Where no wave has gone before: unconventional elastic wave fields in exotic regimes

Thomas Bohlen

Crew of Enterprise

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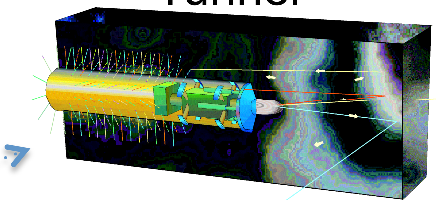
Gauss-Lecture
Deutsche Geophysikalische Gesellschaft
EGU, April 25, 2012

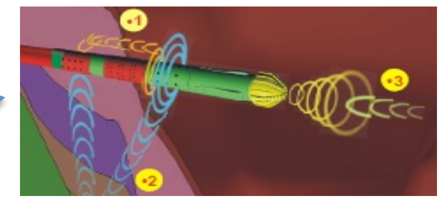
Outline

- Introduction
- Unconventional waves
  - Tunnel
  - Borehole
  - Seafloor
- Continuing mission
  - full waveform inversion

Tunnel

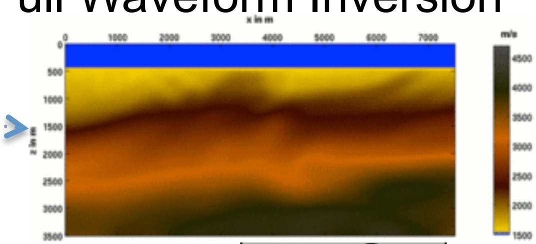


Borehole

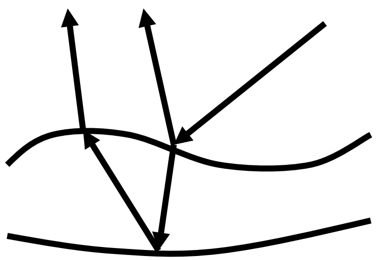


Seafloor

Full Waveform Inversion



Goals of seismic technique



1. **Imaging**: localisation of interfaces (migration)

2. **Material parameter** (tomography)
   - P-wave velocity
   - S-wave velocity
   - Density
   - Attenuation
   - Anisotropy

petrophysical relations: pore scale

- porosity
- gas/fluids
- composition

Conventional seismic methods

- Analyse specific wave types only, e.g.
  - P-wave reflection seismics
  - First arrival tomography
  - Surface waves
- Use only a small portion of the information available
  - Travel times
  - Amplitudes of specific waves
- <u>Most information is neglected</u>

Send out new waves and methods

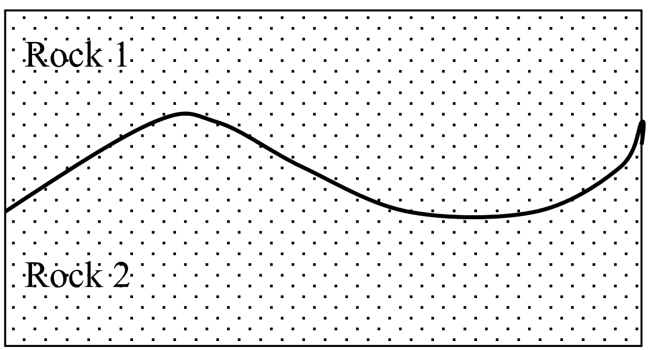
- **Use more information**
  - multi-parameter imaging
  - higher resolution
  - reduction of ambiguities
- **Strategies**
  1. “unconventional” elastic wavefields
  2. full waveform inversion

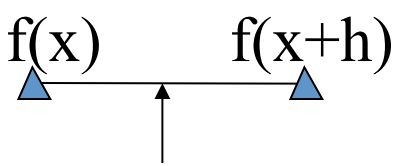
→ **<u>Simulation of elastic wavefields</u>**

Simulation

- Motivation
  - understand complex wave propagation
  - verify new methods
  - kernel of full waveform inversion
- Requirements
  - full elastic wave field
  - arbitrary media including strong contrasts

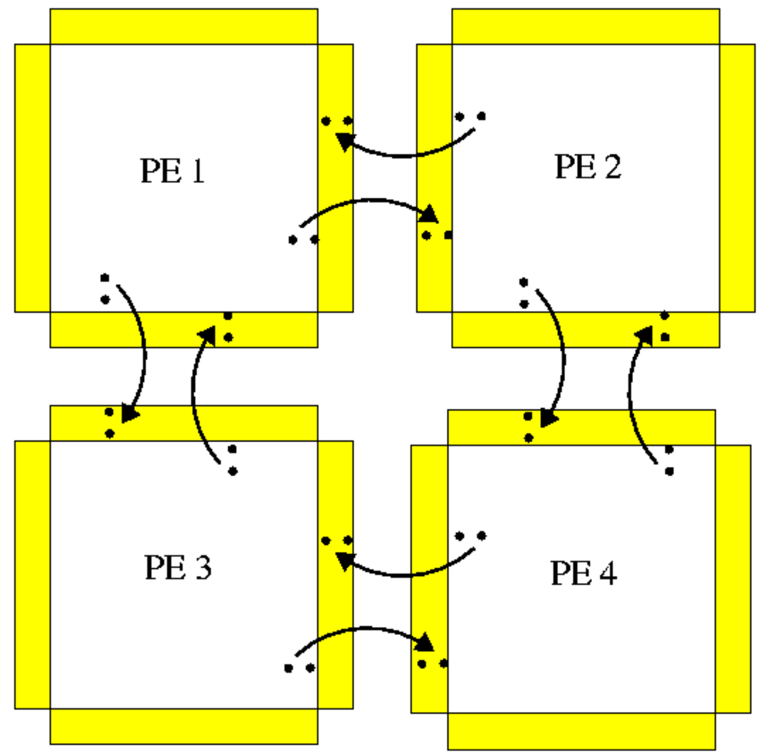
Parallel Finite-Difference Method





$$\frac{\partial f}{\partial x} \approx \frac{1}{h}\left(f\left(x+h\right) - f\left(x\right)\right)$$

Domain Decomposition



MPI

(Bohlen, 2002; Bohlen & Saenger, 2006)

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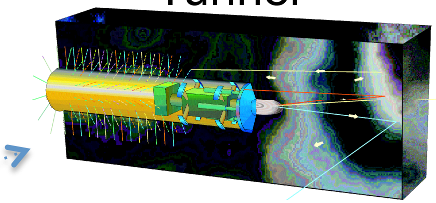
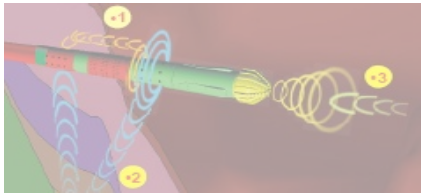
Tunnel

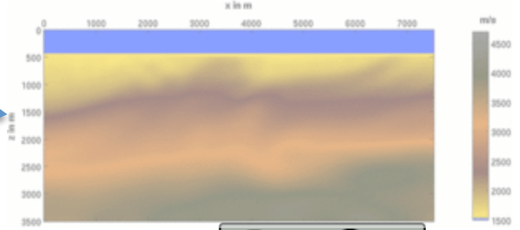


Borehole



Seafloor

Full Waveform Inversion



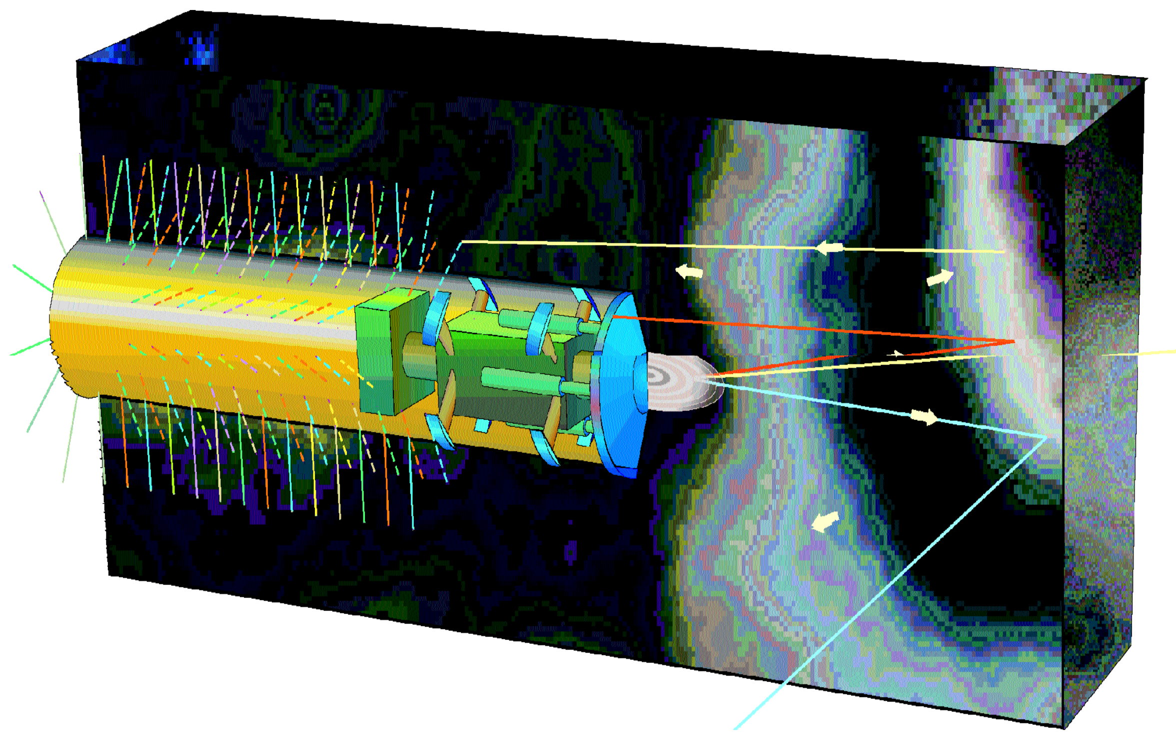
Tunnel Seismic Prediction

Receiver

2m

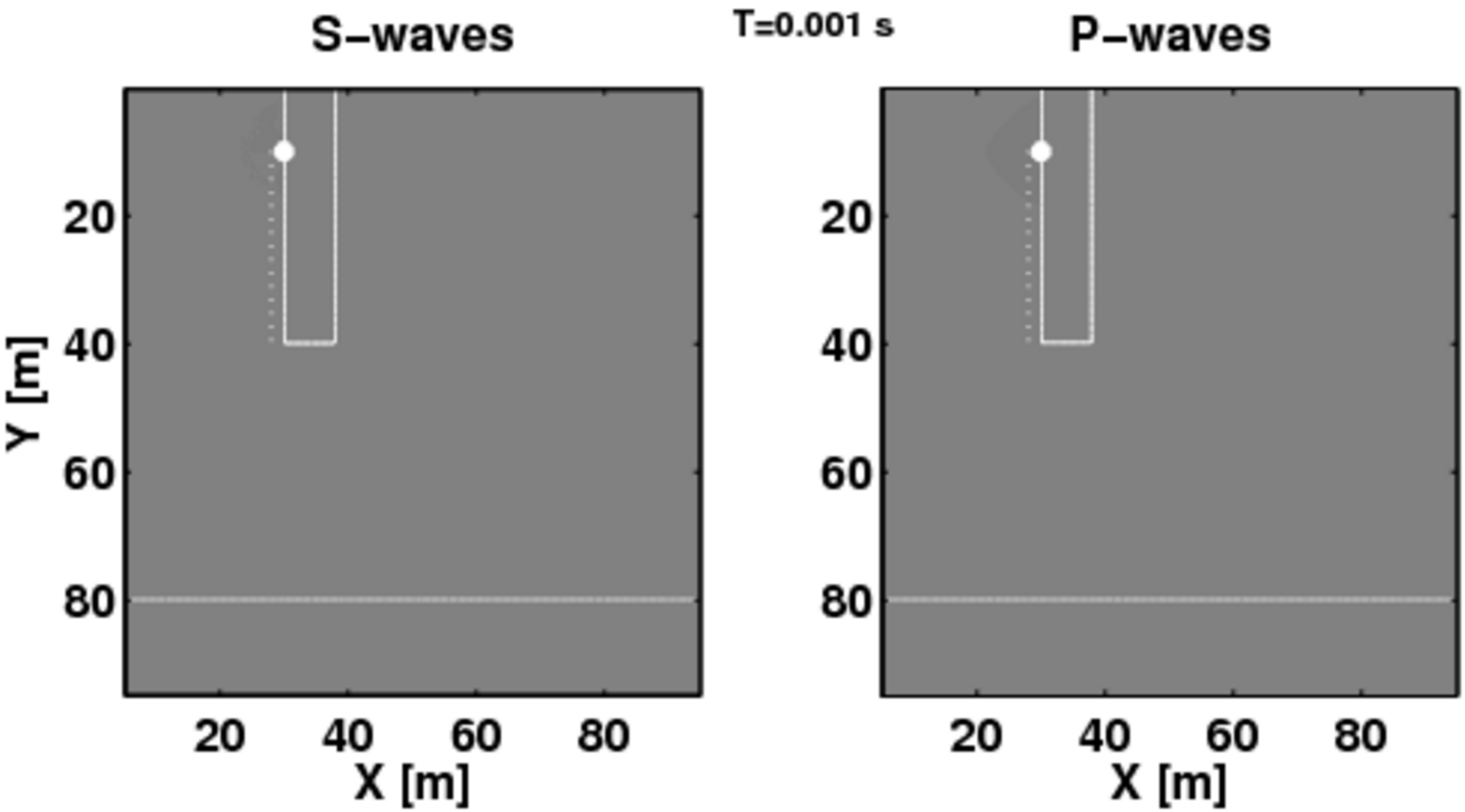
Source: Hammer

Goal: **Prediction ahead**



GFZ
POTSDAM

Send out new waves



(Bohlen et al., 2007)

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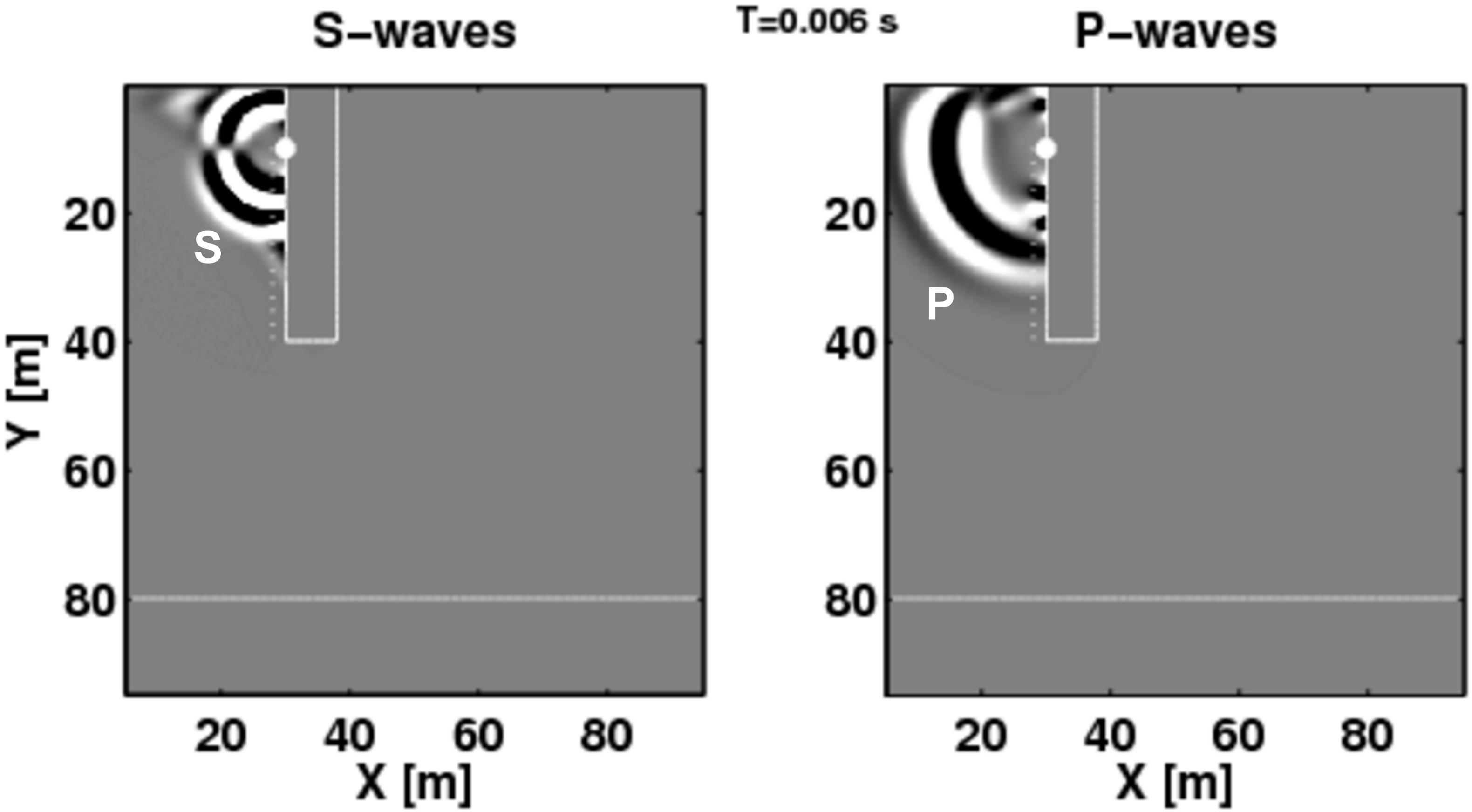

(Bohlen et al., 2007)

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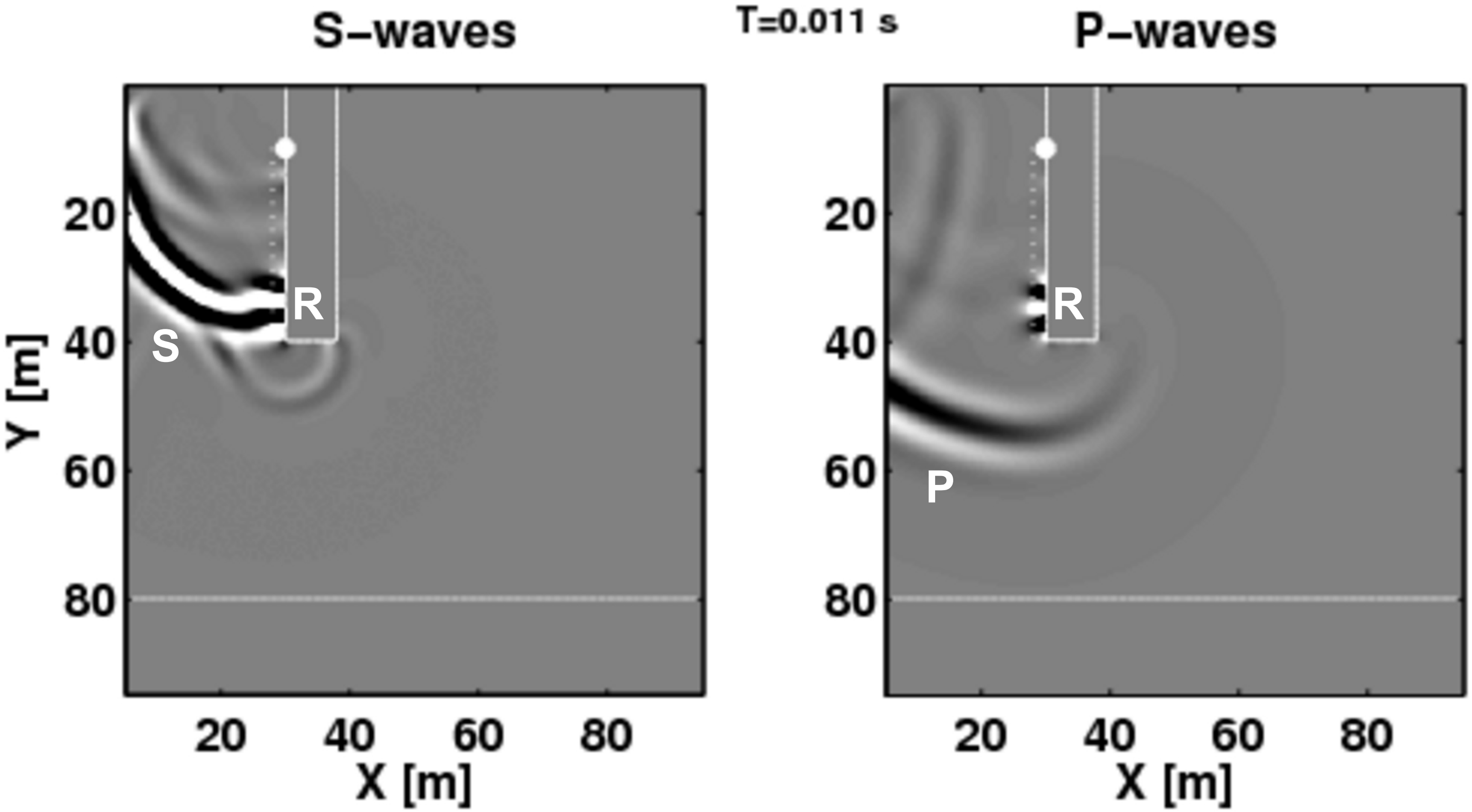

(Bohlen et al., 2007)

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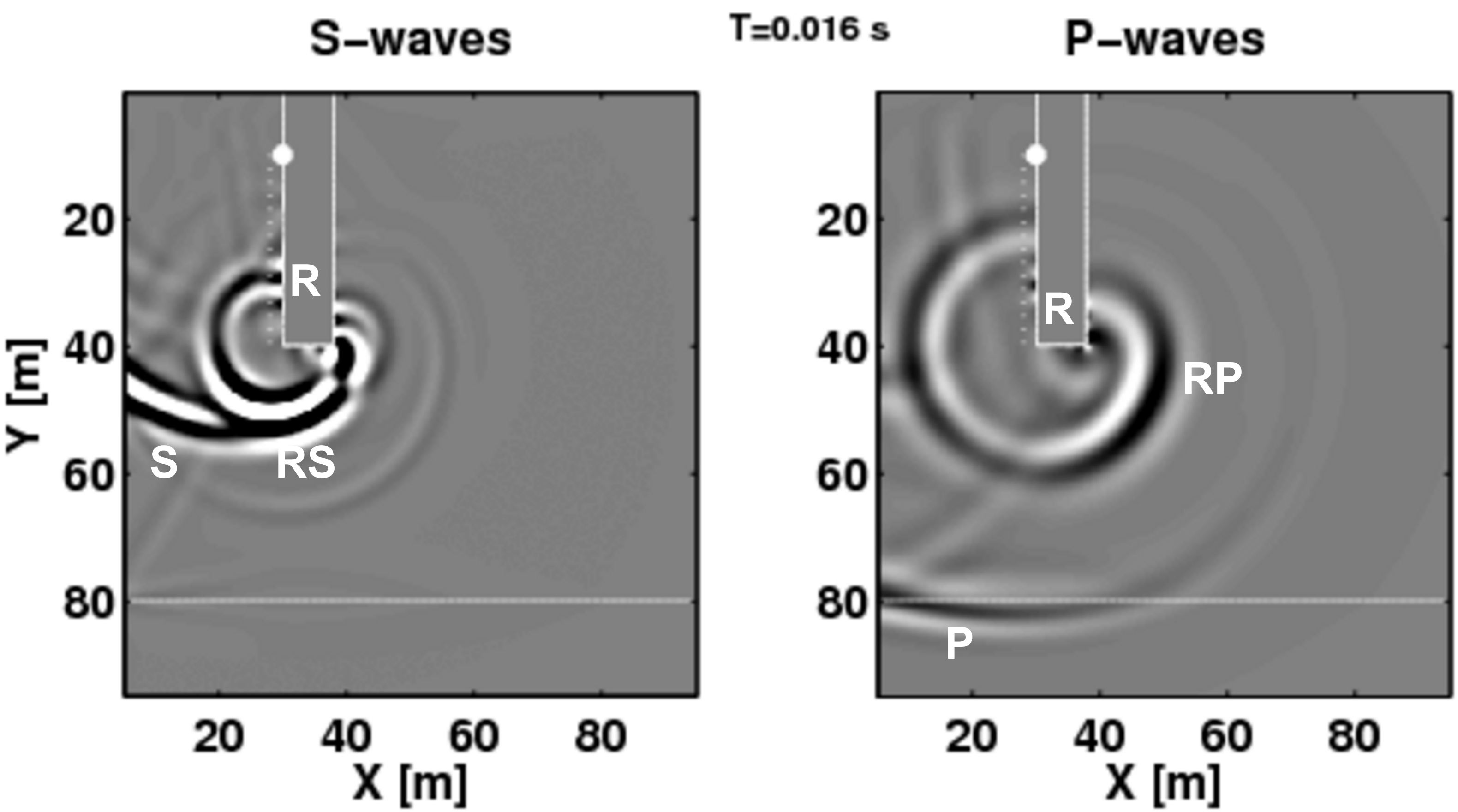

(Bohlen et al., 2007)

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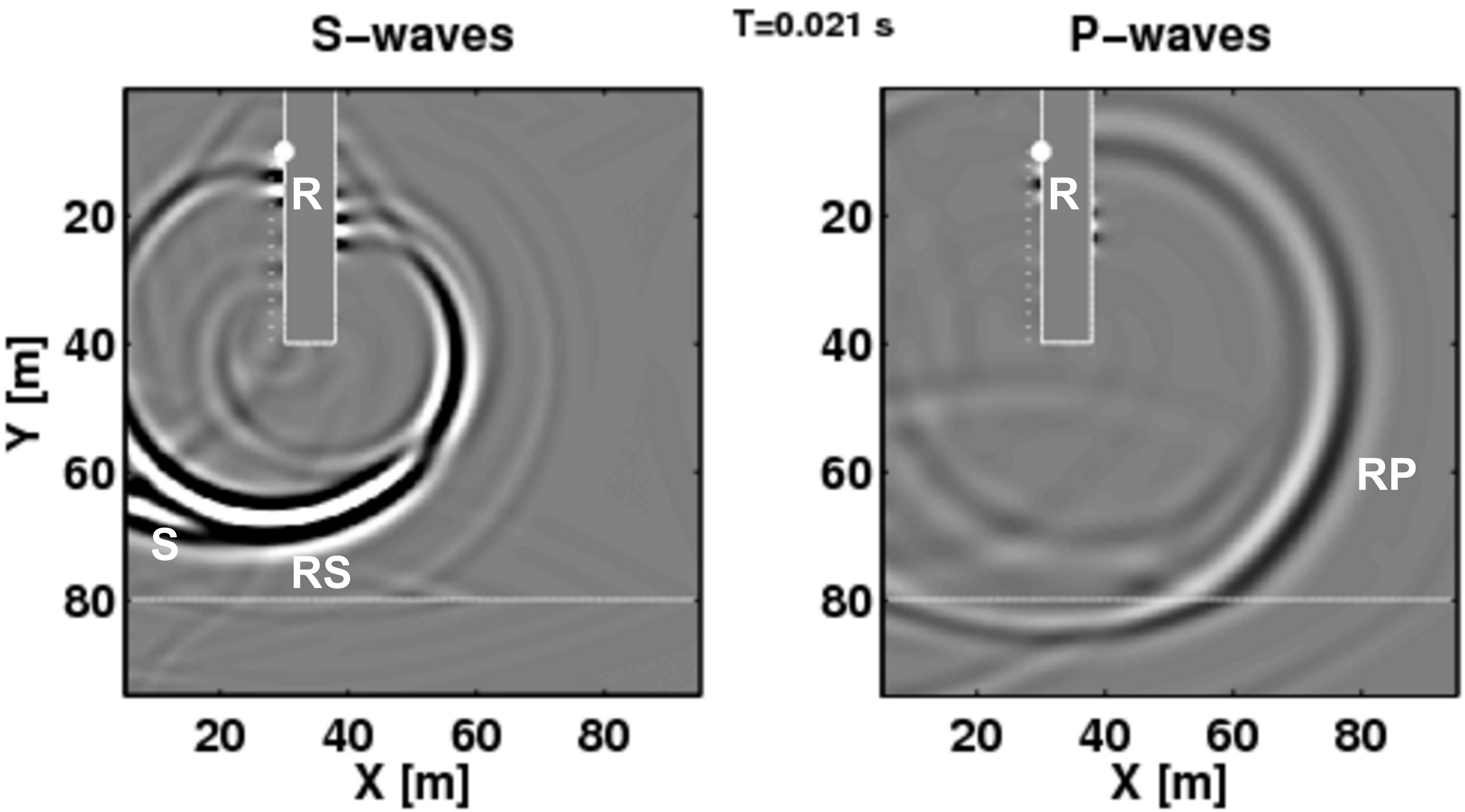

(Bohlen et al., 2007)

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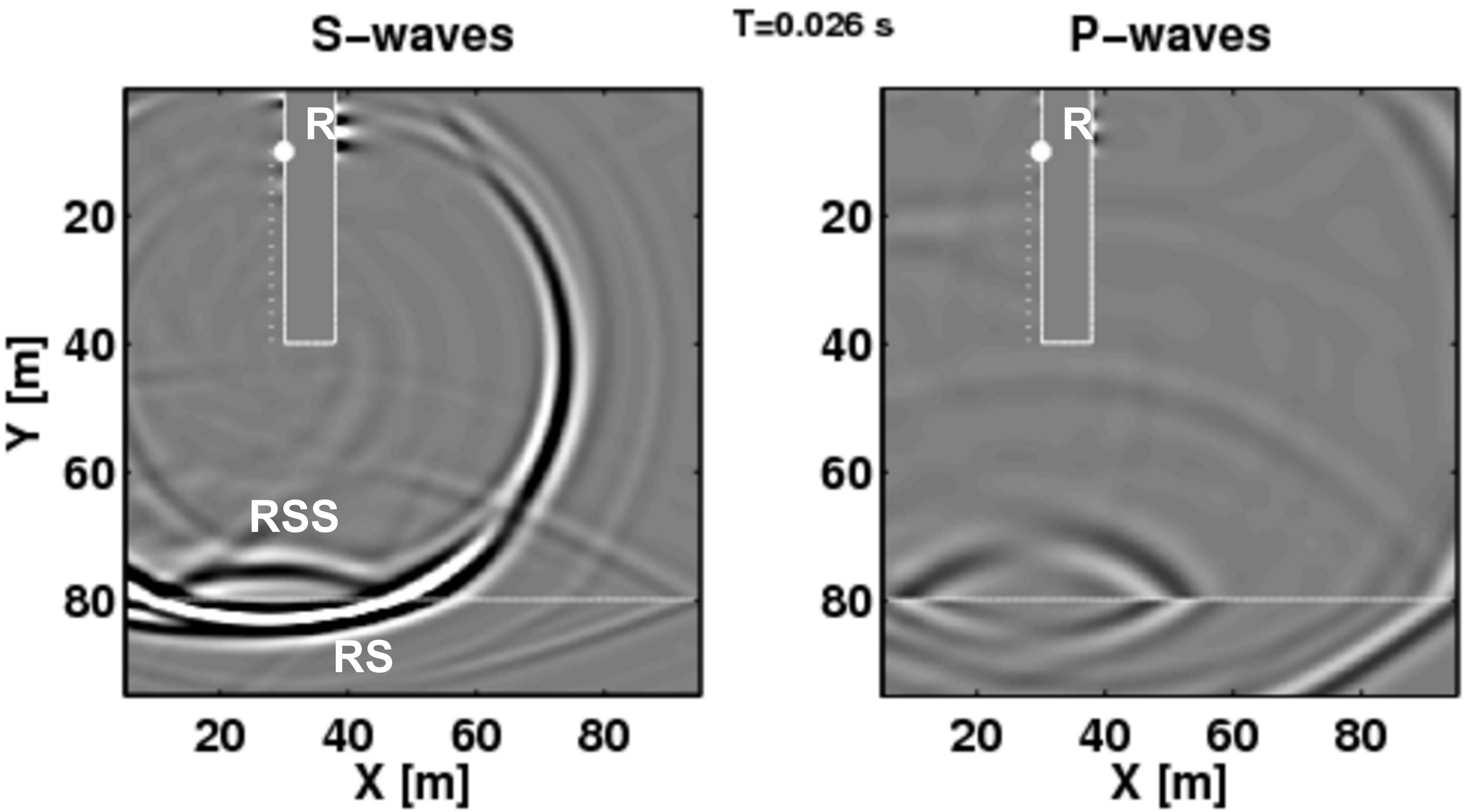

