Challenges for near-surface Full Waveform Inversion (FWI)

By J. Virieux, ISTerre, Université Grenoble Alpes and SEISCOPE group

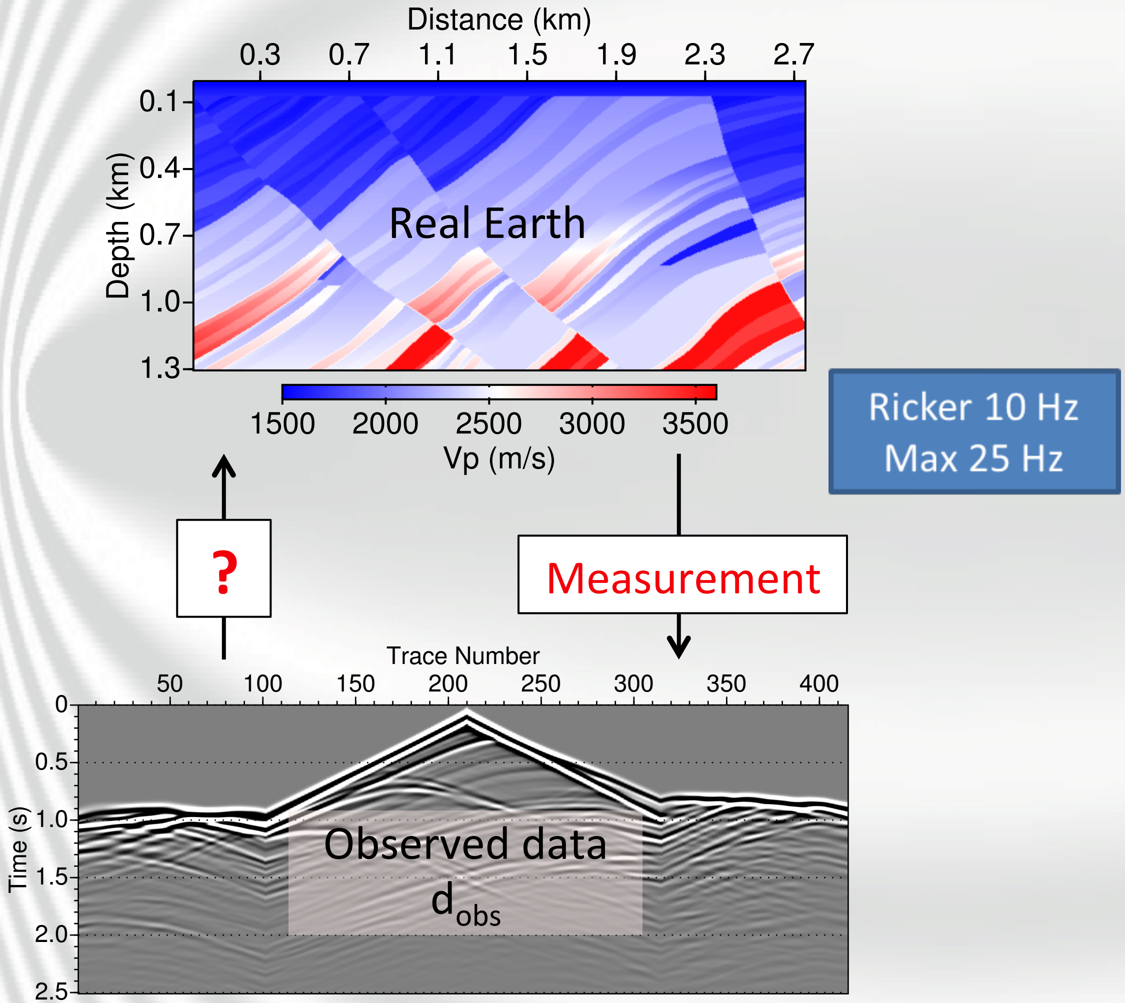
SEISCOPE II http://seiscope2.osug.fr

SEISCOPE

OUTLINE

- Introduction on FWI
- Near surface seismic imaging issues
- Surface wave analysis
- Body wave analysis
  - Direct/refracted waves versus reflection waves
- Model impacts
- Conclusion

FULL WAVEFORM INVERSION (FWI) – PRINCIPLE



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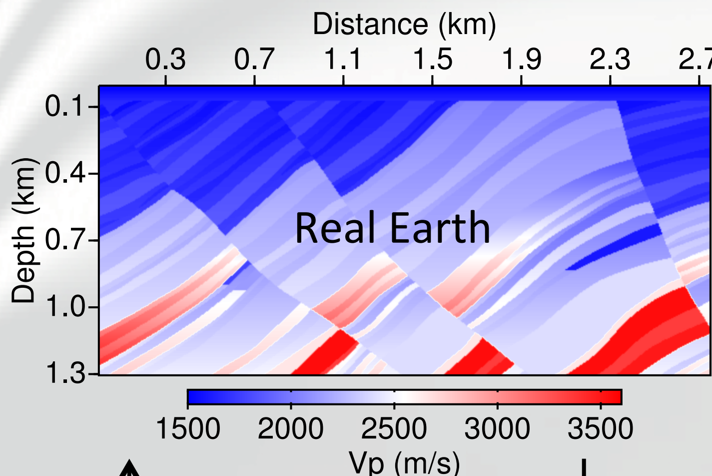
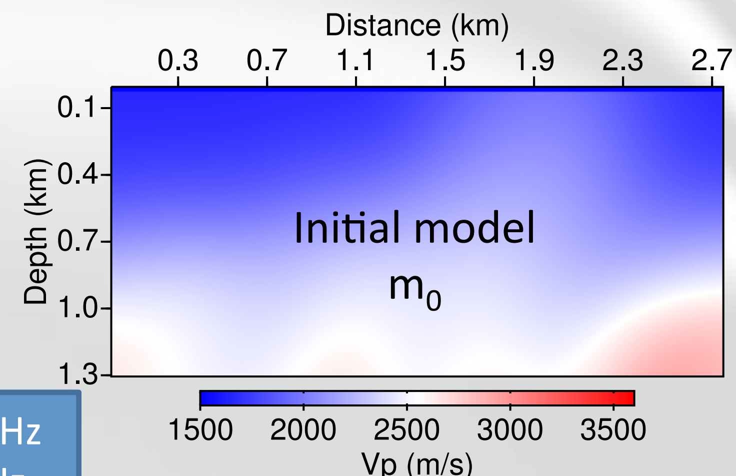
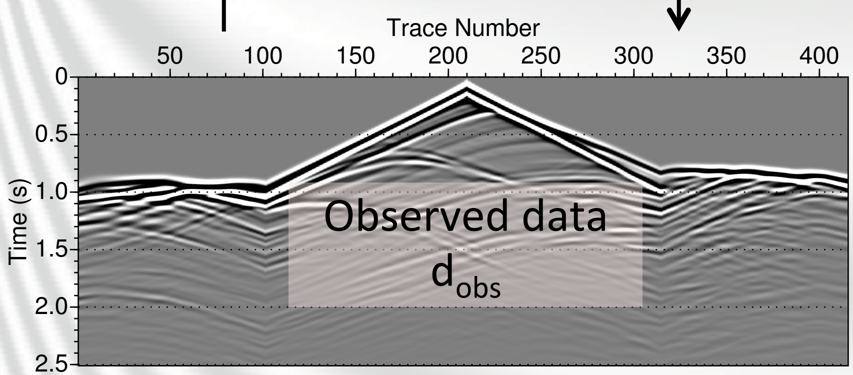




Ricker 10 Hz
Max 25 Hz

?

Measurement



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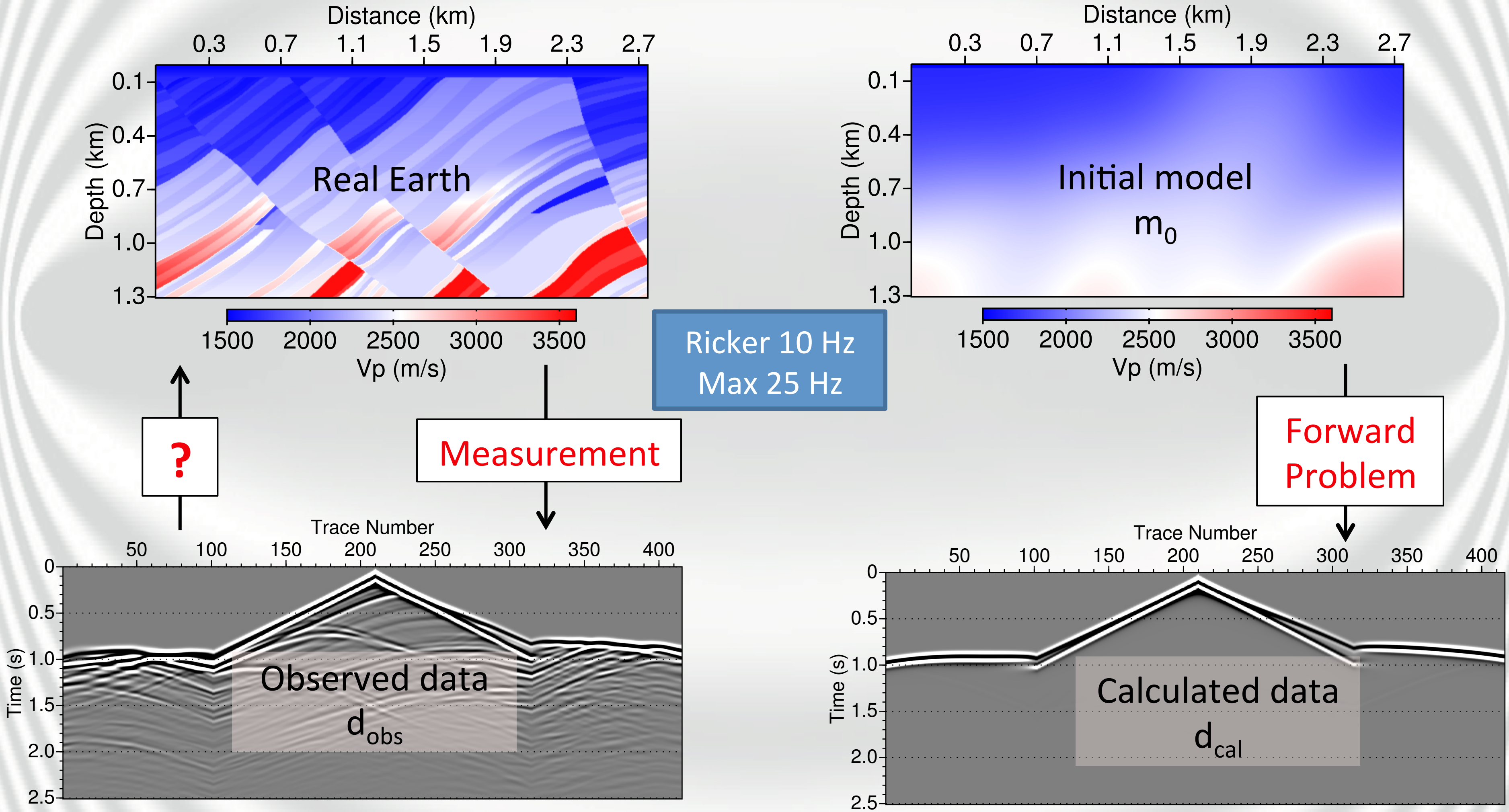

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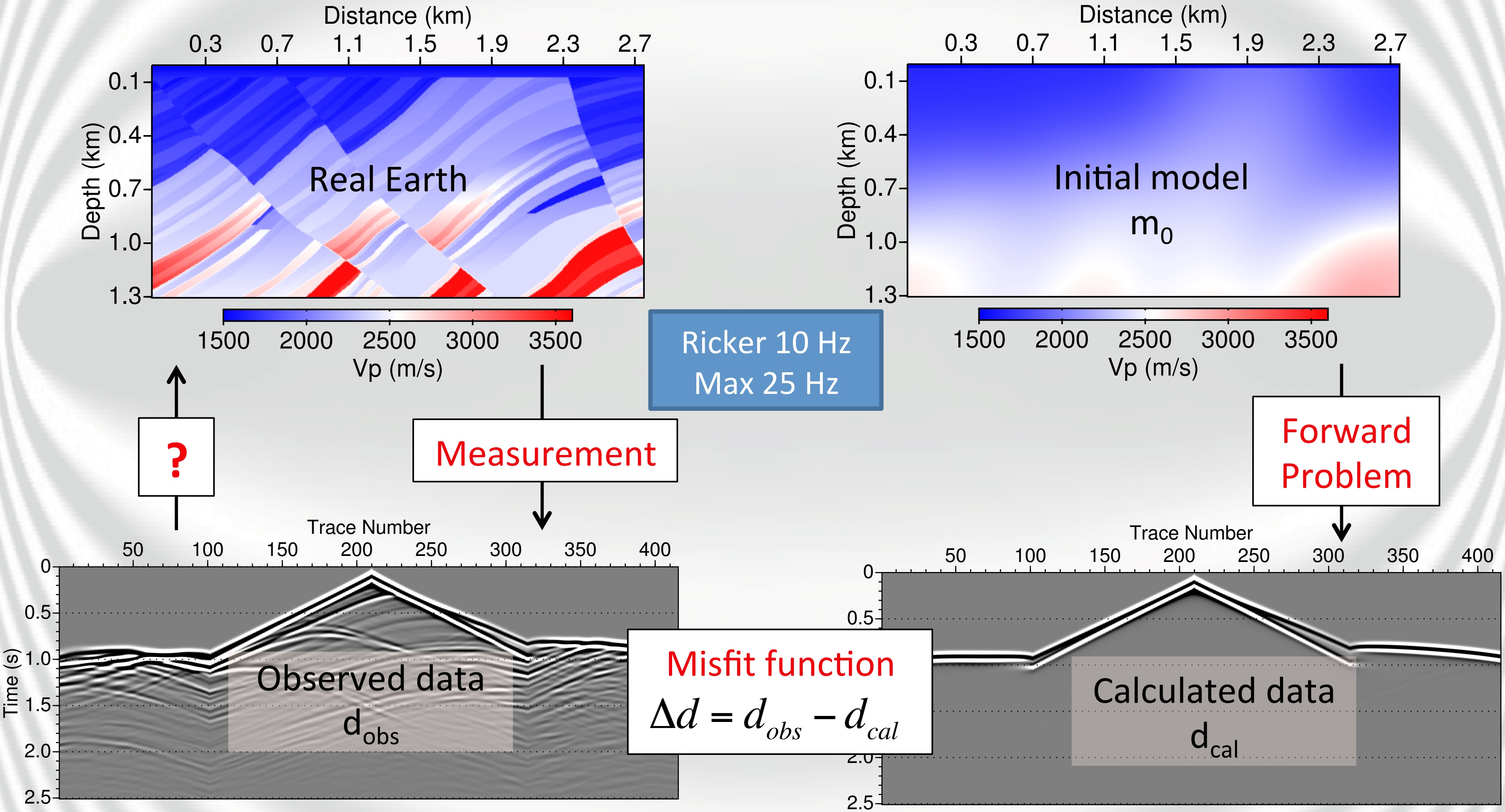

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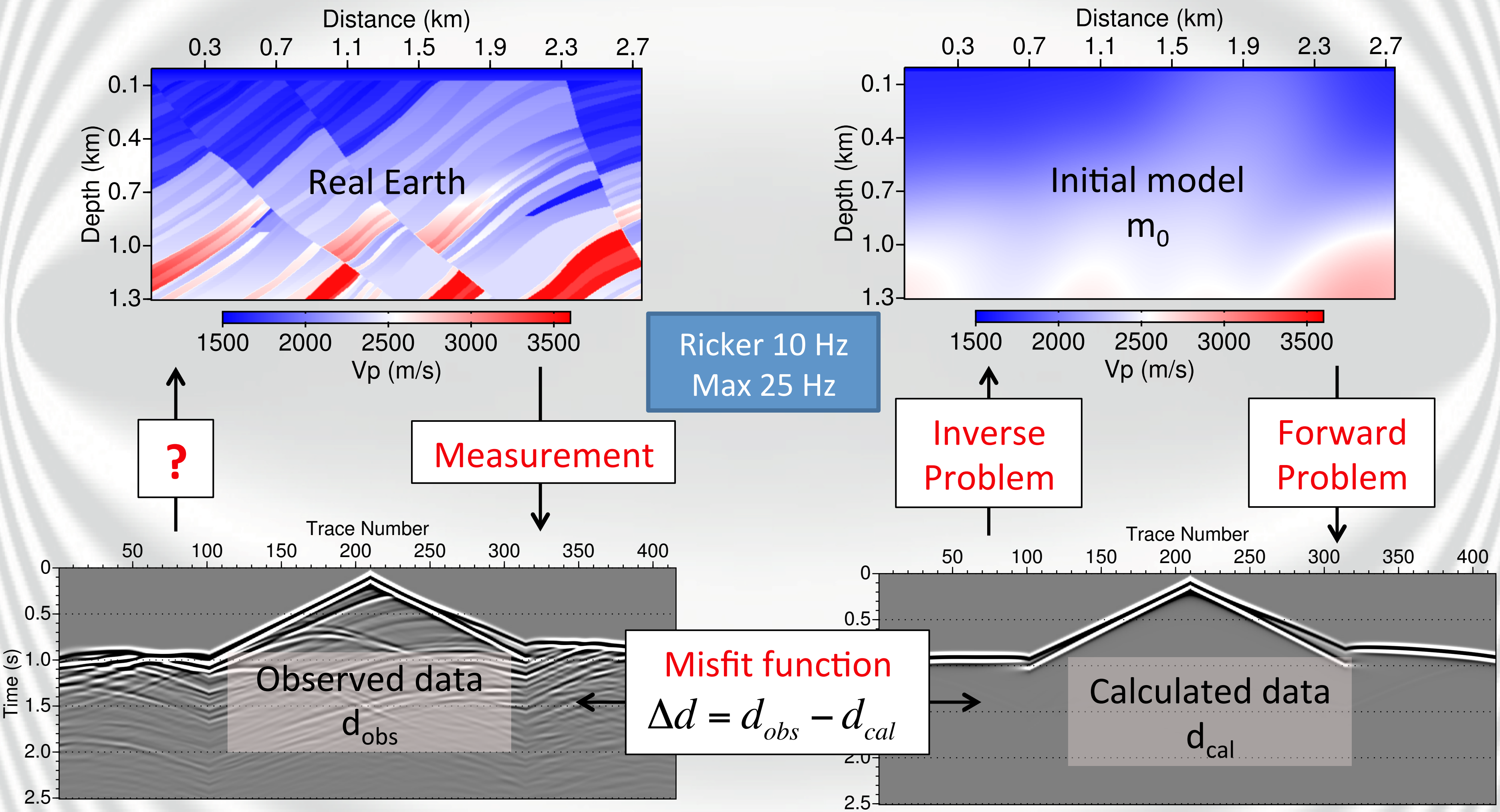

