Efficient data-driven strategy for 3D model-preconditioning FWI

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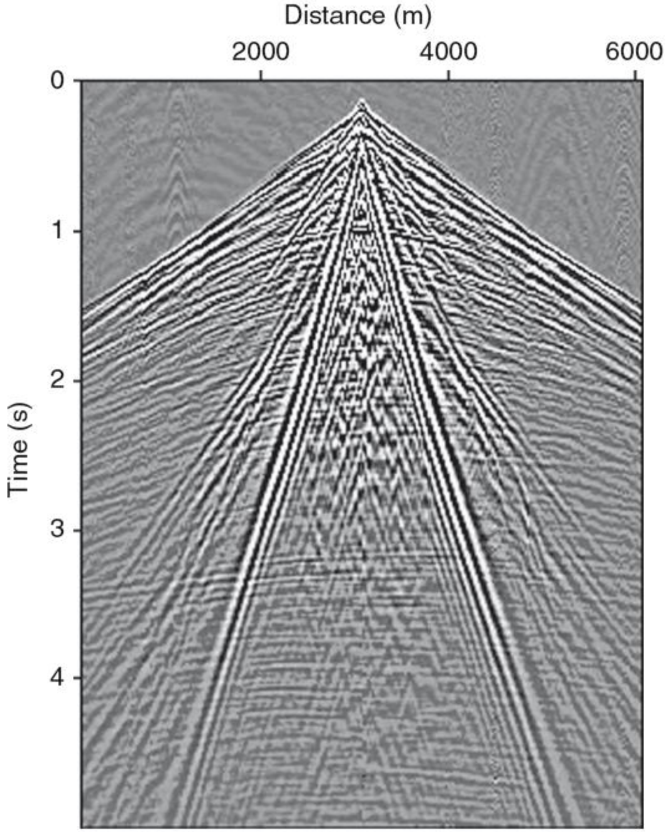
http://seiscope2.osug.fr

Seismic data

SEISMICS



Dense acquisition

Honoring a simple PDE!

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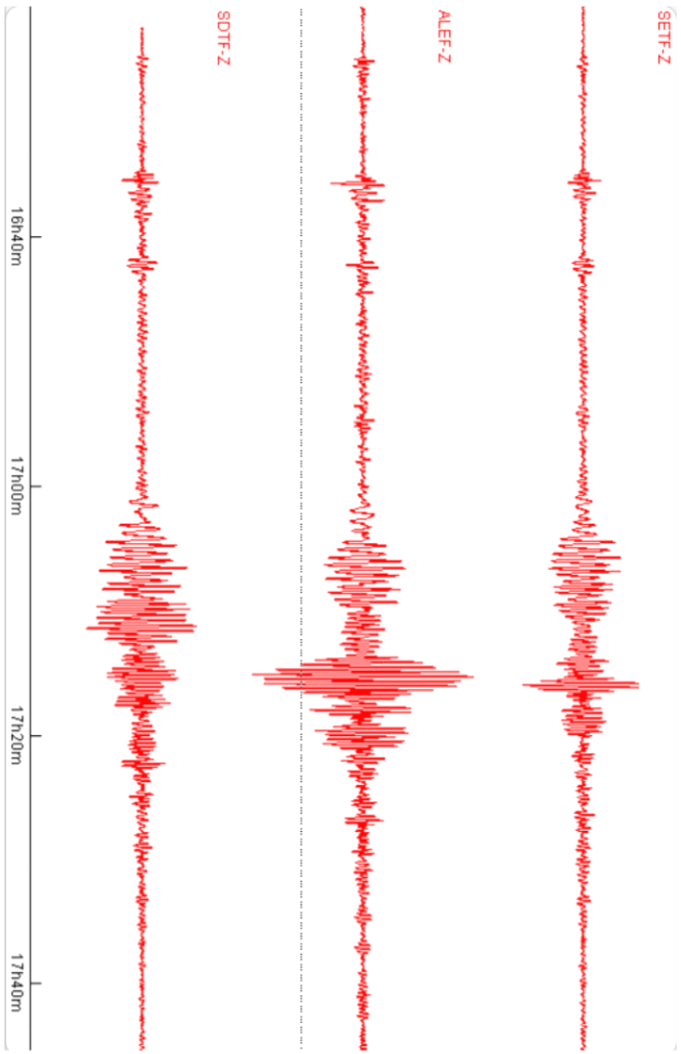
Absolute time: date



Towards continuous recording

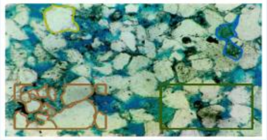
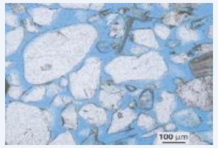
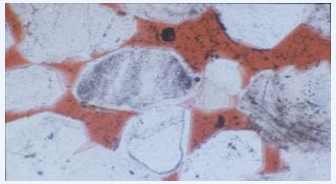
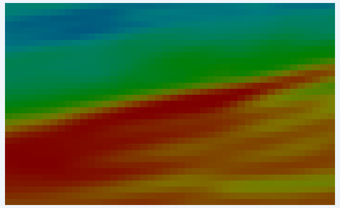
Towards dense recording

Outline

1. Motivation
2. FWI: single scattering
3. PDE visco-elastic wave propagation
4. Model discretization & preconditioning
5. 3D elastic SEAM II Foothills application

Ebook of SEG: encyclopedia of exploration geophysics
http://library.seg.org/doi/abs/10.1190/1.9781560803027.entry6

Model/Physical parameter hunting?

  100*µm	**Micro-scale**	Physical parameters: mineral composition, gas, liquid …
 < or ~ m	Upscaling / Downscaling **Meso-scale**	Inference parameters: one solid skeleton and one fluid. Gassmann rheology Porosity, saturation, tortuosity, consolidation parameter …
 > 10*m	**Macro-scale** (Investigated by FWI)	Model parameters: velocities, attenuation, anisotropy, density for seismic waves

Important parameters at the macro-scale level ?

Attenuation, Elasticity, Anisotropy, Density

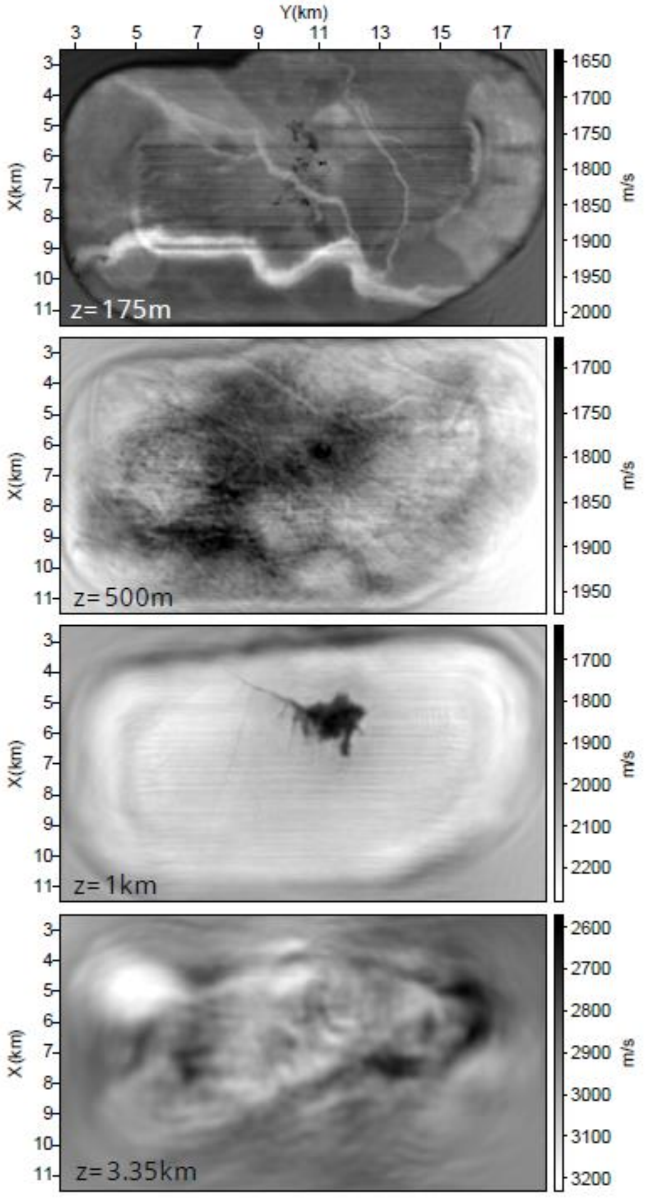
High-resolution seismic imaging

- **Macro-scale imaging: FWI provides high-resolution capacity**
  - Vertical components or 4C data
  - Body waves versus surface waves
  - Diving waves versus reflected waves

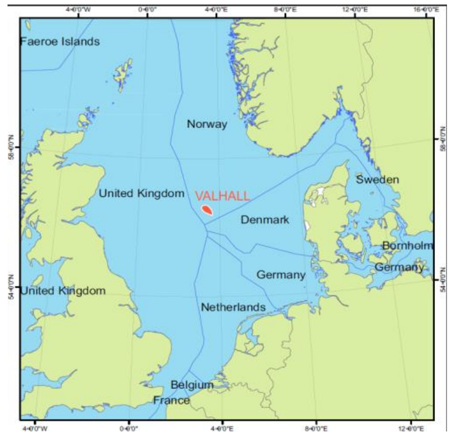
- **Which physics to consider at this scale?**
  - Visco-elastic anisotropic propagation
  - Related model parameters …

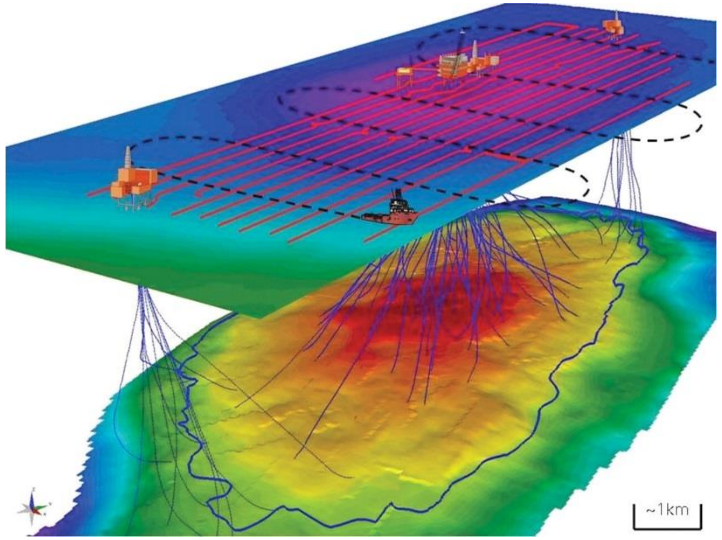
- **Medium interpretation: which physics to consider?**
  - Downscaling using biphasic model (Gassmann relation)
  - Upscaling from multi-phases rock description related to physical parameters …
  - Inference step between downscaling and upscaling

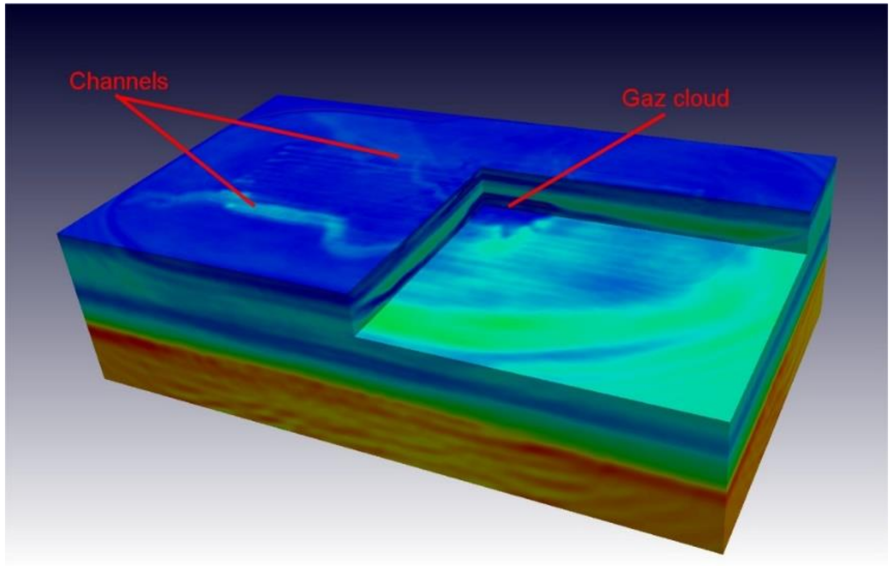
Macro-scale imaging



FWI provides high-resolution capacity







Operto & Miniussi (2017)

High-resolution seismic imaging

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Which physics to consider at macro-scale?

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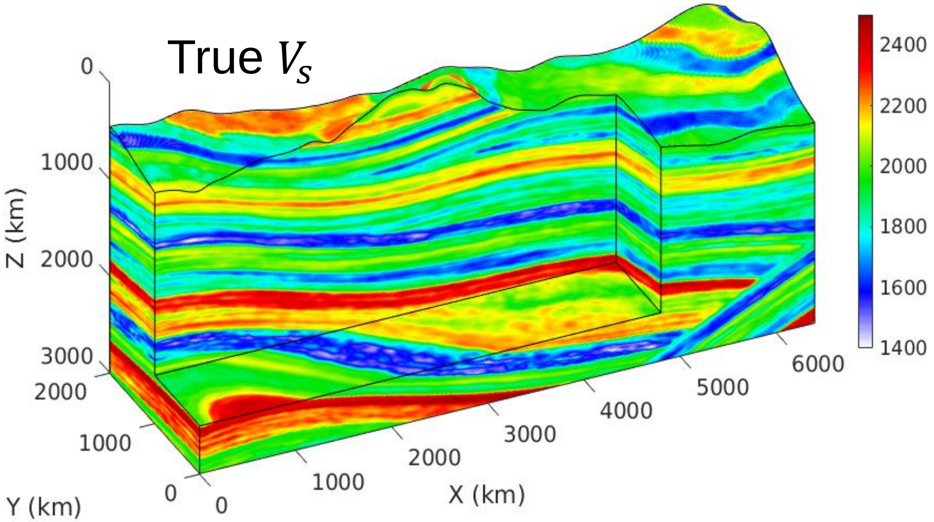
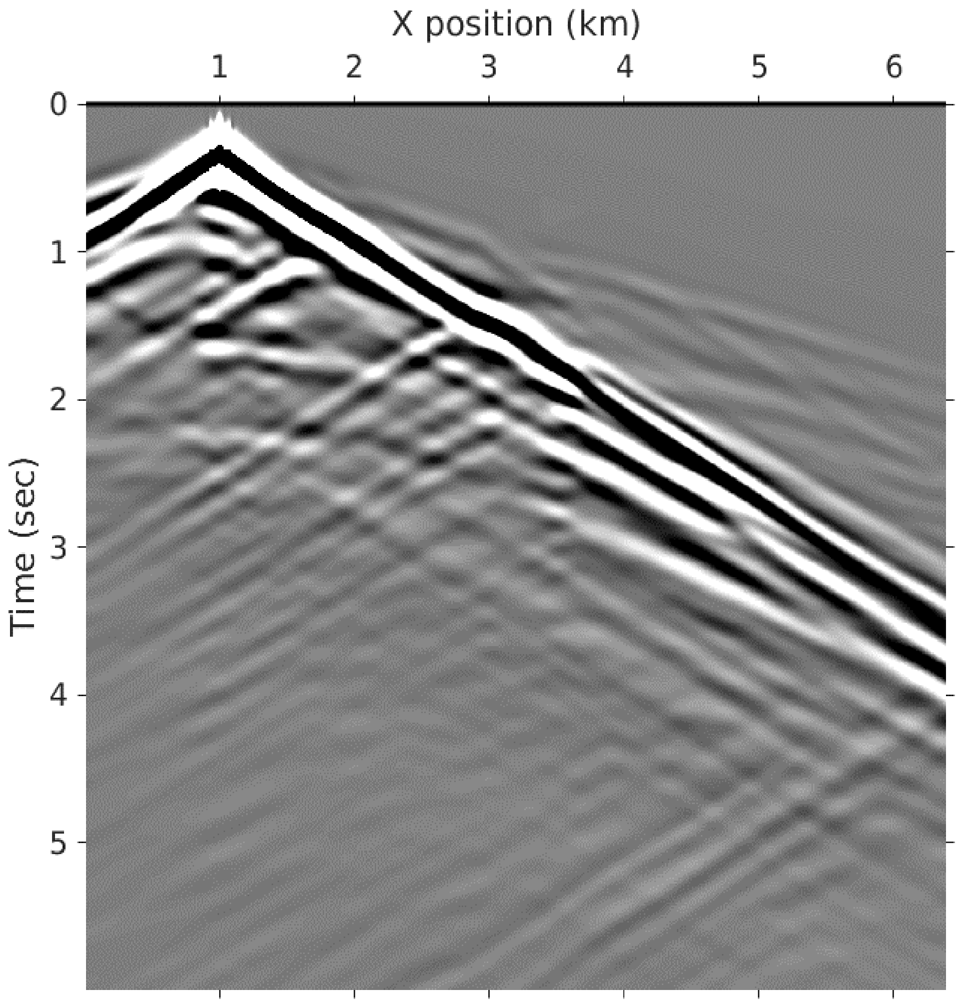
Anisotropic visco-elastic propagation





- Highly dispersive **surface waves**
- Waves **conversion** P-S, body-surface
- **Transmission/Reflection** regimes
- **Back-scattering** due to steep slopes at the free surface

High-resolution seismic imaging

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➢ Macro-scale imaging: FWI provides high-resolution capacity

- Vertical components or 4C data
- Body waves versus surface waves
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➢ Which physics to consider at this scale?