(Bohlen et al., 2007)

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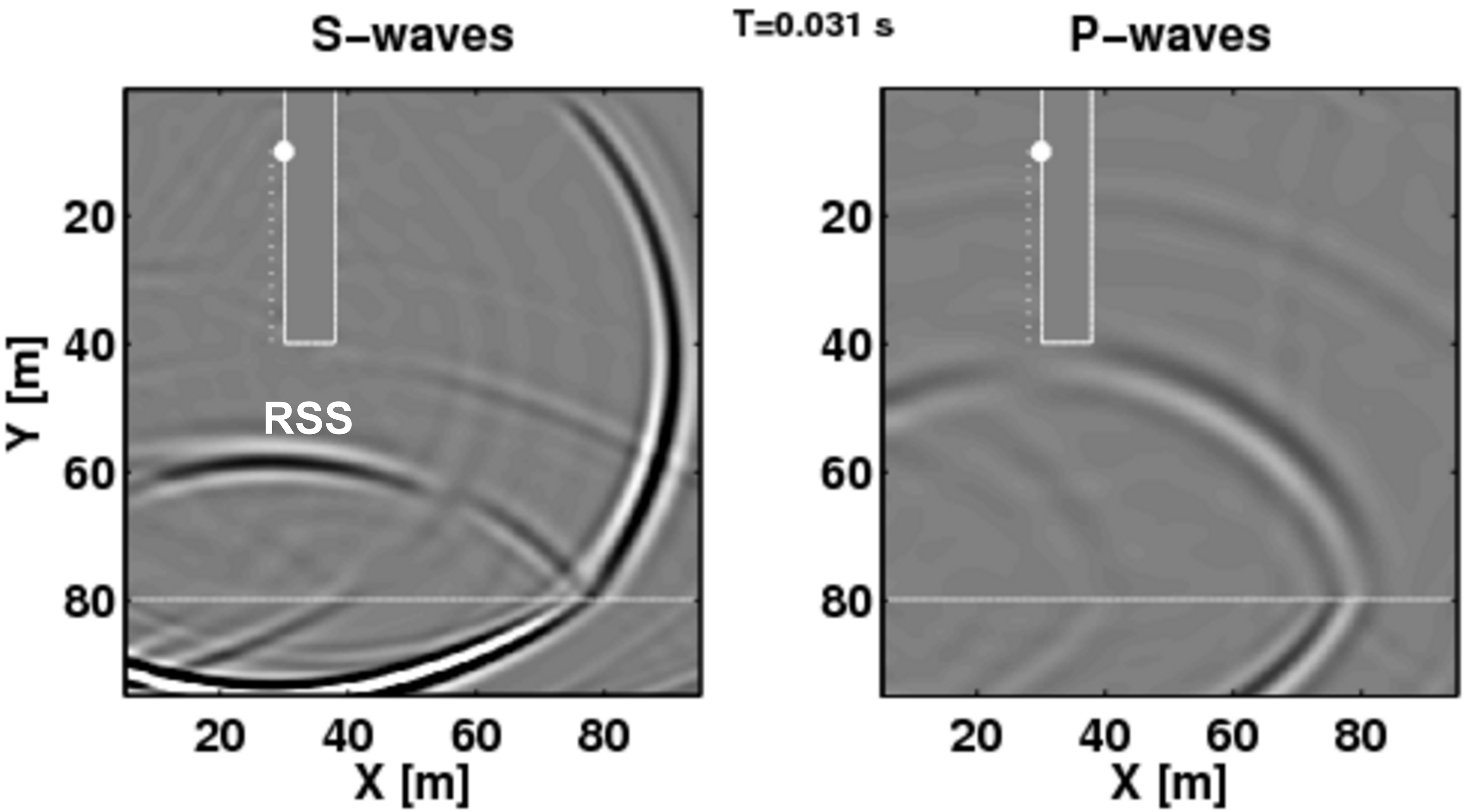

(Bohlen et al., 2007)

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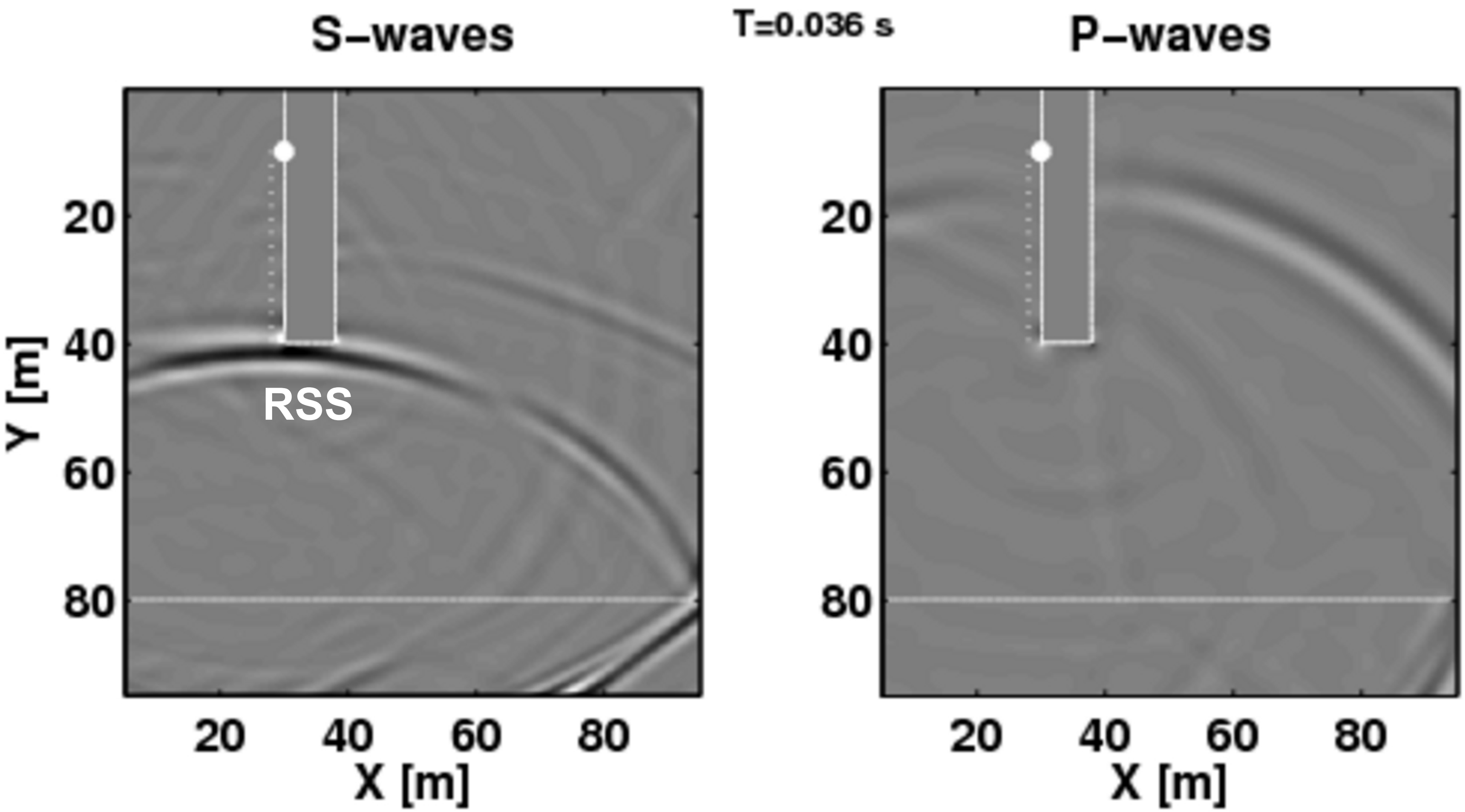

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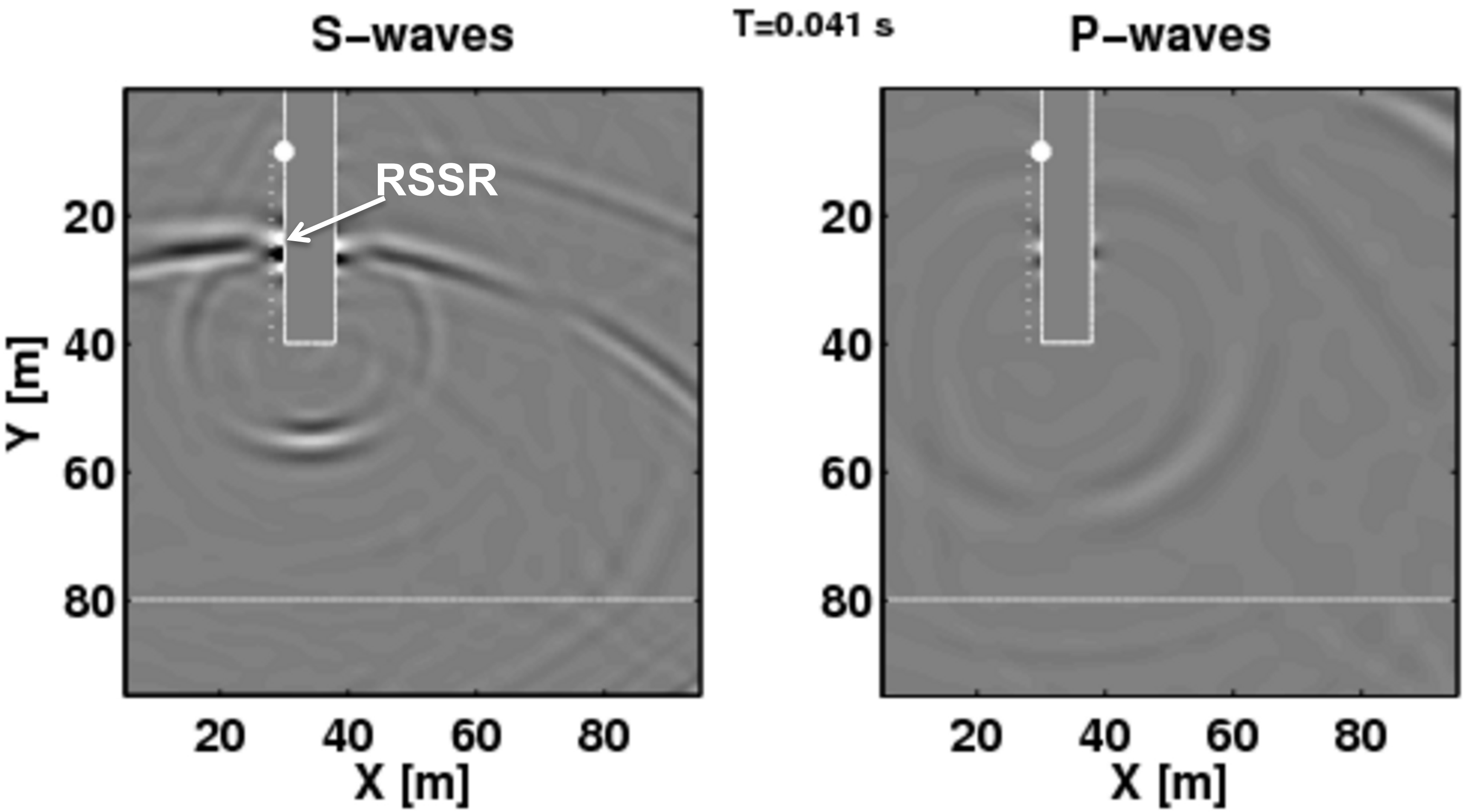

(Bohlen et al., 2007)

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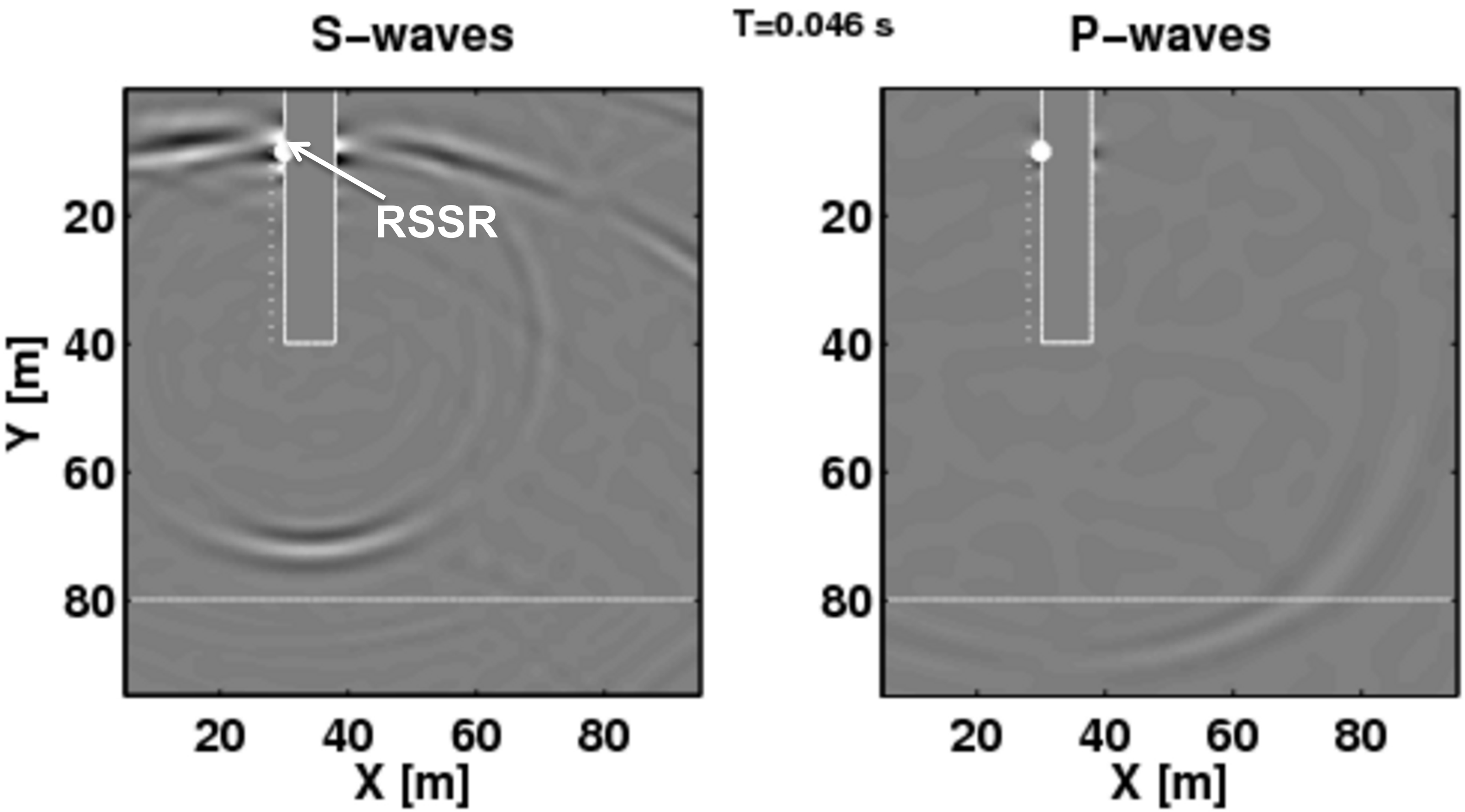
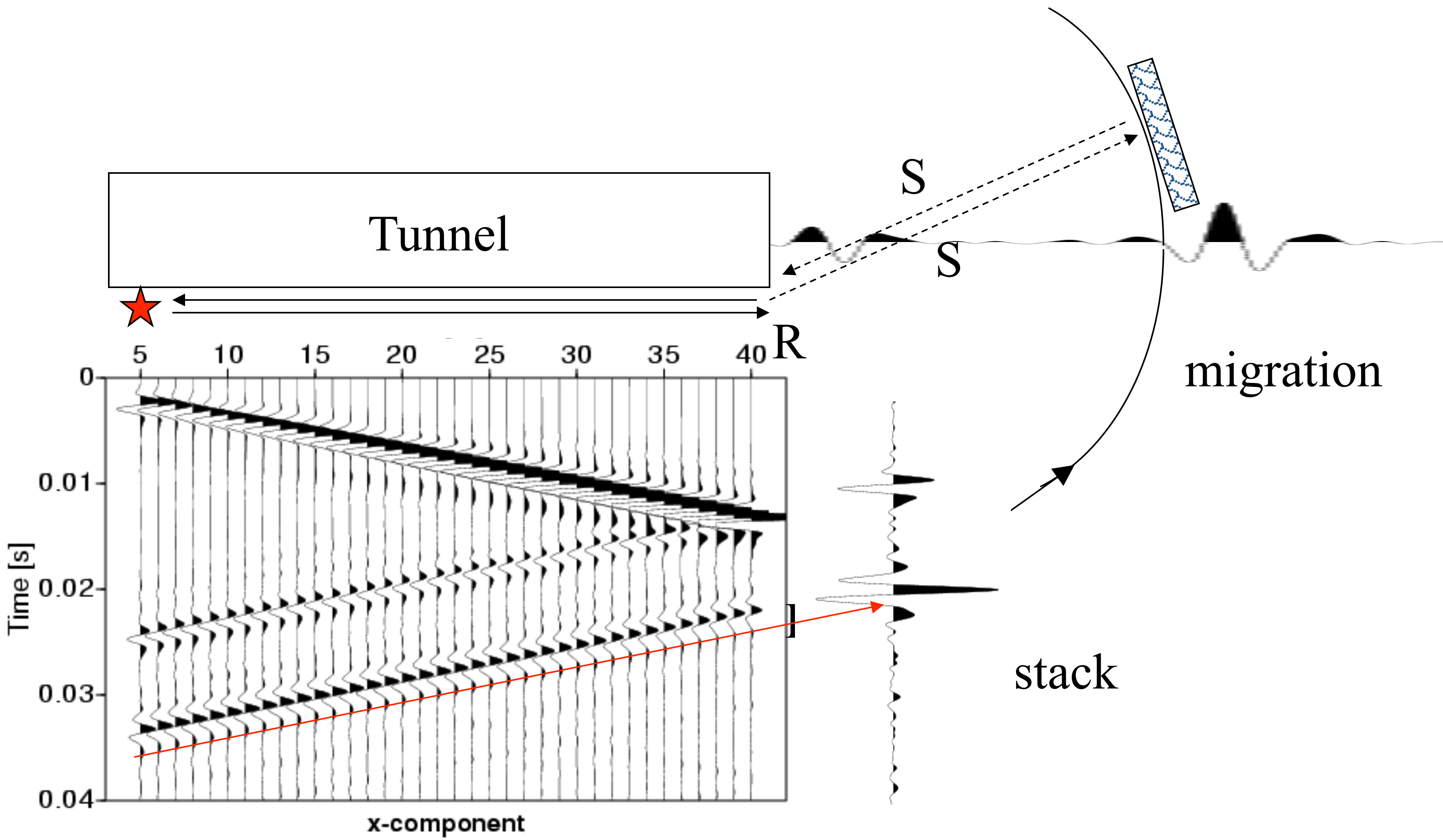
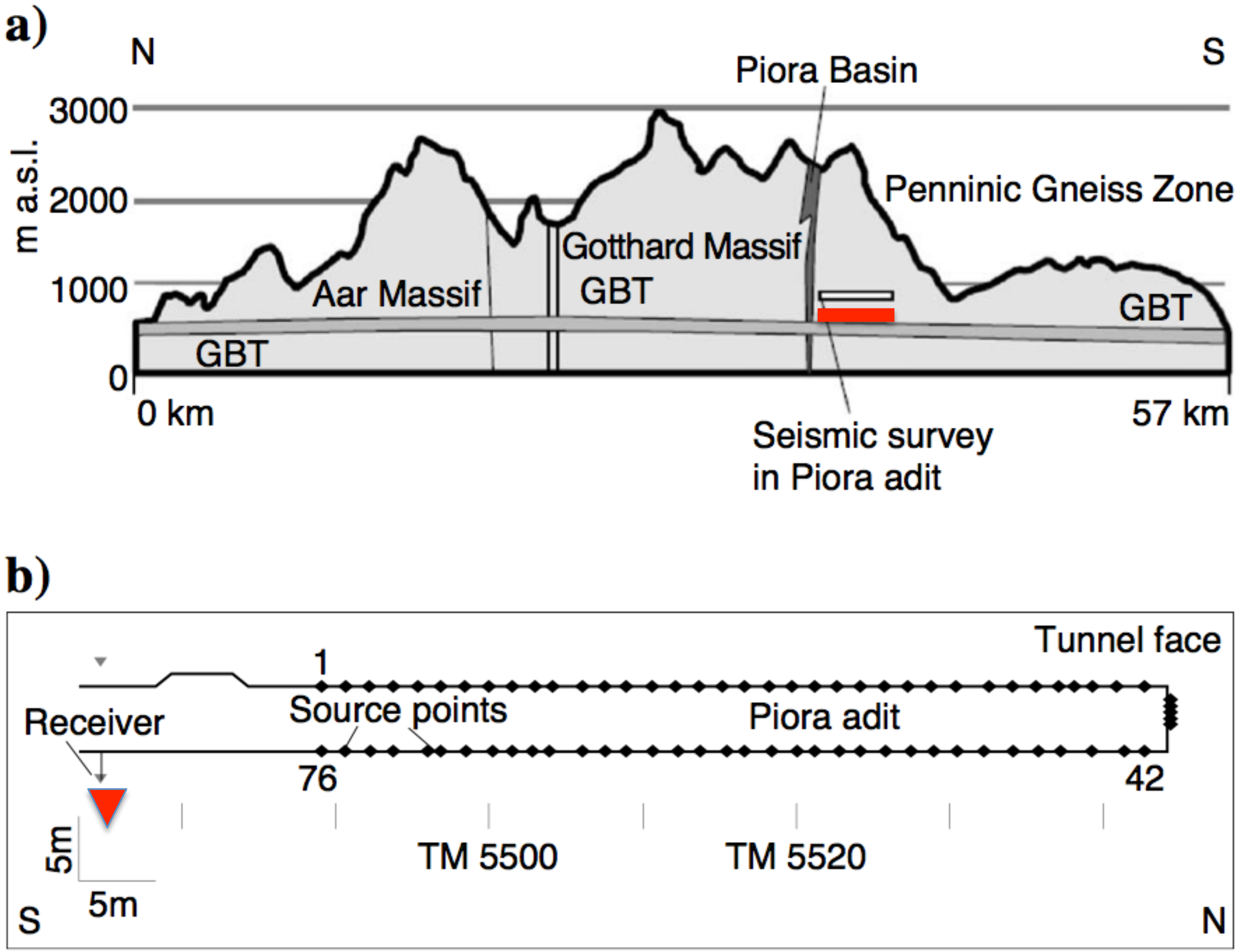


(Bohlen et al., 2007)

Prediction with RSSR waves

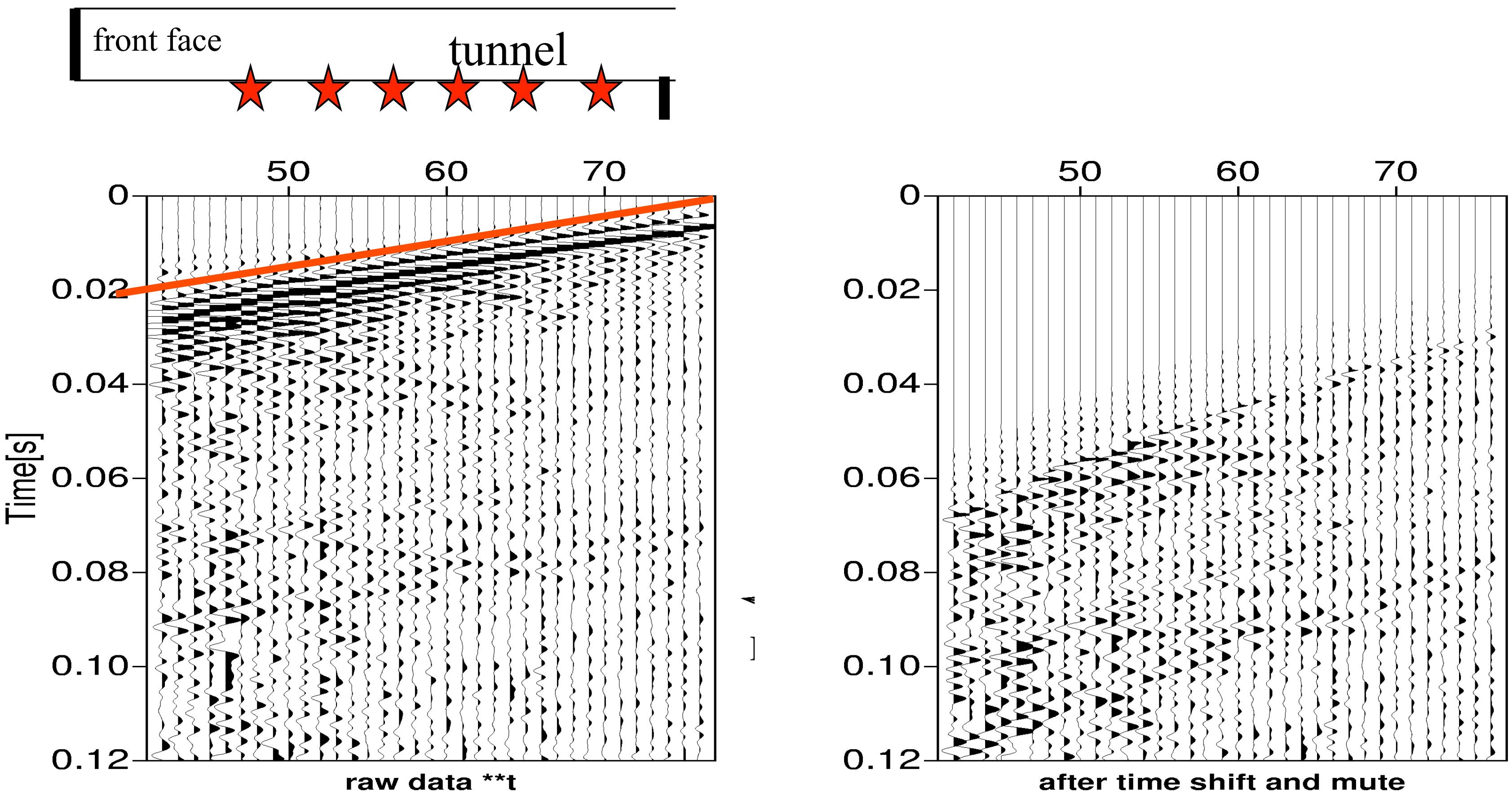


Field application



(Bohlen et al., 2007, Lüth et al., 2007)

Field application

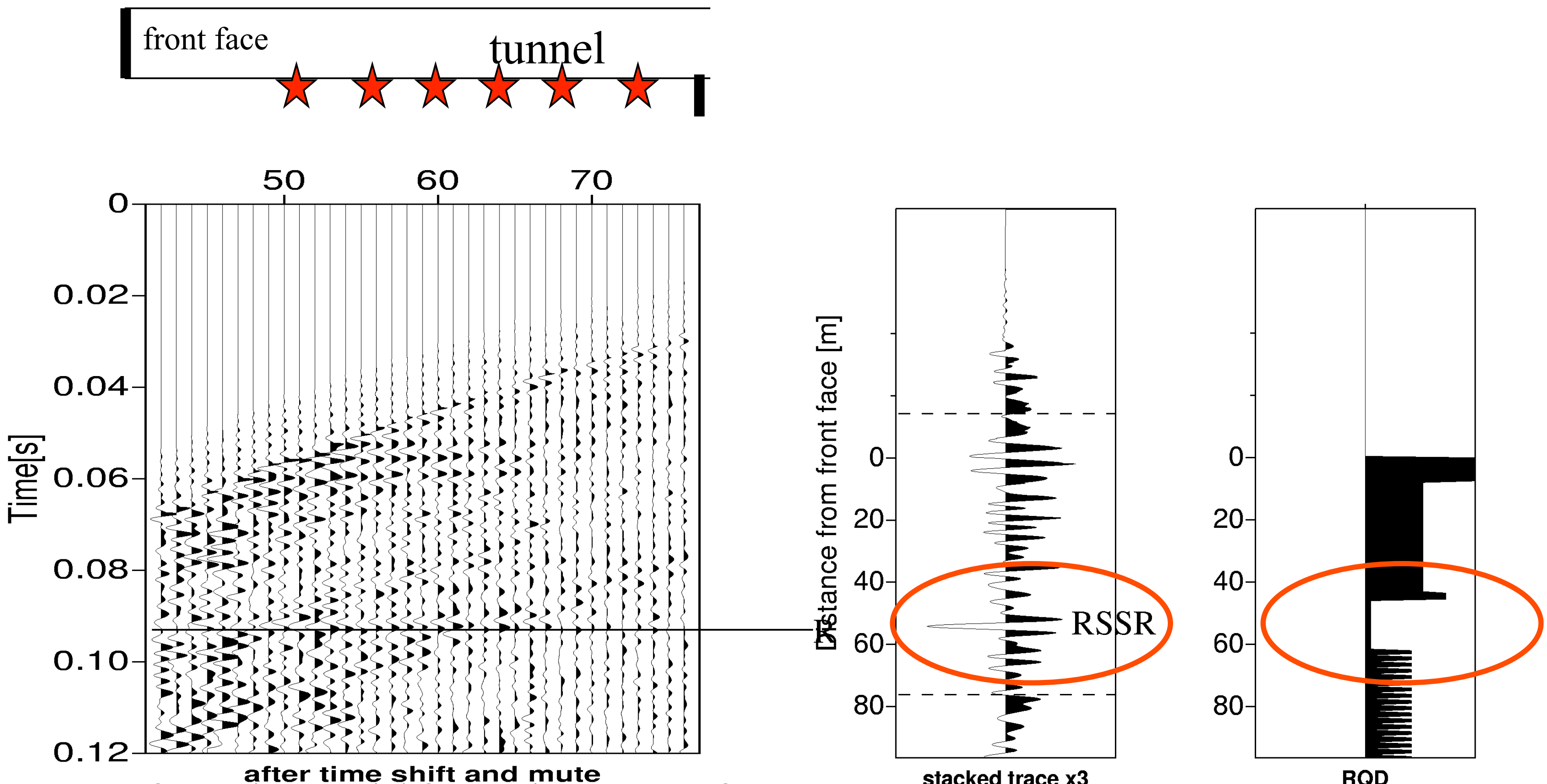


raw data *t

after time shift and mute of direct R-wave

(Bohlen et al., 2007)

