Effects of fractures on seismic wave-fields in the presence of equant porosity.

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June 4th, 2019
81st EAGE Conference & Exhibition

Outline

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Modelling

Discussion & Conclusions

Introduction

Motivation

Dispersion + attenuation + anisotropy

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Fractures Porosity

$\downarrow$

Dispersion + attenuation + anisotropy

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Fractures Porosity

Dispersion + attenuation + anisotropy

Thin-bedded sequence

Motivation

Combine the **full-wavefield anisotropic modelling**

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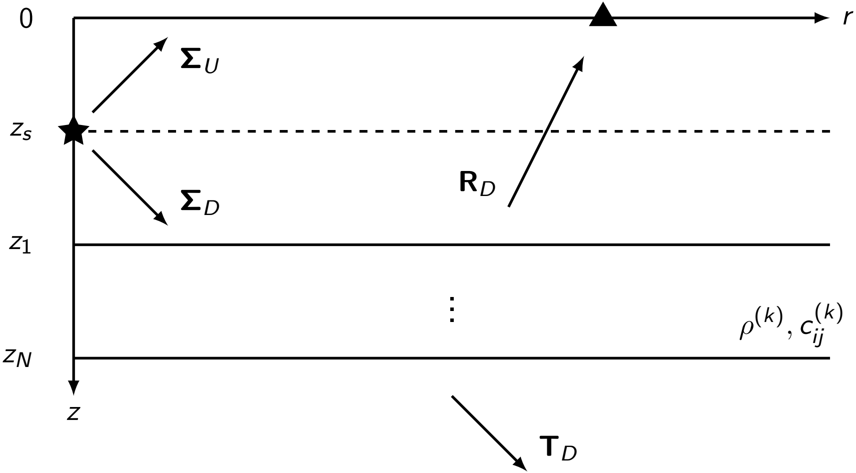
Reflectivity modeling

Model: unbounded stack of layers



Equations: P-SV system

Equation of motion in $t - x$ domain:

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i. \tag{1}$$

Consecutive equation (Hooke's law):

$$\sigma_{ij} = \frac{1}{2} c_{ijkl} \left(\frac{\partial u_k}{\partial x_l} + \frac{\partial u_l}{\partial x_k} \right). \tag{2}$$

Equations: Fourier-Bessel transform

$$F(k, \omega) = \mathscr{F}_\nu(f) = \int\limits_{-\infty}^{\infty} dte^{i\omega t} \int\limits_{0}^{\infty} drrJ_\nu(kr)f(r, t), \tag{3}$$

where $\nu = 0, 1$.

Equations: P-SV system

Wave equation in $\omega - k$ domain (post Fourier-Hankel transform $\mathscr{F}$):

$$\frac{d\mathbf{b}}{dz} = \omega \begin{bmatrix} 0 & \mathbf{A} \\ \mathbf{B} & 0 \end{bmatrix} \mathbf{b} + \mathbf{F}, \tag{4}$$

where

$$\mathbf{b} = [\omega U_z, -S_r, S_Z, \omega U_r]^T ,$$

and

$$U_r, S_r = \mathscr{F}_1(u_r, \sigma_{zr}), \quad U_z, S_z = \mathscr{F}_0(u_z, \sigma_{zz})$$

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Equations: wavefields separation

Up/down wavefield separation:

$$\mathbf{b} = \mathbf{L}\begin{bmatrix}\mathbf{u}\\\mathbf{d}\end{bmatrix}, \tag{5}$$

where $\mathbf{L} = \mathbf{L}(p, \omega, \rho, c_{ij})$, and $\mathbf{W} = \begin{bmatrix}\mathbf{u}\\\mathbf{d}\end{bmatrix}$ is the wave vector.

Equations: reflectivity recursion

Reflectivity response of the stack then:

$$\mathbf{R}_D(z_{j-1}|z_N) = \mathbf{E}_j\Big\{\mathbf{R}_{D_j} + \mathbf{T}_{U_j}\mathbf{R}_D(z_j|z_N)\times \Big[\mathbf{I} + \mathbf{R}_{D_j}\mathbf{R}_D(z_j|z_N)\Big]^{-1}\mathbf{T}_{D_j}\Big\}\mathbf{E}_j, \quad (6)$$

where $\mathbf{E}_j = \exp\left(i\omega\mathbf{q}z_j\right)$ and $\mathbf{q} = \operatorname{diag}\left(q_\alpha, q_\beta\right)$.

