Karlsruhe Institute of Technology

Full Waveform Inversion

Applications to shallow seismic surface waves

Thomas Bohlen

GEOPHYSICAL INSTITUTE, DEPARTMENT OF PHYSICS

Outline

1 Introduction

2 Methodology

- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

- Layered subsurface
- 2-D local trench
- Fault Zone

4 Towards 3D viscoelastic FWI of 3D 9-C field data

5 Summary

Introduction

Near Surface in this context refers to

- “Critical Zone”
- Up to 20-30 m depth
- Very strong vertical and sometimes lateral variations of visco-elastic material properties (a few 100% per cent)
- Weathering zone – transition zone between earth and atmosphere

Imaging of the “critical zone” is important for

- Geotechnical site characterization, e.g. stability of buildings
- Hazard analysis
    - Detection of cavities
    - Vs30: local site amplification due to surface waves
- Prospecting archeological objects
- etc.

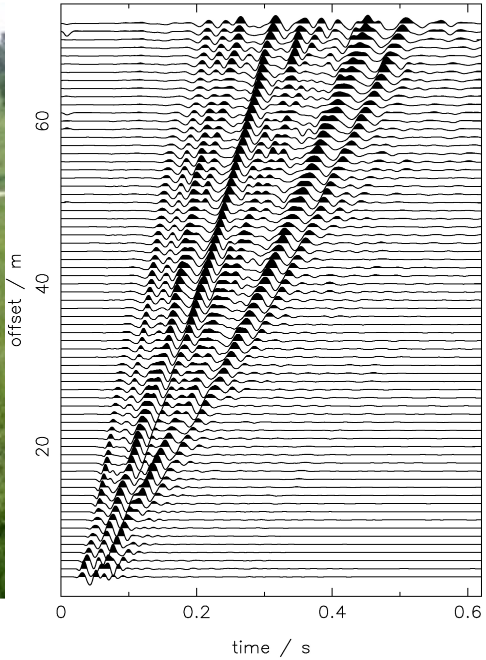
Introduction

Shallow seismic surface waves are

- easily excited
- strong signals
- highly sensitive for Vs (depth)
- penetrating up to 30-40 m depth

useful for geotechnical site characterization

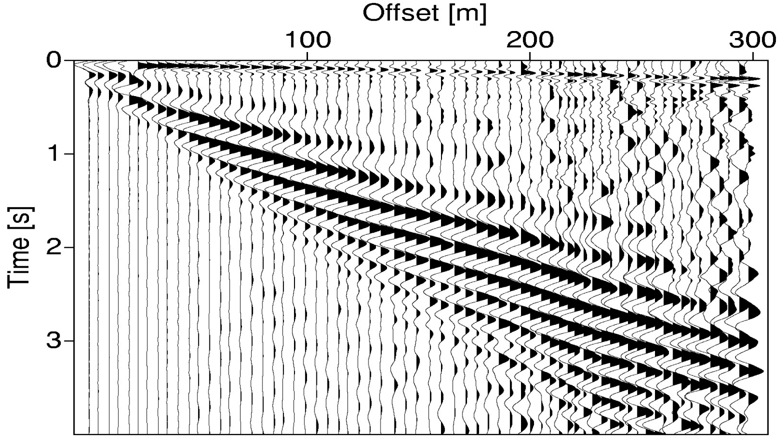
Field data acquisition



Introduction

Classical approach: 1-D inversion of (local) dispersion curves

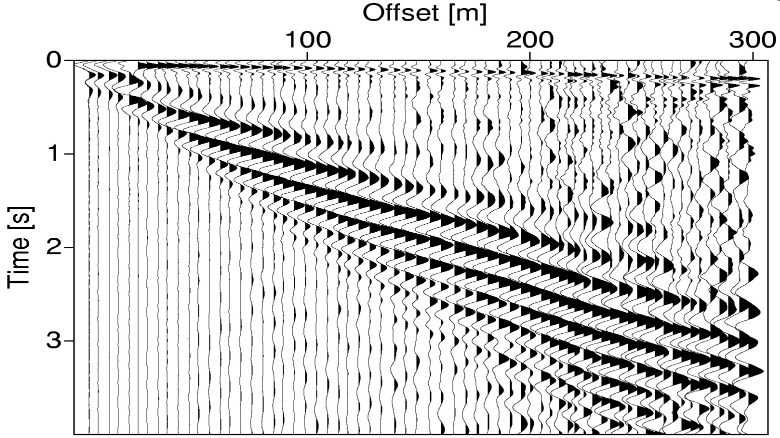
wavefield



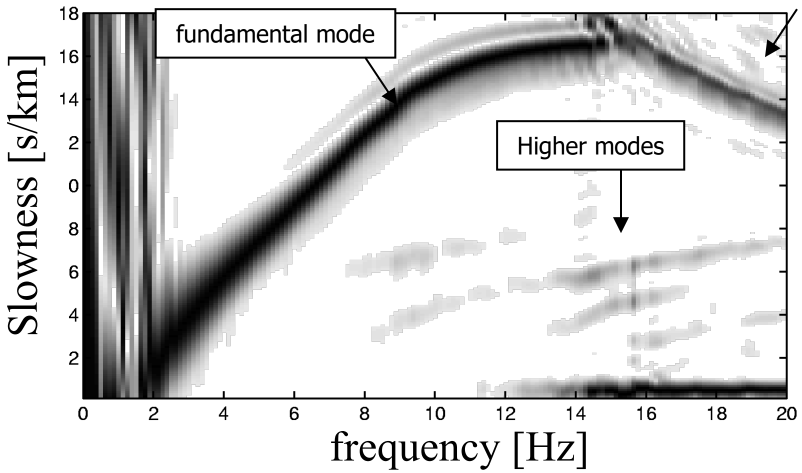
Introduction

Classical approach: 1-D inversion of (local) dispersion curves

wavefield



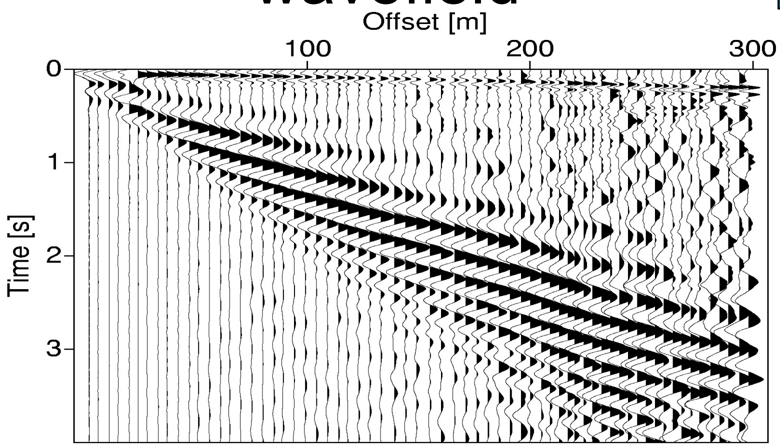
dispersion



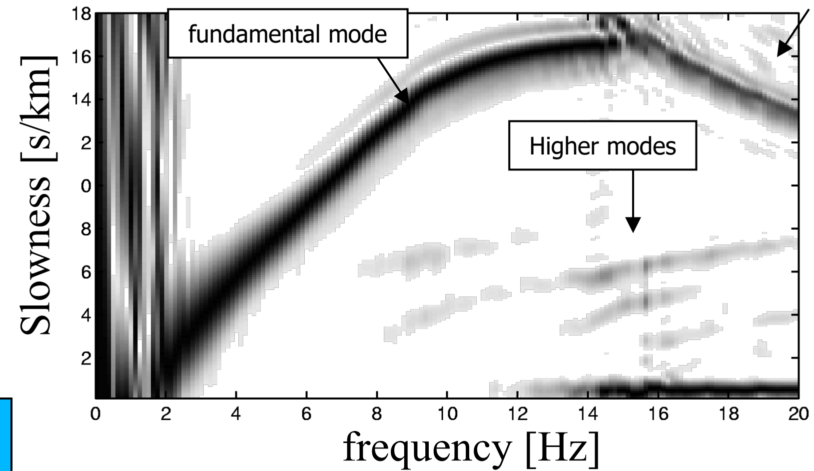
Introduction

Classical approach: 1-D inversion of (local) dispersion curves

wavefield



dispersion



(local) 1-D model

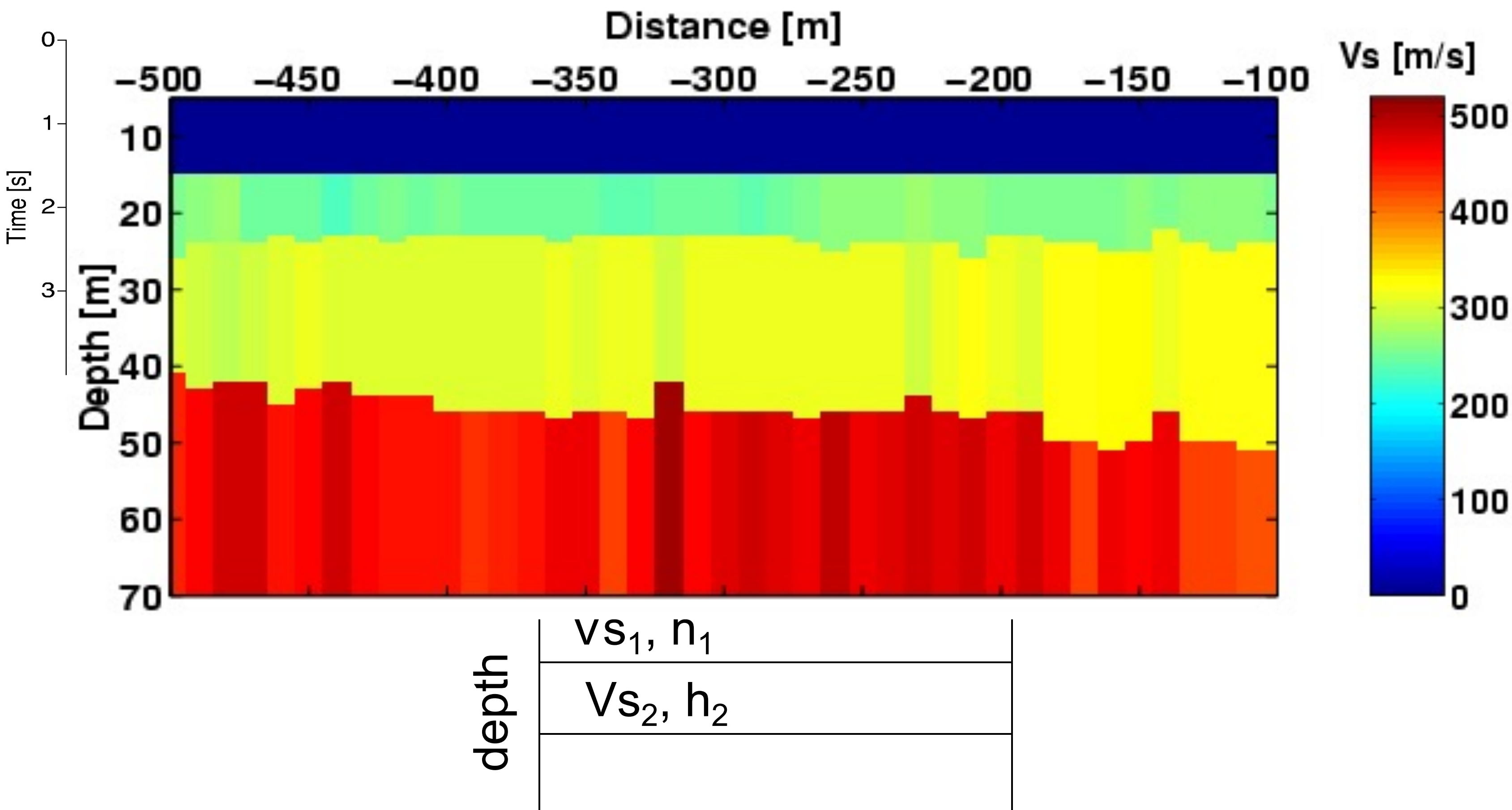
depth

Vs_1, h_1
Vs_2, h_2

Introduction

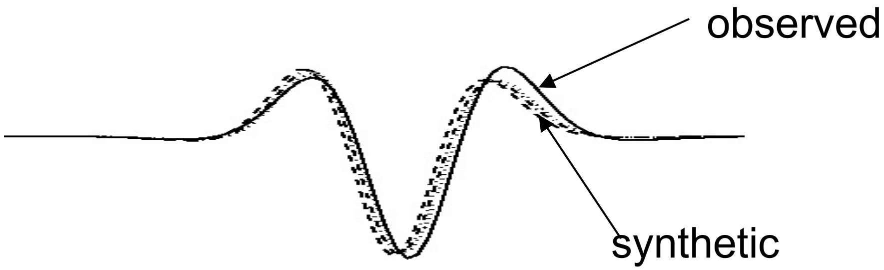
Classical approach: 1-D inversion of (local) dispersion curves

wavefield → dispersion



Introduction

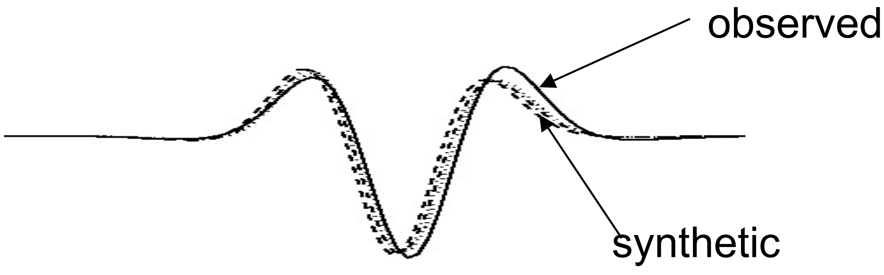
FWI exploits the full information content of seismic signals !



surface waves,
refracted and
reflected waves

Introduction

FWI exploits the full information content of seismic signals !



surface waves, refracted and reflected waves

Challenges for 2-D/3-D elastic FWI of surface waves

1. **Robust workflow** ?
2. Can we infer **lateral variations of Vs** ?
3. Can we derive **multi-parameter models** of Vs, Vp, Qp, Qs, density ?

Outline

1 Introduction

2 Methodology

- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

- Layered subsurface
- 2-D local trench
- Fault Zone

4 Towards 3D viscoelastic FWI of 3D 9-C field data

5 Summary

2D elastic Full Waveform Inversion (FWI)

- 2D elastic FWI : joint inversion of Vp, Vs, density

2D elastic Full Waveform Inversion (FWI)

- 2D elastic FWI : joint inversion of Vp, Vs, density

- L2-Misfit of normalized seismograms

$$E = \frac{\sum_i^{N_s} \sum_j^{N_r} \left| \hat{\mathbf{s}}_{i,j} - \hat{\mathbf{d}}_{i,j} \right|^2}{N_s \, N_r}$$

$\hat{\mathbf{d}}_{i,j} = \mathbf{d}_{i,j} / |\mathbf{d}_{i,j}|$: normalized observed seismograms

$\hat{\mathbf{s}}_{i,j} = \mathbf{s}_{i,j} / |\mathbf{s}_{i,j}|$: normalized synthetic seismograms

2D elastic Full Waveform Inversion (FWI)

- 2D elastic FWI : joint inversion of Vp, Vs, density

- L2-Misfit of normalized seismograms

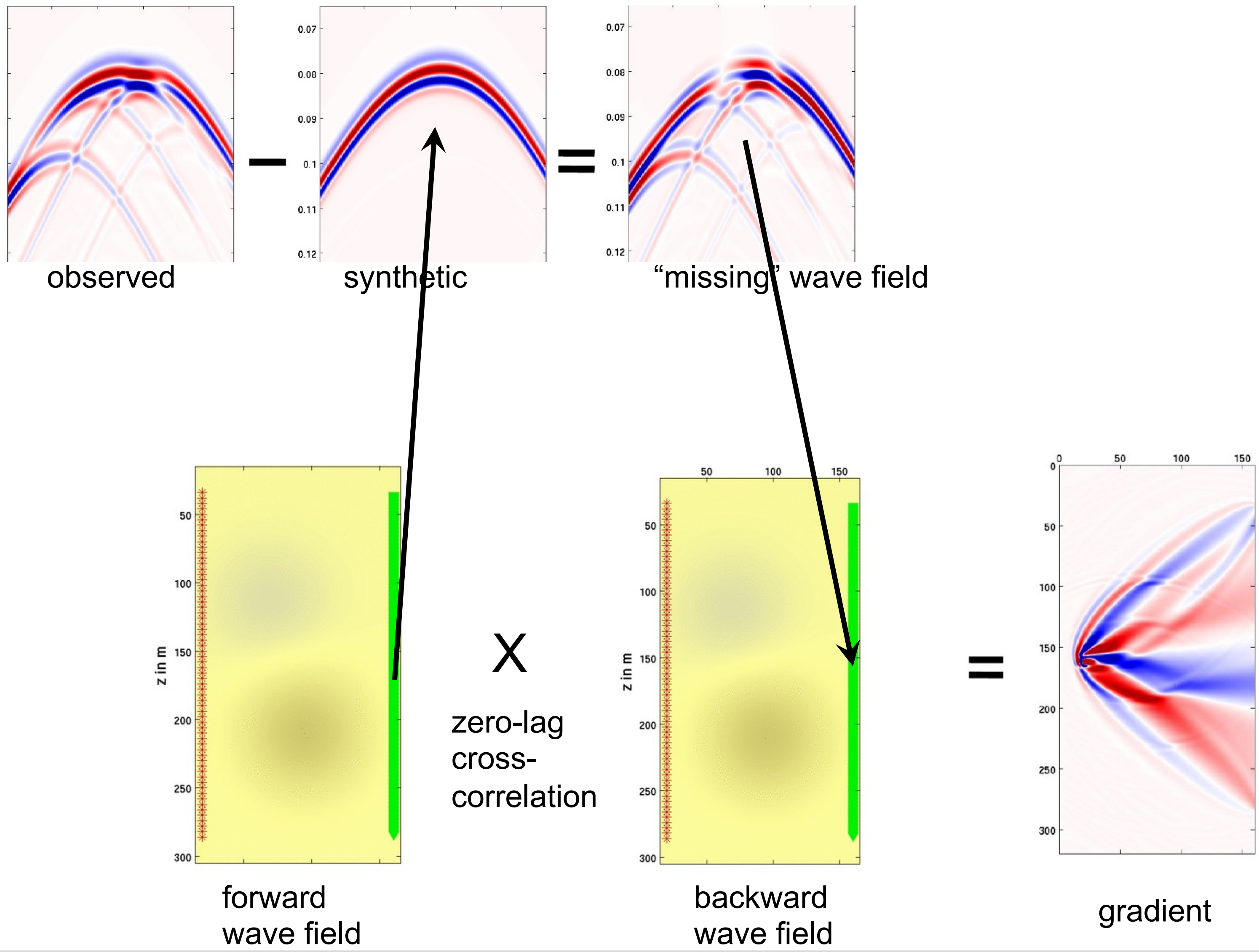
$$E = \frac{\sum_i^{N_s} \sum_j^{N_r} \left| \hat{\mathbf{s}}_{i,j} - \hat{\mathbf{d}}_{i,j} \right|^2}{N_s \, N_r}$$