Field application



after time shift and mute of direct R-wave

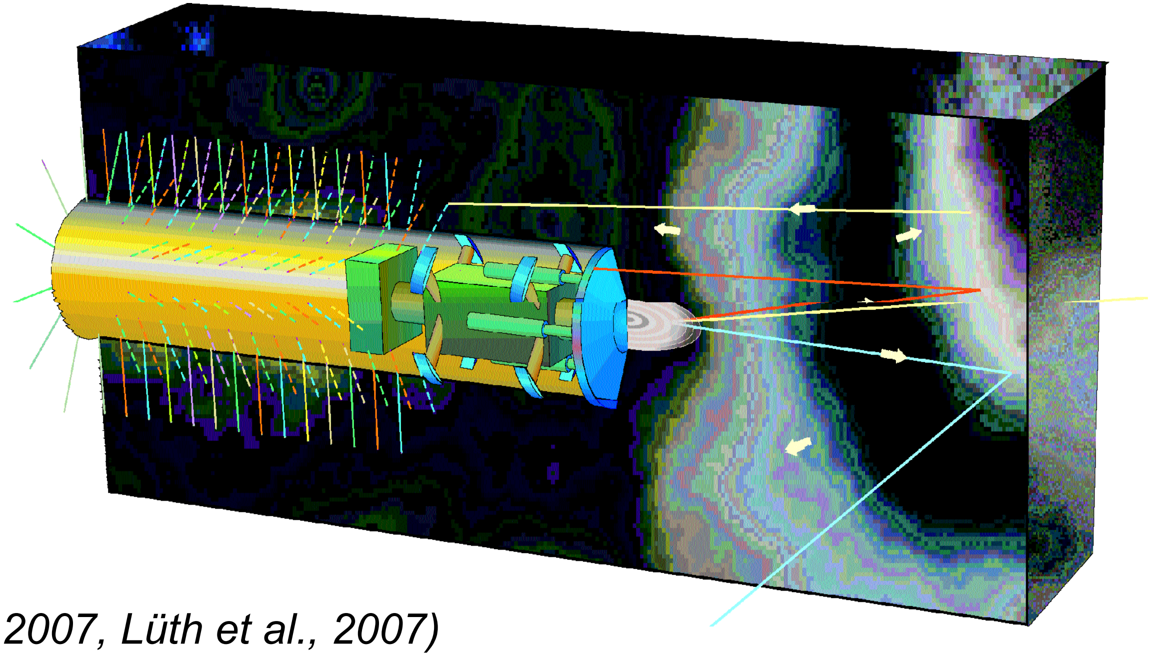
stack

RQD from drill core

(Bohlen et al., 2007)

Tunnel seismic prediction - conclusions

- „New“ wave type discovered by wave simulation
- RSSR is becoming practise for tunnel seismic prediction



(*Bohlen et al., 2007, Lüth et al., 2007*)

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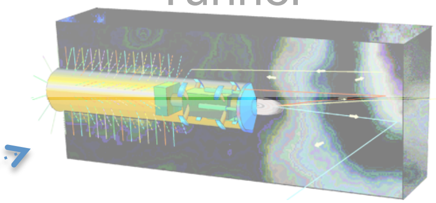
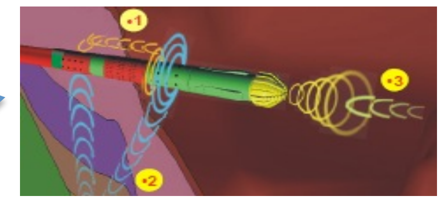
Tunnel



Borehole



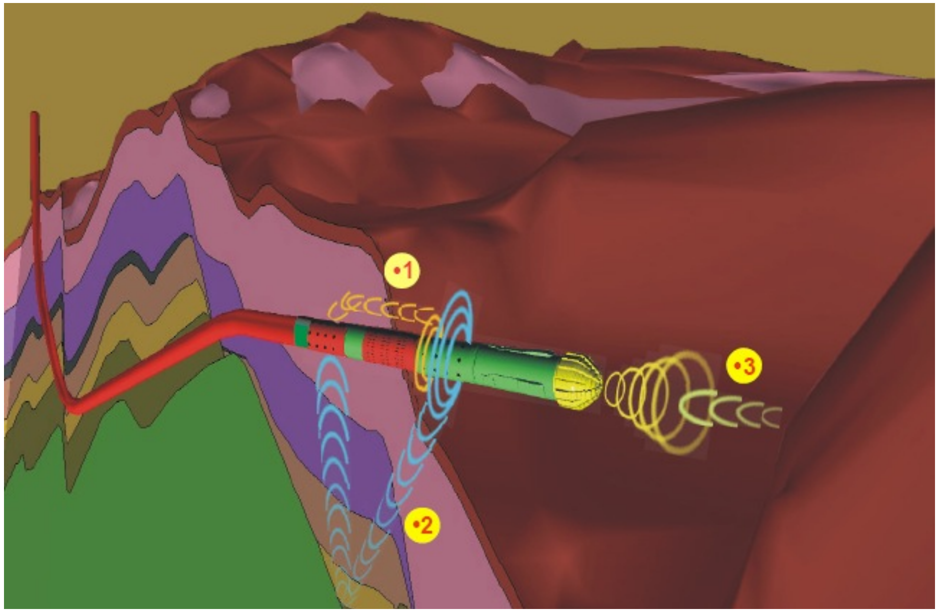
Seafloor

Full Waveform Inversion

Borehole seismic prediction

Prediction ahead of the bit → Logging While Drilling (LWD)

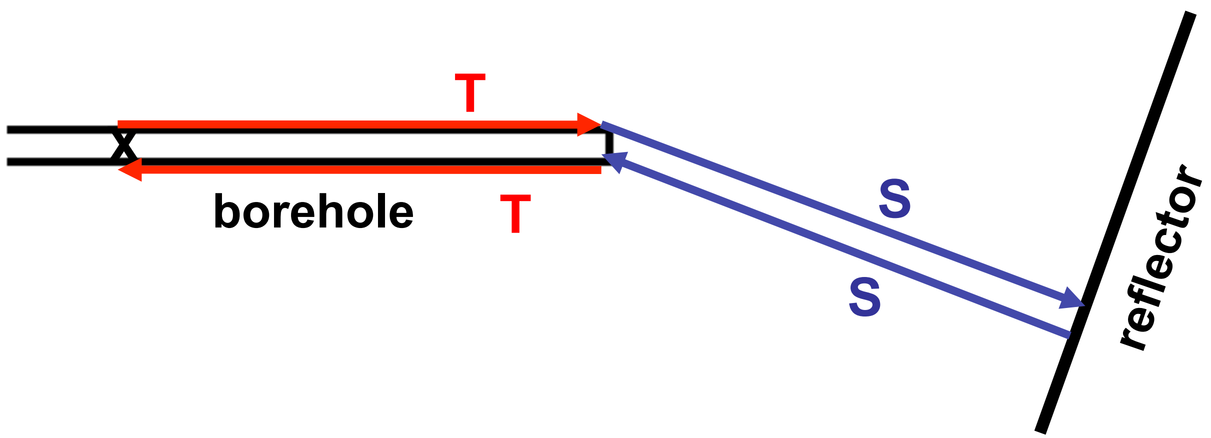
- Depth reference for marker horizons
- Fault detection
- Geo-steering



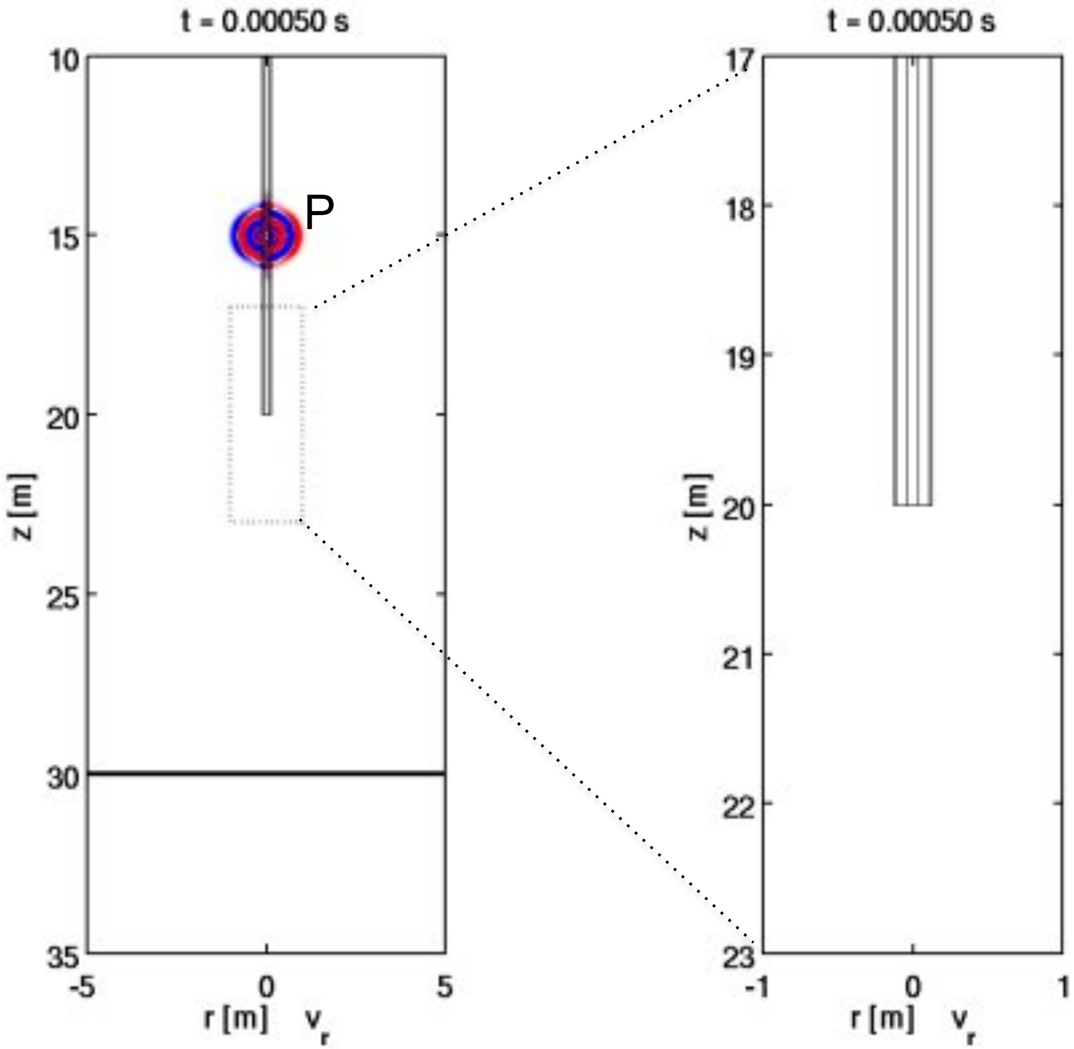
Problem: Vicinity of the bit not suited for seismic sources and receivers

Borehole seismic prediction

Prediction ahead using TSST-waves ?



2.5-D Simulation



(Hellwig & Bohlen, 2008)

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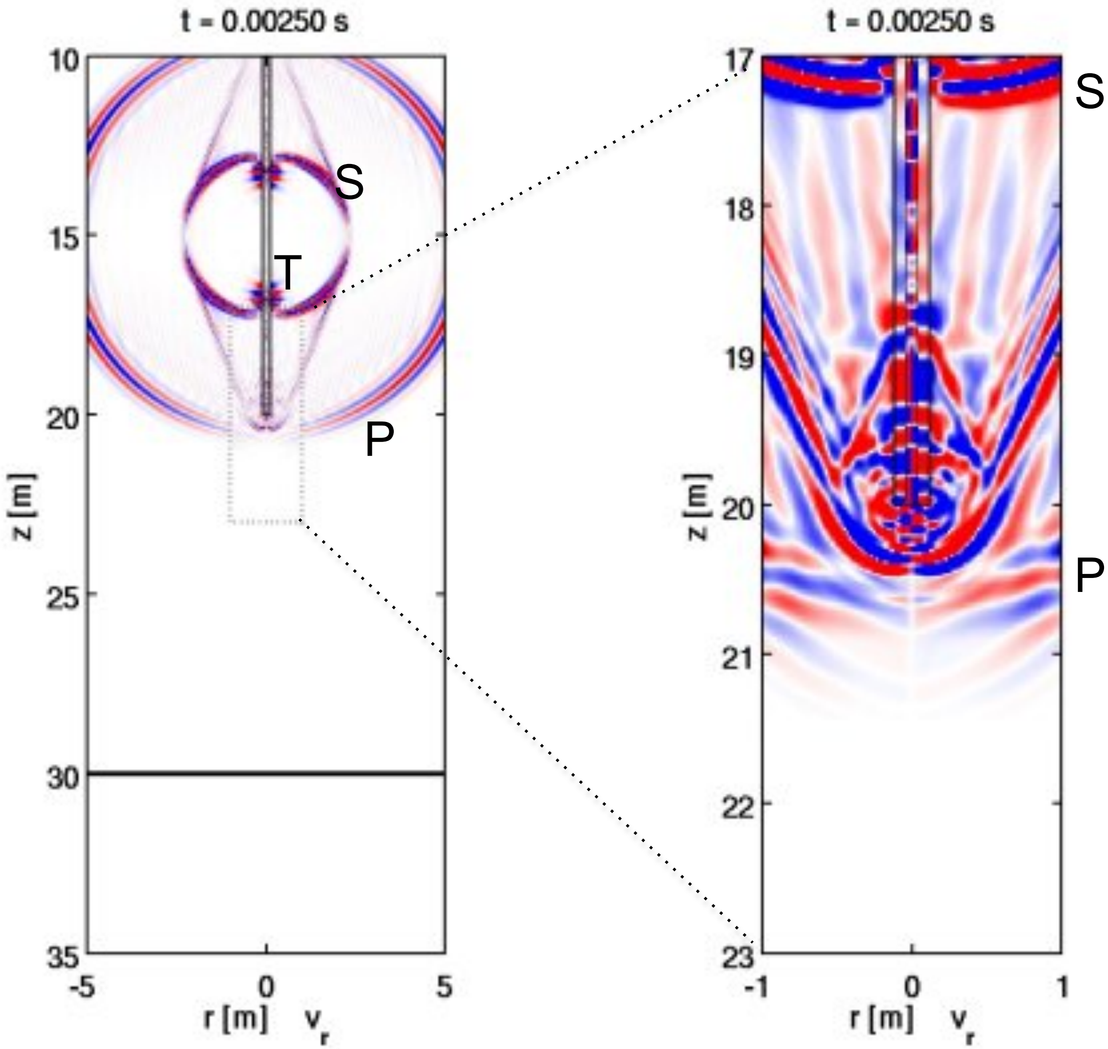

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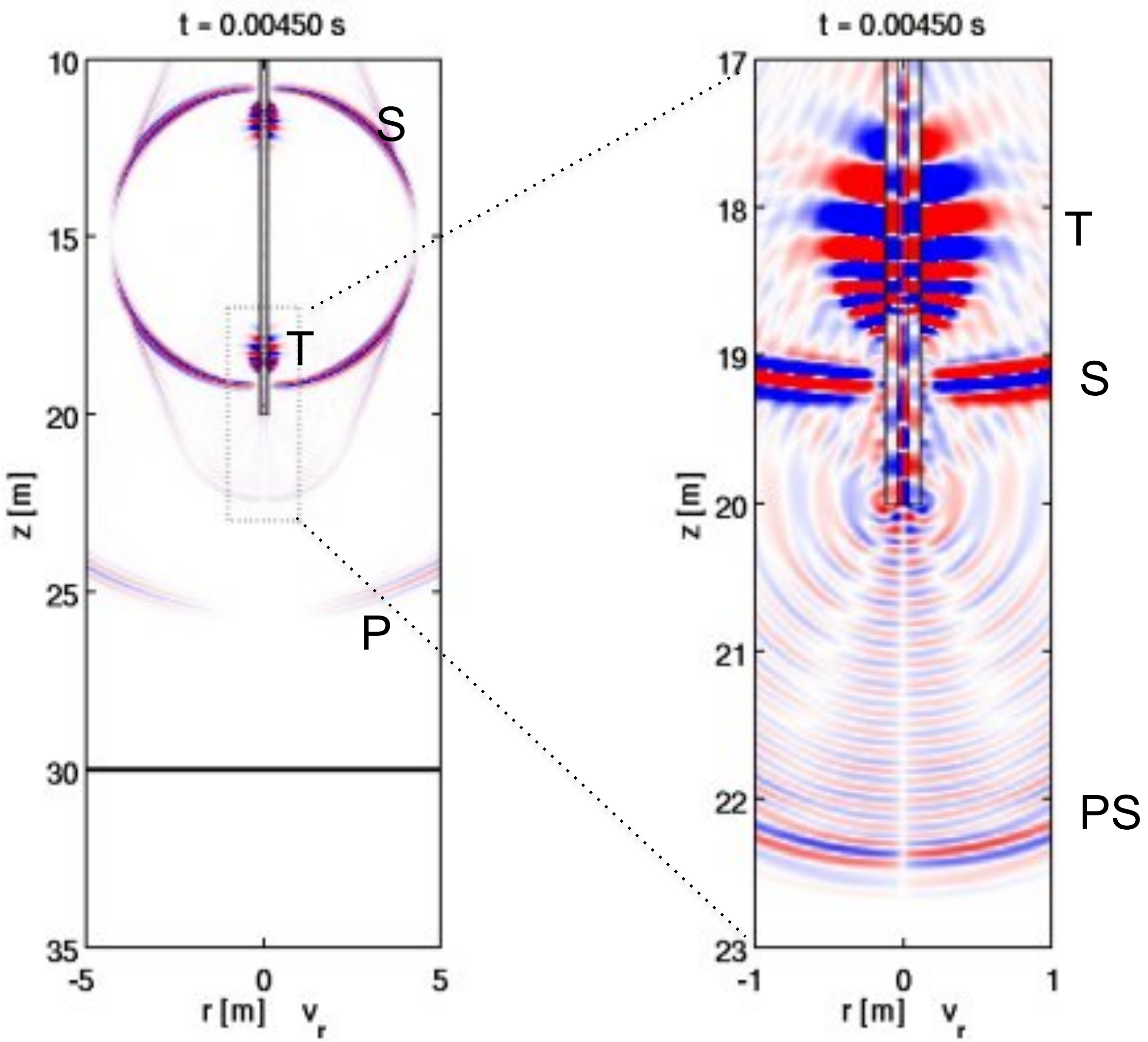

(Hellwig & Bohlen, 2008)

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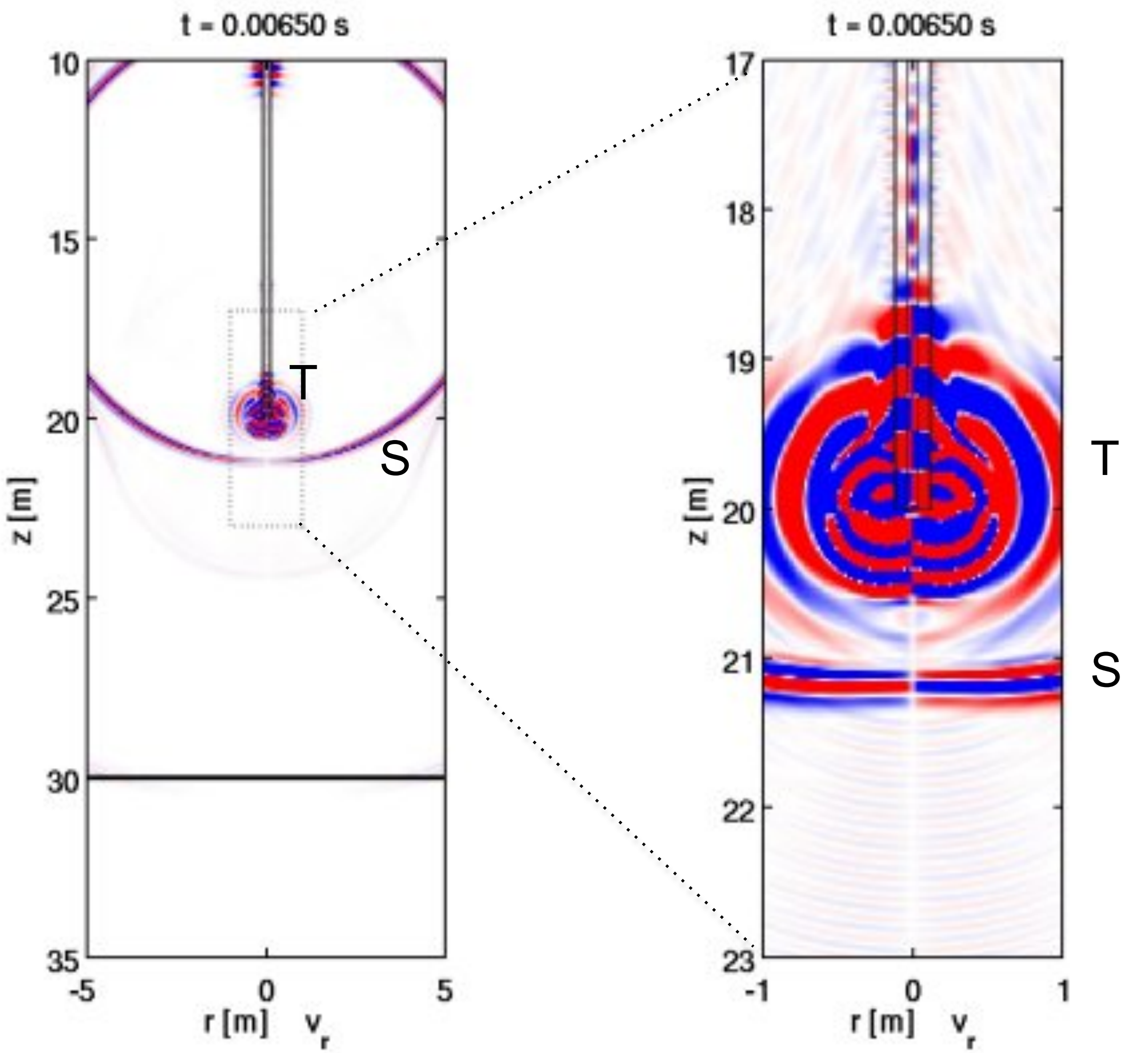

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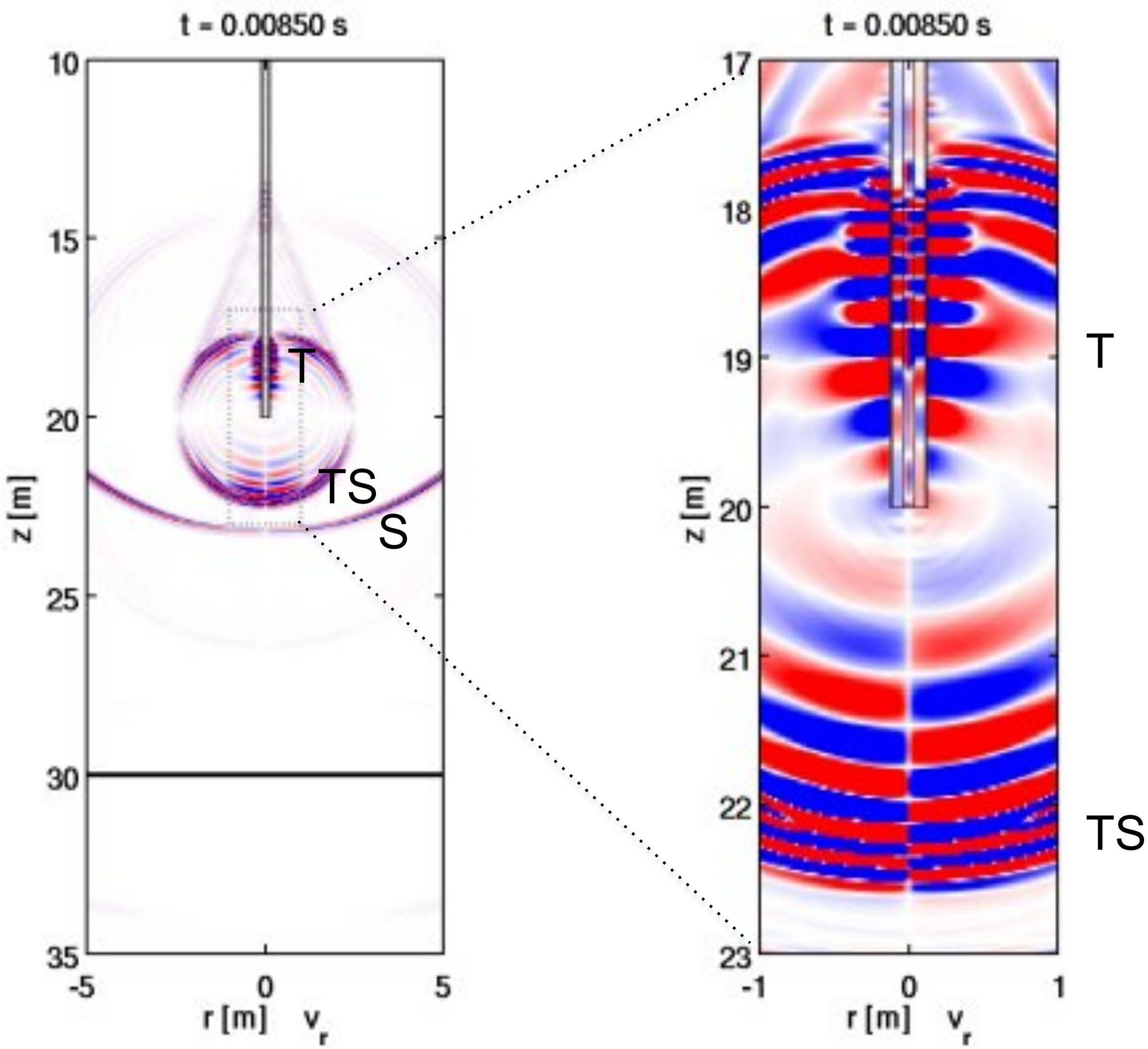

(Hellwig & Bohlen, 2008)

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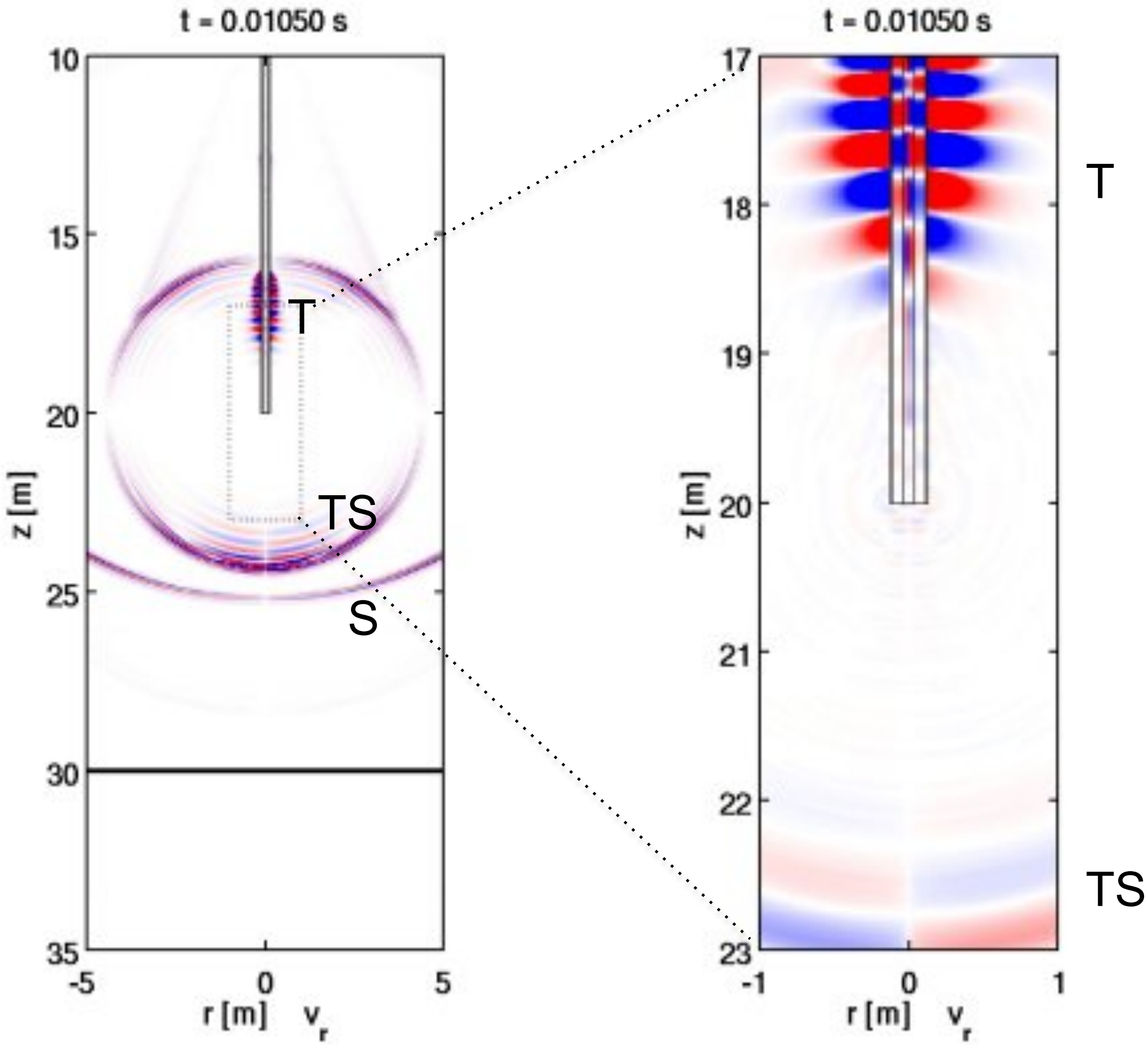

(Hellwig & Bohlen, 2008)

