Characterization of crustal models for quantitative ground motion estimation

C – Model Design
(short-scale velocity structure)

Jean Virieux

Emeritus Professor at UGA

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

Translucent Earth

Medium upscaling and downscaling

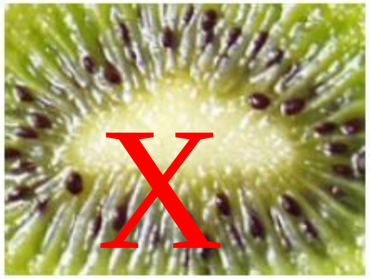
Real medium

Seismic imaging – upscaling

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

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

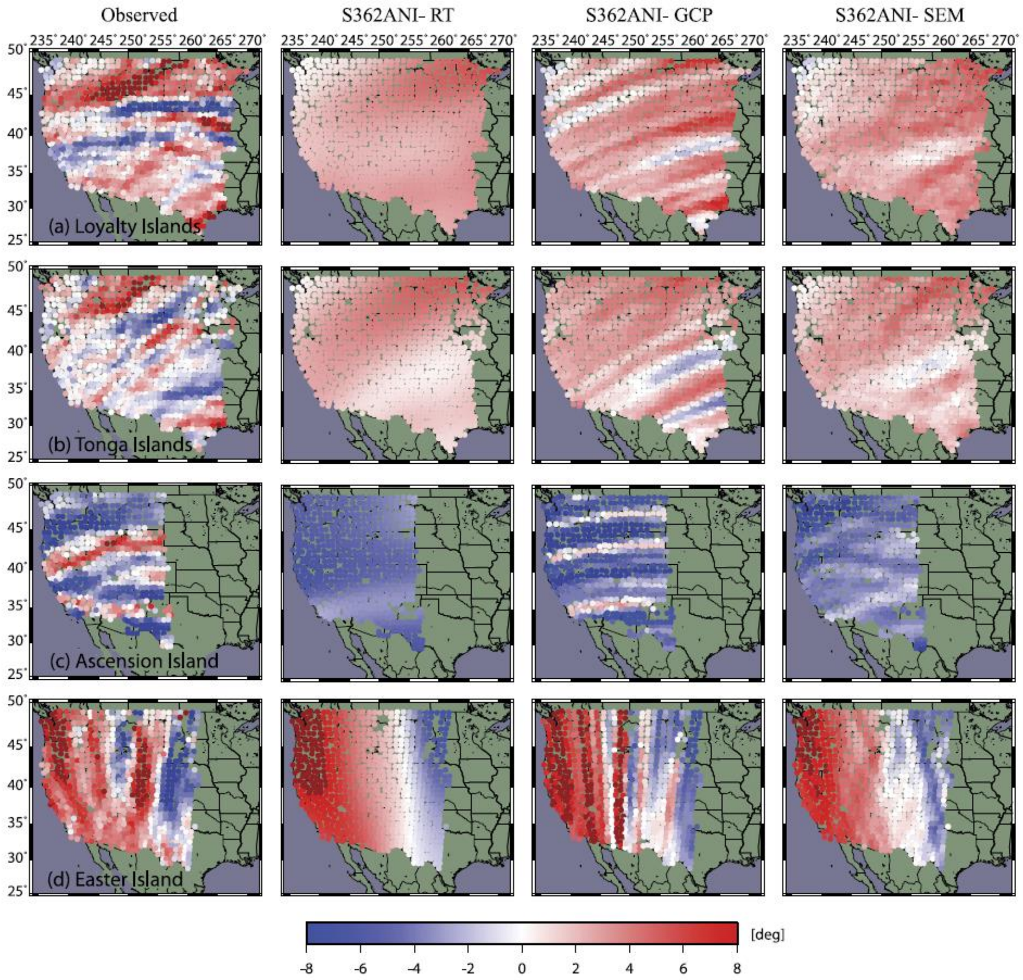
Waveform information ($\frac{\lambda}{2}$)



Interpretation (downscaling)

Ground motion estimation: waveform evaluation

Wave information: back-Az observables



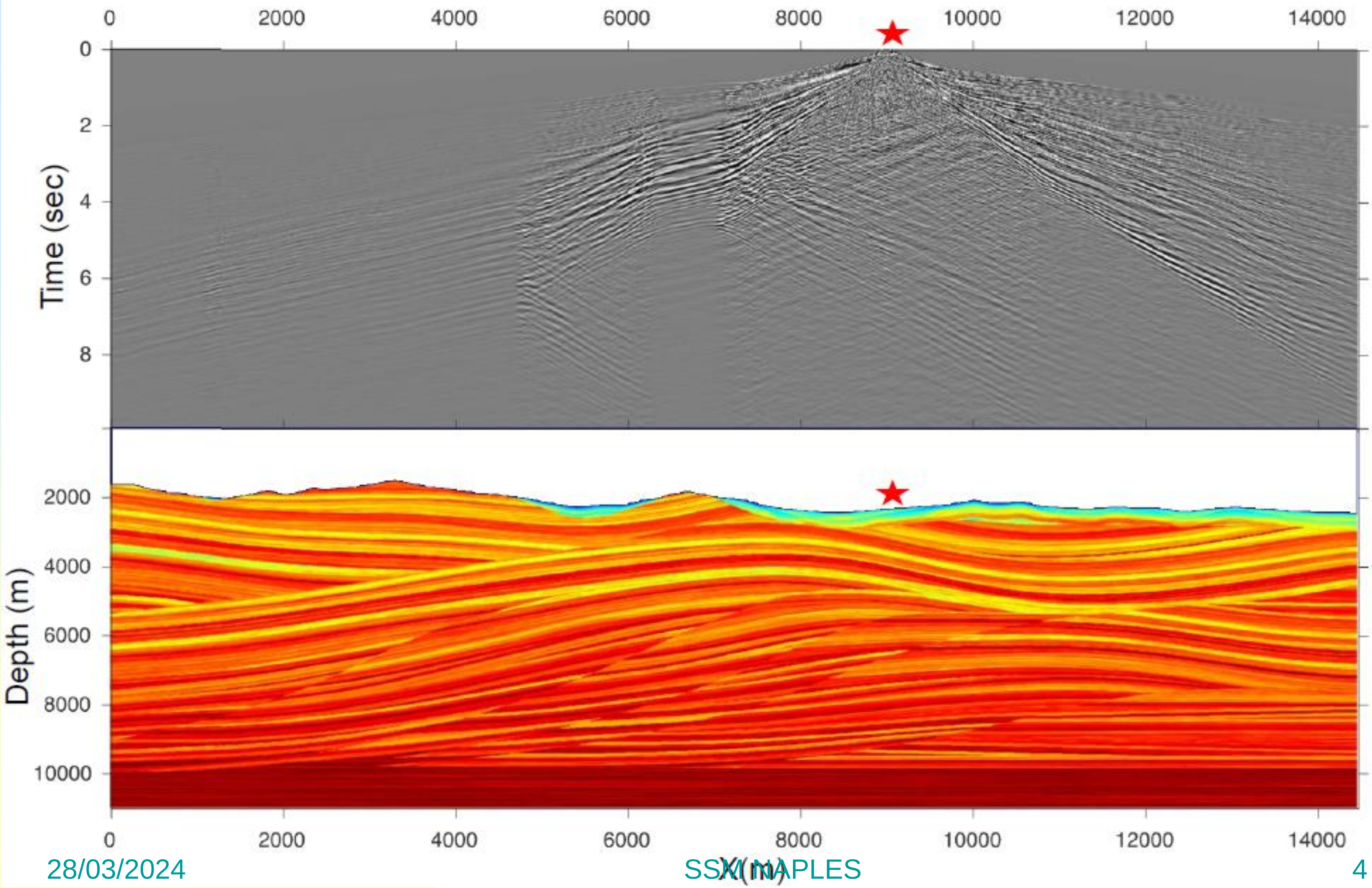
For 4 earthquakes,
measured arrival angles across the USArray network &
predicted angles for a S362ANI model using
(1) ray tracing,
(2) great-circle approximation and
(3) SEM modeling

Observables have more information than those predicted by built Earth models

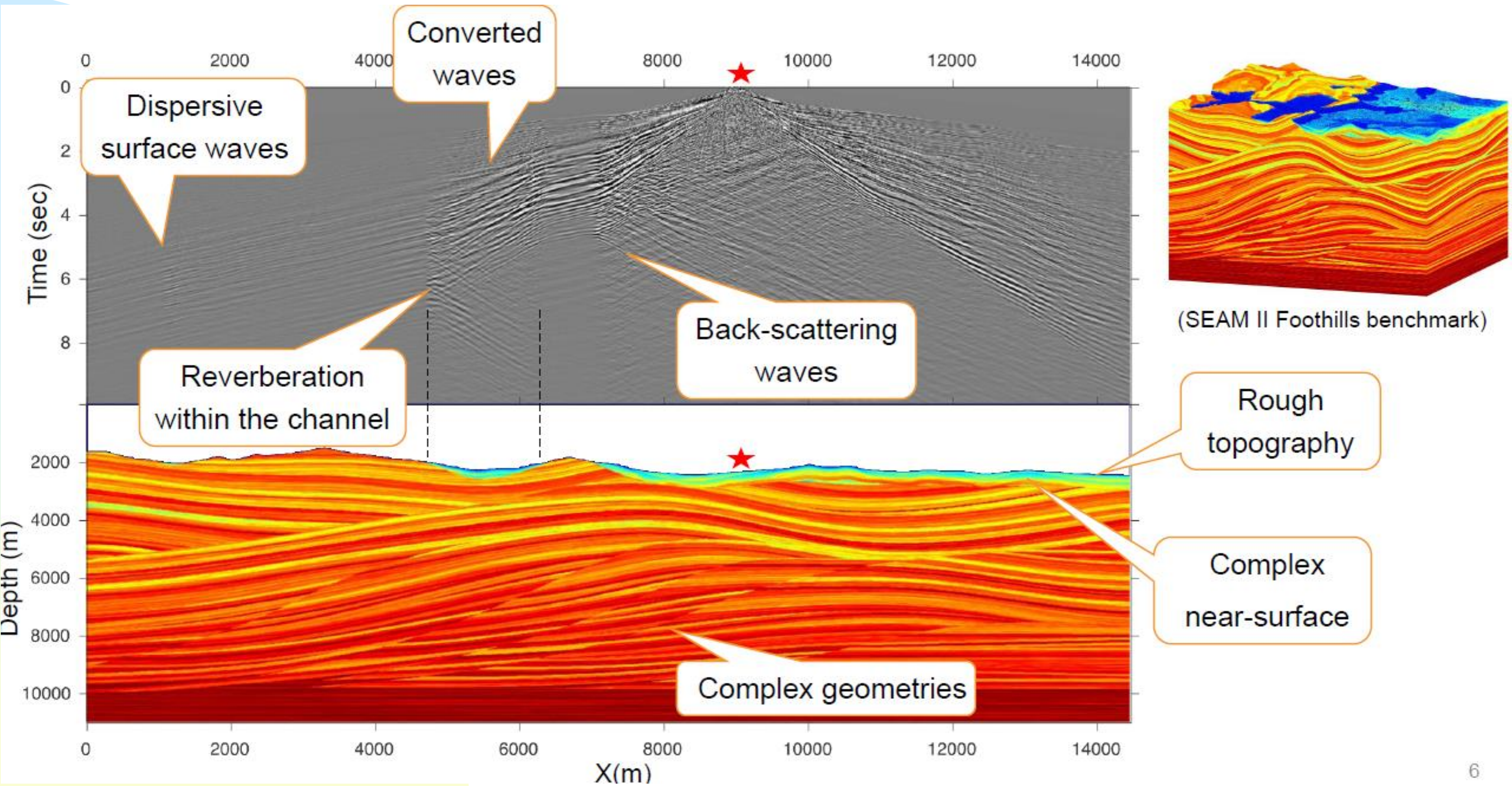
How to improve tomographic approaches for honoring both traveltimes (or phases) and azimuthal (and/or slowness) measurements?