Equations: response of a point source

Up-going wavefield at $z = 0$ (no free surface) (Ursin, 1983):

$$\mathbf{U}(z_0) = \mathbf{R}_D(z_0)\mathbf{S}_2 - \mathbf{S}_1, \tag{7}$$

where

$$\mathbf{S} = \mathbf{Q}(z_0|z_s)\boldsymbol{\Sigma}(z_s) = \begin{bmatrix} \mathbf{S}_1 \\ \mathbf{S}_2 \end{bmatrix}, \tag{8}$$

and $\mathbf{Q} = \begin{bmatrix} \exp\left(i\omega\mathbf{q}z_s\right) & \\ & \exp\left(-i\omega\mathbf{q}z_s\right) \end{bmatrix}.$

Equations: source vector

Source is included as a wave-vector discontinuity (Kennett, 2009):

$$[\mathbf{W}(z_s)]^{\pm} = \mathbf{\Sigma}(z_s) = \begin{bmatrix} \mathbf{\Sigma}_U(z_s) \\ \mathbf{\Sigma}_D(z_s) \end{bmatrix}. \tag{9}$$

Alternatively, a stress-displacement vector discontinuity

$$\mathbf{\Sigma}(z_s) = \mathbf{L}^{-1}[\mathbf{b}]^{\pm} = \mathbf{L}^{-1}\mathbf{F}. \tag{10}$$

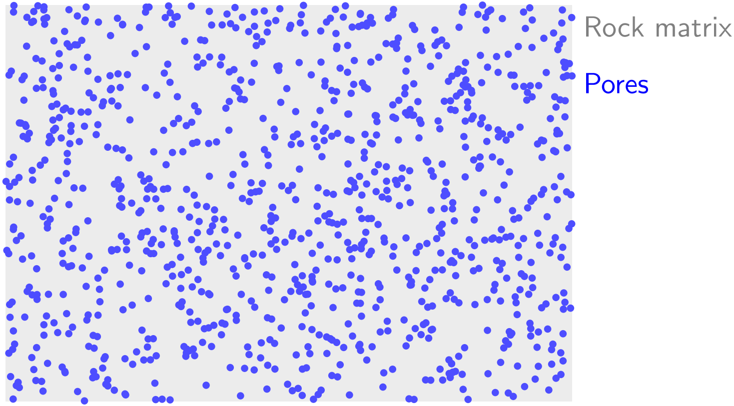
Rock-physics model

Rock-physics model[1]

Rock matrix

[1] Chapman (2003)

Rock-physics model[1]



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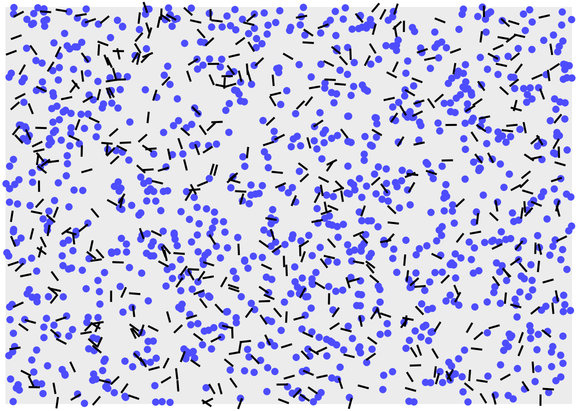

Rock matrix

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Micro-cracks

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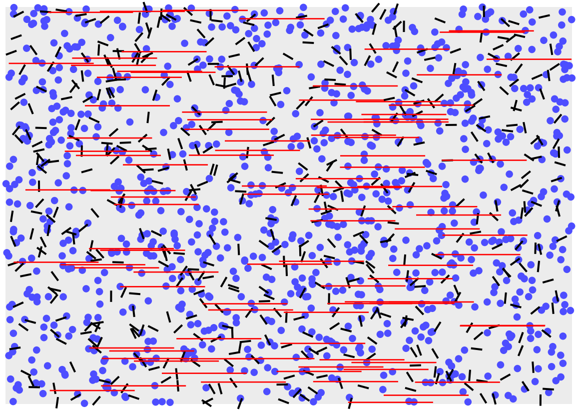

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Dispersion

$\lambda = 10.69$ GPa $\qquad \mu = 21.97$ GPa

$\rho = 2.15$ g/cc

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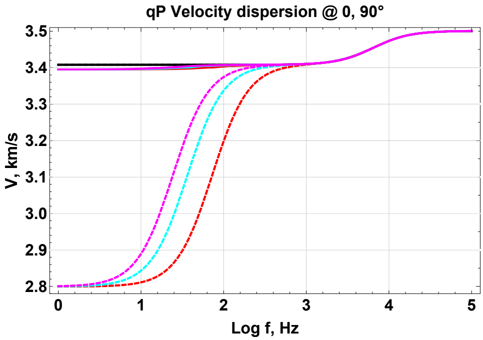