$\hat{\mathbf{d}}_{i,j} = \mathbf{d}_{i,j} / |\mathbf{d}_{i,j}|$: normalized observed seismograms

$\hat{\mathbf{s}}_{i,j} = \mathbf{s}_{i,j} / |\mathbf{s}_{i,j}|$: normalized synthetic seismograms

- Conjugate gradient method or L-BFGS method for model update
- Gradient calculation with the **adjoint state method**
- 2D viscoelastic Finite Difference time domain modeling
- Implementation of viscoelastic damping by a generalized Standard Linear Solid (GSLS)

Adjoint State Method



Outline

1 Introduction

2 Methodology

- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

- Layered subsurface
- 2-D local trench
- Fault Zone

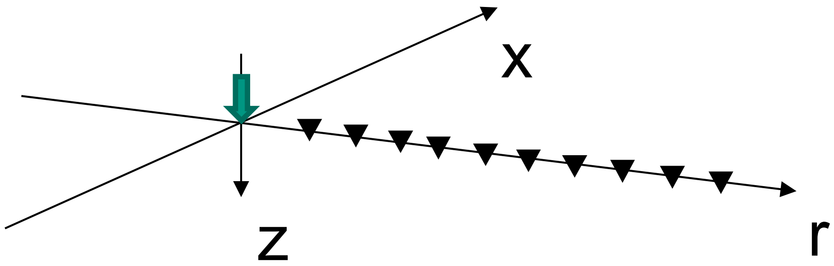
4 Towards 3D viscoelastic FWI of 3D 9-C field data

5 Summary

Geometrical spreading in homogenous acoustic medium

Point source (field data)

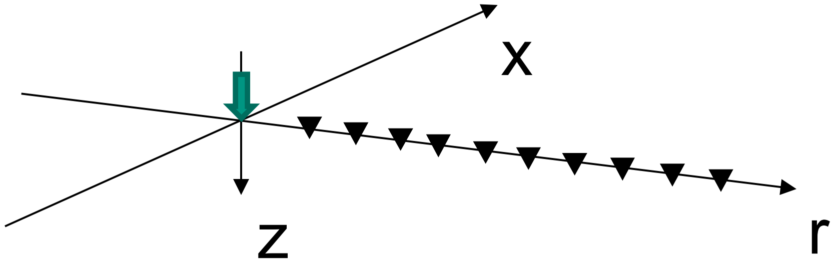
$$G^{3D} = \frac{1}{r} e^{ikr}$$



Geometrical spreading in homogenous acoustic medium

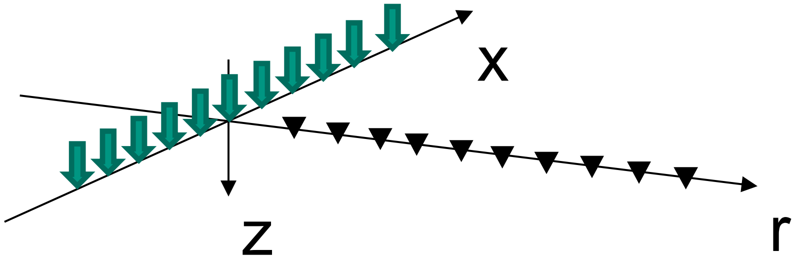
Point source (field data)

$$G^{3D} = \frac{1}{r} e^{ikr}$$



Line source (2D FWI)

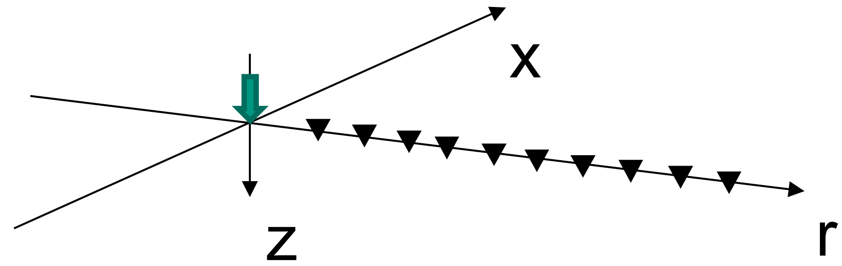
$$G^{2D} \simeq \sqrt{\frac{2\pi}{kr}} e^{ikr} e^{i\pi/4}$$



Geometrical spreading in homogenous acoustic medium

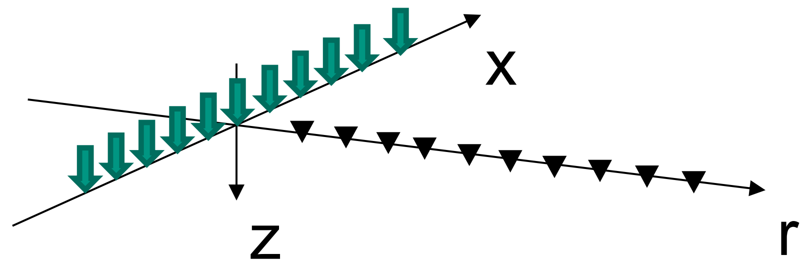
Point source (field data)

$$G^{3D} = \frac{1}{r} e^{ikr}$$



Line source (2D FWI)

$$G^{2D} \simeq \sqrt{\frac{2\pi}{kr}} e^{ikr} e^{i\pi/4}$$



Correction

(Forbriger et al., 2014)

$$\frac{G^{2D}}{G^{3D}} \simeq \sqrt{\frac{2\pi r}{k}} e^{i\pi/4} \overset{k=\frac{\omega}{c}}{=} \underbrace{\sqrt{2rc}}_{F_{amp}} \underbrace{\sqrt{\frac{\pi}{\omega}} e^{i\pi/4}}_{\tilde{F}\left(\sqrt{t^{-1}}\right)}$$

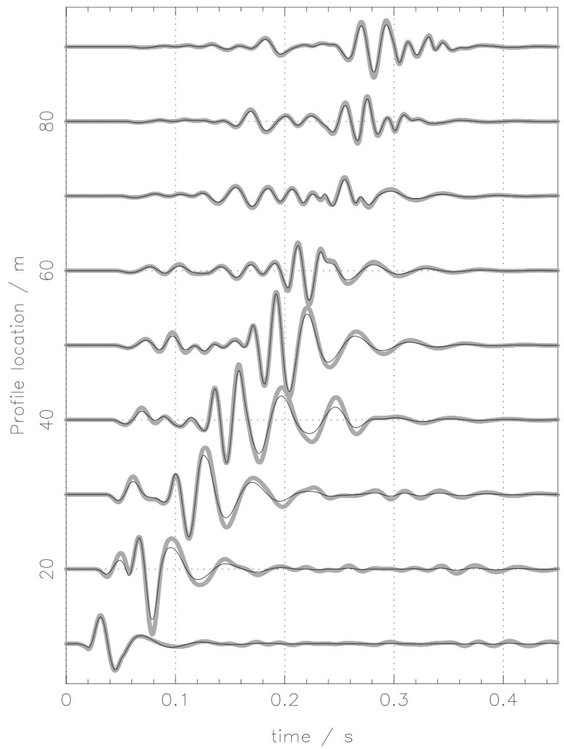
$$F_{amp} = r\sqrt{2}\sqrt{t^{-1}}$$

far field

near field

Synthetic Test of 2D/3D-Transformation

after correction



line source seismograms
corrected point source seismograms

- works surprisingly well for shallow seismic wave fields
- single-trace transformation
- applicable also in case of lateral heterogeneity

(Schäfer et al., 2014)

Outline

1 Introduction

2 Methodology
- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- **Attenuation**

3 2D Field data applications
- Layered subsurface
- 2-D local trench
- Fault Zone

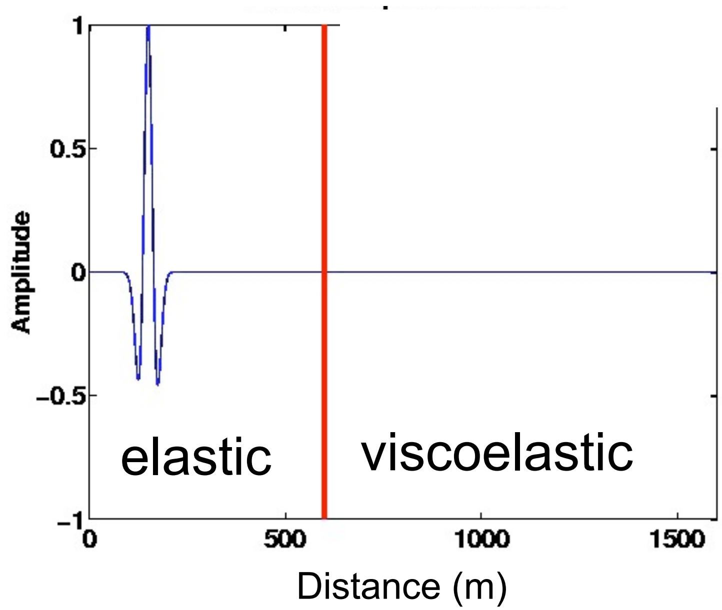
4 Towards 3D viscoelastic FWI of 3D 9-C field data

5 Summary

Effects of Attenuation

1. Amplitude decay with distance
2. Loss of high frequencies with distance
3. Dispersion

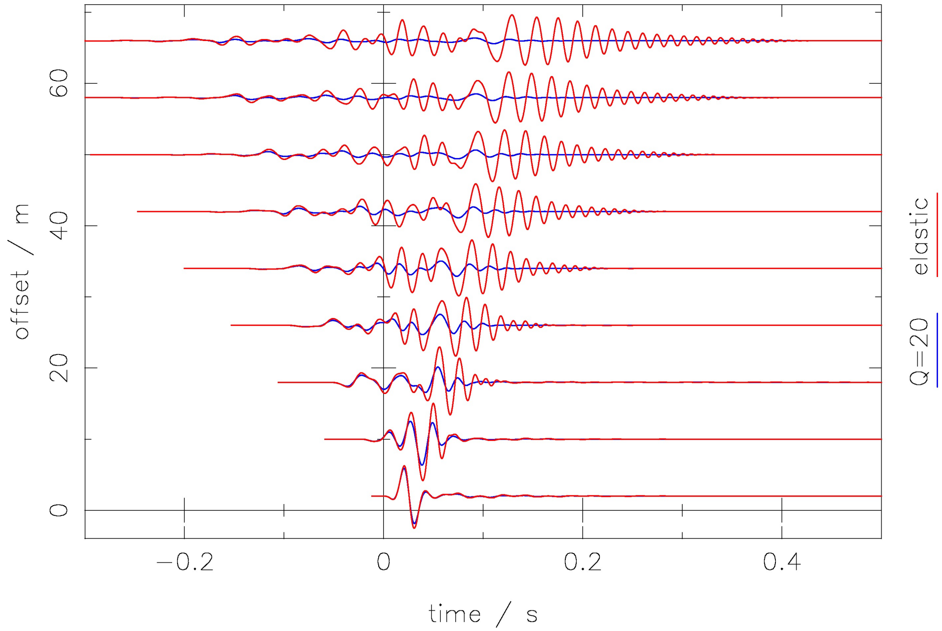
plane wave



Challenge II: Attenuation

1. Amplitude decay with distance
2. Loss of high frequencies with distance
3. Dispersion

raw seismograms



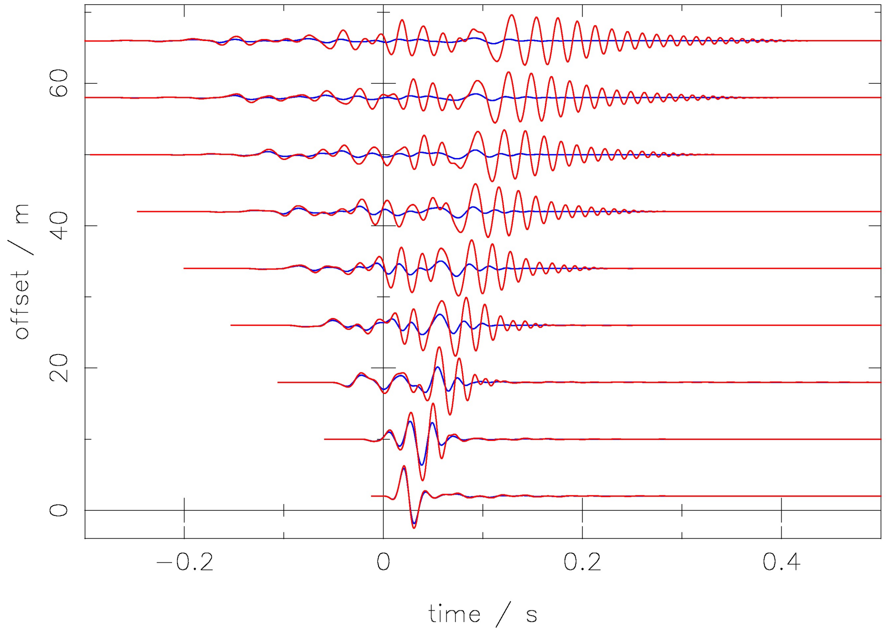
Elastic data

Viscolastic data (Q=20)

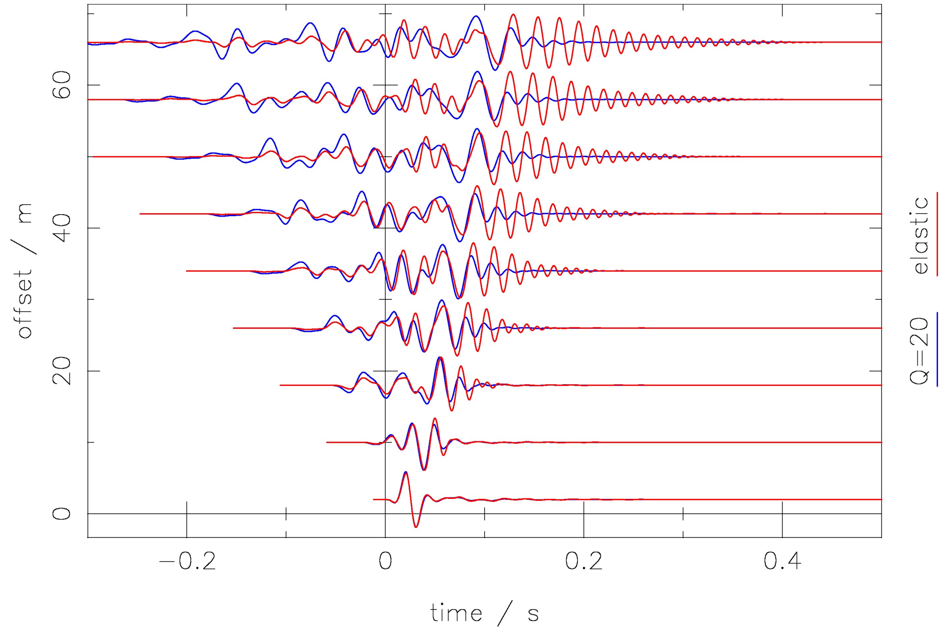
Challenge II: Attenuation

1. **Amplitude decay with distance→ misfit definition**
2. Loss of high frequencies with distance
3. Dispersion

raw seismograms



Misfit definition using normalized seismograms



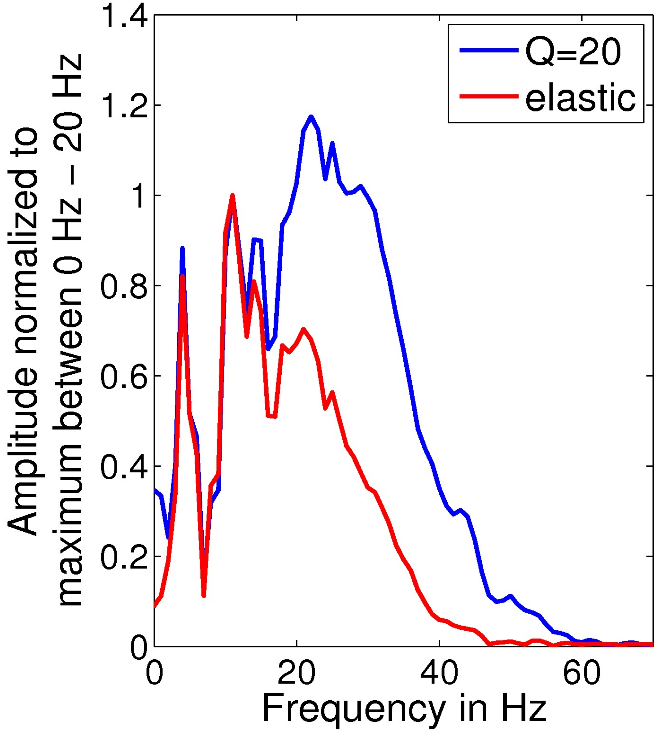
Elastic data

Viscolastic data (Q=20)

Challenge II: Attenuation

1. Amplitude decay with distance
2. **Loss of high frequencies with distance → source signal inversion**

Amplitude spectra of source time functions



Stabilized deconvolution in the frequency domain

The source wavelet correction filter acts as a low-pass-filter

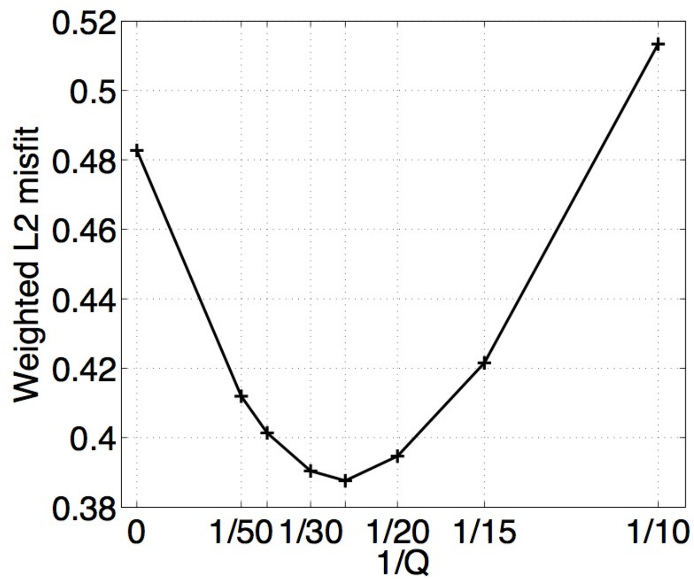
(Groos et al., 2014)