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

Richness of seismograms!



Richness of seismograms!

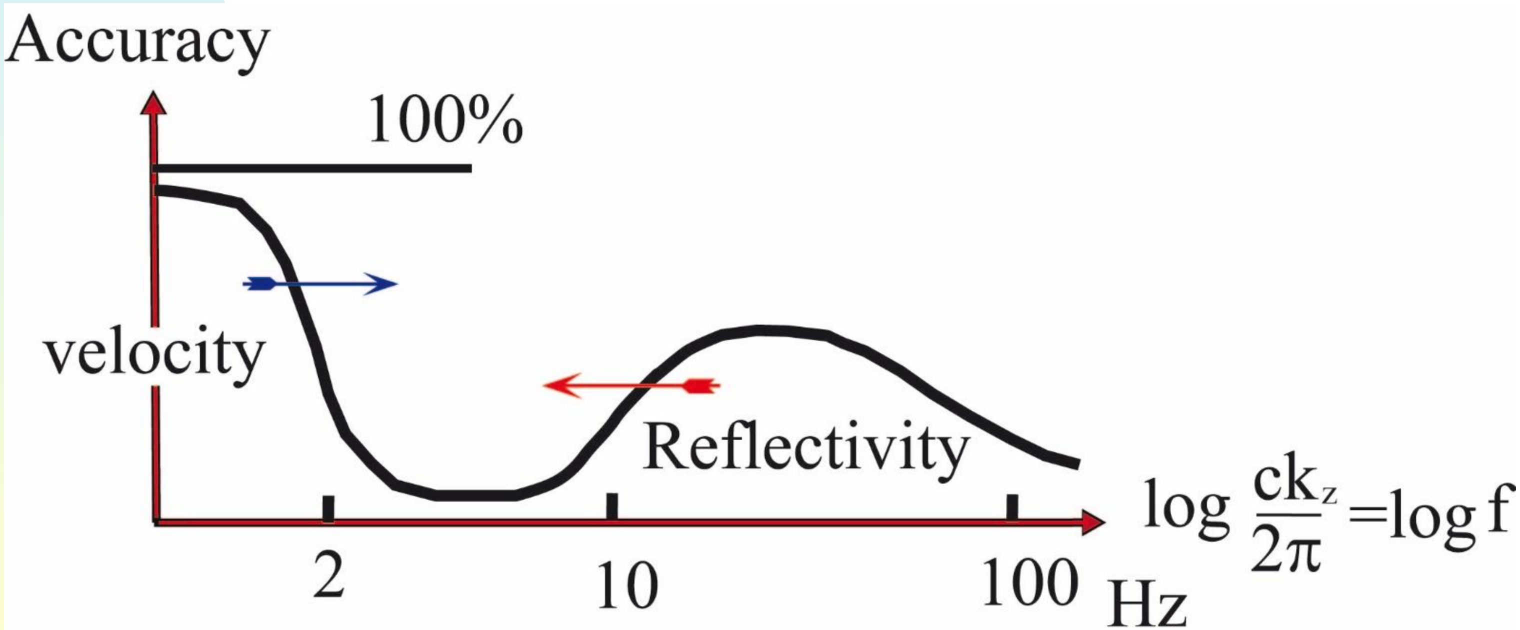


Related hierarchical structure

SEISCOPE

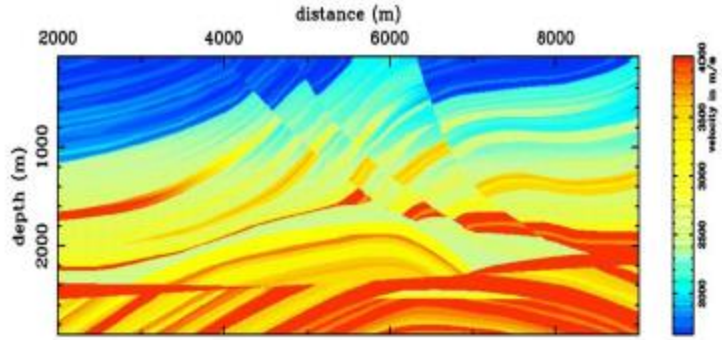
Two scales show up in the model reconstruction

Recorded seismic traces bring different information from medium properties

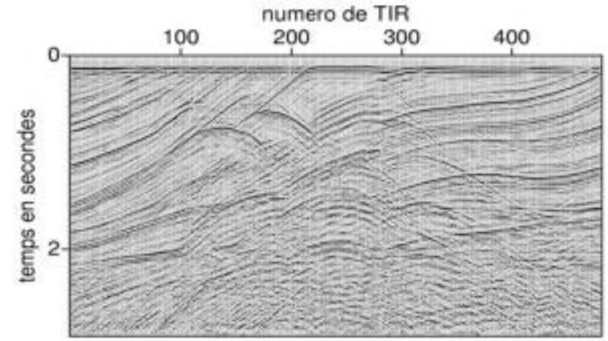


from Claerbout (1984)

