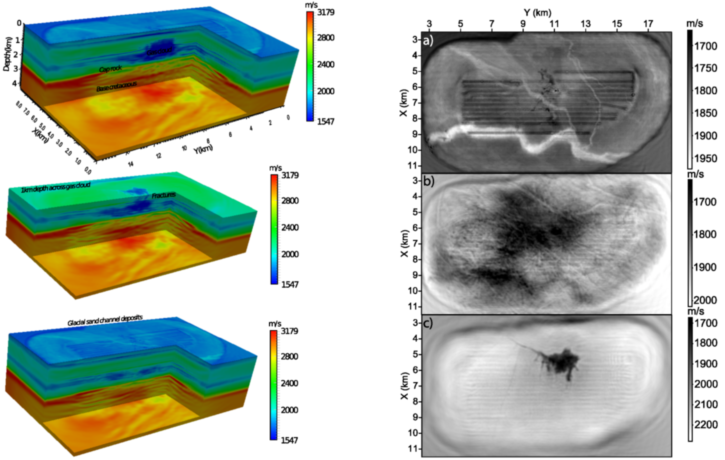

from Operto et al. (2015) on the Valhall 3D OBC data, in the frequency domain with attenuation and anisotropy but requirement to go toward time-domain

- limitation of 3D modeling at early times
  $\rightarrow$ most early applications in 2D

HPC Challenges for time-domain wave simulation and FWI

- limitation of 3D modeling at early times
  $\rightarrow$ most early applications in 2D
- intrisic cost of the 3D forward problem
  $\approx C \times 1/\lambda^4 = C \times f^4/V^4$

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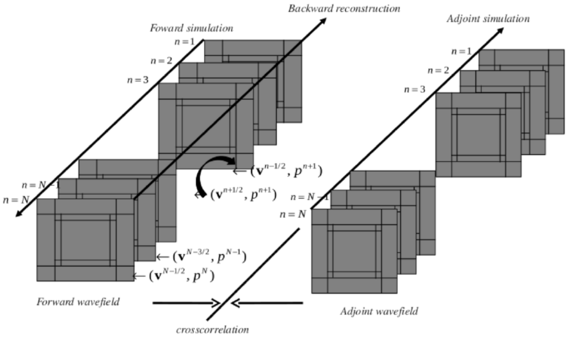
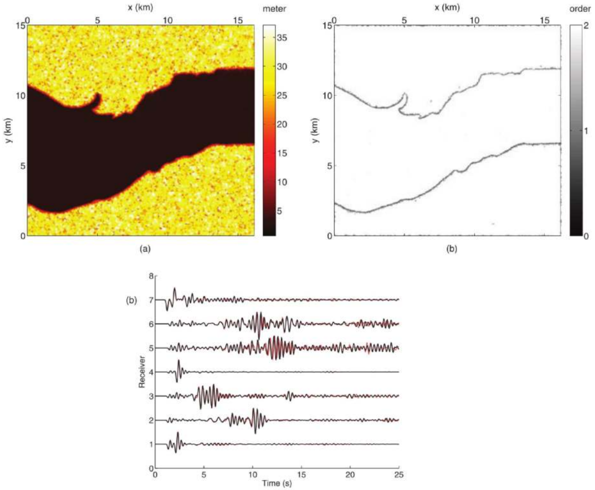
  $\approx C \times 1/\lambda^4 = C \times f^4/V^4$
- wave physics $\nearrow C$ (and $\searrow V$ in elastic)
- imaging condition challenges for the correlation of both fields(Symes, 2007; Anderson et al., 2012; Yang et al., 2016; Komatitsch et al., 2016; Robertsson et al., 2021, among others)



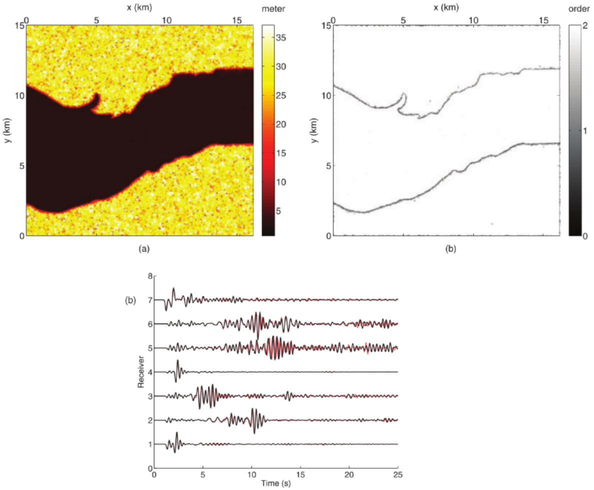
Yang et al. (2016)