- Visco-elastic anisotropic propagation
- Related model parameters …

➢ Medium interpretation: which physics to consider?

- Downscaling using biphasic model (Gassmann relation)
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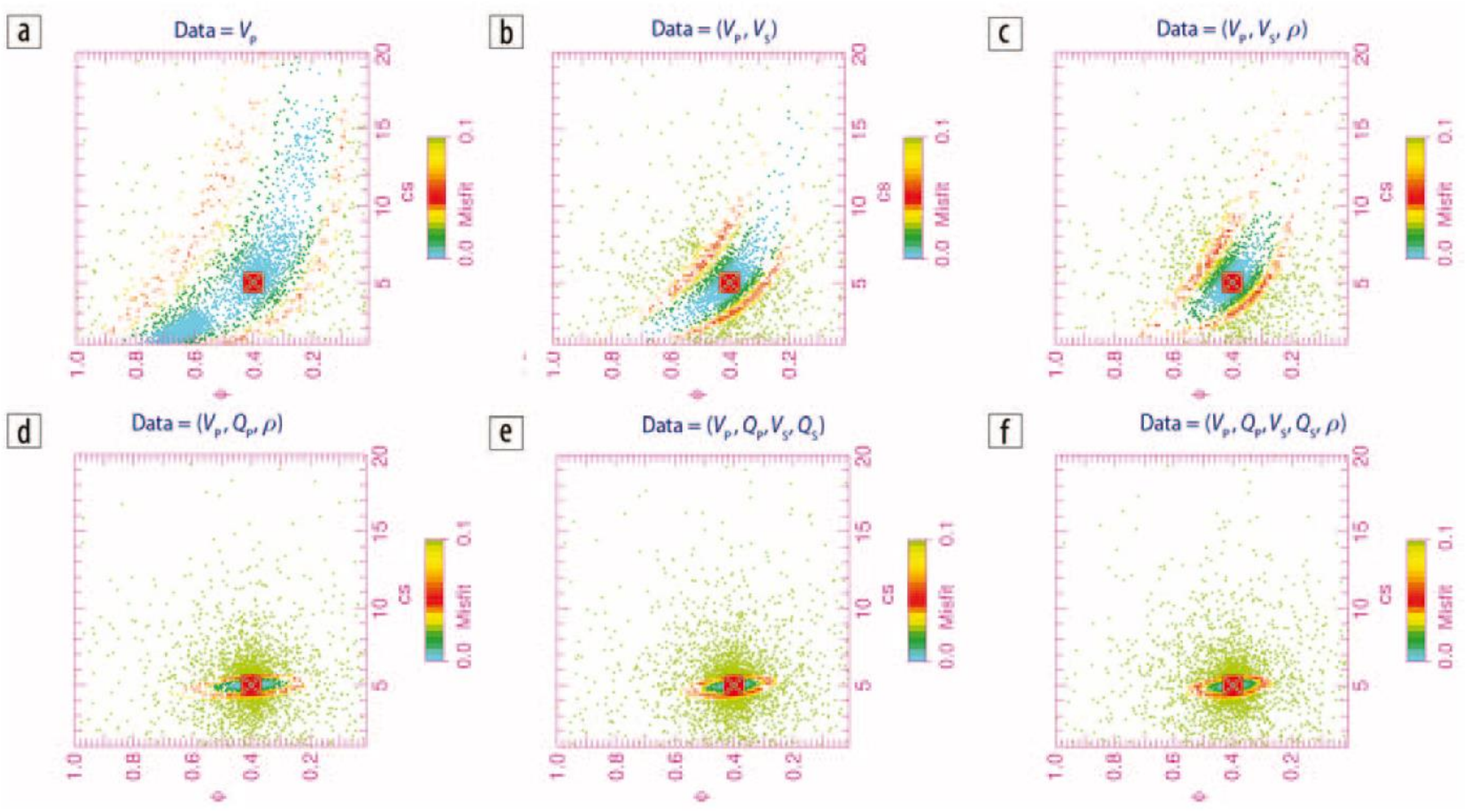
$\Longrightarrow$ Towards reservoir interpretation and monitoring

Which physics to consider?

Physical interpretation = Many model parameters?

Model parameters are now the data used for downscaling …



Gassmann's equation: **porosity ϕ** and **consolidation parameter c_s**

Pride (2005);
Chopra & Marfurt (2007);
Mavko et al. (2009);
Dupuy et al. (2016)

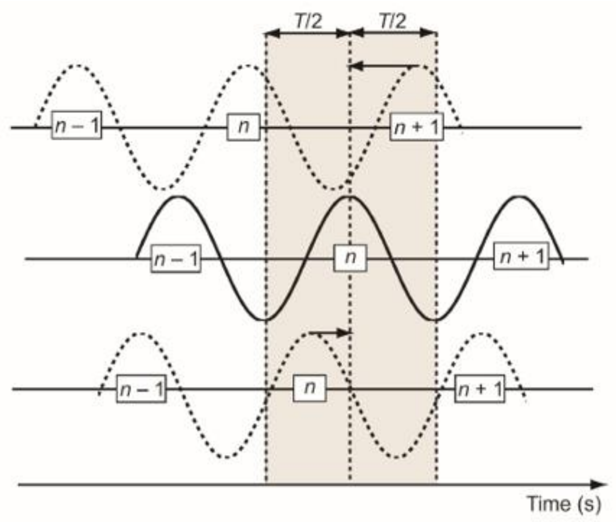
Visco-elastic FWI: challenges

- Model parameters reconstruction
- FWI pros and cons
- *Non-linearity of FWI*

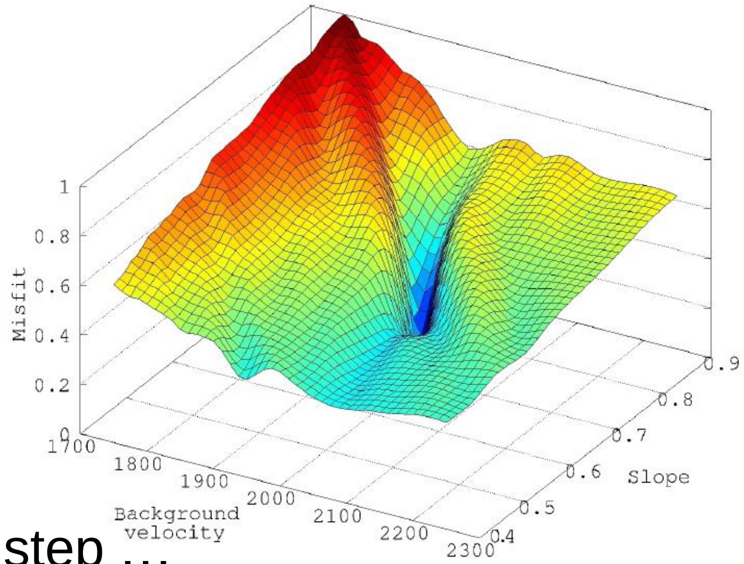
High-resolution seismic imaging

We face different difficulties …

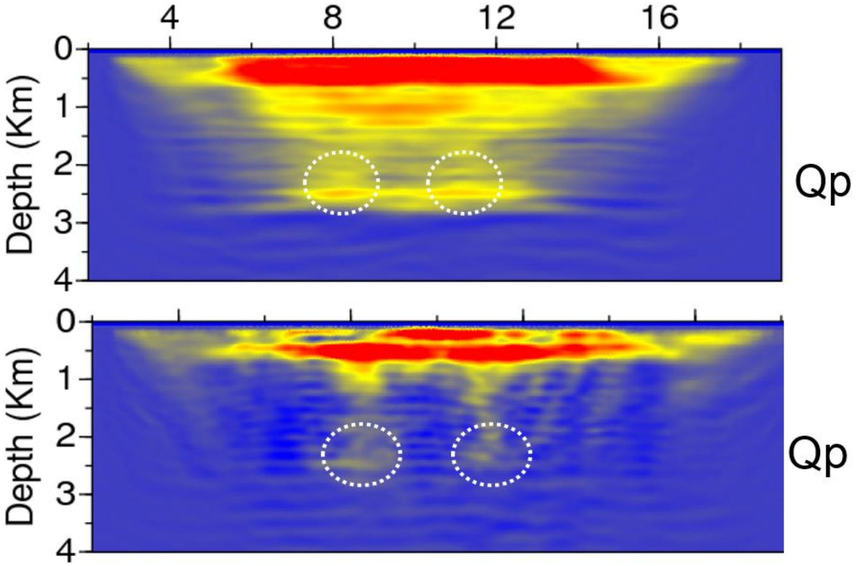
Cycle-skipping issue



Local minimum challenge



Multiple-parameters reconstruction



- Initial model design is a key step …
- Model parameter trade-off …
- Uncertainty quantification …

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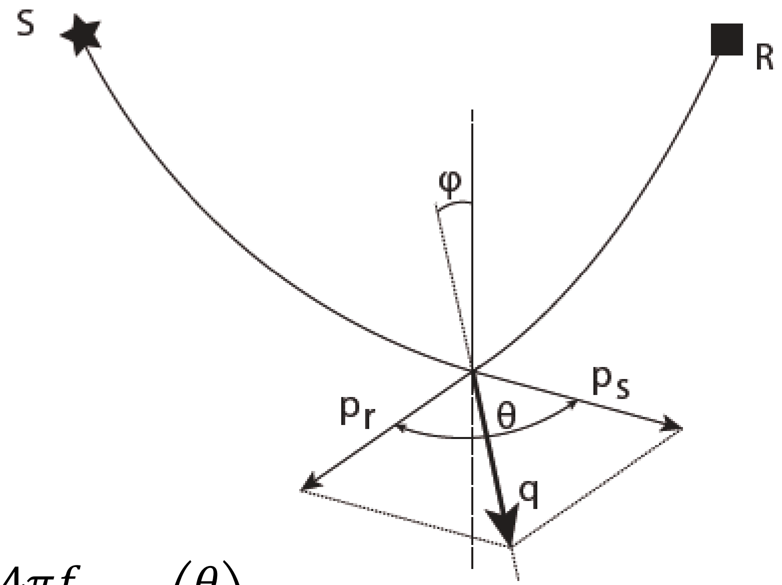
FWI = simple wave-matter interaction

(Devaney, 1982)



$$\boldsymbol{k} = 2\pi f \boldsymbol{q} = \frac{4\pi f}{c} \cos\left(\frac{\theta}{2}\right) \boldsymbol{n}$$

$$\boldsymbol{k} = \frac{4\pi}{\lambda} \cos\left(\frac{\theta}{2}\right) \boldsymbol{n}$$

- FWI is an ill-posed problem based on a single-scattering formulation
- Model is described through a pixel structure (# from a blocky structure)
- The model wavenumber spectrum is probed through this pixel strategy

f – Frequency

θ – Aperture or illumination angle

Controlling parameters of the model velocity spectrum

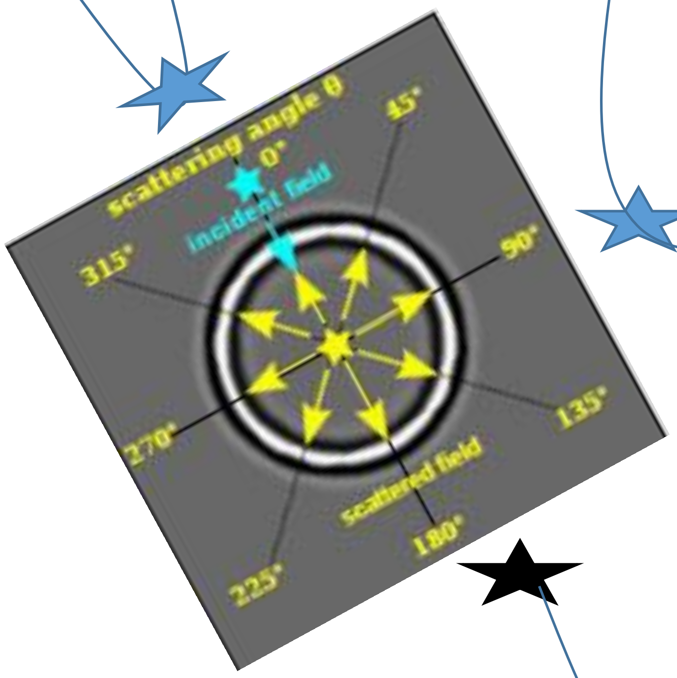
Low $\boldsymbol{k}$ – low frequency f or aperture angle θ around π (weak interaction)

High $\boldsymbol{k}$ – high frequency f or aperture angle θ around 0 (strong interaction)

Scattering diagram

Strong interaction: reflection regime

$\theta \sim 0°$

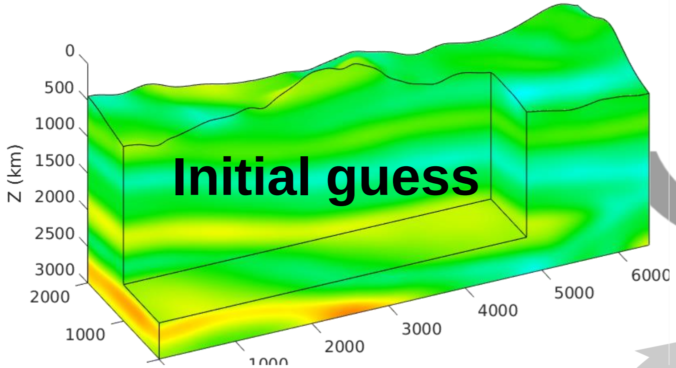


Intermediate interaction $\theta \sim \pi/2$

Weak interaction: transmission regime $\theta \sim \pi$

How waves interact with matter!