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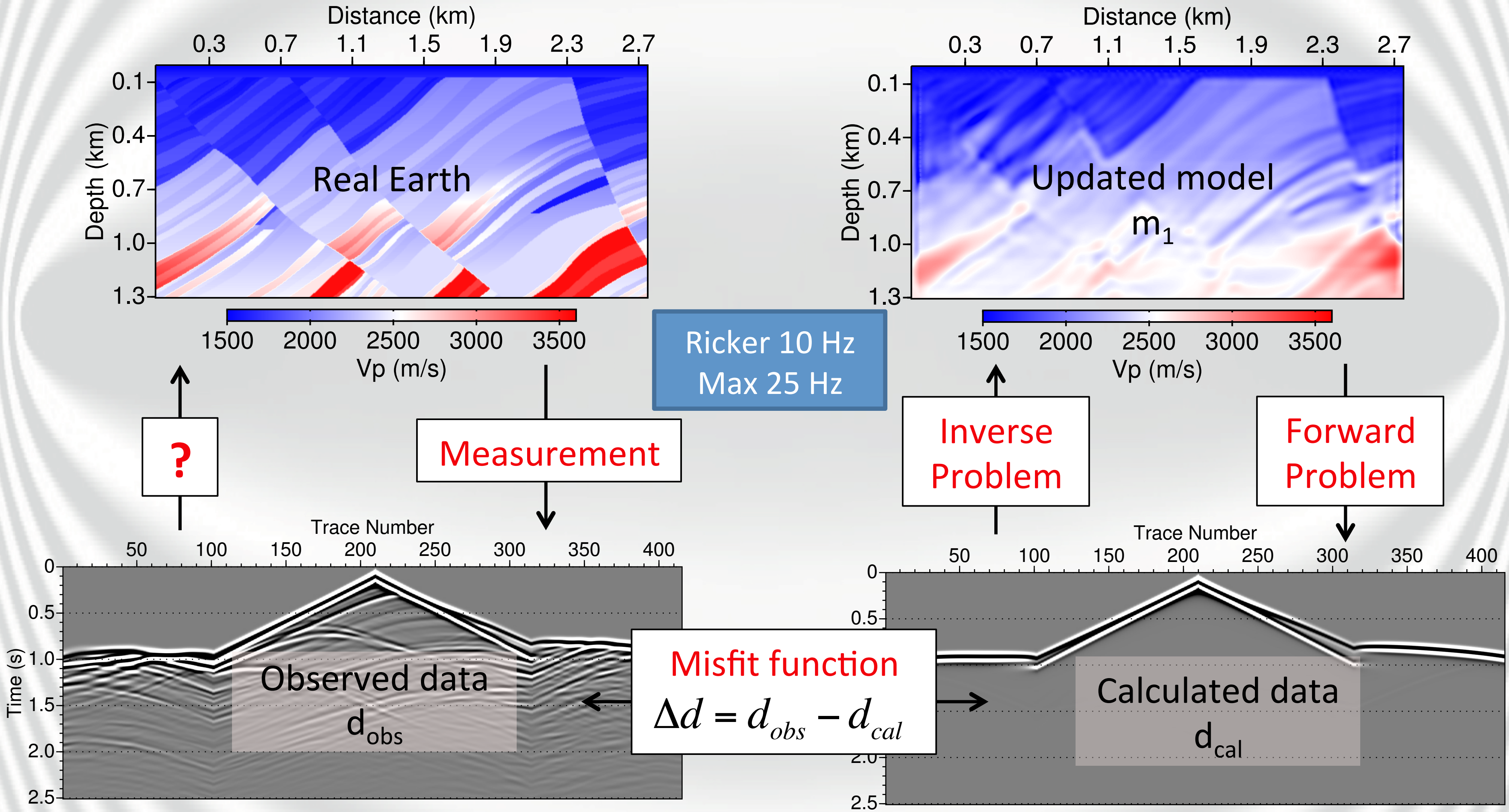

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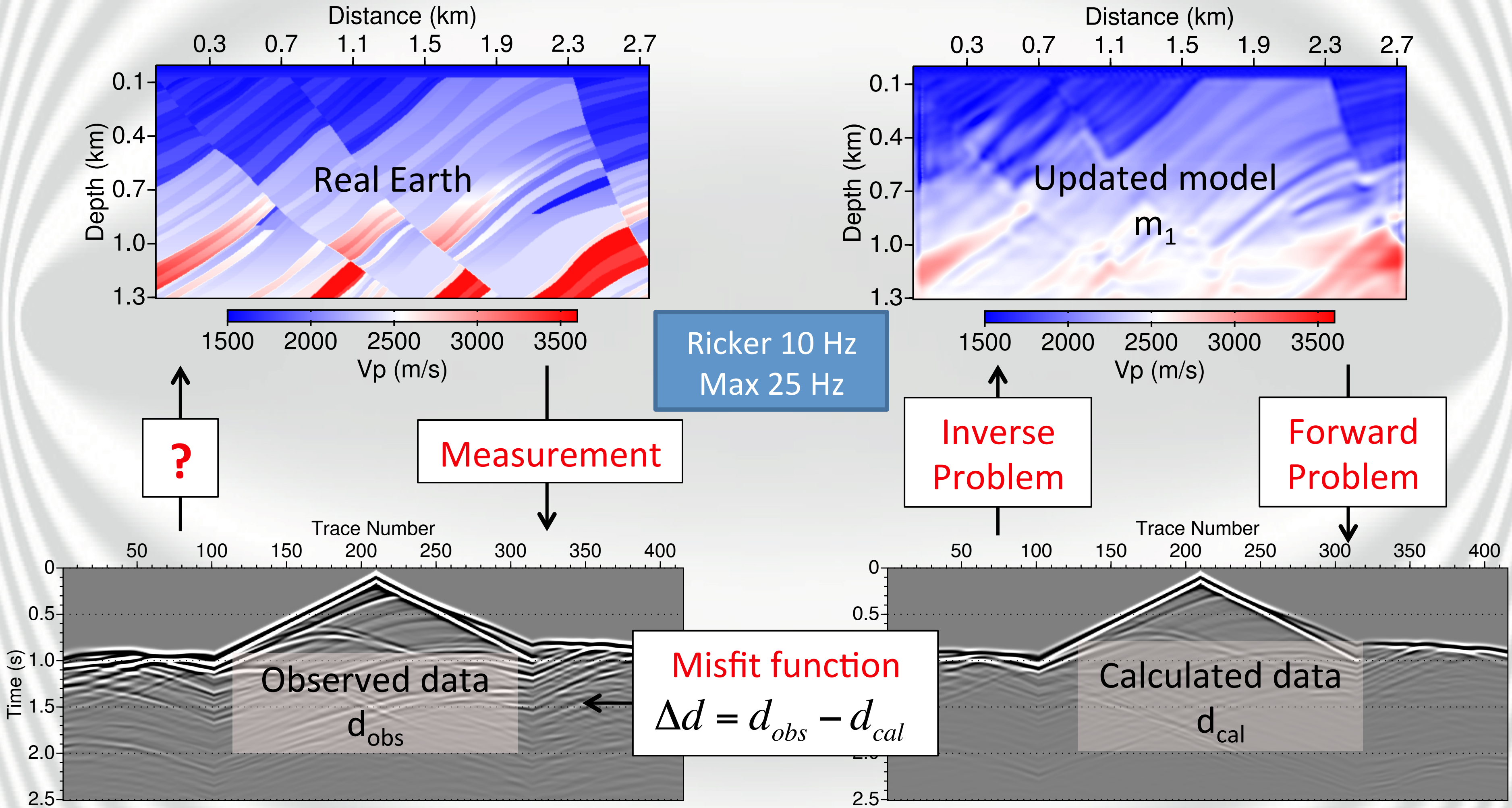

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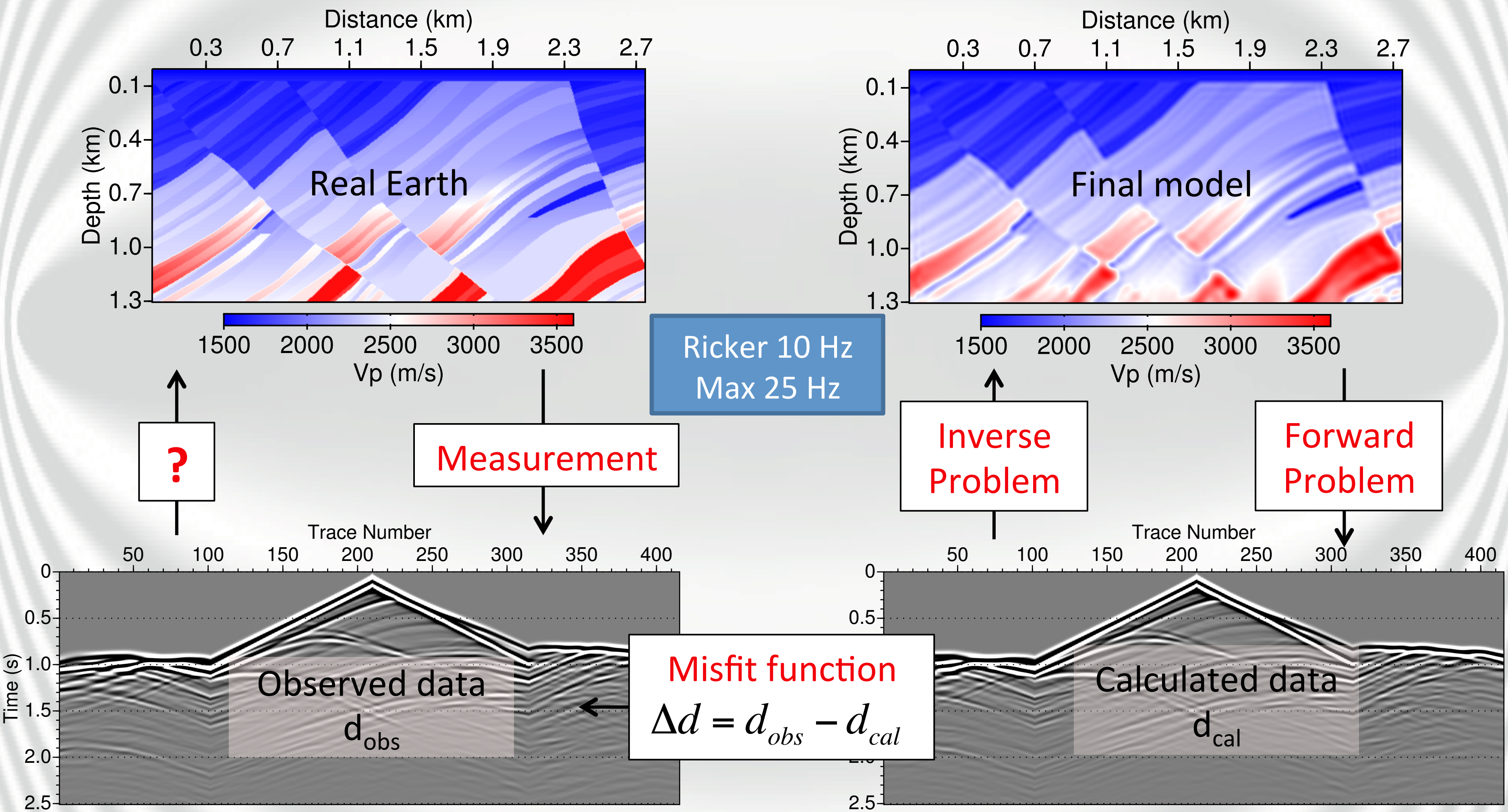

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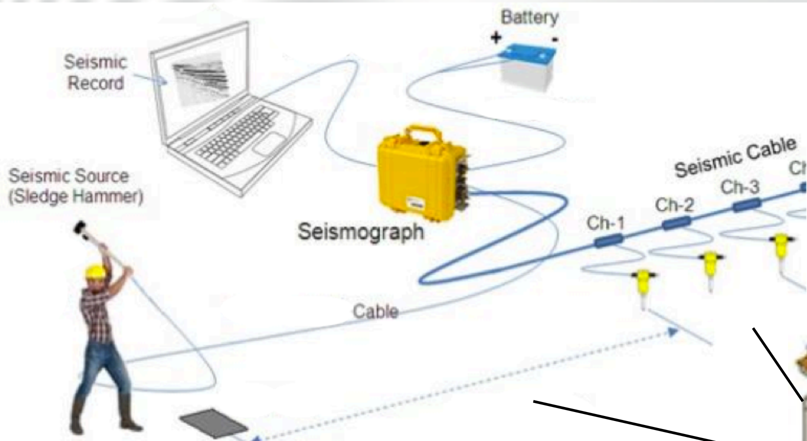
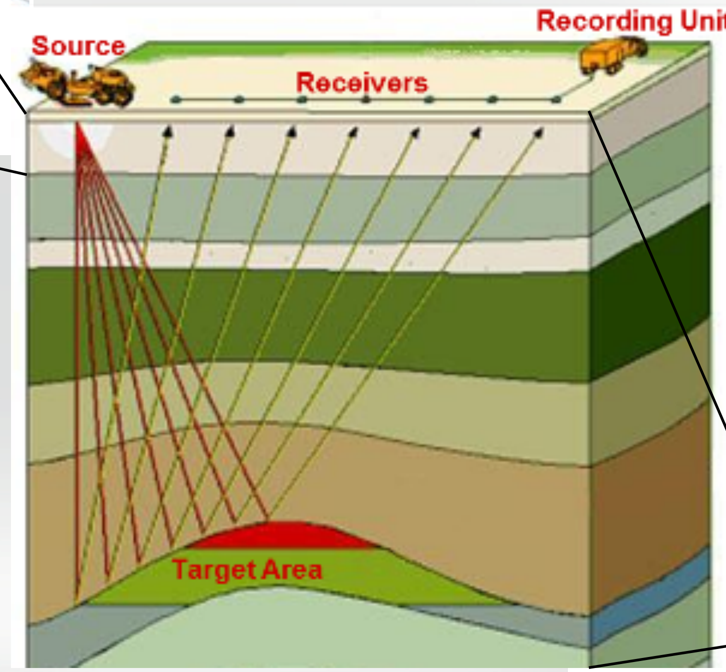
FWI ISSUES ON DIFFERENT SCALES

Near surface scale

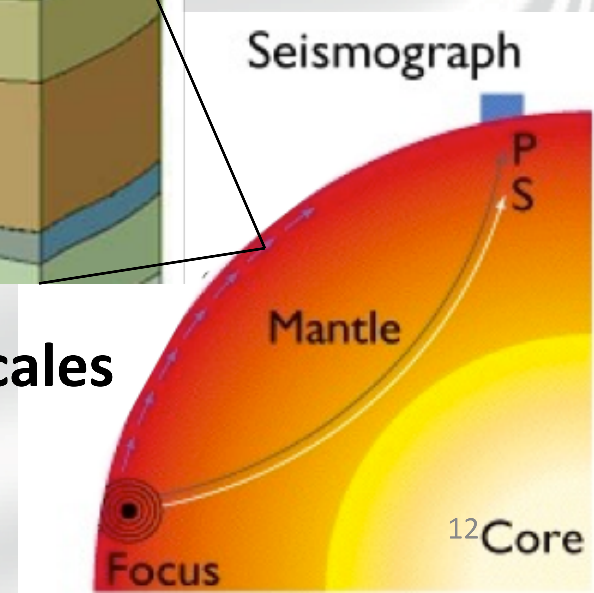
- complexity of the near-surface
- lack of high frequencies
- strong surface waves & elastic effects





Crustal exploration scale

- lack of low frequencies
- limited illumination and/or aperture
- complexity of target

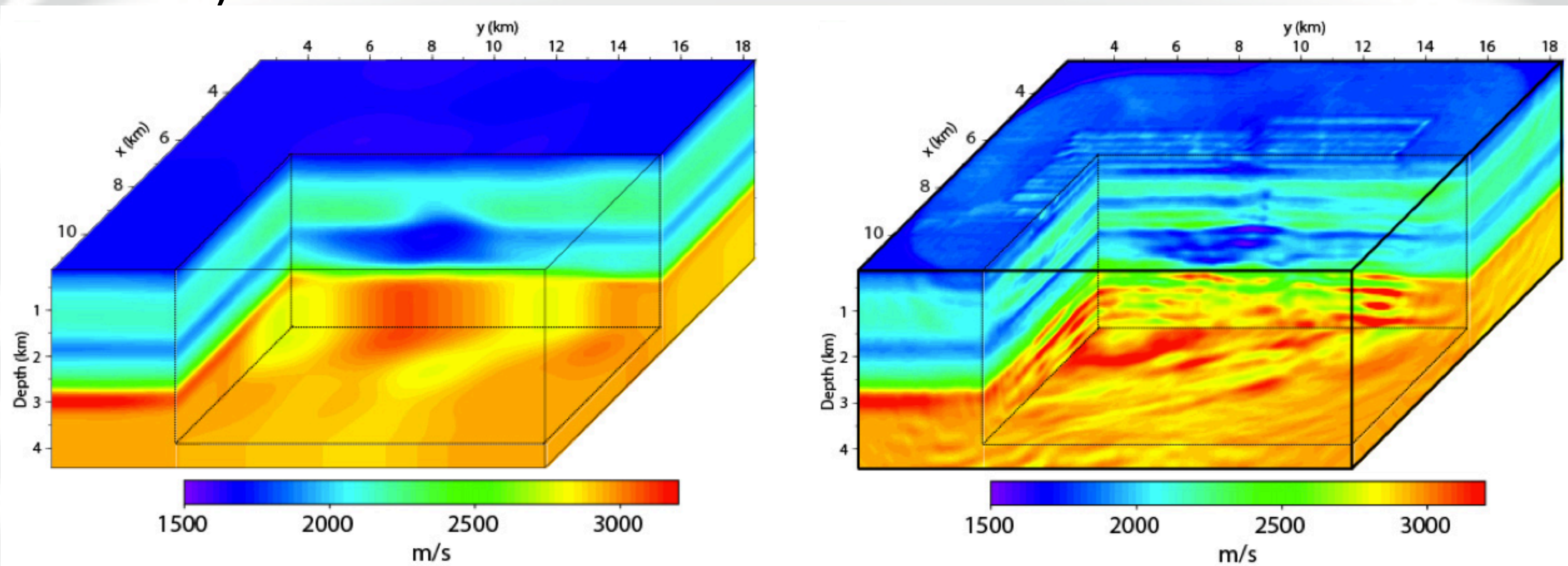


Seismology at regional and global scales

- difficulties with data sampling

ACOUSTIC FWI (crustal targets)

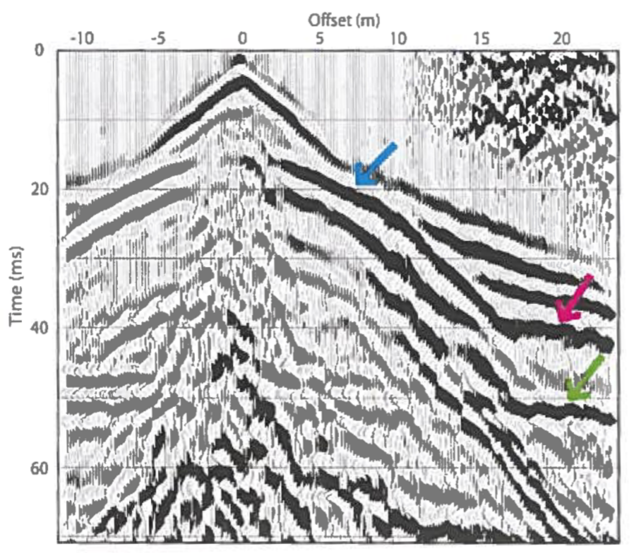
- 3D Acoustic FWI on the Valhall data, North Sea (Etienne et al., 2012)



Initial model (v_P) Final model (v_P)

- Yet the classical FWI workflow for most successful industry applications remains with an **acoustic approximation**.