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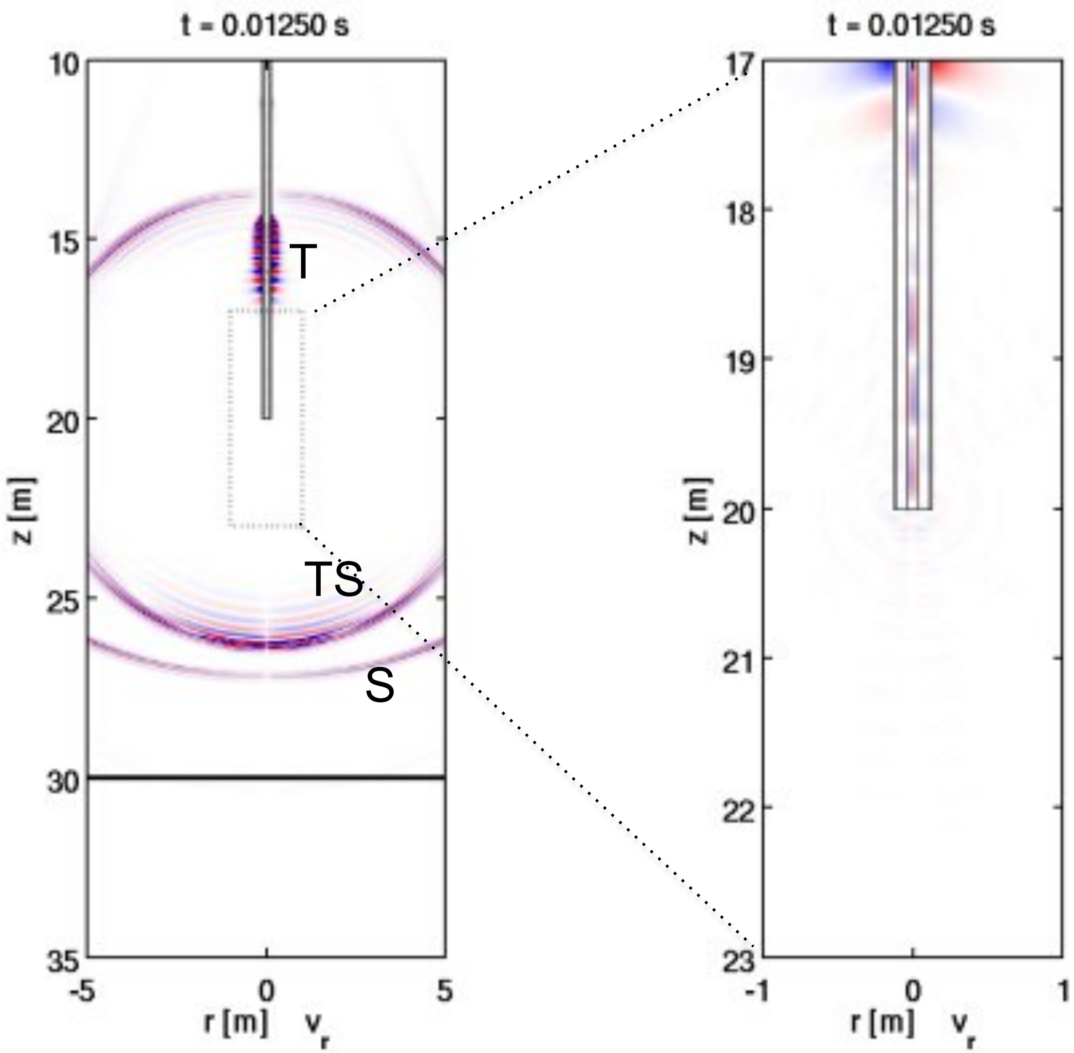

(Hellwig & Bohlen, 2008)

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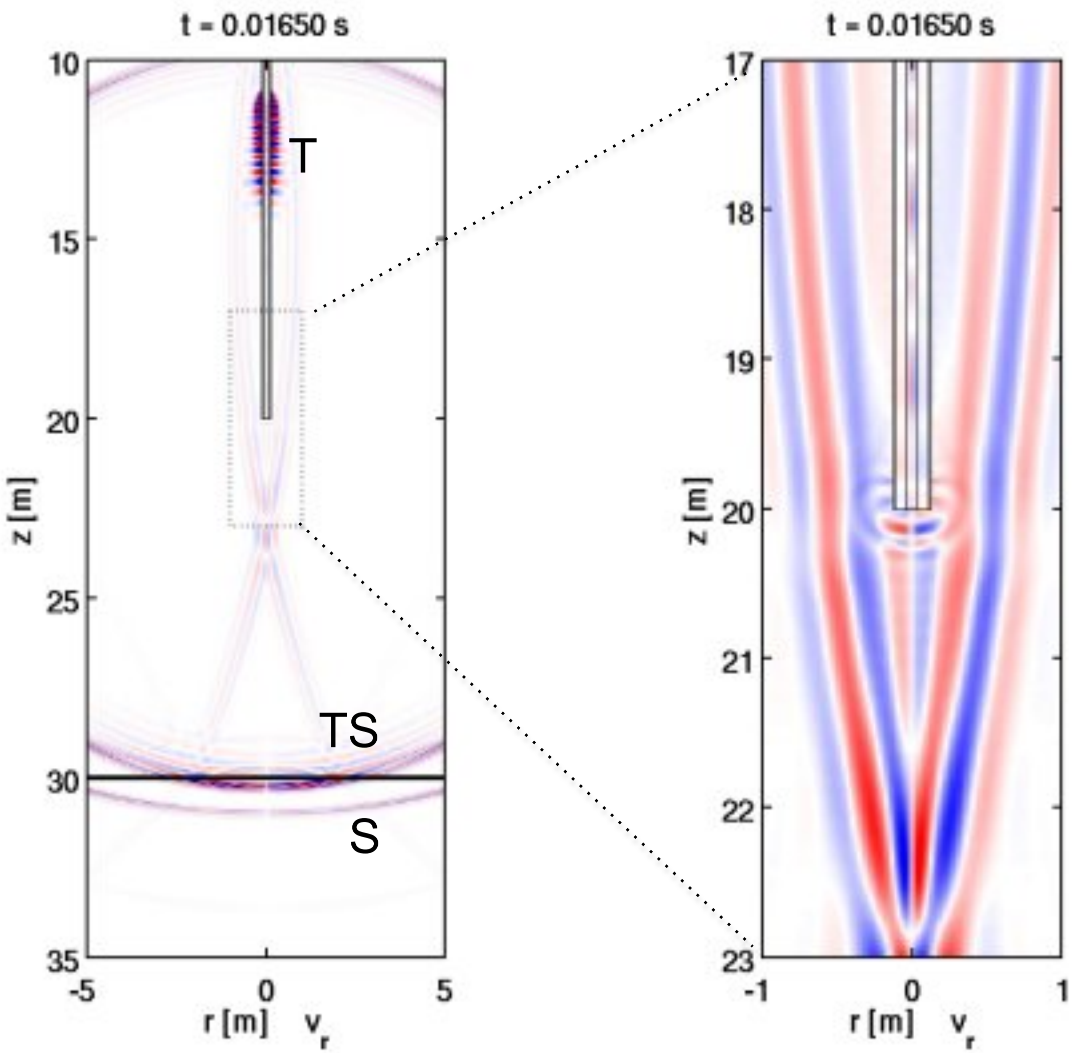

grid boundary reflection

(Hellwig & Bohlen, 2008)

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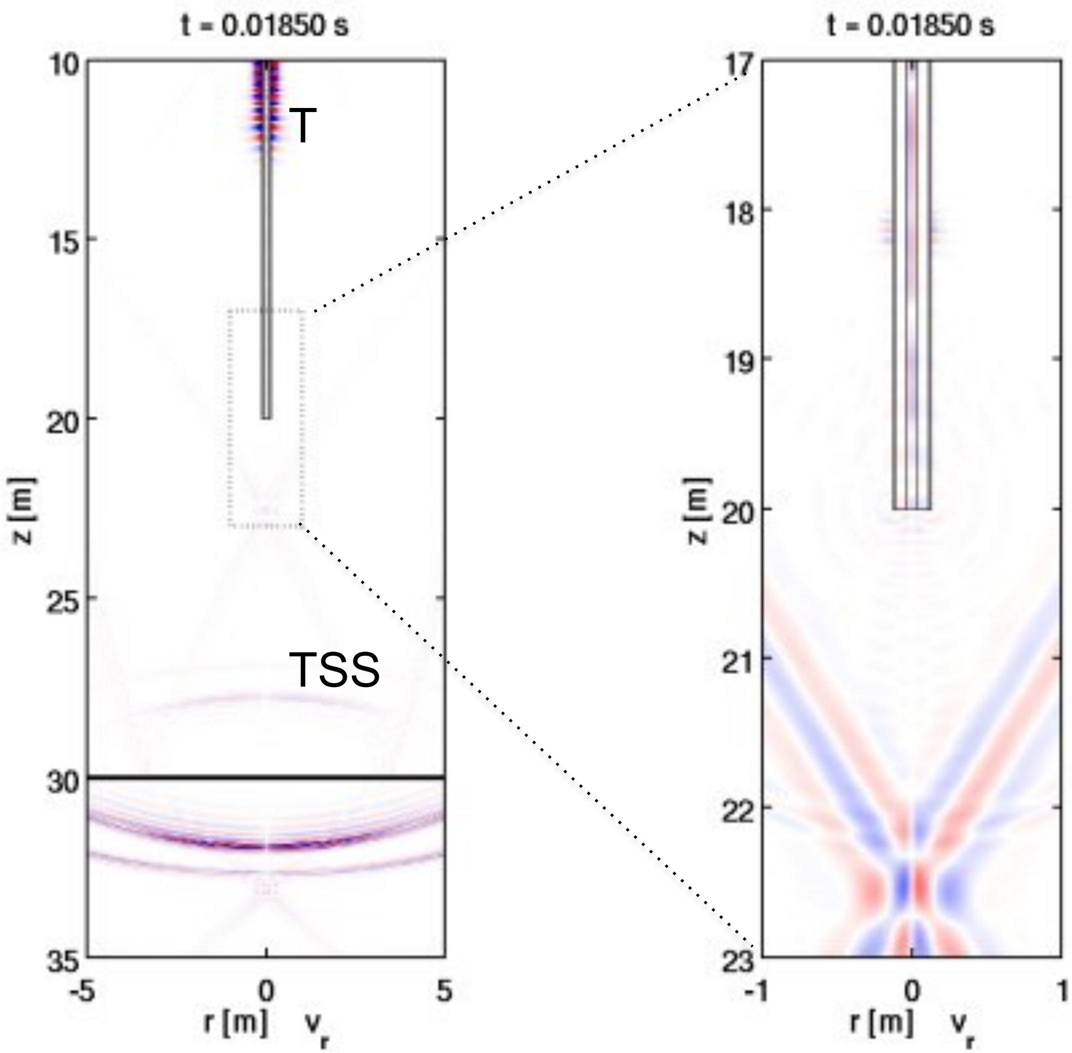

(Hellwig & Bohlen, 2008)

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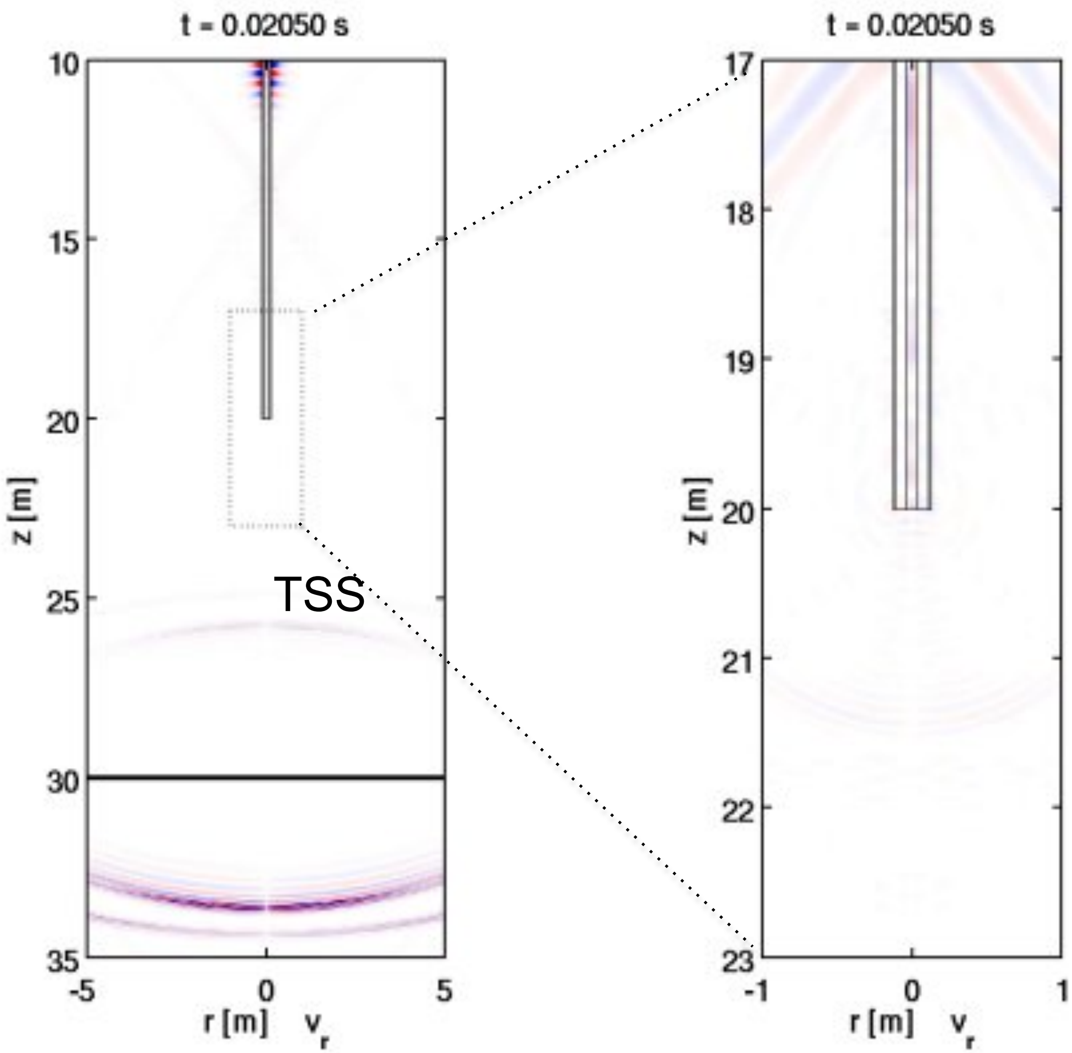

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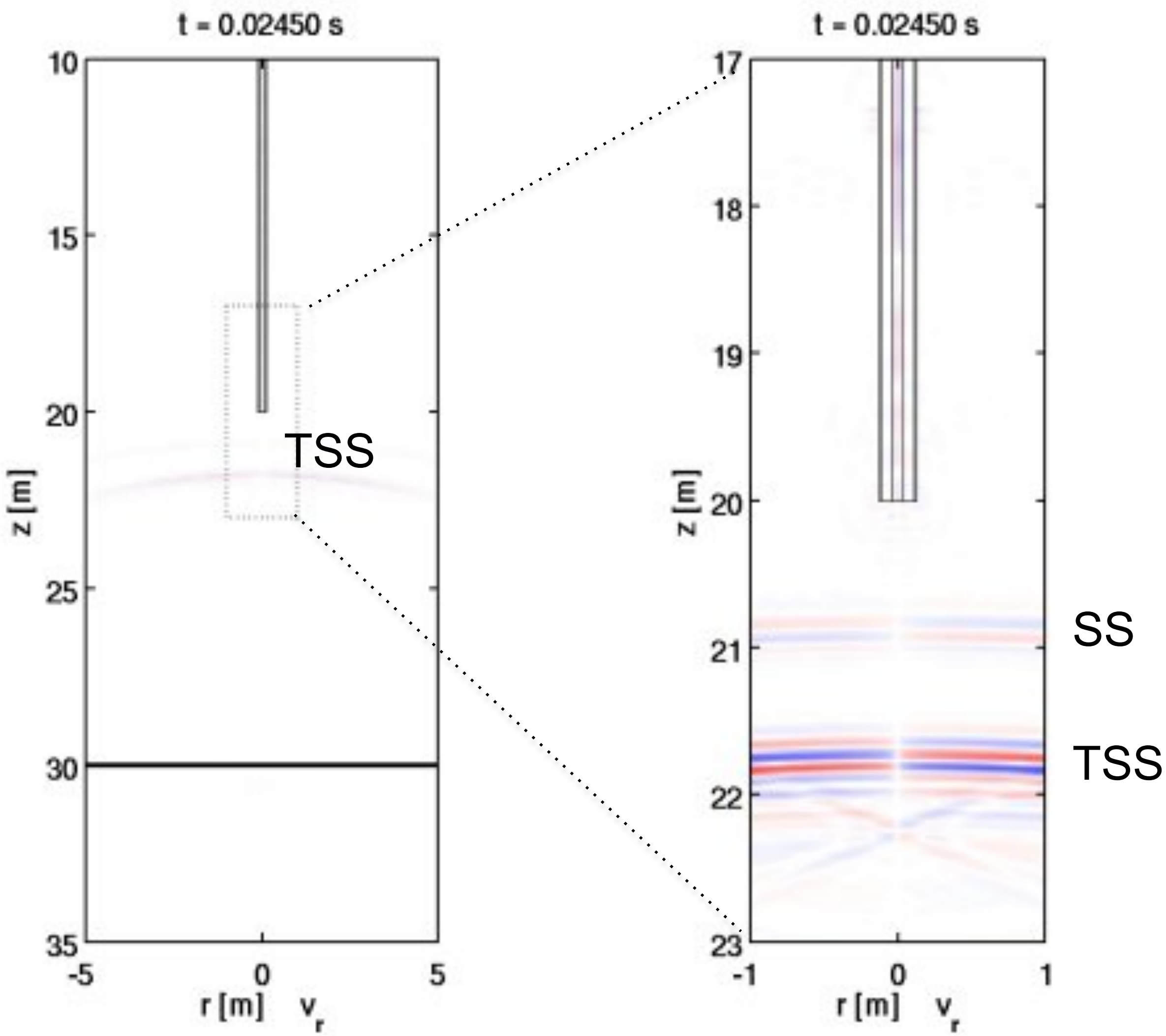

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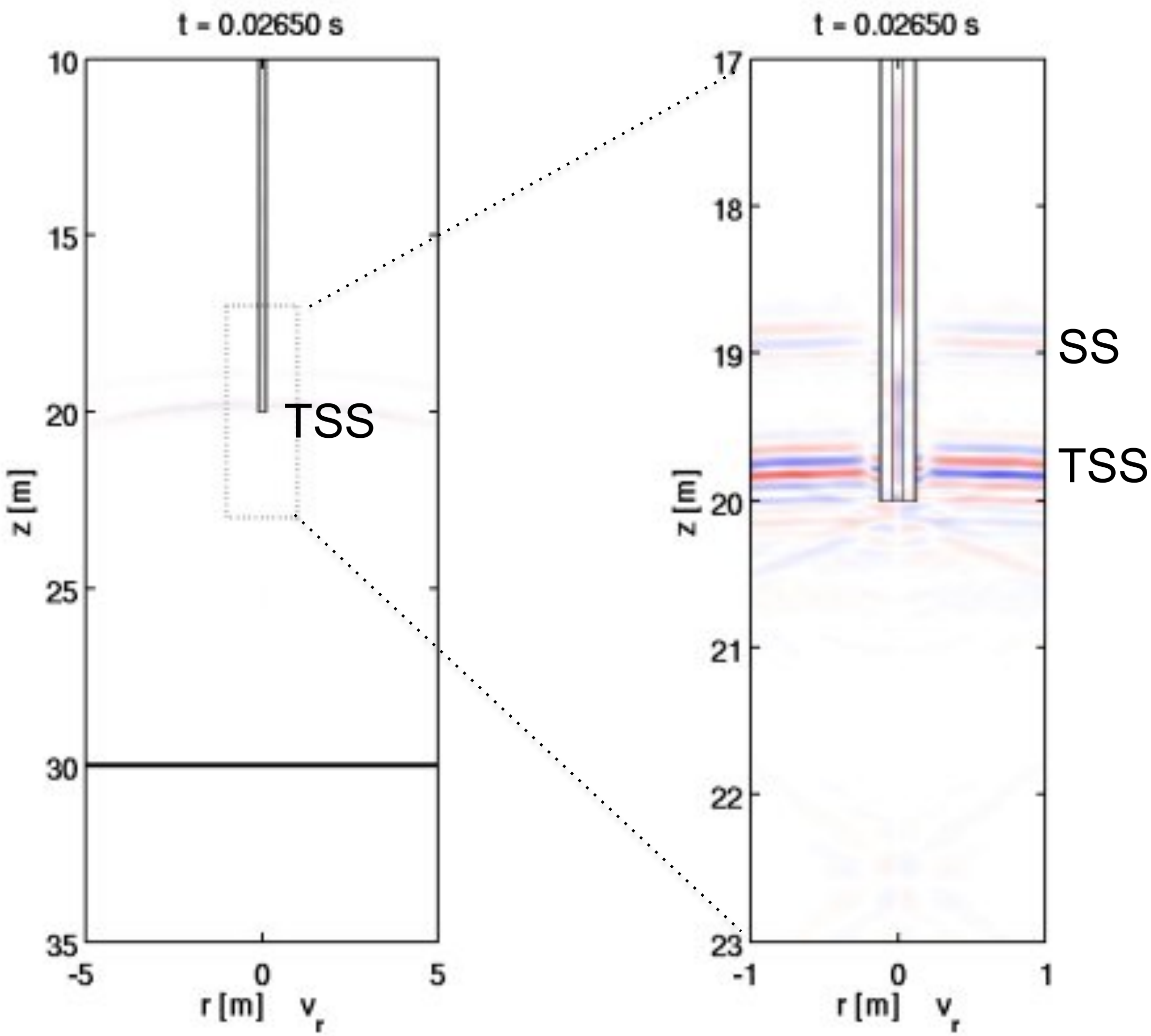

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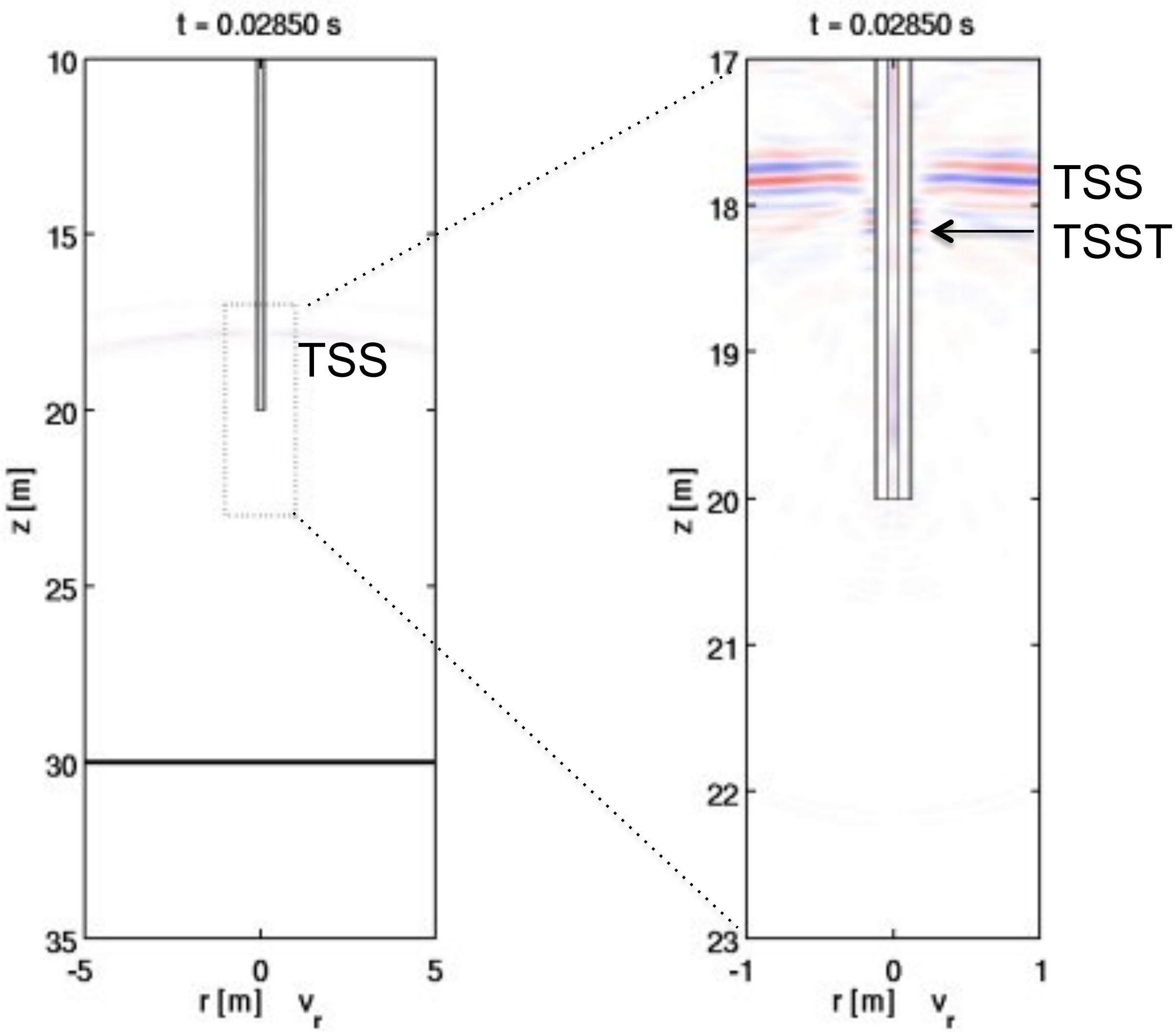

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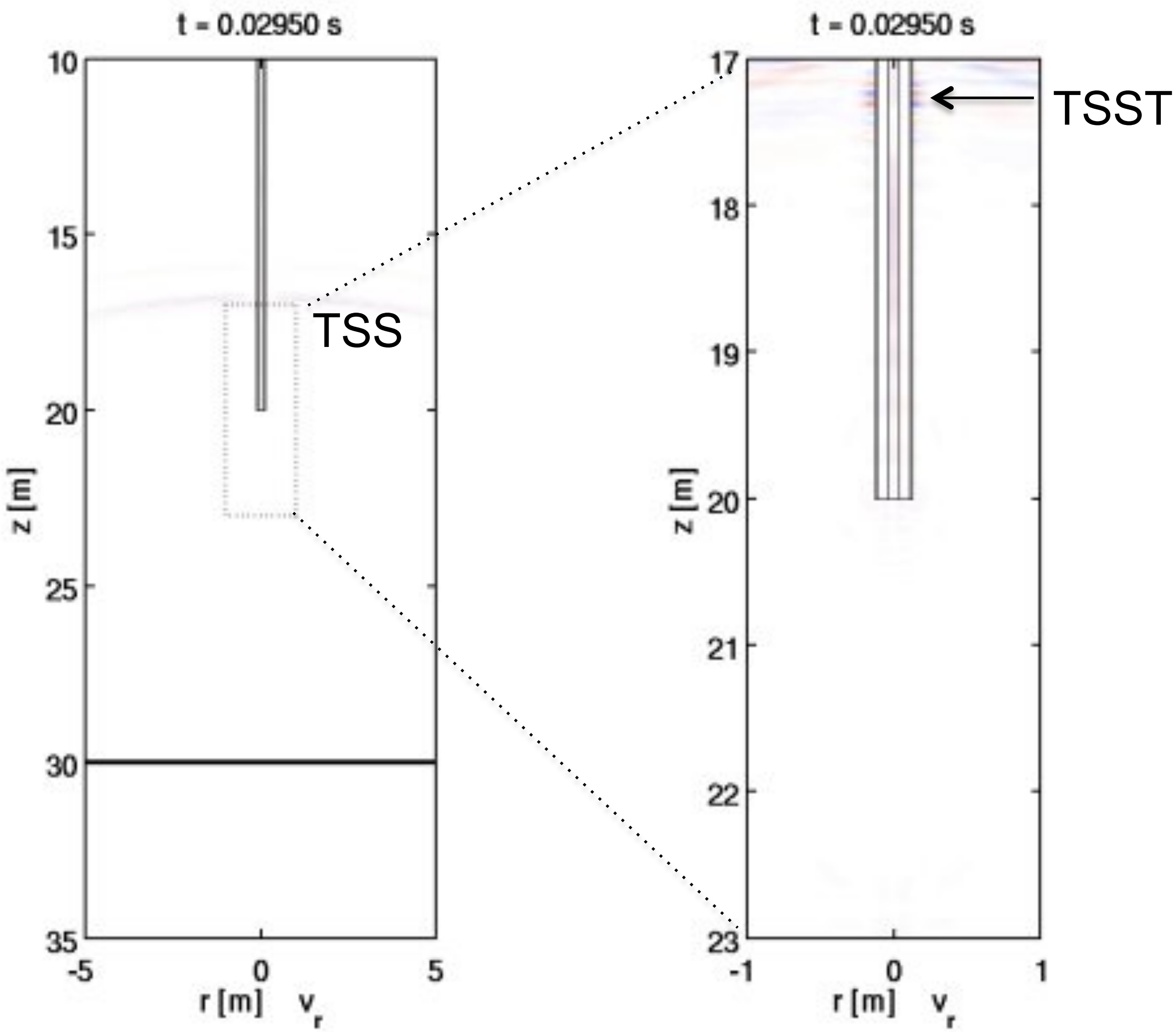
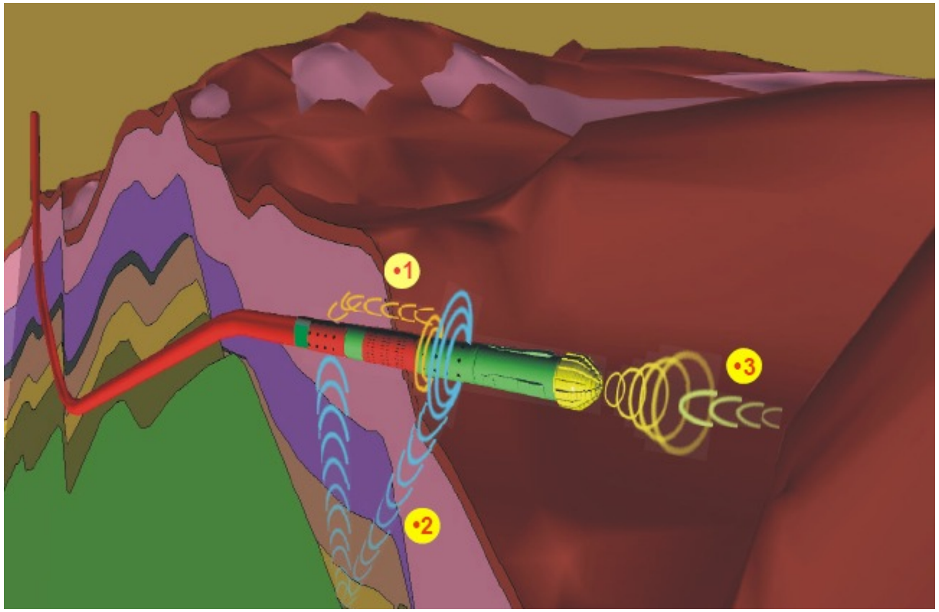


(Hellwig & Bohlen, 2008)

Borehole seismic prediction - conclusions

- TSST is strongest seismic response from reflectors ahead of the bit
- Maximum between 10° and 30° reflector dip



(Hellwig & Bohlen, 2008)

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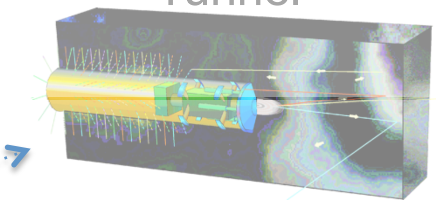
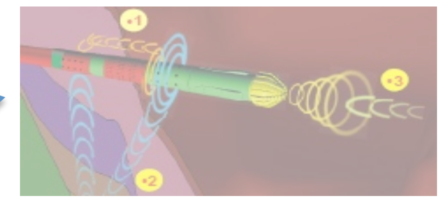


