

# Characterization of crustal models for quantitative ground motion estimation

## C – Model Design (short-scale velocity structure)

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Some slides are inspired from Seiscope Group (Pis  
Romain Brossier & Ludovic Métivier

# Translucent Earth

## Medium upscaling and downscaling



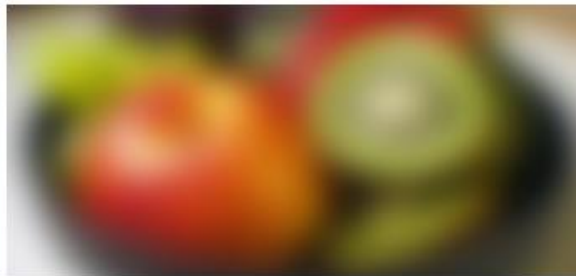
Real medium

## Seismic imaging – upscaling

- Seismic finite frequency (sources/receivers)
- Observer effect (acquisition design)
- Attenuation (Q)
- Imaging methods (e.g. travel-time tomography, FWI)
- ...



Traveltime information ( $\sqrt{\lambda L}$ )



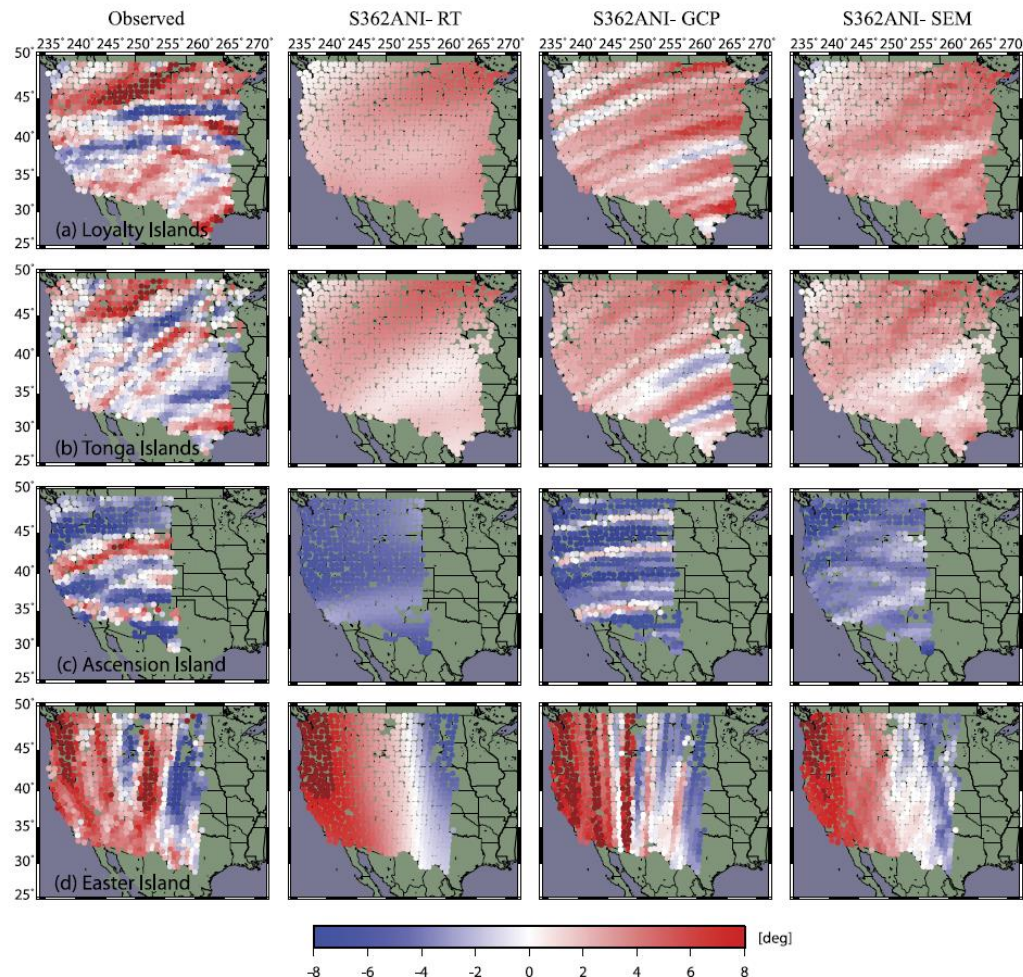
Waveform information ( $\frac{\lambda}{2}$ )



Interpretation (downscaling)

Ground motion estimation: waveform evaluation

# Wave information: back-Az observables



For 4 earthquakes,  
measured arrival angles across the  
USArray network &  
predicted angles for a S362ANI  
model using  
(1) ray tracing,  
(2) great-circle approximation and  
(3) SEM modeling

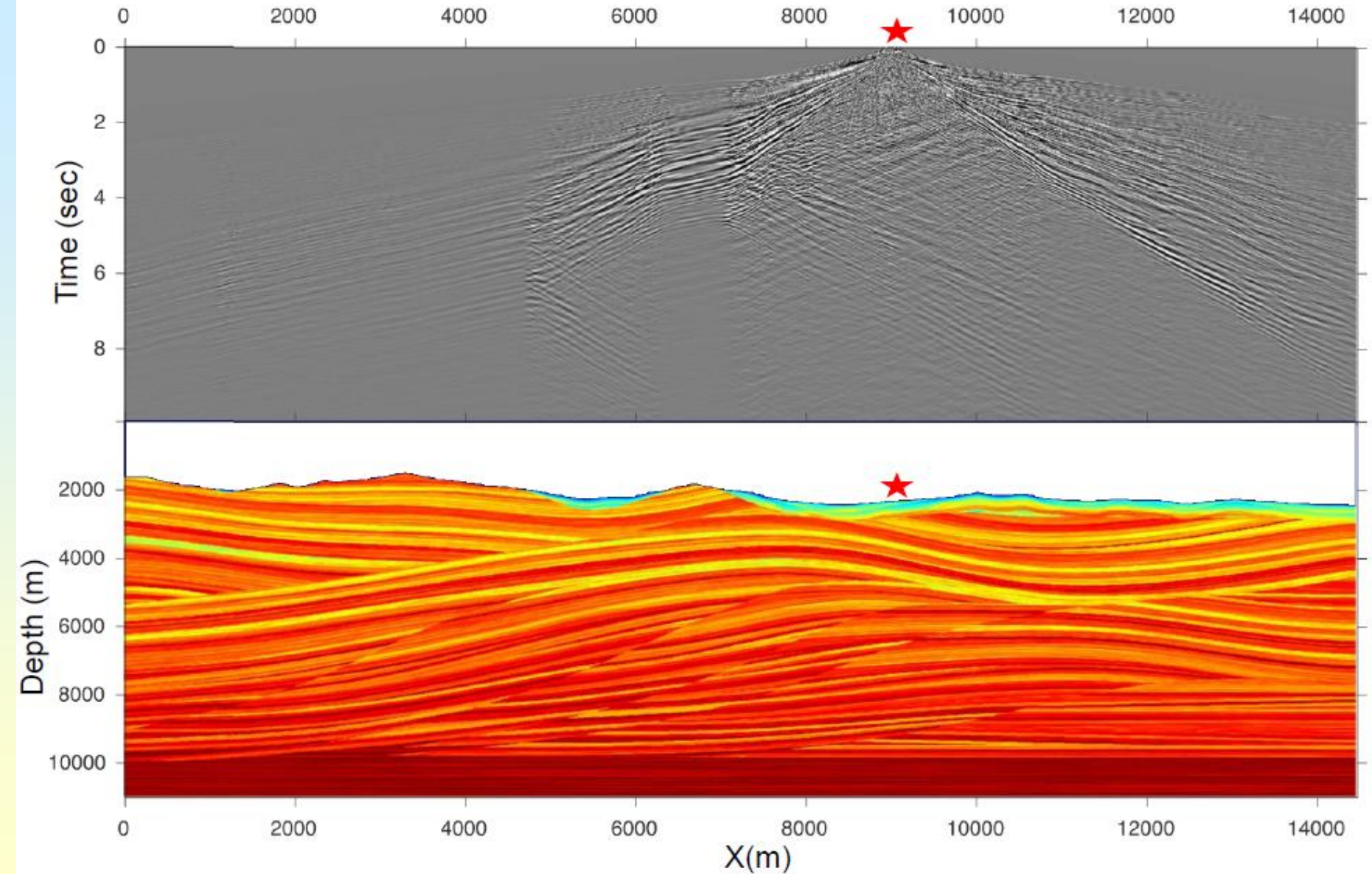
Observables have more information than  
those predicted by built Earth models

How to improve tomographic  
approaches for honoring both  
traveltimes (or phases) and azimuthal  
(and/or slowness) measurements?

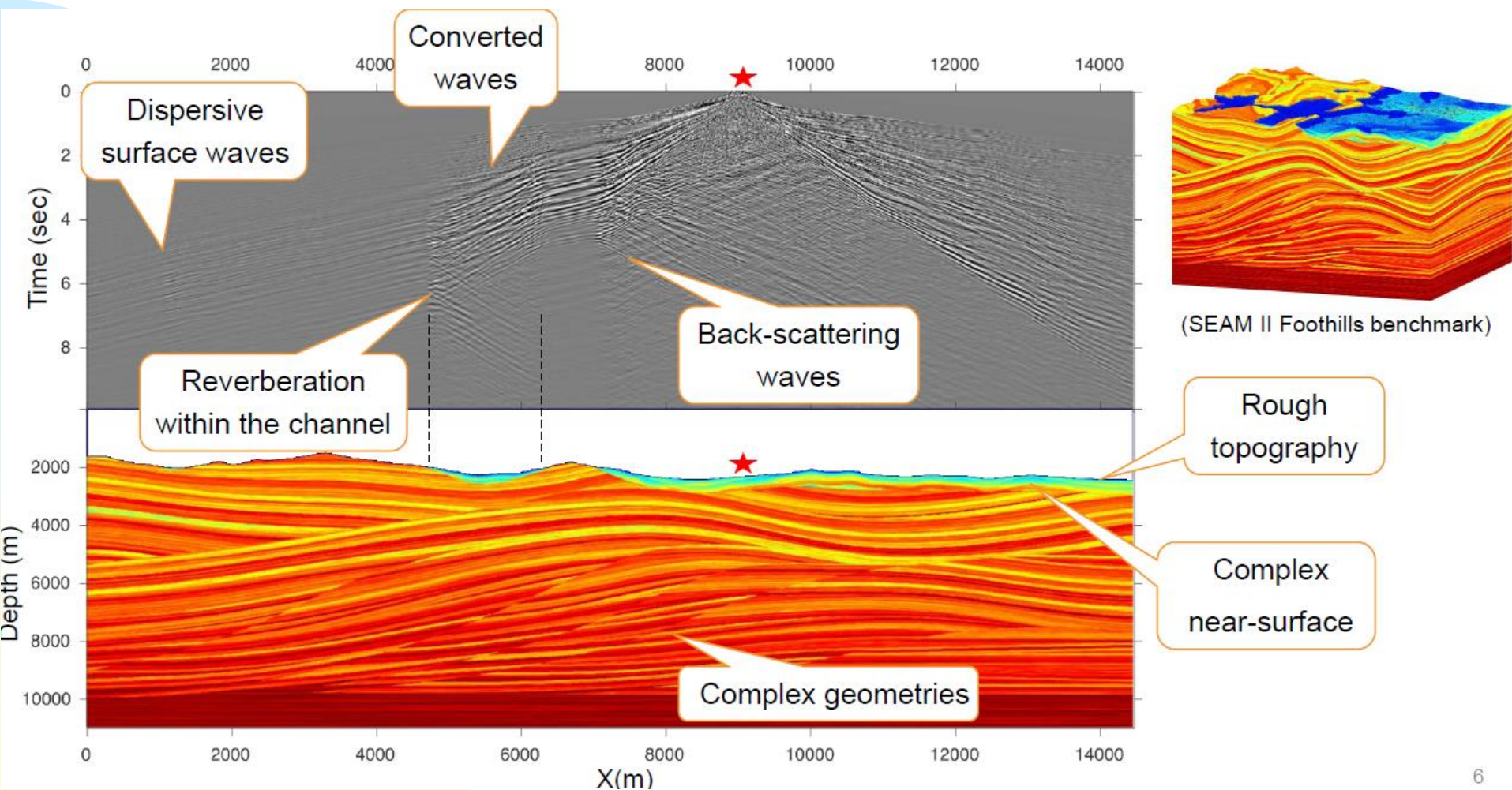
Figure 7 from Foster, Ekström & Hjörleifsdóttir (EPSL, 2014)