Seismic data hierarchy



- Frequency content > and ~100 Hz
- Phase identification and interpretation
- Separate interpretation
- Collaborative interpretation

(Zhang et al, 1998; Ivanov et al, 2006; Dal Moro & Pipan, 2007; Fabien-Ouellet & Fortier, 2014)

(Sloan et al, 2009, NSG)

- Refraction analysis – first arrival time tomography

(Hagedoorn, 1959; Palmer, 1981; Brueckl, 1987, Zelt & Ellis, 1992; Yilmaz, 2001 …)

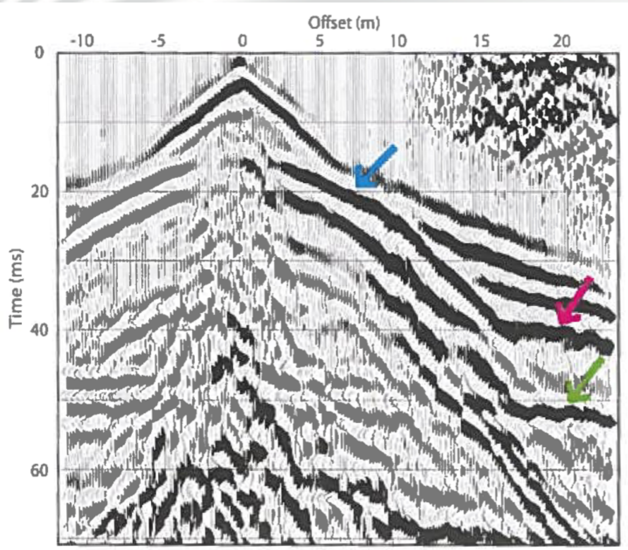
- Surface wave dispersion curve analysis – phase analysis

(McMechan & Hedlin, 1981; Heisey et al, 1982; Stokoe et al, 1994; Park et al, 1999; Socco & Strobiia, 2004; Boiera & Socco, 2010 …)

- Reflection analysis – reflection time tomography

(Inazaki et al, 2000; Wang et al, 2003; Pugin et al, 2004 …)

Seismic data hierarchy



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- Refraction analysis – first arrival time tomography
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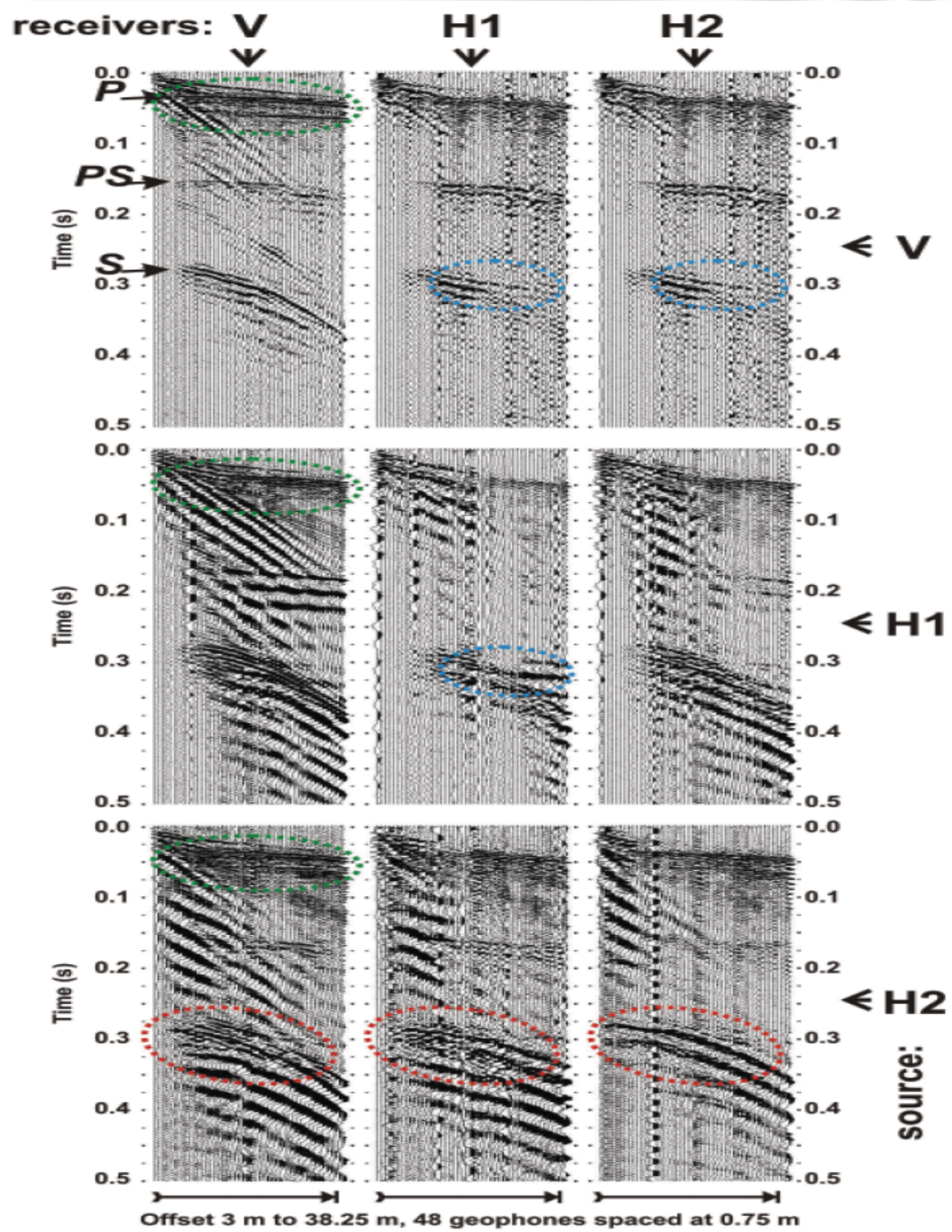
- Reflection analysis – reflection time tomography
  (Inazaki et al, 2000; Wang et al, 2003; Pugin et al, 2004 …)

PHASE INFORMATION

Multi-component data (2D lines)

(Pugin et al, 2009, TLE)



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Body and surface waves contributions to FWI

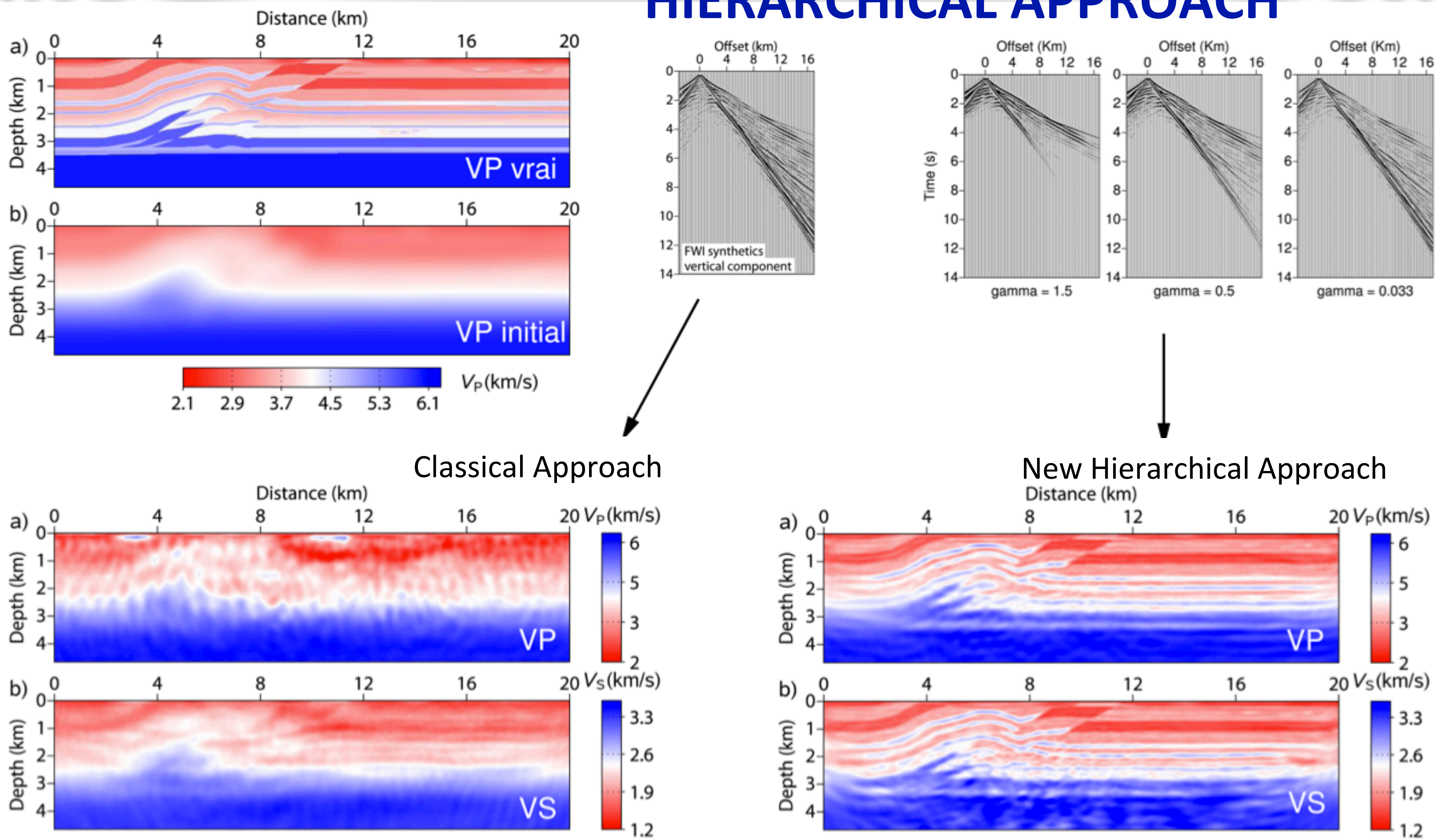
The near surface is characterized with

- heterogeneous velocity/attenuation structure
- complex topography

There have been several attempts in elastic FWI (in the framework of the SEISCOPE consortium):

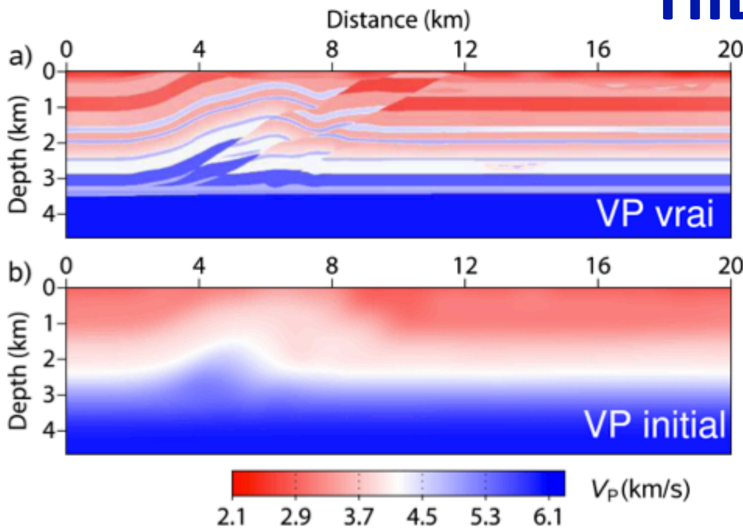
- Gelis (2005) concluded that including surface waves for elastic FWI makes the inversion highly **non-linear**.
- Brossier et al. (2009) concluded that, if the **starting model** did not **predict the kinematics** of the surface waves, the inversion would get locked in a local minimum.

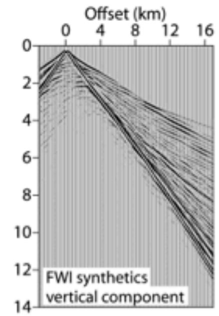
ELASTIC FWI
HIERARCHICAL APPROACH

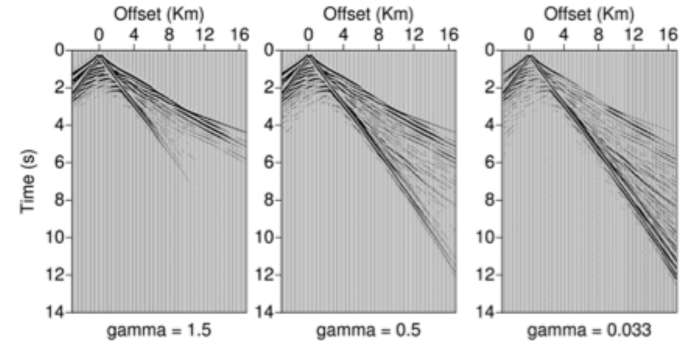


(Brossier et al., 2009)

ELASTIC FWI
HIERARCHICAL APPROACH

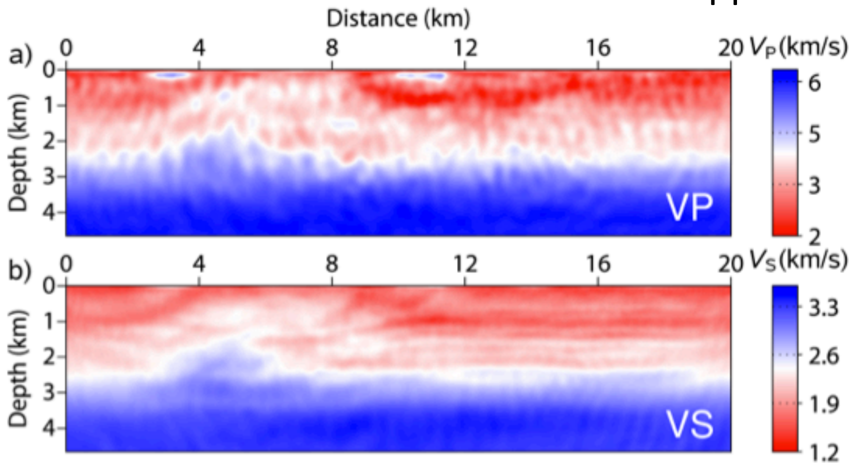




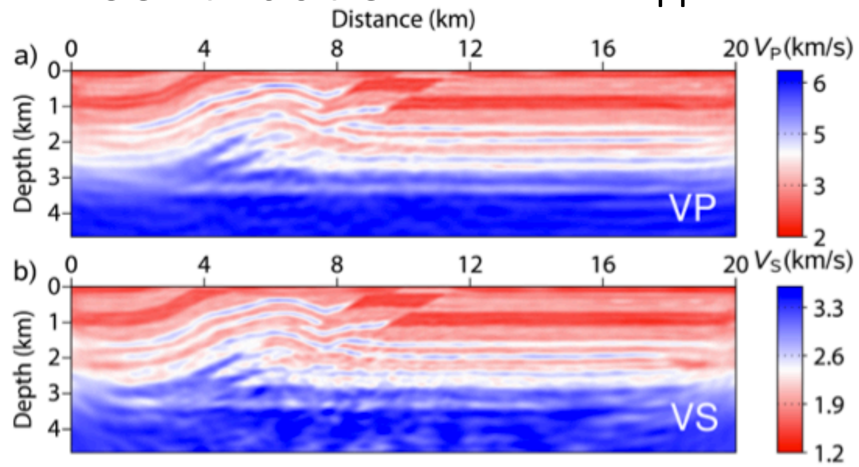


What is exactly the surface wave contribution?