2010's - toward 3D elastic modeling for FWI



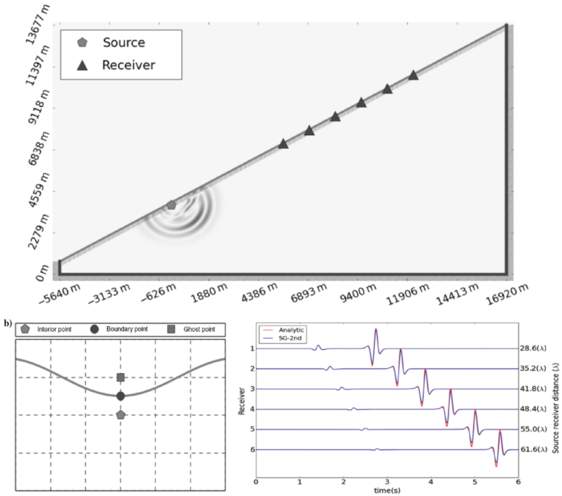
Etienne et al. (2010), exploration of Discontinuous Galerkin in 3D

2010's - toward 3D elastic modeling for FWI

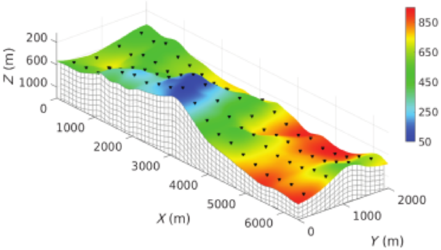


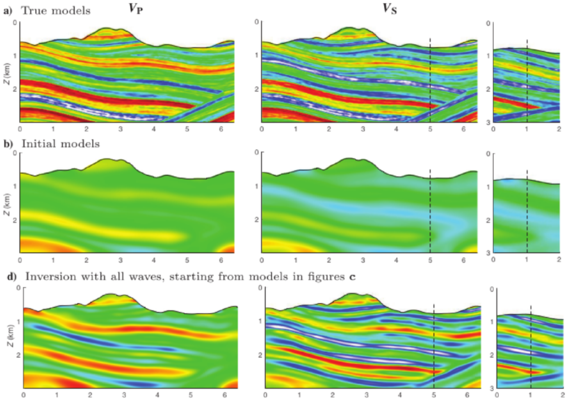
Etienne et al. (2010), exploration of Discontinuous Galerkin in 3D, but high computing cost for FWI perspective (for the crust)

2010's - toward 3D elastic modeling for FWI

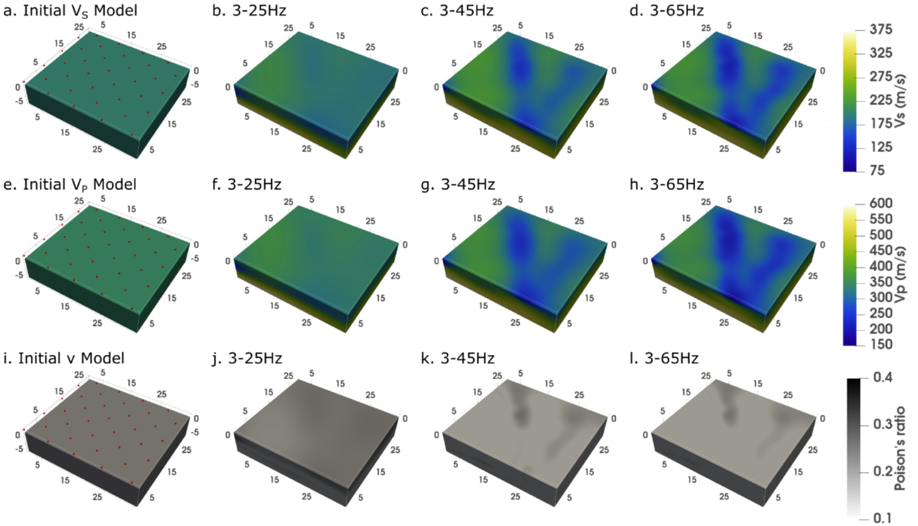


Gao et al. (2015), exploration of Immersed Free-Surface Boundary Condition in finite-difference