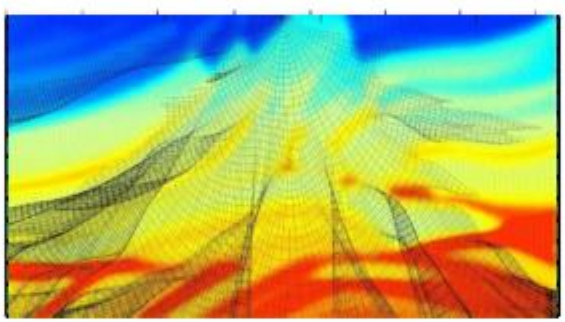
Two-steps procedure



Medium

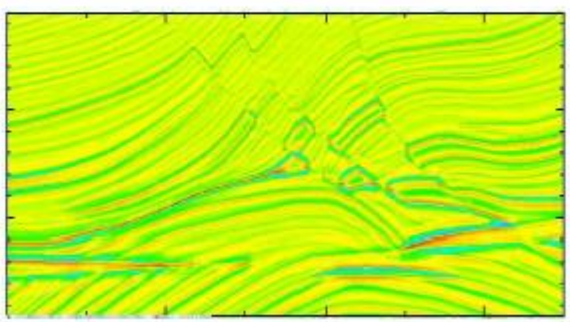


Data



Velocity model

+



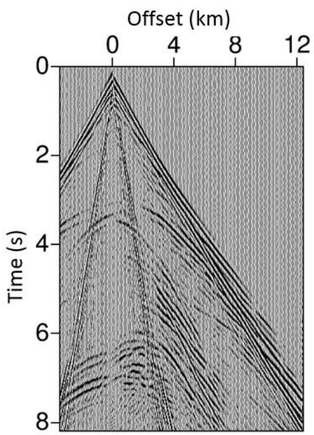
Migration/Inversion

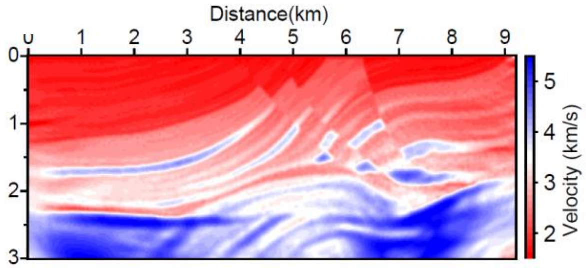
Basic seismic imaging workflows

Phase (traveltime for non-dispersive wave) drives imaging

Quantitative model?
Velocity based on waveform

Data

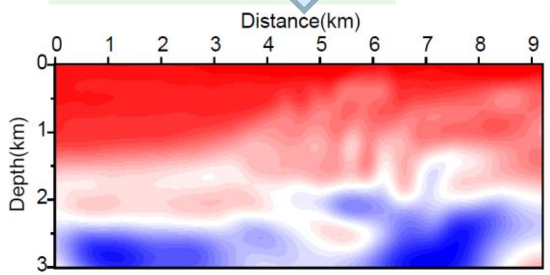




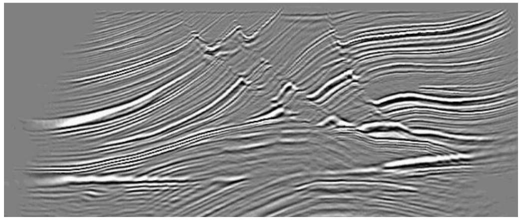
FWI

LSRTM

low-k



high-k



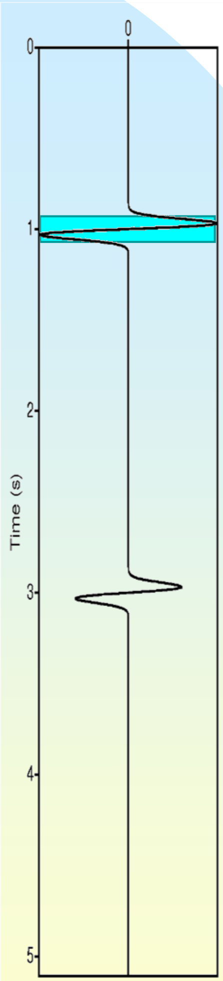
RTM
or
PDM

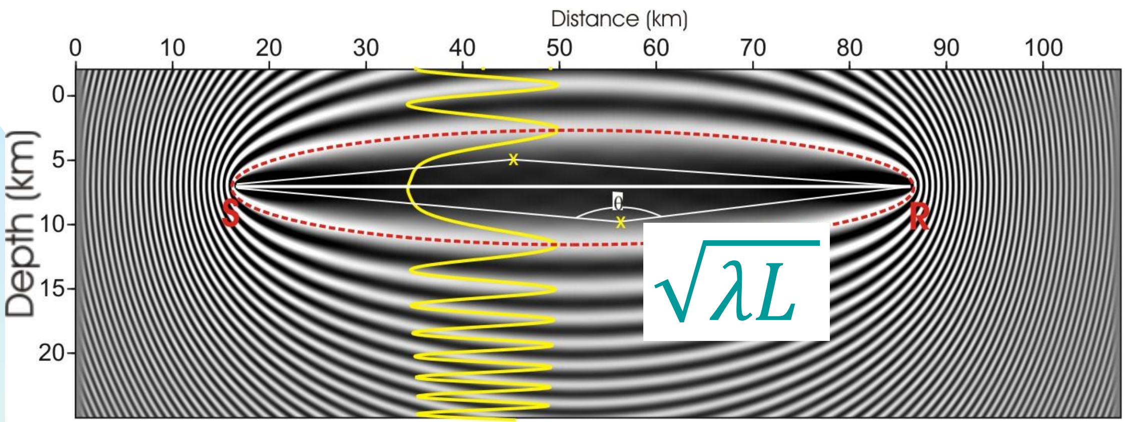
Macro-model based on velocity analysis

Qualitative model?
Reflectivity based on migration

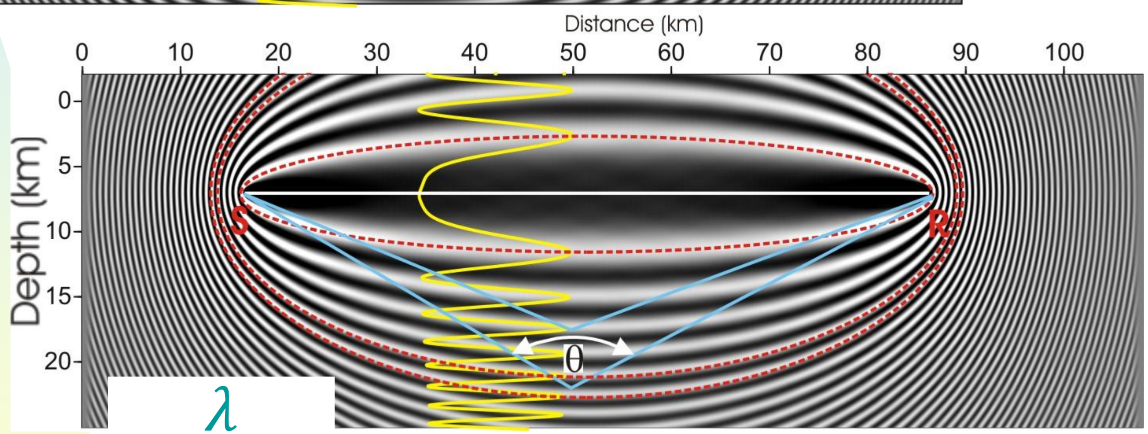
Wavepath: sensivitiy kernel

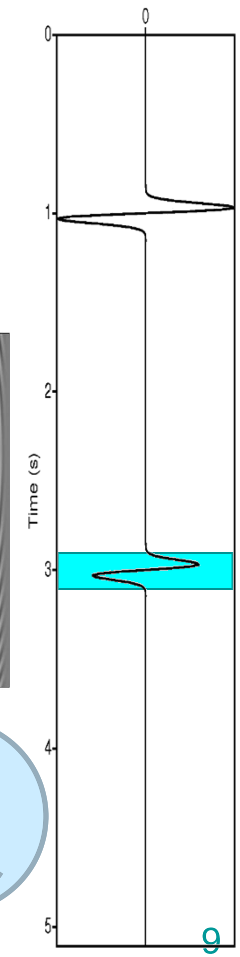
From transmission information (velocity analysis) …





$$\sqrt{\lambda L}$$





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

Inverse of Kz

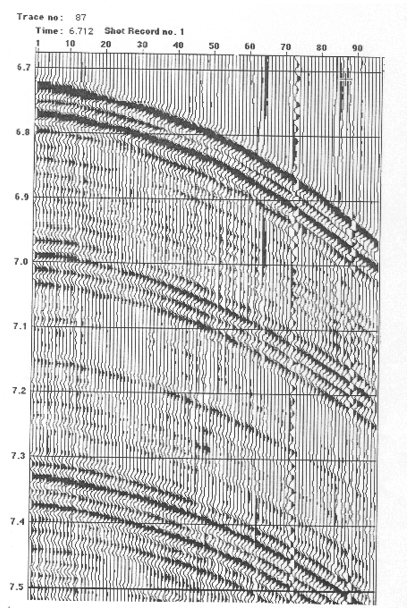
… to reflection information (migration,fwi)

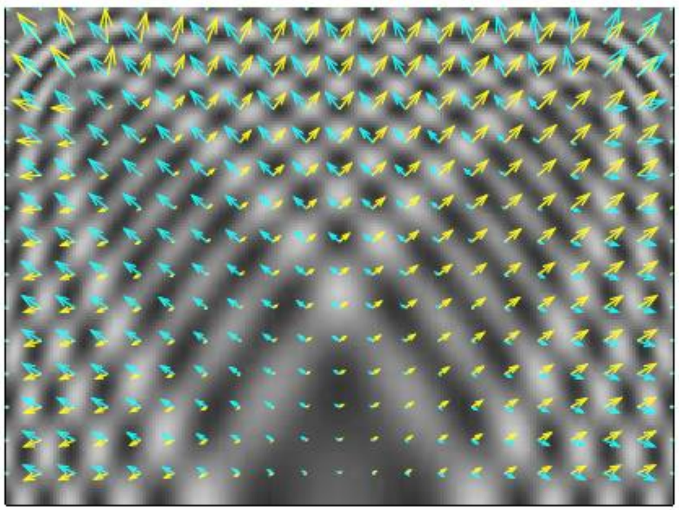
Misunderstood concept

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

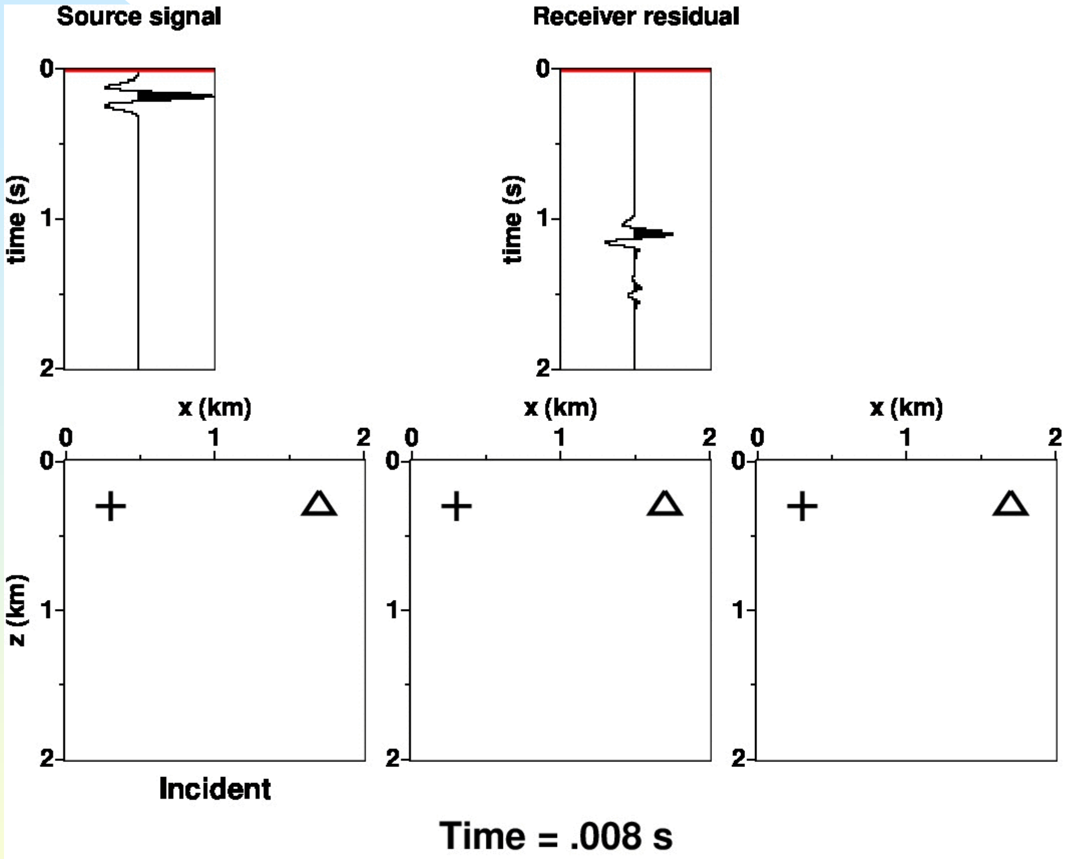
Pr. A. Tarantola

1st paper on FWI: Geophysics, 1984

Full Waveform Inversion
FWI

No prior identification ->
No prior scale separation!

FWI of body waves

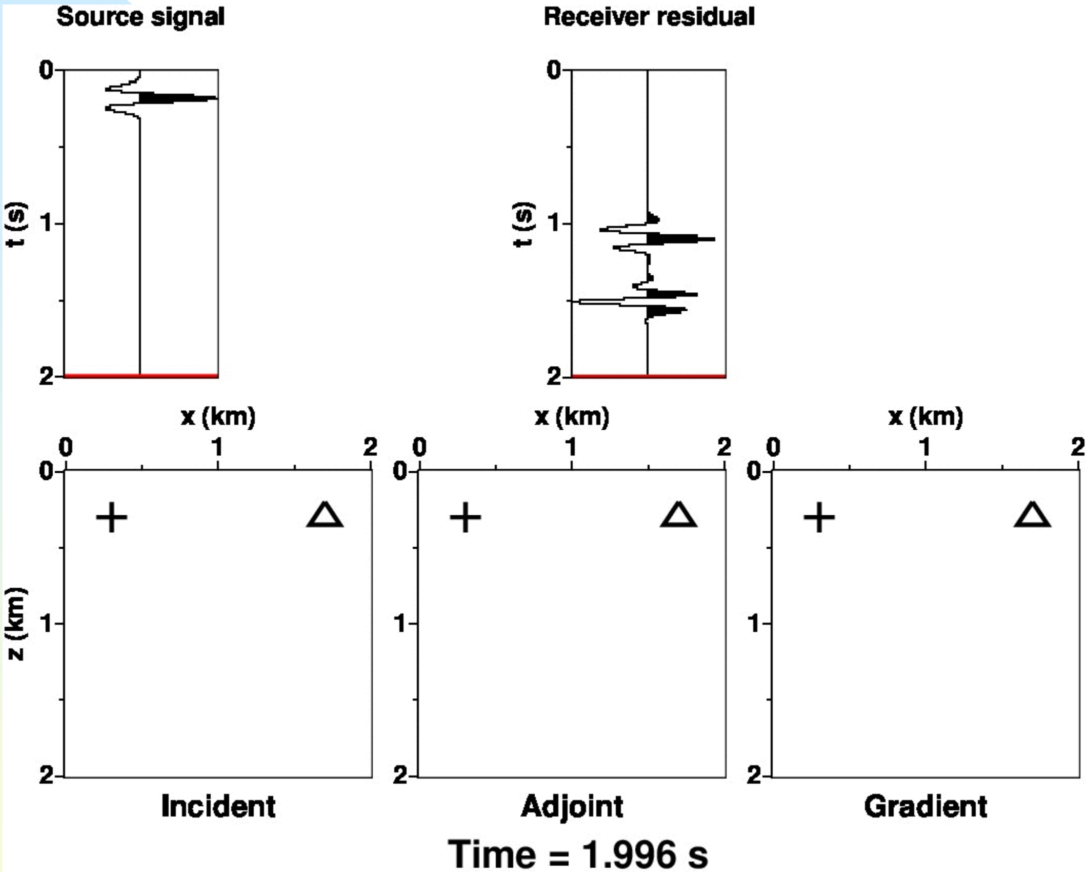


Considering diving waves and reflected waves information has led to the success of the FWI

no seismic phase identification and, therefore no scale separation

Incident wave modeling

FWI of body waves



Gradient field connected to model update

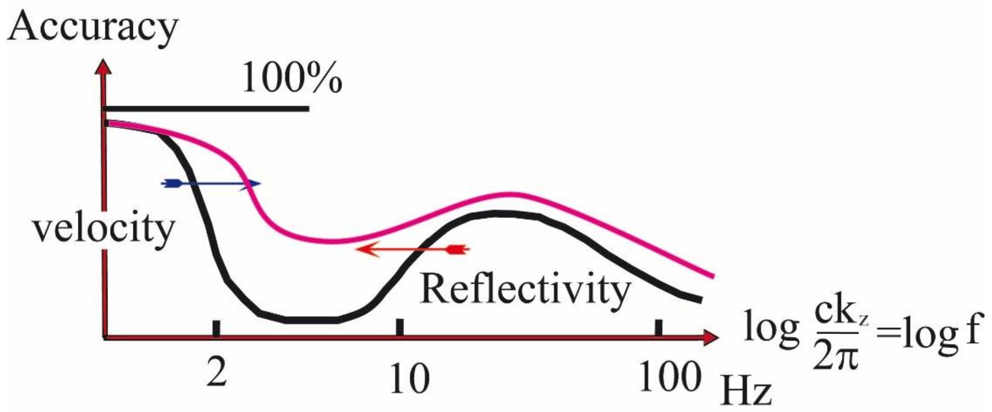
$\gamma = f(\Delta d)$

Residuals are sent back and not data (#LSM)