Classical Approach



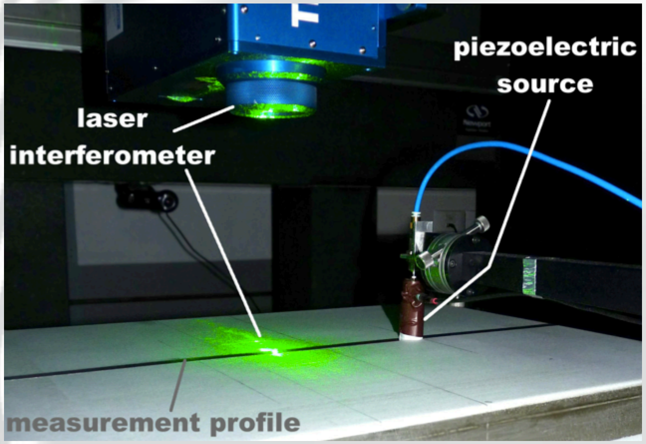
New Hierarchical Approach

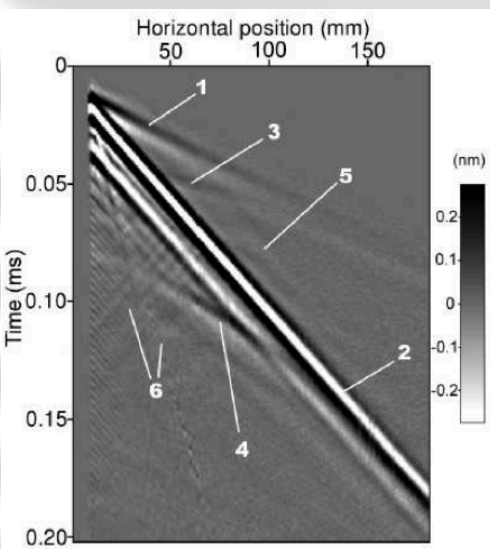


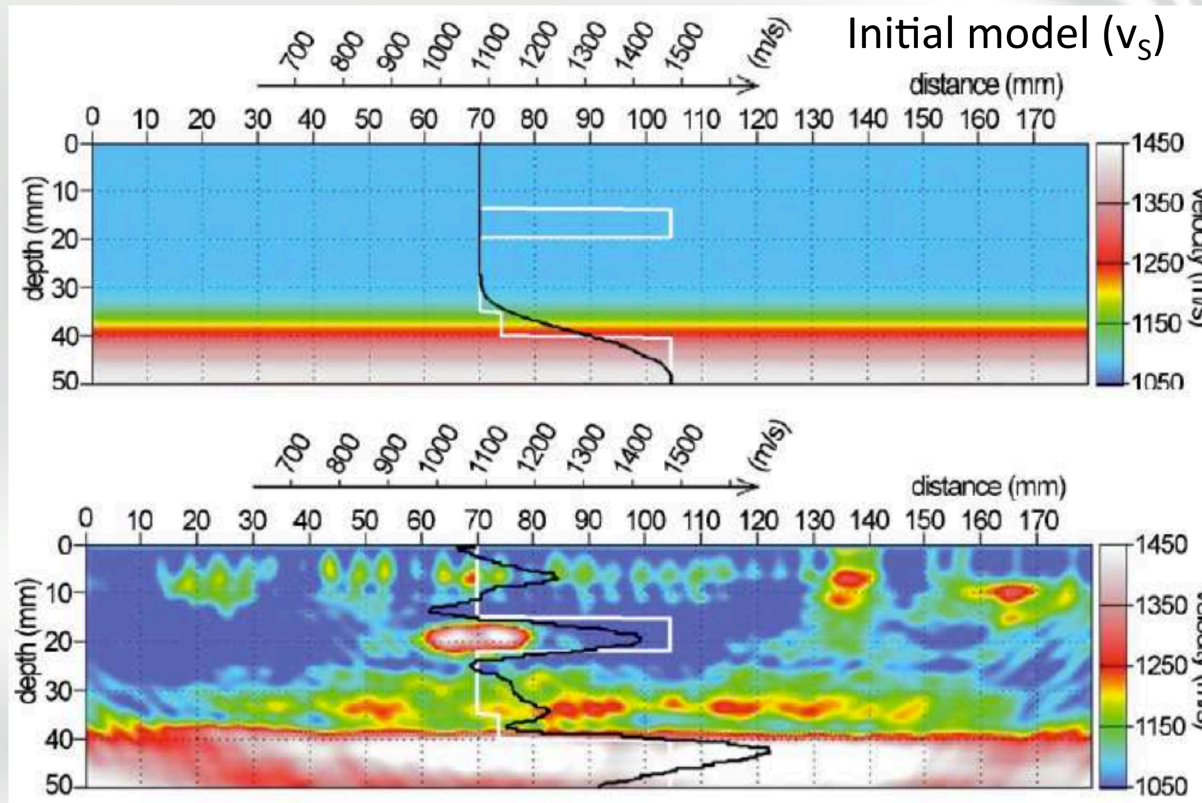
(Brossier et al., 2009)

LABORATORY EXPERIMENTS

Bretaudeau et al. (2013) exploited the diffraction of surface waves to detect anomalies using lab-scale data



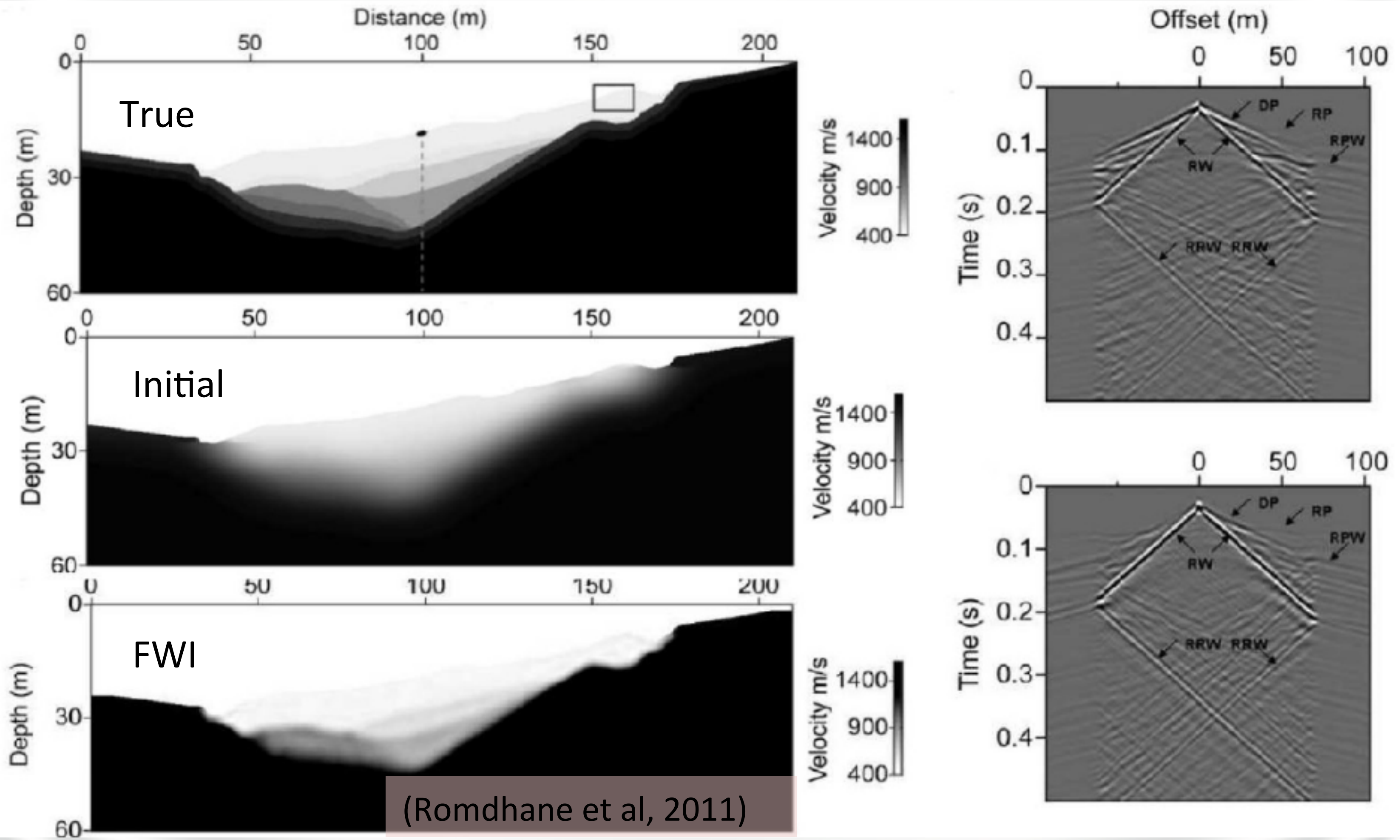




Initial model (v_S)

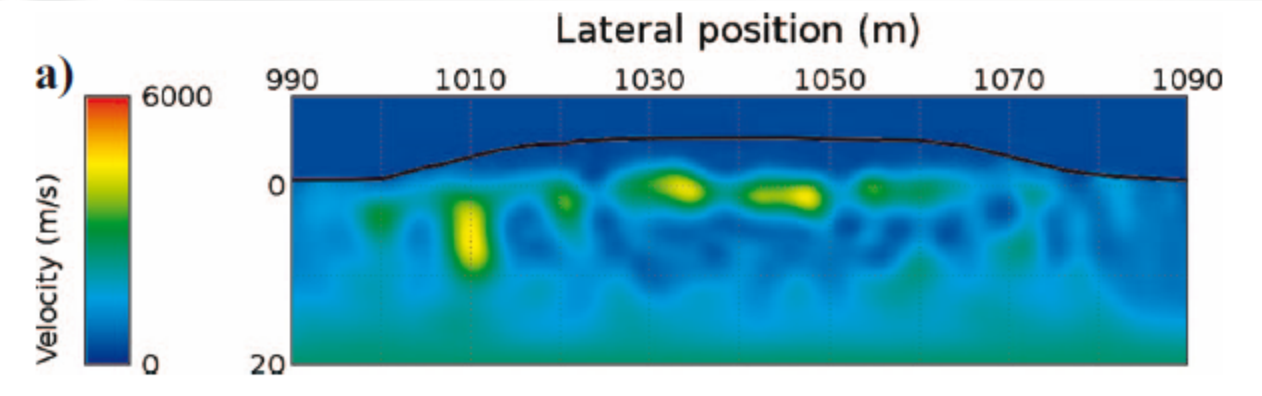
Final model (v_S)

FWI: Synthetic landslide



(Romdhane et al, 2011)

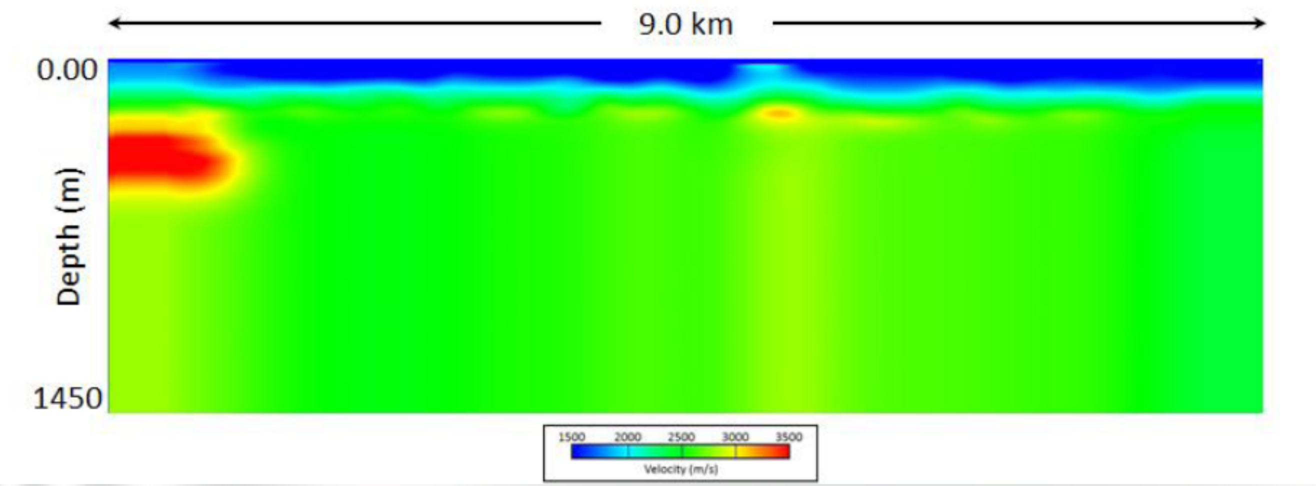
Real data application



(Smithyman et al, 2009)

Shallow target

Only acoustic …



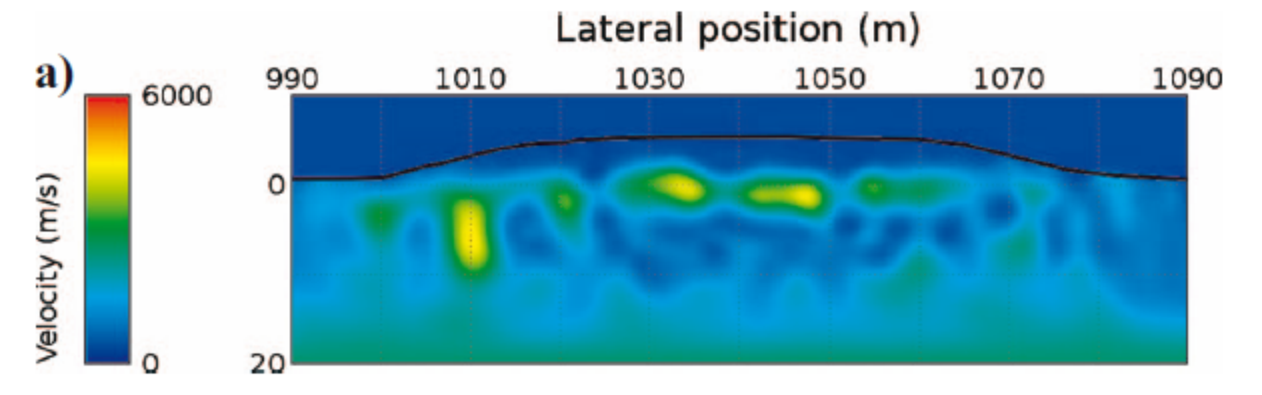
(Tonellot et al, 2013)

Near surface target

Travel time tomography

Real data application

(Smithyman et al, 2009)



Shallow target

Only acoustic …

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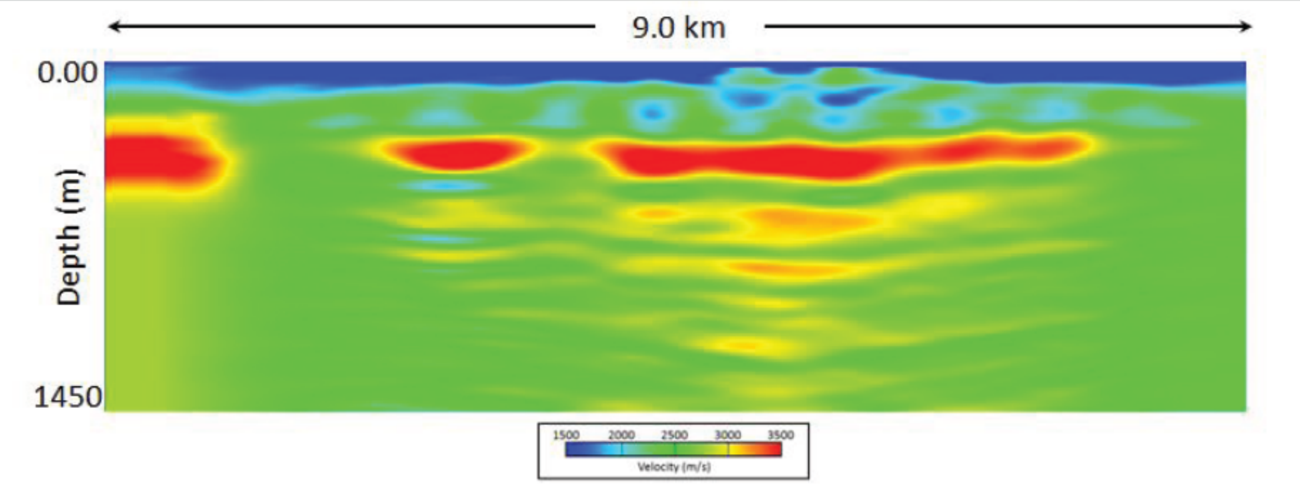

Near surface target

FWI result

Why image reconstruction so difficult?
Near surface is complex!

Cycle skipping ambiguity
Attenuation
Free surface
Large amplitude variation

but seismic phases are there!

FWI of SEPARATE PHASES

A more robust FWI formalism is needed when considering near surface seismic data: specific contributions of surface waves, reflection waves aside direct and refracted waves.

→ **find suitable misfit function for each phase (dispersive and non-dispersive)**

→ **Reconstruction of each phase**

- Direct and refracted phases sensitive to velocities
- Reflected phases sensitive to velocities and impedances (density)
- Surface phases sensitive to shear velocity (density&P velocity)

→ **Collaborative reconstruction between phases?**

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FWI of SURFACE WAVES

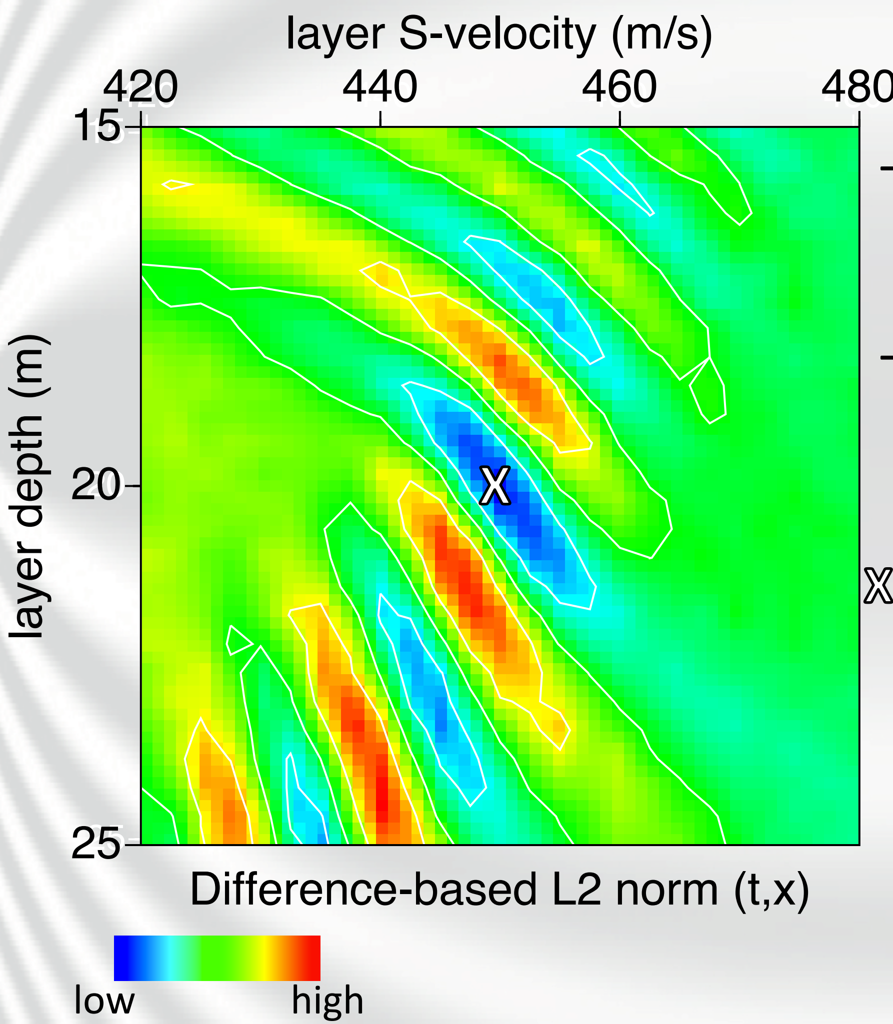
From dispersion curve data
to
velocity spectrum data

PhD of Isabella Masoni (2015)

(Ryden and Park, 2006; Maraschini and Foti, 2010)

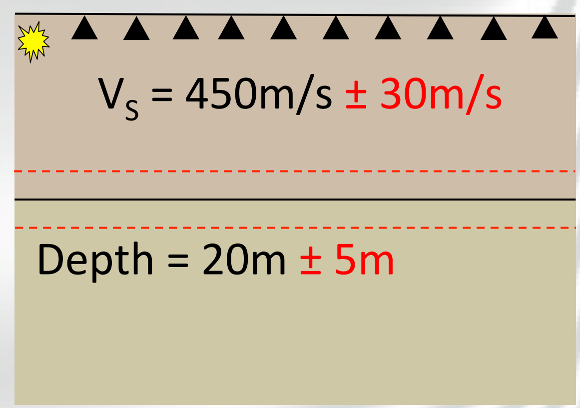
SURFACE WAVE MISFIT

$$C_{diff} = \sum_t \sum_x \frac{1}{2}\left(d_{\mathbf{obs}}(t,x) - d_{\mathbf{cal}}(t,x)\right)^2$$