# Richness of seismograms!



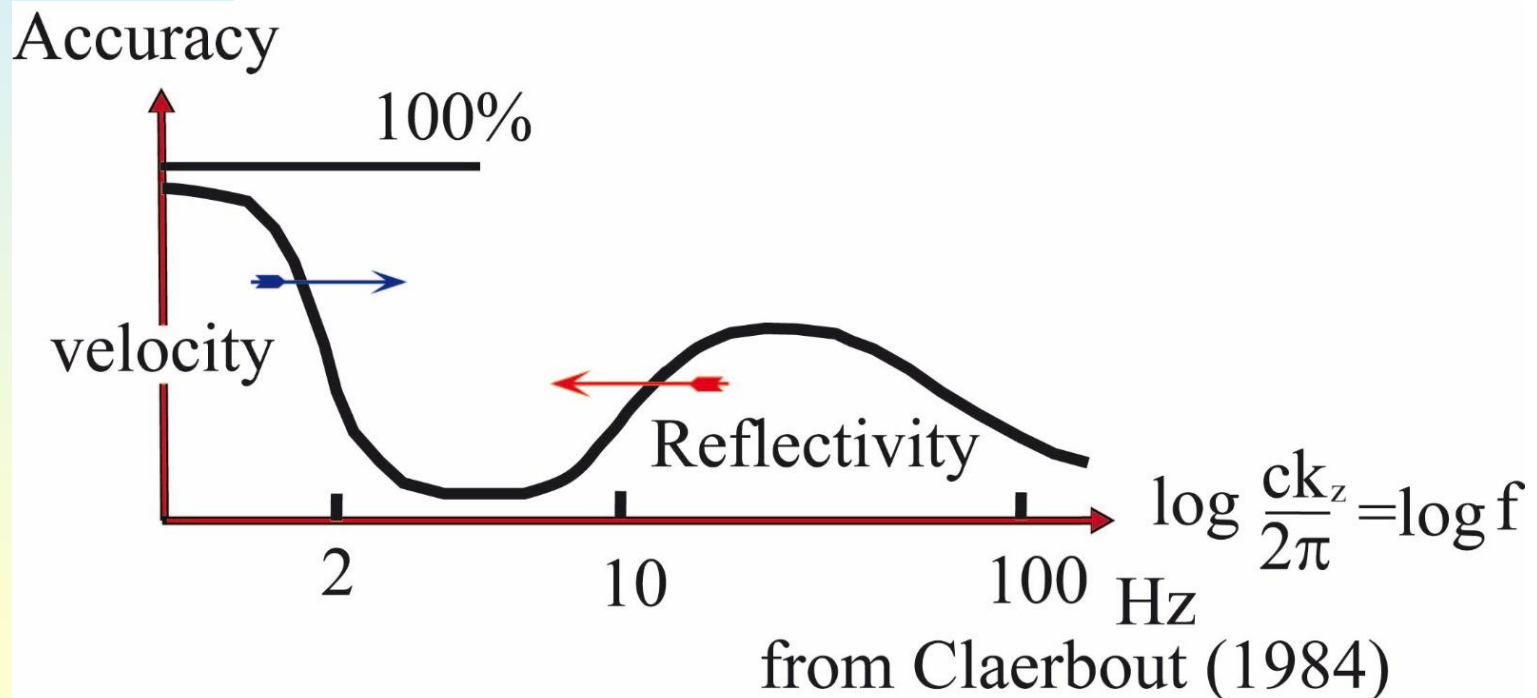
# Richness of seismograms!



# Related hierarchical structure

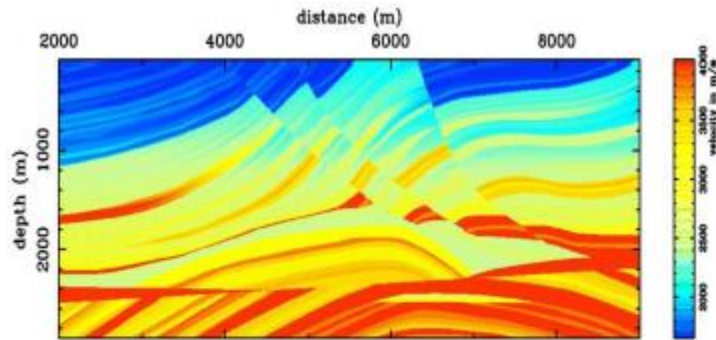
## Two scales show up in the model reconstruction

Recorded seismic traces bring different information from medium properties

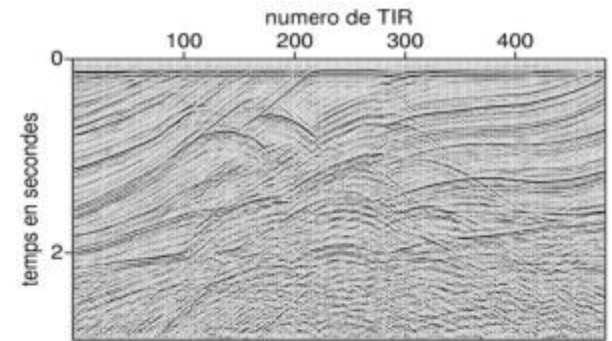




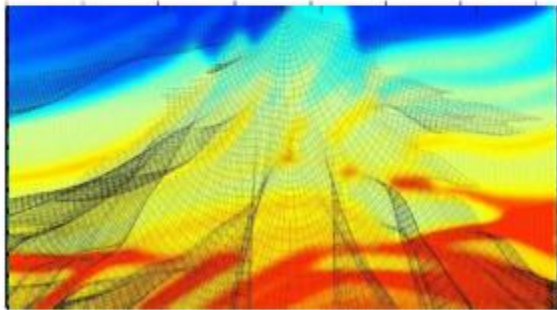
# Two-steps procedure



Medium

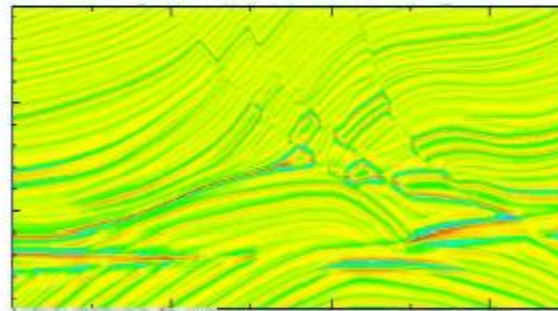


Data



Velocity model

+

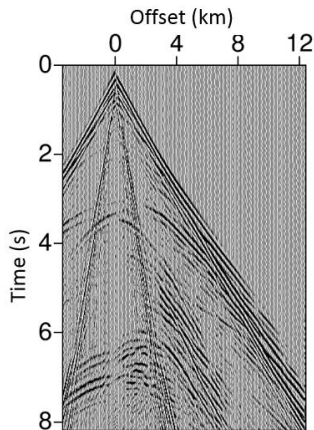


Migration/Inversion

# Basic seismic imaging workflows

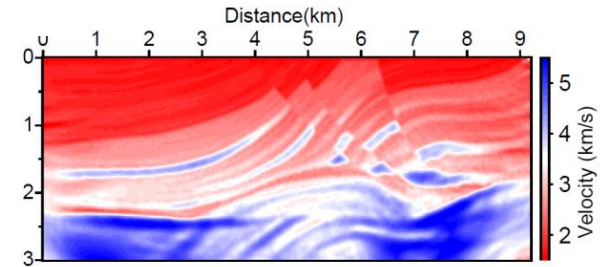
Phase (traveltime for non-dispersive wave) drives imaging

Data



Quantitative model?

Velocity based on waveform



FWI

LSRTM

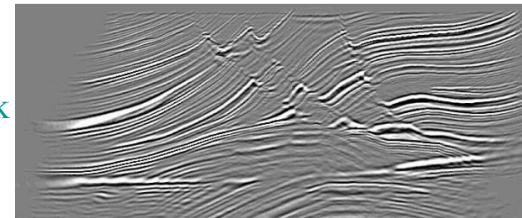


RTM

or

PDM

high-k



Qualitative model?