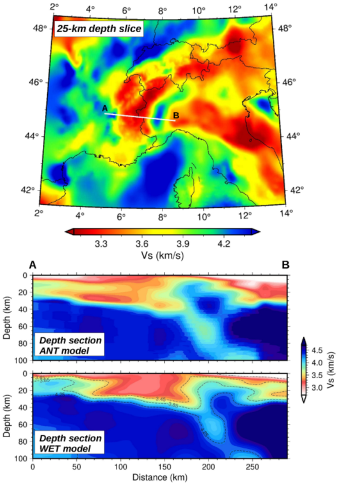


Trinh et al. (2019), finaly end up with Spectral Element Methods



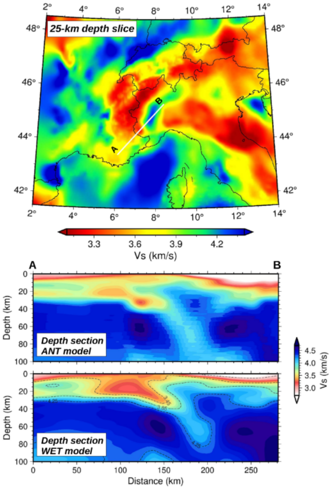
Irnaka et al. (2019), application on 9-Componant near-surface dense dataset, driven by surface waves

2020's - application for regional-scales



Nouibat et al (in prep), application on "noise-based" data at the Alpes scale

2020's - application for regional-scales



Nouibat et al (in prep), application on "noise-based" data at the Alpes scale

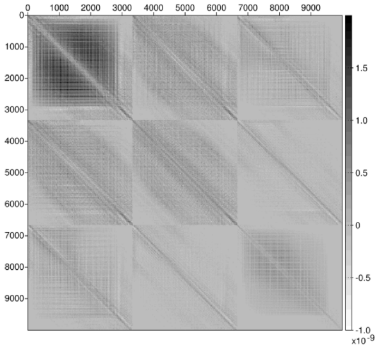
Multi-parameter, coupling, and the Hessian matrix

Elastic FWI: multi-parameter problem
V_P, V_S $(+\ \rho, Q_P, Q_S, c_{ijkl}...)$

Inter- and intra-parameter couplings are encoded in the Hessian operator

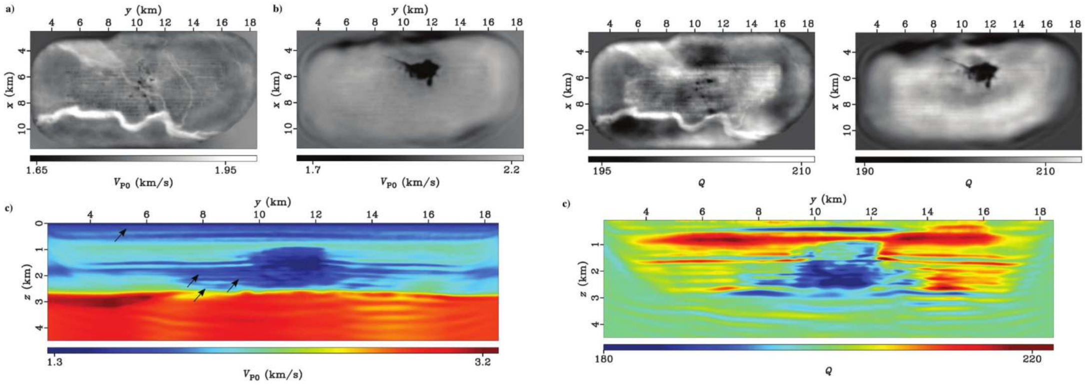
How to exploit it

- optimization schemes : l-BFGS, truncated-Newton (Métivier et al., 2013, 2014; Métivier and Brossier, 2016)
- preconditioning strategies (asymptotic-based, phases again!) (Métivier et al., 2015b)