Challenge II: Attenuation

1. Amplitude decay with distance
2. **Loss of high frequencies with distance**
3. **Dispersion**

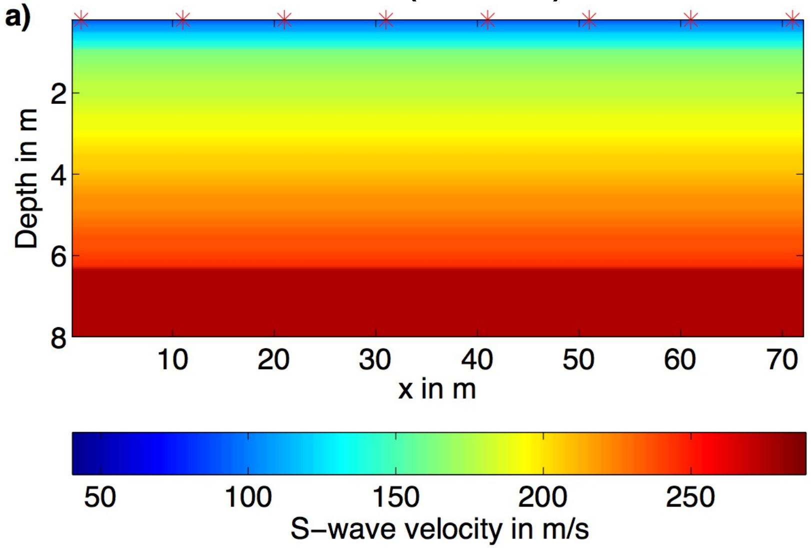
} **Viscoelastic forward modelling**

A priori Q-estimation

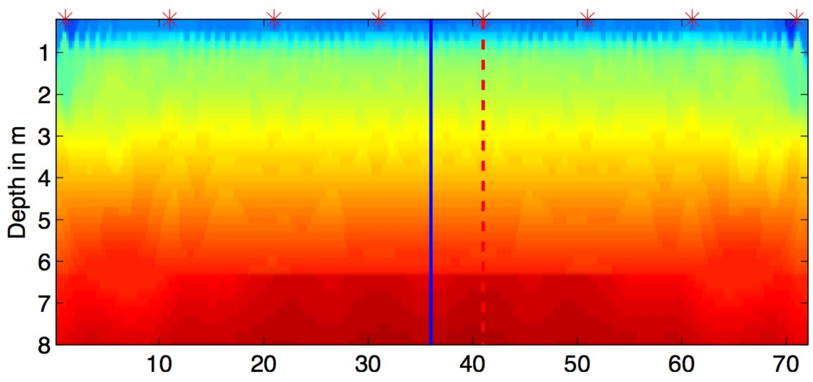


Synthetic reconstruction tests are successful

True modell (Q=20)



Inverted modell



Pre-processing

1. Geometrical spreading correction by single-trace transformation

1. Q-estimation

During the elastic FWI

1. Use L2-misfit of normailzed seismograms

2. Source wavelet inversion

3. Viscoelastic forward modelling

(Groos et al., 2014)

Outline

1 Introduction

2 Methodology

- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

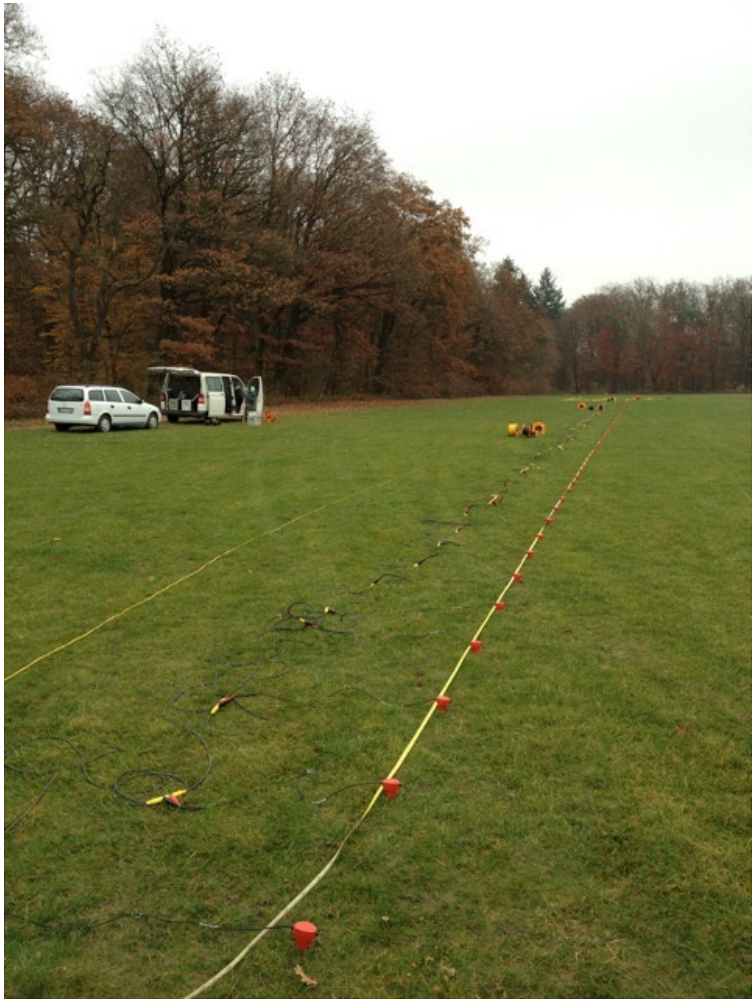
- **Layered subsurface**
- 2-D local trench
- Fault Zone

4 Towards 3D viscoelastic FWI of 3D 9-C field data

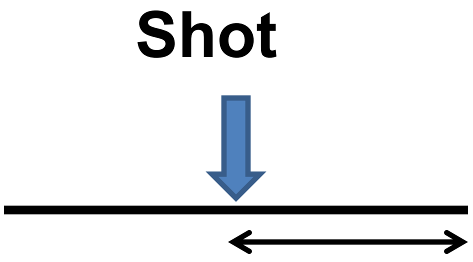
5 Summary

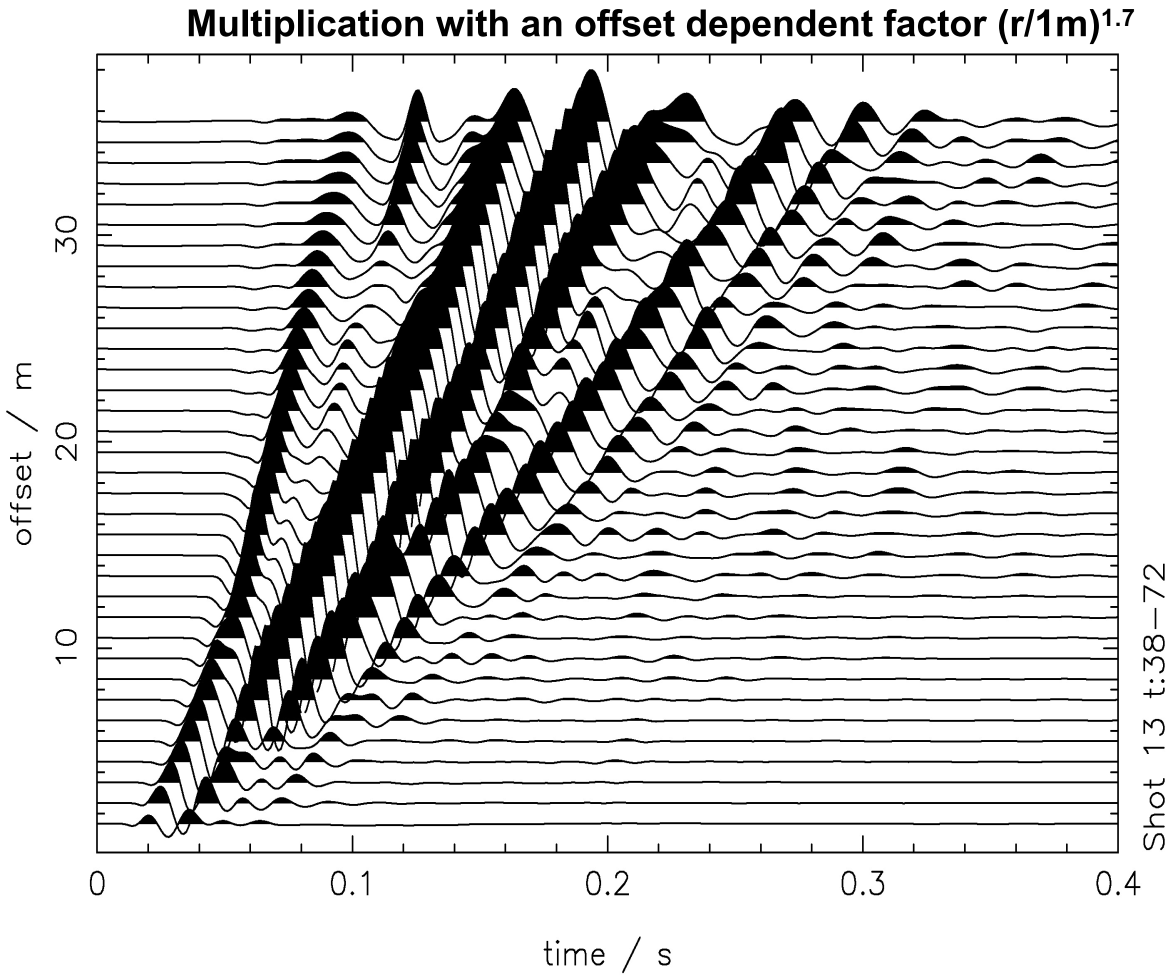
Field data: 1-D case

- Glider airfield near Karlsruhe (Germany)
- Acquisition
  - linear profile
  - vertical geophones every 1m
  - hammer blows every 2m

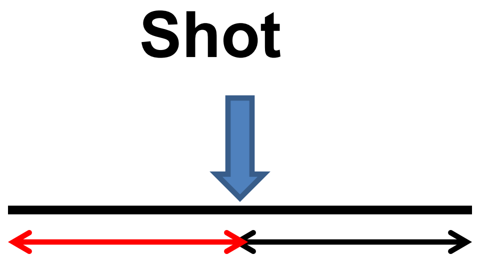


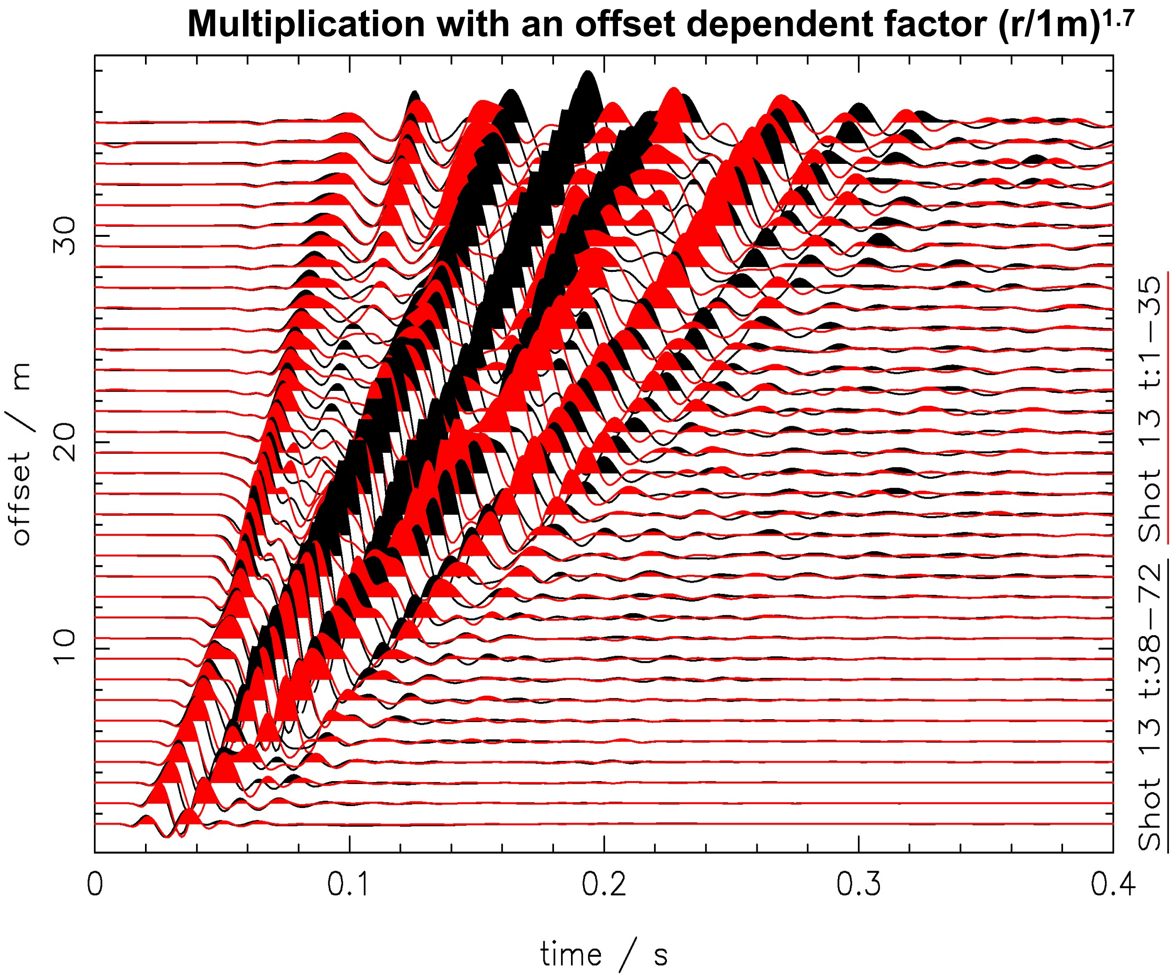
1-D case: Field data





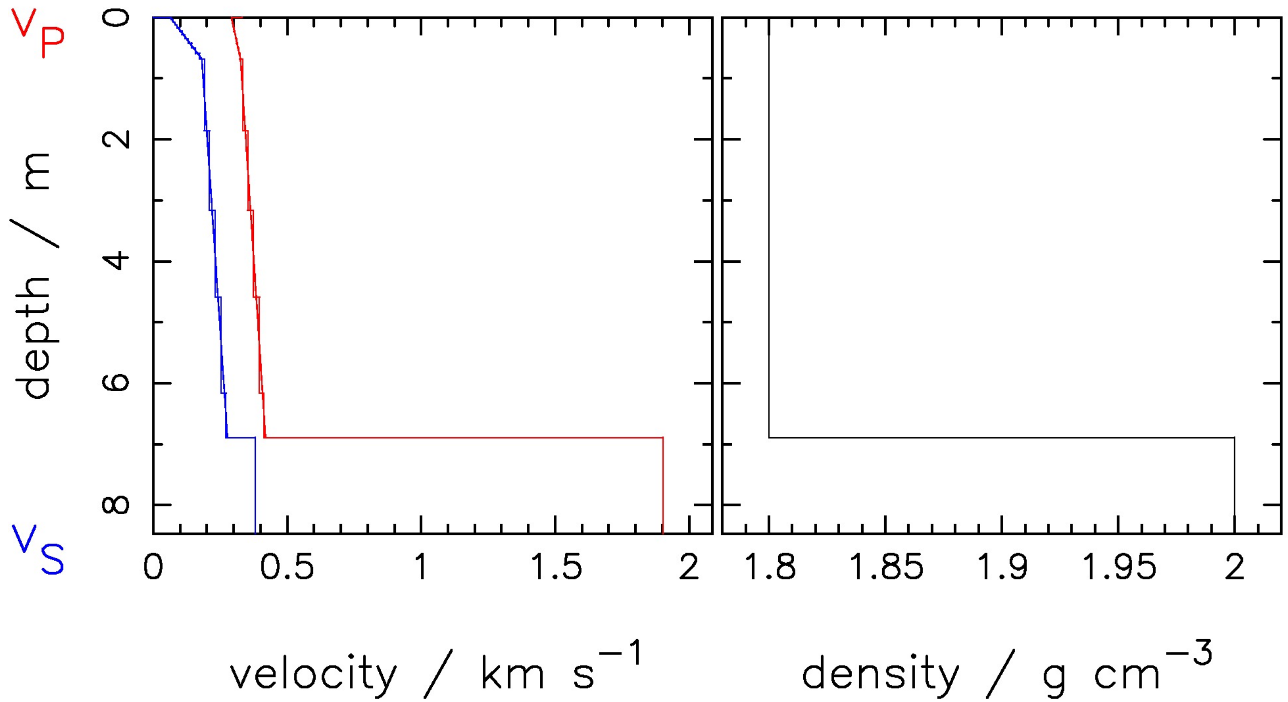
1-D case: Field data





Initial 1D-model

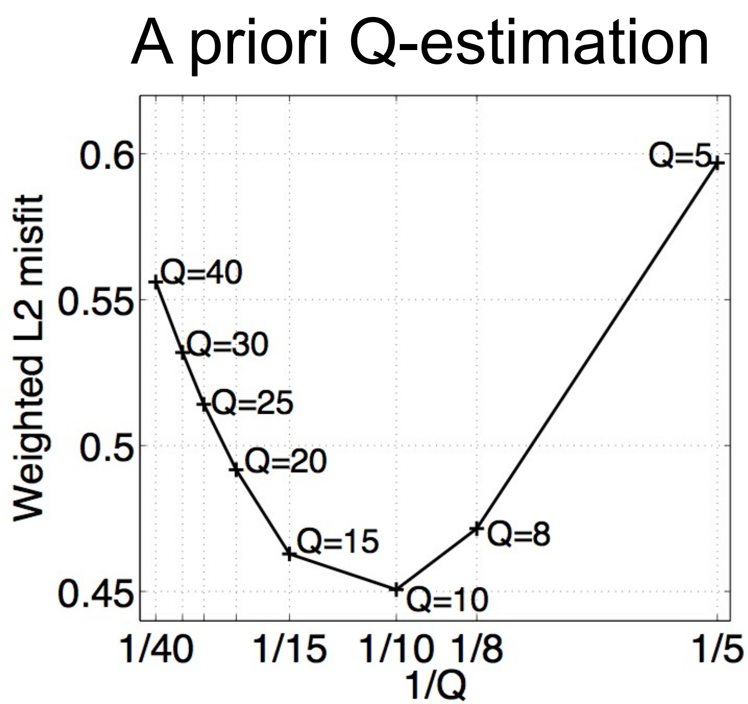
- derived by an inversion of first arrival travel times (v_p) and Fourier-Bessel expansion coefficients (v_s)
  - fluviatile sediments (gravel and sand)
  - ground water table in 6.9 m depth