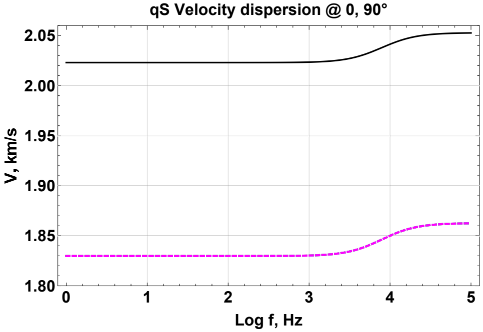

$L = 0$ (—), $L = 100$ (—), $L = 200$ (—), $L = 300$ (—)

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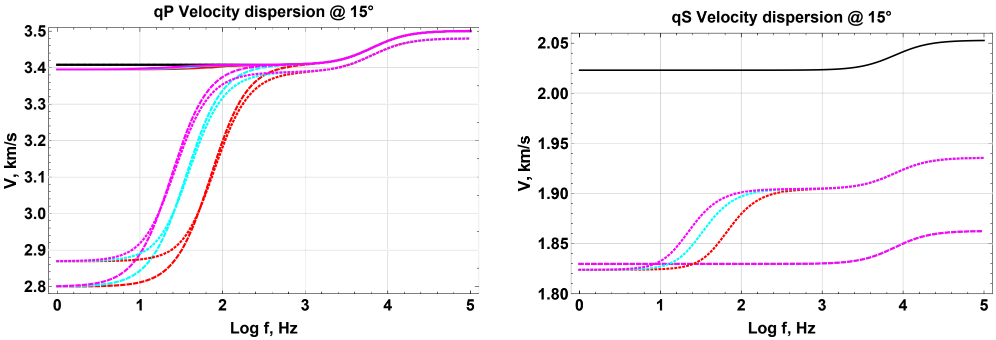

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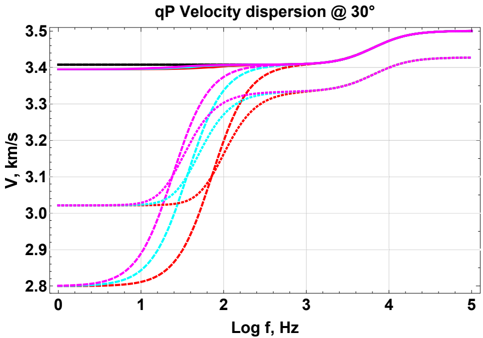

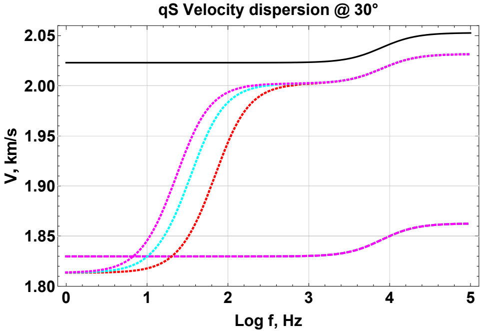

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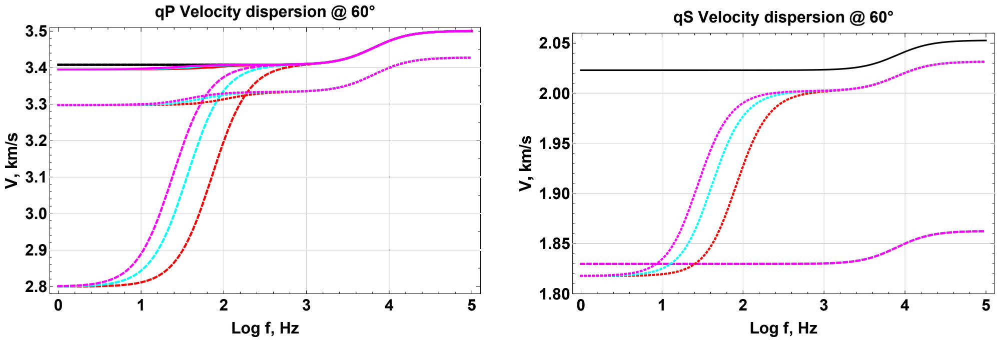