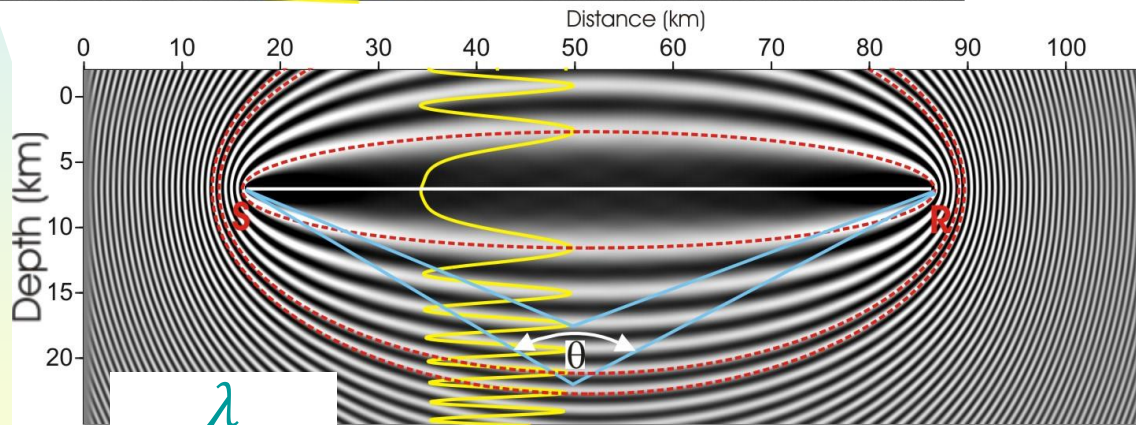
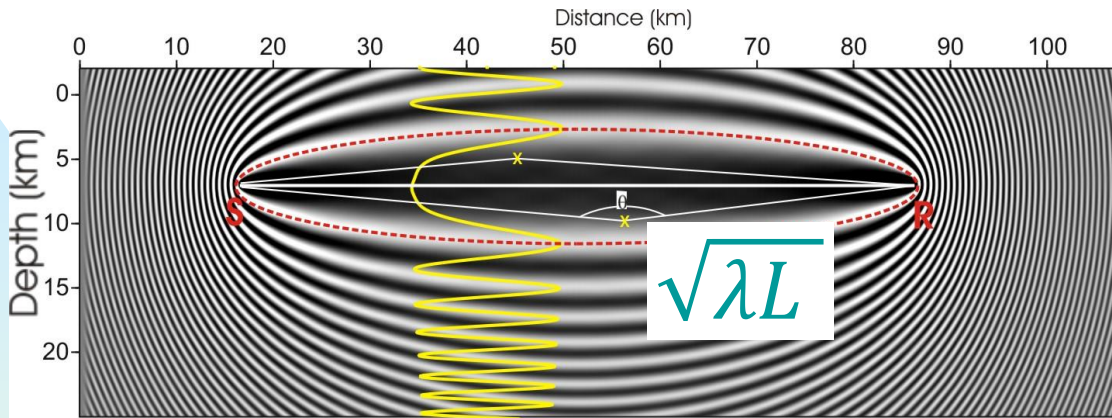
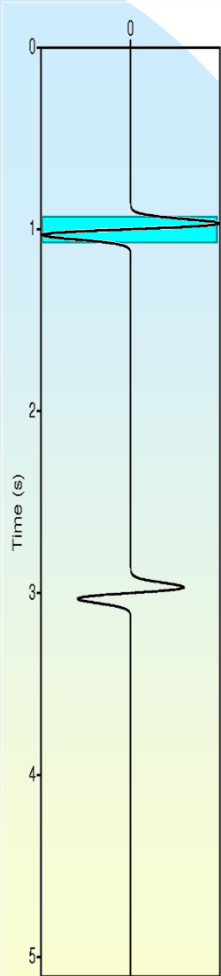
Reflectivity based on migration

Macro-model based on velocity analysis



# Wavepath: sensitivity kernel

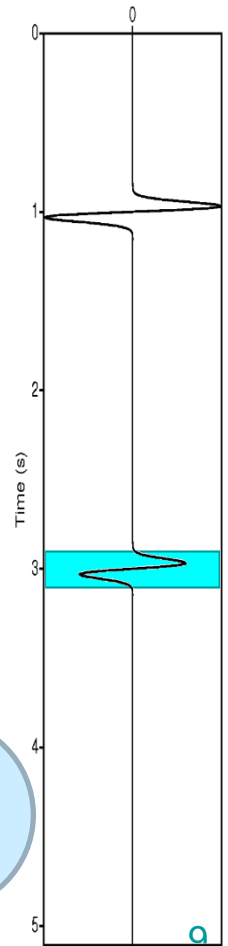
From transmission information (velocity analysis) ...



$$\frac{\lambda}{2\cos(\frac{\theta}{2})}$$

Inverse of  $K_z$

... to reflection information (migration, fwi)

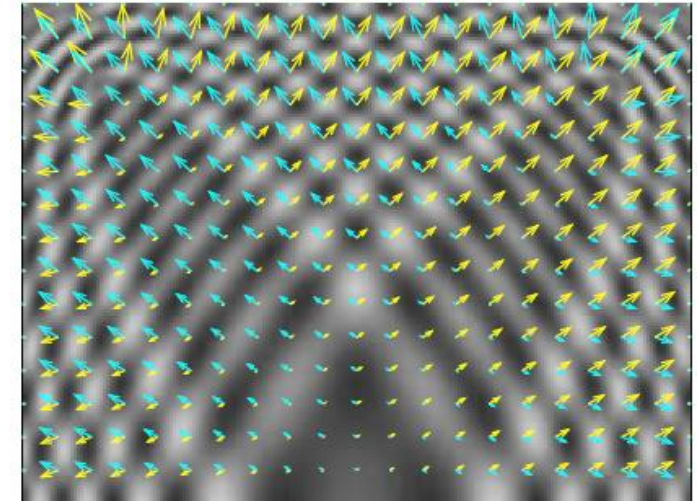
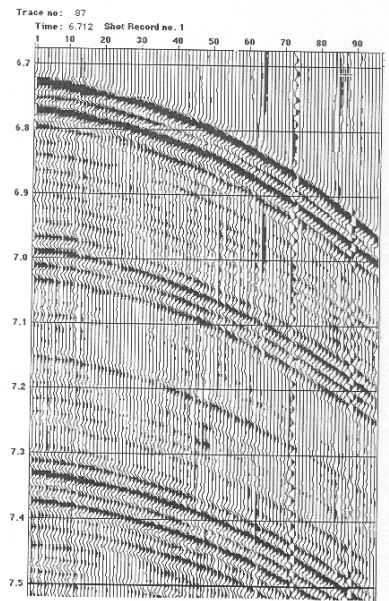


# Misunderstood concept

## Macro-model reconstruction

Kinematic correction:  
NMO velocity

$$T_x^2 = T_0^2 + \frac{X^2}{V_{nmo}^2}$$

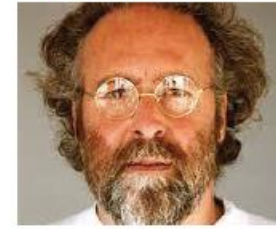


NMO velocity: hyperbolae lines of reflections gives information on down/up propagation ...

Wave-matter interaction: transmission regime based on reflection events

# FWI: using complete records

Pr. A. Tarantola



*1<sup>st</sup> paper on FWI: Geophysics, 1984*

## Full Waveform Inversion FWI

No prior identification ->  
No prior scale separation!



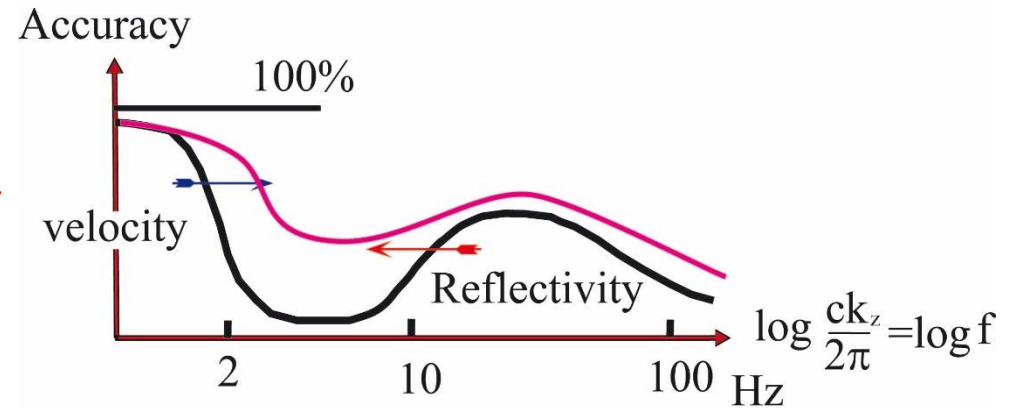
# FWI: the dream

**Broadband sources**  
**Complete illumination**  
**of targets**

**The dream ...**

Merging the velocity-model building and the migration into one integrated task when considering full waveforms

Continuous sampling of the wavenumber spectrum and filling the intermediate wavelength gap.

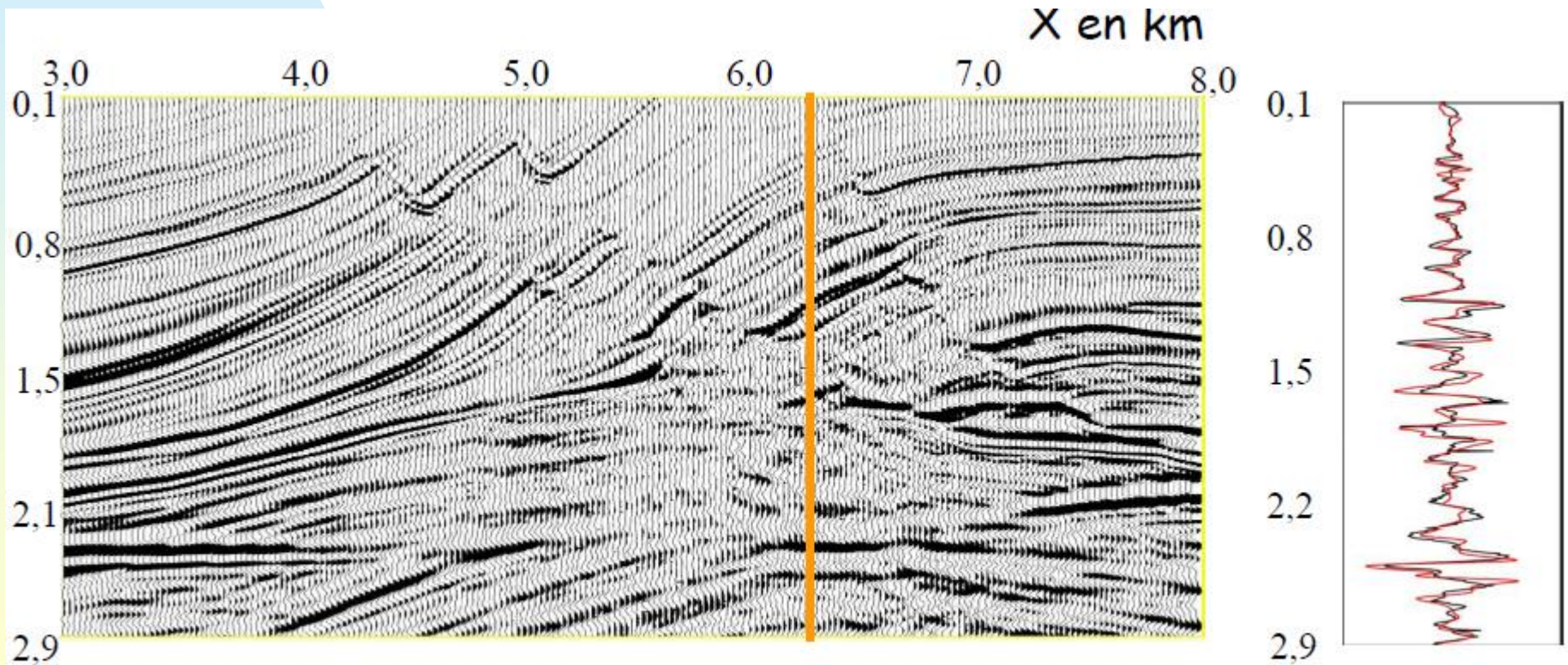


Tarantola (1984, 1987)

# Quantitative interpretation

Short-scale variation of physical properties

allowing wave propagation



# Data calibration issues

## Using records as they are

Acquisition design (source & receiver positioning & orientation?)