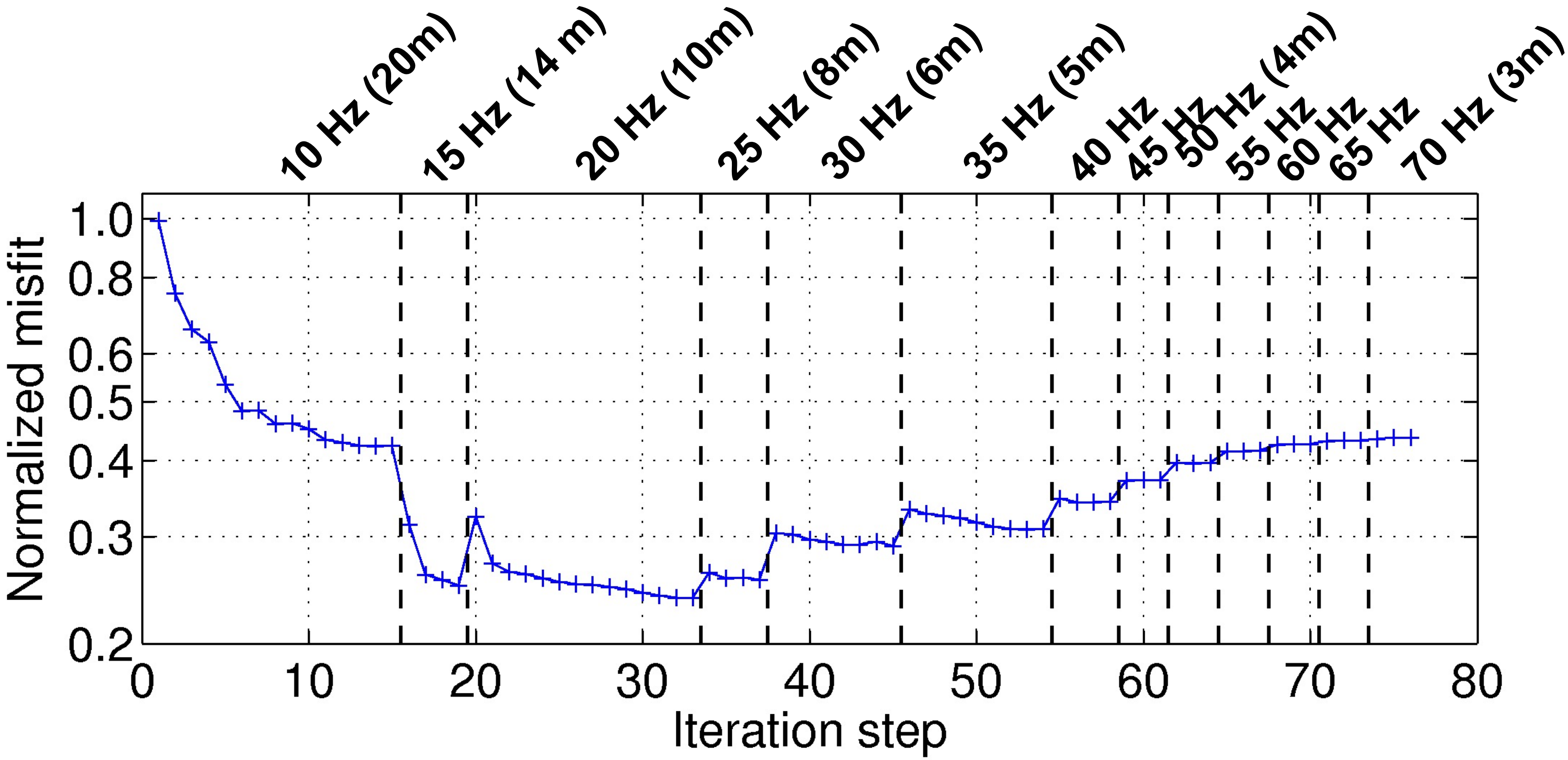
(Groos, 2013; Groos et al., 2017)

1-D case: Preprocessing

1. 2D/3D geometrical spreading correction
2. Estimation of quality factor: Q_s=Q_p=15



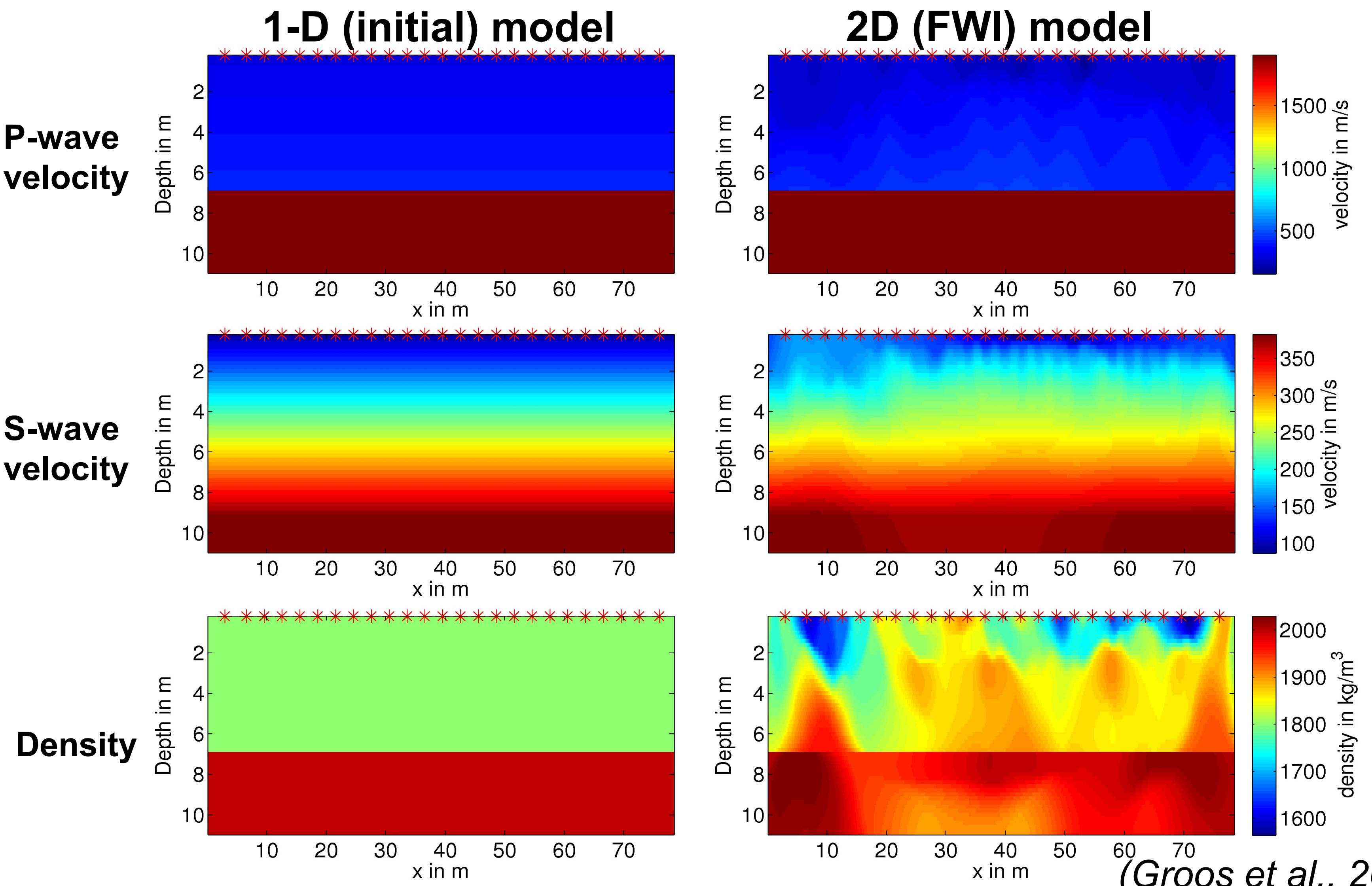
1-D case: Evolution of data misfit



Total computation time: 9 h on 16 CPUs

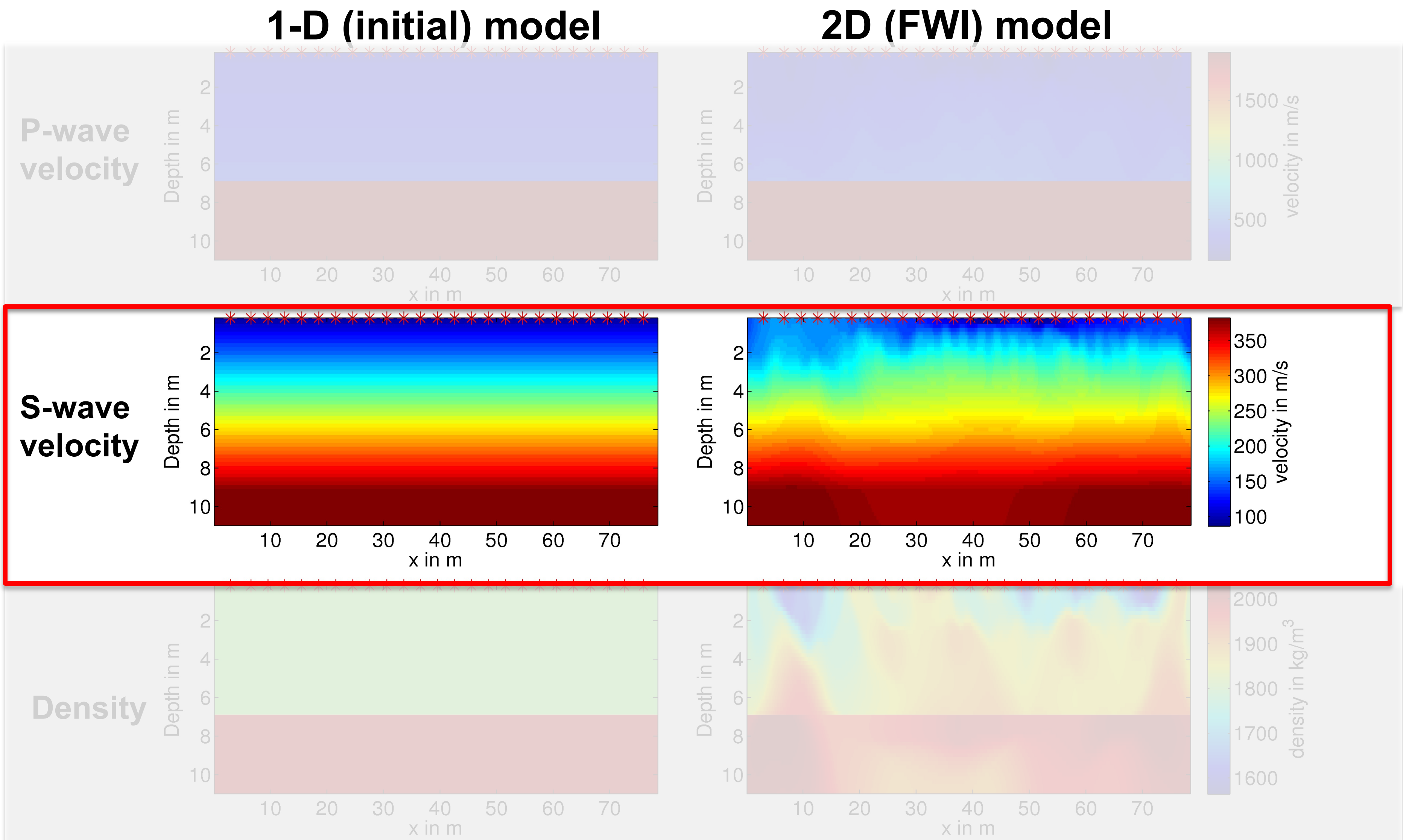
(Groos, 2013)

1-D case: inversion result



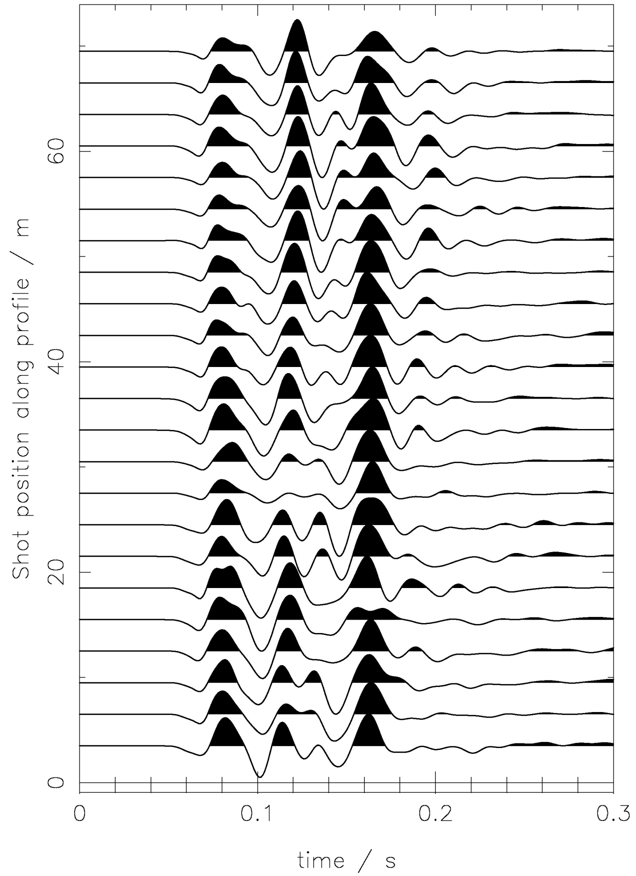
(Groos et al., 2017)

1-D case: inversion result



1-D case: common offset gather (20.5 m)

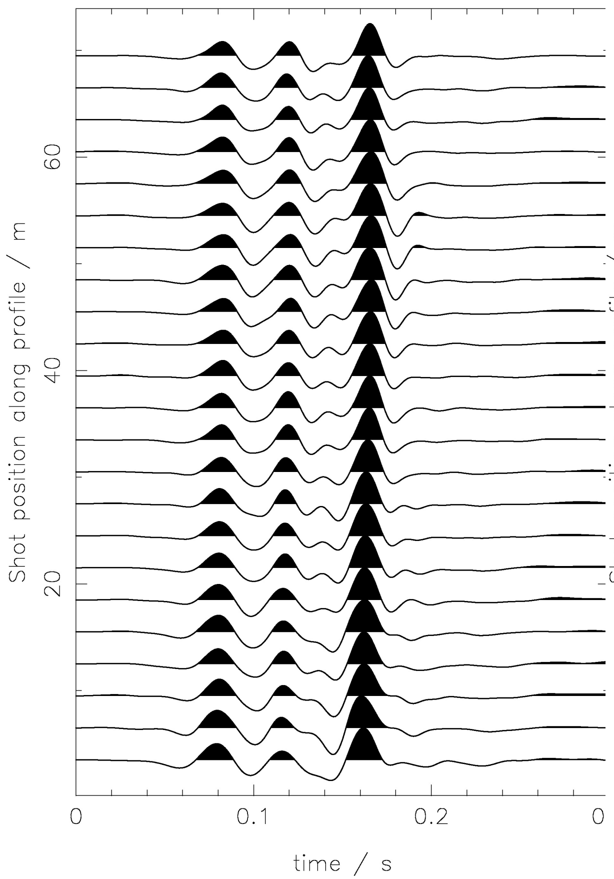
Field data



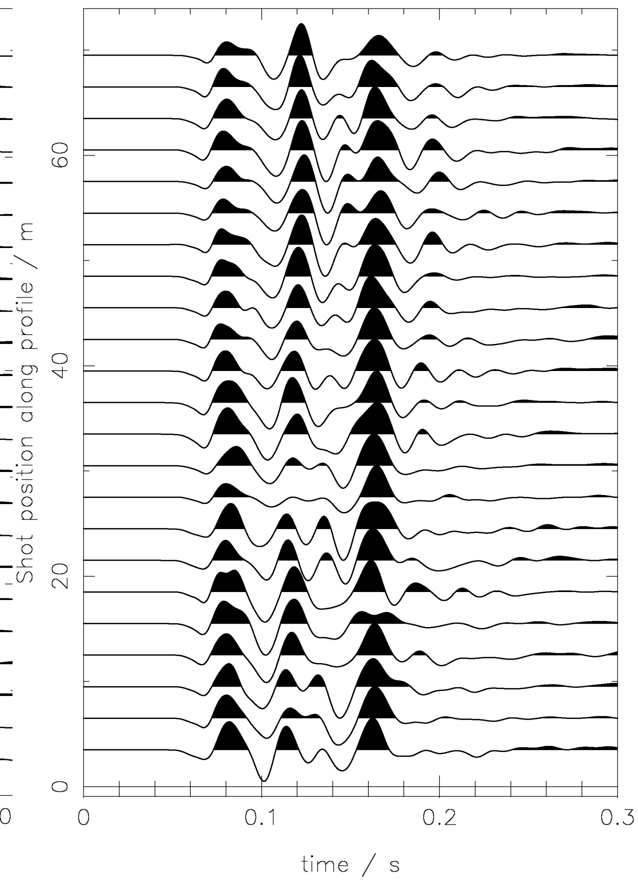
(Groos et al., 2017)

1-D case: common offset gather (20.5 m)