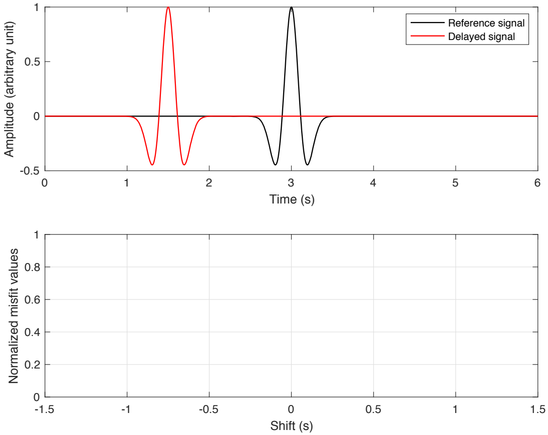


Multi-parameter Hessian for 2D multi-parameter visco-acoustic FWI: V_P, ρ, Q_P (Métivier et al., 2015a)

V_P and Q_P reconstruction from Valhall data (Kamath et al., 2021)



- FWI is a non convex minimization problem!
- Local exploration for computational cost: global exploration impossible



Fighting with an ill-posed inverse problem

- FWI is a non convex minimization problem!
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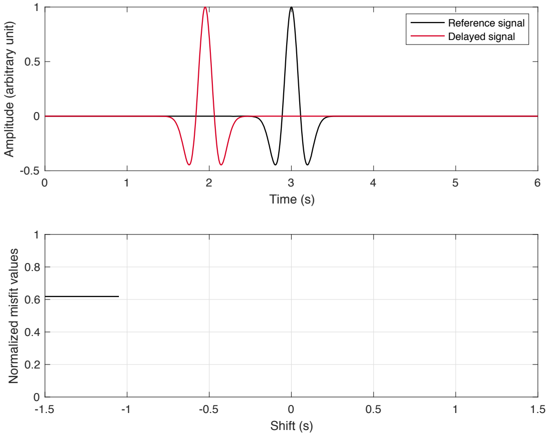

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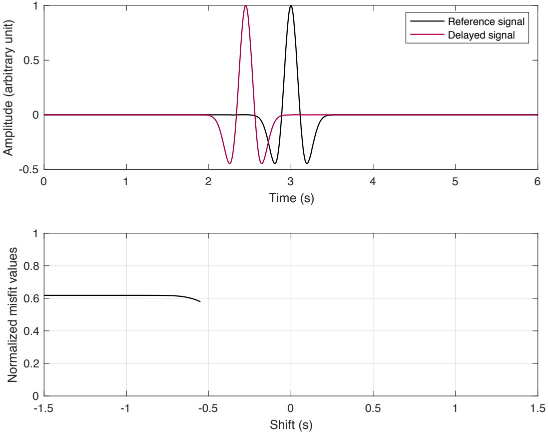

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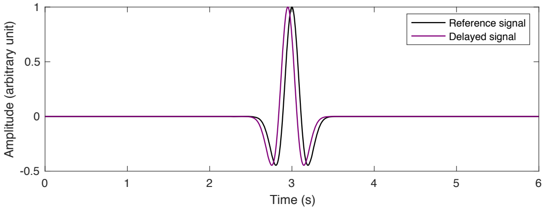

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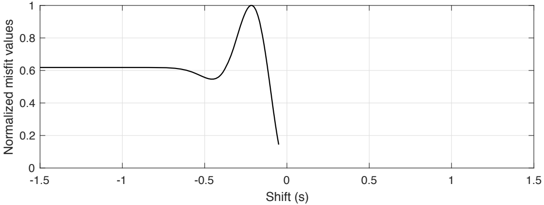

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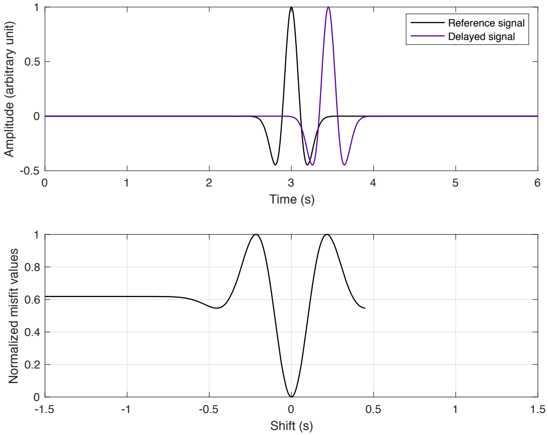