Borehole

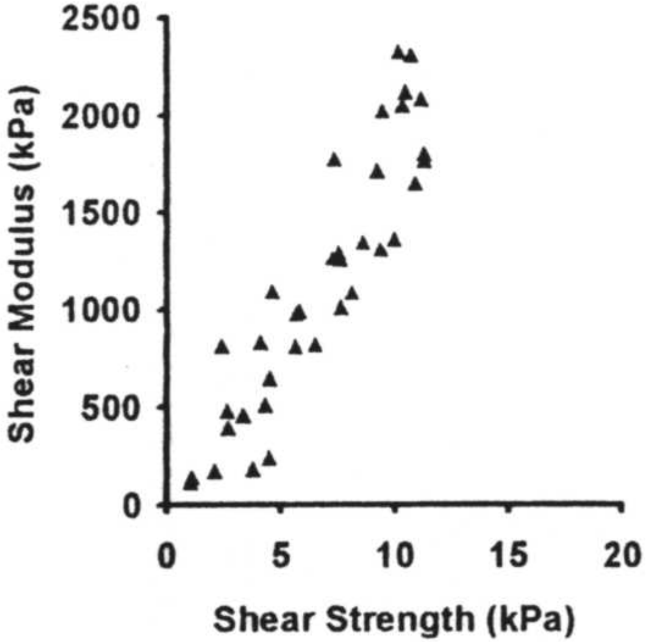


Seafloor

Full Waveform Inversion

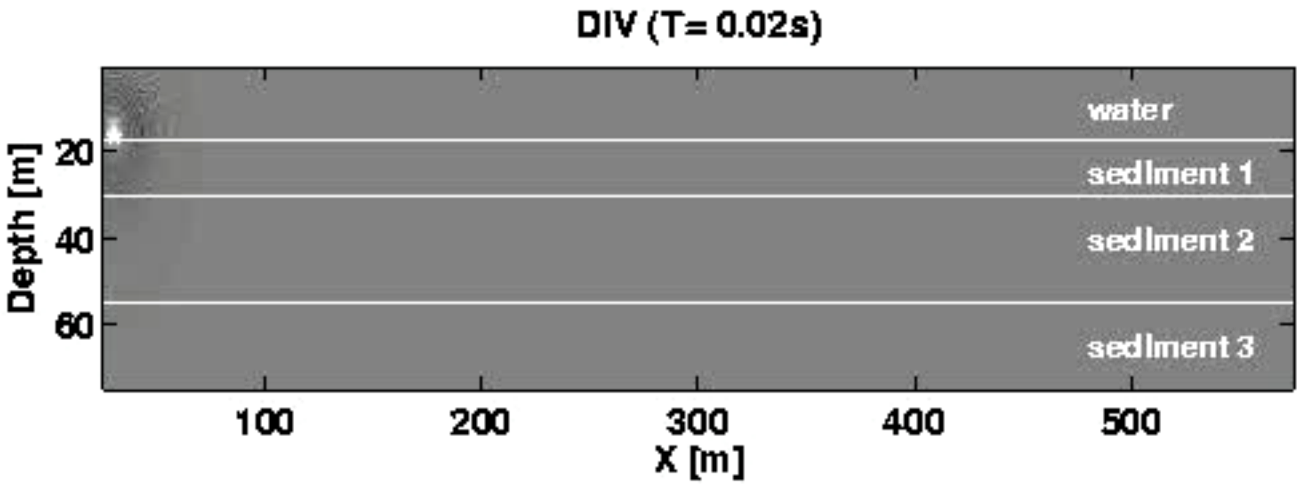
Motivation

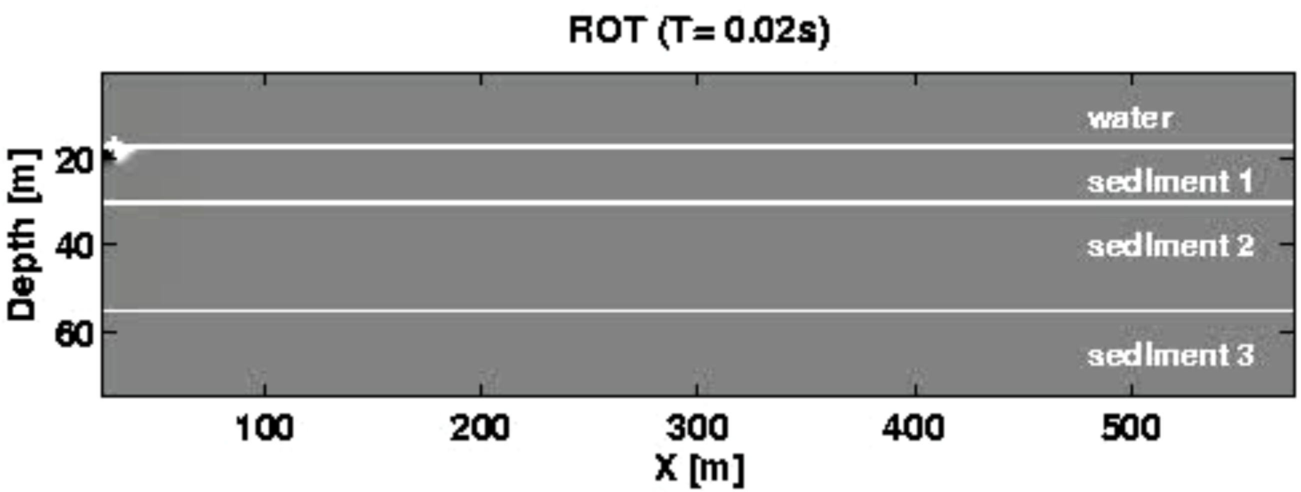
- Inversion of shear wave velocity Vs
- Vs correlates with shear strength
- Applications
  - Offshore constructions, e.g. windparks



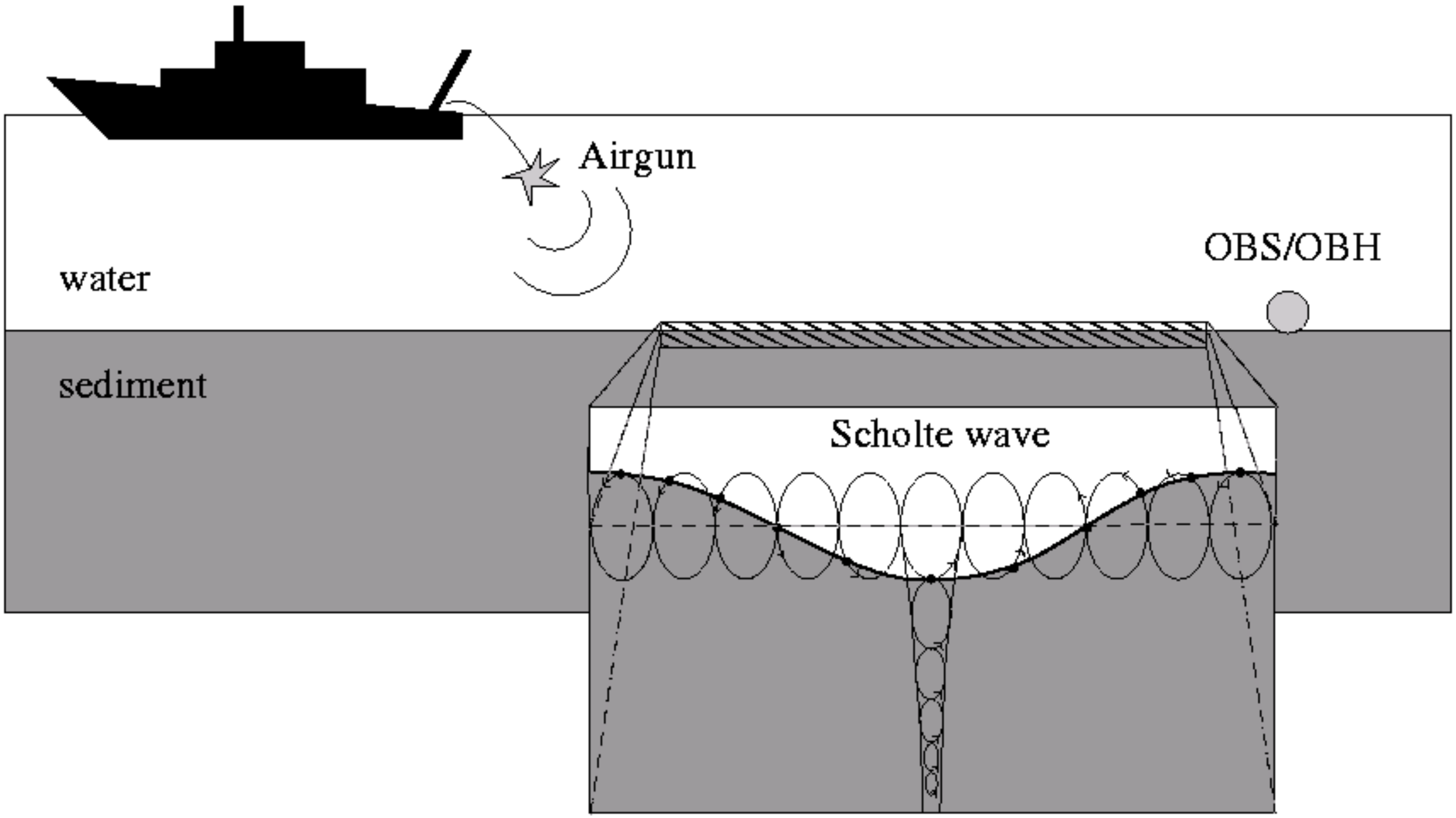
(Ayres, 1998)

Elastic waves in shallow water





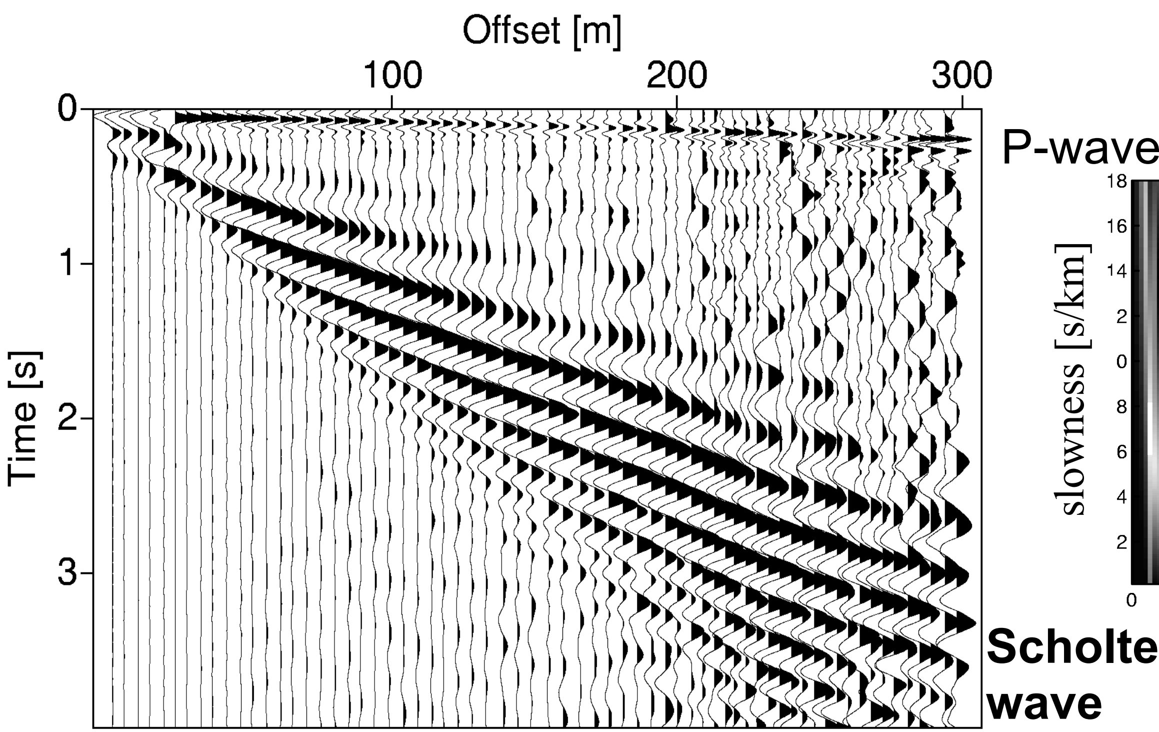
Scholte wave acquisition



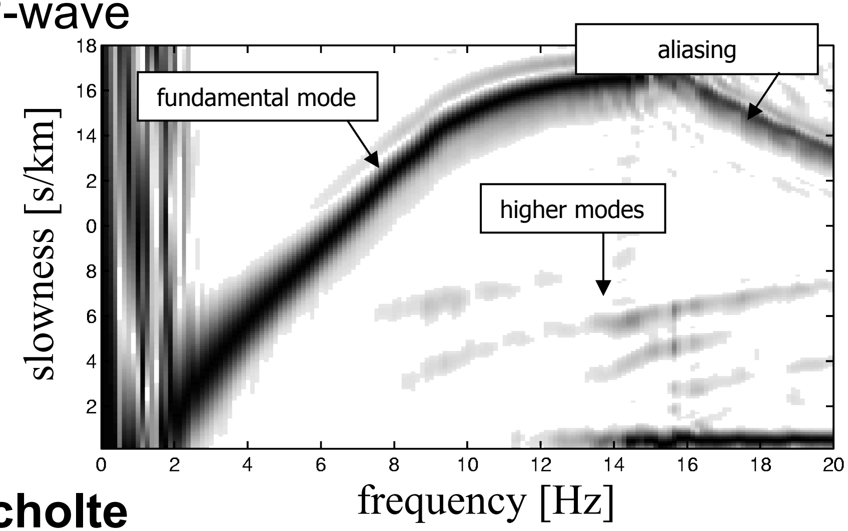
(Bohlen et al., 2004)

Scholte wave observations

Common-Receiver Gather



Slowness-frequency spectrum



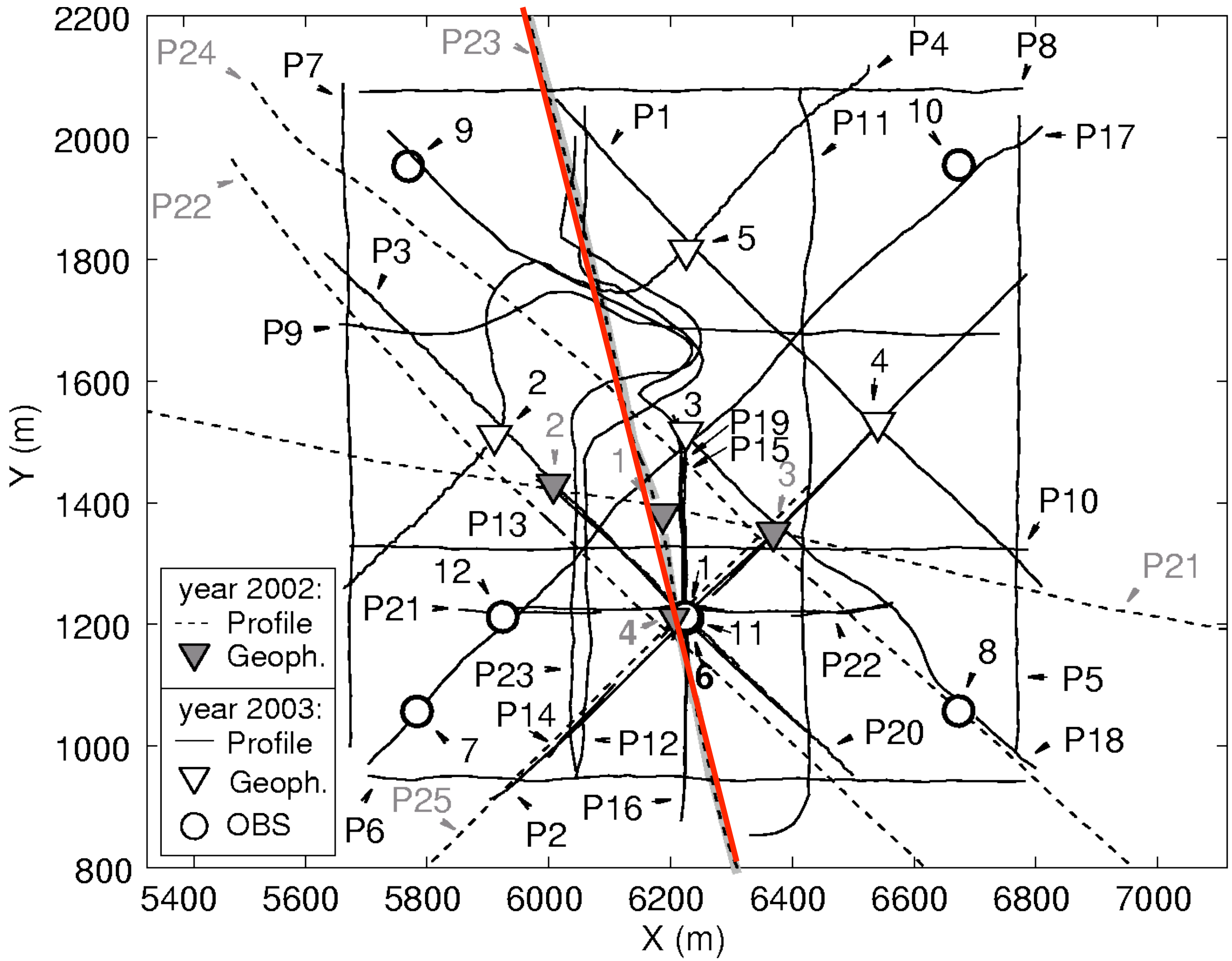
(Bohlen et al., 2004; Kugler et al., 2005; Klein et al., 2005; Kugler et al., 2007)

Scholte wave tomography

Area: ~1km²

40000

seismograms

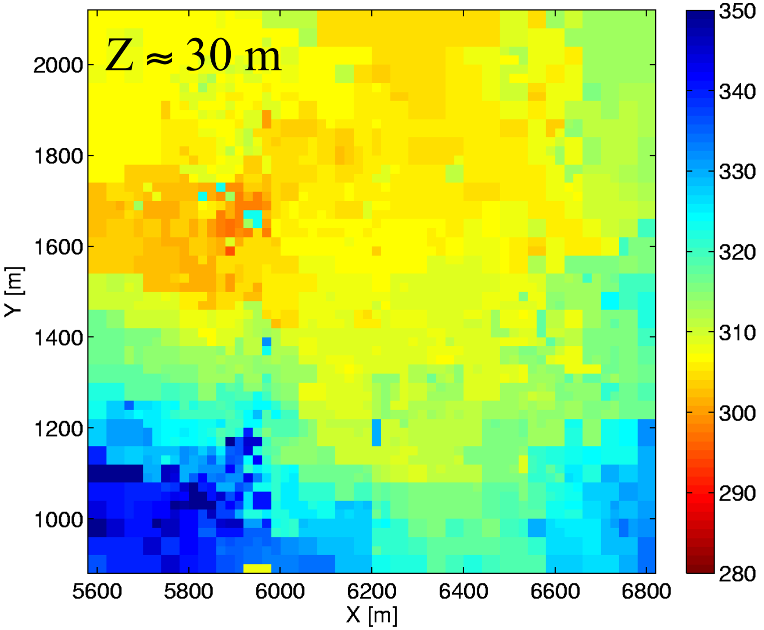


(Kugler et al., 2007)

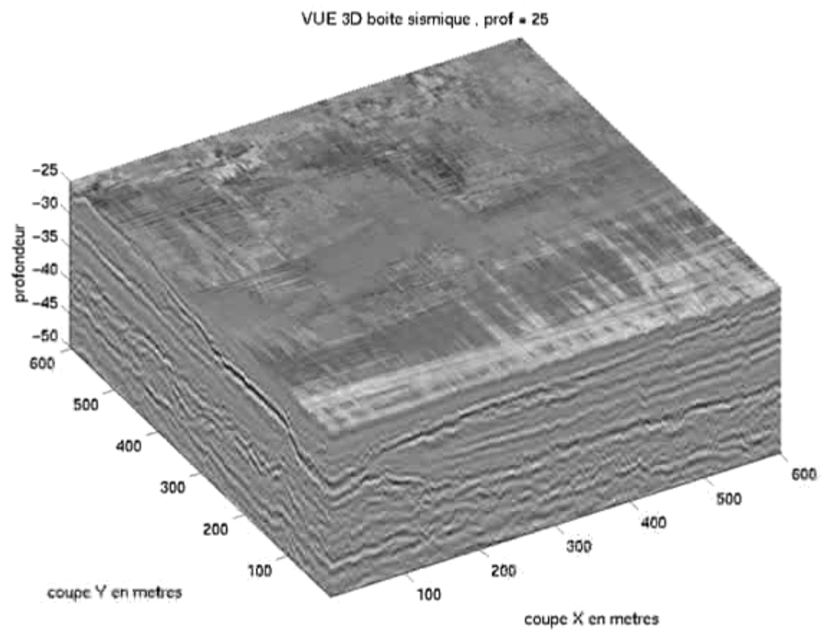
Scholte wave tomography

Scholte waves: Vs

HF reflection seismics



Joint-inver-sion



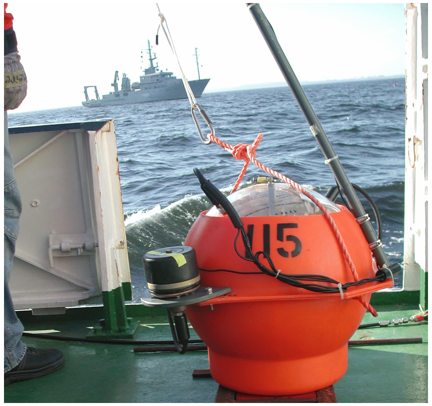
(Kugler et al., 2007)

(Müller et al., 2002)

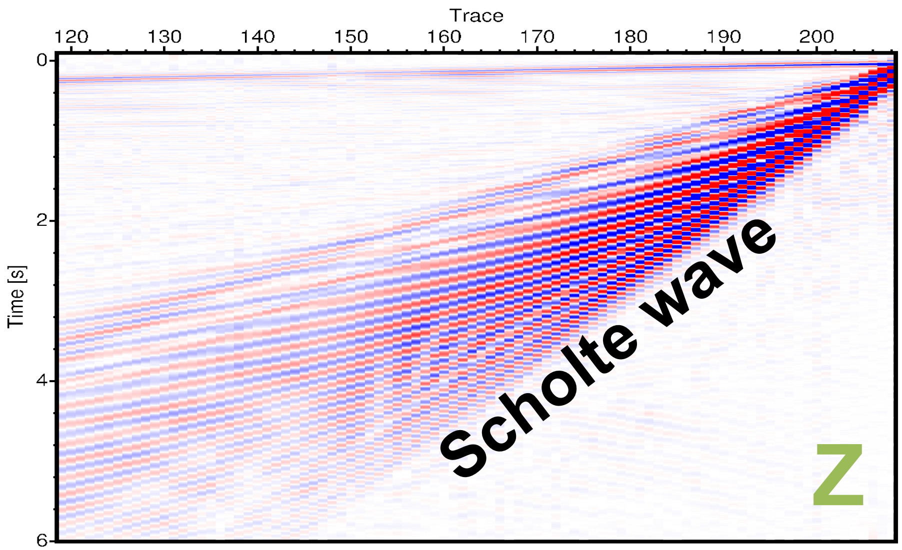
Additional information on shear properties

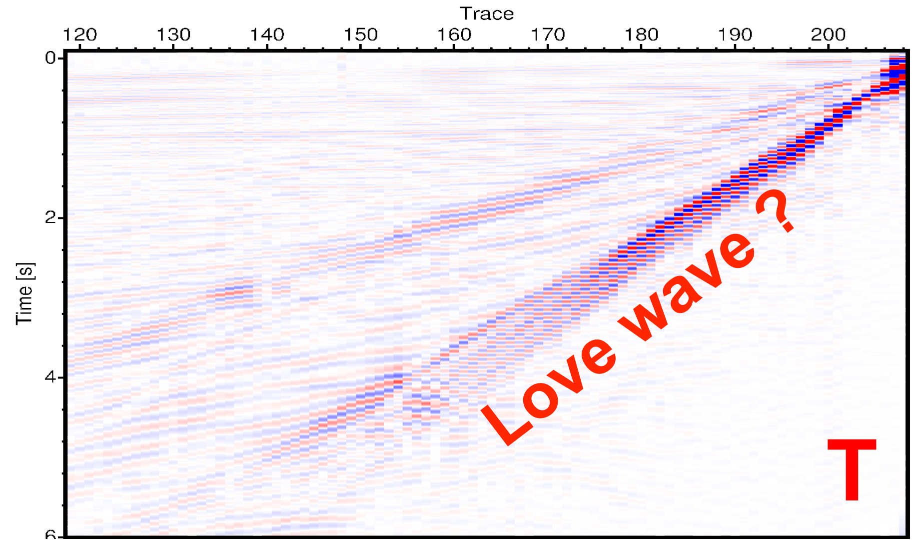
Scholte waves - Conclusions

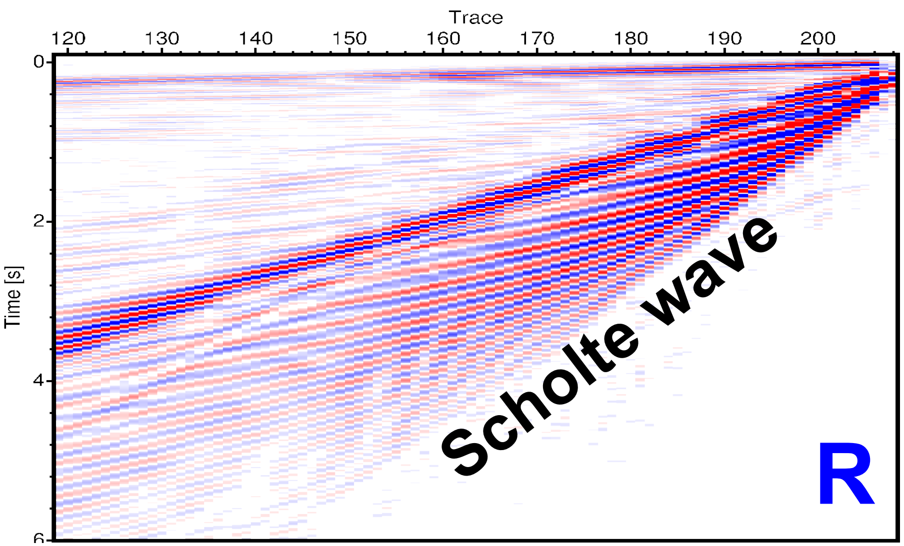
- Scholte waves are most prominent wavefield in shallow water
- Scholte tomography yields 3-D Vs models
- Important for seafloor stability exploration

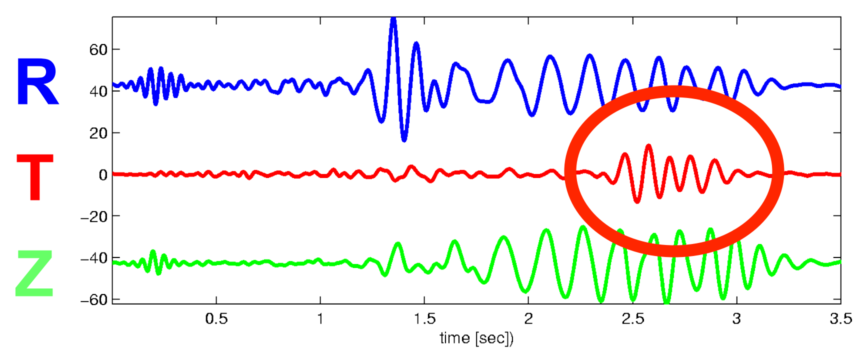


Strange new wave: **Love wave ?!**



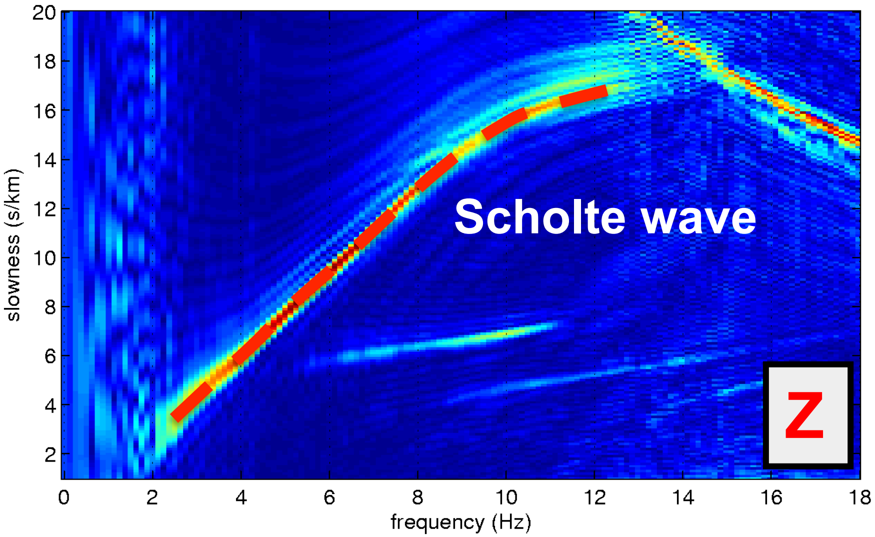


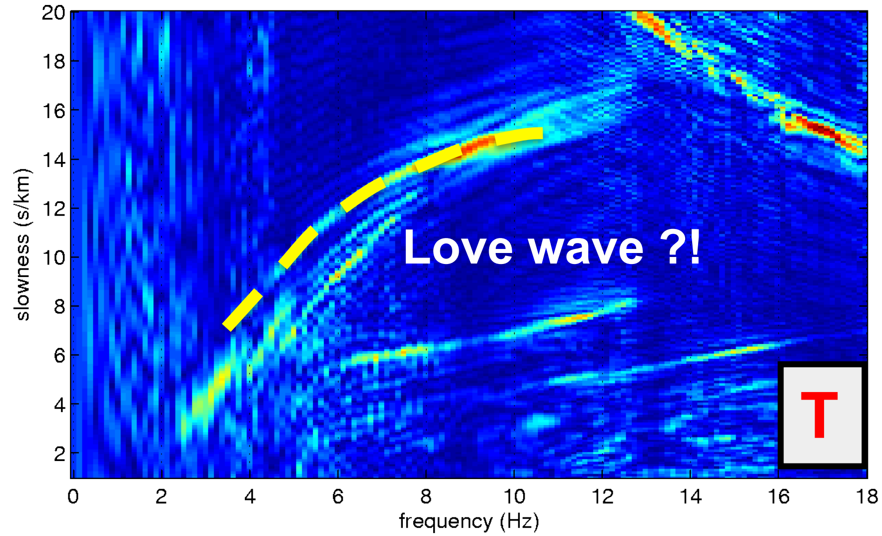


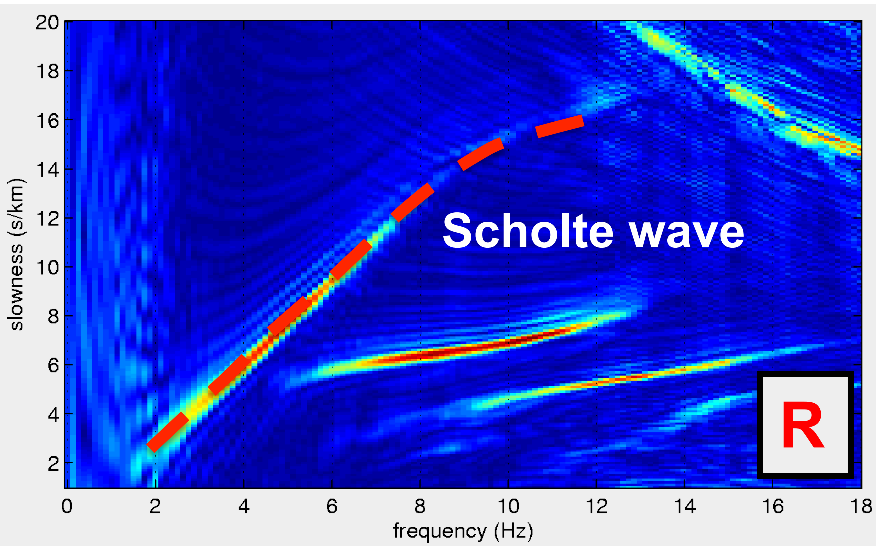


(Bussat, 2006, PhD thesis)