Time synchronization (GPS now! Clock precision  $< 1 \text{ ms}$   $\rightarrow 0.1 \text{ ms}$ )

Amplitude calibration (instrument!; installation coupling!)  
(wavefield  $\rightarrow$  waveform) relaxes installation & experimental procedure !

## The main difficulty!

Source knowledge (source signature; radiation pattern)

quite challenging for natural sources (earthquakes: focal mechanism)

still difficult for active sources (shots, blasts: source signal  $s(t)$ )

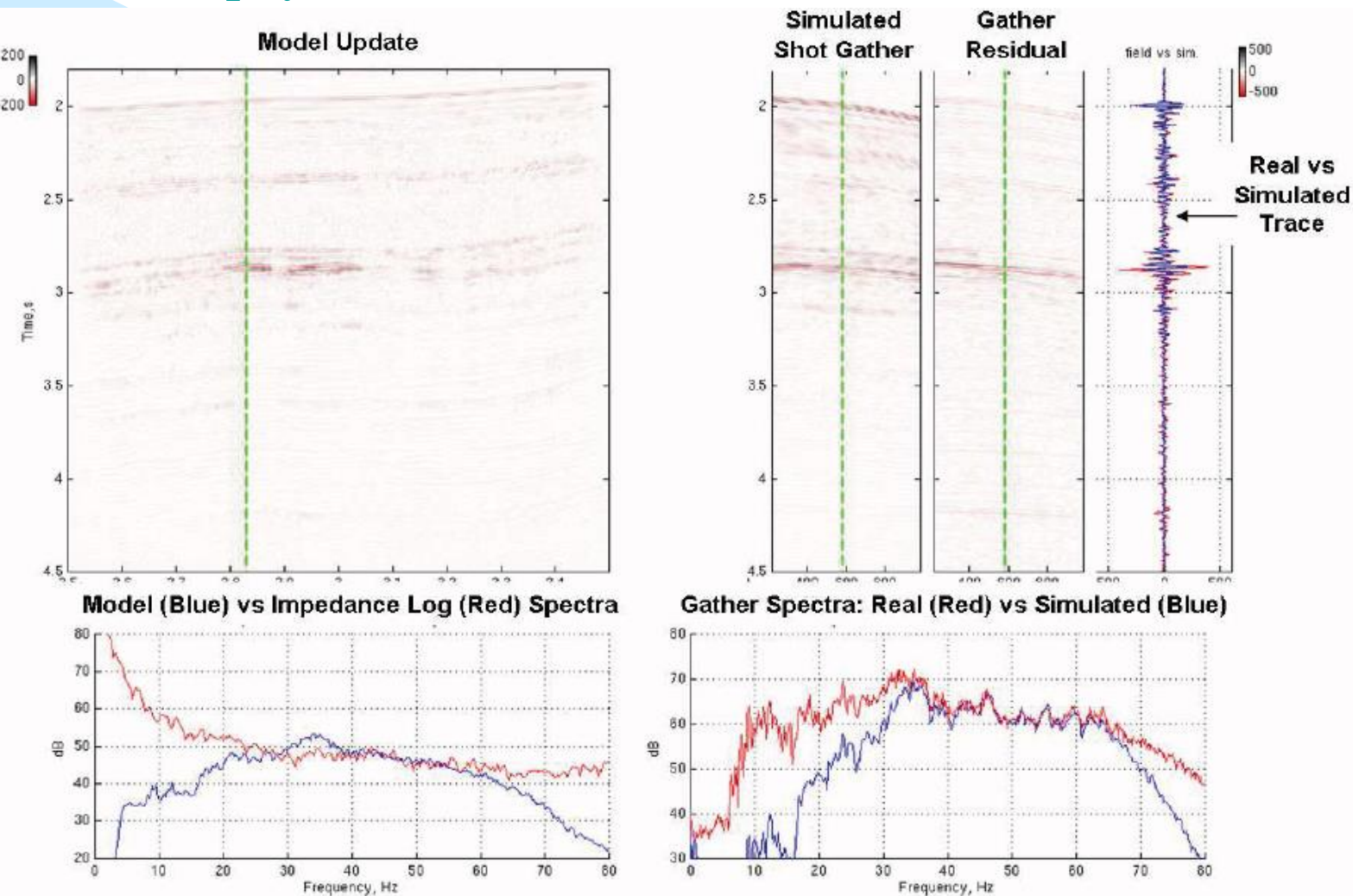
(wavefield  $\rightarrow$  waveform) mitigates these issues



# Source spectral shaping

(Lazaratos et al, 2011)

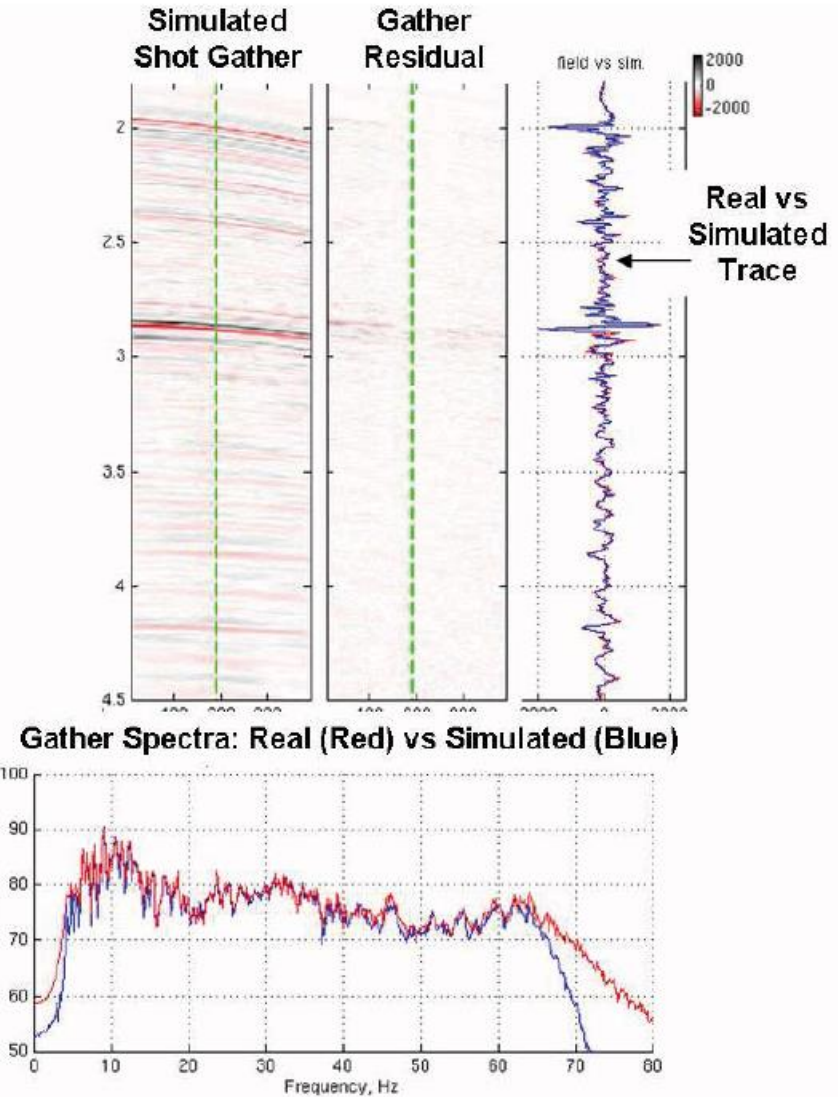
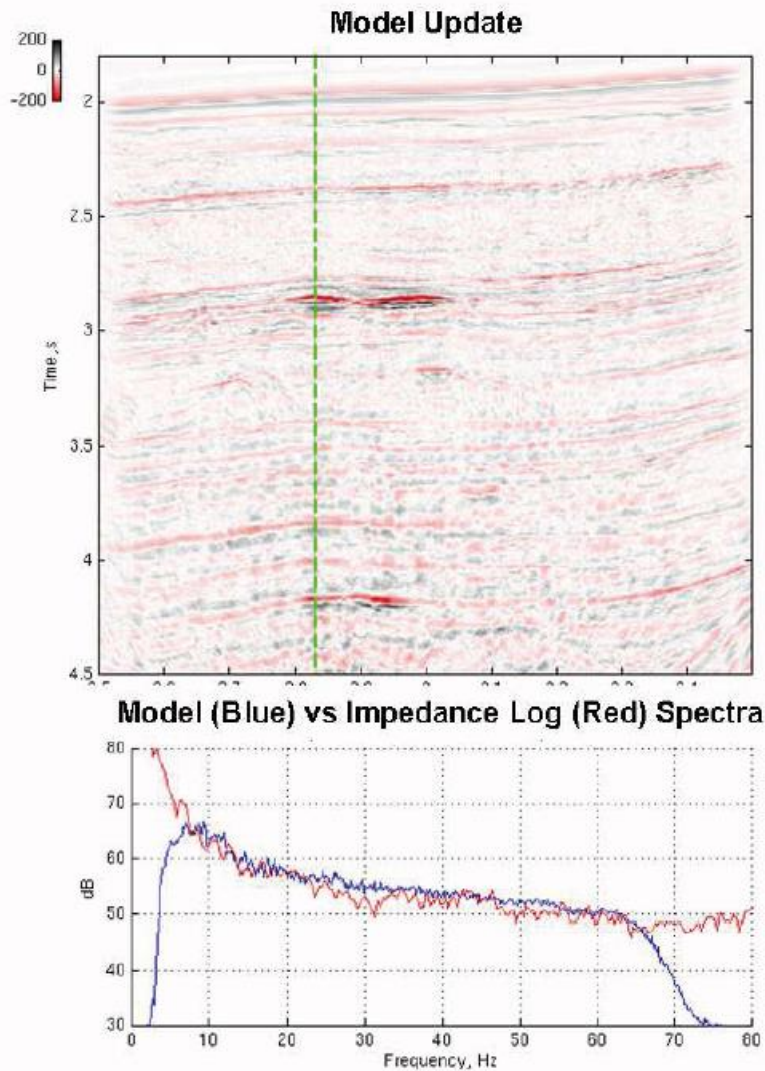
Same physics in both cases



Missing low frequency content in the source wavelet (STF)!