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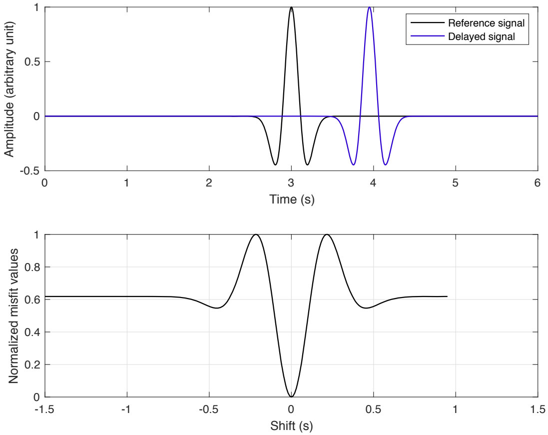

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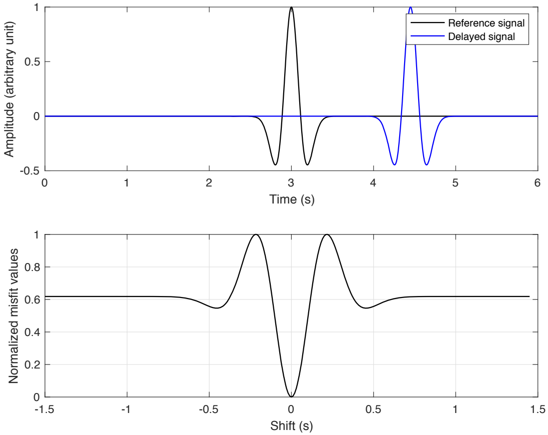


Conventional: hierarchy in the data

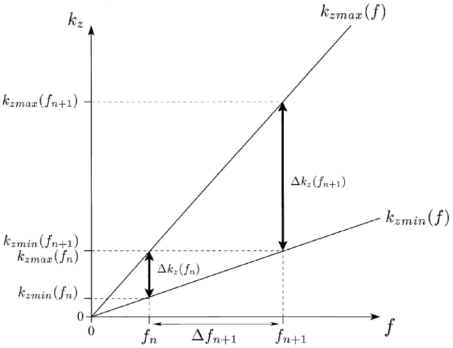


Image adapted from Sirgue and Pratt (2004)

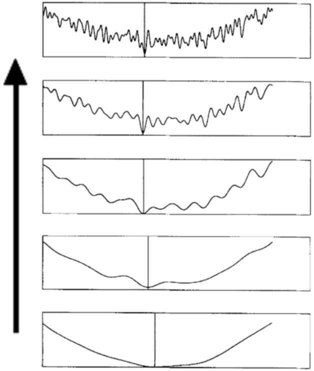


Image adapted from Bunks et al. (1995)

Modify the misfit function using optimal transport distances

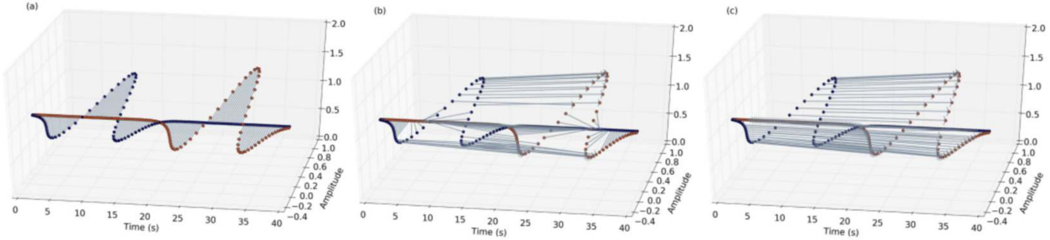
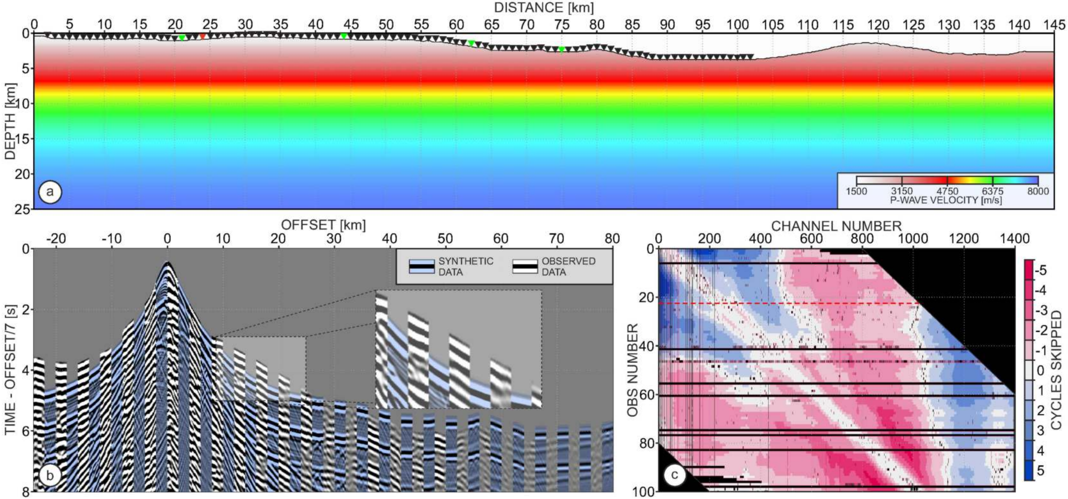