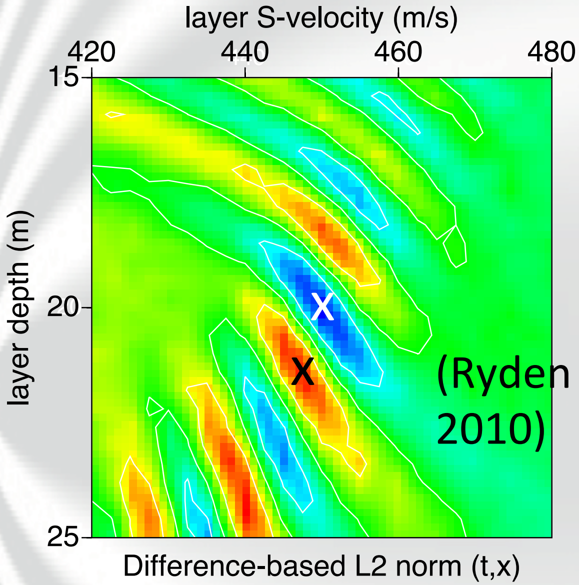


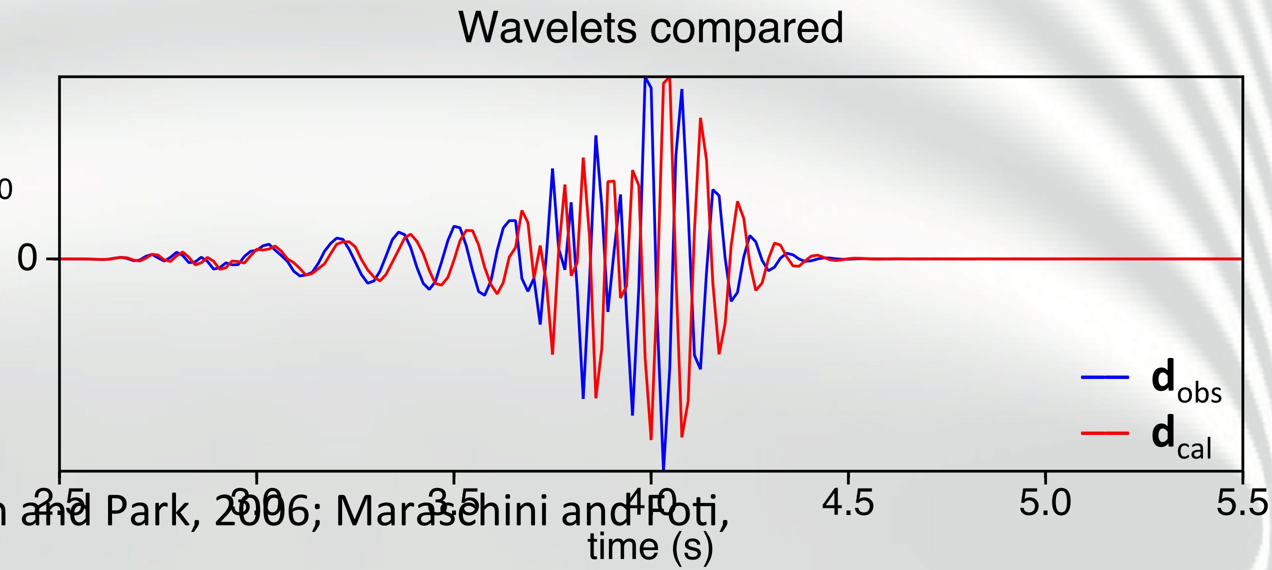
- Narrow valley of attraction and presence of local minima
- Initial velocity model needs to be accurate for convergence

X = zero misfit (true model)

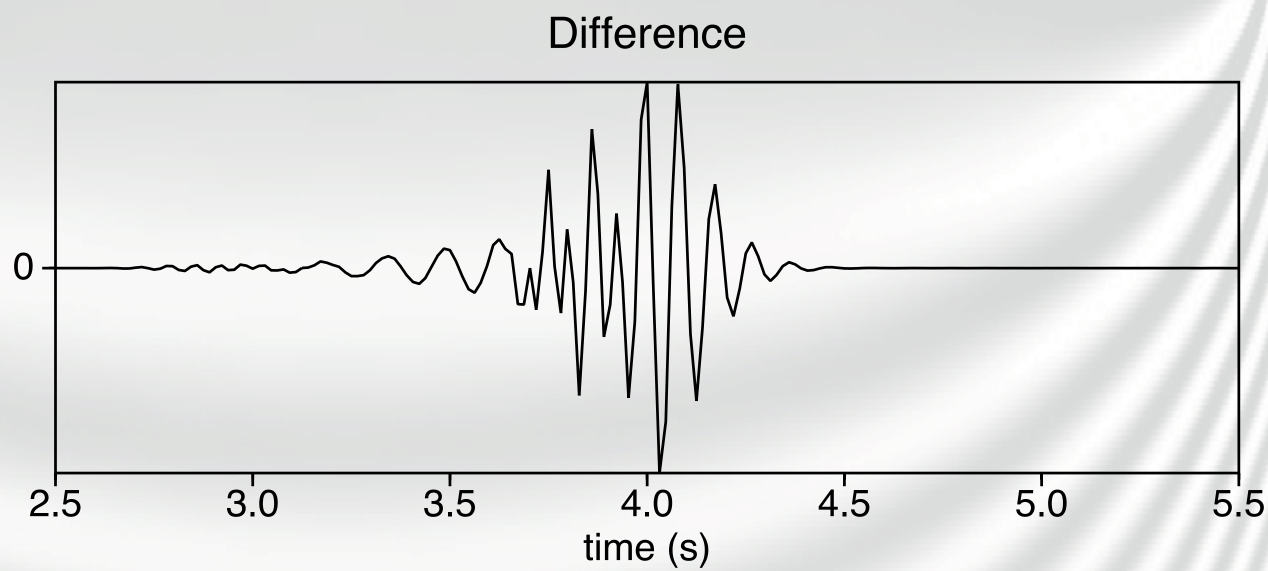


SURFACE WAVE MISFIT





(Ryden and Park, 2006; Maraschini and Foti, 2010)



Minimize

$$\mathbf{d}_{\mathbf{obs}}(t) - \mathbf{d}_{\mathbf{cal}}(t)$$

SEISCOPE

ALTERATIVE DATA DOMAINS AND MISFIT FUNCTIONS

Classical difference-based misfit function in t-x domain

$$C = \frac{1}{2}\left(\mathbf{d}_{\text{obs}}(x,t) - \mathbf{d}_{\text{cal}}(x,t)\right)^2$$

General formulation for alternative data domain

$$C = \frac{1}{2}\left(T\left(\mathbf{d}_{\text{obs}}(x,t)\right) - T\left(\mathbf{d}_{\text{cal}}(x,t)\right)\right)^2$$

Data transformed to another data domain by operator T

tau-p domain

$$C = \frac{1}{2}\left(\mathbf{d}_{\text{obs}}(\tau,p) - \mathbf{d}_{\text{cal}}(\tau,p)\right)^2$$

LMO transform applied

Omega-p domain

$$C = \frac{1}{2}\left(\left|\mathbf{d}_{\text{obs}}(\omega,p)\right| - \left|\mathbf{d}_{\text{cal}}(\omega,p)\right|\right)^2$$

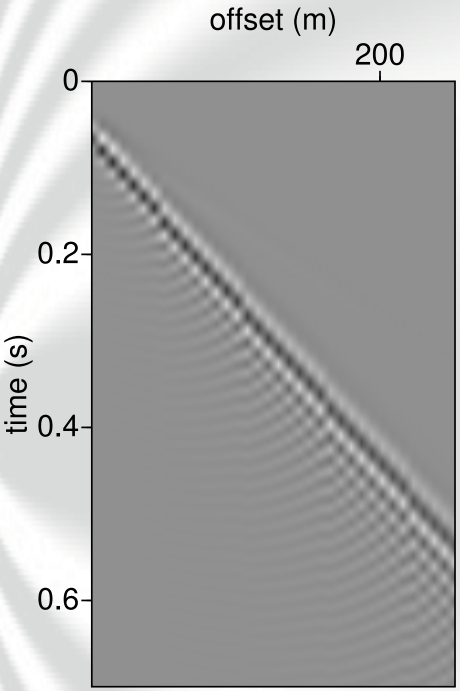
LMO transform and temporal Fourier transform applied

Omega-k domain

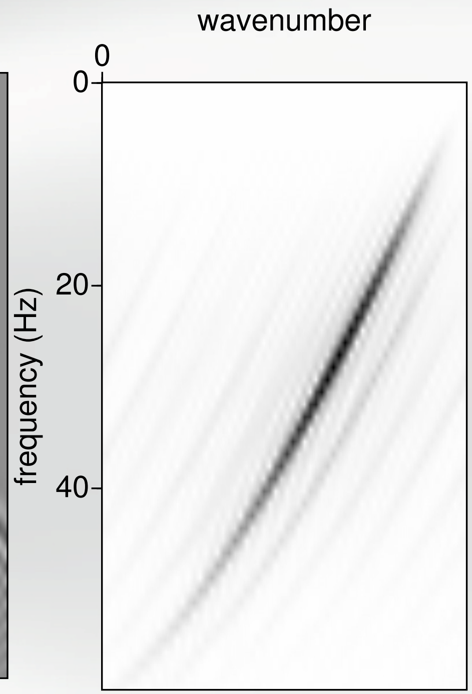
$$C = \frac{1}{2}\left(\left|\mathbf{d}_{\text{obs}}(\omega,k)\right| - \left|\mathbf{d}_{\text{cal}}(\omega,k)\right|\right)^2$$

Temporal Fourier transform and spatial Fourier transform applied

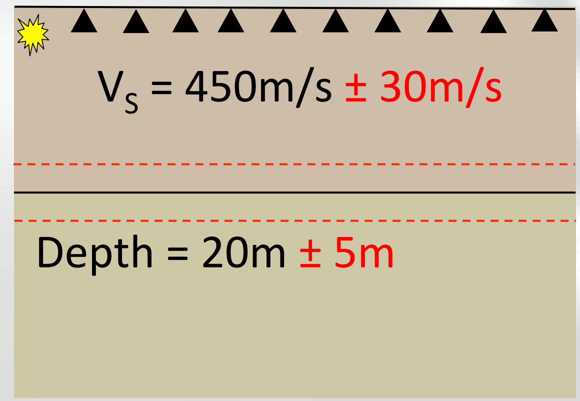
ALTERATIVE DATA DOMAINS AND MISFIT FUNCTIONS