Strange new wave: **Love wave ?!**

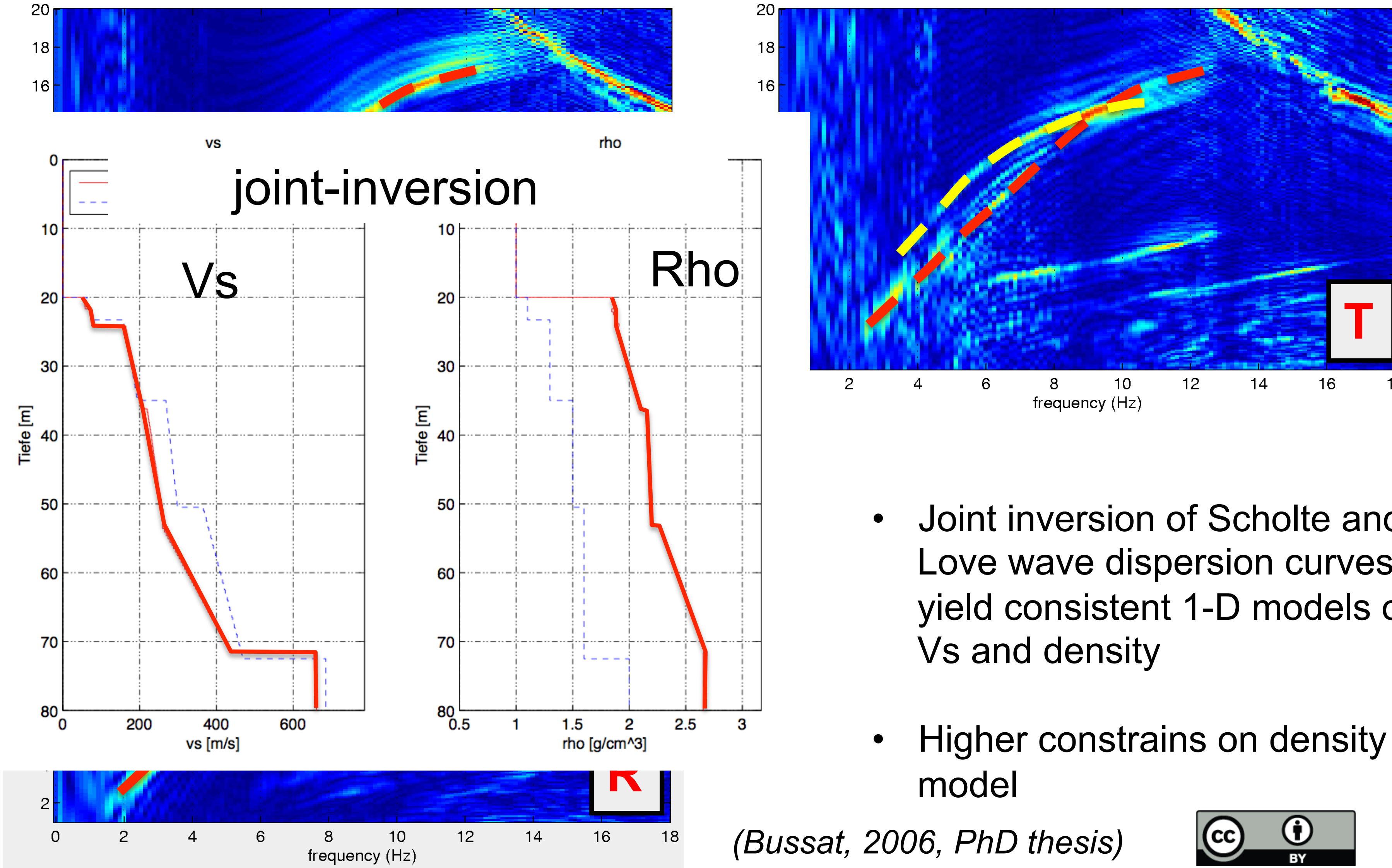






(Bussat, 2006, PhD thesis)

Surprising observation: **Love wave** excited by airgun



- Joint inversion of Scholte and Love wave dispersion curves yield consistent 1-D models of Vs and density
- Higher constrains on density model

(Bussat, 2006, PhD thesis)

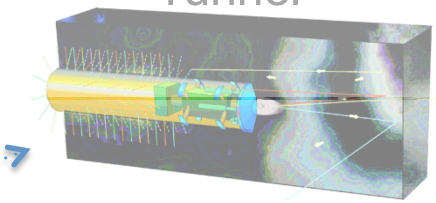
Strange new wave: **Love wave ?!**

Sea floor roughness/ripples ?

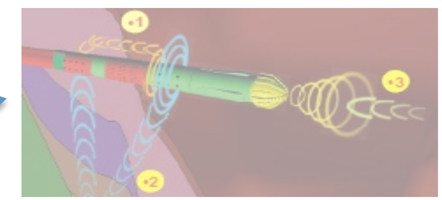
Outline

- Introduction
- Unconventional waves
  - Tunnel
  - Borehole
  - Seafloor
- **Continuing mission**
  - **full waveform inversion**

Tunnel

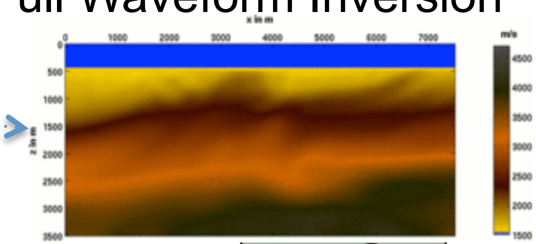


Borehole



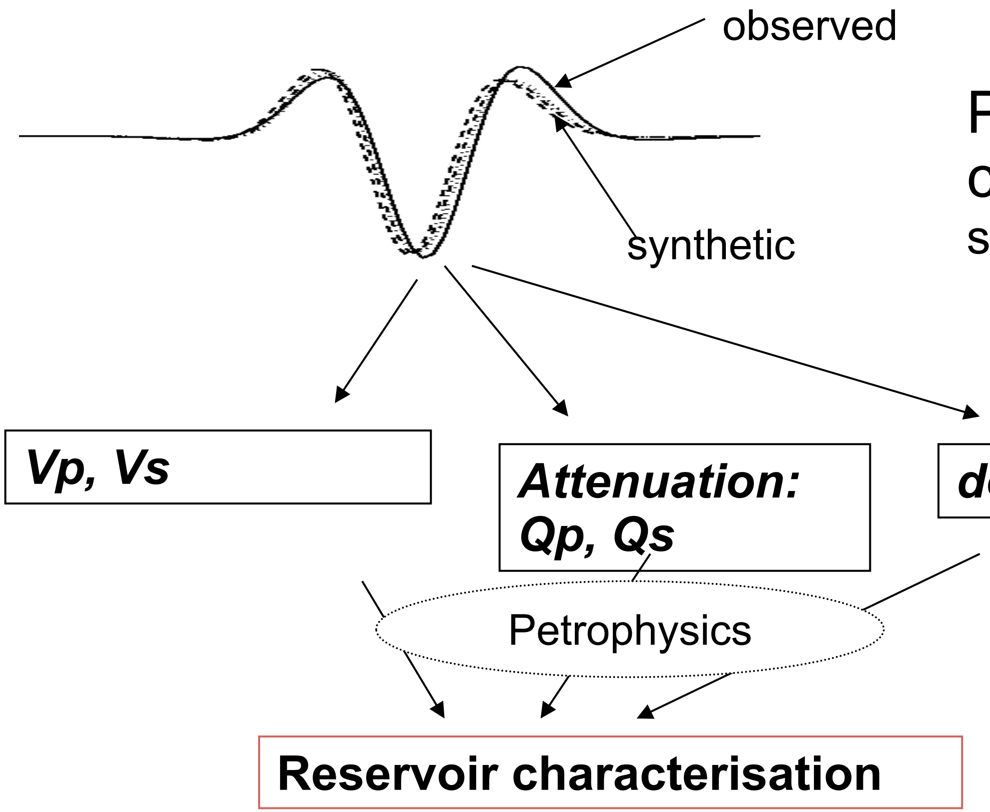
Seafloor

Full Waveform Inversion



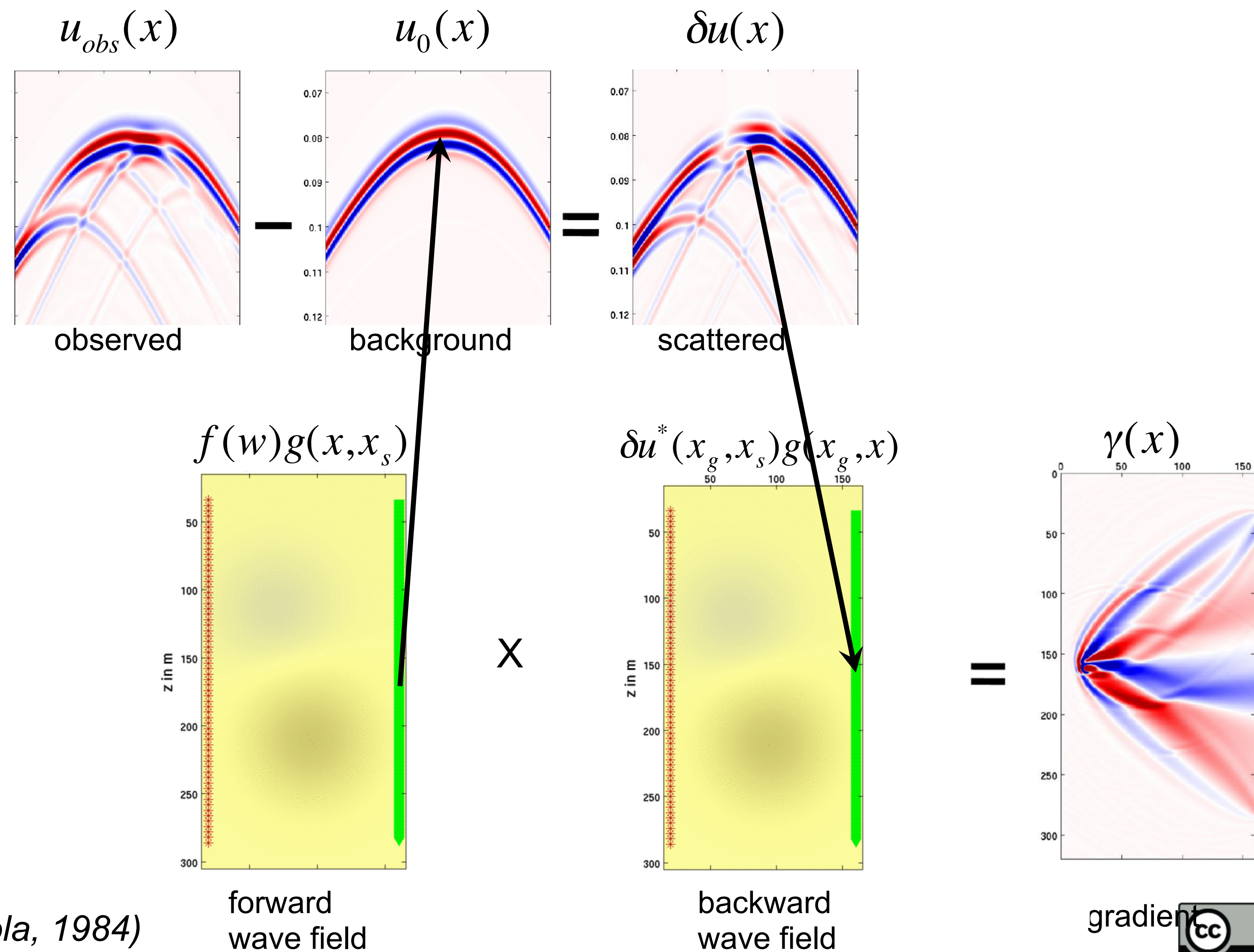
Seismologist dream

Exploit the full information content of seismic signals !



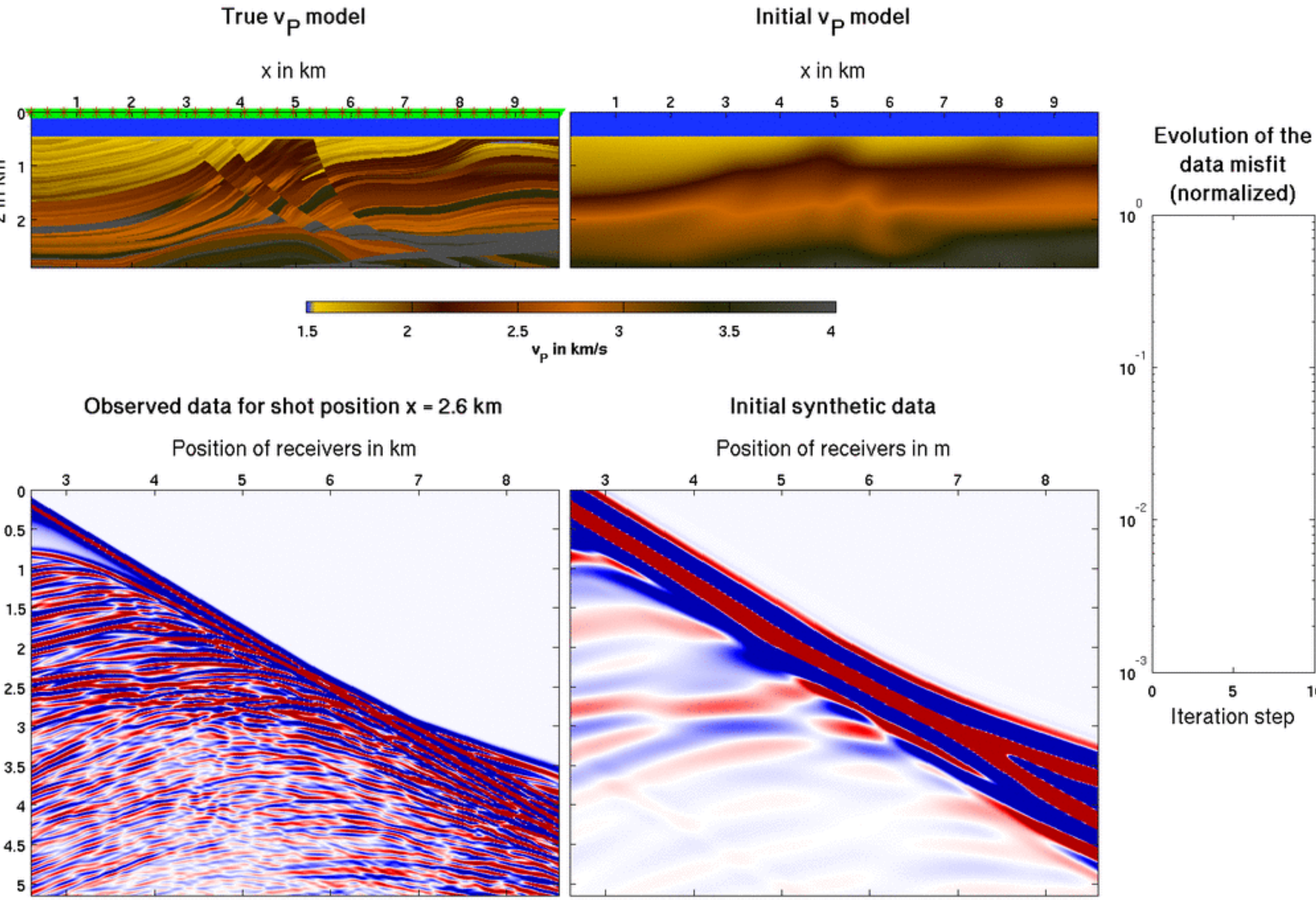
P- and S-waves,
converted waves,
surface waves

Numerical implementation of adjoint FWI



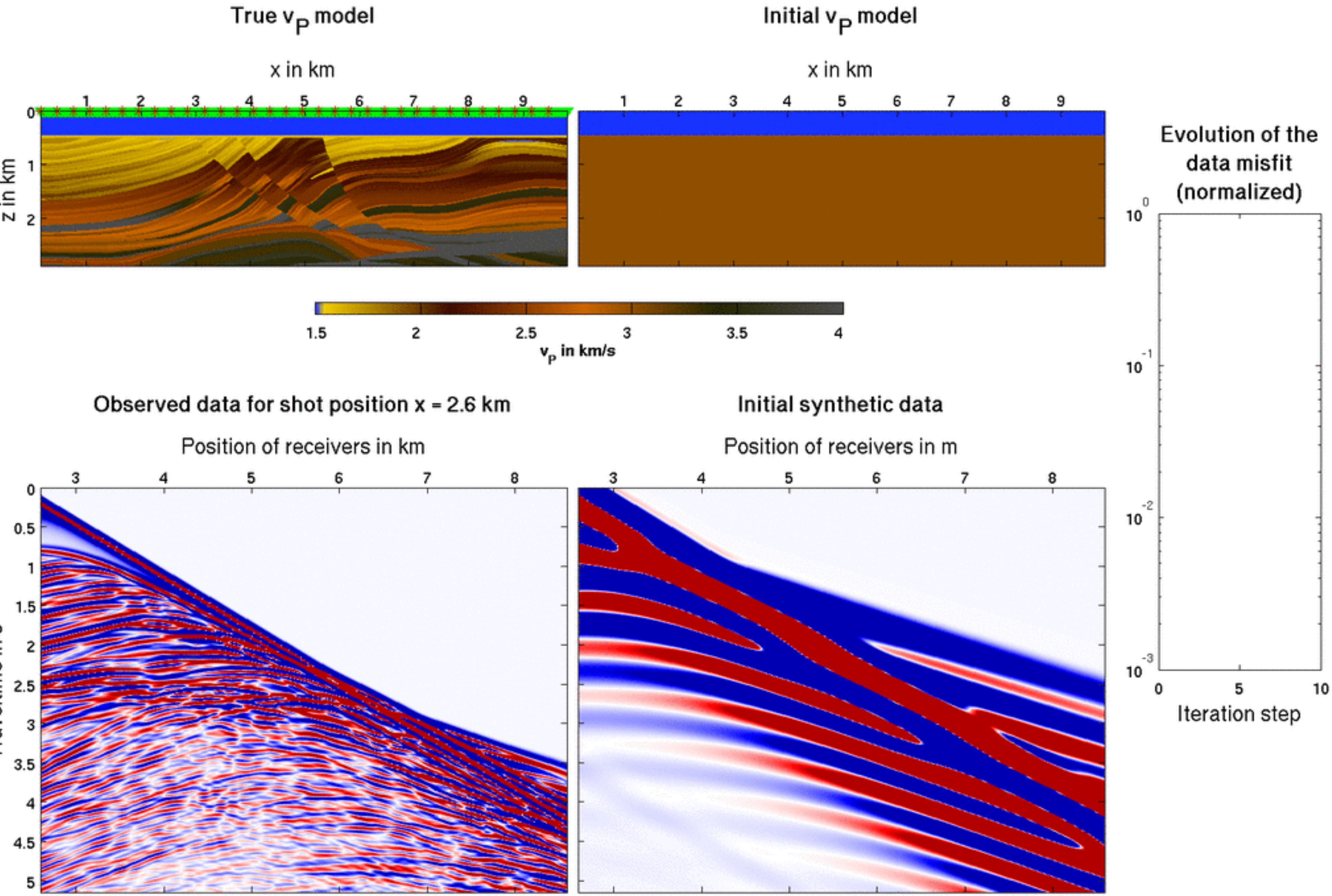
(Tarantola, 1984)

Starting point of FWT



(Kurzmann, 2012)

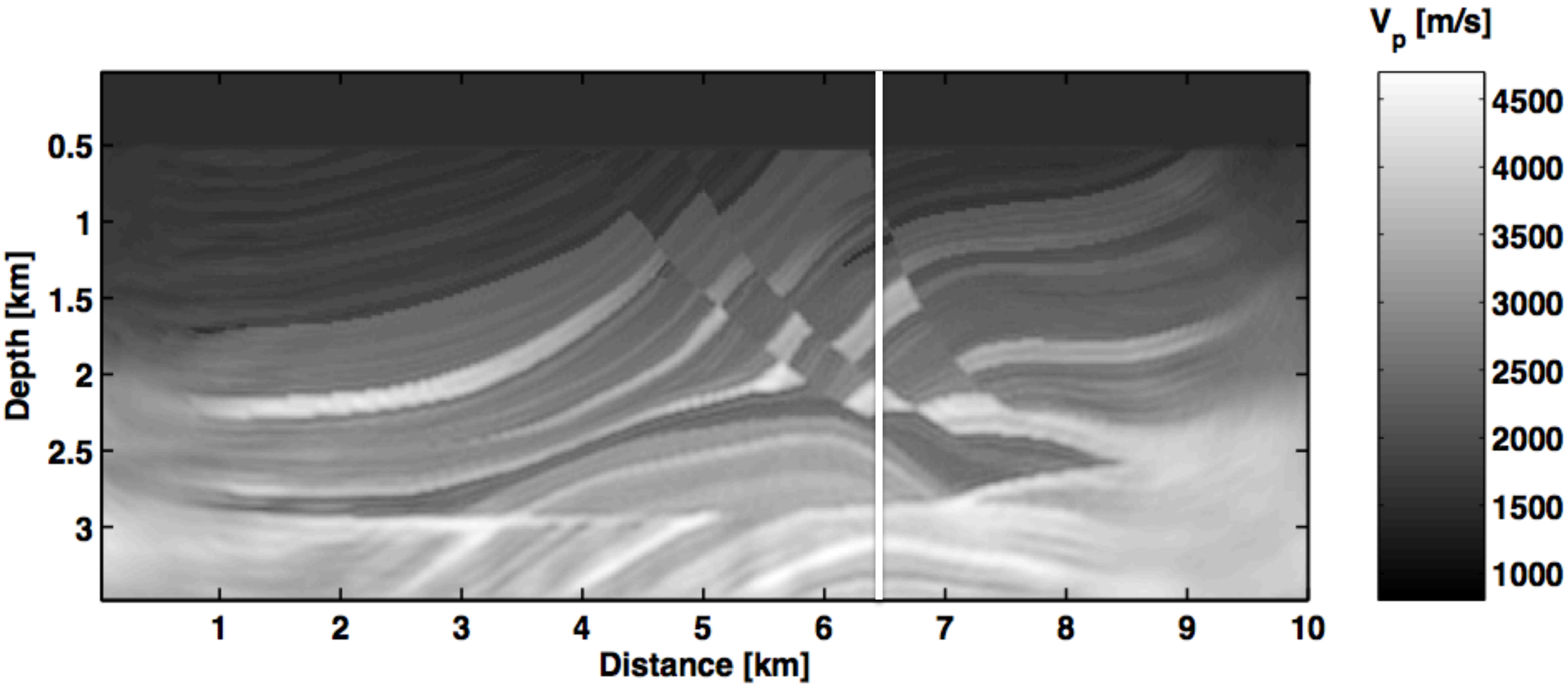
Starting point of FWT



(Kurzmann, 2012)

Results of elastic FWI

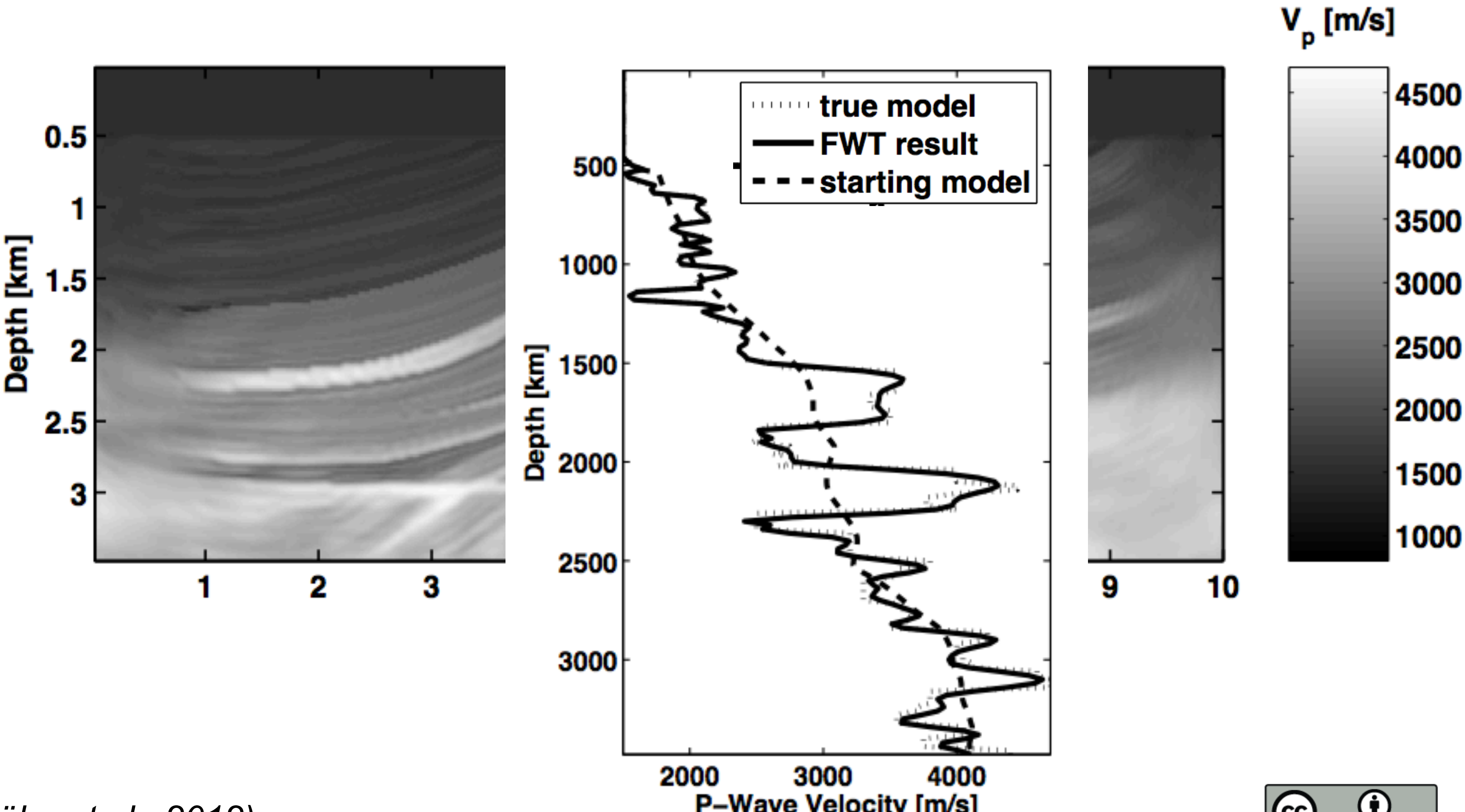
Inverted **P-wave** velocity model



(Köhn et al., 2012)

Results of elastic FWI

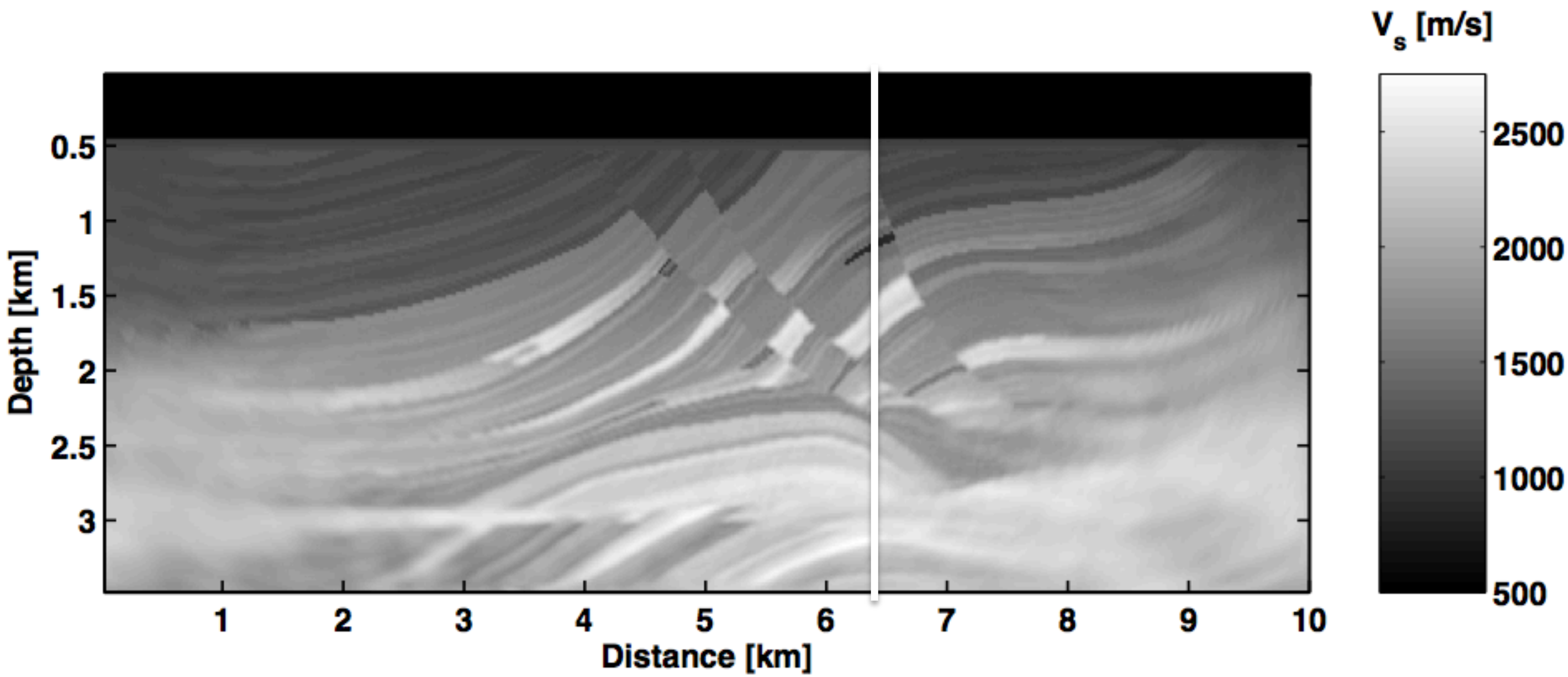
Inverted **P-wave** velocity model



(Köhn et al., 2012)