Direct and reflected waves are interpreted the same way through first-order scattering (no 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

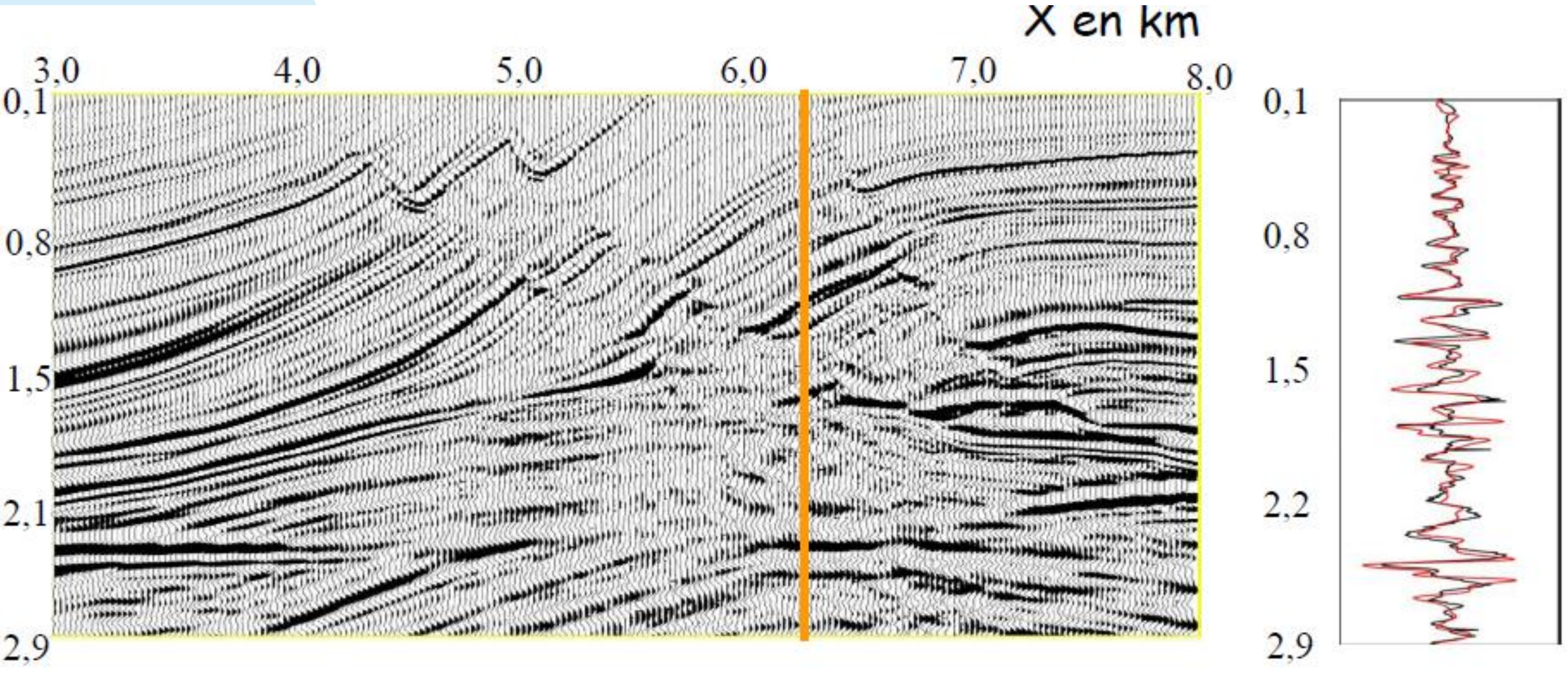
Continuous sampling of the wavenumber spectrum and filling the intermediate wavelength gap.

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 ms   -> 0.1ms)

Amplitude calibration (instrument!; installation coupling!)
(wavefield -> waveform) relaxes installation & experimental procedure !

The main difficulty!

Source knowledge (source signature; radiation pattern)

quite challenging for natural sources (earthquakes: focal mechanism)

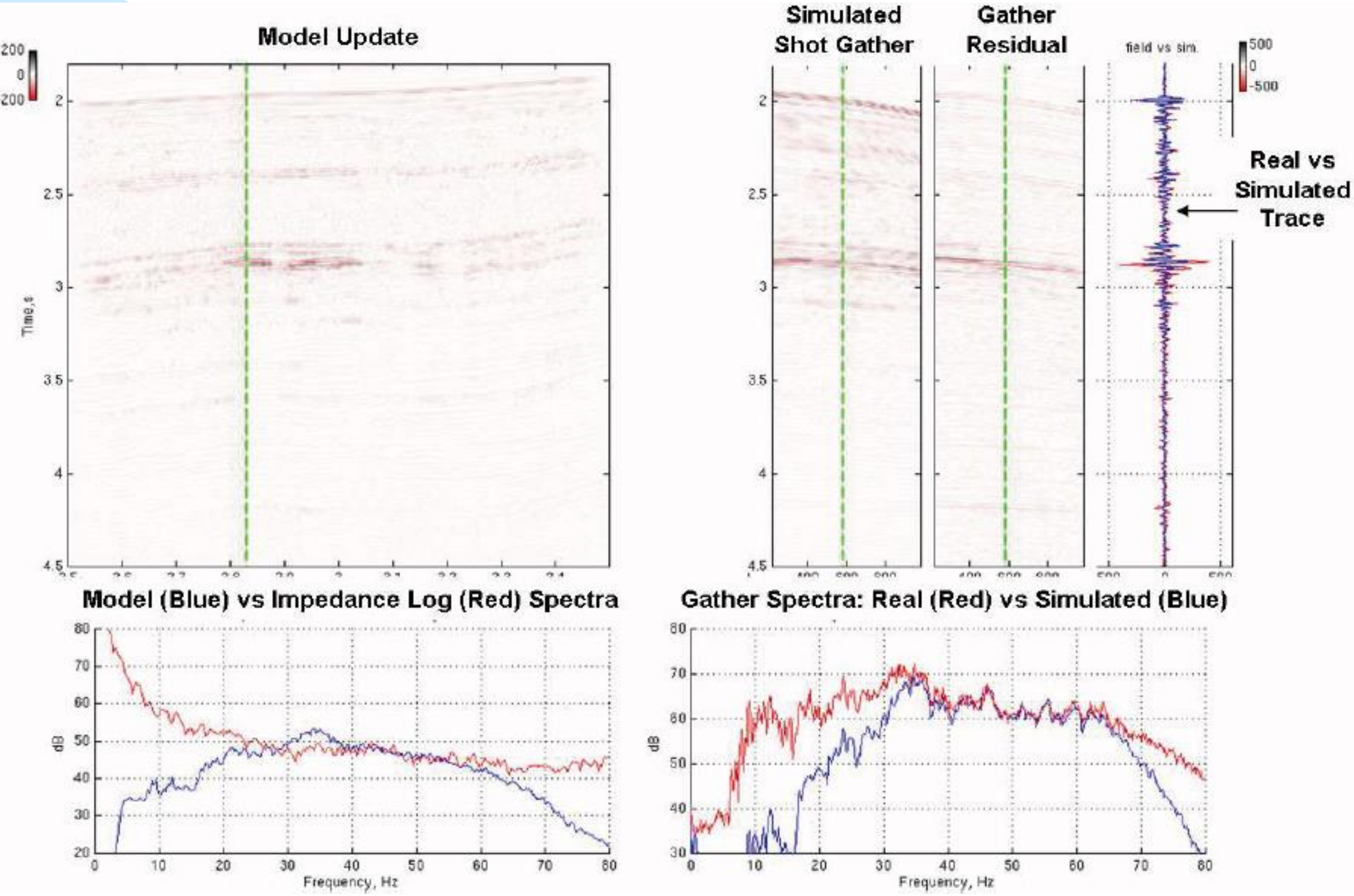
still difficult for active sources (shots, blasts: source signal s(t))

(wavefield -> waveform) mitigates these issues

Source spectral shaping

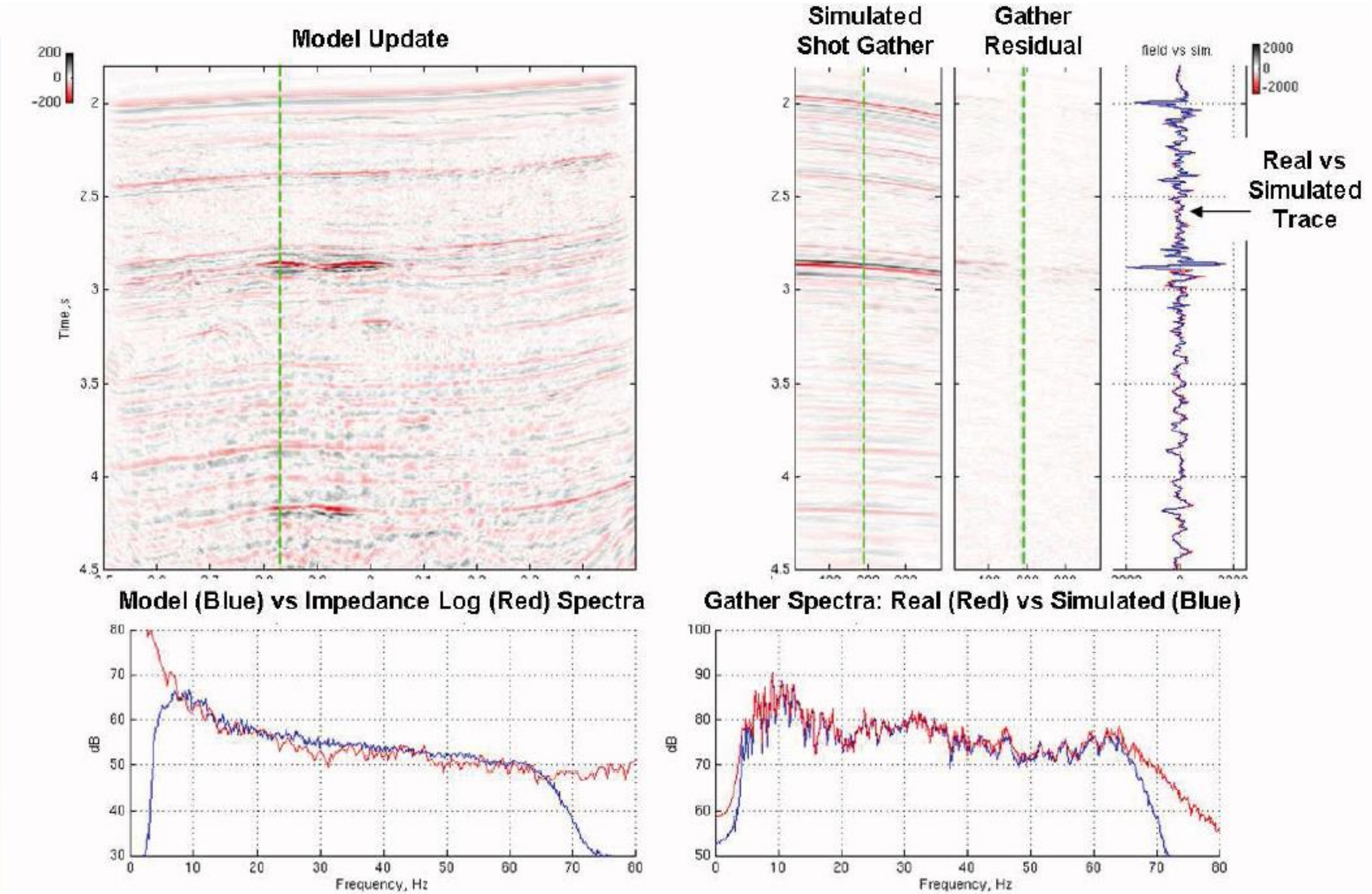
(Lazaratos et al, 2011)