1D (initial) model

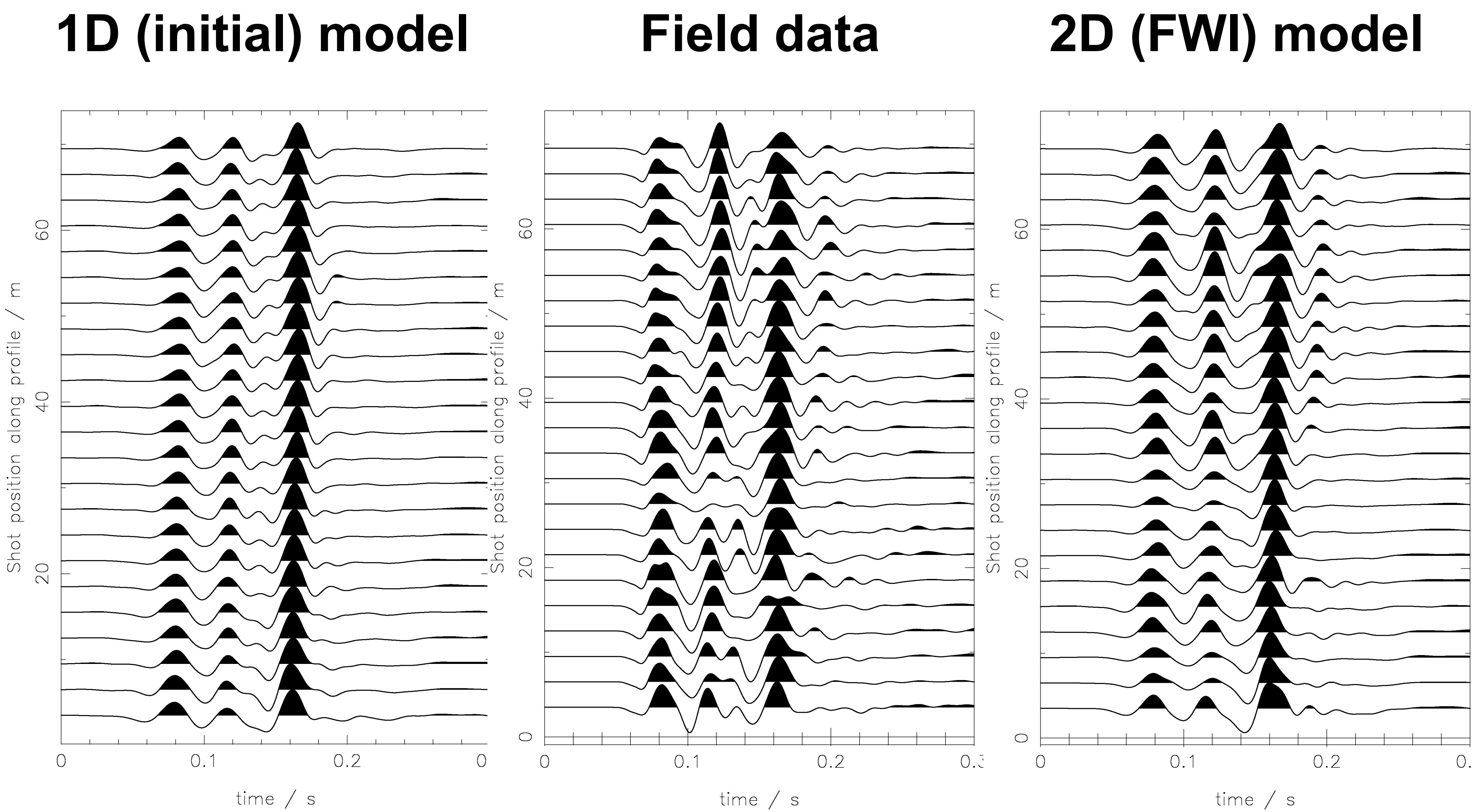


Field data



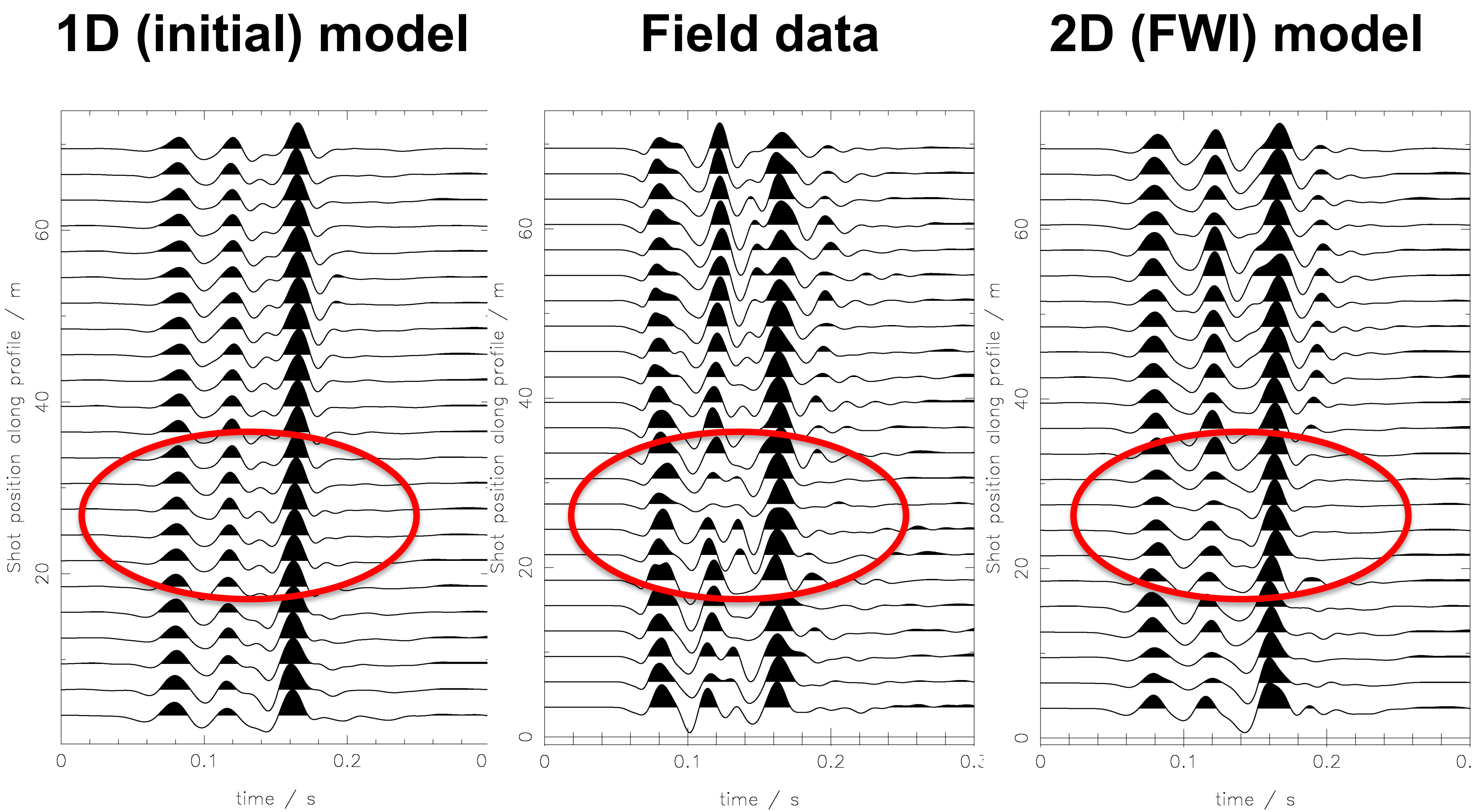
(Groos et al., 2017)

1-D case: common offset gather (20.5 m)



(Groos et al., 2017)

1-D case: common offset gather (20.5 m)



2-D FWI model explains lateral variations

Outline

1 Introduction

2 Methodology

- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

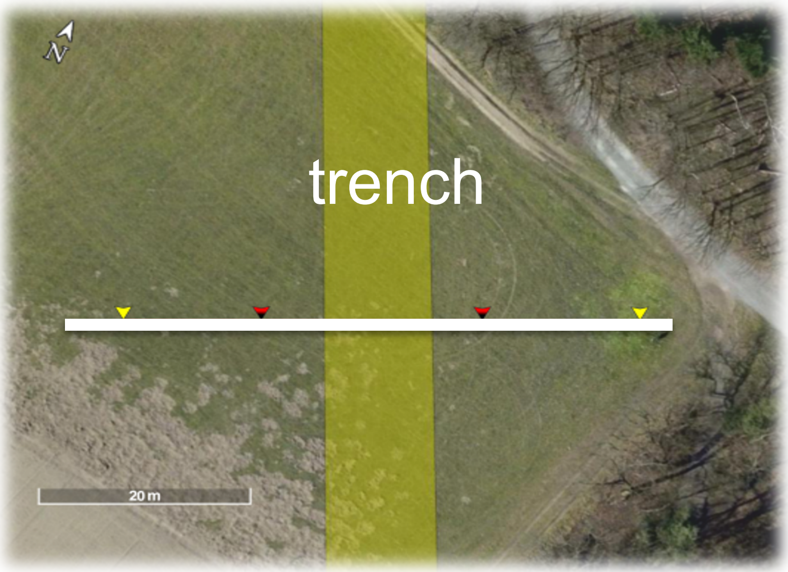
- Layered subsurface
- **2-D local trench**
- Fault Zone

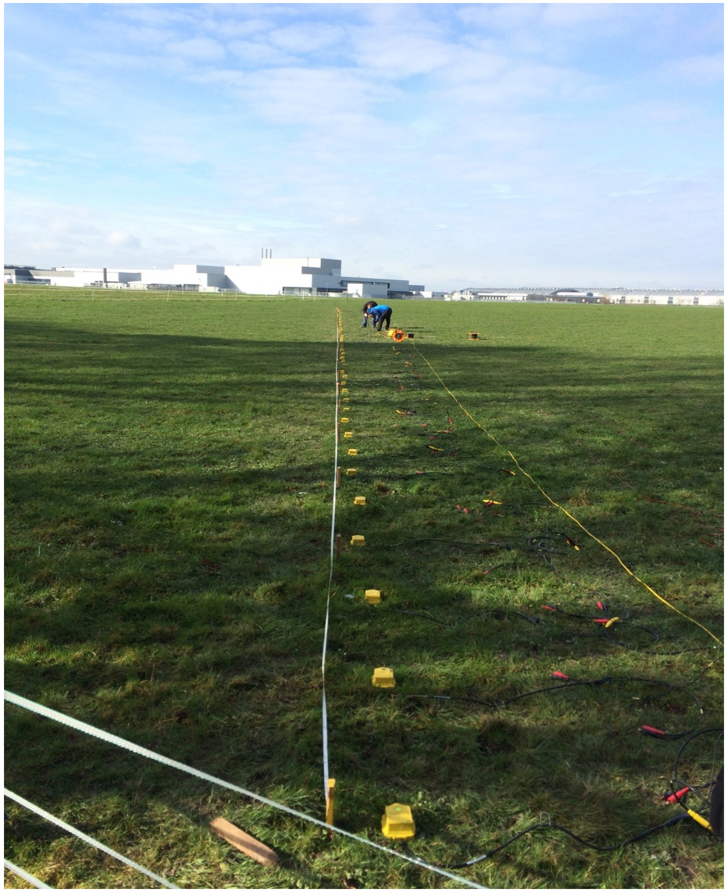
4 Towards 3D viscoelastic FWI of 3D 9-C field data

5 Summary

2. Example: Small-scale trench

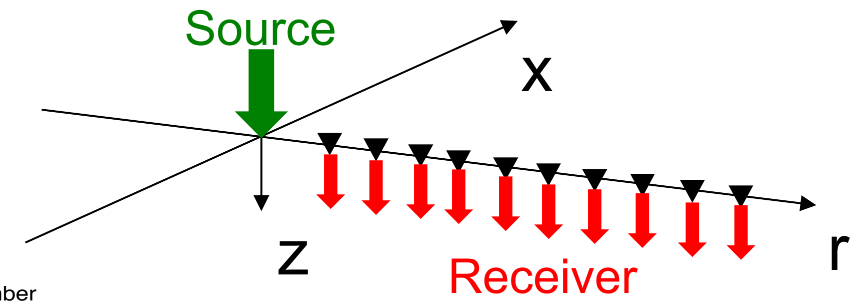
- Profile crosses known trench „Ettlinger Linie“ excavated in the 18th century



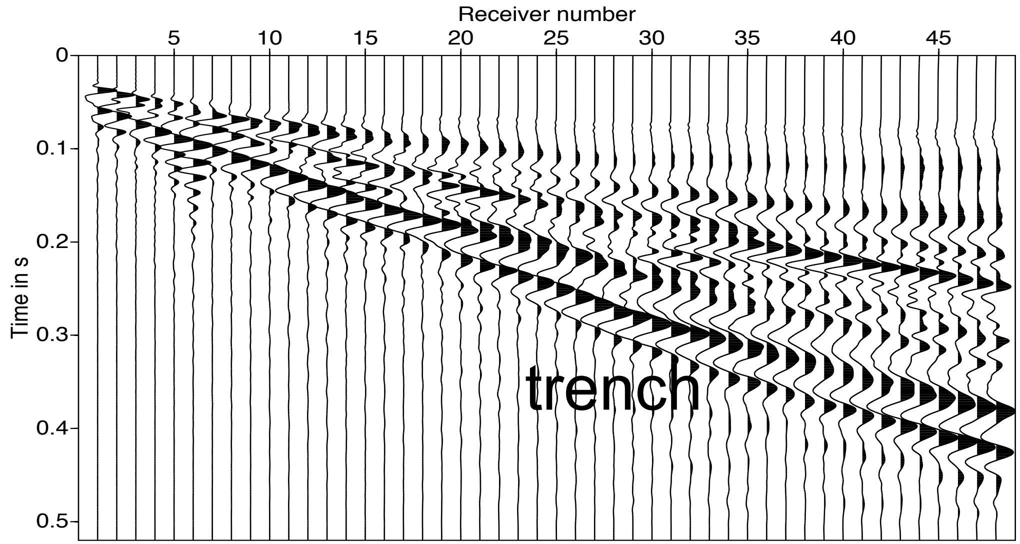


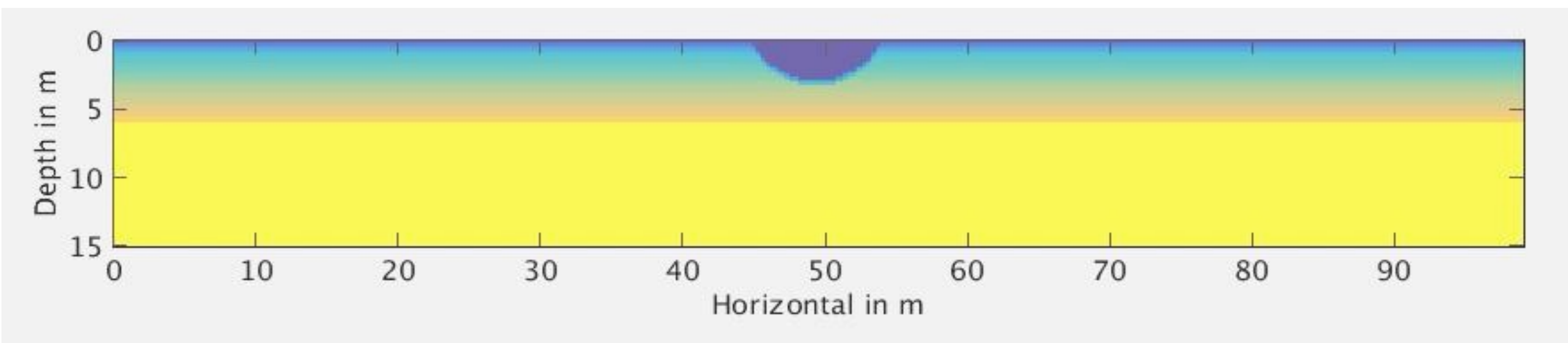
(Wittkamp & Bohlen, 2016)

Rayleigh waves



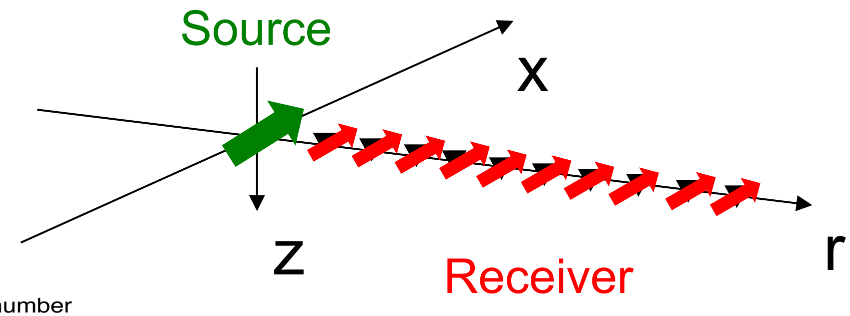
Rheinstetten field data



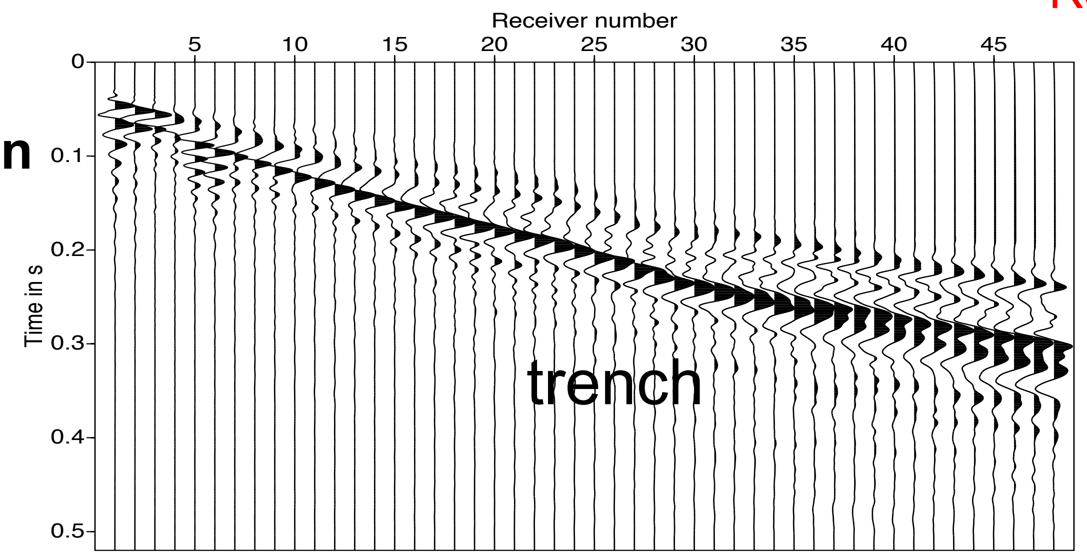


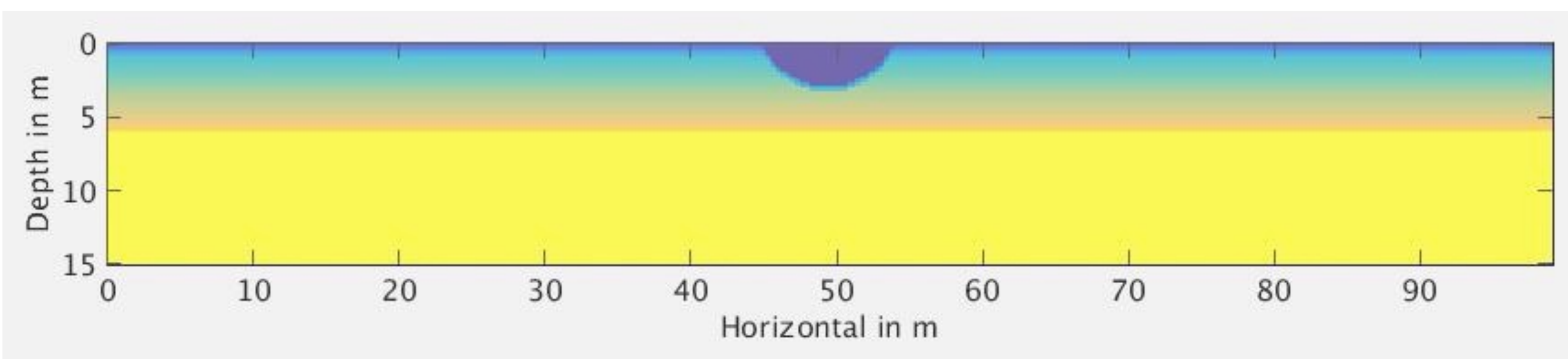
(Wittkamp & Bohlen, 2016)