FWI strategy



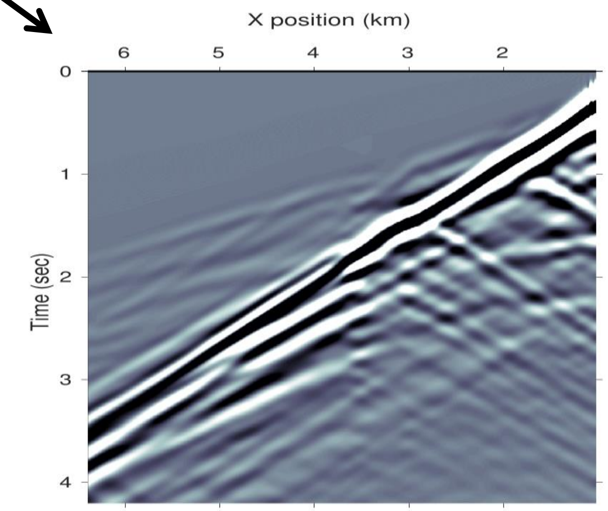
$$\mathbf{d}_{cal} = \mathcal{F}(\mathbf{m})$$

Forward modeling

Data-fitting technique

Data misfit

$$C(\mathbf{m}) = \frac{1}{2} \|\mathbf{d}_{obs} - \mathbf{d}_{cal}\|^2$$



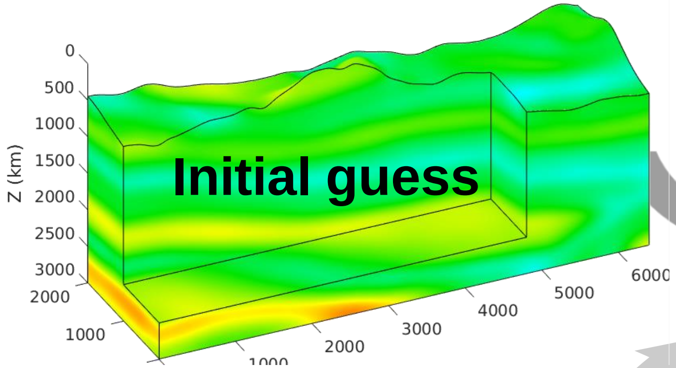
Model estimation

$$\mathbf{m} = \mathbf{m} + \Delta\mathbf{m}$$

Inverse problem

- Gradient estimation $\mathbf{g}(\mathbf{x}) = \partial C(\mathbf{m})/\partial \mathbf{m}$
- Gradient smoothing $\mathbf{s}(\mathbf{x}) = \mathbf{B}(\mathbf{x}) * \mathbf{g}(\mathbf{x})$
- Model update $\Delta\mathbf{m} = \alpha \times \mathbf{s}(\mathbf{x})$

FWI strategy



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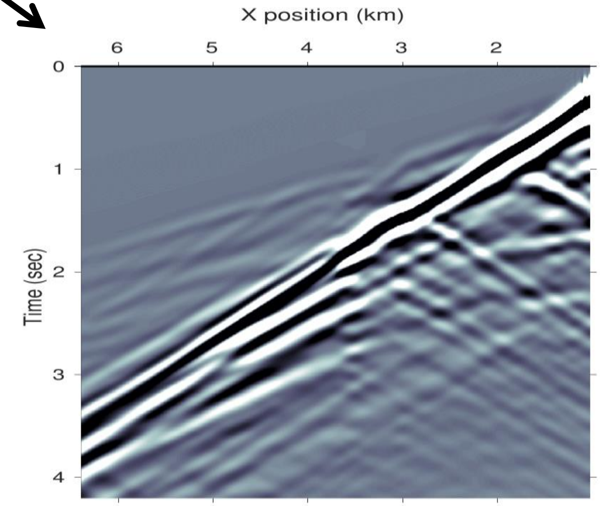

Model estimation

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Inverse problem

1. **SEM-based modeling & inversion kernels**

- Gradient estimation $\mathbf{g}(\mathbf{x}) = \partial C(\mathbf{m})/\partial \mathbf{m}$
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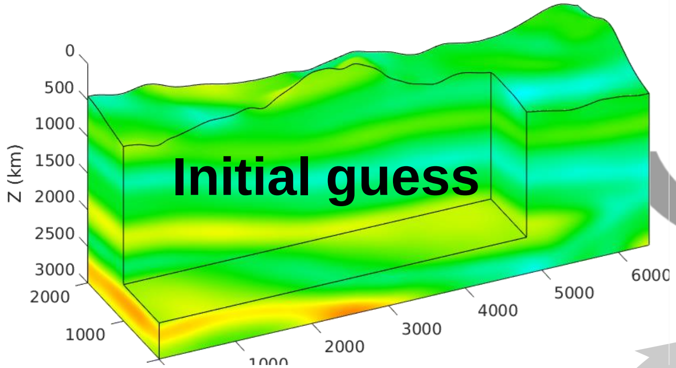
FWI strategy



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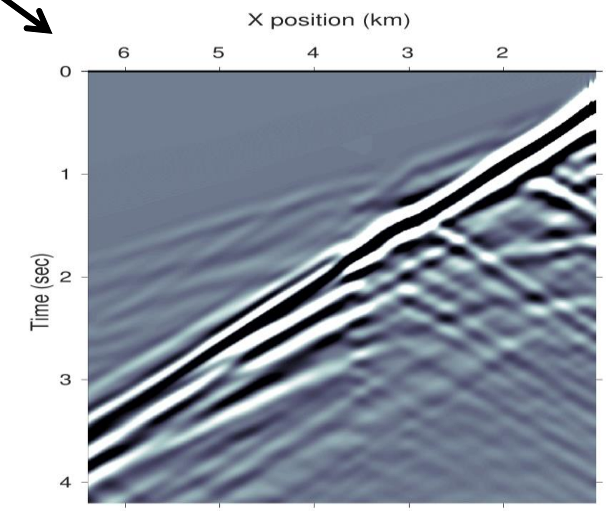
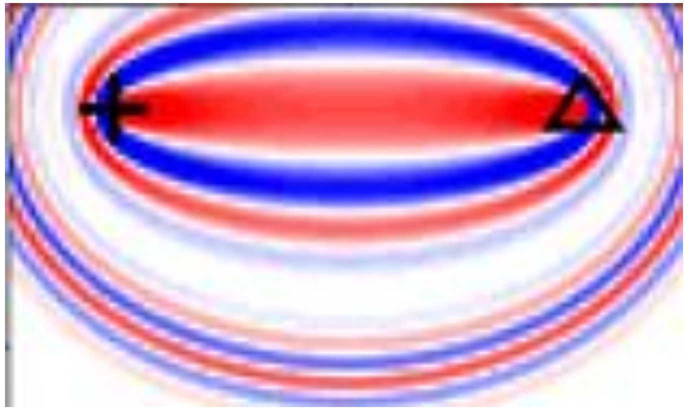


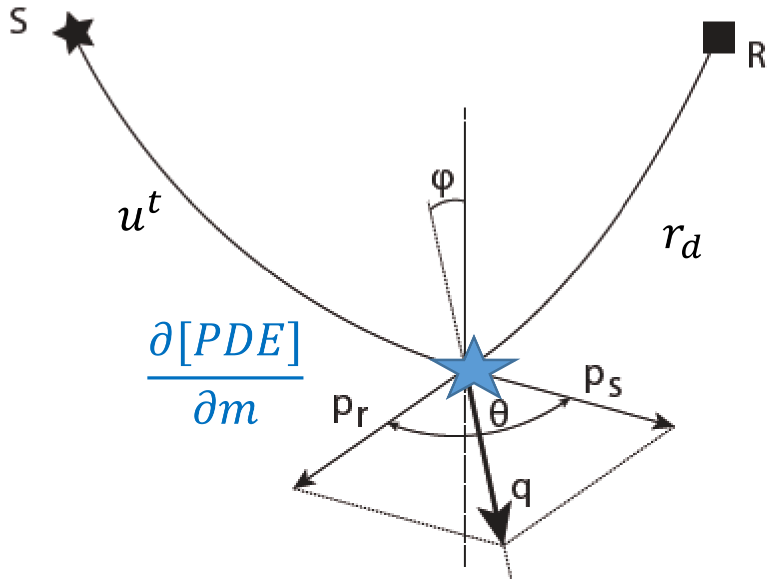
1. ***SEM-based modeling & inversion kernels***
2. **Bessel FWI gradient smoothing for SEM mesh**

Model preconditioning

- Gradient estimation $\mathbf{g}(\mathbf{x}) = \partial C(\mathbf{m})/\partial \mathbf{m}$
- Gradient smoothing $\mathbf{s}(\mathbf{x}) = \mathbf{B}(\mathbf{x}) * \mathbf{g}(\mathbf{x})$
- Model update $\Delta\mathbf{m} = \alpha \times \mathbf{s}(\mathbf{x})$

FWI gradient: often all you need





S.K. $$u^t \frac{\partial[PDE]}{\partial m} r_d$$

Sensitivity kernel

Zero-lag cross-correlation *of incident u^t and adjoint r_d fields through interlaced backward-incident and adjoint integration*

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Designing PDE solver

Integrated approach: FWI design should not be reduced to wave propagation design

Complex topography

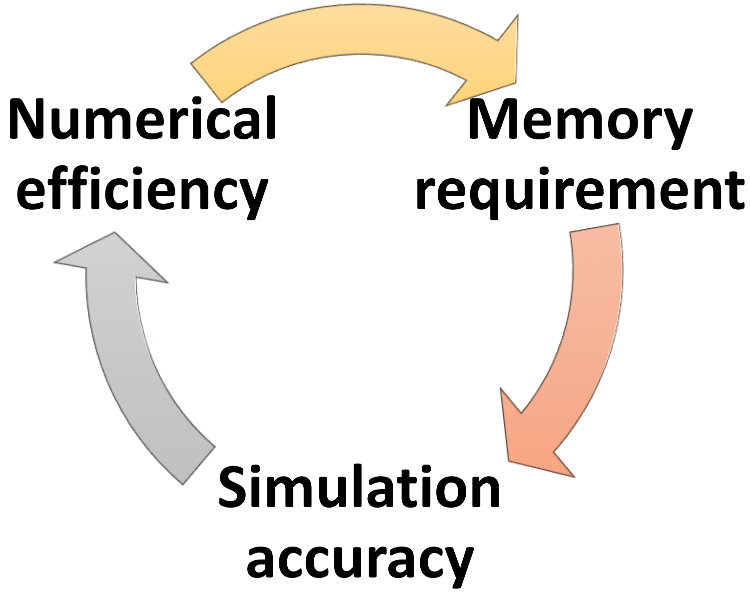
- Simple geometry representation.
- Accurate boundary free-surface conditions.

3D (visco)elastic modeling & FWI

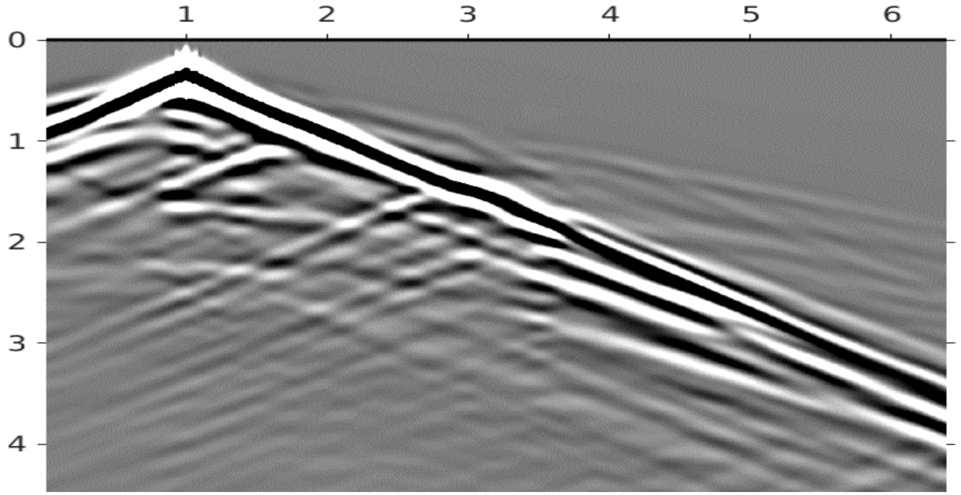
- Complete and accurate physics seen by waves
- Simultaneous design of modeling/adjoint/gradient

Time-domain

- Signal muting and multi-frequencies processing
- Data-component hierarchy FWI, thanks to the causality



Attenuation: Efficient implementation



Complex seismic data (i.e. land data):

- Acoustic might not be enough!
- Elastic neither: Attenuation is required when fitting phase & amplitude!

Visco-elastic 3D aniso-elastic reconstruction

- ✓ Tarantola (1988): **Convolutional rheology** with application by Charara et al. (2000)
  $\Longrightarrow$ **Computationally intensive.**
- ✓ Tromp (2005) & Liu and Tromp (2006): General **multiparameter workflow with adjoint methods**.
- ✓ Fichtner & van Driel (2014): Clarification of the **Q parameter imaging** of Tromp (2005)
  $\Longrightarrow$ **Lowering the computational needs**.
- ✓ Yang et al (2016): **Explicit formulations** for FWI gradients using visco-anisotropic elastic wave propagation based on standard linear solid (SLS) mechanisms
  $\Longrightarrow$ **Straightforward numerical implementation**.

Wave propagation: lossy medium

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Time domain

$$\begin{cases} \rho \partial_{tt} \mathbf{u} = D \boldsymbol{\sigma} + \mathbf{f} \\ \boldsymbol{\varepsilon} = D^t \mathbf{u} \\ \boldsymbol{\sigma} = C \boldsymbol{\varepsilon} - C^R \sum_{l=1}^{L} \boldsymbol{\psi}_l + \boldsymbol{\mathcal{T}} \\ \partial_t \boldsymbol{\psi}_l + \omega_l \boldsymbol{\psi}_l = \omega_l y_l \boldsymbol{\varepsilon}, \quad l = 1, \dots, L \end{cases}$$

Wavefield conditions

- Medium at rest at initial time (zero initial conditions)
- Unbounded domain (free surface condition -zero stress- and absorbing boundary conditions)

Standard Linear Solid: Generalized Maxwell model or Generalized Zener model

- Attenuation is carried by L sets of **memory variables** $\boldsymbol{\psi}_l$ = non-physical parameters.

  Quantities ω_l and y_l **are uniform inside the medium** (resonance frequencies and relative weights)
- **Attenuation** = $SLS -$ $\boldsymbol{Q}$**-constant approx. over frequencies.**
- Memory variables obey a **1st order** equation.

Additional needs: storing decimated boundaries (inside nearby PML)

and few snapshots for backpropagation

(Yang at al, 2016a,2016b)

Wave propagation: FWD modeling OK

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Time domain

$$\begin{cases} \rho\partial_{tt}\mathbf{u} = D\boldsymbol{\sigma} + \mathbf{f} \\ \boldsymbol{\varepsilon} = D^t\mathbf{u} \\ \boldsymbol{\sigma} = C\boldsymbol{\varepsilon} - C^R\sum_{l=1}^{L}\boldsymbol{\psi}_l + \boldsymbol{\mathcal{T}} \\ \partial_t\boldsymbol{\psi}_l + \omega_l\boldsymbol{\psi}_l = \omega_l y_l\boldsymbol{\varepsilon}, \quad l = 1, \ldots, L \end{cases}$$

Heterogeneities inside the medium described by

C – Unrelaxed (elastic) stiffness tensor (anisotropic);

C^R – Relaxed stiffness tensor (isotropic);

Relaxed « Lamé » coefficients:

$$\lambda^R + 2\mu^R = \frac{1}{3}Q_p^{-1}\sum_{i=1}^{3}C_{ii}\,; \qquad \mu^R = \frac{1}{3}Q_s^{-1}\sum_{j=4}^{6}C_{jj}$$

- **Elastic system** is conservative: **self-adjoint** structure of PDE

$\rho\partial_{tt}\mathbf{u} = DCD^t\mathbf{u} + \mathbf{f}$ $\Longrightarrow$ **Stable backpropagation of the wavefield.**

- **With attenuation**, the system is **no more conservative**!