Same physics in both cases



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

Source spectral shaping (Lazaratos et al, 2011)



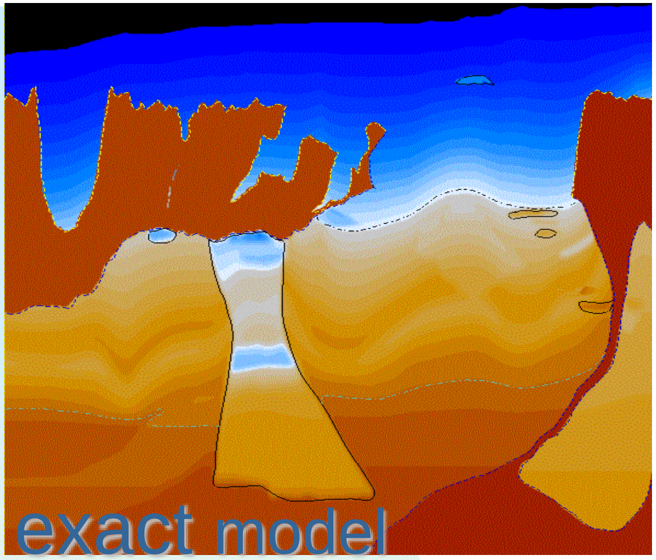
Improving the STF by spectral shaping!

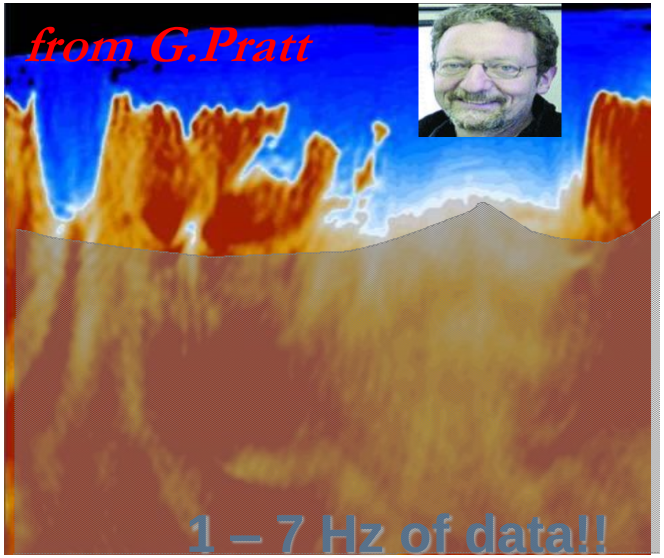
Wavefrom: essential contribution

Low frequency information

2D synthetic example

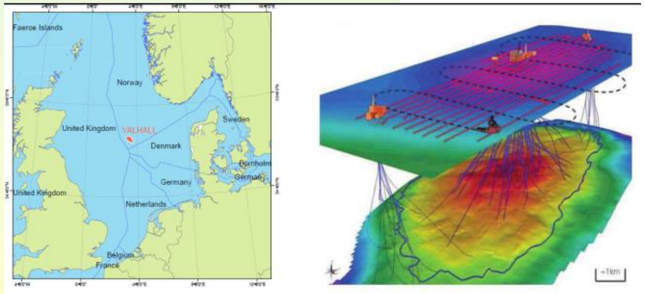
Pratt & Brenders (2004)

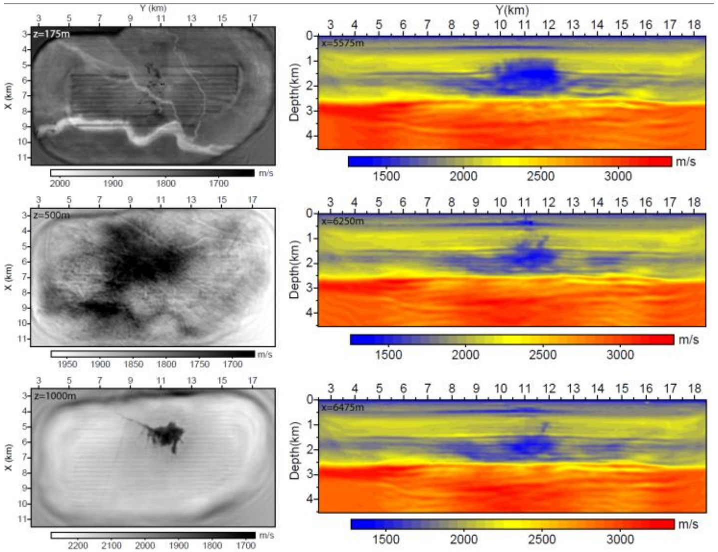




benefit from waves, even when phases interfere

3D real example: Valhall oil field





Operto et al. (2013,2015)

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

Reducing variability!

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

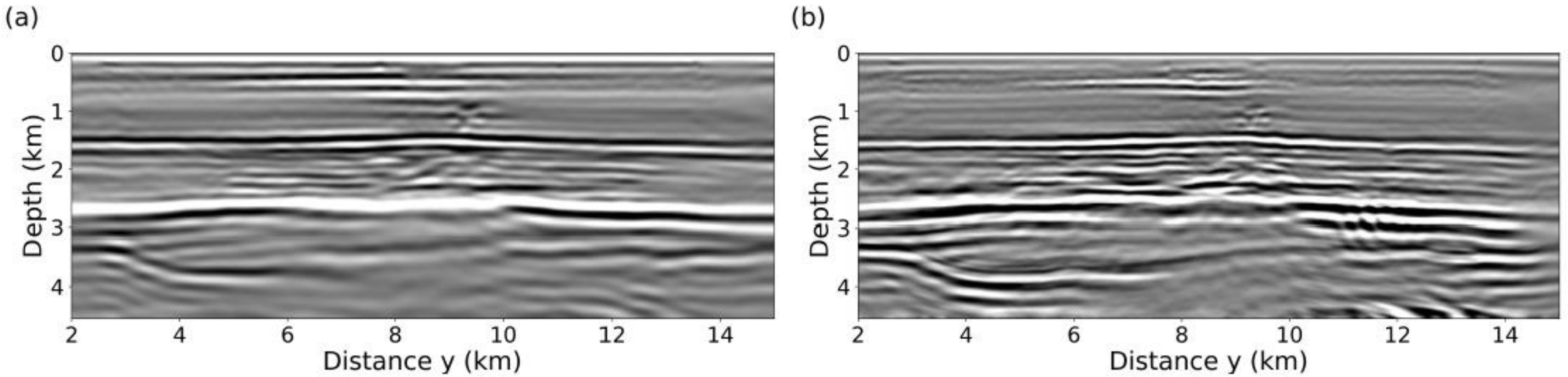


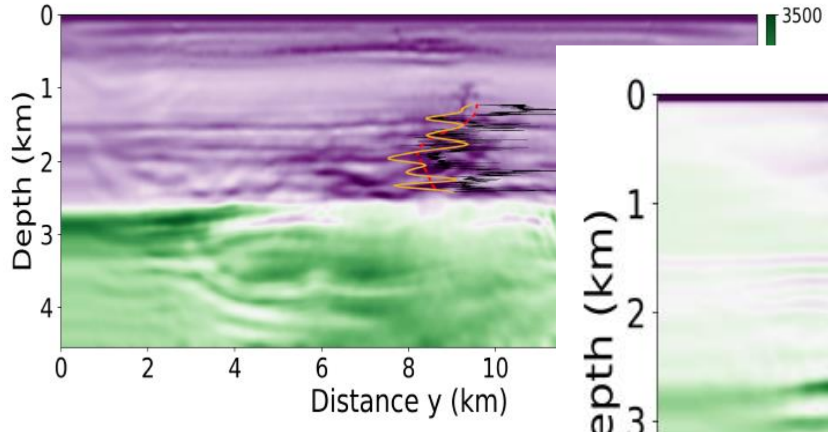
***Figure 2** Reflectivity images derived from P-wave velocity and density at (a) 10 Hz, (b) 22.5 Hz.*

(Métivier et al, 2024)

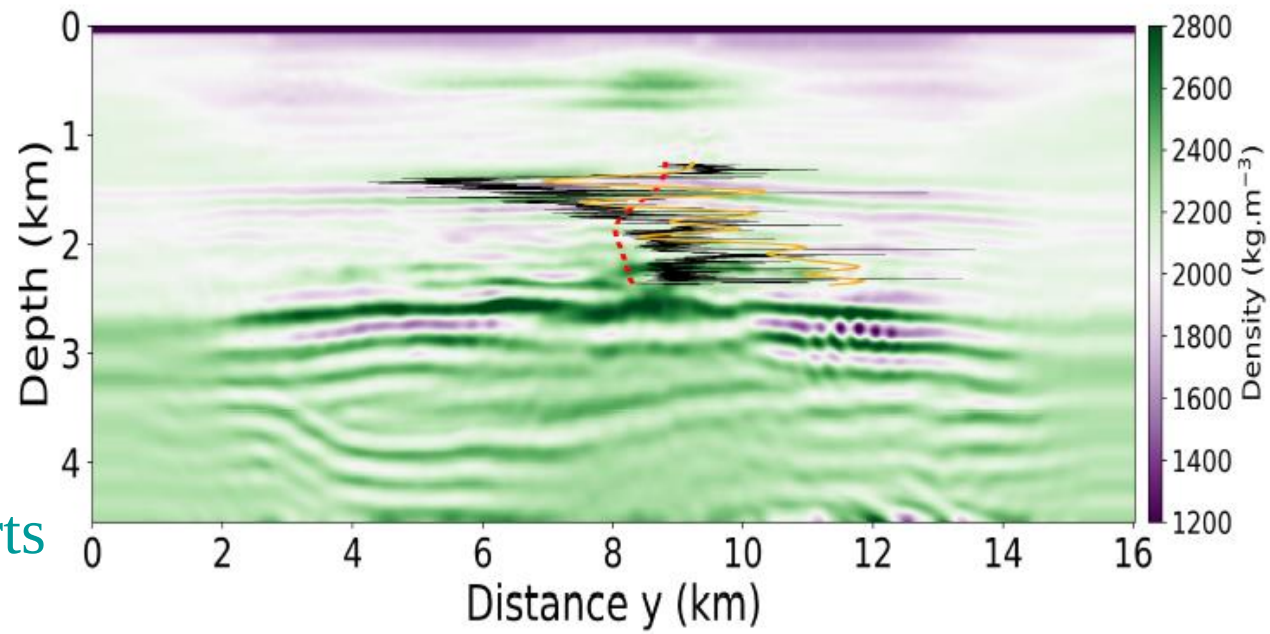
Stochastic strategy could be drastically reduced for wave propagation

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!)