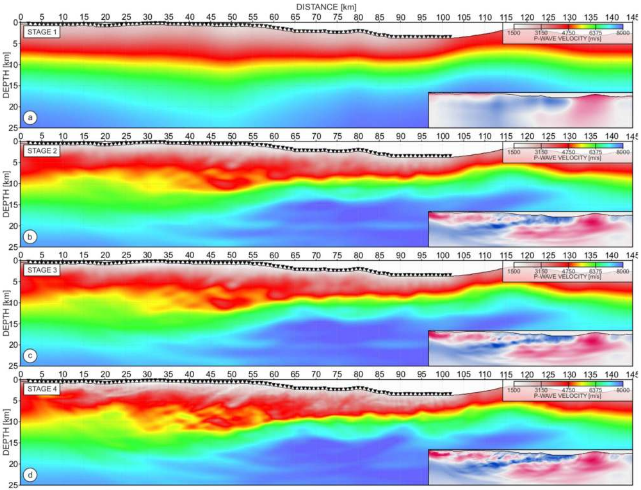
Image adapted from Métivier et al. (2019)

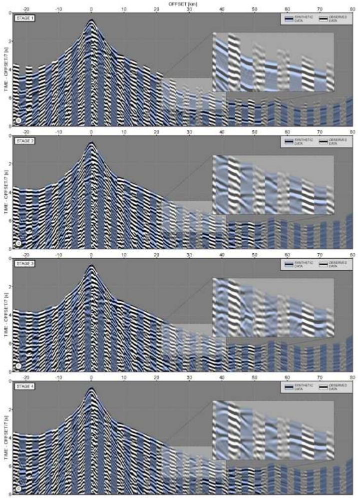
Application on Nankai trough imaging(Górszczyk et al., 2021)



Fighting with an ill-posed inverse problem

Application on Nankai trough imaging(Górszczyk et al., 2021)



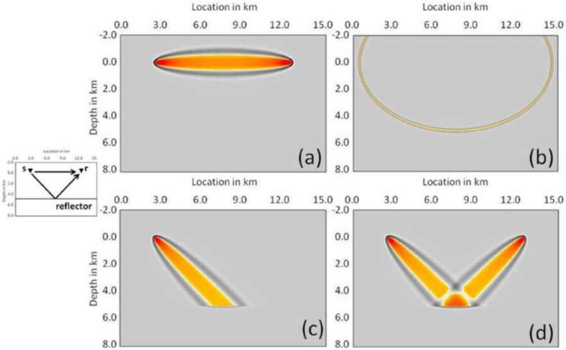


Outline

Reconstruction of the subsurface only where it is sampled by diving waves/transmitted energy