Love waves



Rheinstetten field data





FWI configuration

- **Multi-stage approach:**
  - Gradually increasing frequency content: 4 Hz – 130 Hz
  - Parameter classes: **1.)** v_S & v_P, **2.)** v_S & v_P & ρ
- **Source time function estimation:**
  - Stabilized deconvolution (Pratt, 1999; Groos et al., 2014)
  - Offset range: 5 m – 10 m
- **Optimization:** L-BFGS and subsequently CG

FWI studies:

A) Individual Love wave FWI

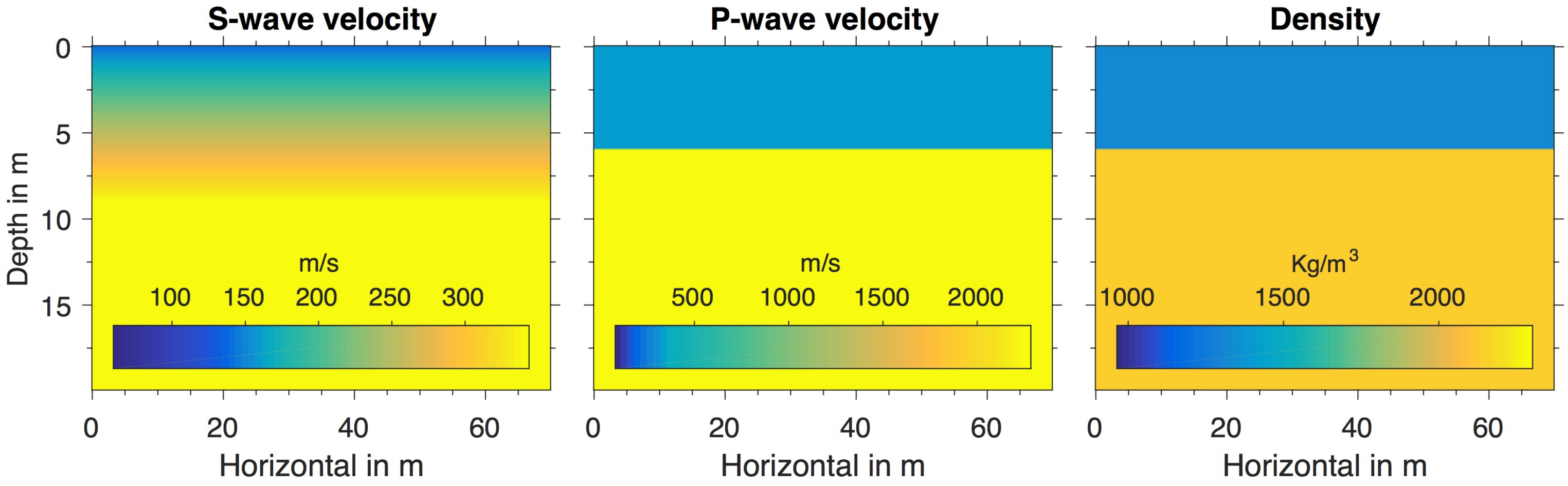
B) Individual Rayleigh wave FWI

C) Simultaneous joint FWI

(Wittkamp & Bohlen, 2016)

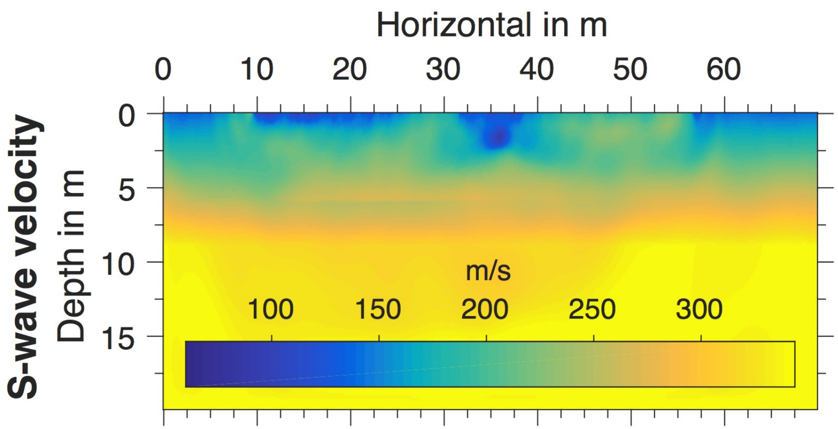
Initial model

- **S-wave velocity:** Educated guess by dispersion spectra
- **P-wave velocity:** P-wave travel time analysis
- **Density:** Gardner's relation from the P-wave velocity
- **Attenuation:** $Q = 15$ by grid-search

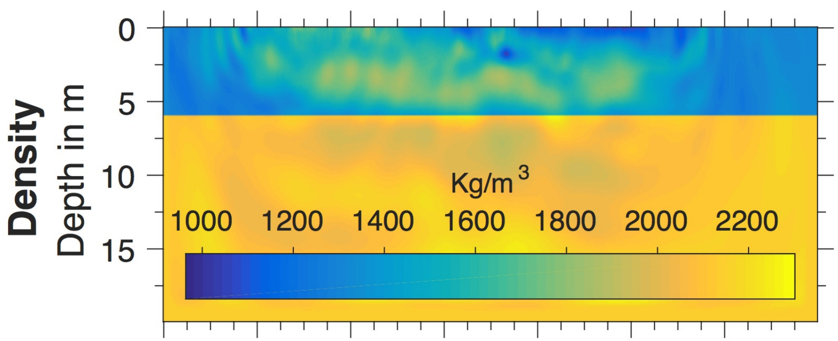


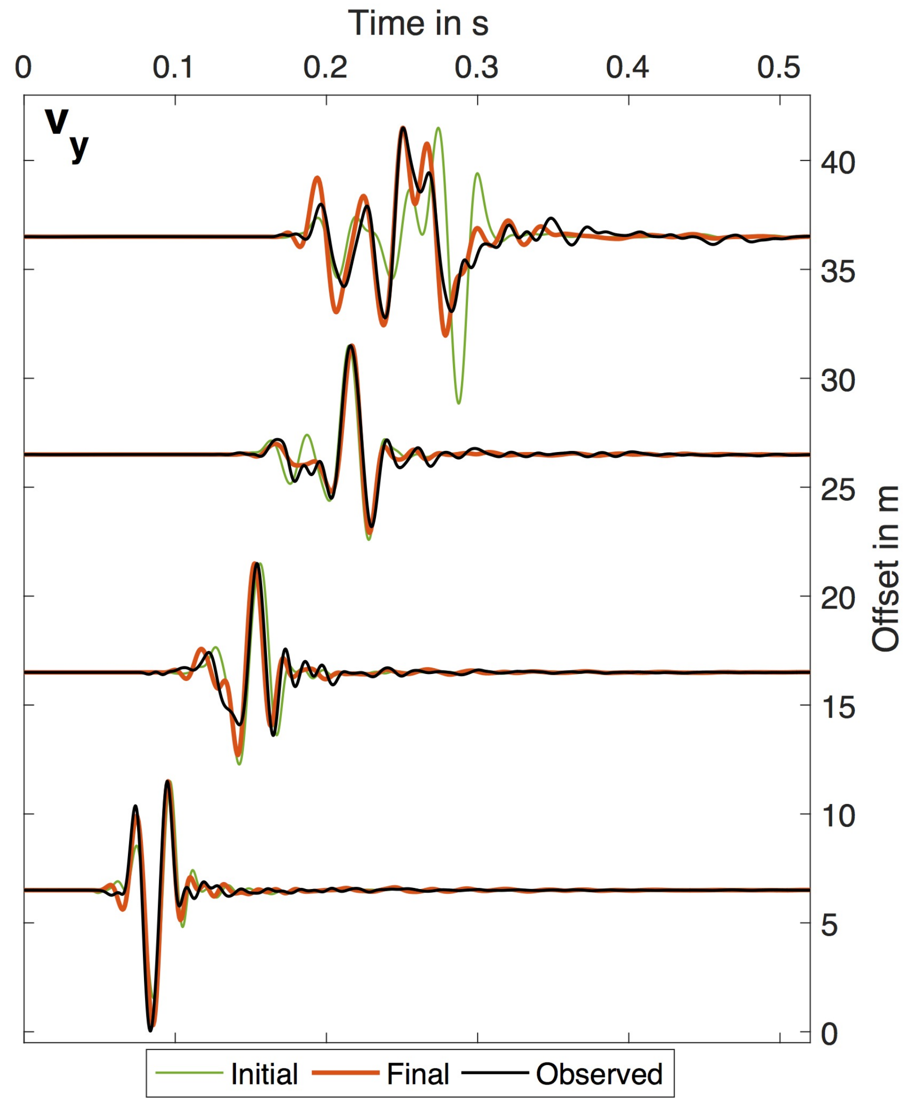
$\Longrightarrow$ Predicts all main phases of the recorded wave field *(Wittkamp & Bohlen, 2016)*