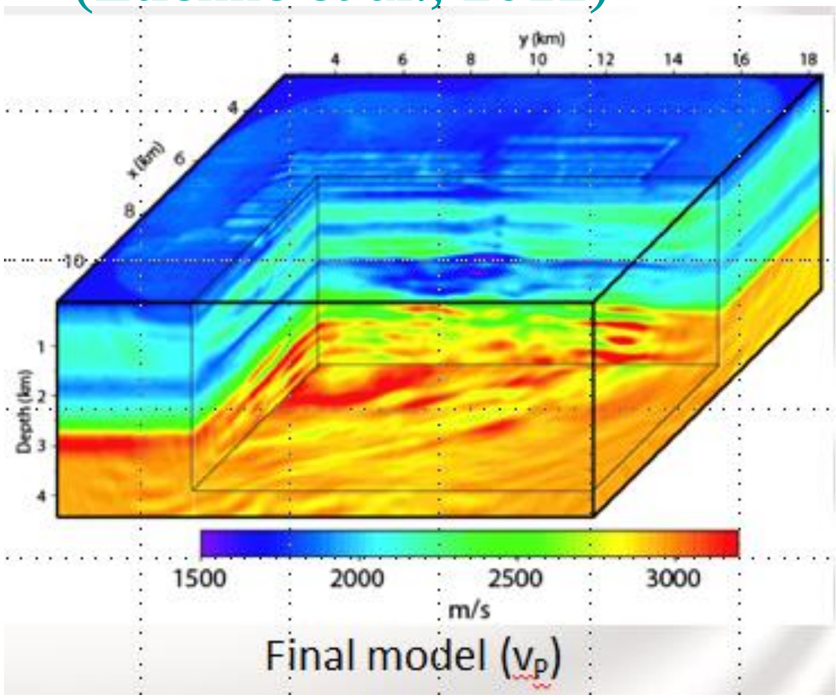
FWI: a rather difficult strategy?

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!)

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

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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) …

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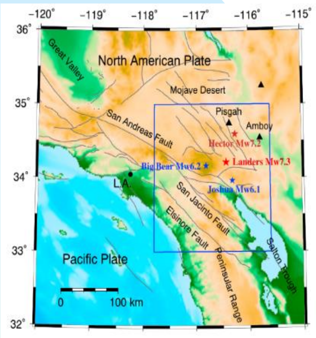
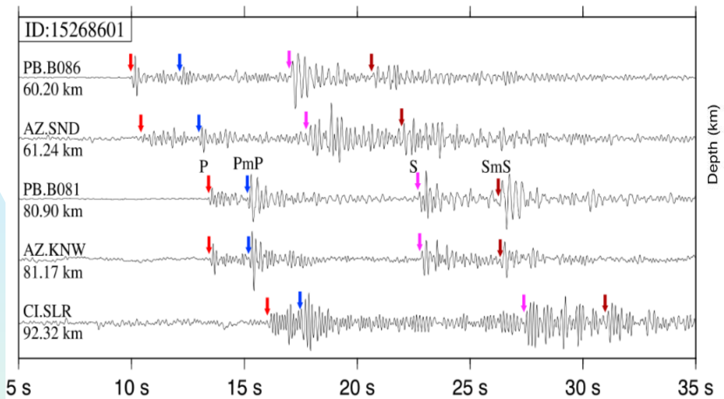
Wave-equation tomography

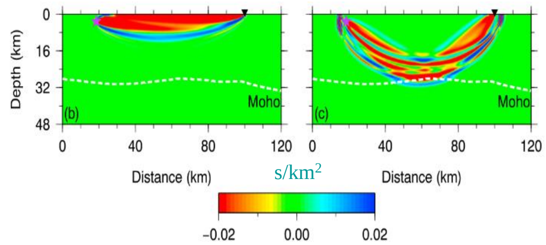
Wave Equation Tomography (WET)

(wide-spread tool in seismology)



(Huang et al, 2016)





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

Sensitive to both amplitudes

- Sensitivity kernel from Wave Equation (WE) (Tape et al., 2009, 2010; …)

Sensitive to synthetic amplitudes

- Sensitivity kernel from Ray Theory (RT) (Dahlen et al, 2000; Dahlen & Nolet, 2005)

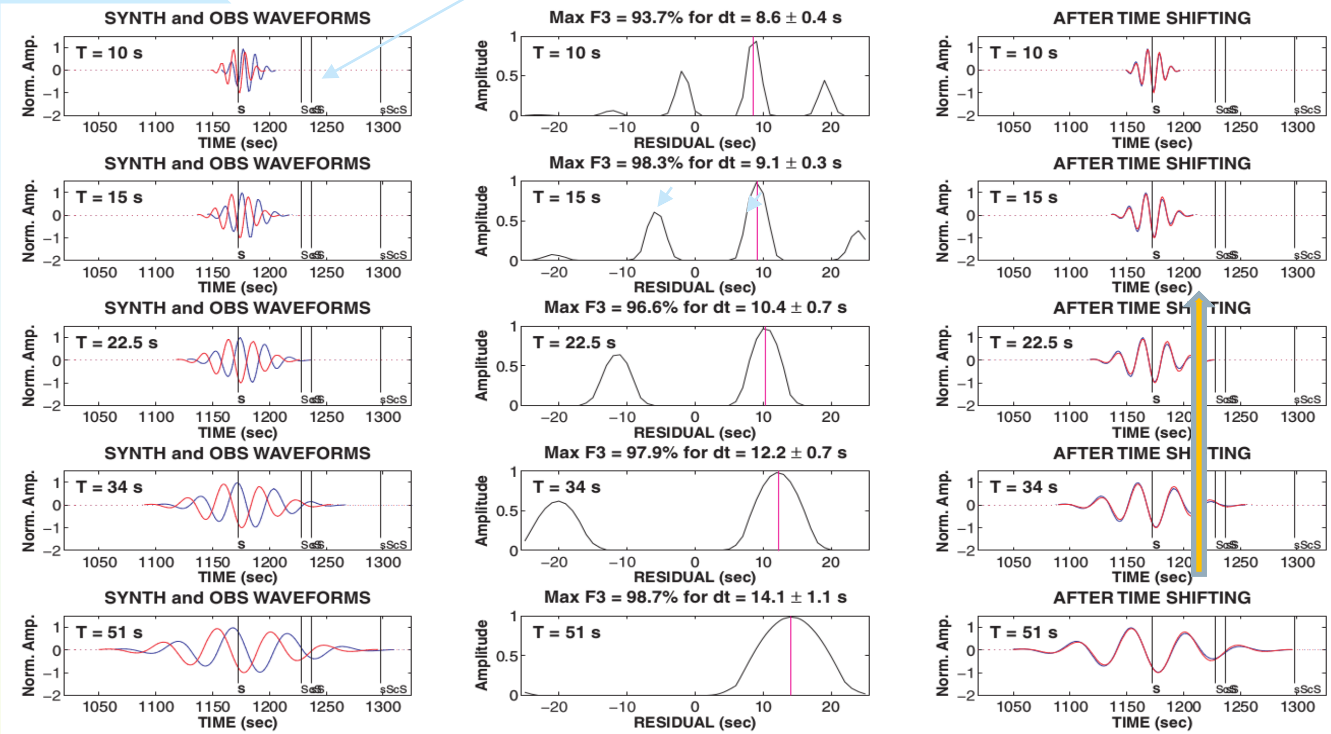
Born approximation (Lippmann & Schwinger, 1950; Dahlen & Tromp, 1998; Zhao et al., 2000; Zhao & Chevrot, 2011a,b)

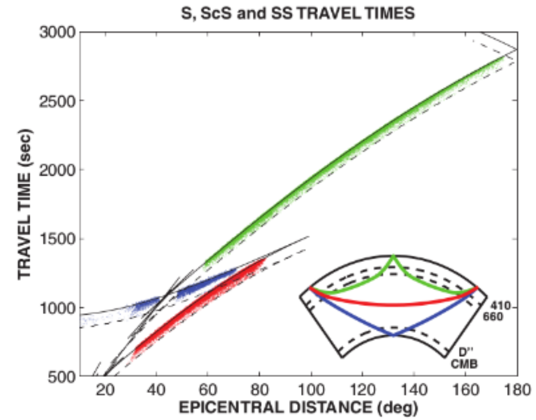
Dynamic phase measurement: Xcorr.

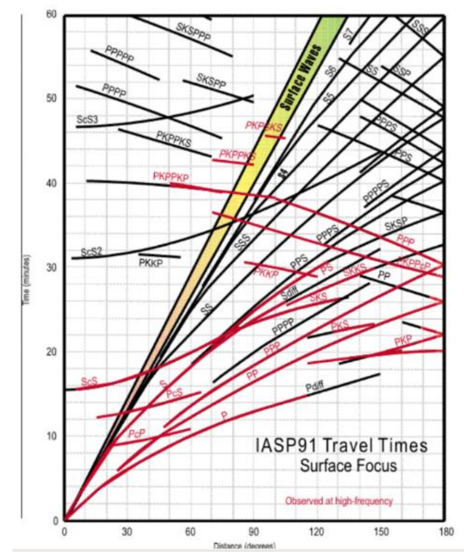
Interference btw ScS and sS

High frequency

« Tagging »







Low frequency

Zaroli et al (2010)

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

Wave-equation tomography

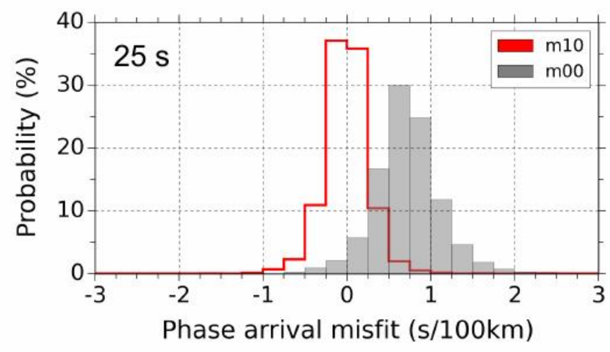
Lu et al (2018)

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

From ambient noise analysis

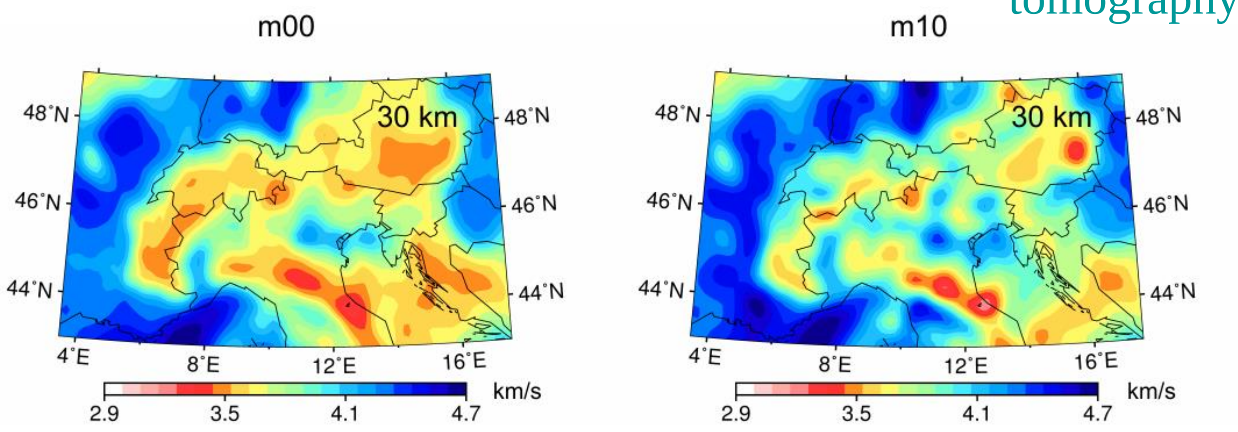
Dispersion curve analysis (fundamental mode)

What kind of phases in WET?