$\rho\partial_{tt}\mathbf{u} = DCD^t\mathbf{u} - DC^R\sum_{l=1}^{L}\boldsymbol{\psi}_l + \mathbf{f}$ $\Longrightarrow$ **Unstable backpropagation of the wavefield!**

Tracking the total energy for detecting the instability during the backpropagation: if divergence is observed, use stored snapshots to restart the backpropagation from them (assisted checkpointing strategy)

Incident + Adjoint propagation

Incident field

$$\begin{cases} \rho\partial_{tt}\mathbf{u} = DCD^t\mathbf{u} - DC^R\sum_{s=1}^{L}\boldsymbol{\psi}_s + \mathbf{S} \\ \partial_t\boldsymbol{\psi}_s + \omega_s\boldsymbol{\psi}_s = \omega_s y_s D^t\mathbf{u} \end{cases}$$

$\mathbf{u}$ – Displacement; $\boldsymbol{\psi}_s$ – Memory variables;

$\boldsymbol{S}$ – Source term;

Adjoint field

$$\begin{cases} \rho\partial_{tt}\bar{\mathbf{u}} = DCD^t\bar{\mathbf{u}} - DC^R\sum_{s=1}^{L}\overline{\boldsymbol{\psi}_s} - R^{\dagger}\Delta d_{\mathbf{u}} \\ \partial_t\overline{\boldsymbol{\psi}_s} - \omega_s\overline{\boldsymbol{\psi}_s} = -\omega_s y_s D^t\bar{\mathbf{u}} \end{cases}$$

$\bar{\mathbf{u}}$ – Displacement; $\overline{\boldsymbol{\psi}_s}$ – Memory variables;

$\Delta d_{\mathbf{u}}$– Data residual;

using Lagrange formulation (final and boundary conditions!)

- **Similar but not identical structure and equations** for incident and adjoint fields
- Computing incident field from initial time with zero initial conditions ☺
- Computing adjoint field from final time with zero final conditions ☺

+ recomputing incident field backward ☹ but ☺

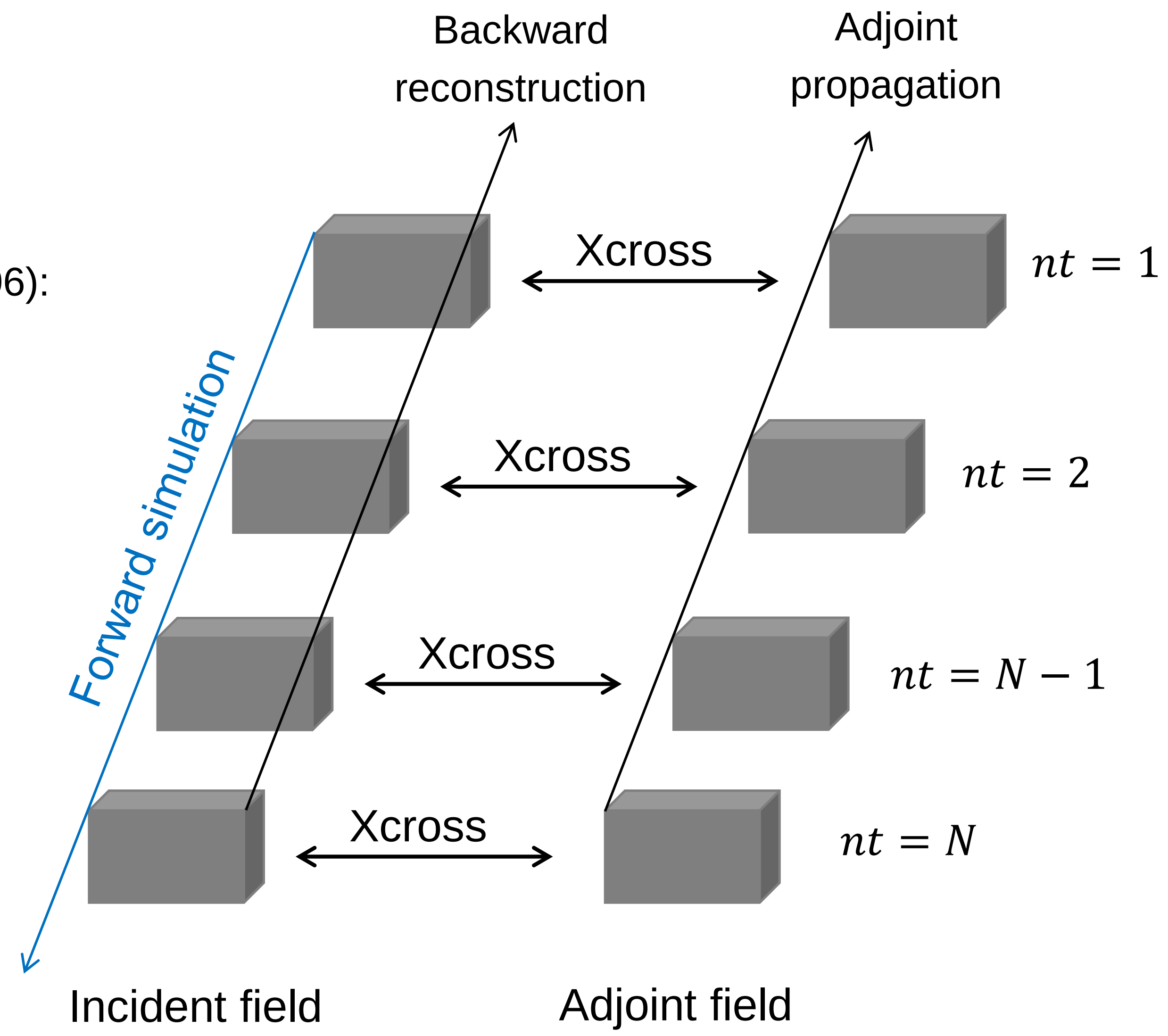
Inversion workflow

- Least-squares norm: $\frac{1}{2}\|\mathbf{d}_{obs} - \mathbf{d}_{cal}(\mathbf{m})\|^2$
- All gradients = **Adjoint-state approach** (Plessix, 2006):

Directly accumulated during the **backpropagation** of the incident field while computing adjoint fields.

$\Longrightarrow$ **No I/O**

Affordable numerical cost



Acoustic case (Yang et al., 2016c)

FWI gradients

$\Longrightarrow$ **Attenuation affects the velocity estimation**

- **L_2 FWI gradient:**

$$\frac{\partial(\text{Data misfit})}{\partial C_{ij}} = \underbrace{\left(\bar{\boldsymbol{\varepsilon}}, \frac{\partial C}{\partial C_{ij}} \boldsymbol{\varepsilon}\right)_{\Omega,t}}_{\text{Elastic rheology}} - \underbrace{\left(\bar{\boldsymbol{\varepsilon}}, \sum_{l=1}^{L} \frac{\partial C^R}{\partial C_{ij}} \boldsymbol{\psi}_l\right)_{\Omega,t}}_{\text{Attenuation mechanism}}$$

$$\frac{\partial(\text{Data misfit})}{\partial Q_{p,s}^{-1}} = -\left(\bar{\boldsymbol{\varepsilon}}, \sum_{l=1}^{L} \frac{\partial C^R}{\partial Q_{p,s}^{-1}} \boldsymbol{\psi}_l\right)_{\Omega,t} \; ; \qquad \frac{\partial(\text{Data misfit})}{\partial \rho} = (\bar{\boldsymbol{u}}, \partial_{tt} \boldsymbol{u})_{\Omega,t}$$

- Separate the **elastic rheology** (C) and the **attenuation mechanism** $\left(C^R \rightarrow \overbrace{\boldsymbol{Q_p}, \boldsymbol{Q_s}}^{\text{Isotropic attenuation}}\right)$.

Anisotropic attenuation: VSP data?

SEM46 for modeling and inversion

Time-domain Spectral Element Method

SEM-based implementation

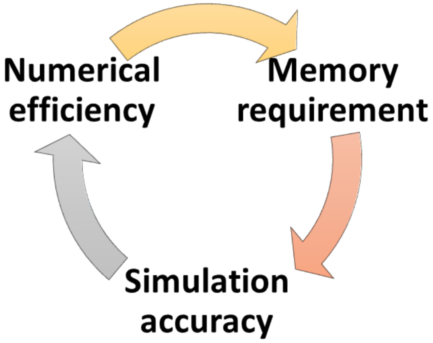
- Topography & simple geometry representation.
- Accurate boundary free-surface conditions.

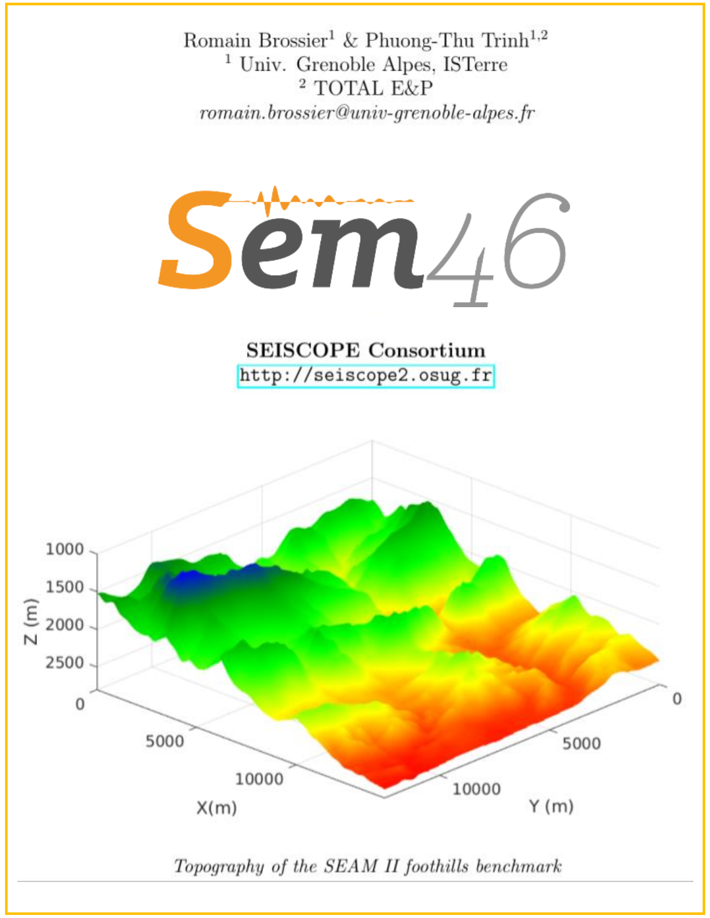
3D (visco)elastic modeling & FWI

- Complete and accurate physics seen by waves.
- Simultaneous design of modeling/adjoint/gradient.

Time-domain

- Signal muting and multi-frequencies processing.
- Data-component hierarchy FWI (causality).

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Sem46

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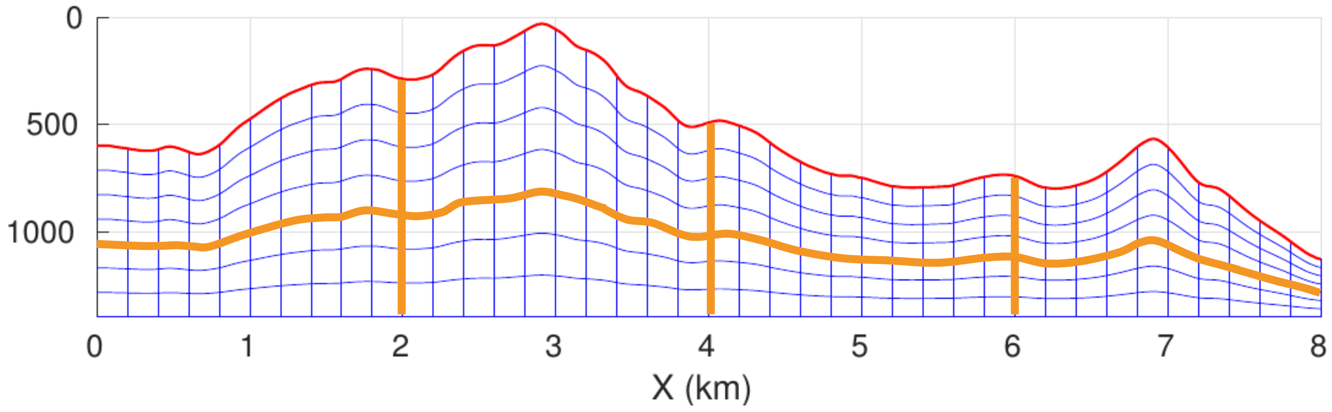
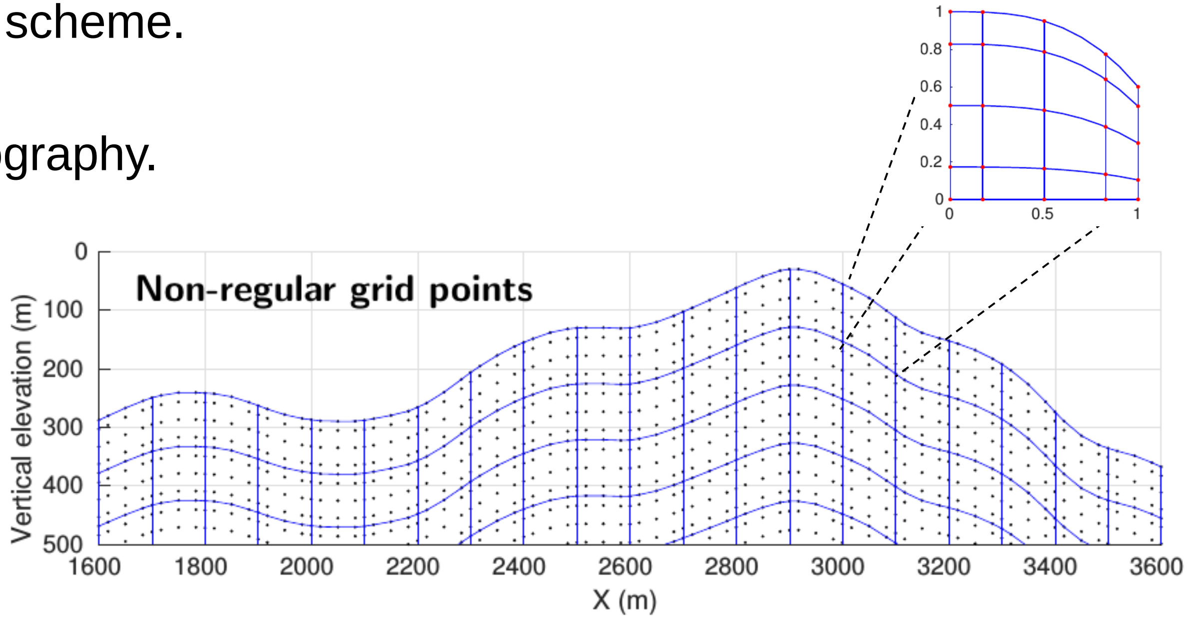
Topography of the SEAM II foothills benchmark

Cartesian-based deformed mesh



- Combine the accuracy of FE mesh with the easiness of implementation of FD grid.
- **Avoid** the heavy **searching operator** over the global mesh.
- **Efficient domain-decomposition** in a parallel scheme.