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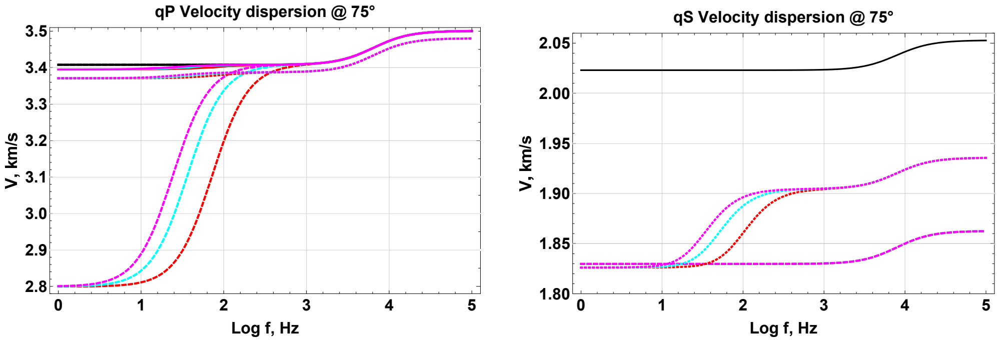

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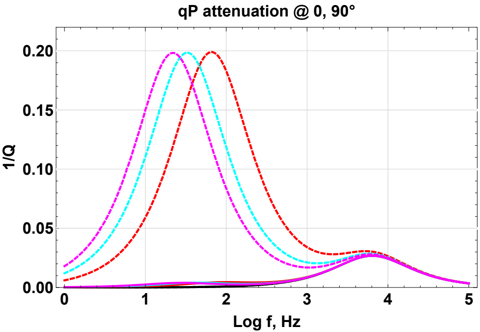
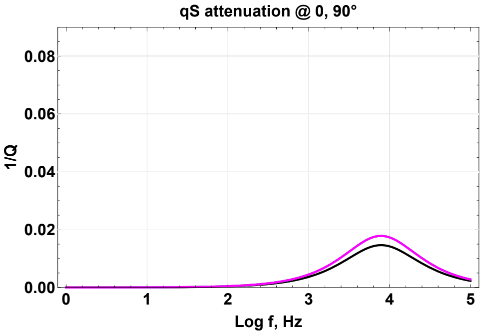
Attenuation





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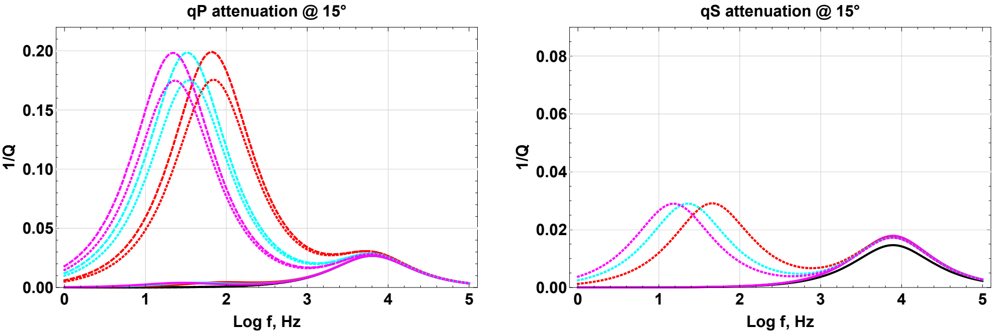

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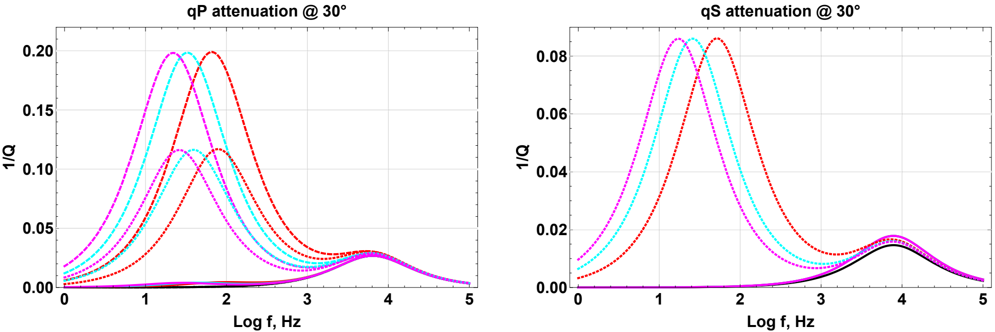