Results of elastic FWI

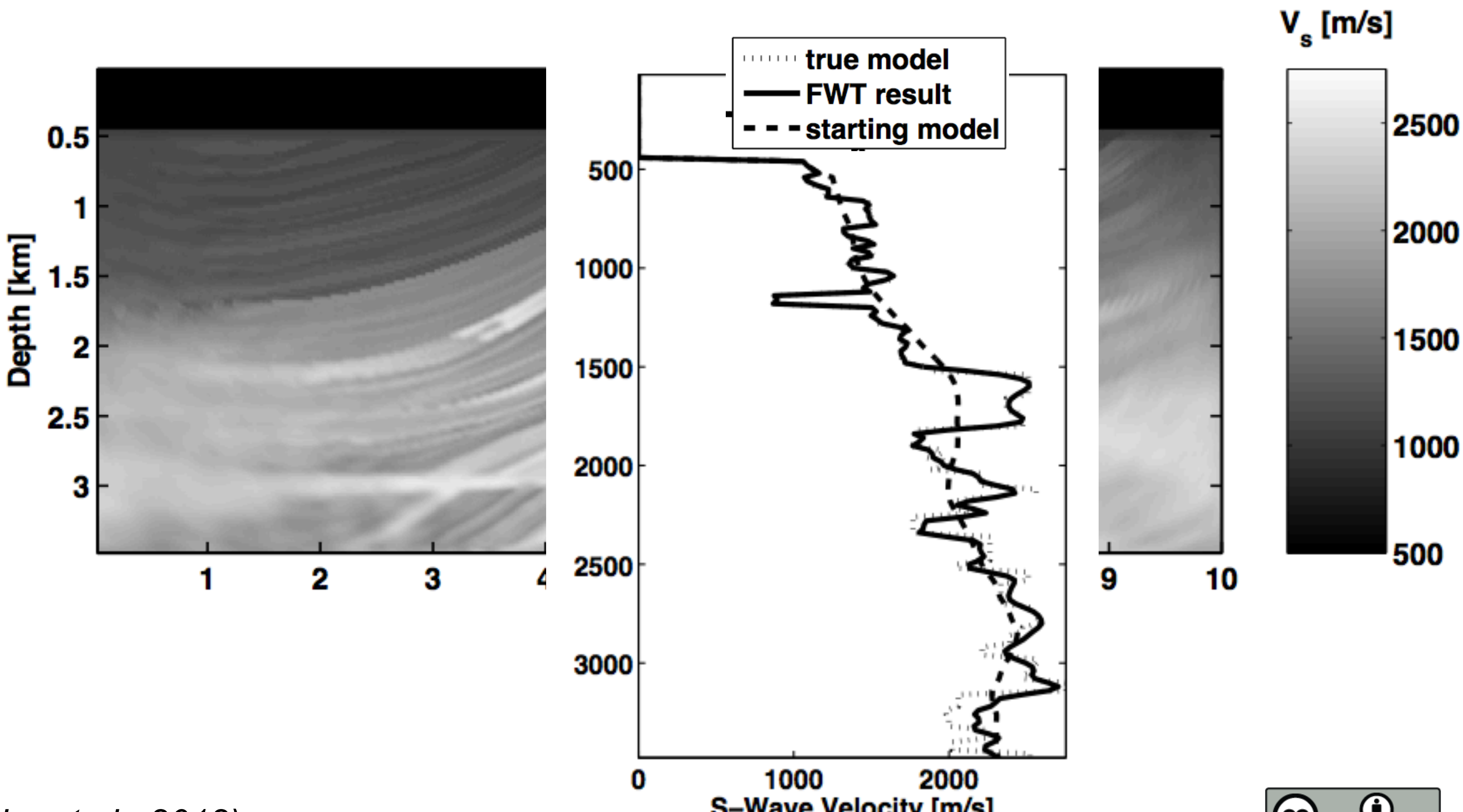
Inverted **S-wave** velocity model



(Köhn et al., 2012)

Results of elastic FWI

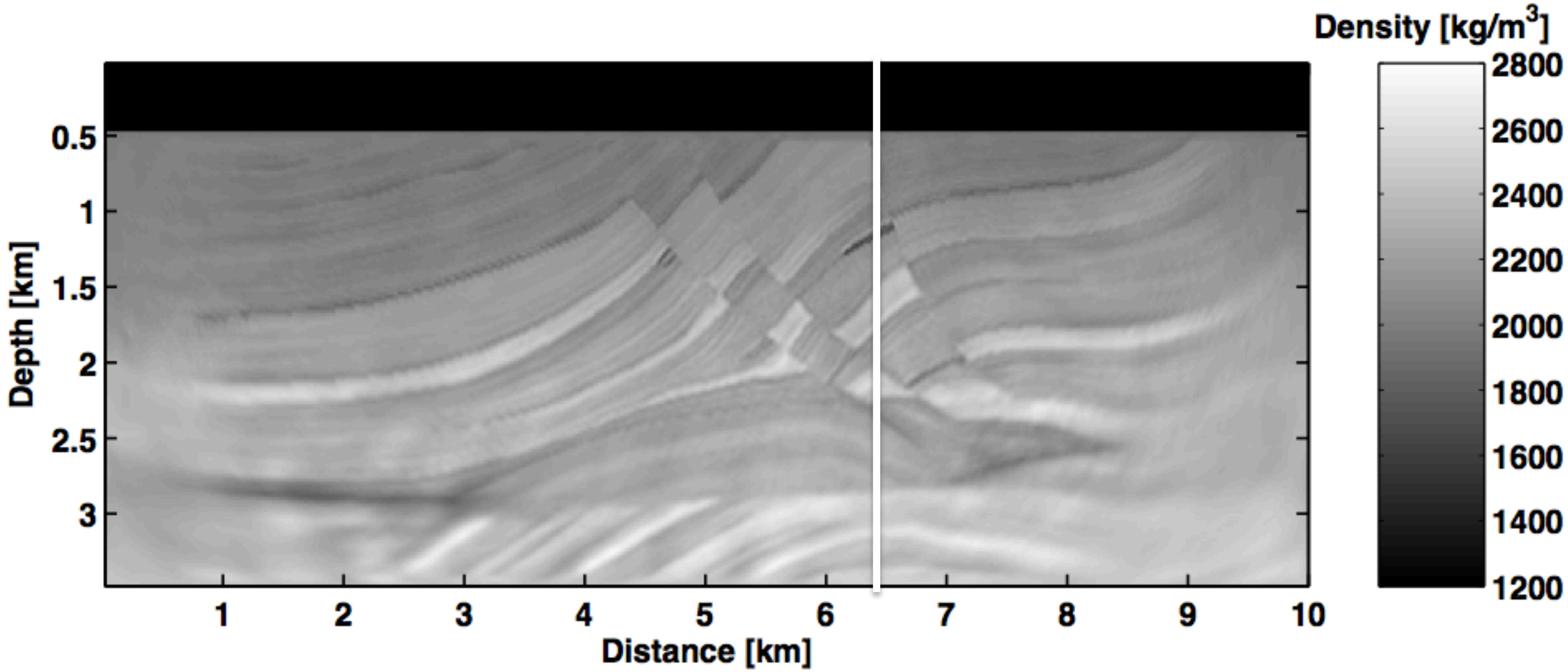
Inverted **S-wave** velocity model



(Köhn et al., 2012)

Results of elastic FWI

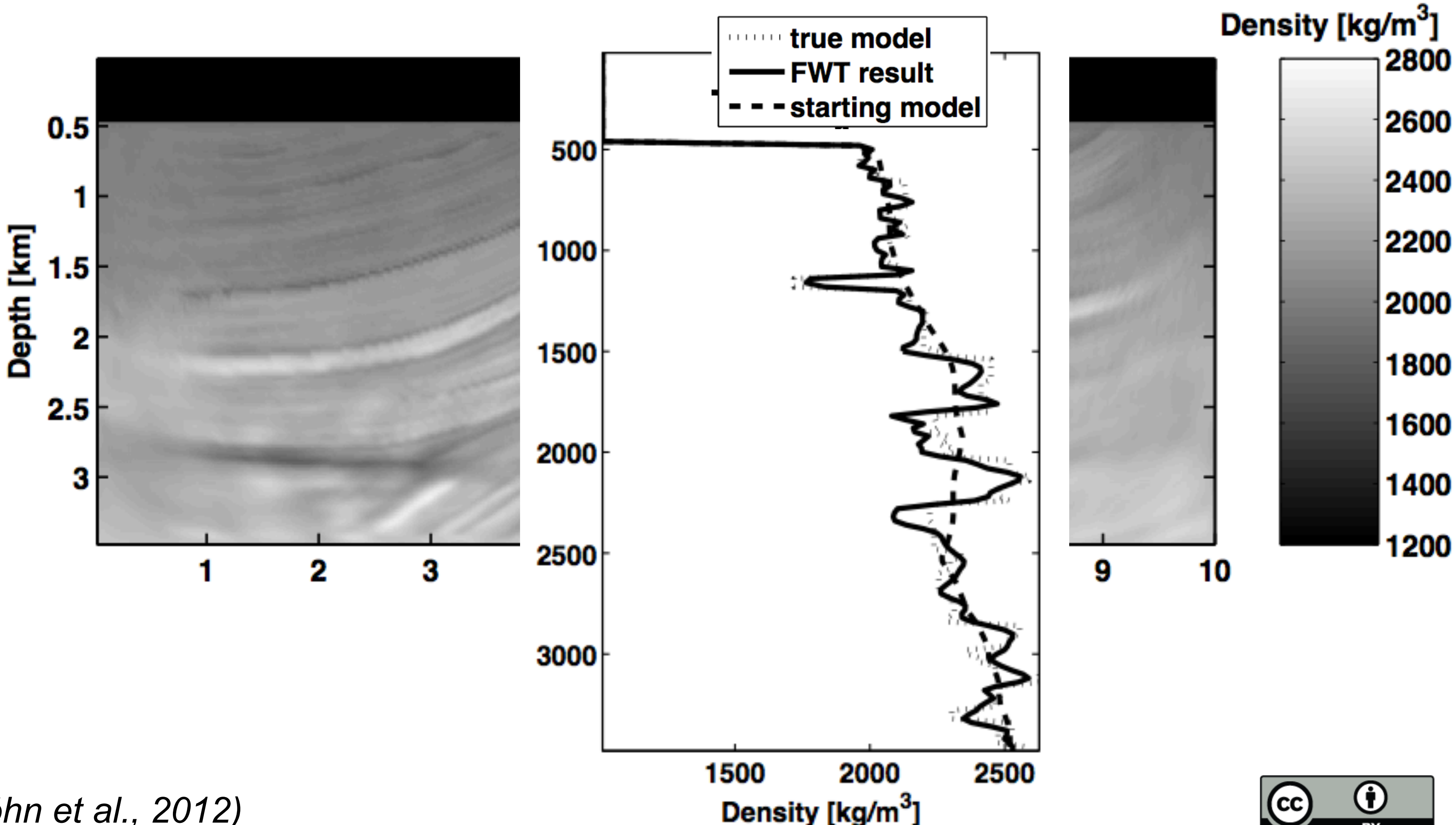
Inverted **density** model



(Köhn et al., 2012)

Results of elastic FWI

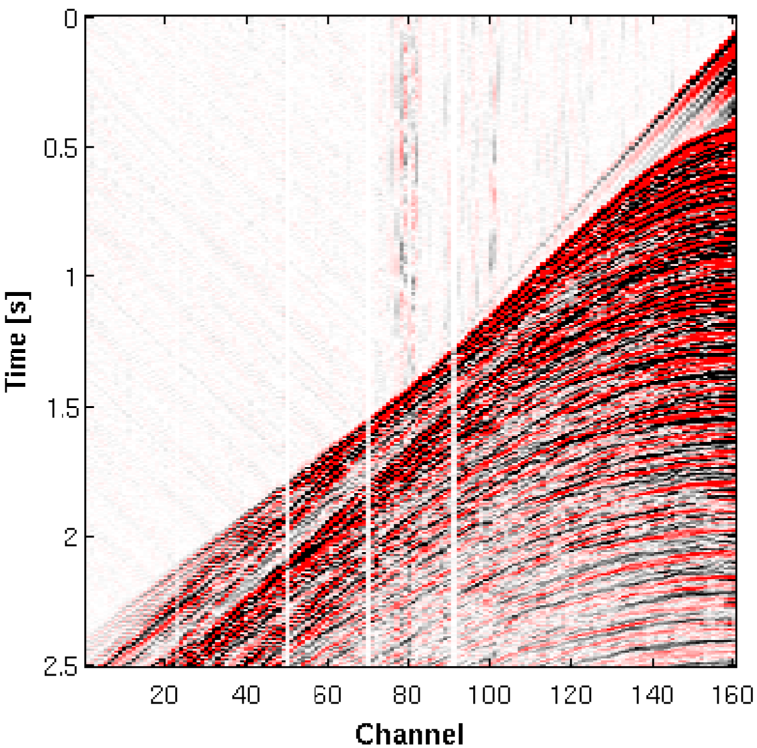
Inverted **density** model

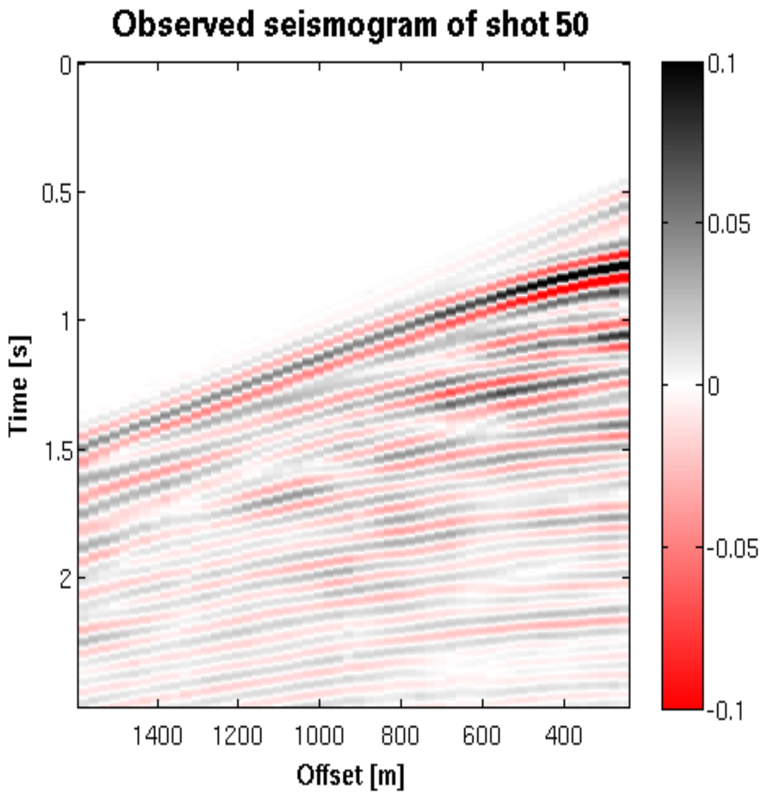


(Köhn et al., 2012)

Application to marine streamer data (North Sea)

raw shot gather

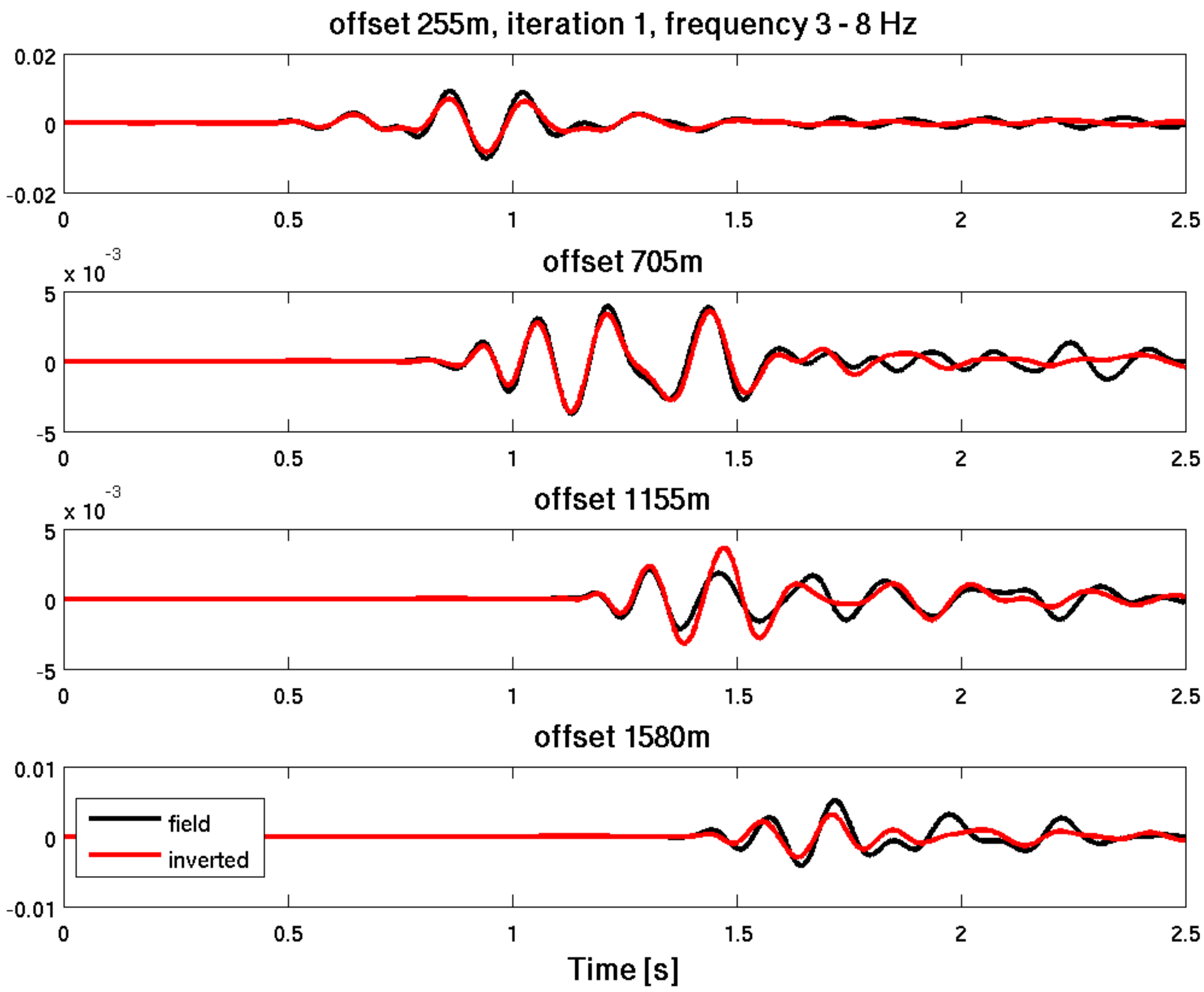




Data pre-processing: Noise attenuation, spreading transformation, near offsets

(Przebindowska et al., 2011, 2012)

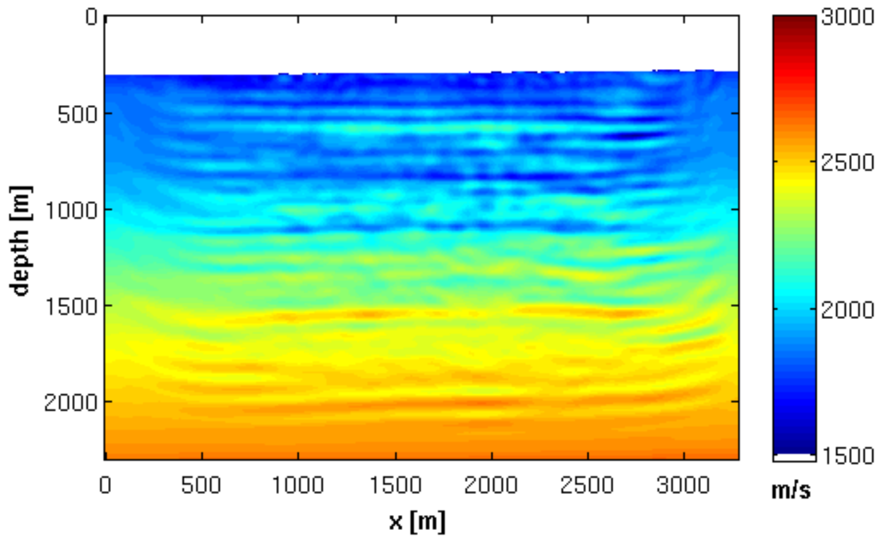
Data fitting



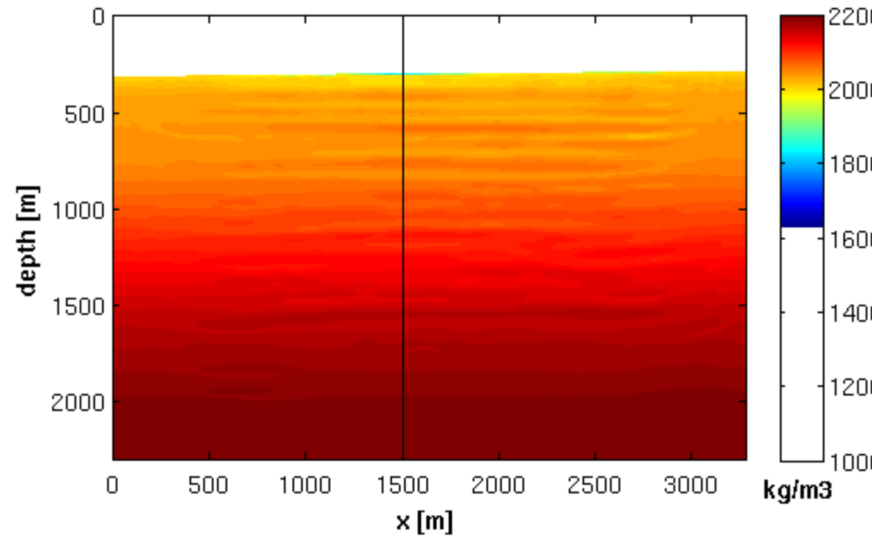
(Przebindowska et al., 2011, 2012)

Preliminary results

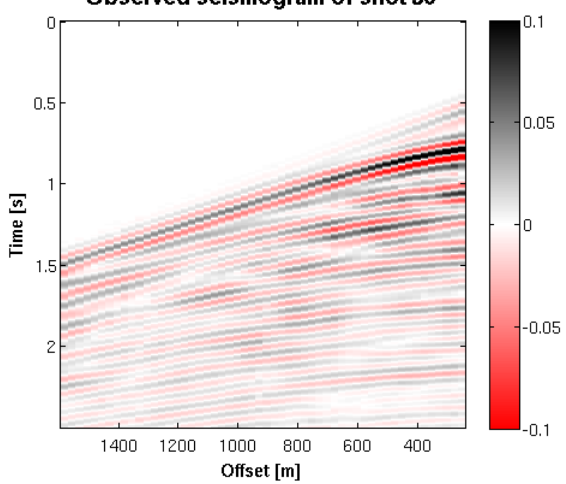
Inverted Vp model



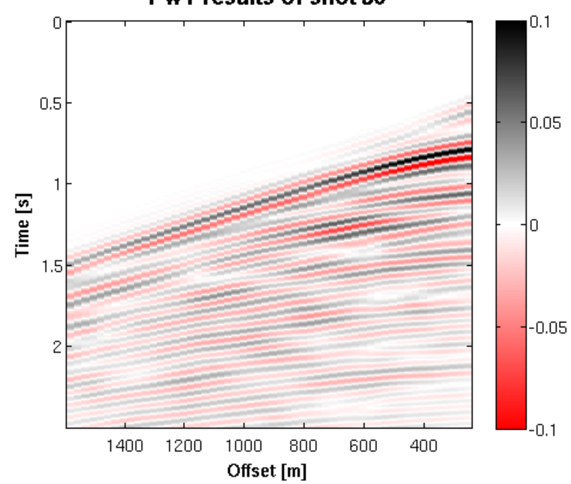
Inverted density model



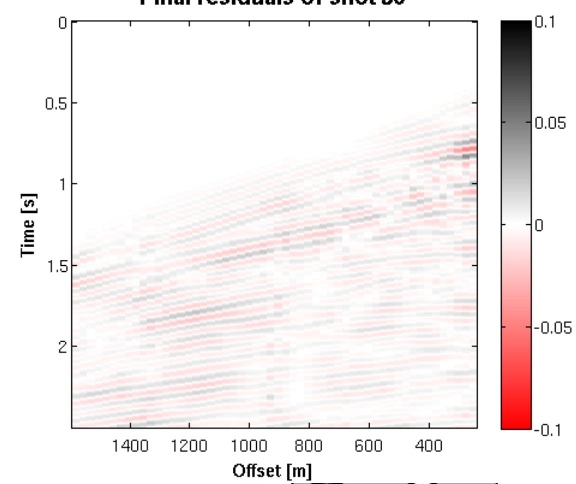
Observed seismogram of shot 50



FWT results of shot 50



Final residuals of shot 50

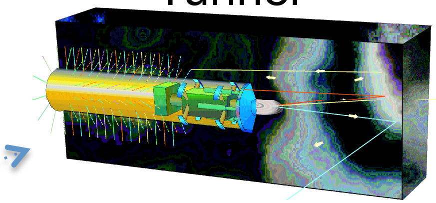


(Przebindowska et al., 2011, 2012)

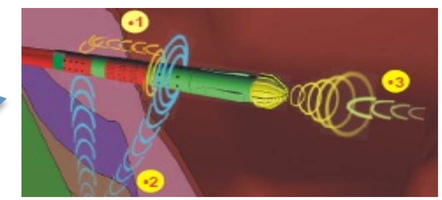
Summary

- Introduction
- Unconventional waves
  - Tunnel
  - Borehole
  - Seafloor
- Continuing mission
  - full waveform inversion

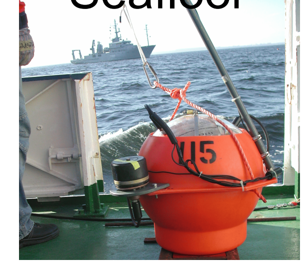
Tunnel



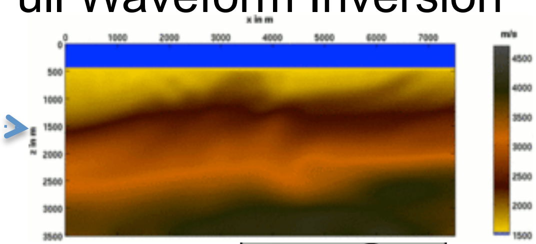
Borehole



Seafloor



Full Waveform Inversion




... to boldly go where no man has gone before
Thank you for your attention !

Acknowledgements

The results described in this study are the outcomes of various research projects in which we were involved during the last years. These were supported by the German Ministry of Education and Research (BMBF), the German Research Foundation (DFG), Baker Hughes Inteq (Celle), Verbundnetz Gas AG (VNG) Leipzig and the sponsors of the Wave Inversion Technology (WIT) Consortium.

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Kugler, S., Bohlen, T., Forbriger, T., Bussat, S. and Klein, G., Scholte-wave tomography for shallow-water marine sediments, Geophysical Journal International, 168, 2, 551-570, 2007.

Kugler, S., Bohlen, T., Forbriger, T., Bussat, S. and Klein, G., Scholte-wave tomography for shallow-water marine sediments, Geophysical Journal International, 168, 2, 551-570, 2007.

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Kugler, S., Bohlen, T., Bussat, S., Klein, G., Variability of Scholte wave dispersion in shallow-water marine sediments, Journal of Environmen- tal and Engineering Geophysics (JEEG), special edition on surface waves, volume 10, issue 2, pp 203-218, 2005.

Klein, G., Bohlen, T., Theilen, F., Kugler, S., Forbriger, T., Acquisition and inversion of dispersive seismic waves in shallow marine environ- ments, Marine Geophysical Researches, Volume 26, Issue 2 - 4, June 2005, Pages 287 – 315, 2005.