- **Vertical deformed elements** to follow the topography.
- High-order presentation of the topography

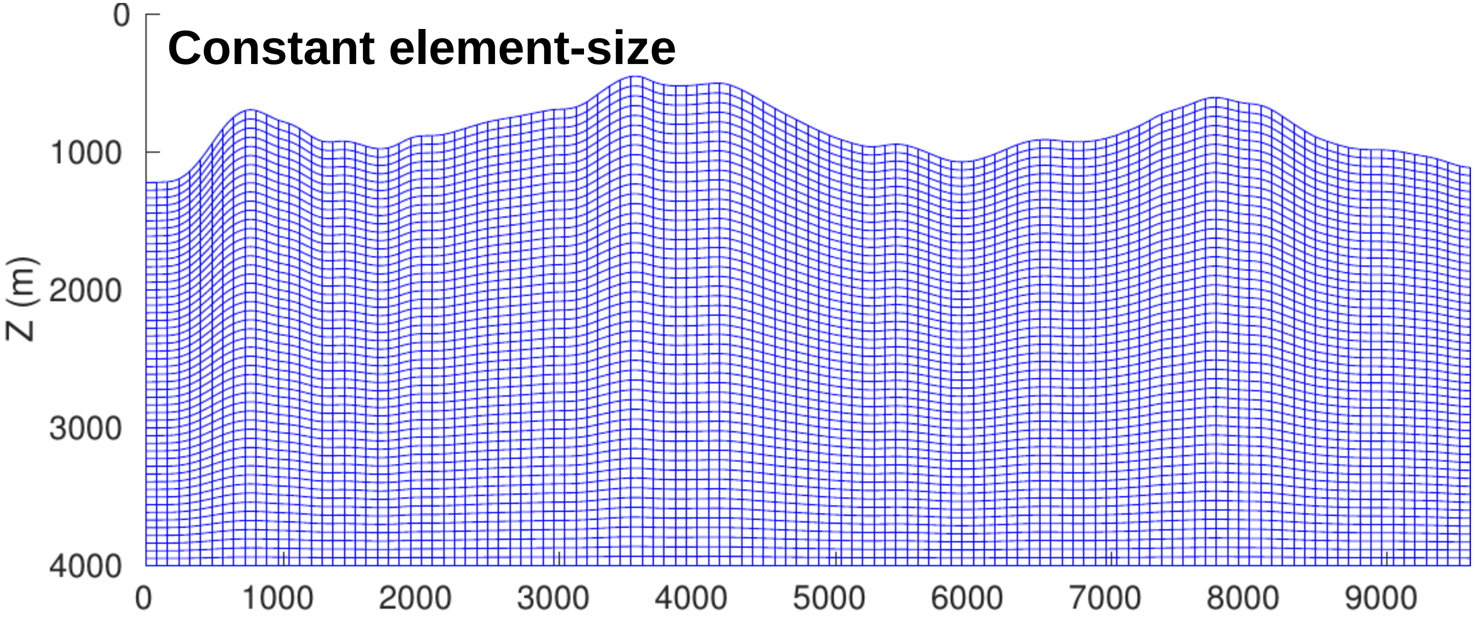


Numerical cost vs. simulation accuracy

Variable element-size for modeling

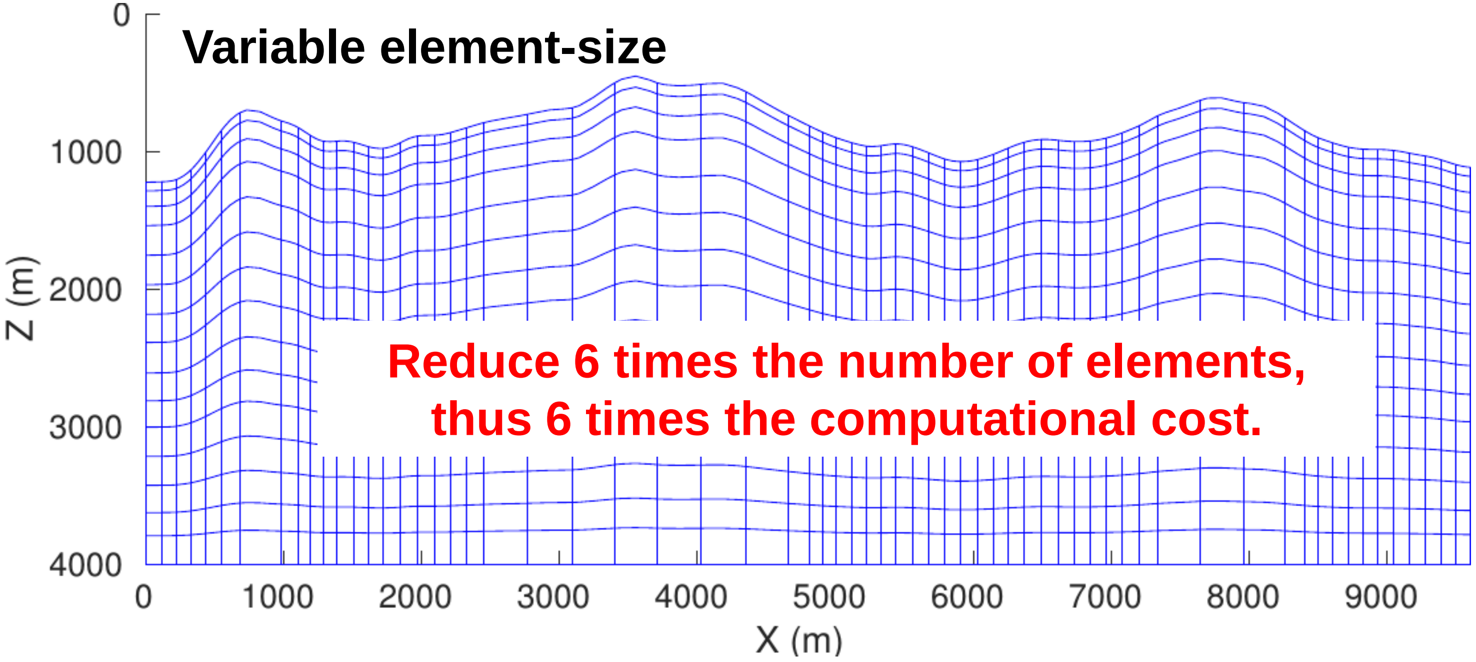
Mesh design is constrained by
$\geq$ 5 GLL points /min (wavelength)

- Same element-size everywhere.



- Respect the **theoretical resolution of FWI** $(0.5\lambda_s)$.

- Follow the **velocity variation**.



Outline

1. Motivation

2. FWI: single scattering

3. PDE visco-elastic wave propagation

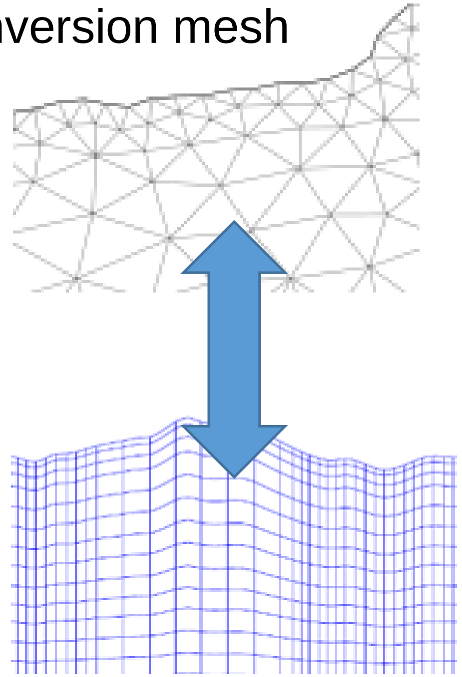
4. Model discretization & preconditioning

5. 3D elastic SEAM II Foothills application

Model discretization

Pixel-oriented FWI: which sampling strategy for this ill-posed problem ?

Inversion mesh



Model meshing adapted to the expected FWI resolution (few λs).

Expensive back and forth projections, especially in 3D

An alternatrive could be the ROM strategy

Modeling meshing adapted to the required local sampling of wavelengths for wave propagation (fractions of λ)

- **Same mesh** for forward/inverse problems $\Longrightarrow$ Efficient computation.
- Mathematically **ill-posed** features of FWI: expected low-wavenumber content.
- **Preconditioning** and/or regularization is mandatory in FWI.

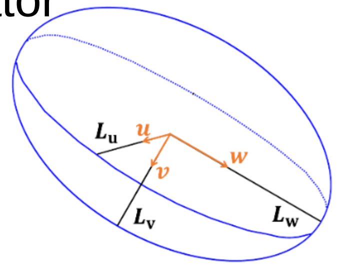
Smoothing the FWI gradient!

Why?

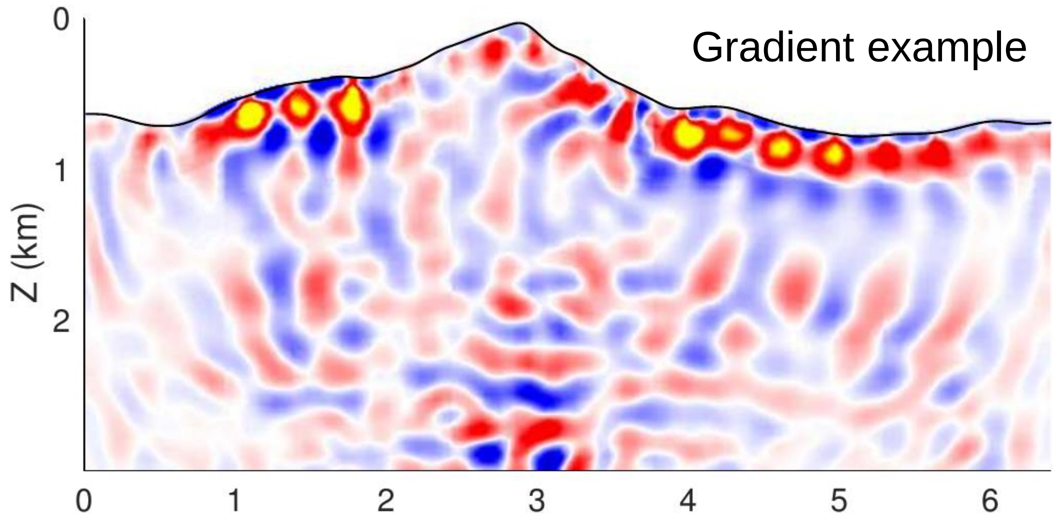
- **Suppress high-wavenumber artifacts**
  - Acquisition footprints
  - Poor **illumination**
- **Guide the inversion** towards a desired solution

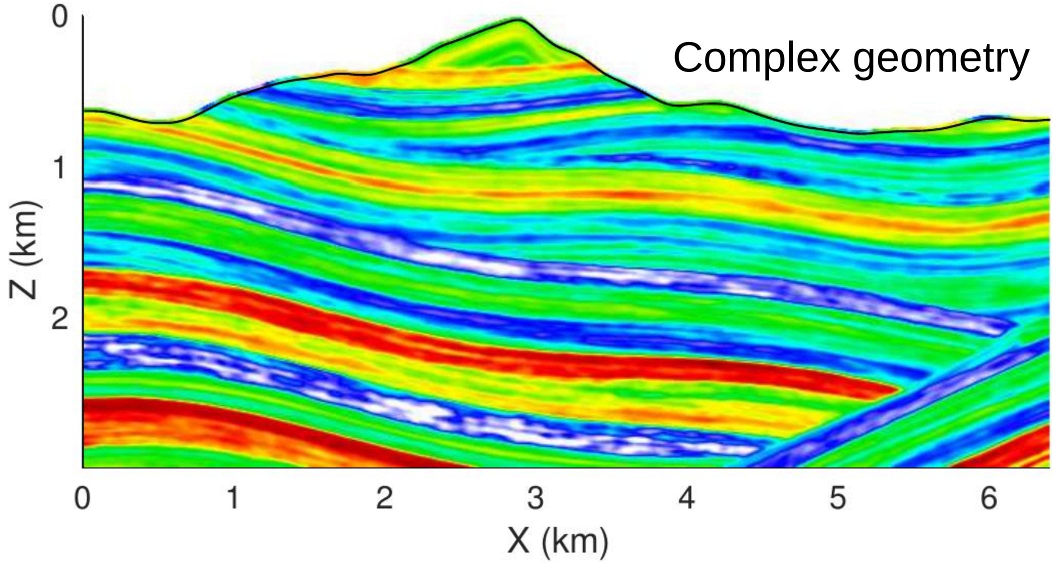
Need?

- **Nonstationary & anisotropic** operator
  - Anisotropic coherent lengths
  - Local 3D rotation



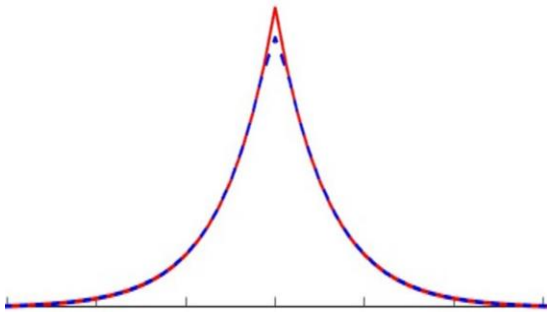
- **Numerical efficiency**
- **SEM mesh compatible:** Non-regular grid points





Bessel smoothing for SEM mesh

- Considering the sparse **inverse operator**: $B_{3D}^{-1}(\mathbf{x}) * \overbrace{\mathbf{s}(\mathbf{x})}^{\text{Smoothed gradient}} = \overbrace{\mathbf{g}(\mathbf{x})}^{\text{Raw gradient}}$



- **0° rotation**, **homogeneous** coherent lengths:

$$\left[1 - \left(L_z^2 \frac{\partial^2}{\partial z^2} + L_x^2 \frac{\partial^2}{\partial x^2} + L_y^2 \frac{\partial^2}{\partial y^2}\right)\right] \mathbf{s}(\mathbf{x}) = \mathbf{g}(\mathbf{x})$$

- Fully **anisotropic** & **nonstationary** filter:

$$\left[1 - \nabla_{z,x,y}^t \mathbf{P}(\mathbf{x}) \mathbf{P}^t(\mathbf{x}) \nabla_{z,x,y}\right] \mathbf{s}(\mathbf{x}) = \mathbf{g}(\mathbf{x}) \qquad \nabla_{z,x,y} = \left(\partial_z, \partial_x, \partial_y\right)^t$$