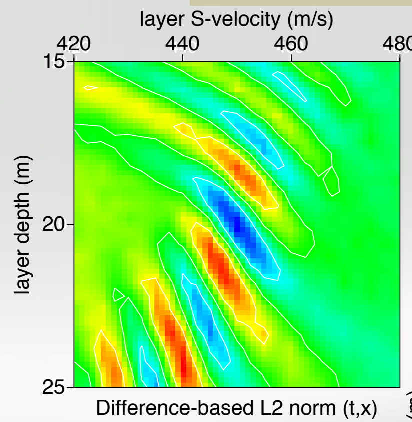


t-x domain

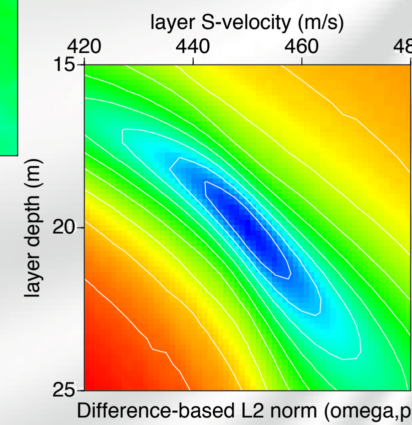


omega-k domain





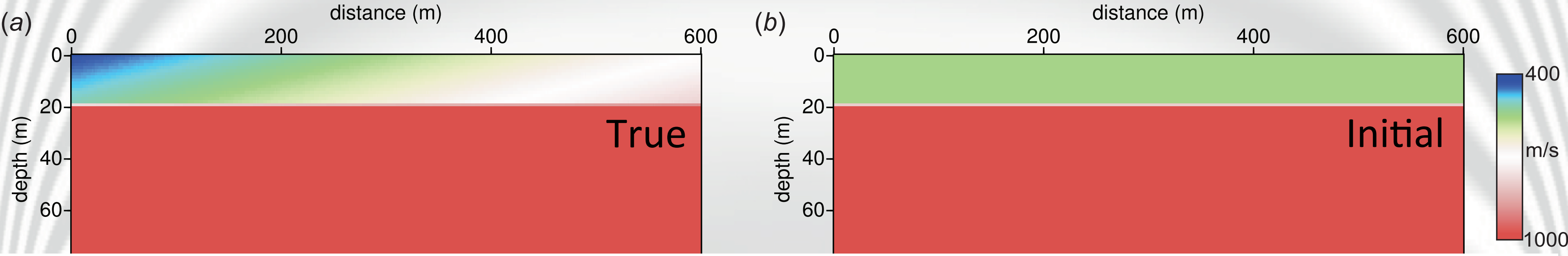
t-x domain

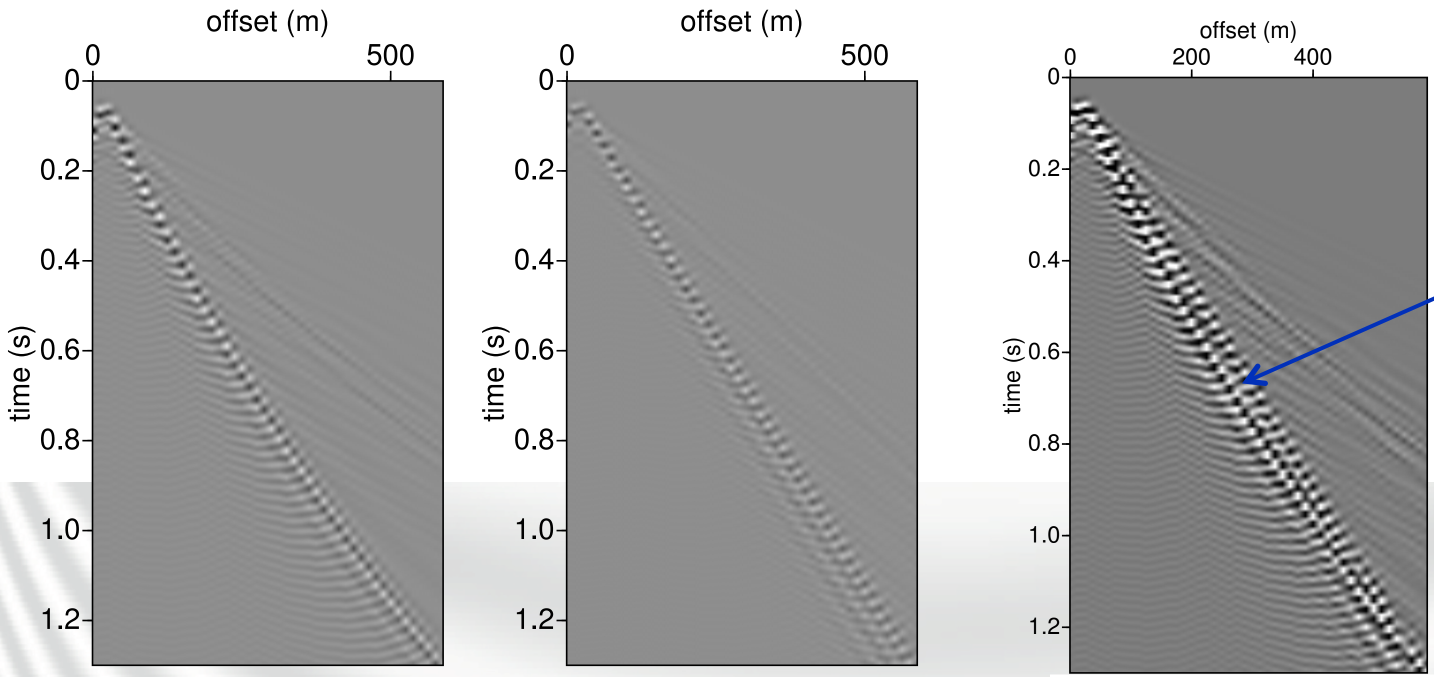


ω-k domain

Move to domains and misfits where local coherence is important

INVERSION OF VS ONLY





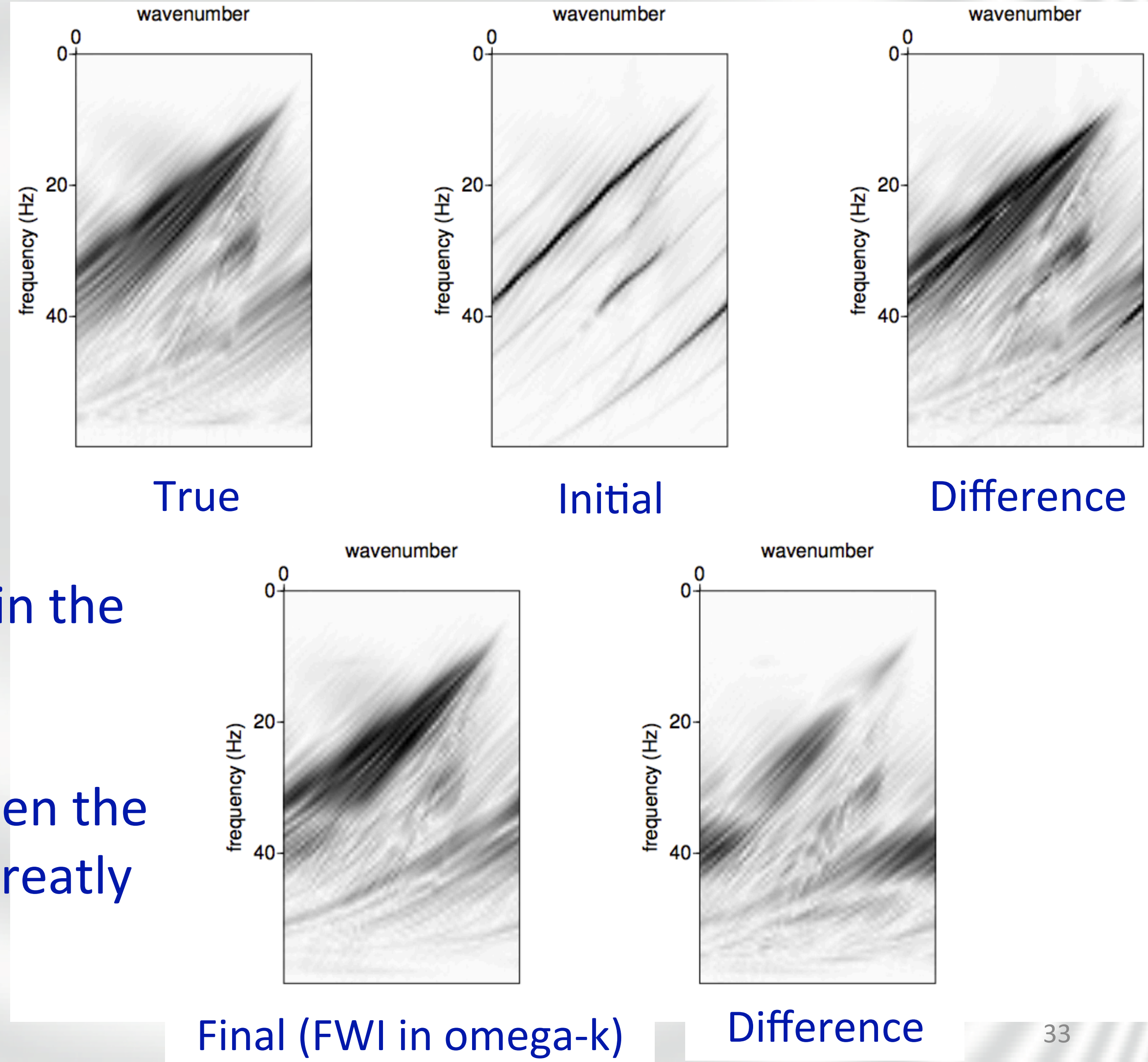
True | Initial | Difference

Lateral velocity gradient causes curve lines in surface waves

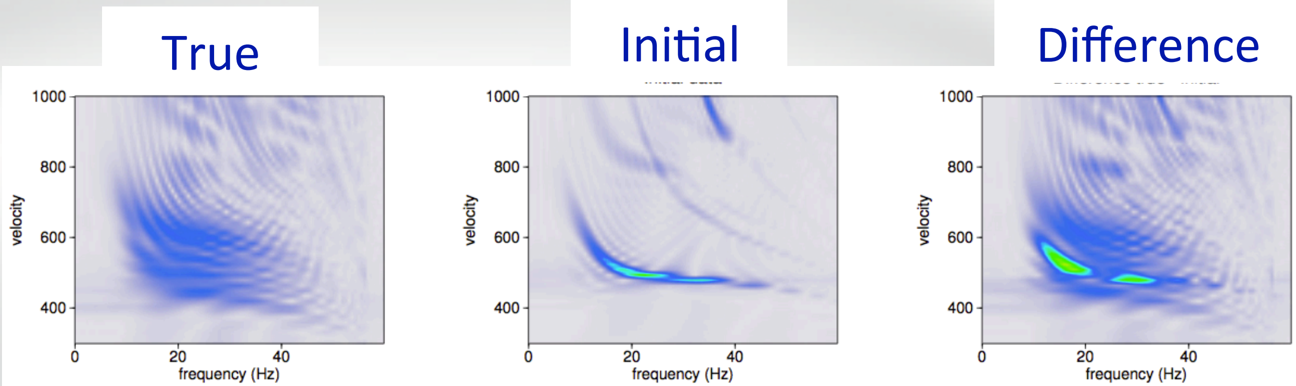
Data for the first source

DATA USED IN FWI

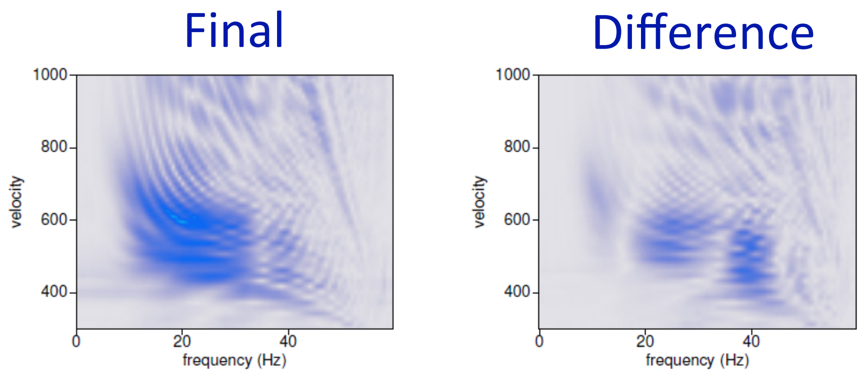
- Data in the omega-k domain
- Inversion moves in the right direction
- Difference between the true and final is greatly reduced



LOOKING AT THE DISPERSION CURVES



Dispersion curves are used in conventional surface wave analysis

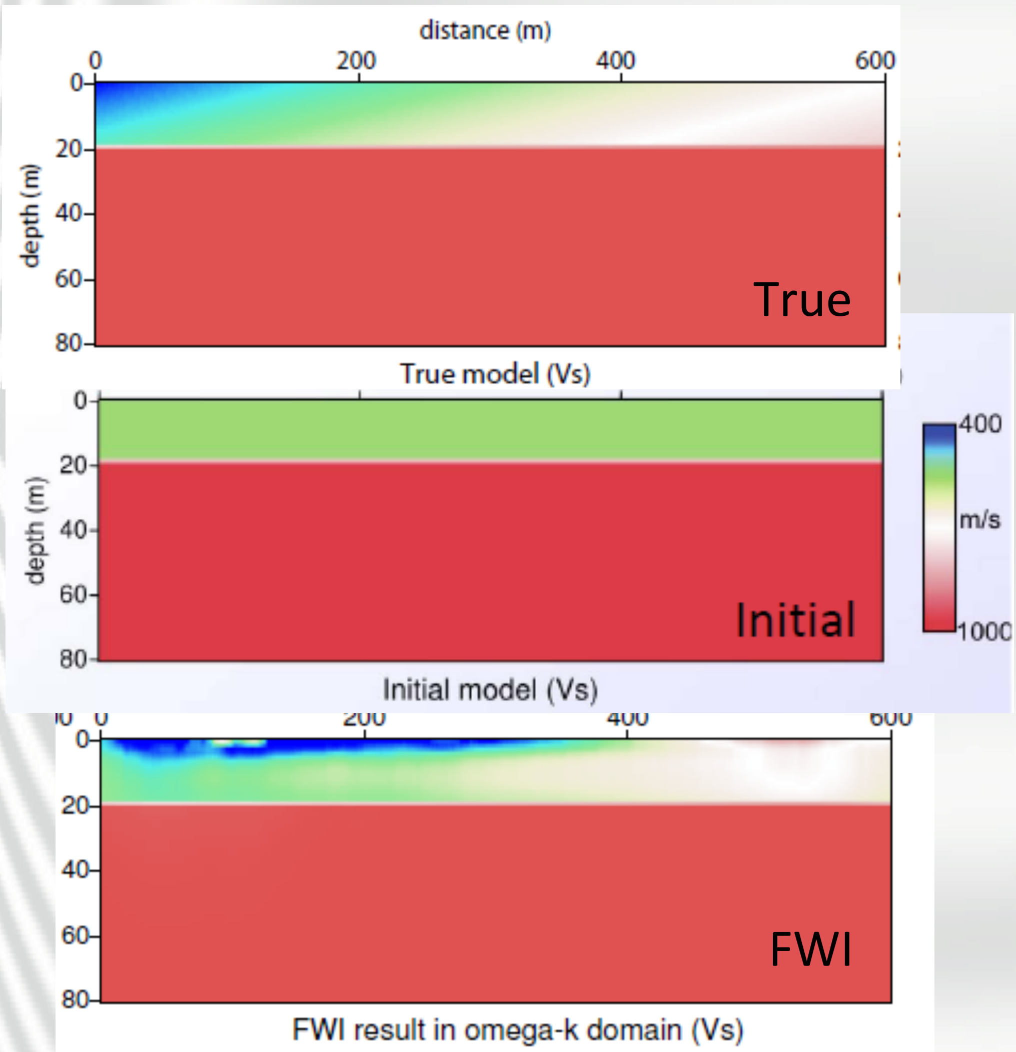


FWI result in omega-k

We could extract more information beyond dispersion curve analysis in the framework of FWI

(Ryden and Park, 2006; Maraschini and Foti, 2010)

MODEL UPDATING



Promising results: lateral variations for Vs parameter are recovered partially

Work in progress

- Starting from MASW initial model
- Inversion from this initial model

(Masoni et al, 2013; Masoni et al, 2014)

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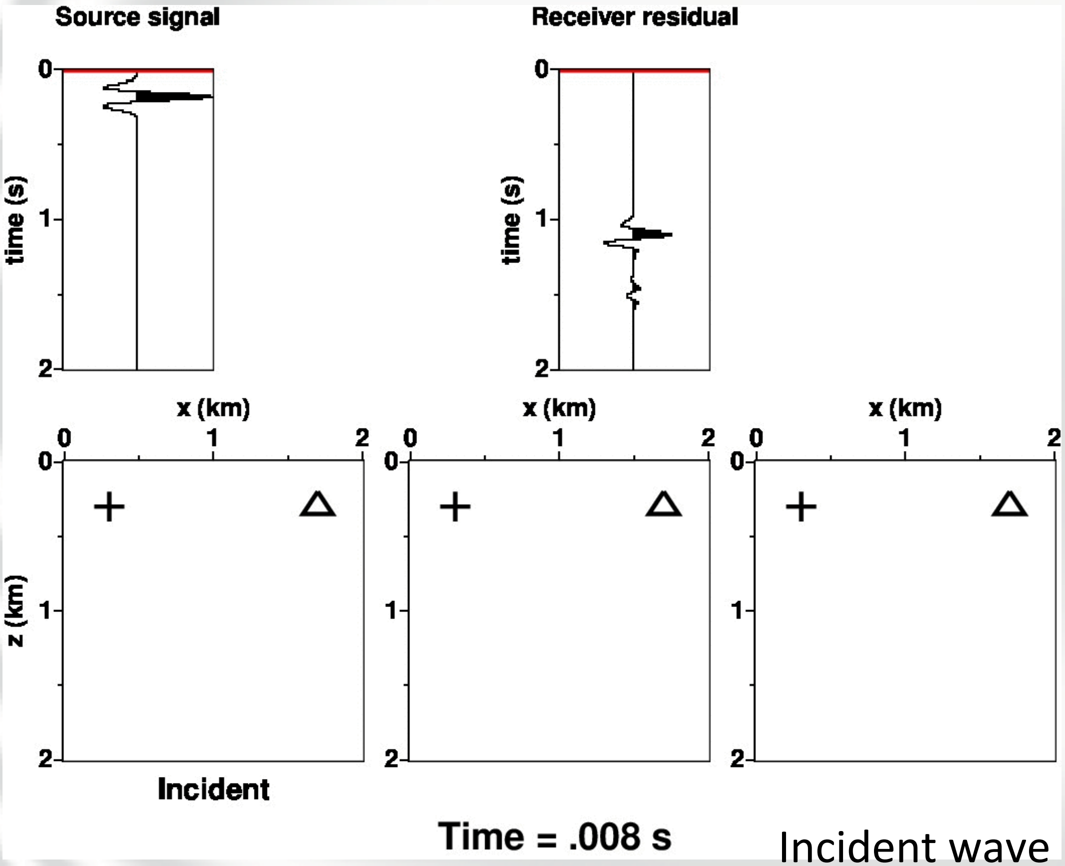
FWI of BODY WAVES



Considering diving waves and reflected waves information has led to the success of the FWI (no seismic phase identification)

Needs
Long offsets
Low frequency

Incident wave modeling

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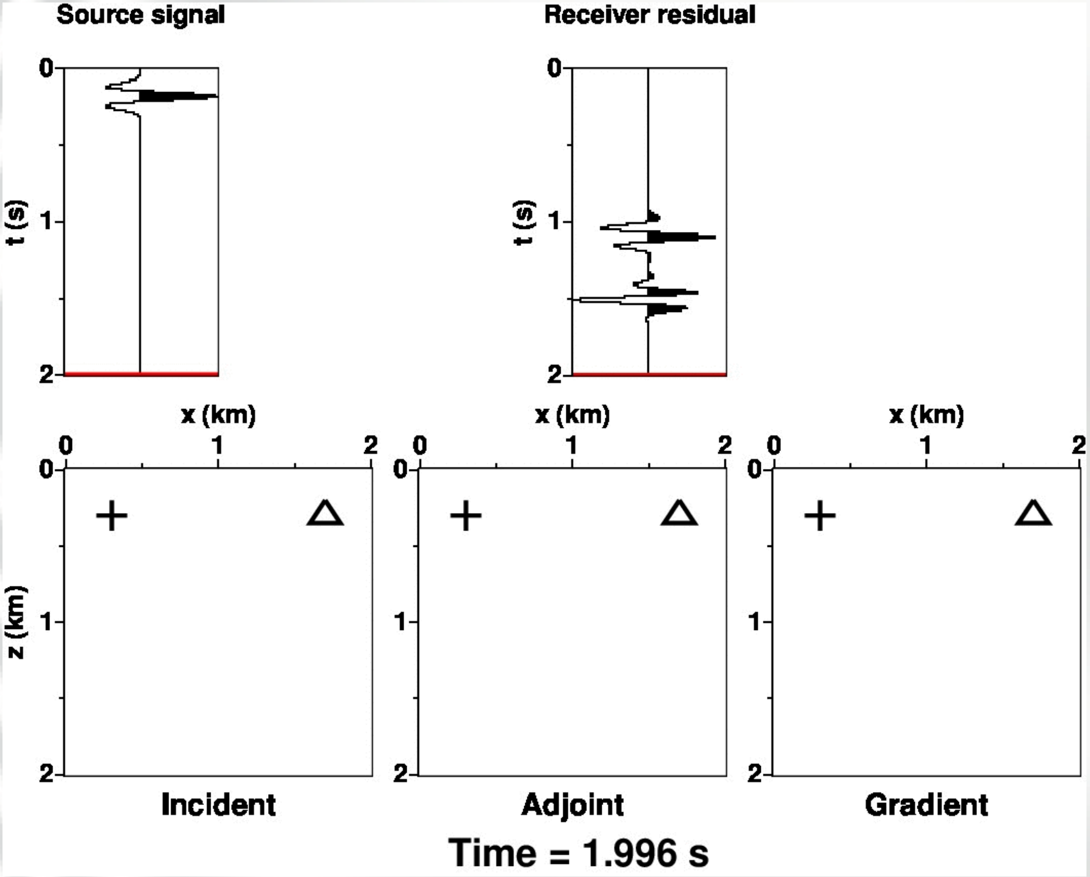
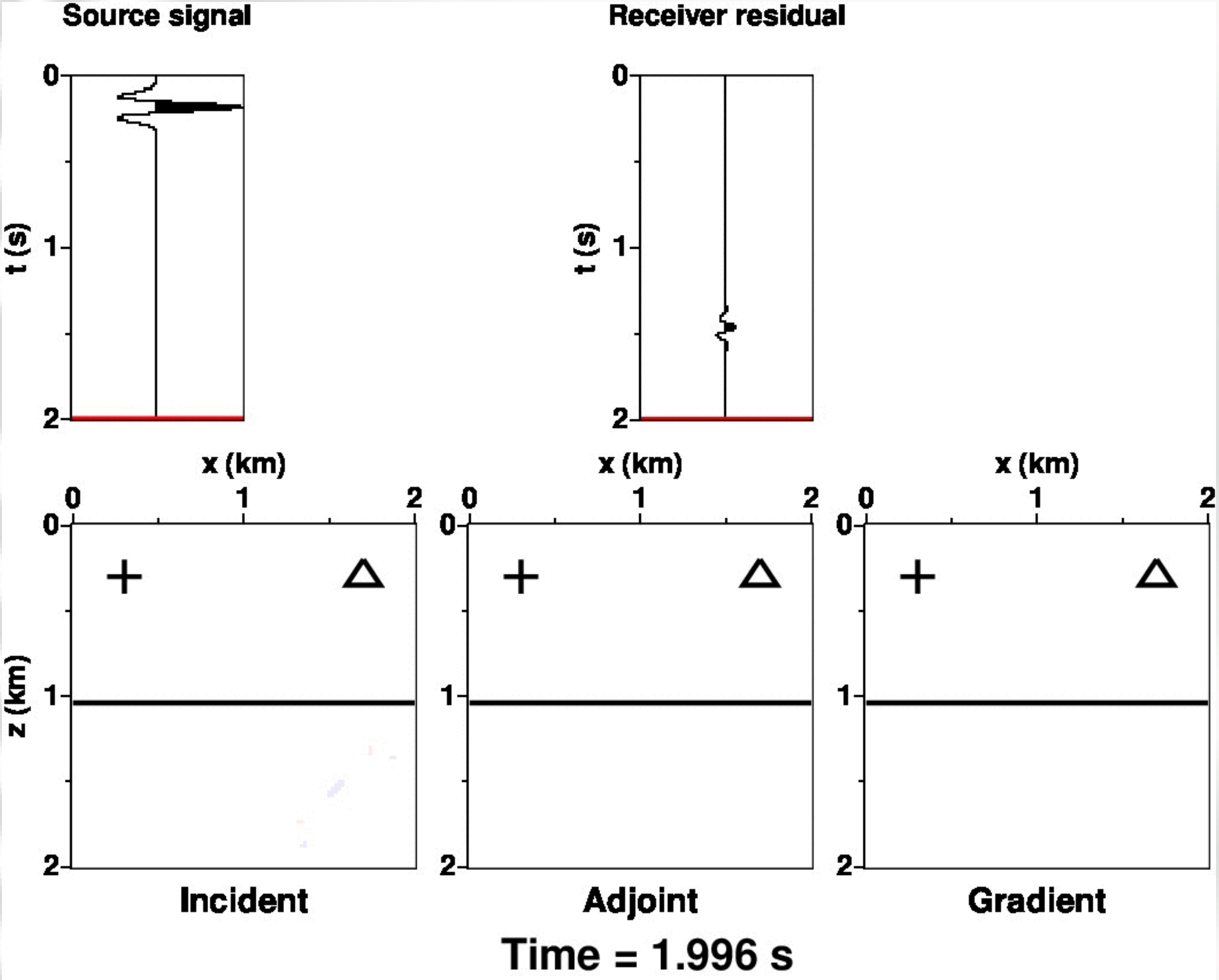
FWI of BODY WAVES



Gradient field connected to model update

Direct and reflected waves are interpreted the same way through first-order scattering (FWI)