FWI of Love waves

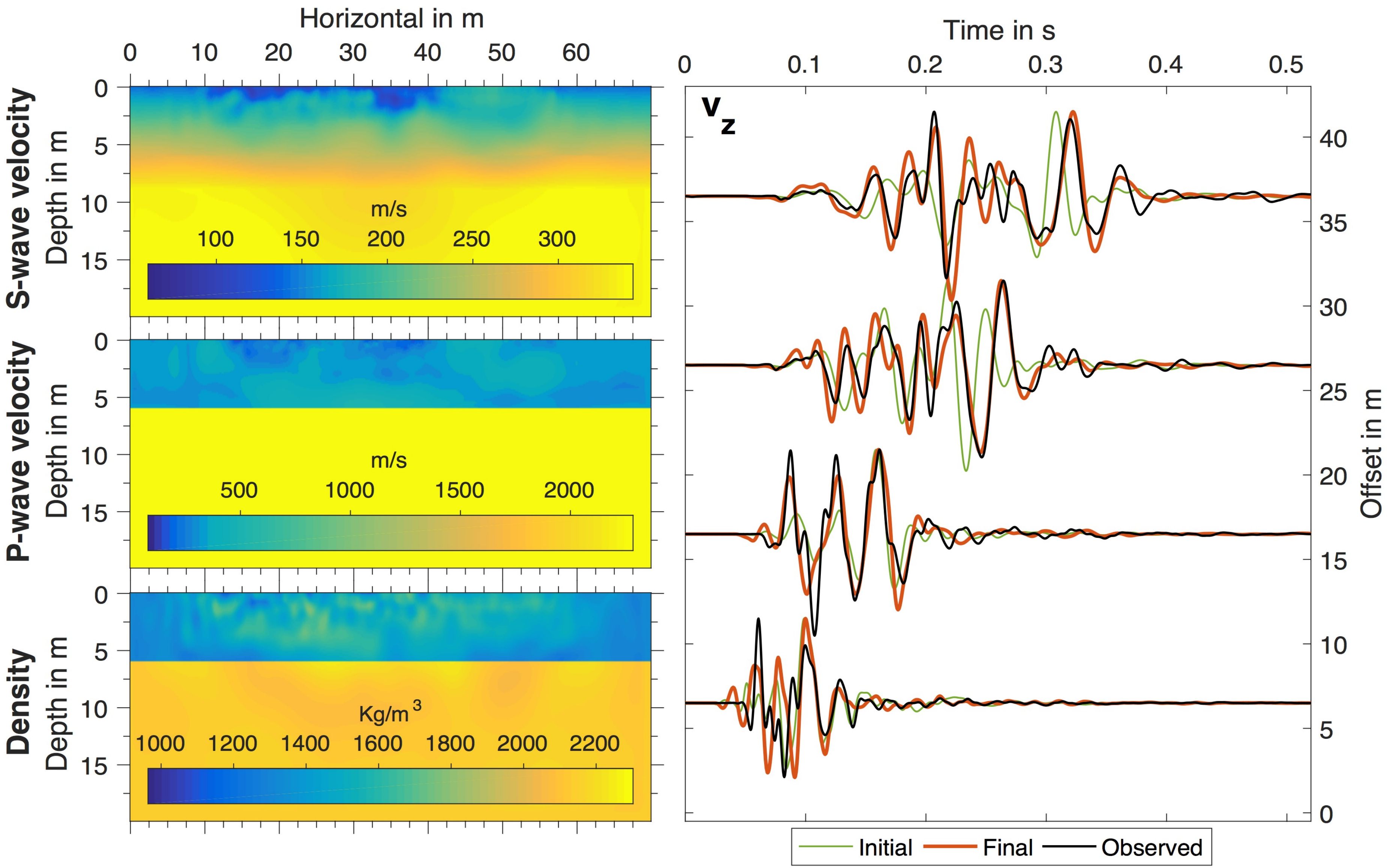


No update of the P-wave velocity by a SH-wave FWI

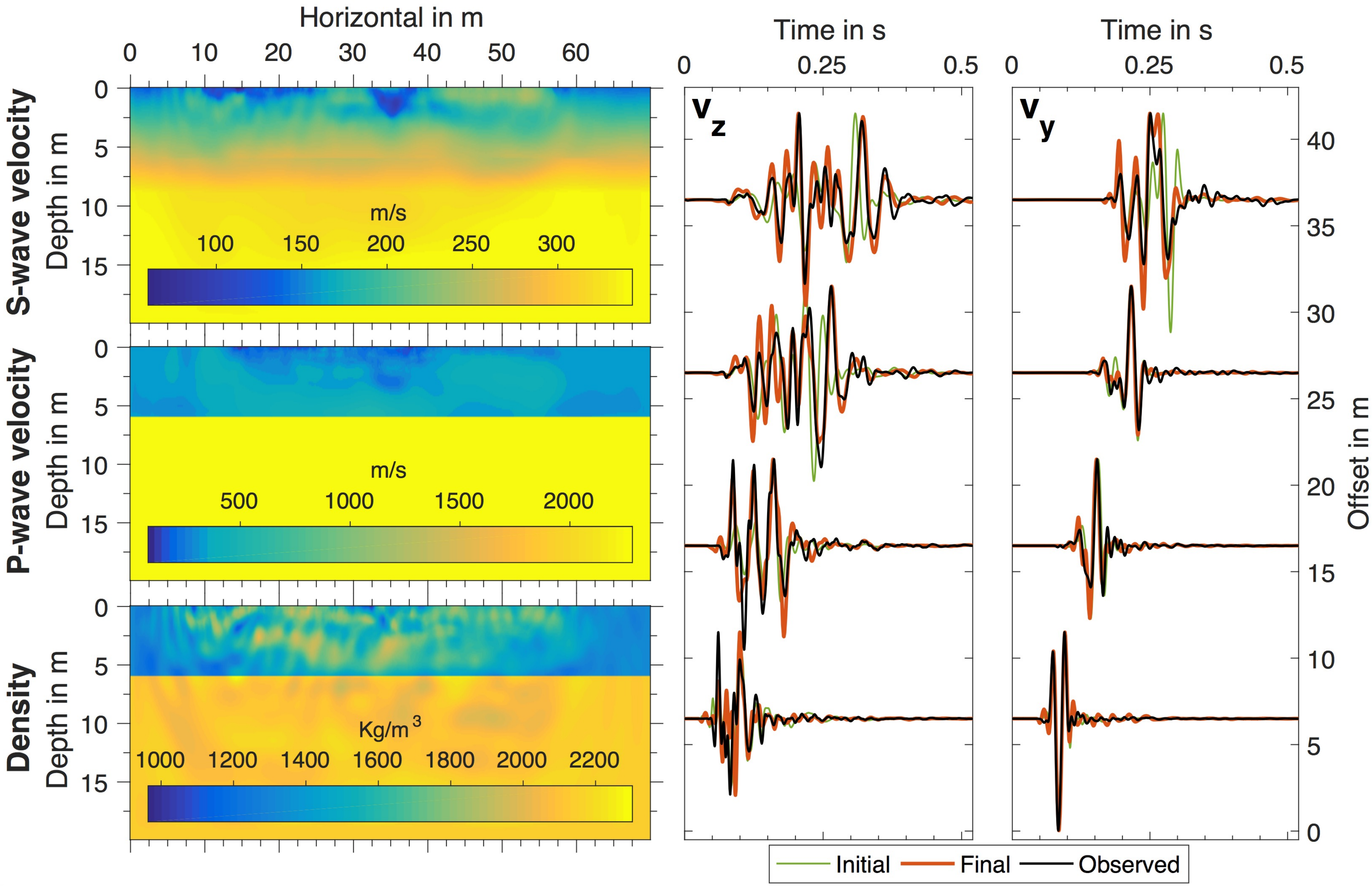




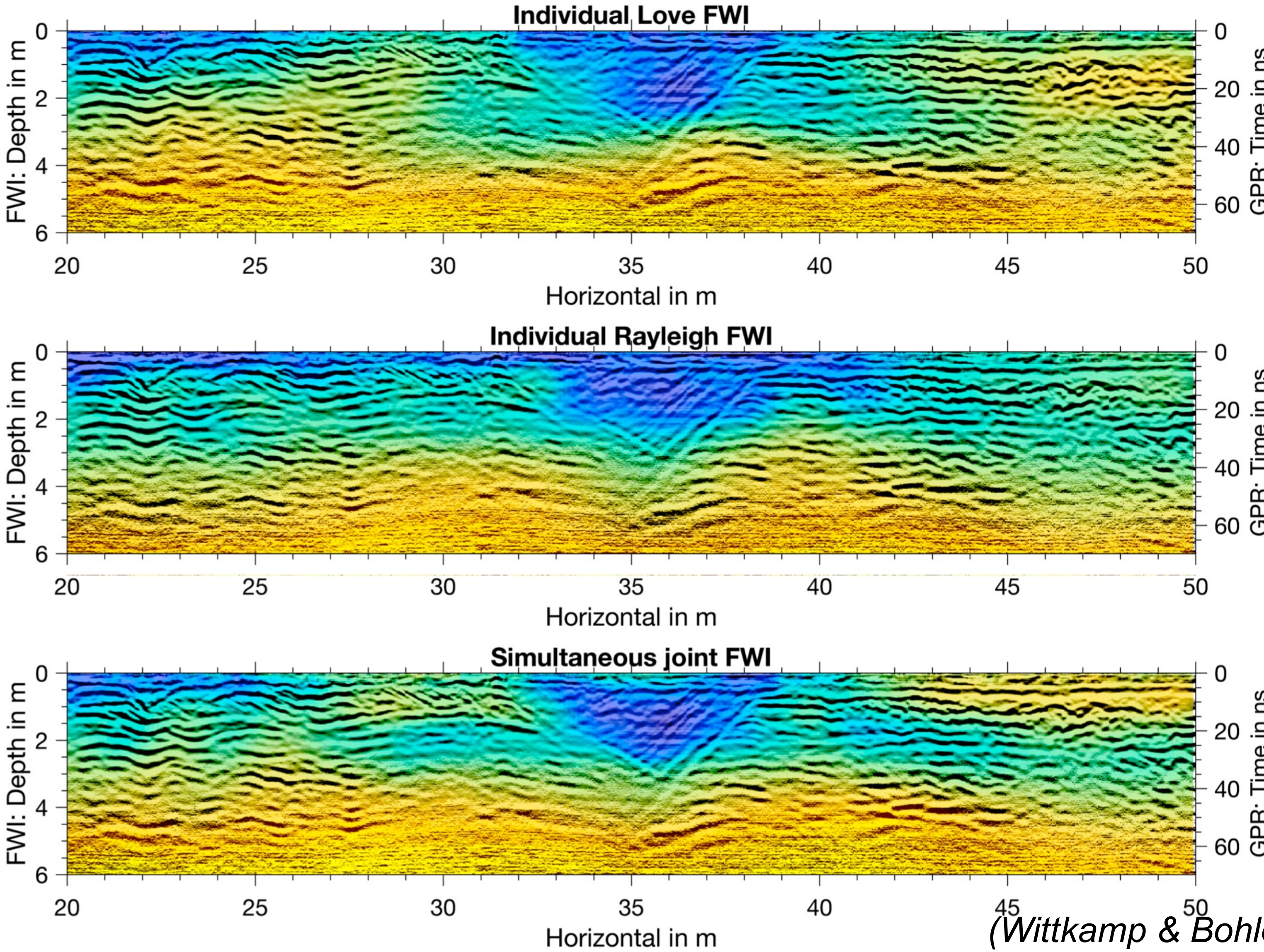
FWI of Rayleigh waves



Joint FWI of Rayleigh and Love waves



Comparison of S-wave velocity models



(Wittkamp & Bohlen, 2016)

Outline

1 Introduction

2 Methodology

- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

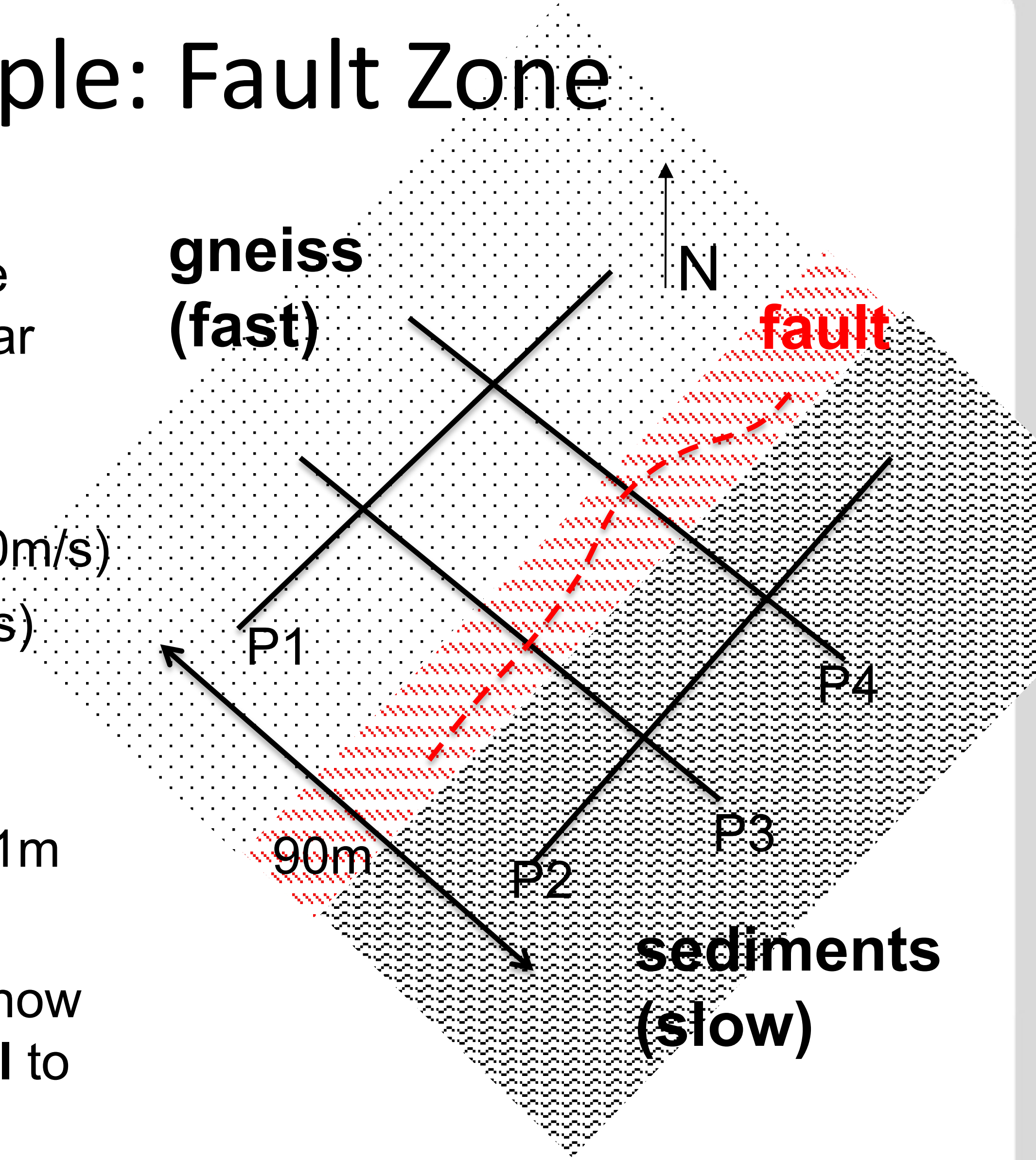
- Layered subsurface
- 2-D local trench
- **Fault Zone**

4 Towards 3D viscoelastic FWI of 3D 9-C field data

5 Summary

3. Example: Fault Zone

- 2D structure across fault at the southern rim of the Taunus near Frankfurt (Main), Germany
- NW: sericite-gneiss (fast > 300m/s)
- SE: sediments (slow < 300 m/s)
- 4 linear profiles
  - Vertical geophones every 1m
  - Hammer blows every 4m
- Geophysical measurements show small lateral variations **parallel** to the fault



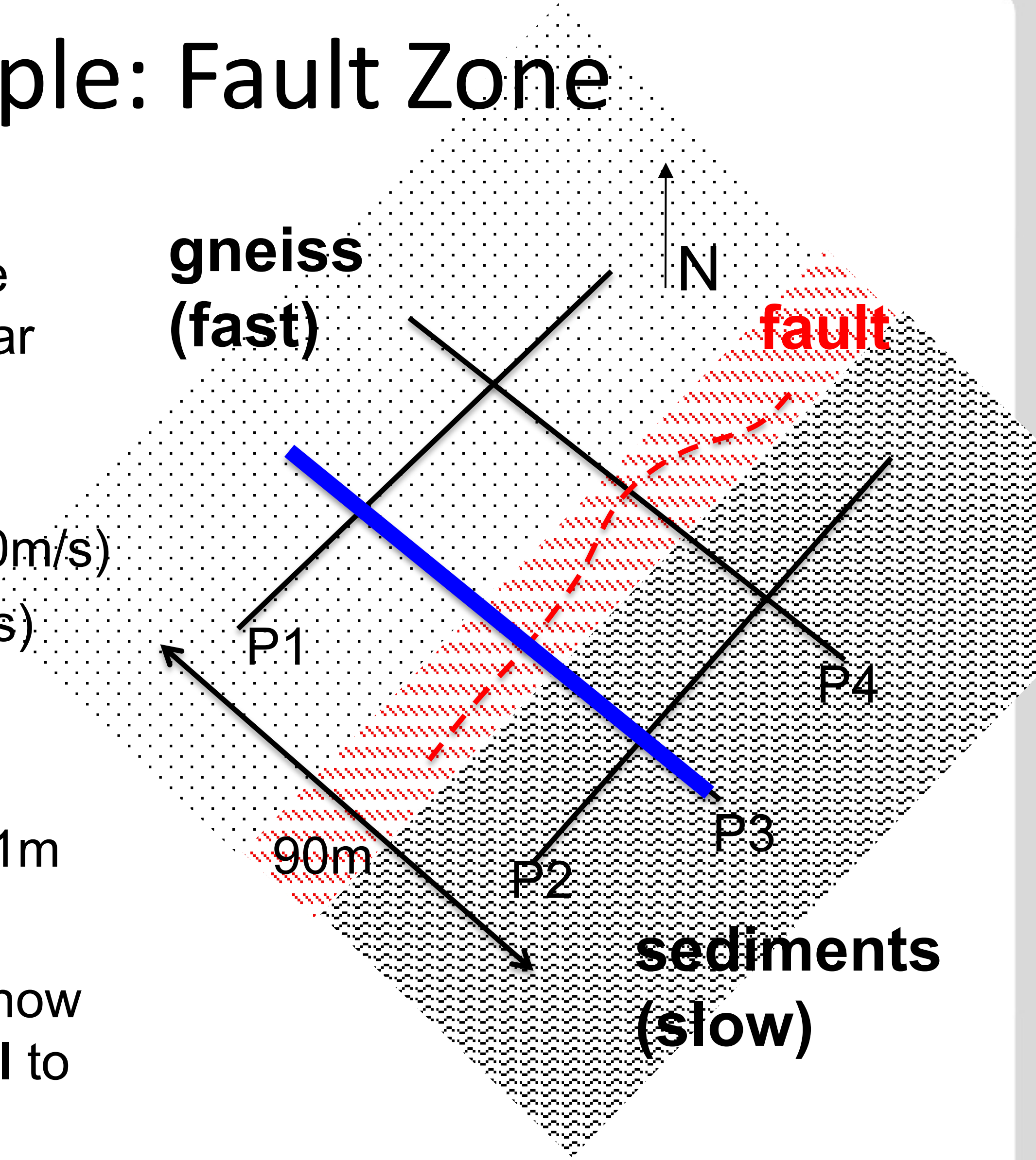
(Schäfer, 2014)

3. Example: Fault Zone

- 2D structure across fault at the southern rim of the Taunus near Frankfurt (Main), Germany

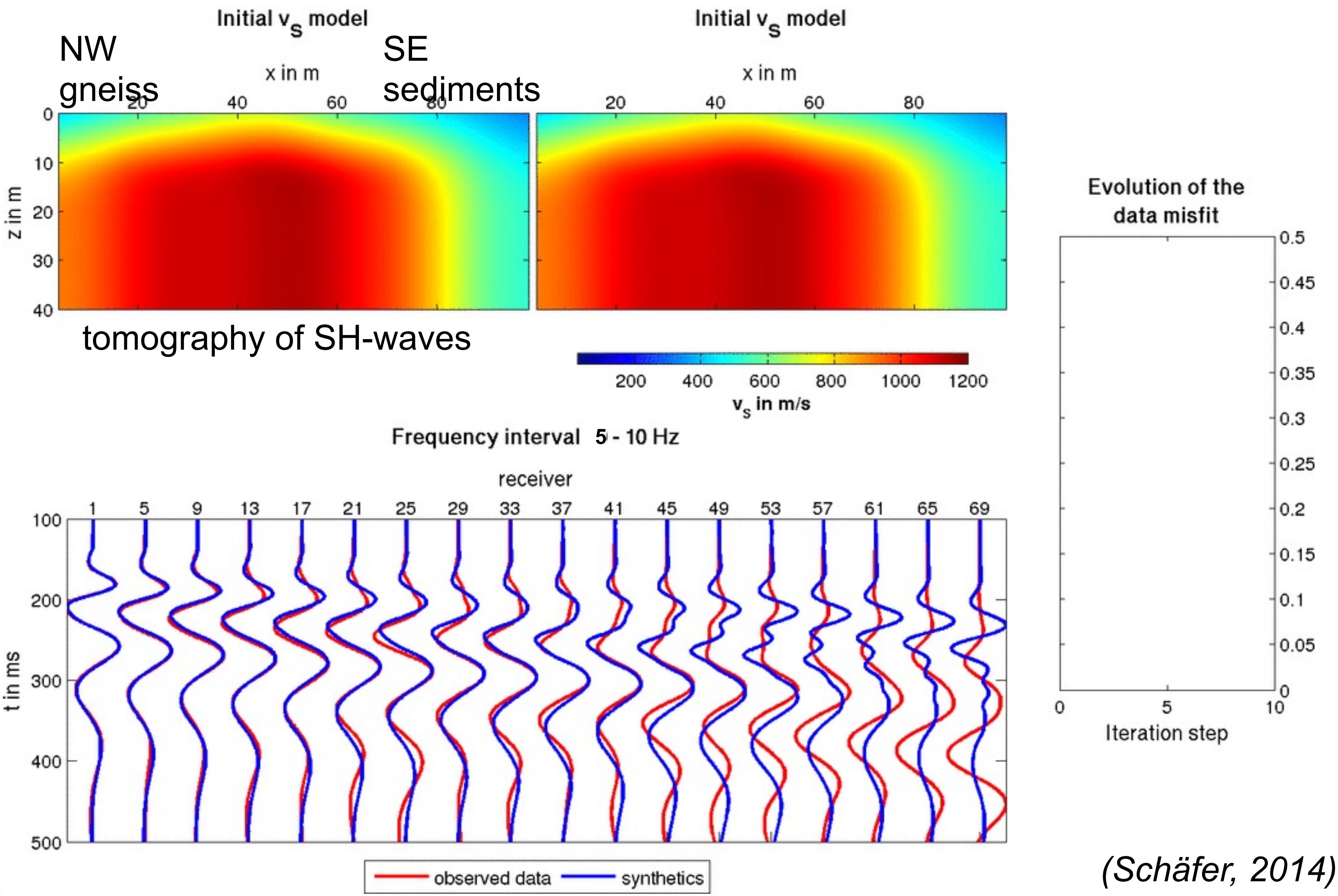
- NW: sericite-gneiss (fast > 300m/s)
- SE: sediments (slow < 300 m/s)

- 4 linear profiles
  - Vertical geophones every 1m
  - Hammer blows every 4m
- Geophysical measurements show small lateral variations **parallel** to the fault

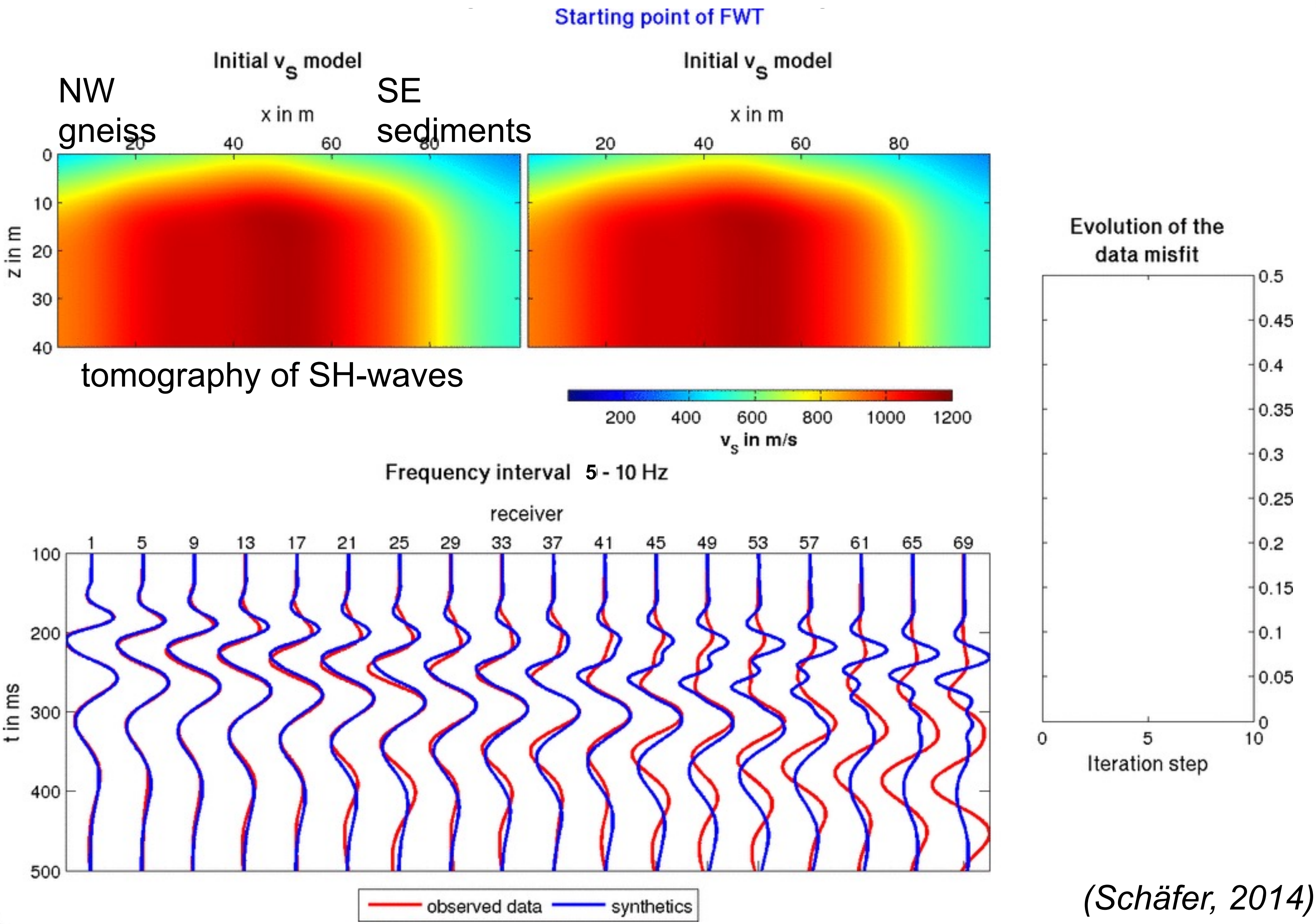


(Schäfer, 2014)