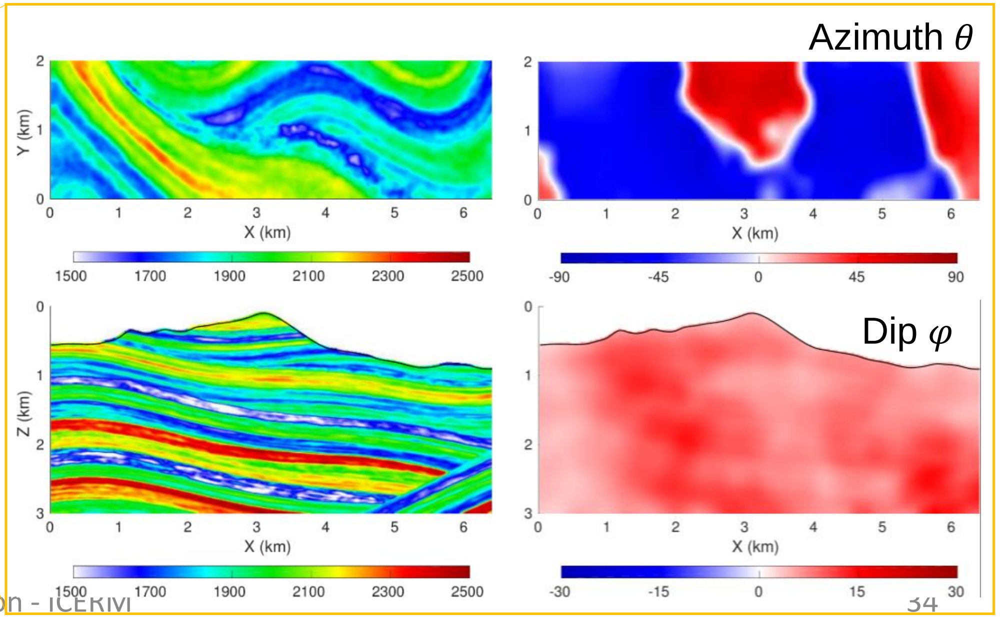
→ **Self-adjoint** PDE

✓ **Variable coherent lengths and angles**

✓ **3D rotation**

$$\mathbf{P}(\mathbf{x}) = \begin{bmatrix} L_v \cos\varphi & L_u \sin\varphi & 0 \\ -L_v \cos\theta \sin\varphi & L_u \cos\theta \cos\varphi & L_w \sin\theta \\ L_v \sin\theta \sin\varphi & -L_u \sin\theta \cos\varphi & L_w \cos\theta \end{bmatrix}$$

Geological prior information



(Trinh et al, 2017b; Wellington et al, 2017)

Parallel implementation

$$\left[1 - \nabla^t_{z,x,y}\mathbf{P}(\mathbf{x})\mathbf{P}^t(\mathbf{x})\nabla_{z,x,y}\right]\mathbf{s}(\mathbf{x}) = \mathbf{g}(\mathbf{x})$$

$$\mathbf{As} = \mathbf{g}$$

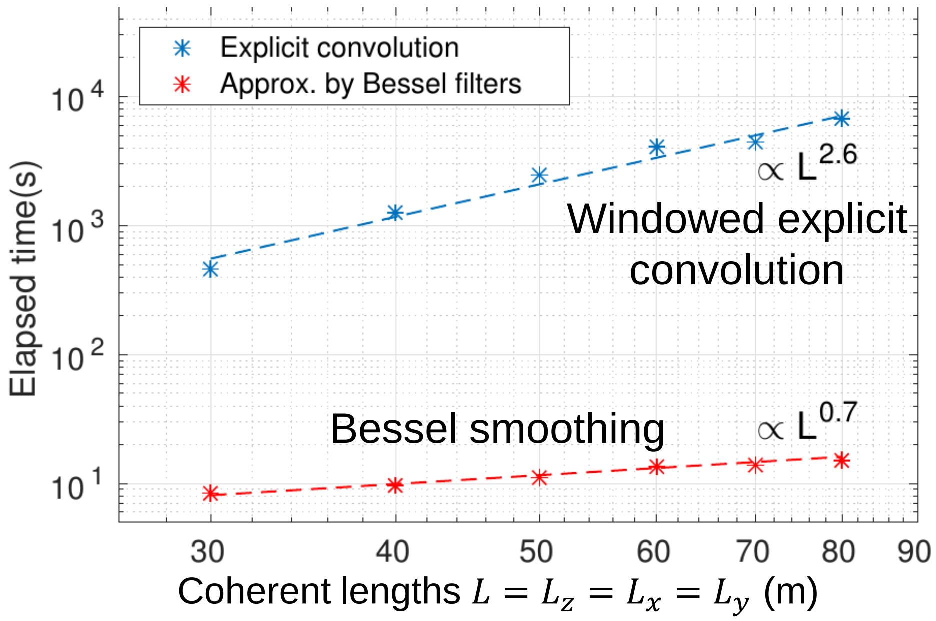
- Self-adjoint PDE = **Symmetric, well-conditioned, positive-definite linear system**

  $\Longrightarrow$ Efficiently solved by a **matrix-free parallel conjugate-gradient**

- **Linear** numerical complexity $\mathcal{O}(\textbf{Coherent length})$

  In **FD** scheme: **as cheap as tensorized Gaussian convolution.**

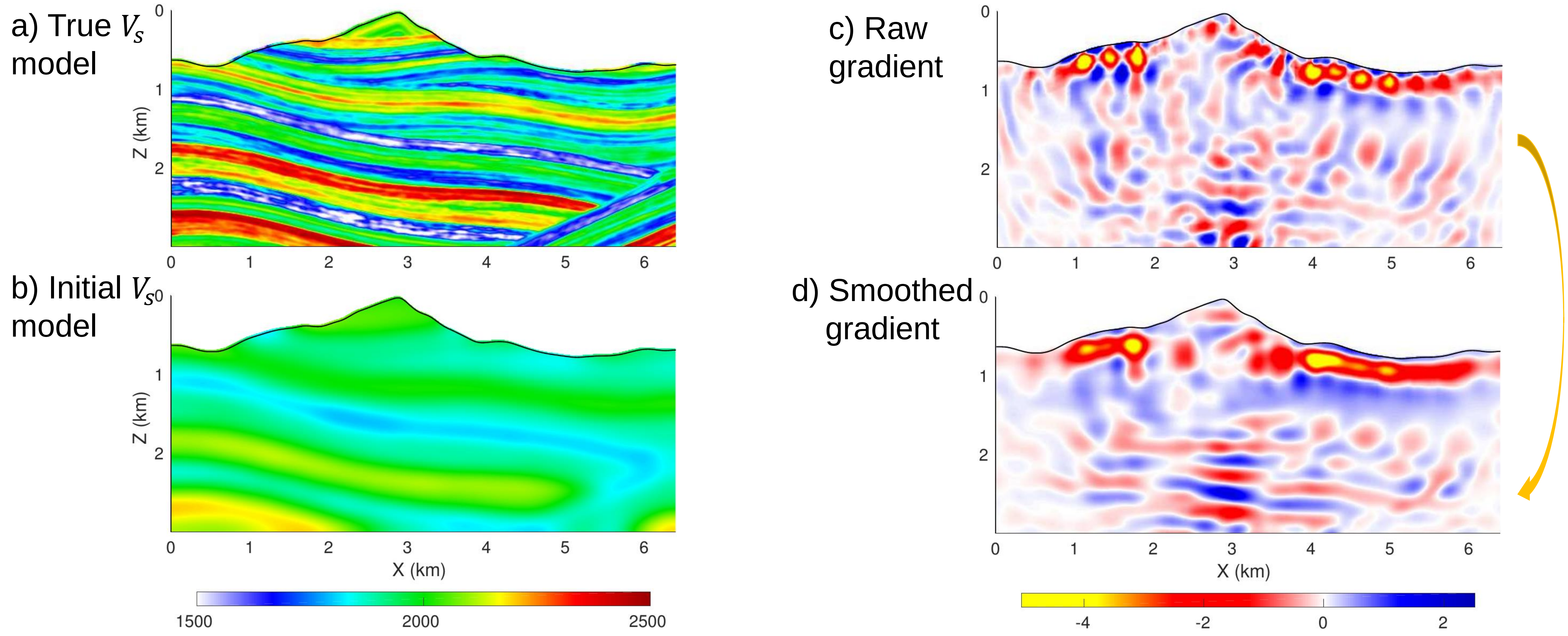
- **Smoothing** $\approx$ **0.4 % cost of 1 iteration**



(Trinh et al, 2017b; Wellington et al, 2017)

Structure-oriented preconditioning

Nonstationary & anisotropic Bessel gradient preconditioning

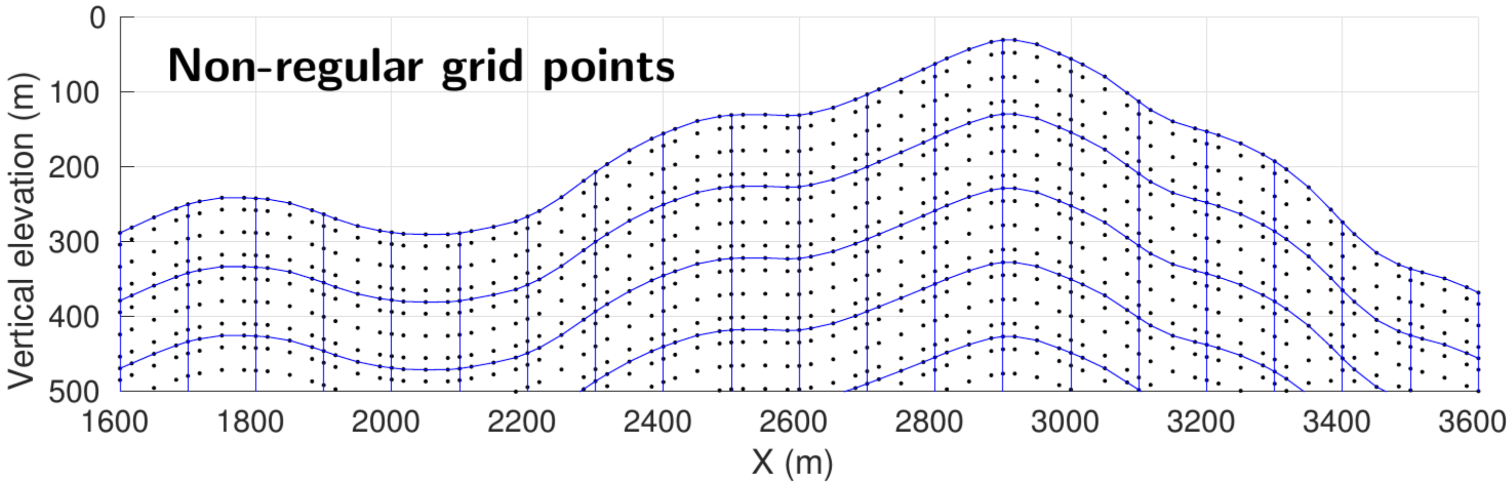


Prior information? $L_w = 25\text{m}$ and $L_u, L_v = 25\text{~}100\text{m}$; Dip & azimuth from true models.

(Trinh et al, 2017d)

Preconditioning for FE mesh

	Accuracy	Efficiency	Nonstationarity
Projection between SEM & Cartesian meshes	?	?	?
Explicit truncated **convolution** $\underbrace{\mathbf{s}(\mathbf{x})}_{\text{Smoothed gradient}} \approx B_{3D}(\mathbf{x}) *_{\Omega_r} \underbrace{\mathbf{g}(\mathbf{x})}_{\text{Raw gradient}}$	✓	?	✓
Bessel smoothing $B_{3D}^{-1}(\mathbf{x}) * \underbrace{\mathbf{s}(\mathbf{x})}_{\text{Smoothed gradient}} = \underbrace{\mathbf{g}(\mathbf{x})}_{\text{Raw gradient}}$	✓	✓	✓



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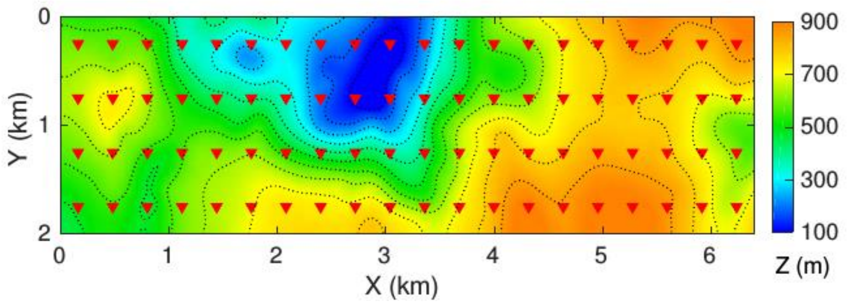
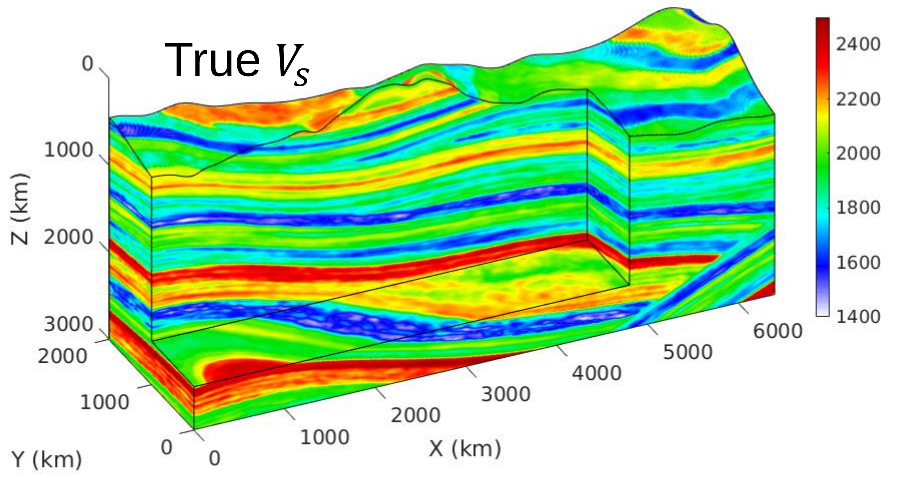
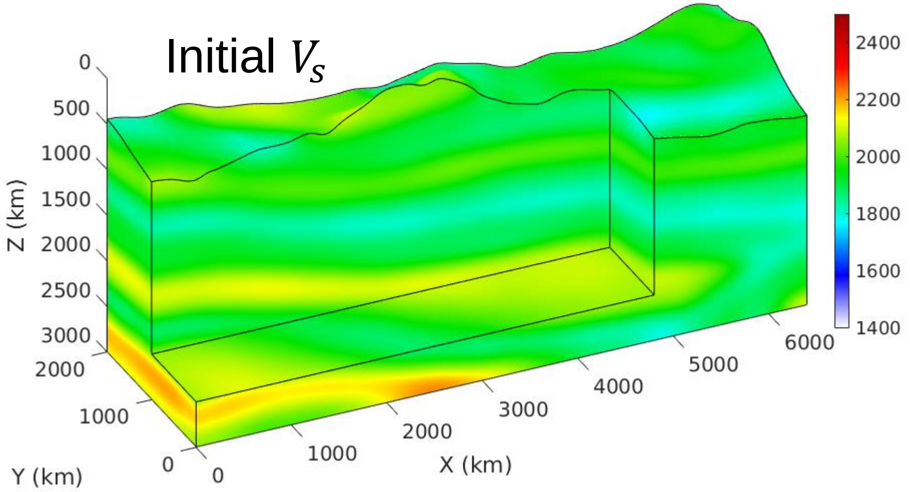
3D elastic example: subset of SEAM II

- Significant topography variation: $\Delta Z \approx 800$ m.
- **3D surface acquisition**:
  - ➢ 4×20 sources
    $\Delta S_x = 320$ m
    $\Delta S_y = 500$ m
  - ➢ 82600 receivers,12.5m, **3C**