# Source spectral shaping

(Lazaratos et al, 2011)

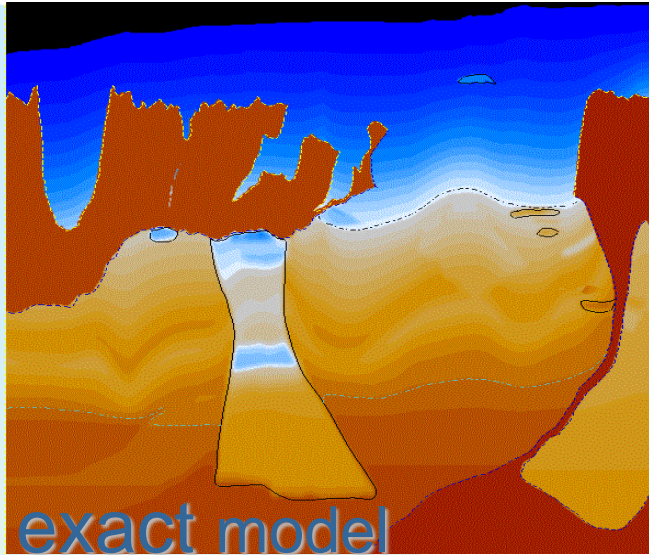


Improving the STF by spectral shaping!



# Waveform: essential contribution

Low frequency information



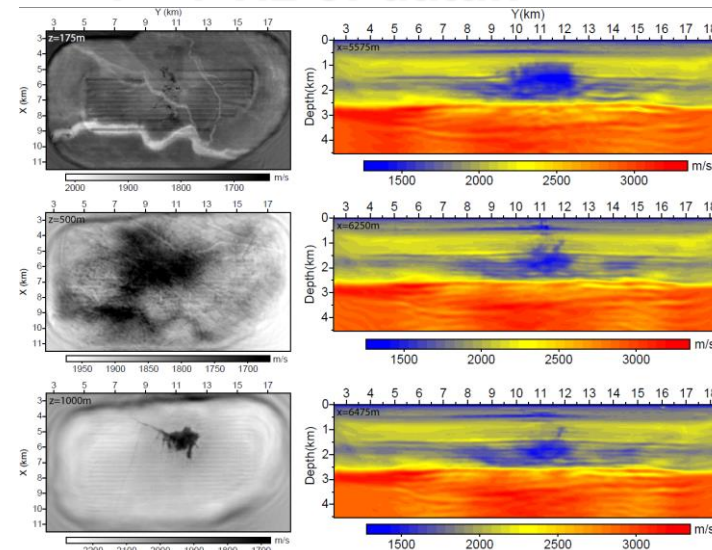
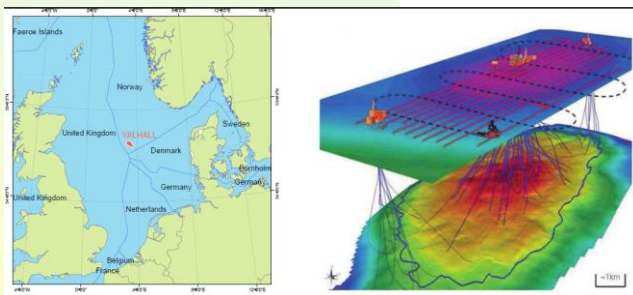
2D synthetic example



Pratt & Brenders (2004)

benefit from waves, even when phases interfere

3D real example:  
Valhall oil field



Operto et al. (2013,2015)

(Warner et al., 2008; Sirgue et al., 2010 ...)

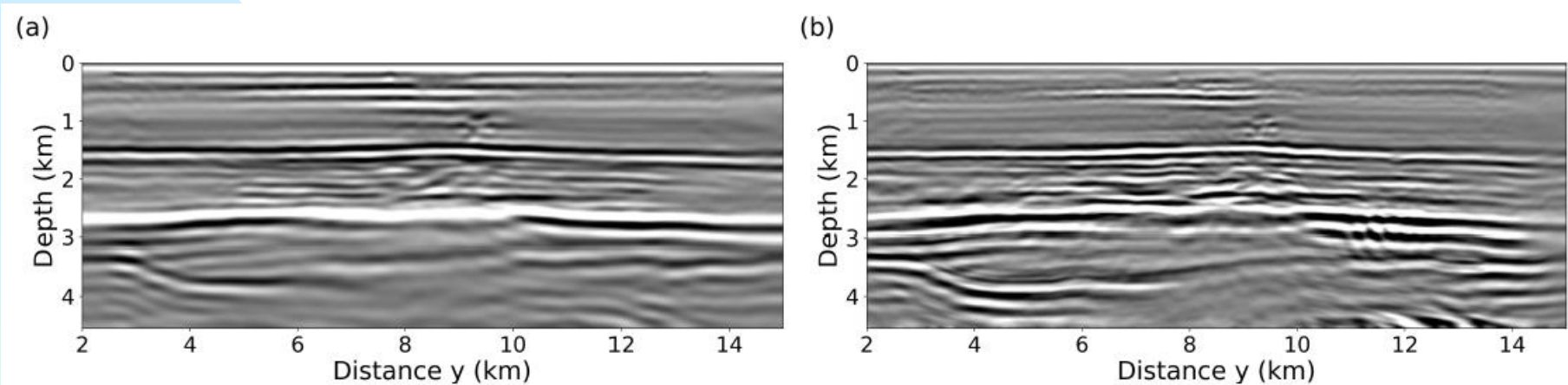
17/11/2021

Phases and waves



# Reducing variability!

Moving from 0.5/2 Hz to 10/22.5 Hz is expected to be feasible in the future with dense data!



*Figure 2 Reflectivity images derived from P-wave velocity and density at (a) 10 Hz, (b) 22.5 Hz.*

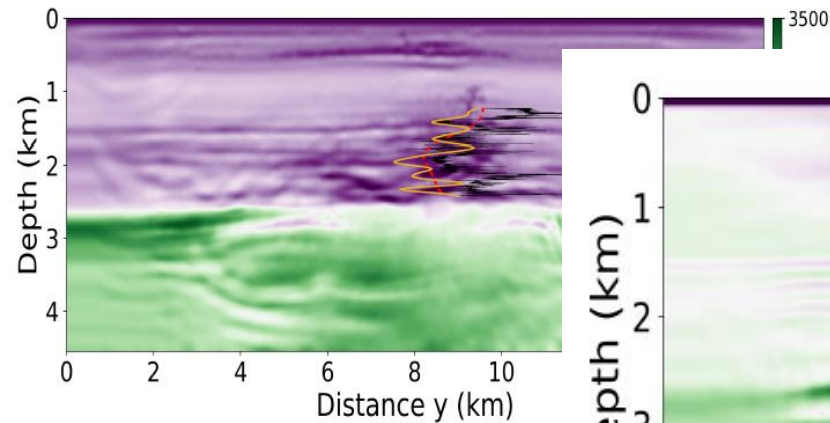
(Métivier et al, 2024)

Stochastic strategy could be drastically reduced for wave propagation

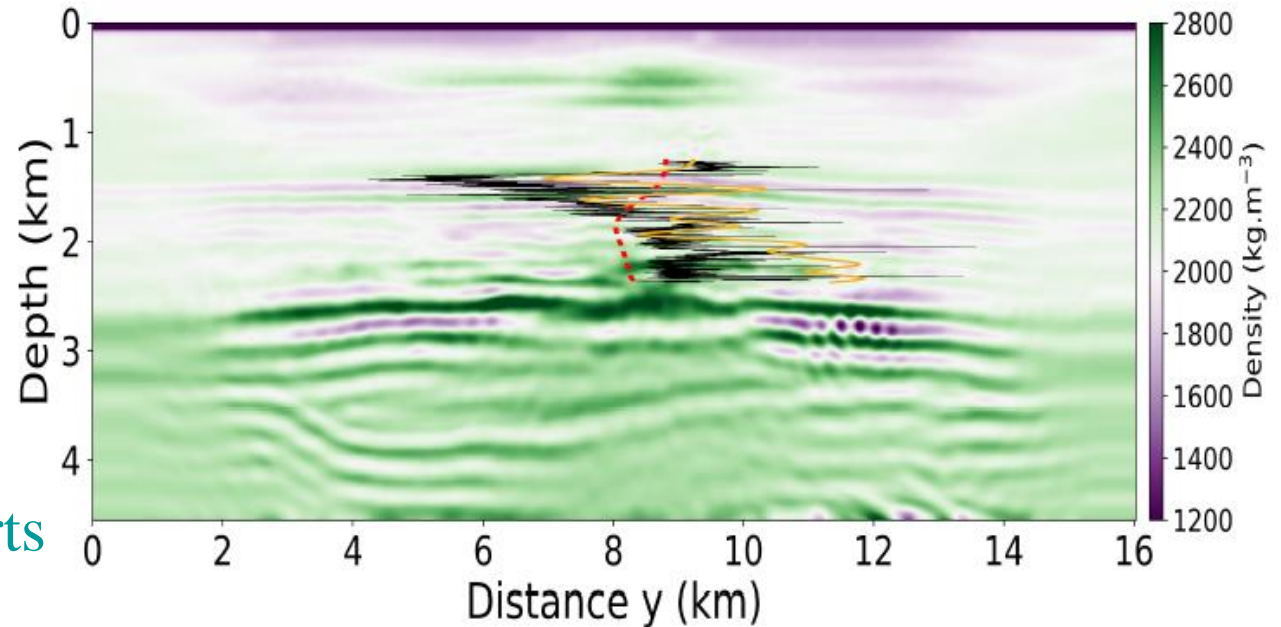
Deep understanding of the physics of wave propagation

Frugal tools of accurate prediction of waveforms (wavefields!)

# Multiple parameters!



Aside velocity variation



Density variation starts to be recovered (at least HW content)

(Métivier et al, 2024)

Stochastic strategy could be drastically reduced for wave propagation

Deep understanding of the physics of wave propagation  
Frugal tools of accurate prediction of waveforms (wavefields!)

# FWI: a rather difficult strategy?

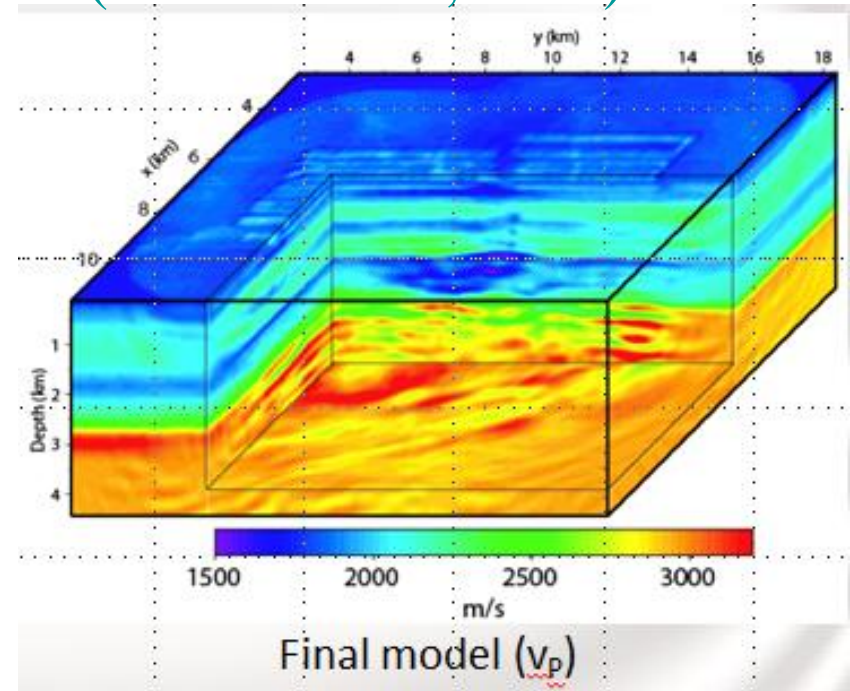


Full data content: Traveltime (**phase**) and **amplitude** of all arrivals

Most of the time, the inversion does not iterate because unable to find a better model improving the fit of the data!