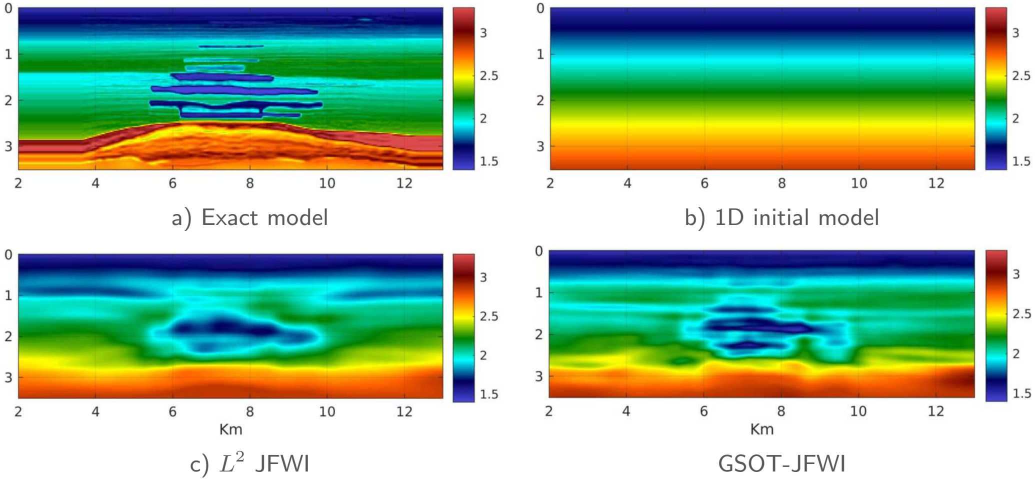
We propose a Joint-FWI framework based on an explicit separation between

- transmitted and reflected energy
- a smooth background velocity model and a sharp impedance model



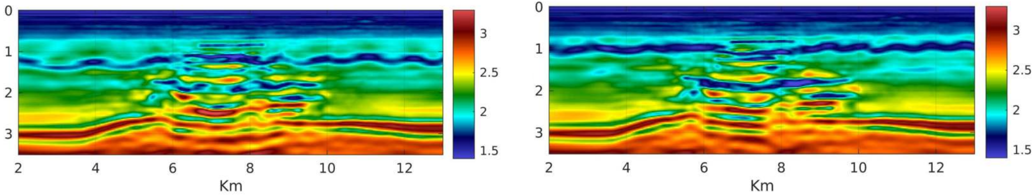
From Xu et al. (2012)

Increasing the illumination zone by better exploiting reflected phases



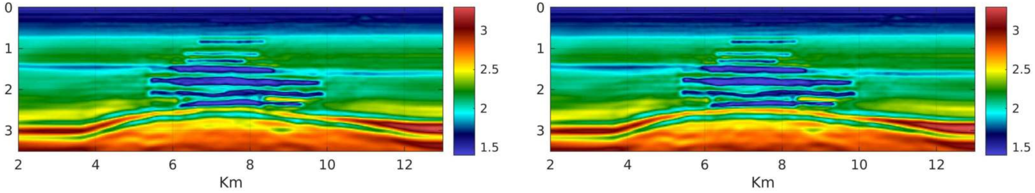
Latest results combining Joint-FWI with optimal transport distances, asymptotic preconditioning for impedance reconstruction, and clever multi-parameter handling based on time-to-depth conversion (Provenzano et al., 2022)

Increasing the illumination zone by better exploiting reflected phases



a) GSOT-FWI from 1D

b) L^2-FWI from 1D



c) GSOT-FWI from GSOT-JFWI

d) L^2-FWI from GSOT-JFWI

Latest results combining Joint-FWI with optimal transport distances, asymptotic preconditioning for impedance reconstruction, and clever multi-parameter handling based on time-to-depth conversion (Provenzano et al., 2022)

Motivation: subsurface time evolution tracking

Challenges

- subtle changes to be extracted from noisy data
- repeatability of acquisition
- making the most of low cost acquisition

Methods

- reflection oriented Joint-FWI + 4D FWI
- optimal experimental design

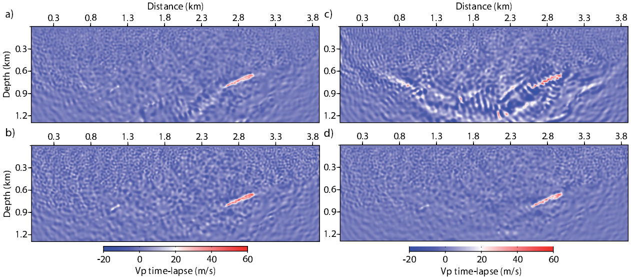


Image taken from Asnaashari et al. (2015)