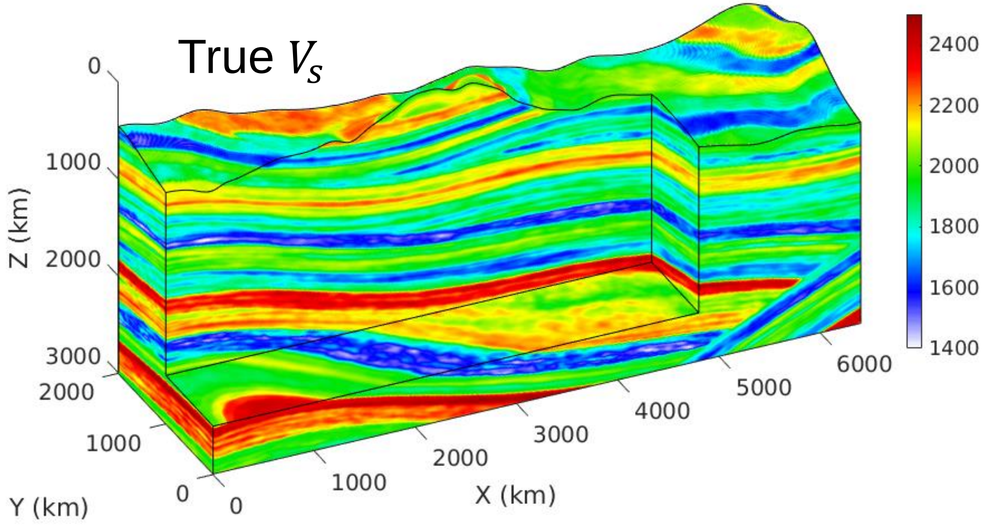


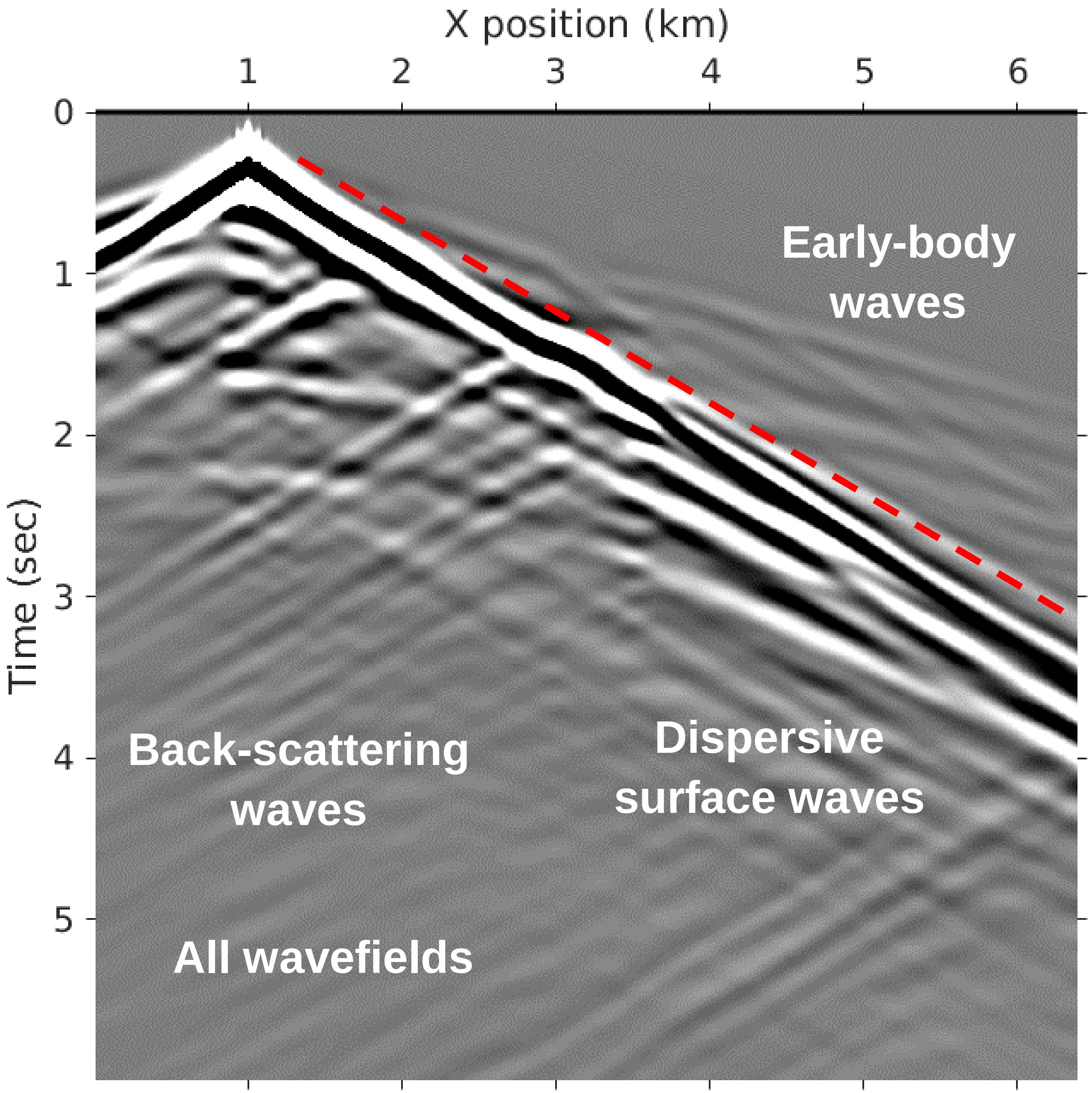


- $S(t) =$ Ricker wavelet centered at 3.5 Hz
- **Meshing**: P4 high-order topography representation.
- Initial models = Smoothed version of true model.
- **Simultaneous** inversion for V_p and V_s
- Smoothed density is kept unchanged.
- 60 FWI iterations using the *l*-BFGS optimization method.



Complex wavefield





- Highly dispersive **surface waves**
- Waves **conversion** P-S, body-surface
- **Back-scattering** due to steep-slope at the surface.

Simple FWI data-driven strategy

SEISCOPE

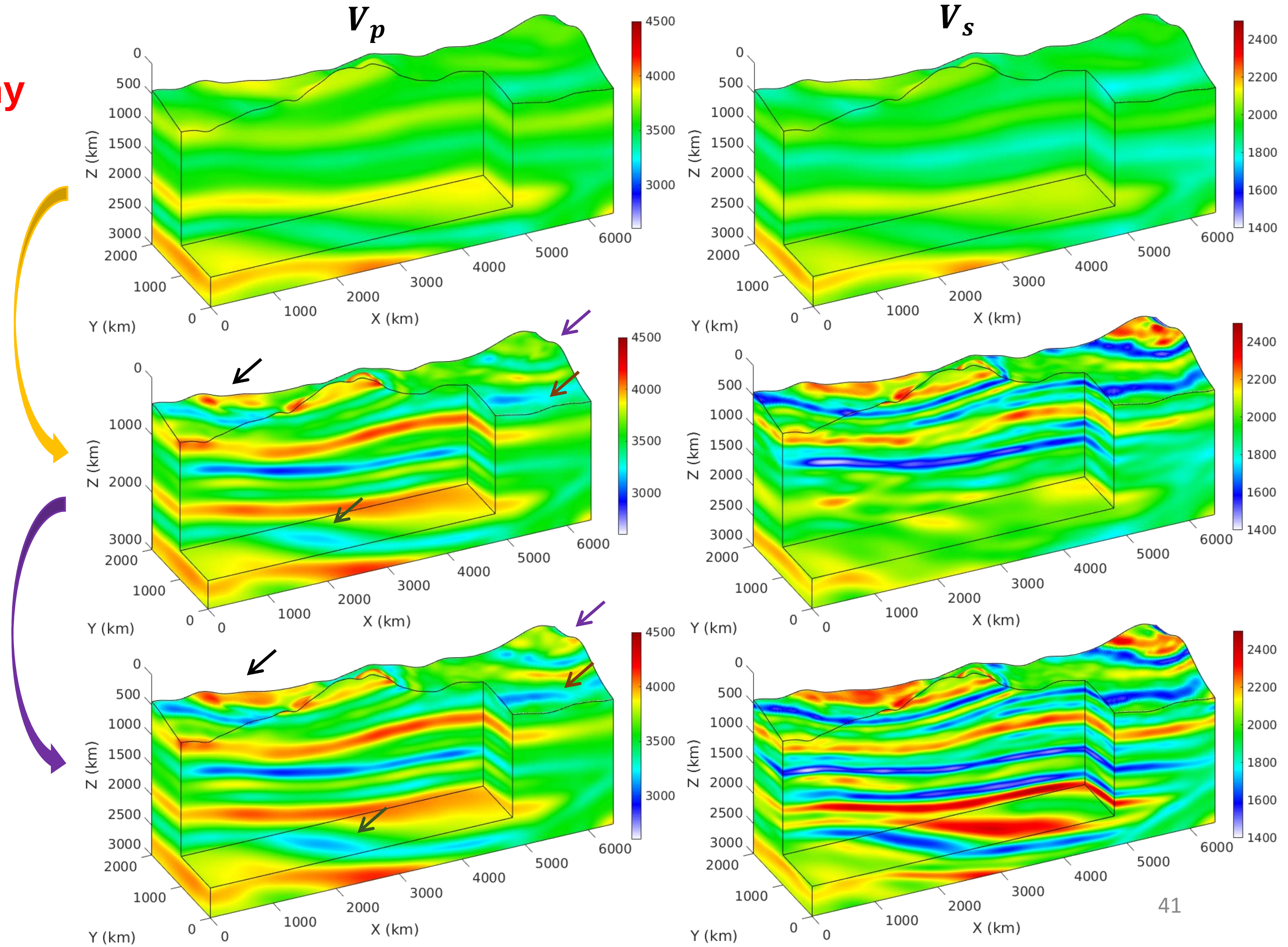
Two-steps data-component hierarchy

Use **early-body waves** (arriving before the surface waves)

$\Longrightarrow$ Main features resolved

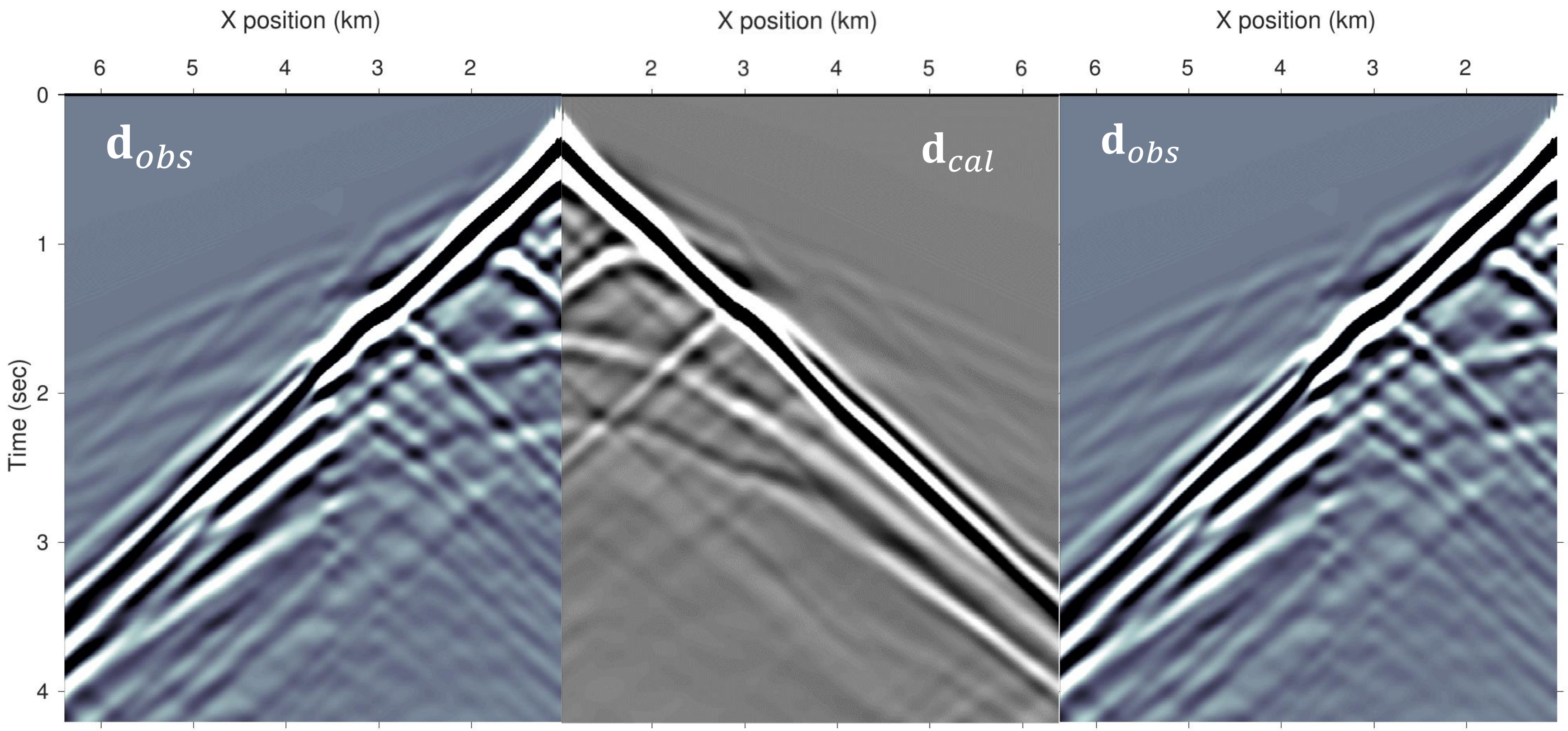
Use **all wavefields** (surface + body waves + back-scattering)

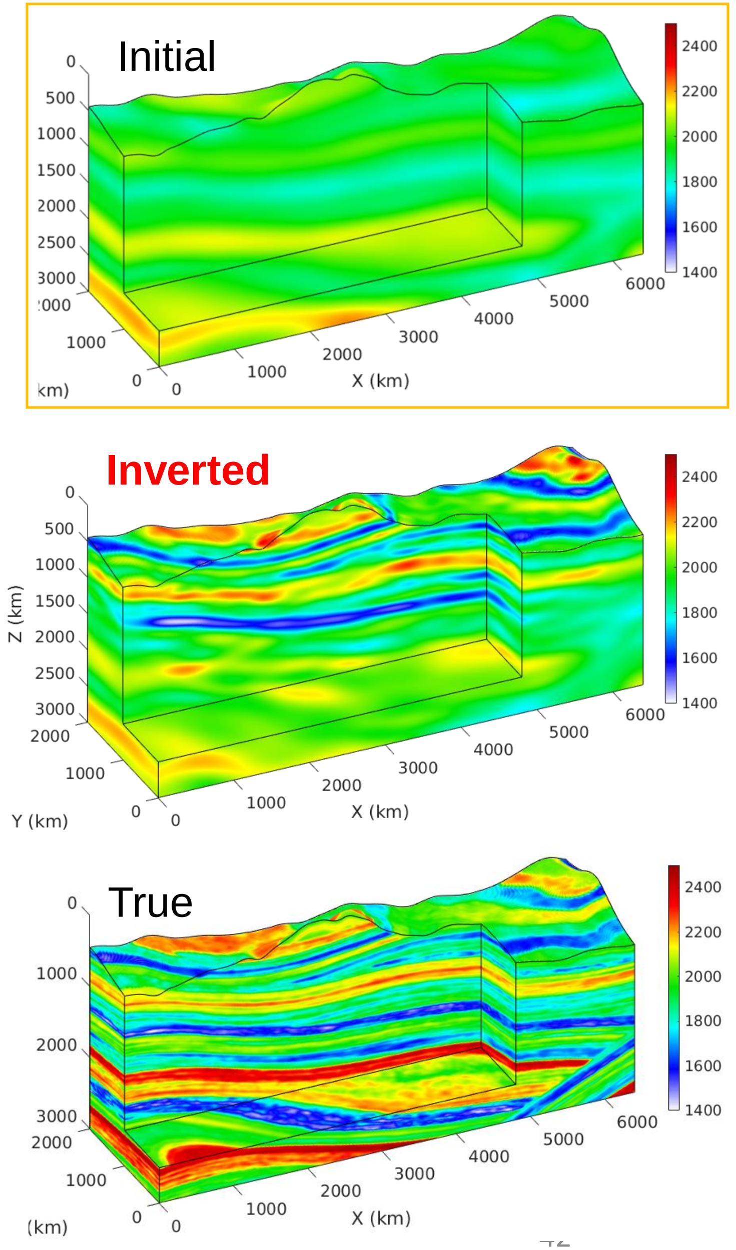
$\Longrightarrow$ Refine near-surface & Enhance deep structures