- ☐ Enough accurate physics!
- ☐ High-quality records!
- ☐ Source wavelet content!
- ☐ Curse of dimensionality!
- ☐ Multiple parameters cross-talk!

(Etienne et al., 2012)



Optimization better for low-frequency data than high-frequency data



# Wave-equation tomography



## Wave Equation Tomography (WET)

(Woodward, 1989; Luo & Schuster, 1991; Woodward, 1992, Van Leeuwen & Mulder, 2010)

- **Time windowing** strategy for waveform extraction (Maggi et al., 2009)
- **Cross-correlation** between observed and synthetic waveforms for time shift evaluation (obtained through wave equation solvers: expensive!)

Somehow immune to amplitude effects

Time delay will be **frequency-dependent**: for example, 0.6 s time shift between P time in band [2-0.5 Hz] and P time in band (0.1-0.03 Hz) ...



- Starting model should be **phase-compatible** (cycle-skipped?)

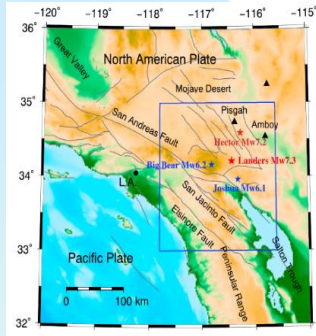
Interference between phases in the same window – non-linear effects (Nolet, 2008)

Model « see » the interference and not each phase ... in a dynamic way (updated phase delays)

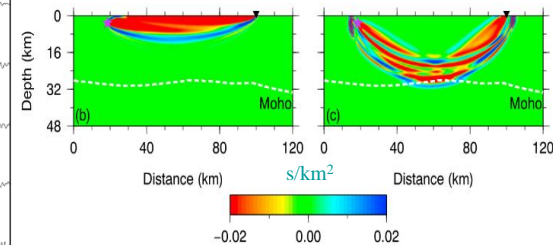
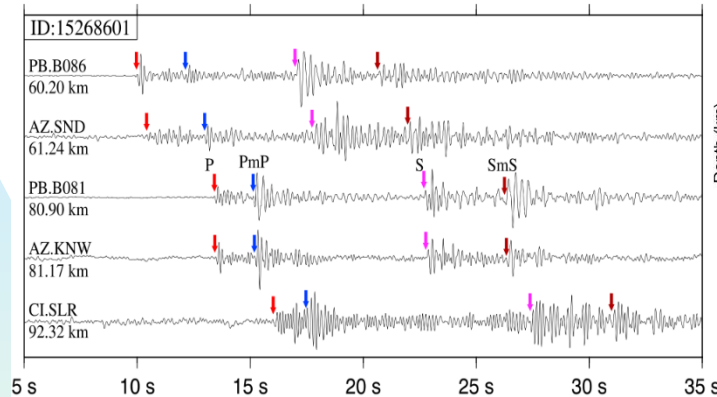
# Wave-equation tomography

## Wave Equation Tomography (WET)

(wide-spread tool in seismology)



(Huang et al, 2016)



Time-domain cross-correlation inside a given window: « **traveltime** » sensitive to **frequency**

- Sensitivity kernel from Wave Equation (WE) (Tape et al., 2009, 2010; ...)
- Sensitivity kernel from Ray Theory (RT) (Dahlen et al, 2000; Dahlen & Nolet, 2005)

Sensitive to both amplitudes

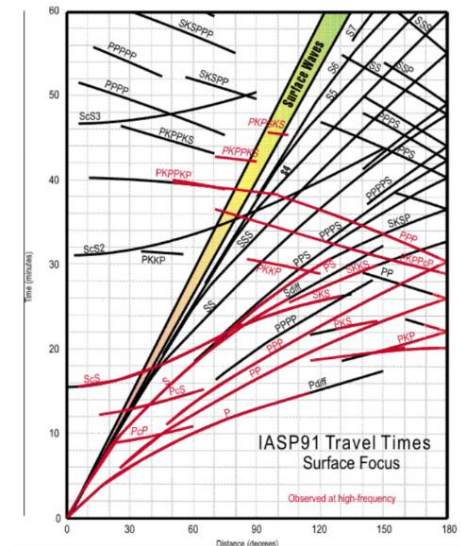
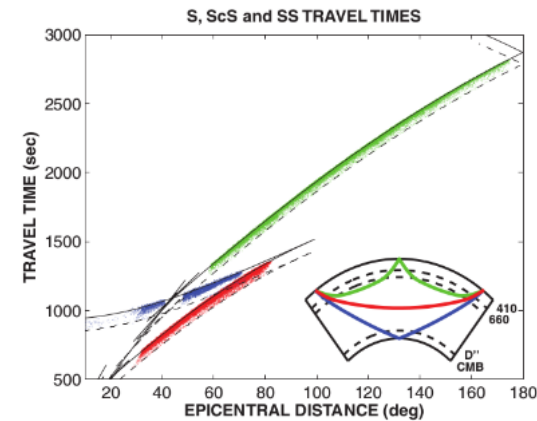
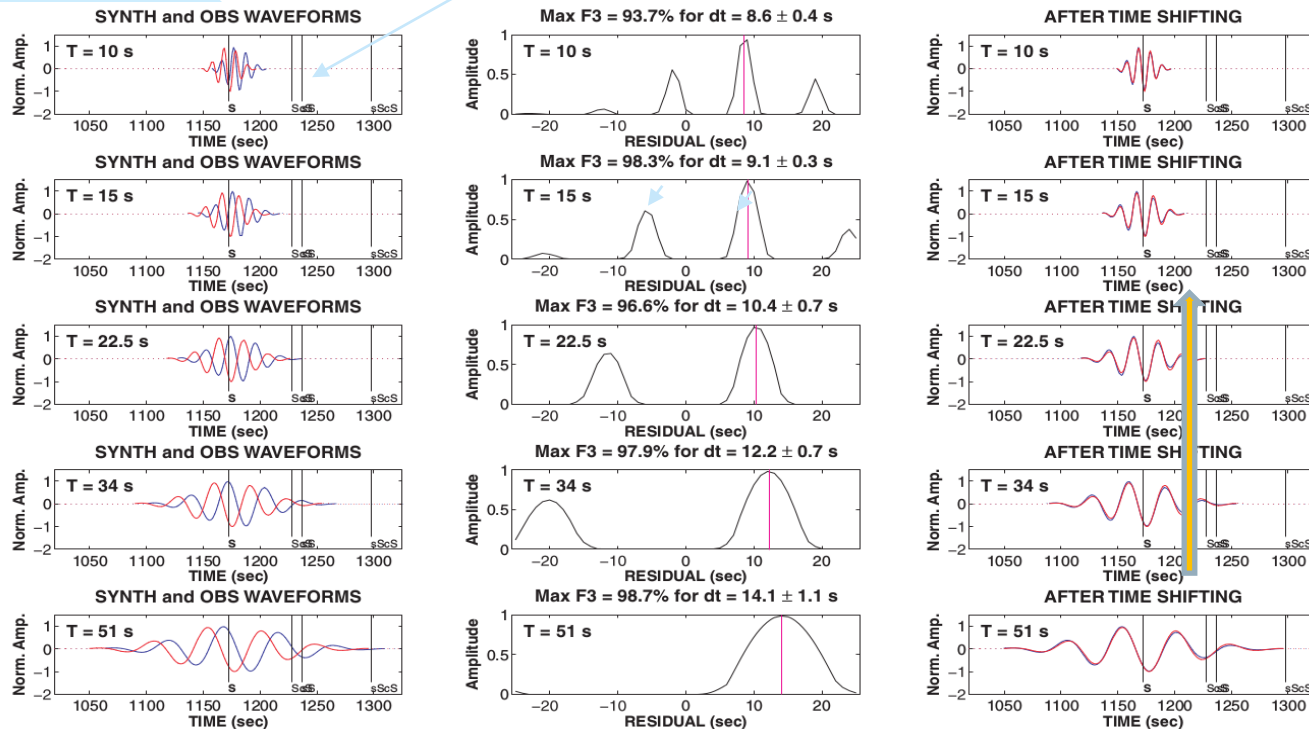
Sensitive to synthetic amplitudes

Born approximation (Lippmann & Schwinger, 1950; Dahlen & Tromp, 1998; Zhao et al., 2000; Zhao & Chevrot, 2011a,b)

# Dynamic phase measurement: Xcorr.

Interference btw ScS and sS High frequency

« Tagging »



Low frequency

Zaroli et al (2010)

~400 000 phases S, SS, ScS  
« nearly » automatically

17-21 September  
2018

# Wave-equation tomography

Lu et al (2018)

Real example for Europe using phases cross-correlation and elastodynamic wave propagation

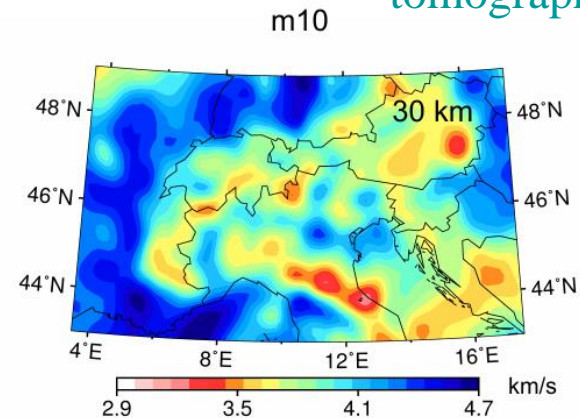
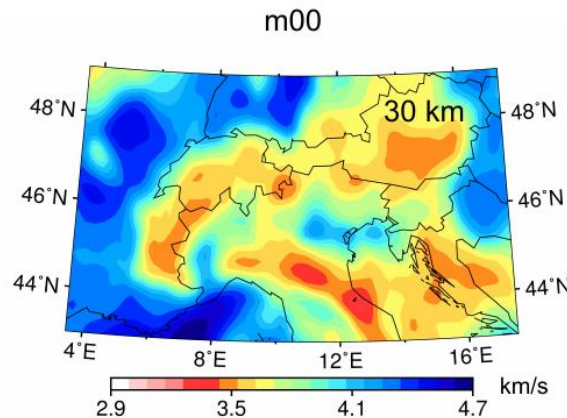
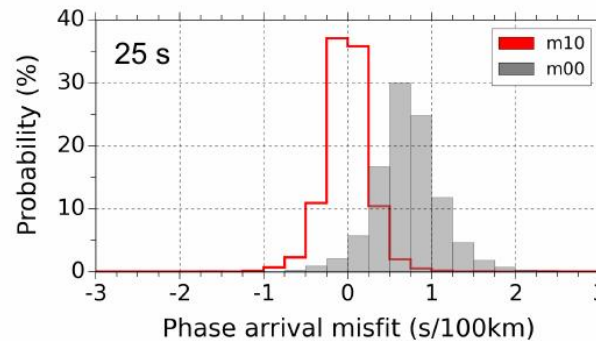
From ambient noise analysis

Seismology ☺

Dispersion curve  
analysis  
(fundamental mode)

Wave equation  
tomography

What kind of phases  
in WET?