Seismology ☺

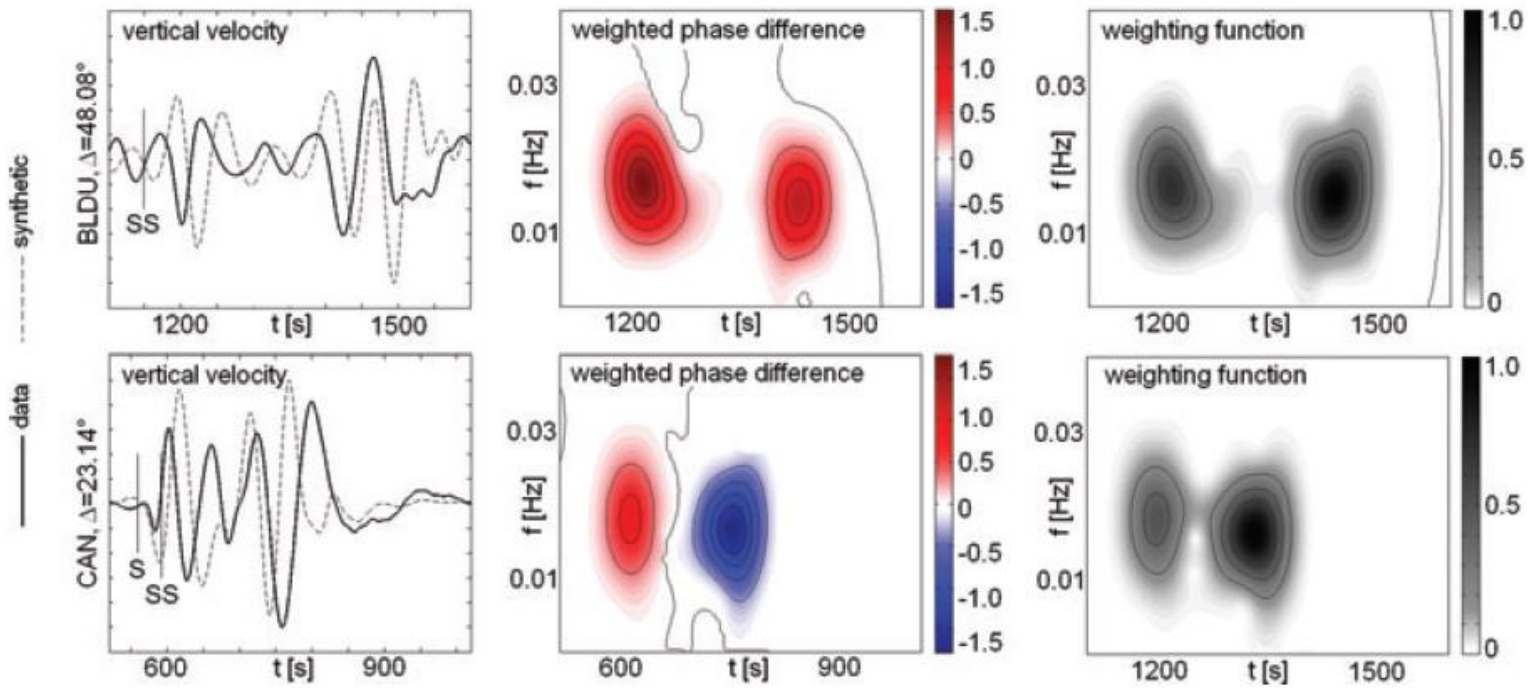
Wave equation tomography



Initial phase tomography

Seismic ☹/☺

WET: independent phase misfit

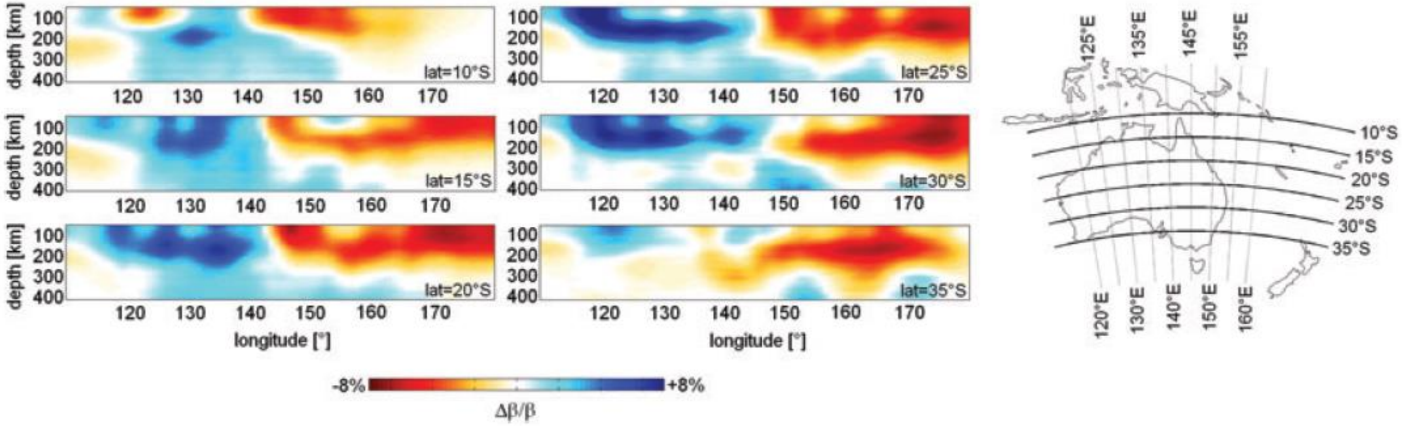


(Fichtner et al., 2008; Fichtner et al., 2009)

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

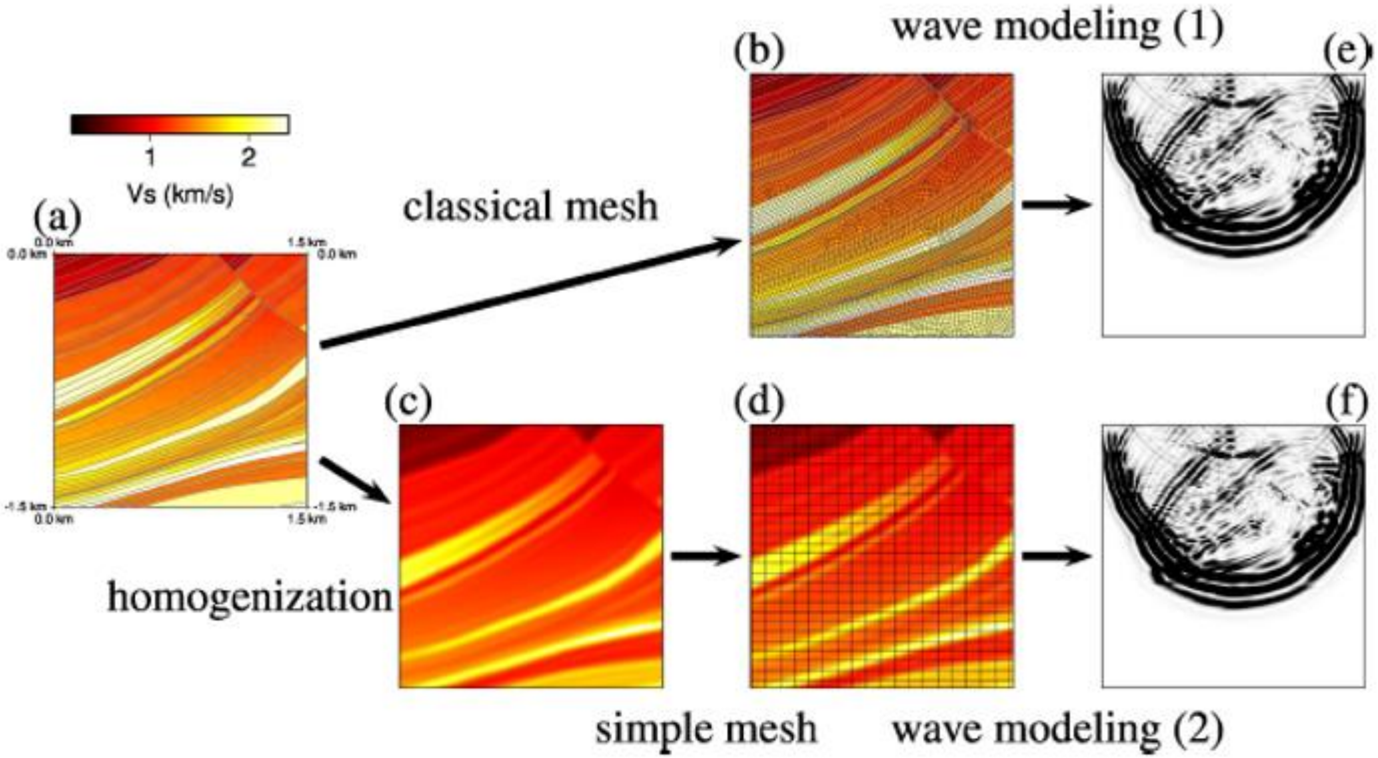


Does WET improve the resolution compared to DRT or DET?