Data comparison

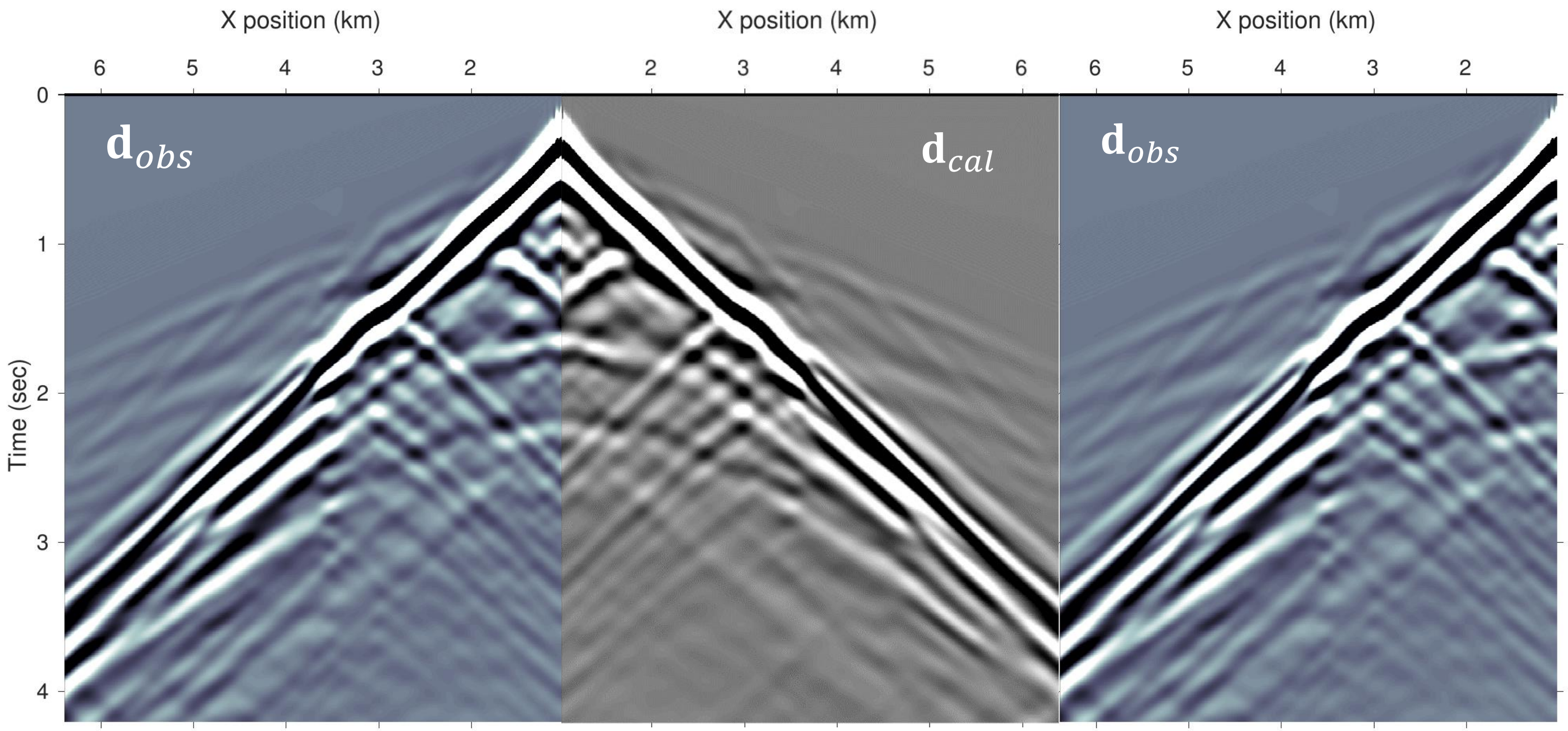
0. Initial models

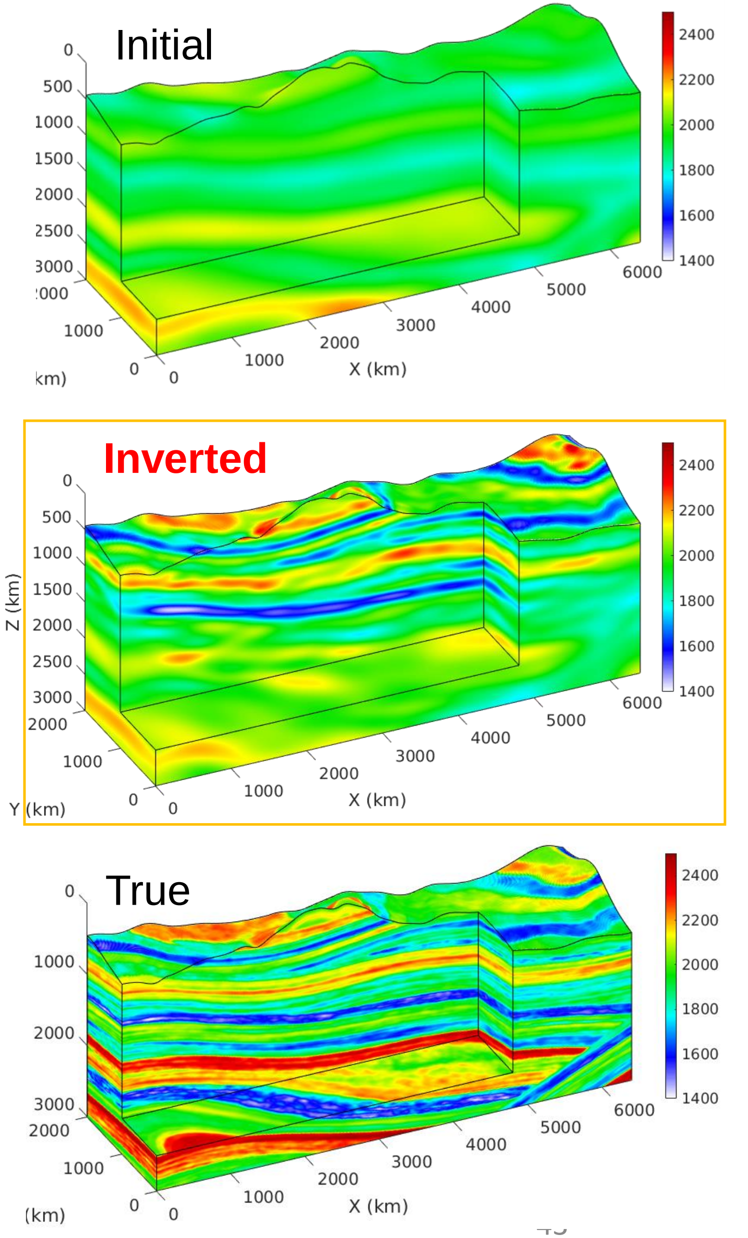




Data comparison

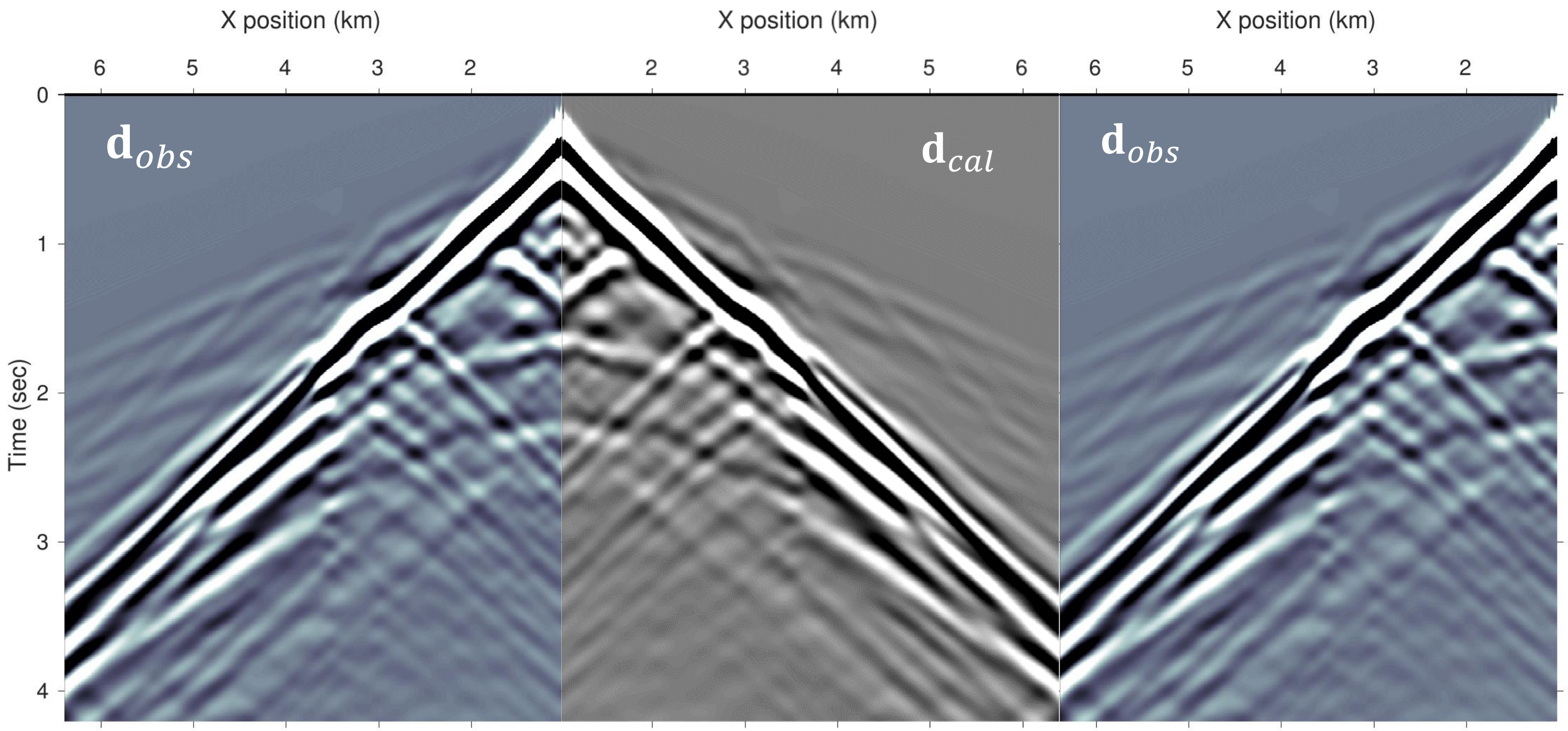
1. FWI with early-body waves

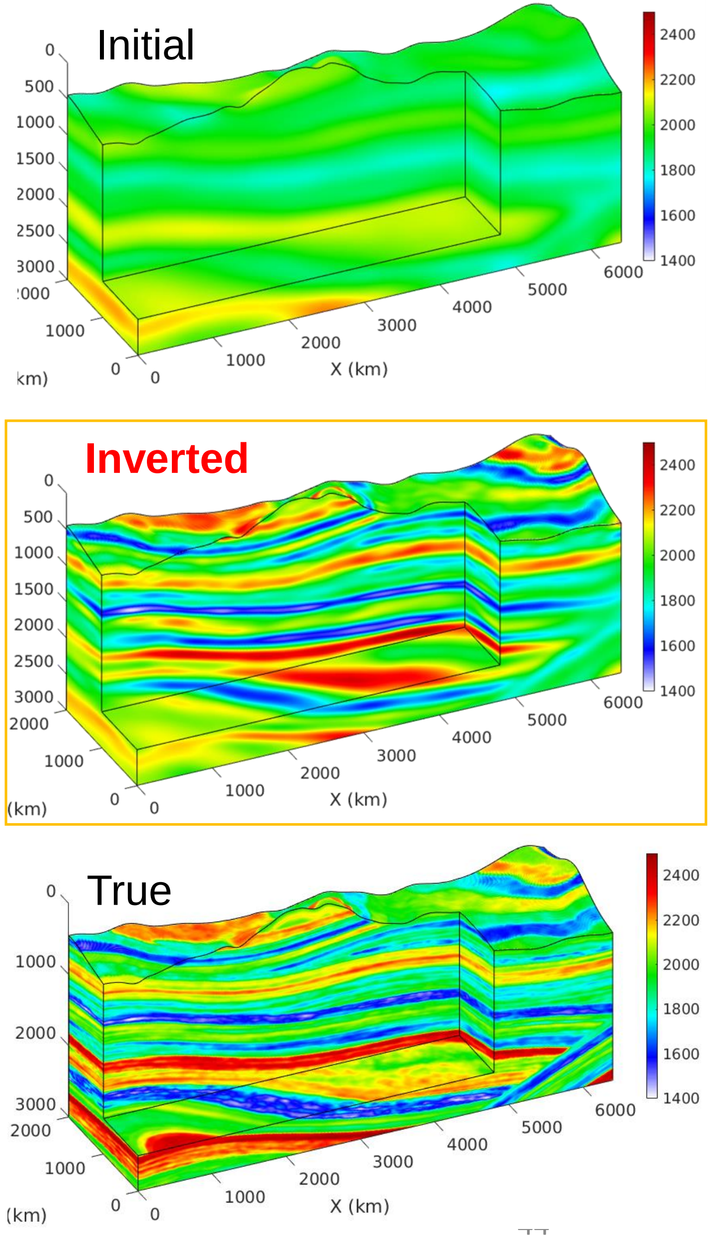




Data comparison

2. FWI with all wavefields





Numerical efficiency

From the 3D elastic example

- Deformed mesh: $32 \times 68 \times 28$ elements ($129 \times 273 \times 113$ dofs).
- 6 sec recording time ($10\ 000$ time-steps).
- 1600 cores (20 cores/shot)

	Memory estimation	Elapsed time 1^{st} gradient	Elapsed time 60 FWI iterations
Elastic	**44 Gb**/shot	20 min	20.8 h
Viscoelastic	**74 Gb**/shot	1.2 h	75 h

Extrapolation for viscoelastic case

- 80 checkpoints for incident wavefield reconstruction.
- Recomputation ratio $\approx \mathbf{3}$.

Conclusion I

- Moving to **3D visco-aniso-elastodynamics** FWI is now possible for crustal land data (PhD topic of P.T. Trinh).
- Application to real datasets: multi-parameters images?
- Which **macro-scale** parameters are important for **meso-scale** downscaling investigation for **micro-scale** interpretation:

➡ Q attenuation factor is important!

Cautiousness in interpretation as FWI results seem often quite realistic.

Conclusion II

- **Different families**: what is the « best » set ???
  - Velocity – slowness-square of slowness
  - Density- Buoyancy-Impedance
  - Attenuation-Inverse of attenuation
  - Log; tanh (or any non-linear transform) …
- **Hints**: mitigate the leakage between parameters …

- Model parameters # inference parameters # physical parameters …
- FWI reconstructs model parameters … at the macro-scale level …

Thank you very much!

FWI=λ/2

- Cycle skipping problem: under control.
- Local minima issue: better mitigation.
- Multiple parameter issue: important for apps.

Do not forget the UQ guy!