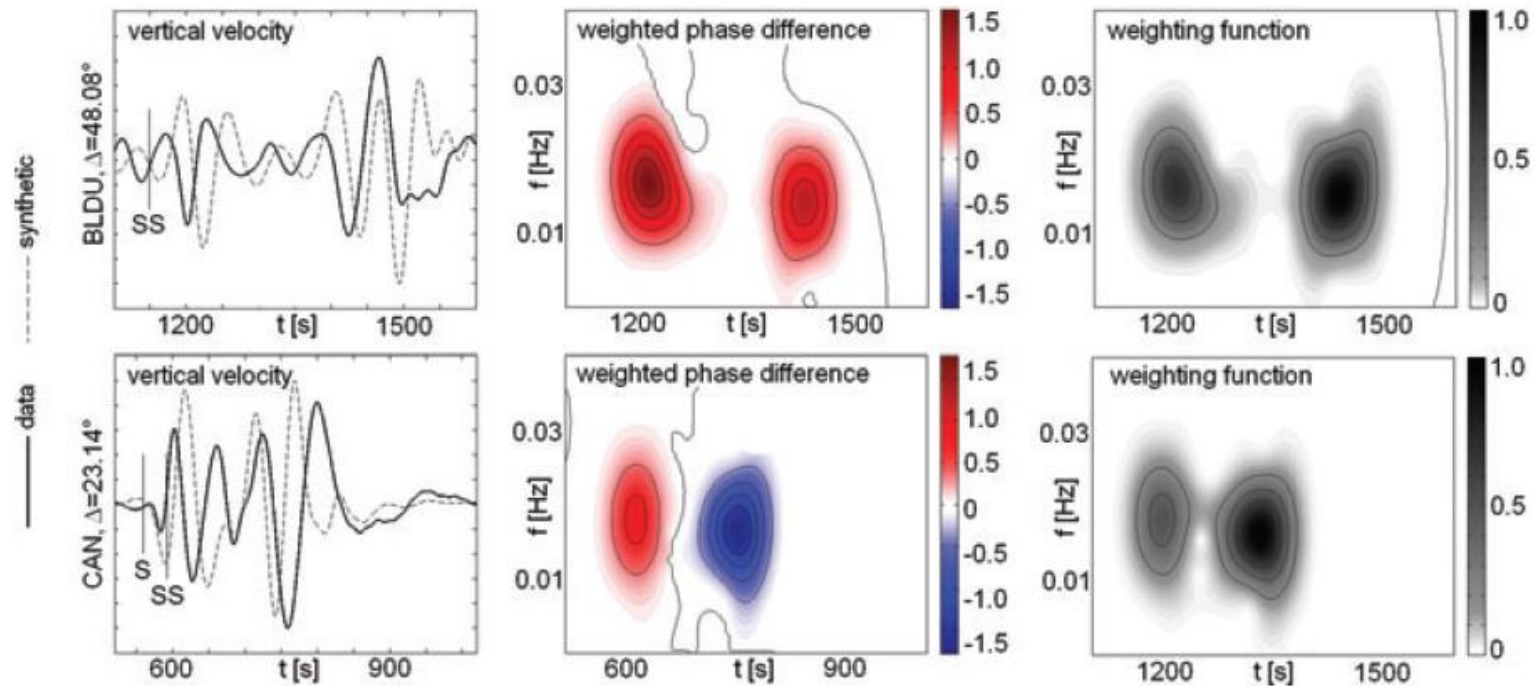


Initial phase  
tomography

Seismic ☹/☺



# WET: independent phase misfit



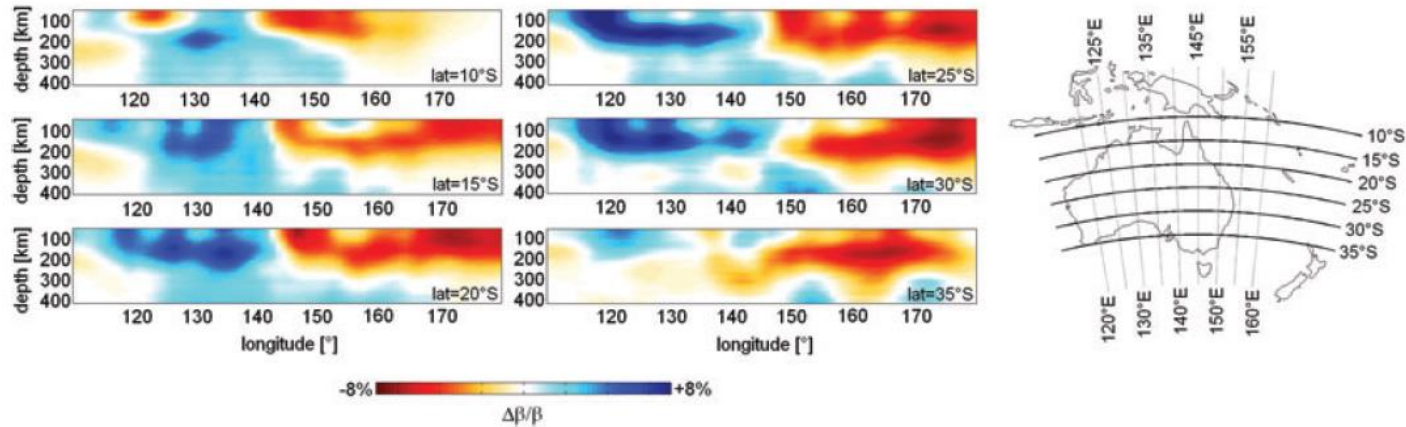
(Fichtner et al., 2008; Fichtner et al., 2009)

Phases are not picked as for DRT or DET (unless dynamic wrapping)!

Phase delays are the extracted observables

highly correlated to current model (Nolet, 2008)

# WET: dynamic phase misfit

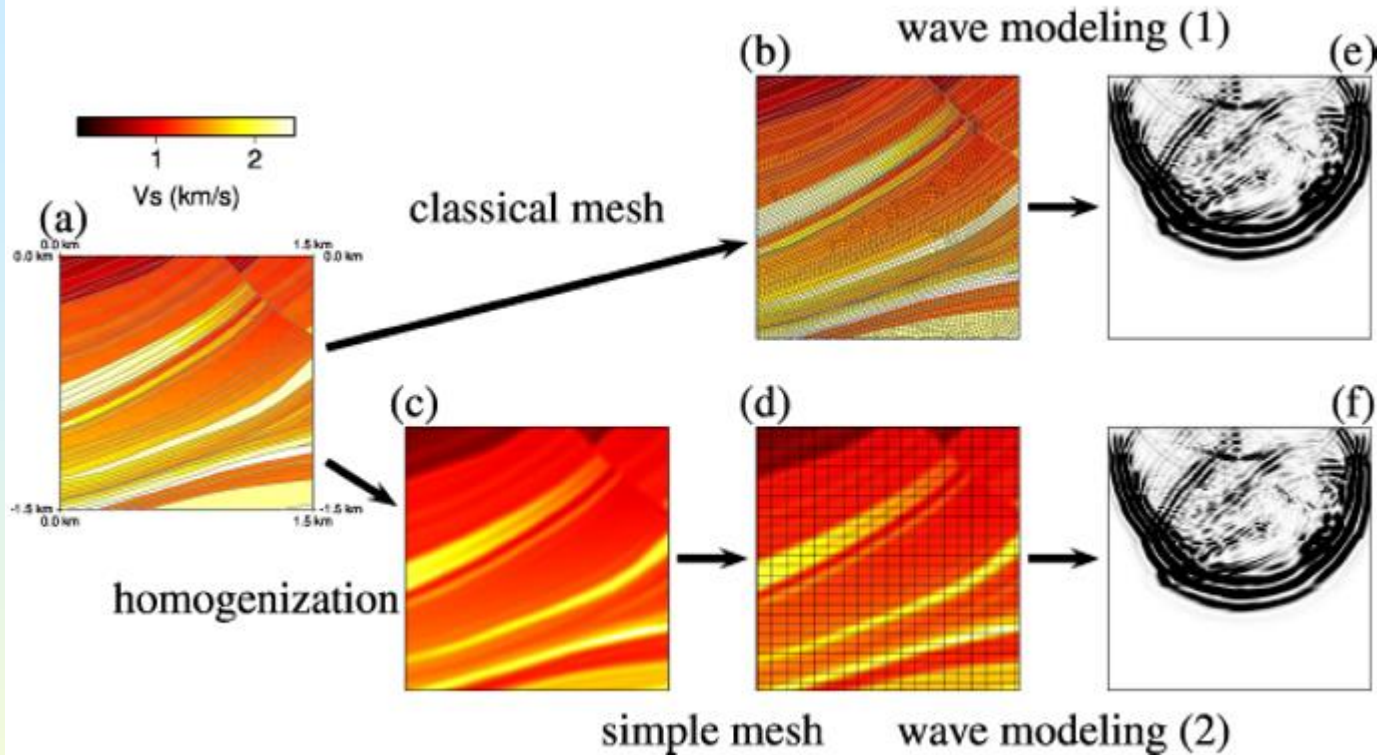


Does WET improve the resolution compared to DRT or DET?