(Fichtner et al, 2009)

Resolution is improved by exploiting more information,
especially interference phases

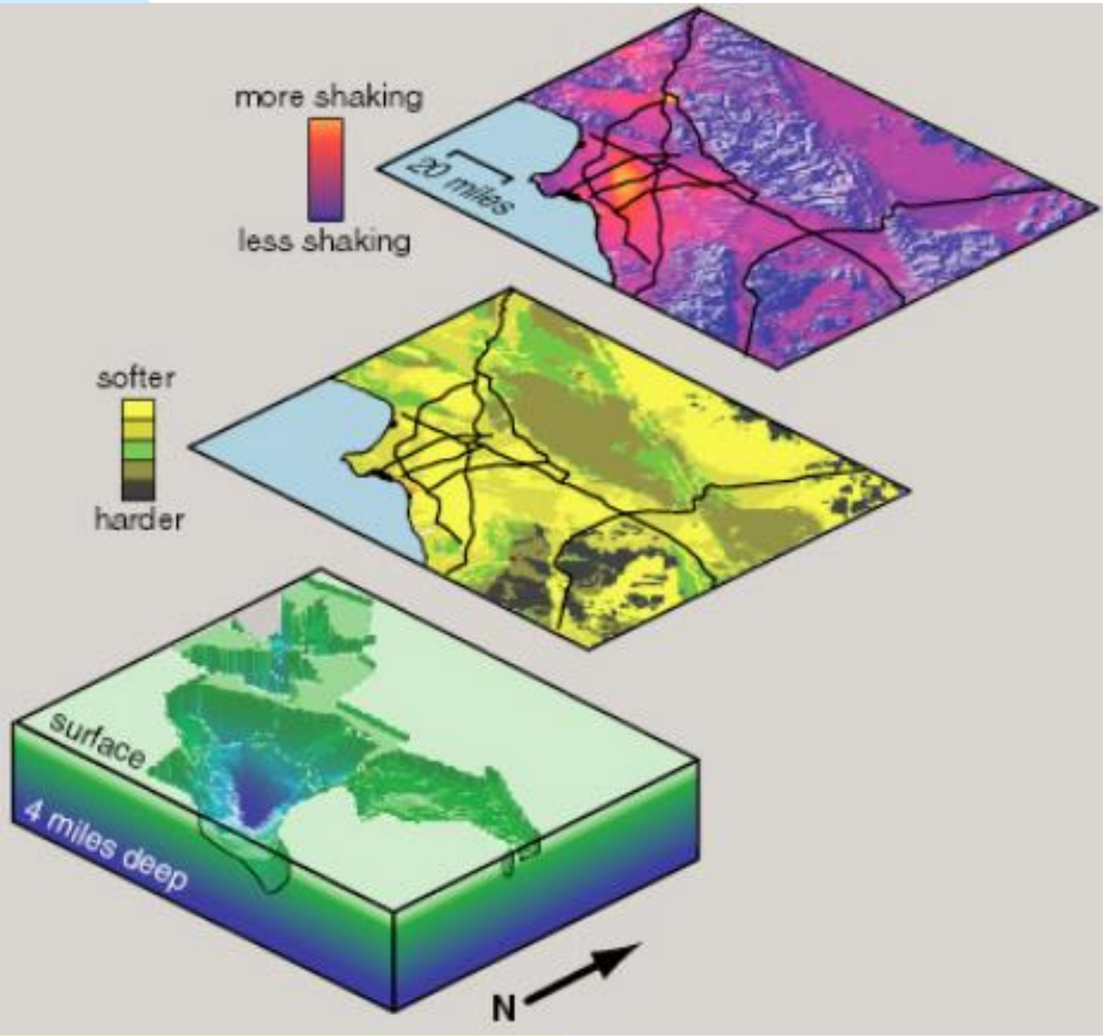
Mitigation of computer needs!



Model homogenization requires anisotropy parameters but reduces significantly computer cost

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

Site: short-scale variation



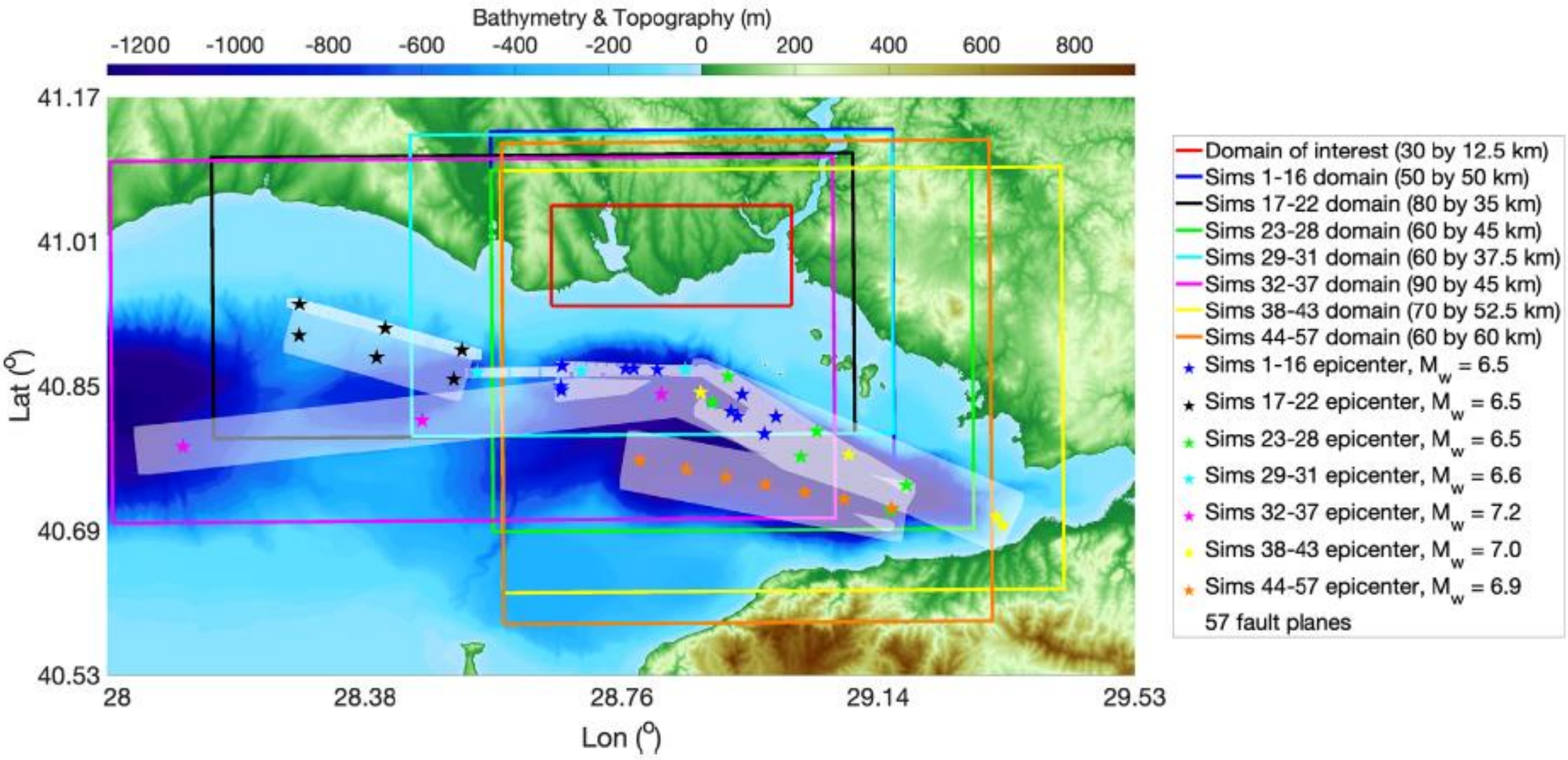
Local ground shaking depends on

softness of the surface rocks

thickness of surface sediments.

(from SCEC website)

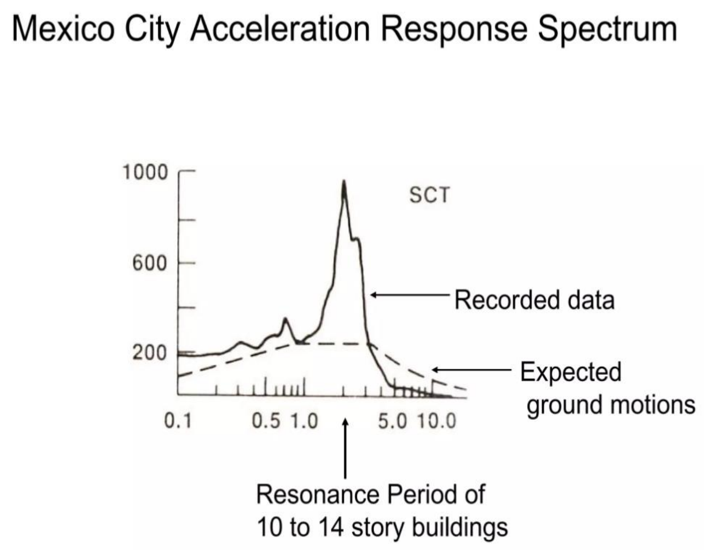
Reduction of GMS scenarios

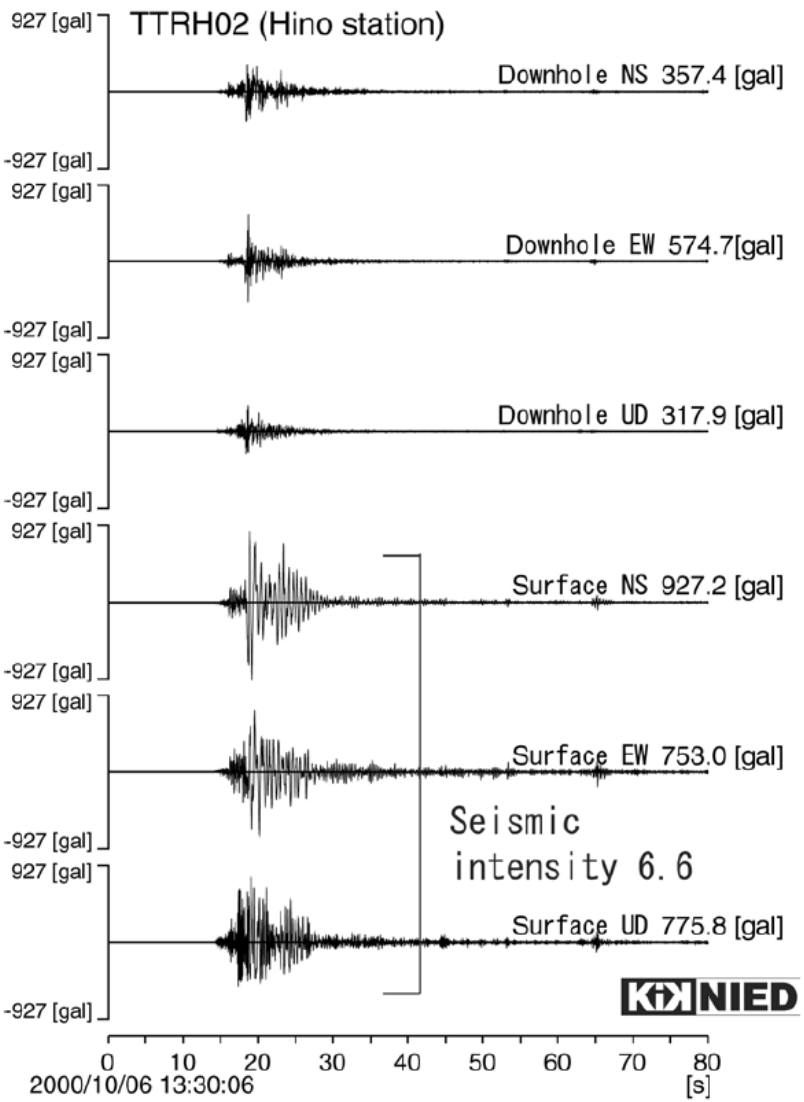


Variability comes from unexpected earthquake description and …

Reduction of GMS

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





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.