Motivation

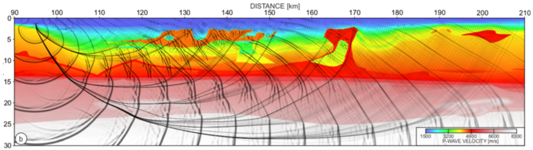
- sources and receivers decoupling: undershooting
- reconstruct V_P and V_S

Challenges

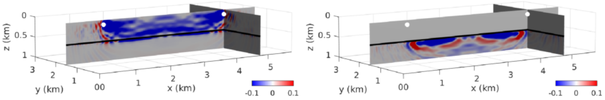
- higher computational cost
- robust multi-parameter scheme

Methods

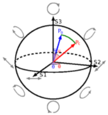
- hierarchical scheme in components (Cao et al., 2022)
- time-dependent polarization (Sambolian et al., 2022)



Ray coverage provided by ultra long offsets



V_P and V_S kernels with fluid/solid coupling

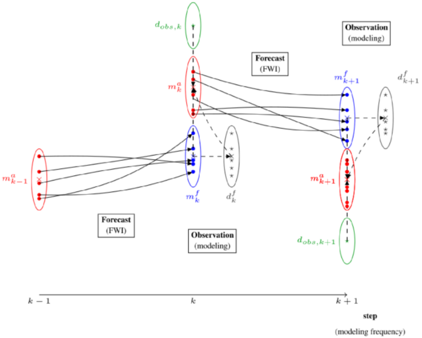


Polarization on the Poincaré sphere

Tarantola's dream: estimating the uncertainties and sampling the model space

Tarantola (2005):

The human brain is not very good at interpreting covariances in high-dimensional problems. But it is very good at comparing random samples of a probability distribution. Knowing this, the usual presentation of 'the solution' of a least-squares problem (in fact, the mean of the posterior Gaussian), together with the covariances (as an expression of 'uncertainties' in the solution), should systematically be replaced with a better presentation. Given the mean $\tilde{m}$ *and the covariance* C_M *of the posterior Gaussian, one should generate pseudorandom samples* $m_1, m_2, \ldots, m_K$ *of the probability density* $\sigma_M(m) = Gaussian(m, \tilde{m}, C_M)$ *and present the samples* $m_1, m_2, \ldots, m_K$ *instead*



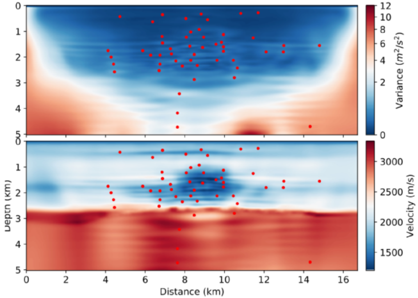


Image taken from Thurin et al. (2019)

Higher resolution, uncertainties: towards exascale computing?

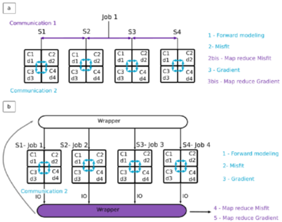
Future of FWI

- 3D visco-elastic approximation
- always higher resolution
- many FWI run for UQ estimation

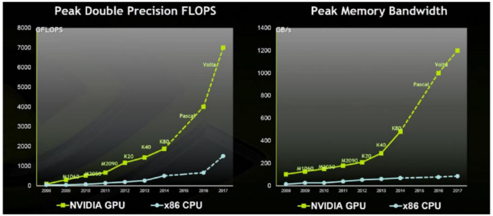
$\Longrightarrow$ exploit exascale HPC resources

How

- task scheduling for better parallel efficiency
- from CPU to other hardware: GPU , ARM ?



Task scheduling



GPU (green) vs CPU (blue) performances

and few words to conclude

Walking in the footsteps of giants is

- a chance
- exciting
- challenging!

What we do now, what we will do in the future, bear the imprint of Jean's own intuitions

and few words to conclude

Thank you Jean !

Thank you for your attention

- IDRIS and TGCC, French national computing centers
- CIMENT, Grenoble computing center
- All SEISCOPE project members
- SEISCOPE sponsors : `http://seiscope2.osug.fr`

Questions?

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