(Fichtner et al, 2009)

Resolution is improved by exploiting more information,  
especially interference phases

# Mitigation of computer needs!

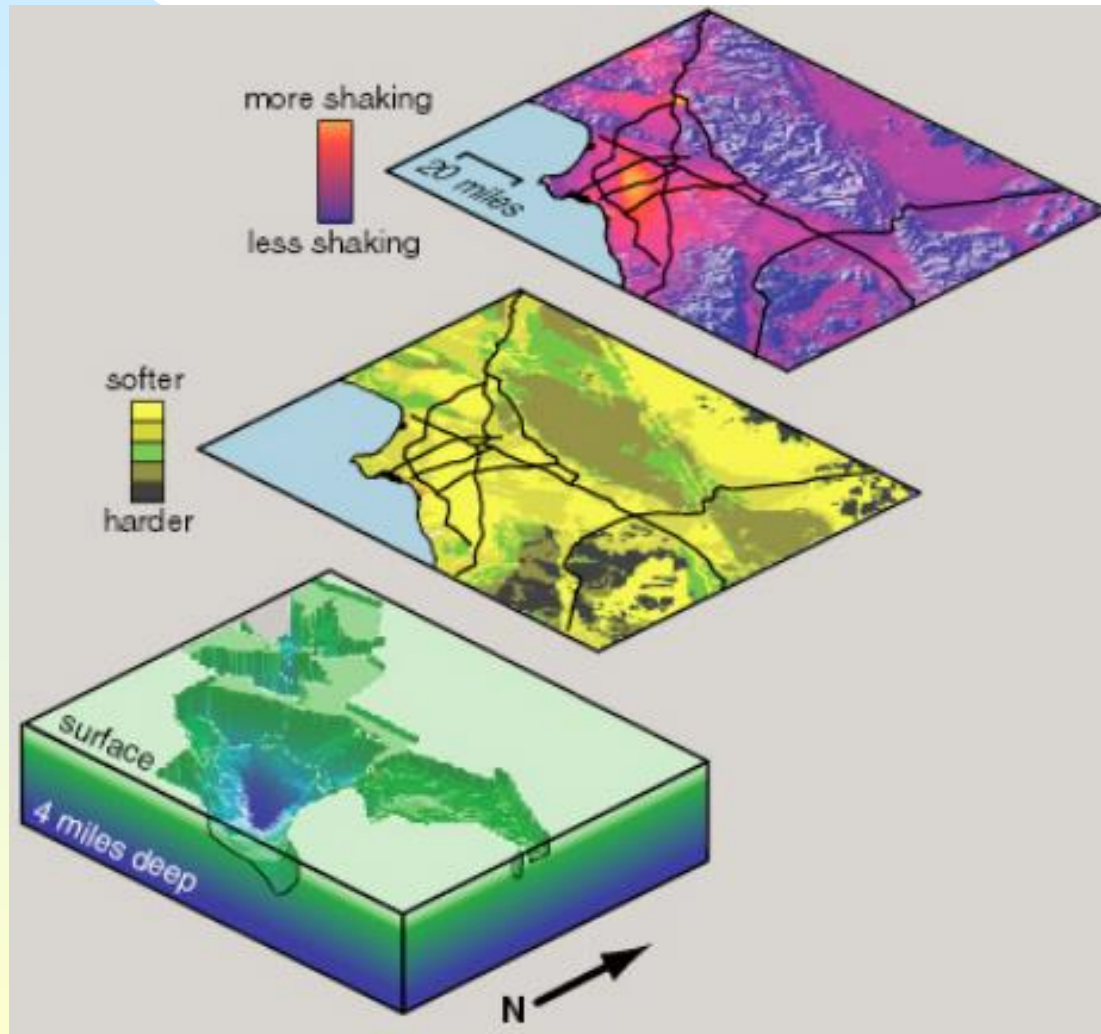


Model homogenization requires anisotropy parameters but reduces significantly computer cost

(Capdeville et al., 2010b; Cupillard & Capdeville, 2018)



# Site: short-scale variation



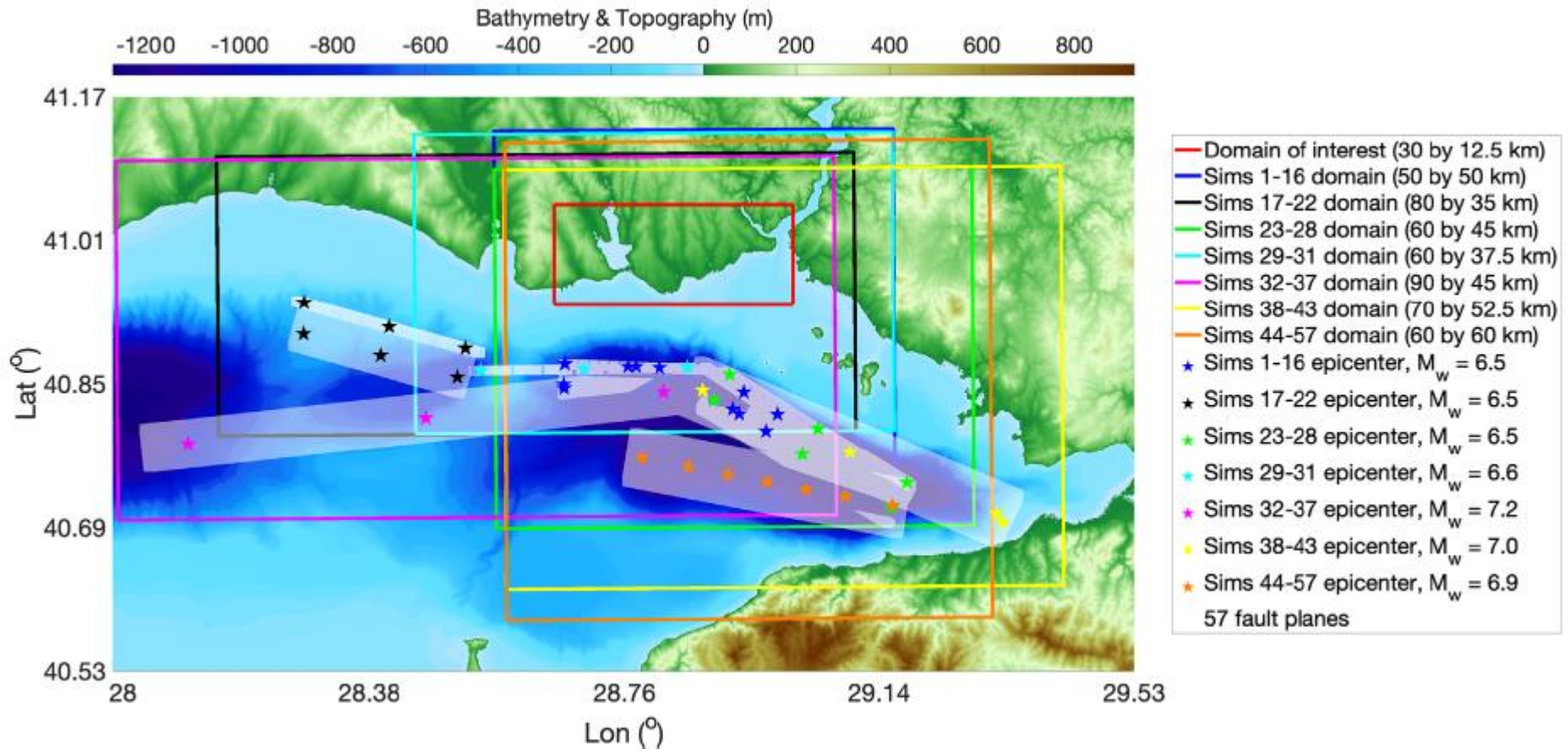
Local ground shaking depends on

softness of the surface rocks

thickness of surface sediments.

(from SCEC website)

# Reduction of GMS scenarios

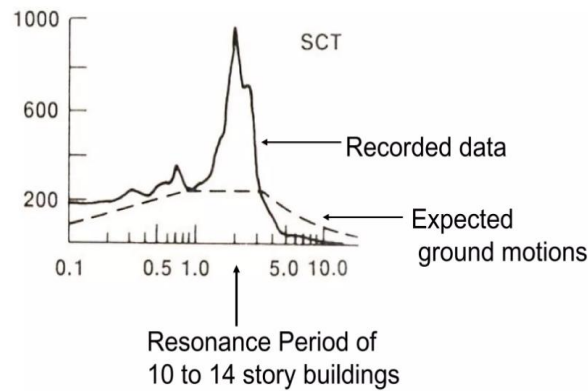


Variability comes from unexpected earthquake description and ...

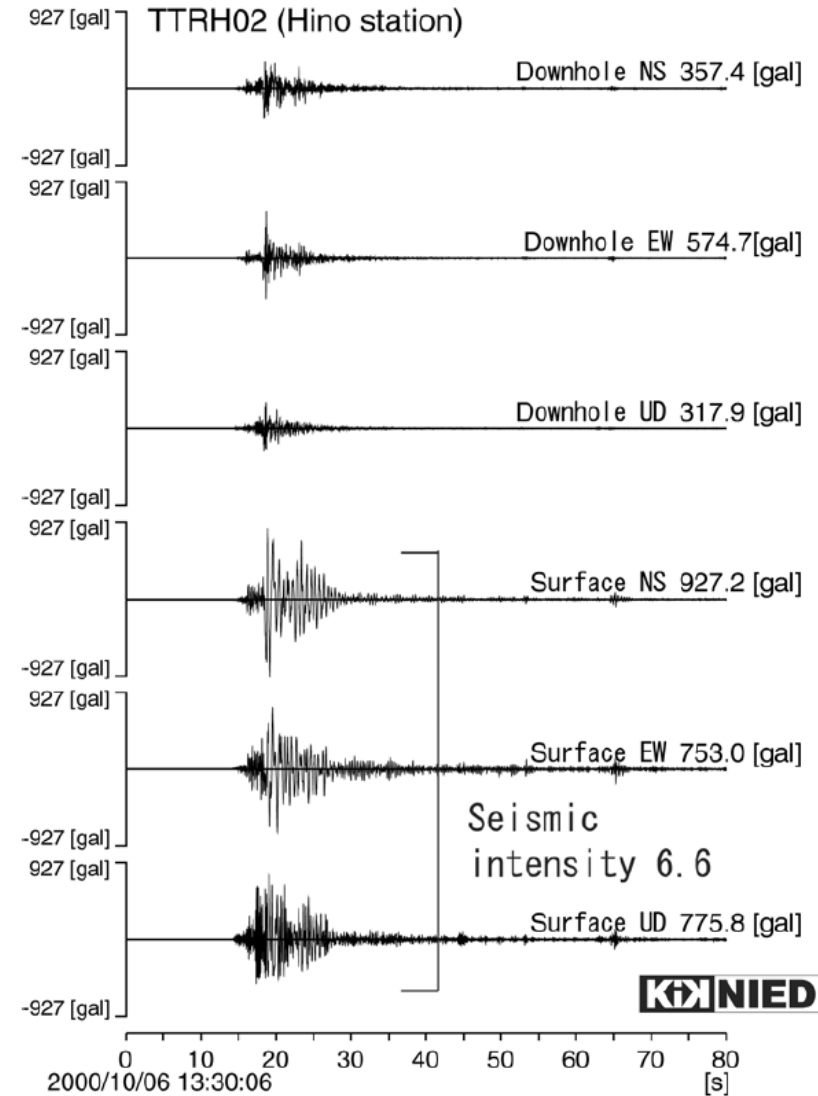
# Reduction of GMS

possible local perturbation which could include site/building interaction in a multi-scale analysis

Mexico City Acceleration Response Spectrum



Large-scale and short-scale models cannot reach this resolution: translucent Earth...





# Conclusion

For ground motion estimation, the wave propagation aspect is the more deterministic part of this challenging problem.

However, often neglected...

# Conclusion

Hope that this training will convince you that the dramatic increase of data is compatible with more accurate evaluation of wave propagation aspect.