FWI of REFLECTED WAVES only

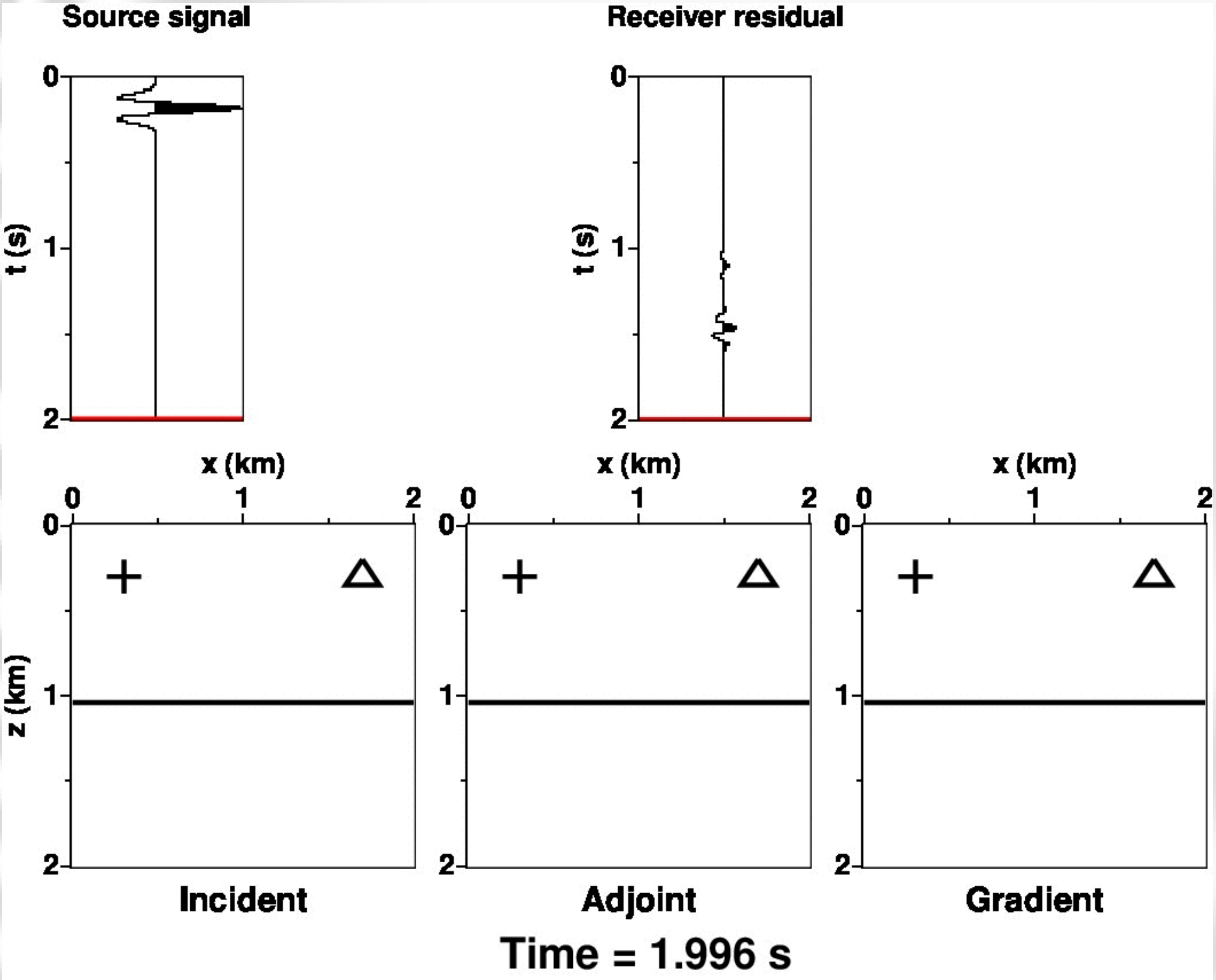


We assume the existence of an interface at the right vertical delay time

The initial model predicts well direct waves …

So only residual reflected waves are left unexplained for the FWI engine

MIXING GRADIENTS



We consider both direct and reflected phases residuals: therefore we select an imperfect initial model

Reflected waves contributes to the low frequency content as well as diving waves

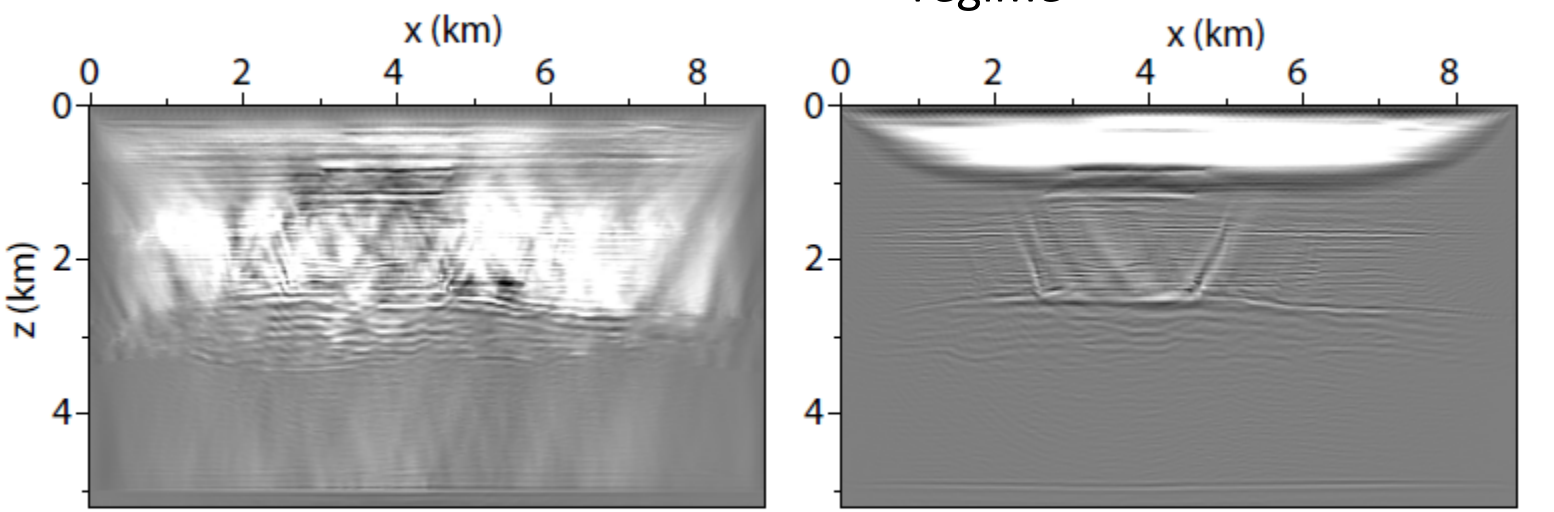
REALISTIC MEDIA

PhD of Wei Zhou (2015)

Both diving waves and reflection waves contribute to the low frequency content of the updating

Only diving (direct&refracted) waves contribute to low frequency

Reflection are on the migration regime



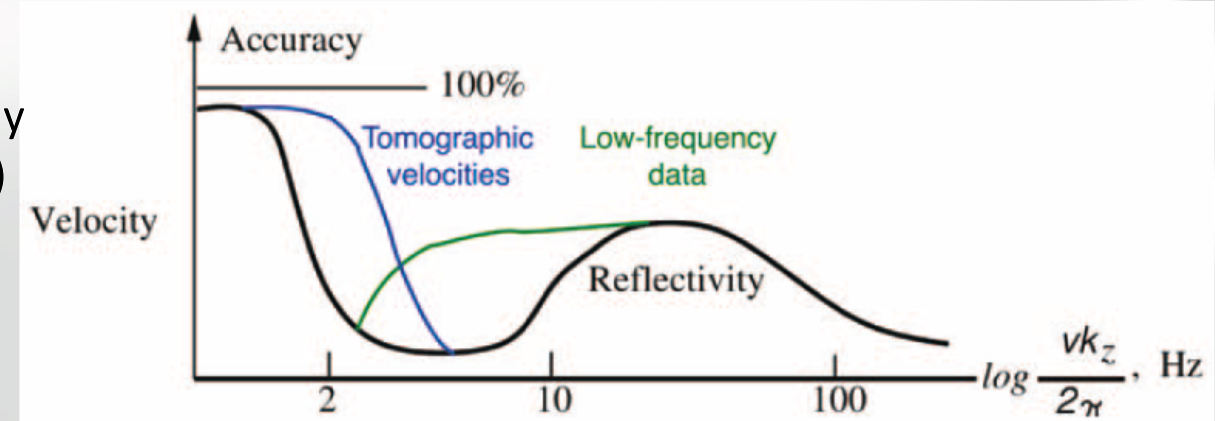
New FWI gradient

Classical FWI gradient

(Zhou et al, 2014)

UPDATING MODEL WITH ALL THESE GRADIENTS

From Biondi & Almomin (2013) inspired from early work of Claerbout (1984)



As done for travel-times and phases, we may combine imaging methods now using « full » traces …

- Direct and refracted phases sensitive to velocities
- Reflected phases sensitive to velocities and impedances (density)
- Surface phases sensitive to shear velocity (density & bulk velocity)

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OUTLINE

- Introduction on FWI
- Near surface seismic imaging issues
- Surface wave analysis
- Body wave analysis
  - Direct/refracted waves versus reflection waves
- Model impacts
- Conclusion

DATA-DRIVEN GRADIENT VERSUS MODEL-DRIVEN GRADIENT

We may be still unsuccessful with this pure data-driven approach

We may wish to introduce model prior information

This means just adding a model gradient to the data gradient

Tikhonov model term

Prior model term

Misfit function

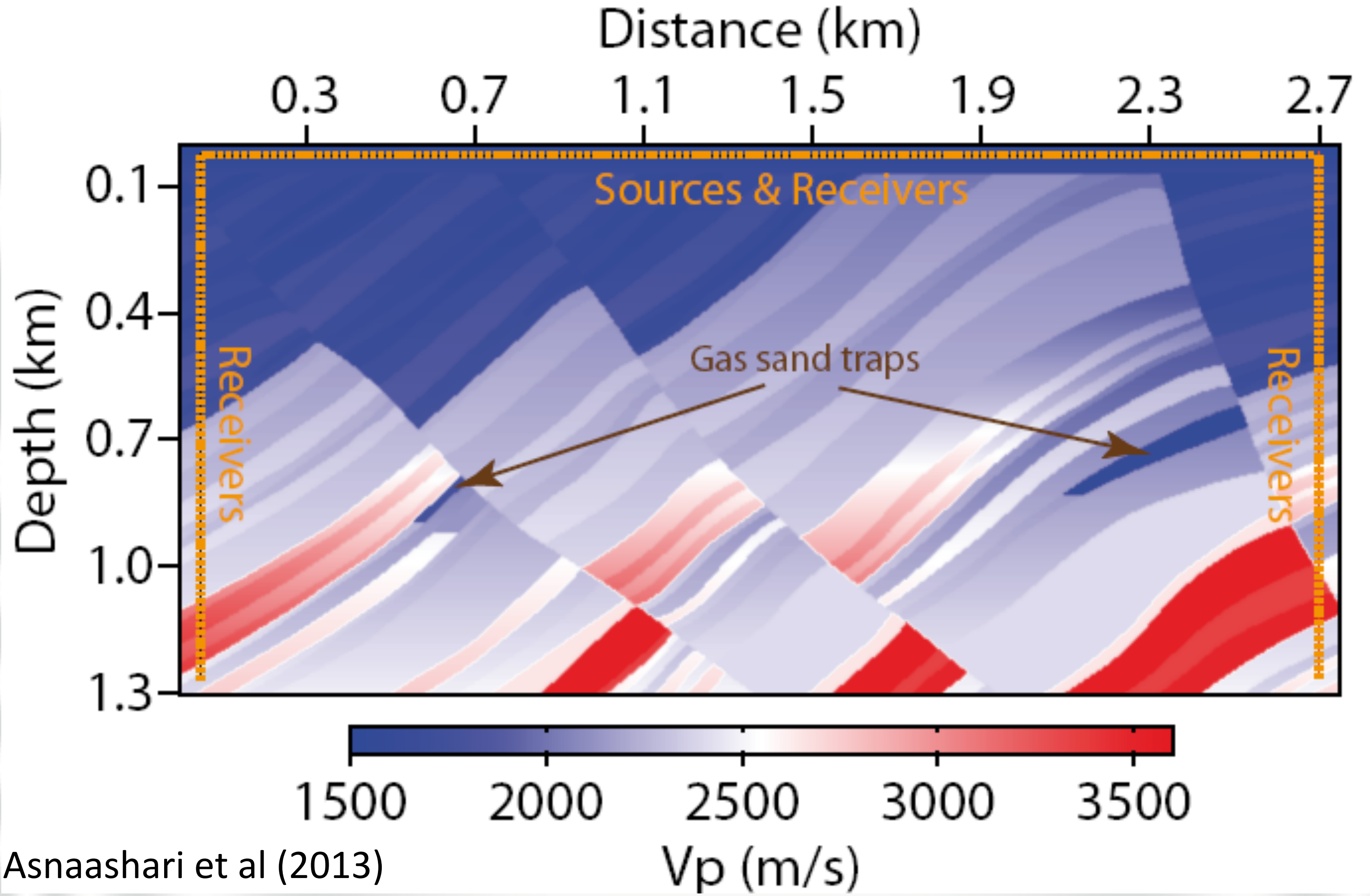
$$C(m)=\frac{1}{2}\Delta d^{\dagger} W_d \Delta d+\frac{1}{2}\lambda_1 m^t D m+\frac{1}{2}\lambda_2 (m-m_{prior})^{\dagger} W_m (m-m$$

Gradient

$$\nabla C_k(m)=J_k^{\dagger} W_d \Delta d+\lambda_1 D m_k+\lambda_2 W_m (m_k-m_{prior})$$

ZOOM ON THE MARMOUSI II

(Martin et al, 2006)

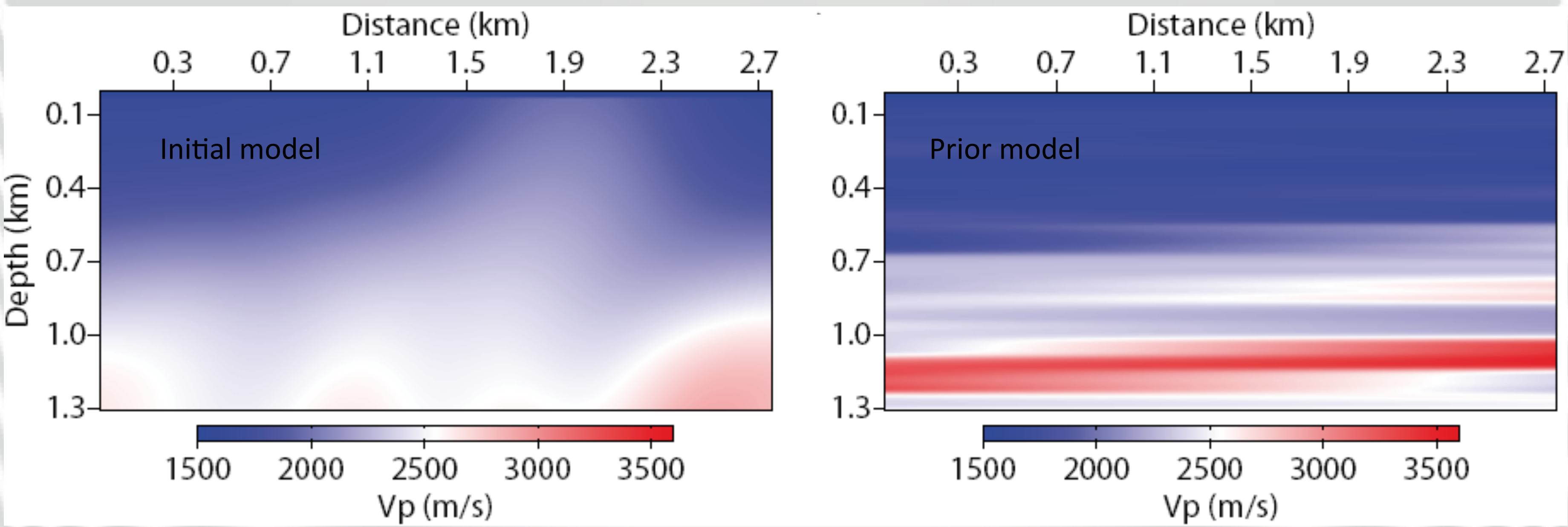


Asnaashari et al (2013)

INITIAL AND PRIOR MODELS

- Initial model: highly smoothed true model
- Prior model: linear interpolation of two velocity profiles in wells

Very small value for λ_1 , since we want to investigate only the effect of prior model to constrain the inversion