Starting point of FWT

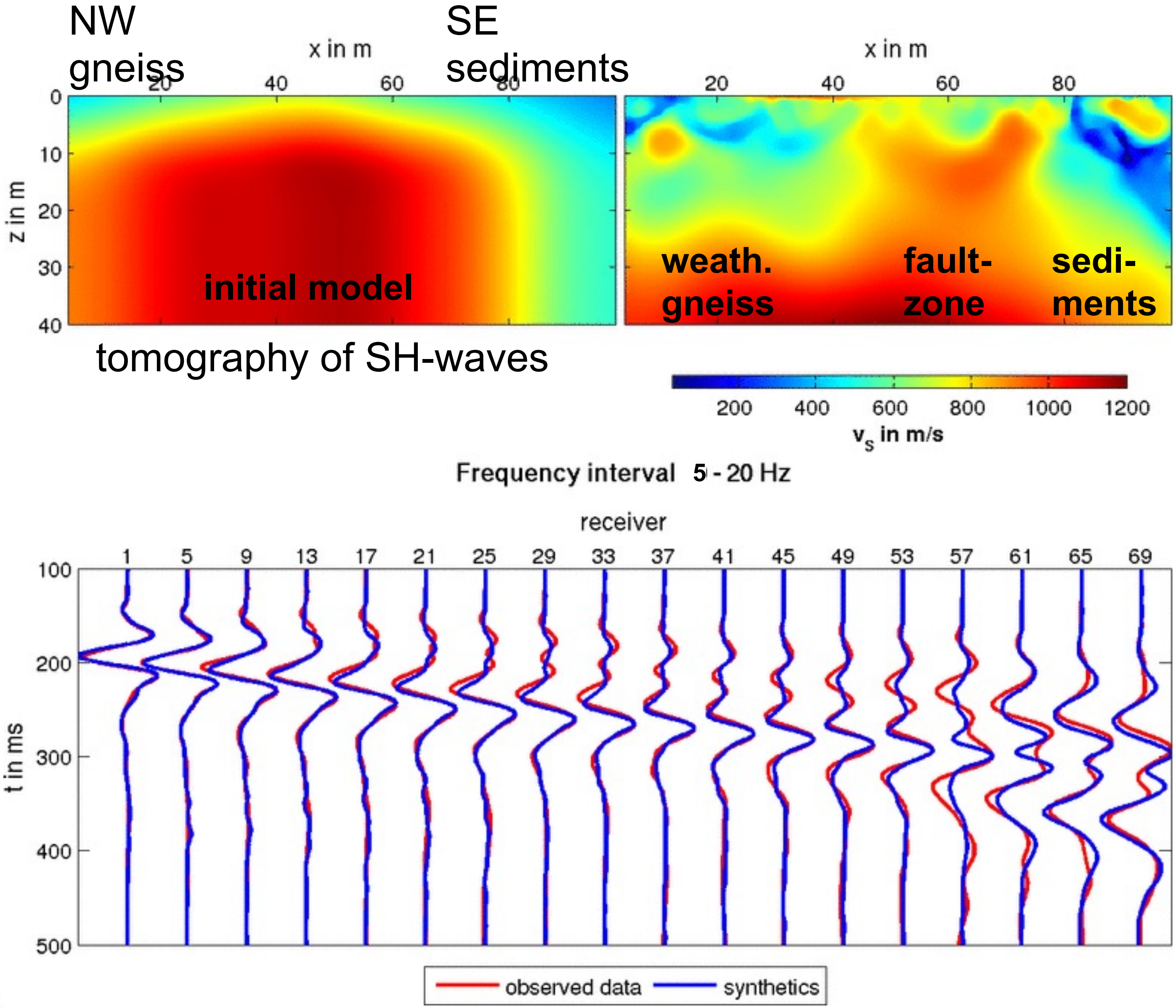


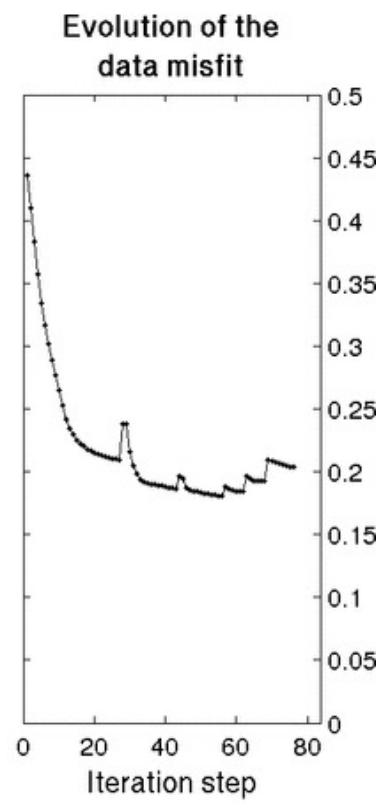
(Schäfer, 2014)



(Schäfer, 2014)

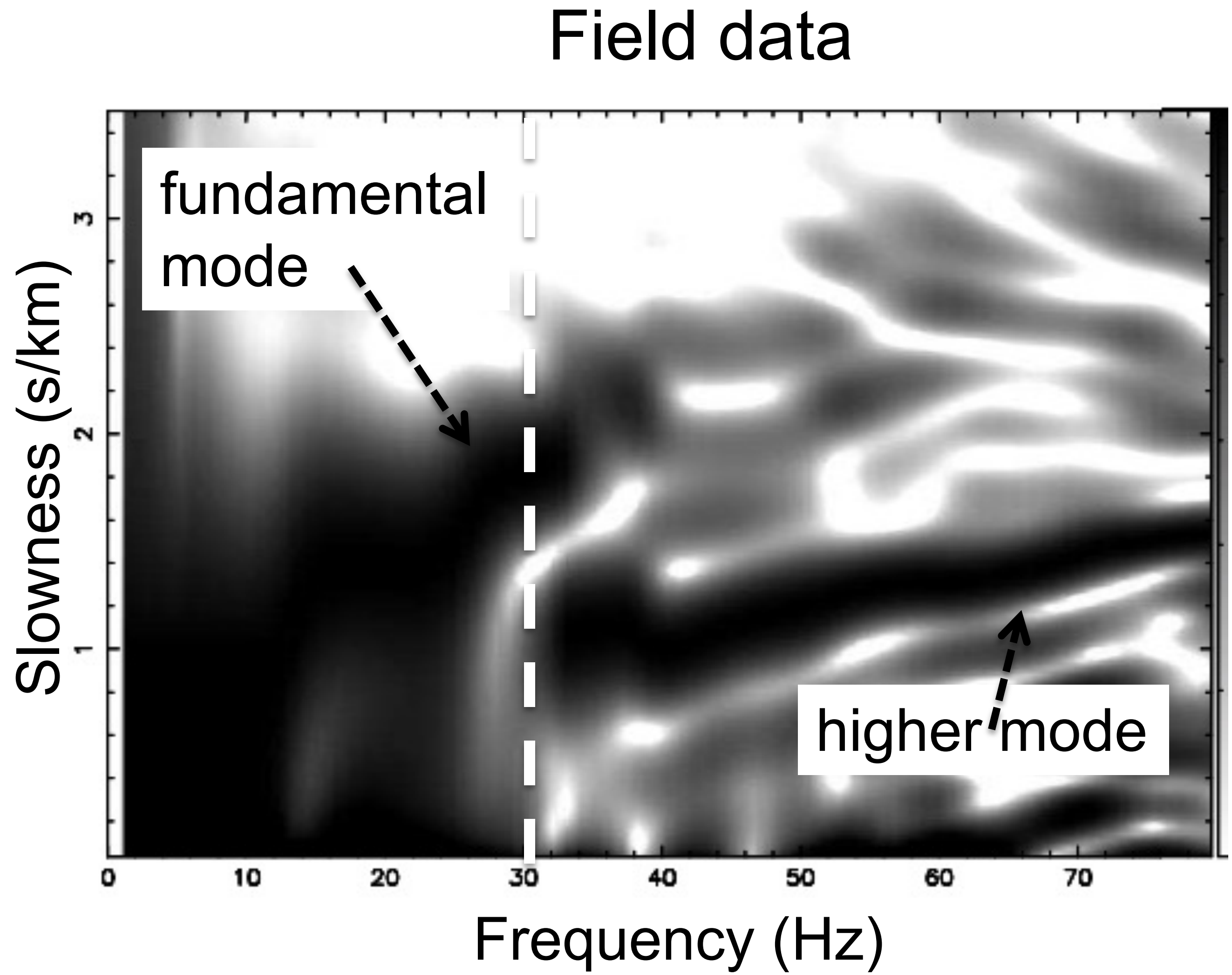
FWI Result <20 Hz



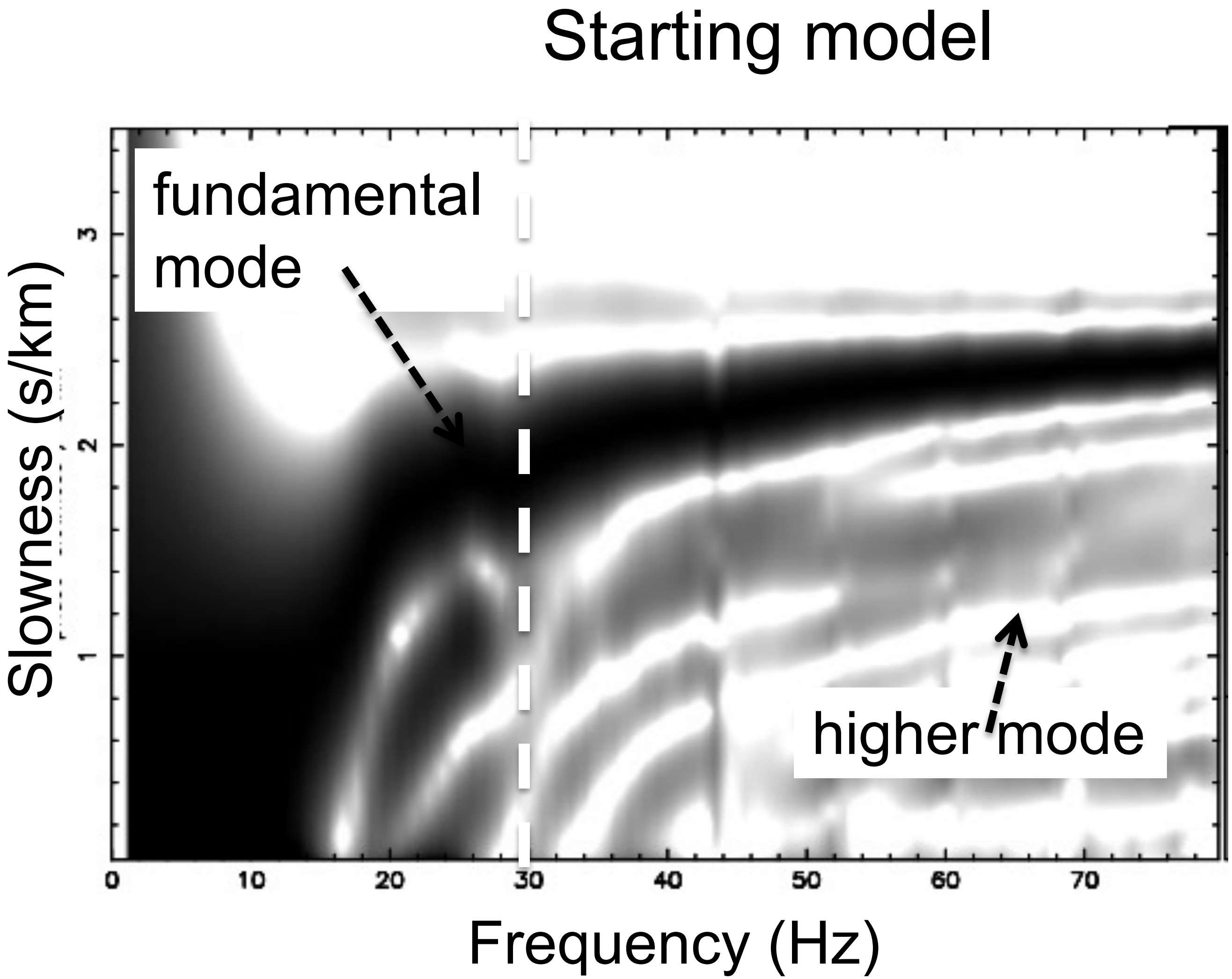


(Schäfer, 2014)

Slowness-frequeny spectra



Slowness-frequeny spectrum



Outline

1 Introduction

2 Methodology

- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

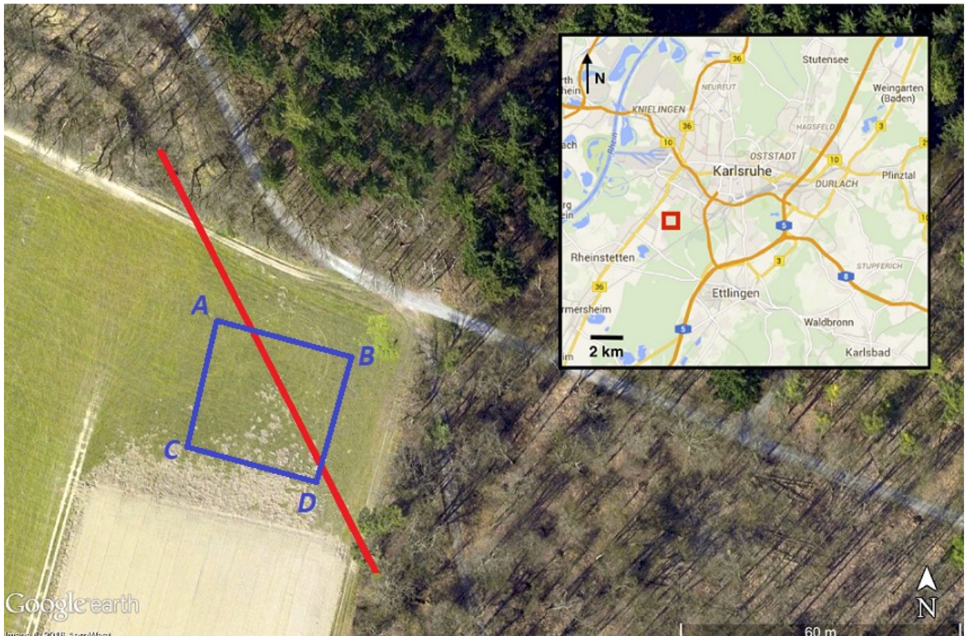
- Layered subsurface
- 2-D local trench
- Fault Zone

4 **Towards 3D viscoelastic FWI of 3D 9-C field data**

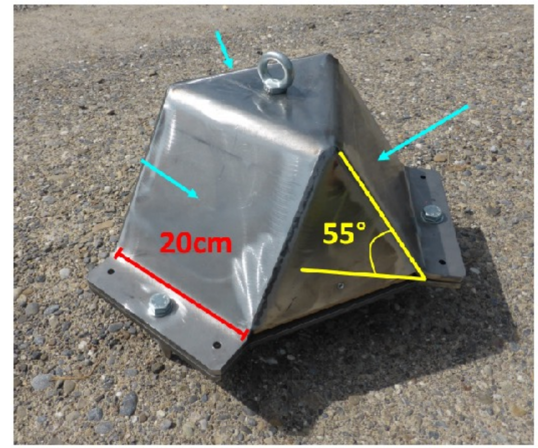
5 Summary

9-C Acquisition

Airfield Rheinstetten



3-C Galperin-Source



3-C Geophone

Outline

1 Introduction

2 Methodology

- FD Simulation
- Elastic FWI
- Geometrical spreading correction
- Attenuation

3 2D Field data applications

- Layered subsurface
- 2-D local trench
- Fault Zone

4 Towards 3D viscoelastic FWI of 3D 9-C field data

5 **Summary**

Summary

- 2-D elastic FWI is applicable to field data and can infer lateral variations of Vs
- Pre-processing:
  - geometrical spreading correction
  - a priori Q-estimation
- Elastic FWI
  - misfit of normailzed seismograms
  - source signal inversion
  - viscoelastic forward modelling
- Outlook
  - Inversion of attenuation
  - 3-D elastic FWI

Thank you for your attention!

References

- Field data applications
  - *Schäfer, M.: Application of full-waveform inversion to shallow-seismic Rayleigh waves on 2D structures. Dissertation, Karlsruher Institut für Technologie, 2014.*
  - *Groos, L.: 2D full waveform inversion of shallow seismic Rayleigh waves. Dissertation, Karlsruher Institut für Technologie, 2013.*
  - *L. Groos, M. Schäfer, T. Forbriger, T. Bohlen. Application of a complete workflow for 2D elastic full-waveform inversion to recorded shallow-seismic Rayleigh waves. Geophysics 82(2), R109-R117, 2017.*
  - *F. Wittkamp, T. Bohlen. Field Data Application of Individual and Joint 2-D Elastic Full Waveform Inversion of Rayleigh and Love Waves. Conference: Near Surface Geoscience 2016.*

- Attenuation
  - *L. Groos, M. Schäfer, T. Forbriger, T. Bohlen. The role of attenuation in 2D full-waveform inversion of shallow-seismic body and Rayleigh waves, Geophysics, Geophysics 79(6):R247-R261, 2014.*

- Spreading correction
  - *T. Forbriger, L. Groos, M. Schäfer, Line source simulation for shallow seismic field data. Part 1: Theoretical background. Geophysical Journal International, 2014.*
  - *M. Schäfer, L. Groos, T. Forbriger, T. Bohlen, Line-source simulation for shallow-seismic data. Part 2: Full-waveform inversion – a 2D case study. Geophysical Journal International, 2014.*