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Full Waveform Inversion

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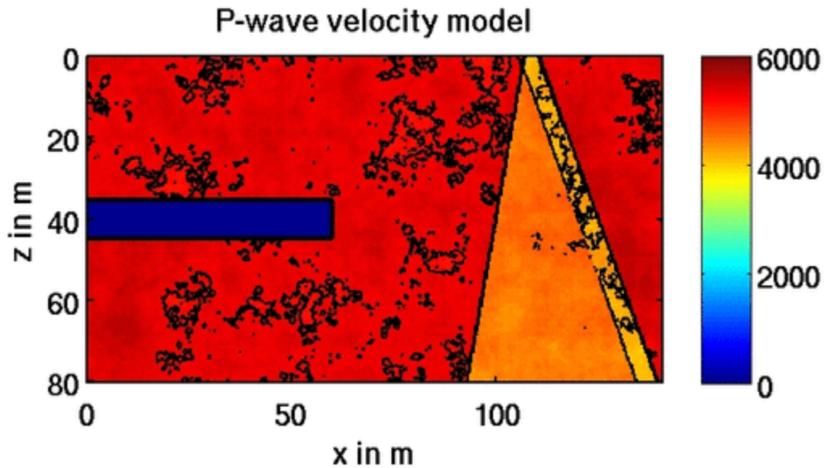
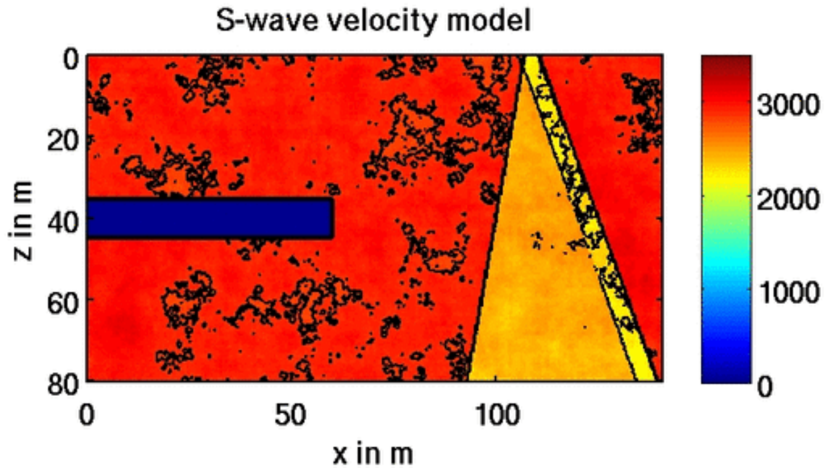
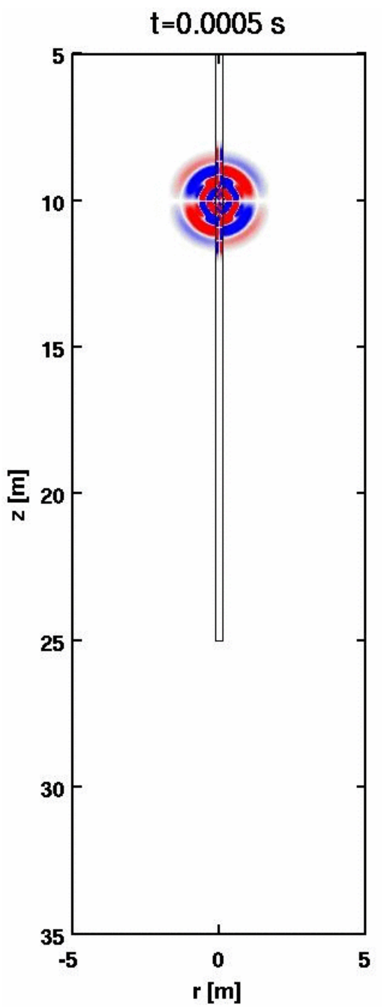
Appendix (additional slides)

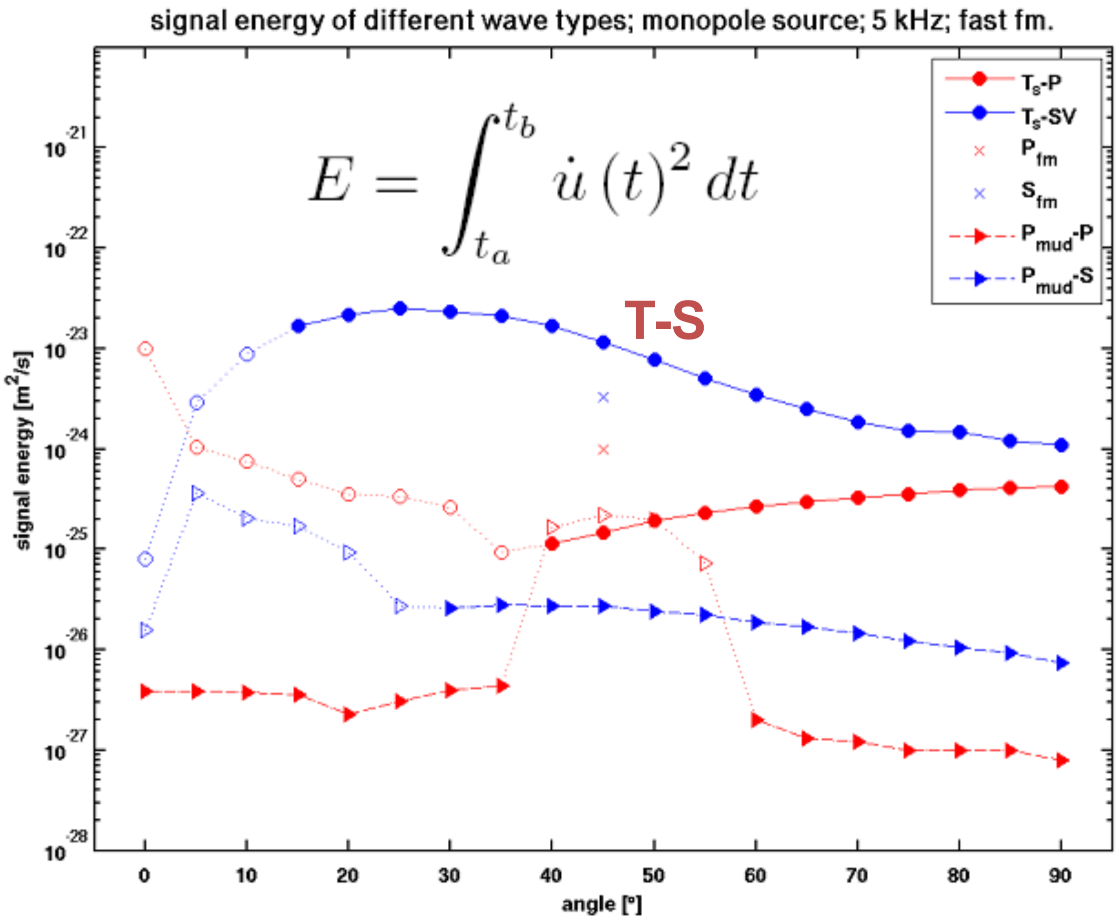
Anatomy of elastic wave field around a tunnel





2.5-D Simulation





Born approximation for scattered wave fields

Helmholtz equation: $$\left[\nabla^2 + \frac{\omega^2}{V^2(x)}\right] u(x,x_s,\omega) = -f(\omega)\delta(x - x_s)$$

I) Linear approximations

Model: $$\frac{1}{V^2(x)} := m(x) = m_0(x) + \delta m(x)$$

Wave field: $$u_{obs}(x,x_s,\omega) = u_0(x,x_s,\omega) + \delta u(x,x_s,\omega)$$

II) Born approximation: $$\delta m \cdot \delta u := 0$$

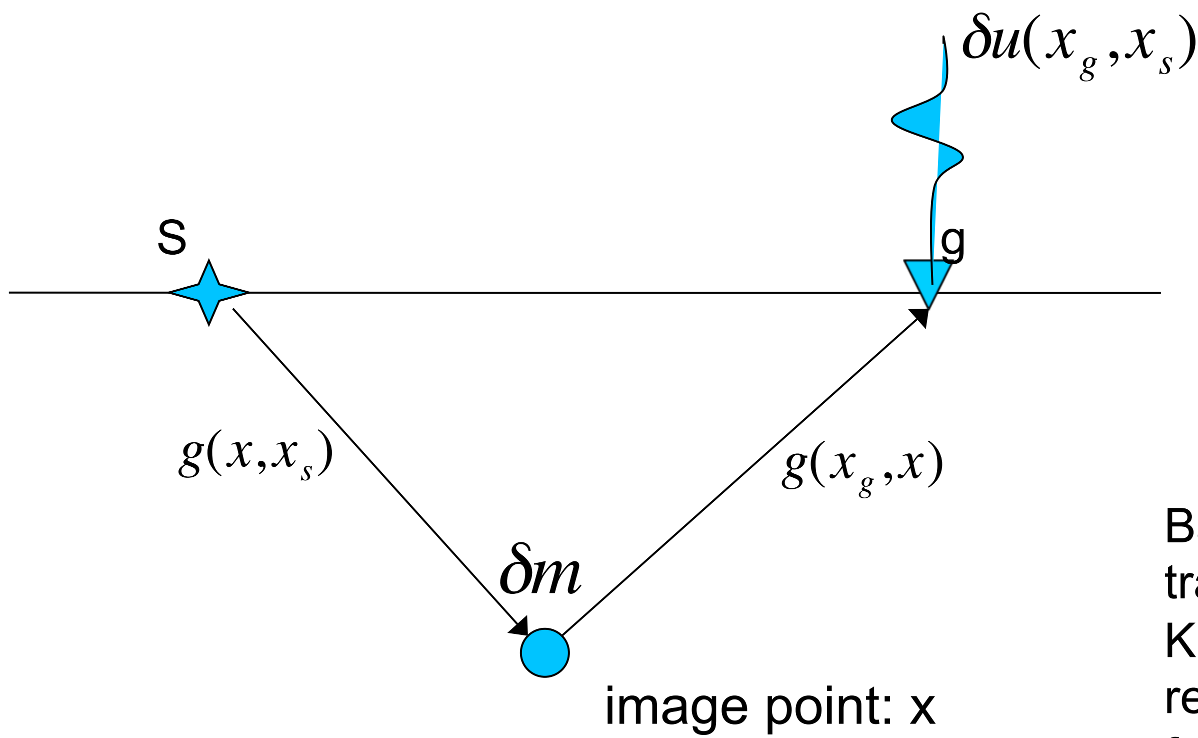
Scattered wave field:

$$\boxed{\delta u(x_g,x_s,\omega) = \omega^2 f(\omega) \int_V \delta m(x) g(x,x_s,\omega) g(x_g,x,\omega) d^3x}$$

Interpretation of scattered wave field

Scattered wave field:

$$\boxed{\delta u(x_g, x_s, \omega) = \omega^2 f(\omega) \int_V \delta m(x) g(x, x_s, \omega) g(x_g, x, \omega) d^3x}$$



Basis for
traveltime tomography
Kirchhoff migration
reverse time migration
full waveform inversion

Derivation of FWI

Misfit: $$E = \frac{1}{2}\int d\omega \sum_s \sum_g \left|\delta u(x_g, x_s, \omega)\right|^2$$

Iterative model update: $$m(x)^{n+1} = m(x)^n + \mu^n \gamma(x)^n$$

along the gradient: $$\gamma(x) = -\nabla_m E = \frac{\partial E}{\partial m}$$

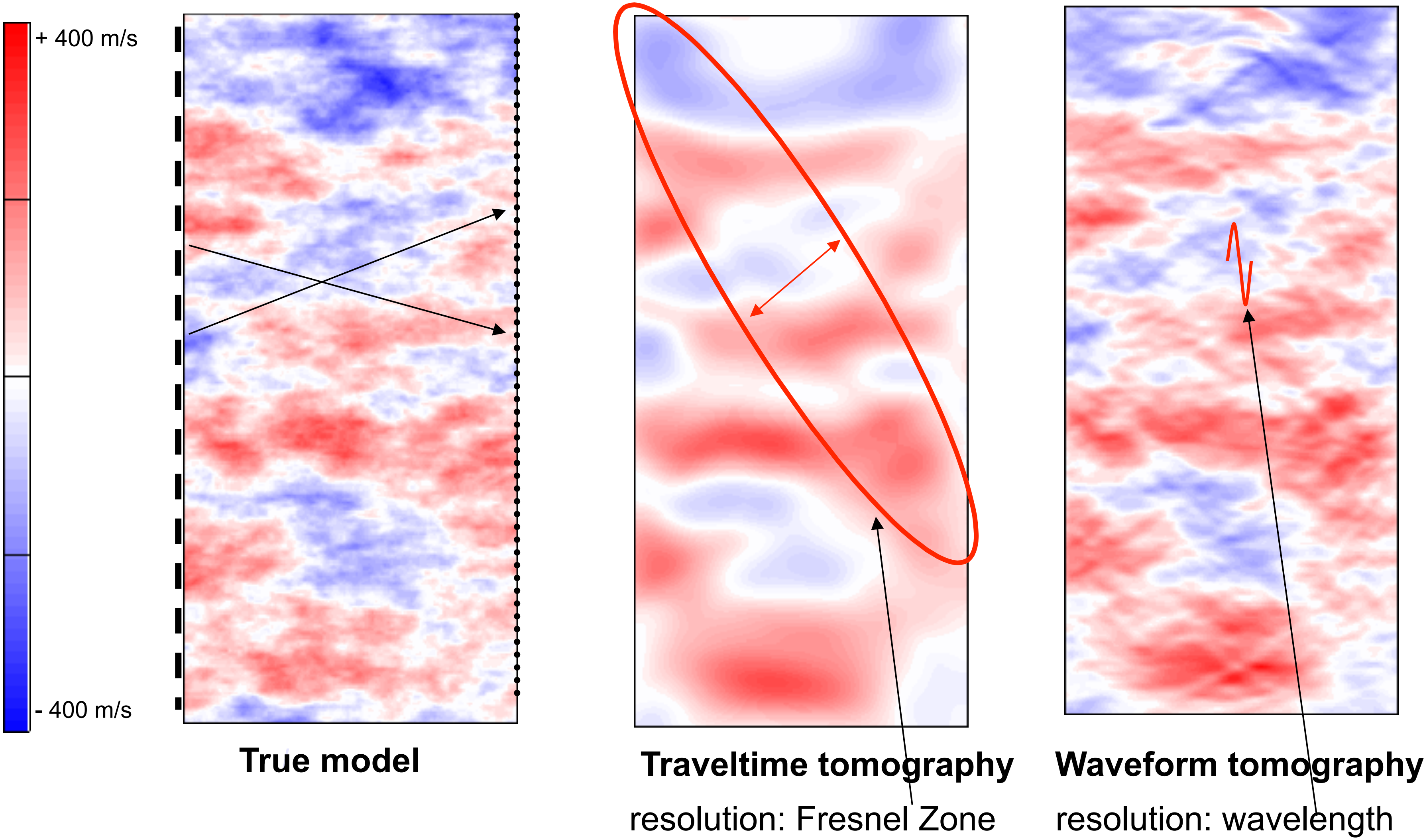
using the Born approximation:

$$\delta u(x_g, x_s, \omega) = \omega^2 f(\omega) \int_V \delta m(x) g(x, x_s, \omega) g(x_g, x, \omega) d^3 x$$

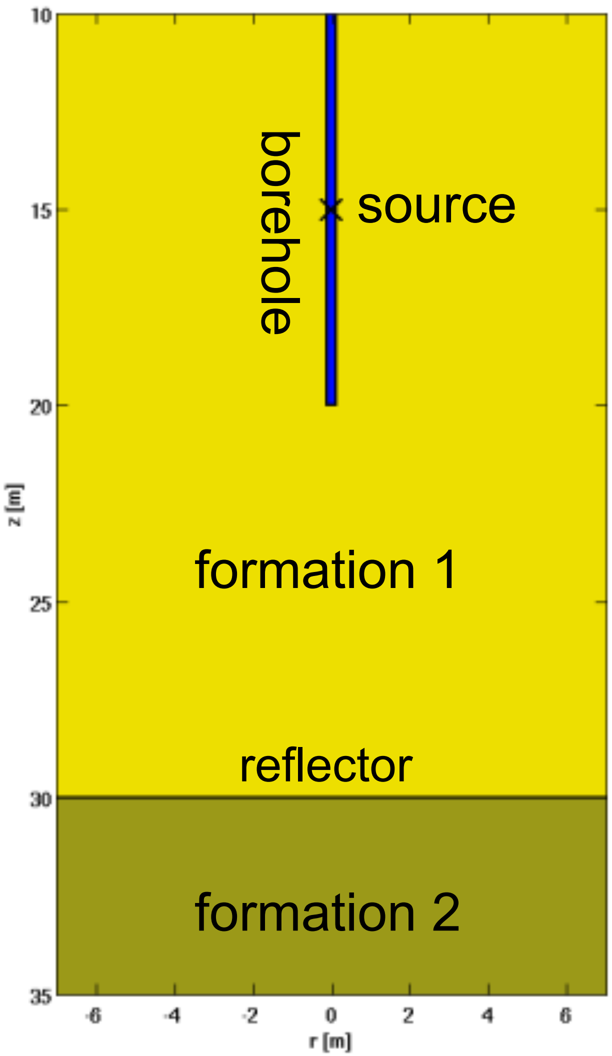
we obtain:

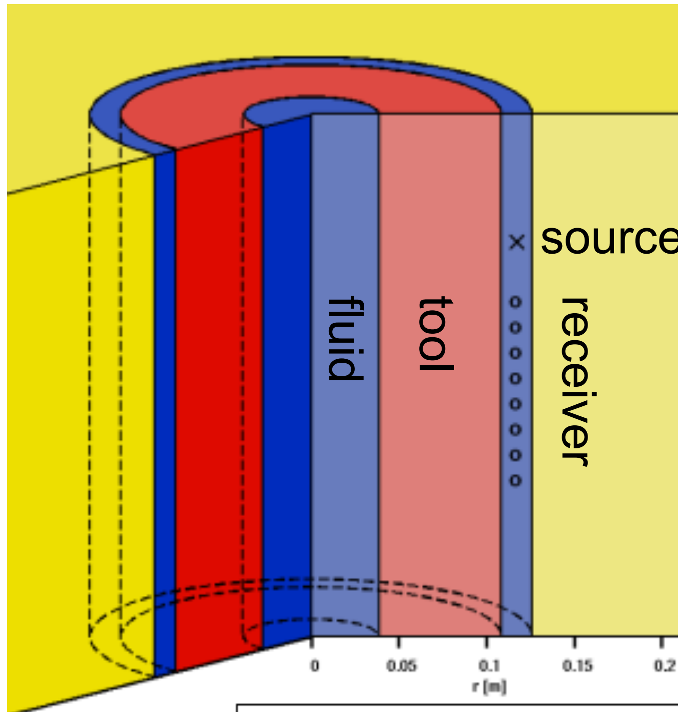
$$\gamma(x) = \int d\omega \sum_s \sum_g \omega^2 \mathrm{Re}\Big[\underbrace{\big(f(w) g(x, x_s, \omega)\big)}_{\text{forward wave field from source}} \cdot \underbrace{\big(\delta u^*(x_g, x_s, \omega) g(x_g, x, \omega)\big)}_{\text{backward wave field from receiver}}\Big]$$

Advantage I: maximum resolution



2.5-D Simulation



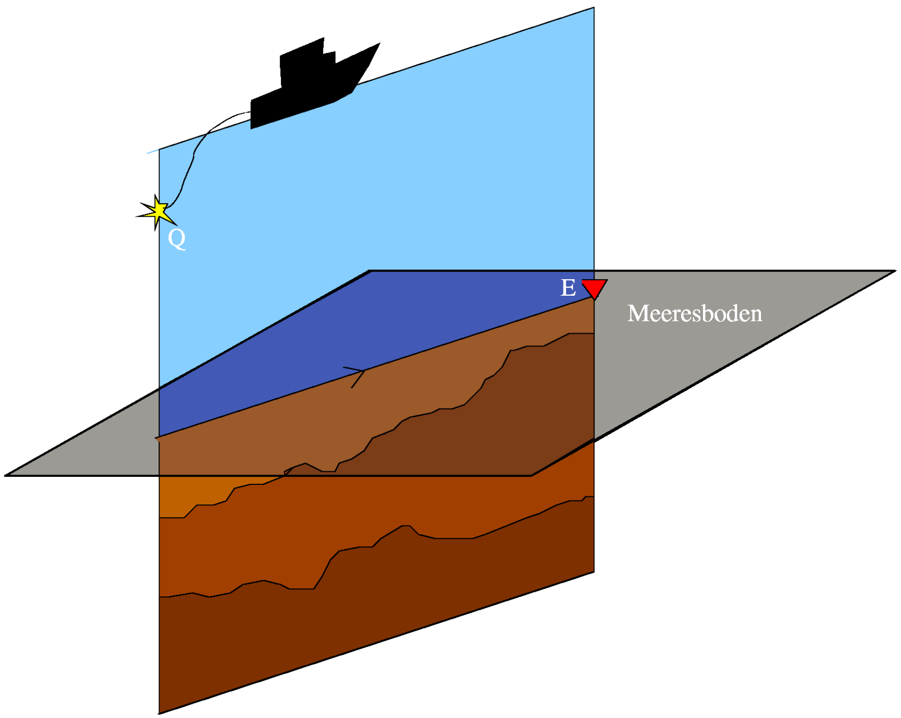


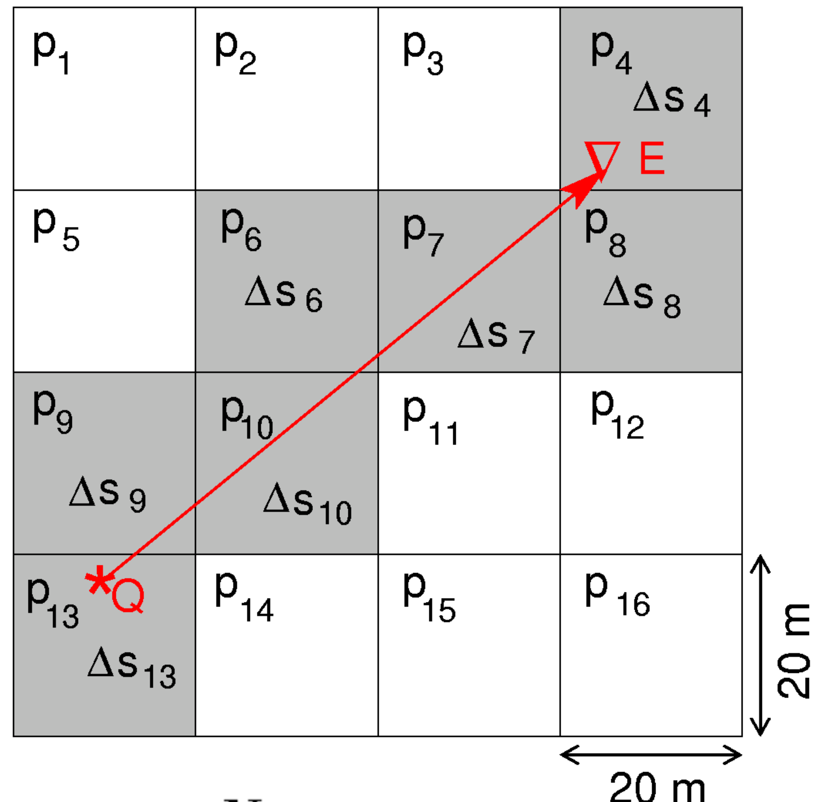
Model:

- dipole source (n = 1)
- vol. injection source
- Ricker-wavelet
- 5000 Hz center frequency

Elastic material parameters			
	v_P in m/s	v_S in m/s	ρ in kg/m^3
formation 1	2520	1000	2300
formation 2	1850	850	2000
borehole fluid	1600	0	1500
drilling tool	5860	3310	7700

Scholte wave tomography

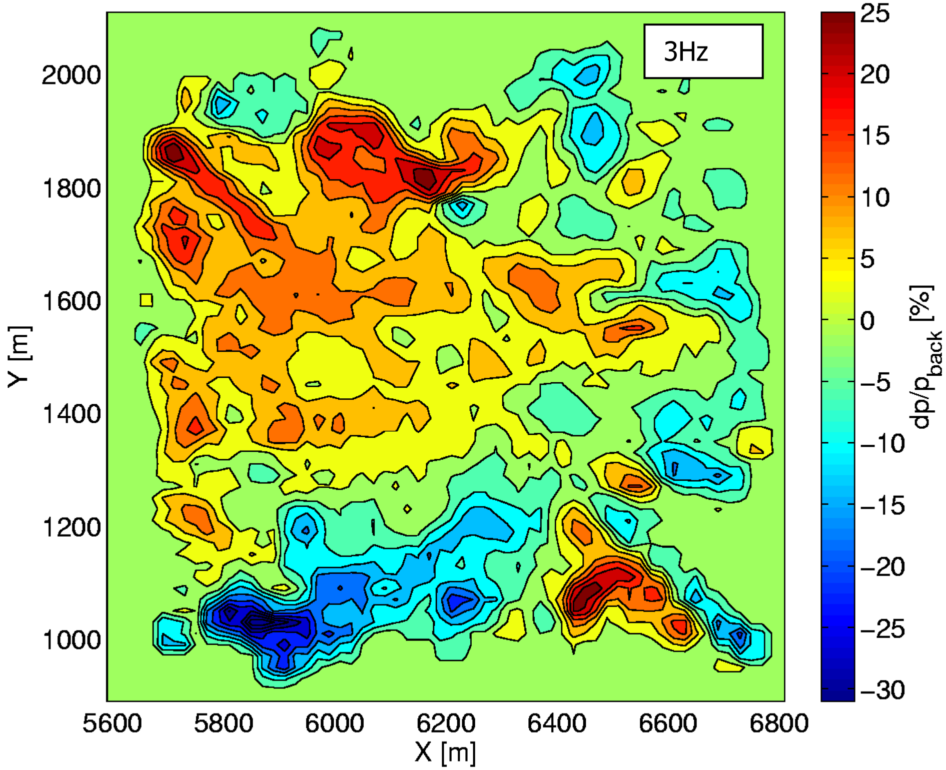




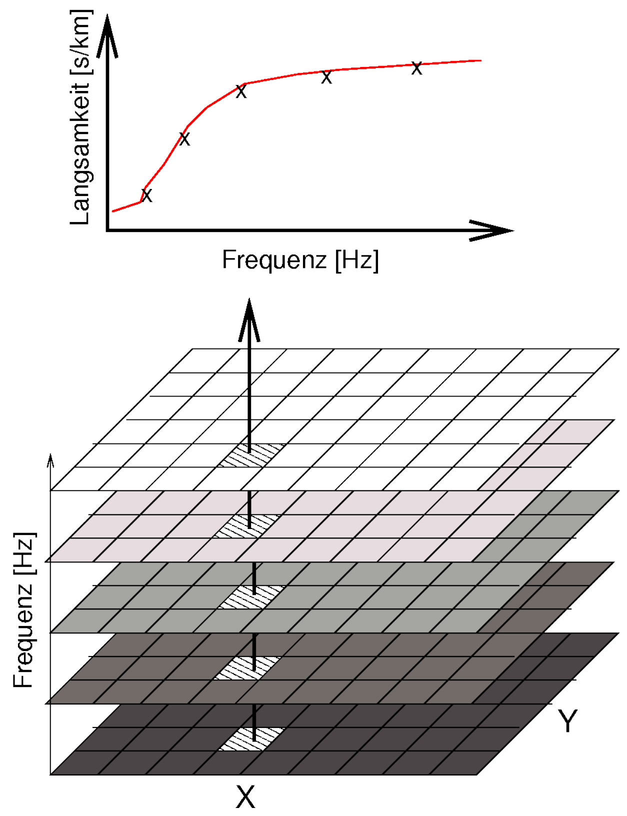
$$\overline{p}_{QE} = \frac{1}{R} \sum_{i=1}^{N} p_i \Delta s_i$$

Scholte wave tomography

phase slowness map



local 1-D inversion



Viscoelastic wave equations

stress-strain relation

$$\dot{\sigma}_{ij} = \frac{\partial v_k}{\partial x_k}\left\{\pi\left(1+\tau^p\right) - 2\mu\left(1+\tau^s\right)\right\} + 2\frac{\partial v_i}{\partial x_j}\mu\left(1+\tau^s\right) + \sum_{l=1}^{L} r_{ijl} \quad \textbf{if } i = j$$

$$\dot{\sigma}_{ij} = \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\mu\left(1+\tau^s\right) + \sum_{l=1}^{L} r_{ijl} \quad \textbf{if } i \neq j$$

memory variables

$$\dot{r}_{ijl} = -\frac{1}{\tau_{\sigma l}}\left\{\left(\pi\tau^p - 2\mu\tau^s\right)\frac{\partial v_k}{\partial x_k} + 2\frac{\partial v_i}{\partial x_j}\mu\tau^s + r_{ijl}\right\} \quad \textbf{if } i = j$$

$$\dot{r}_{ijl} = -\frac{1}{\tau_{\sigma l}}\left\{\mu\tau^s\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) + r_{ijl}\right\} \quad \textbf{if } i \neq j$$

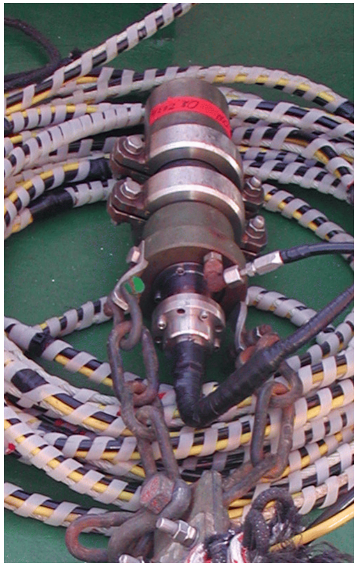
$$\varrho\frac{\partial v_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i$$

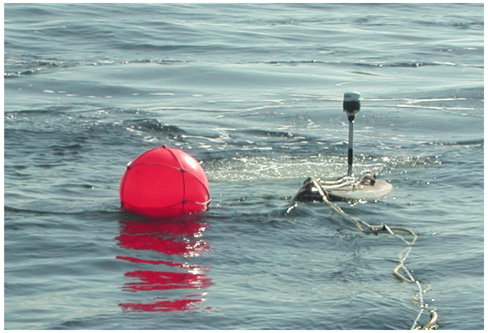
equation of momentum conservation

Scholte wave acquisition

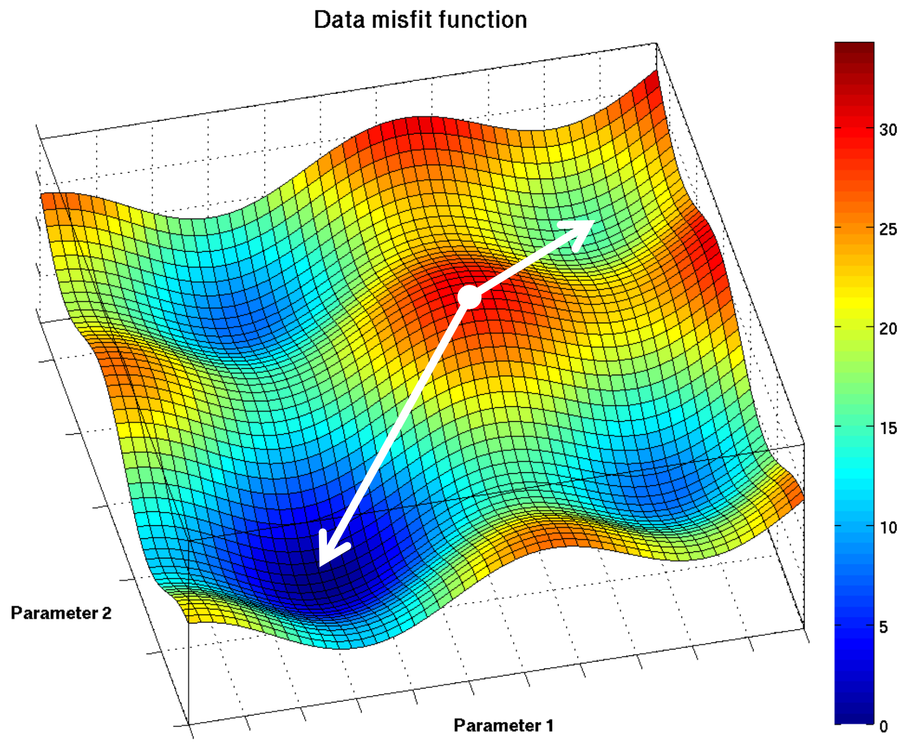
OBH/OBS

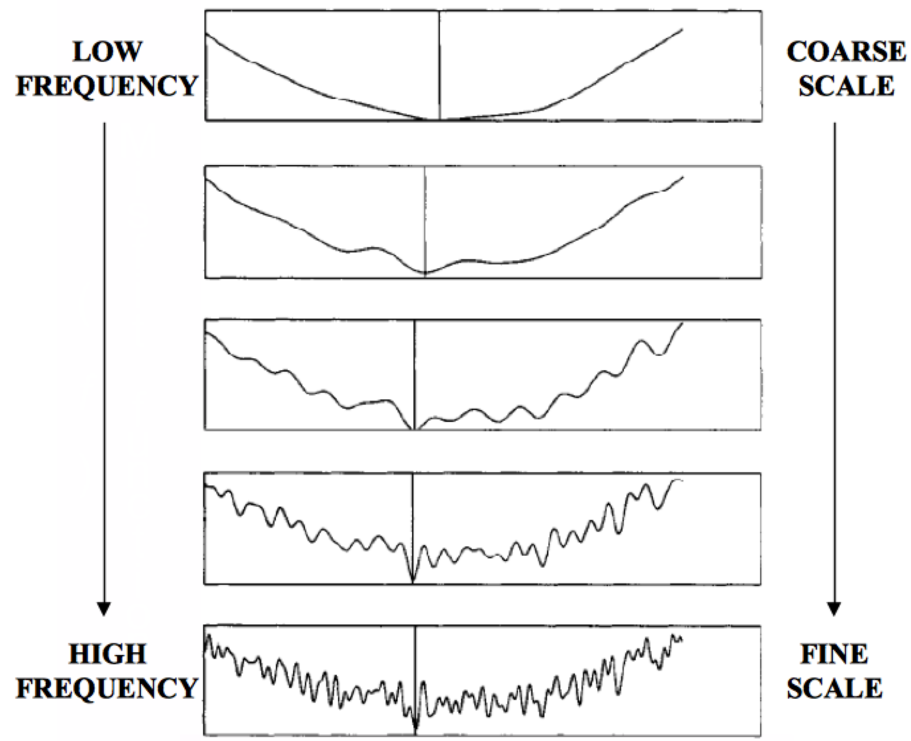
Airgun





Problem: non-linearity of the misfit function





Bunks et al. (1995)

starting model ⟷ low frequencies