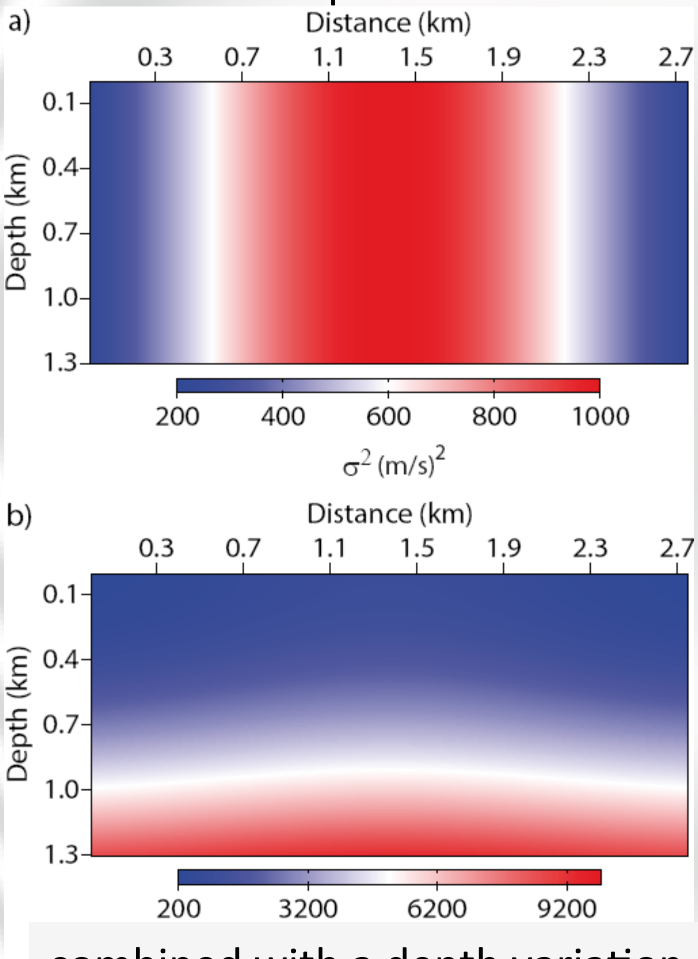


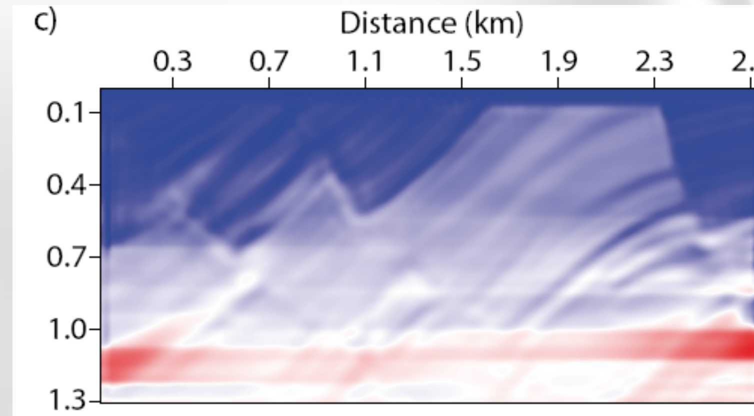
Wm DEFINITION

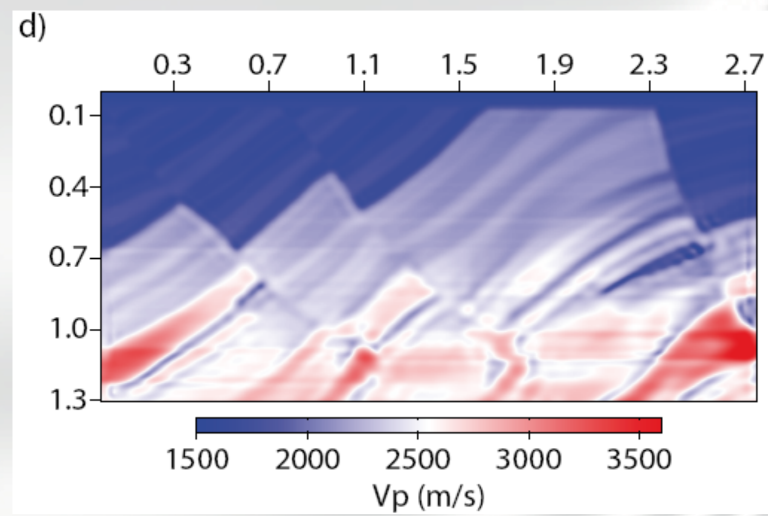
Selected hyper-parameters

$\lambda_1 = 20\ sec^2$ and

Two wells prior information





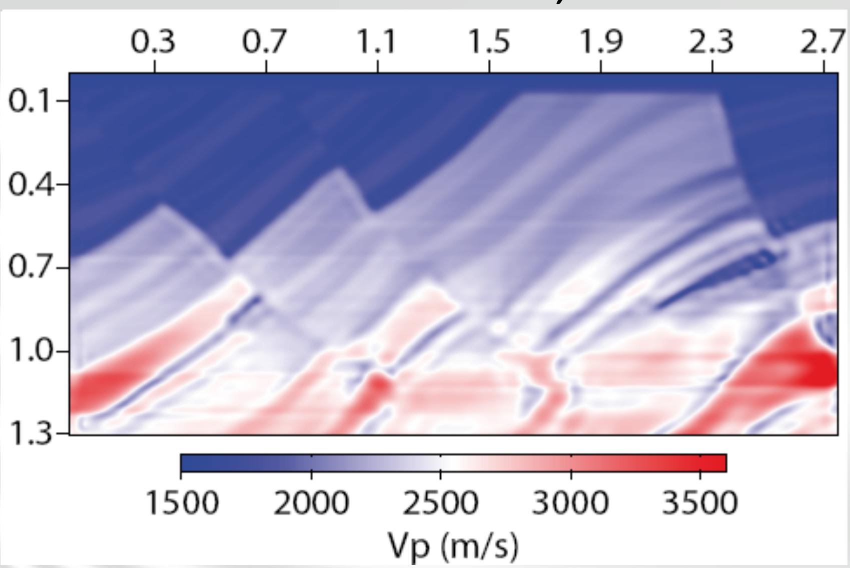


combined with a depth variation

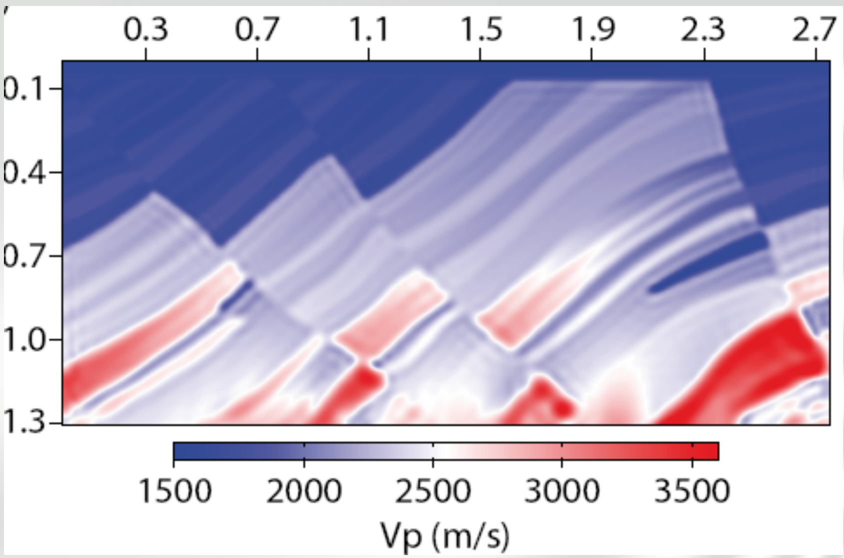
ONLY DATA SHOULD SPEAK

- In practice, the prior model can be far from reality and also the final FWI model can keep a significant footprint of the prior model structure due to fixed weight on prior term.

- Dynamic prior weighting in order to decrease gradually λ_2 with iterations, based on derivatives of cost function evolution.

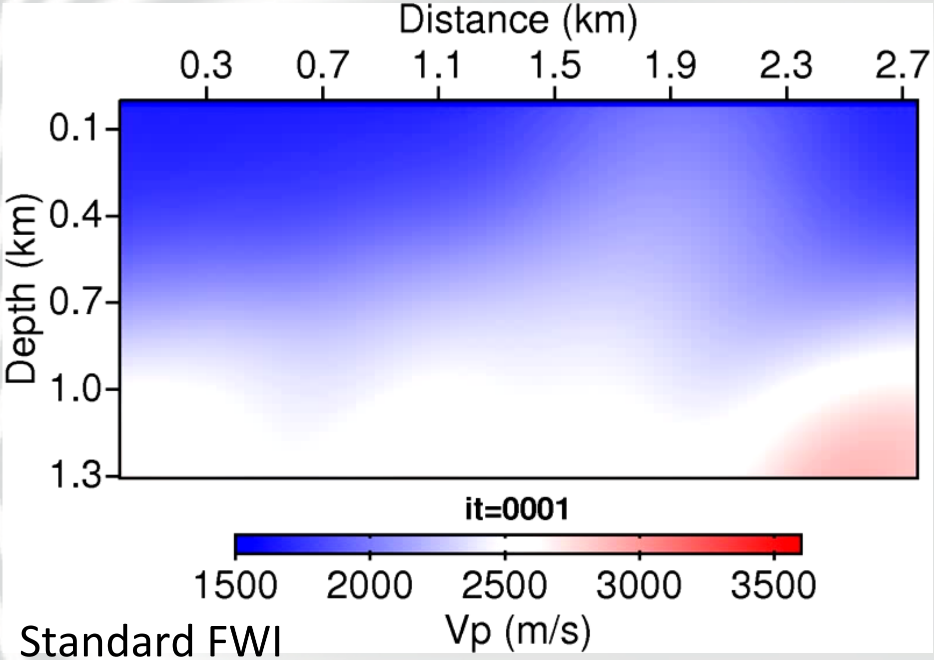


Fixed prior weight



Dynamic prior weight

MODEL-DRIVEN RECONSTRUCTION



Standard FWI

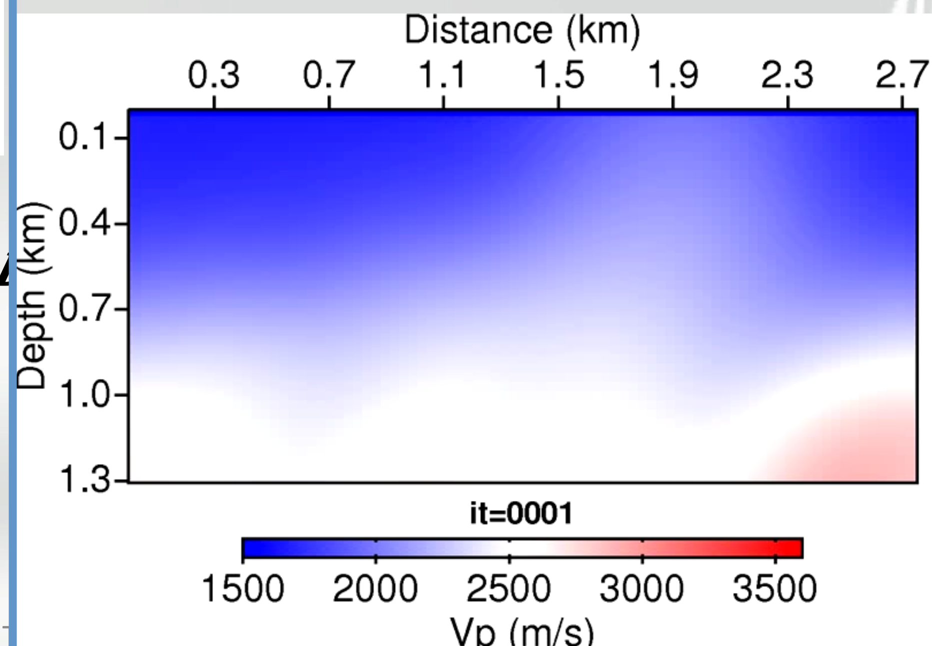
$$C(m)=1/2\ \Delta d^{\dagger} W_d \Delta d+1/2\ \lambda_1\ m^t$$

Data misfit only with simple regularization (Tikhonov term)

Automatic reduction of hyper parameter

$$C(m)=1/2\ \Delta d^{\dagger} W_d \Delta d+1/2\ \lambda_1\ m$$
$$+1/2\ \lambda_2\ (m-m_{prior})^{\dagger}\ W_m$$

Prior model/dynamic weight



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CONCLUSION

Separate phase analysis could increase the low wavenumber part of the velocity spectrum, especially surface waves

Model prior information should also fill in the velocity spectrum and may provide different imprints in the seismic data

New FWI strategies are available for handling the complexity of the near surface

Geology, borehole profiles, constraints on physical properties (density from gravity, for example …)

Models of near surface structures

- Density
- Anisotropy parameters
- Attenuation parameters
- Elastic parameters

PERSPECTIVE

Still the demonstration in a real case has to be done (by us?) …

Isabella Masoni supported by TOTAL R&D.

Amir Asnaashari supported by TOTAL

Wei Zhou supported by SEISCOPE consortium

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FWI ↗ $\lambda/2$

Thank you very much for your attention

Many thanks to sponsors

of the Seiscope consortium

FWI – CLASSICAL WORKFLOW

Initial velocity model
m_0

Forward modeling

Wave equation
ie. finite differences

Synthetic data
$\mathbf{d}_{\mathrm{cal}}(m)$

Observed data
$\mathbf{d}_{\mathrm{obs}}$

Calculate misfit

$$C = \frac{1}{2}\left(\mathbf{d}_{\mathrm{obs}}(x,t) - \mathbf{d}_{\mathrm{cal}}(x,t)\right)^2$$

Minimize L2 norm of difference

Calculate model update

$$C'(m) = g \qquad C''(m) = H \text{ (approx.)}$$

$$H\Delta m = -g$$

*Need to compute the **gradient** and the **adjoint source** for inversion*

Updated velocity model

$$m = m_0 + \Delta m$$

Iterative approach

FWI – CLASSICAL WORKFLOW

Initial velocity model
m_0

Forward modeling
Wave equation
ie. finite differences

Synthetic data
$\mathbf{d}_{\mathbf{cal}}(m)$

Observed data
$\mathbf{d}_{\mathbf{obs}}$

Calculate misfit

$$C = \frac{1}{2}\left(\mathbf{d}_{\mathbf{obs}}(x,t) - \mathbf{d}_{\mathbf{cal}}(x,t)\right)^2$$

Minimize L2 norm of difference

- Suitable misfit function?
- Avoid problem of cycle skipping and local minima?

Calculate model update

$C'(m) = g \quad C''(m) = H$ *(approx.)*

$H\Delta m = -g$ *Need to compute the **gradient** and the **adjoint source** for inversion*

Updated velocity model

$$m = m_0 + \Delta m$$

Iterative approach

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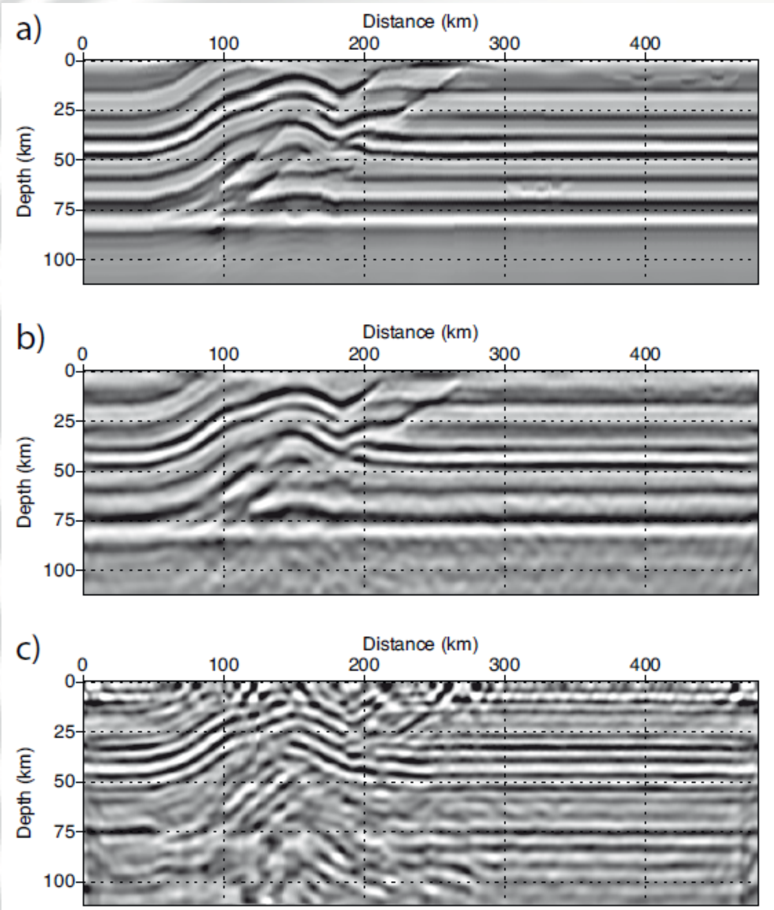
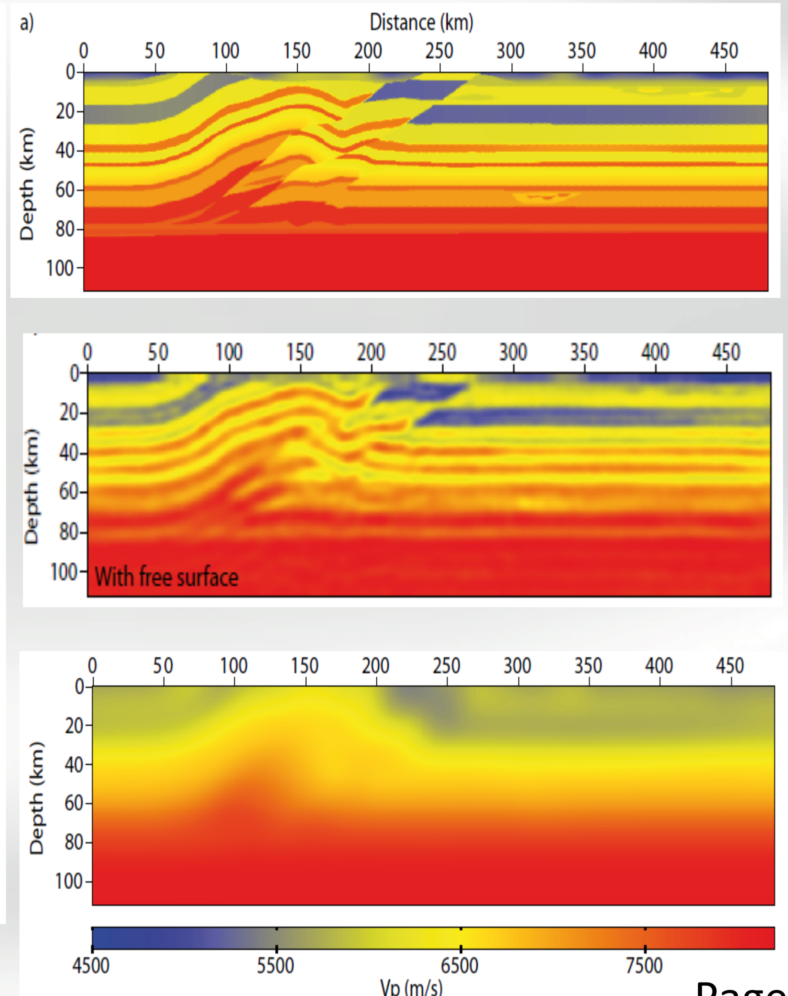
Macromodel building for improved migration



RTM



Exact

FWI

Initial

Pageot et al (2013)

Separation between two scales

Recorded seismic traces bring different information from medium properties

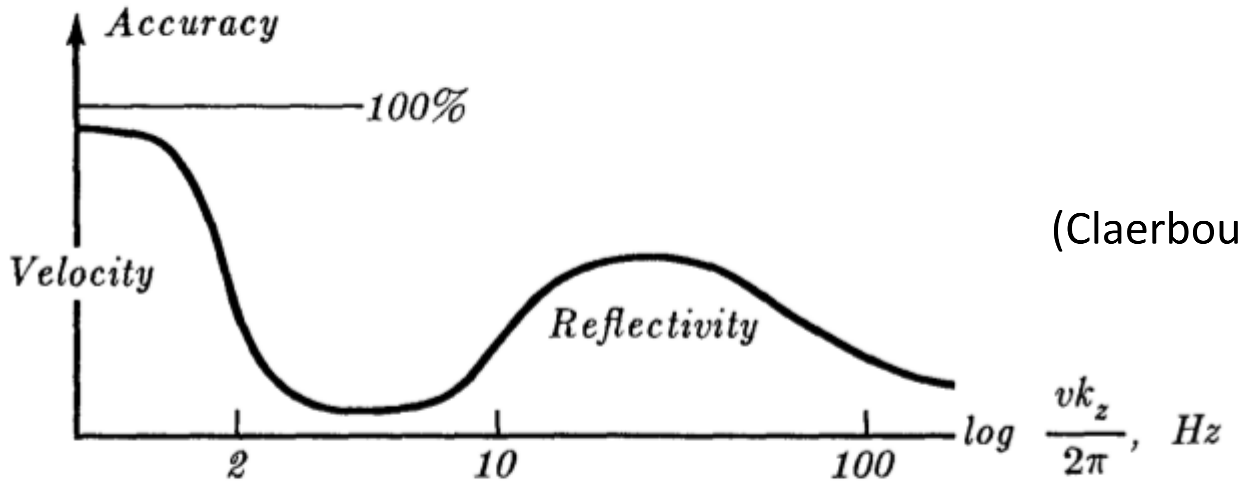


FIG. 1.4-3. Reliability of information obtained from surface seismic measurements.

(Claerbout, 1984)

Macro-model Velocity from low frequency content
Impedance/Reflectivity from high frequency content

Various signatures of parameters on data