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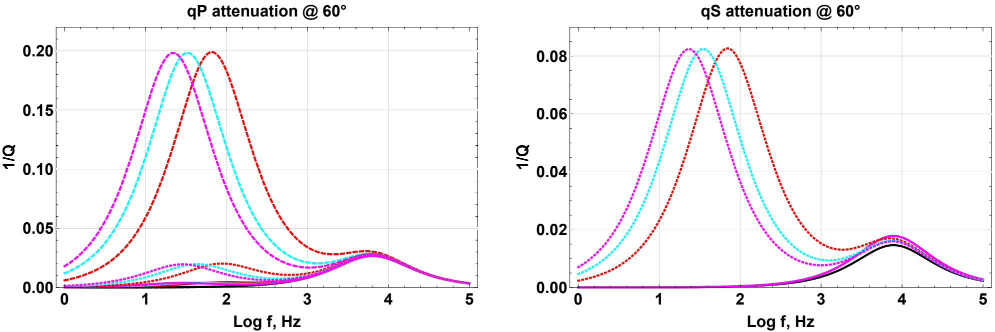

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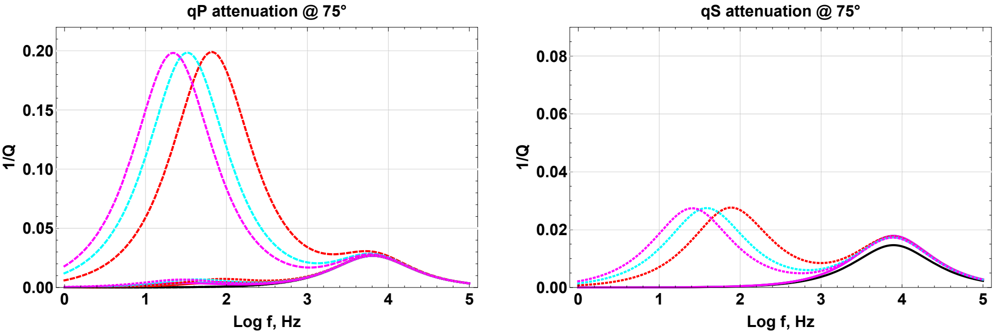

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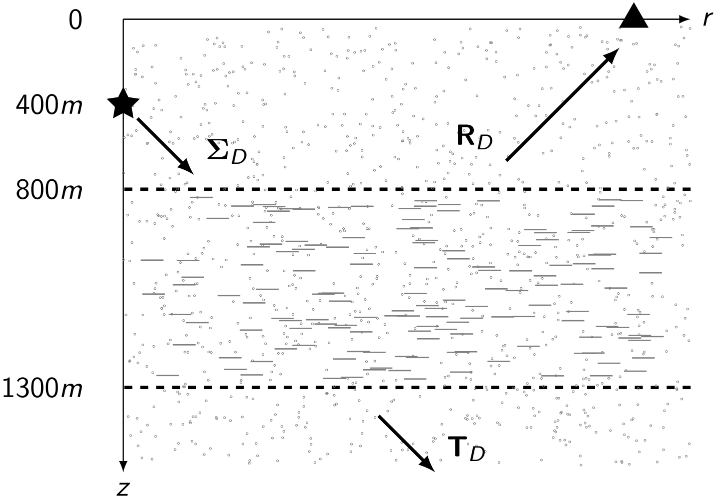
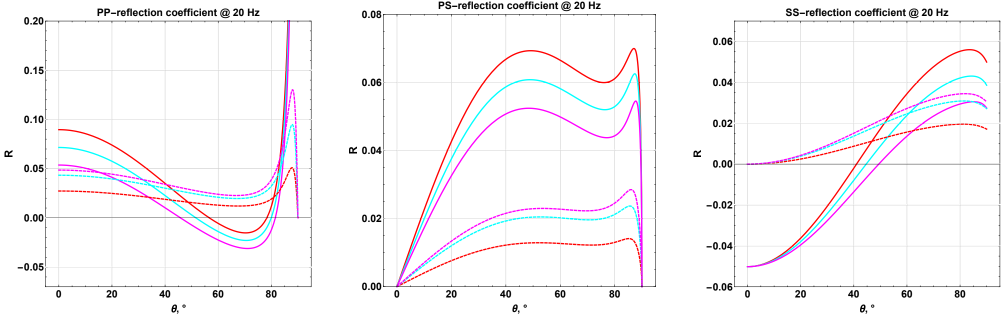
Modelling

2-interface model: fractured porous media



Reflection coefficients



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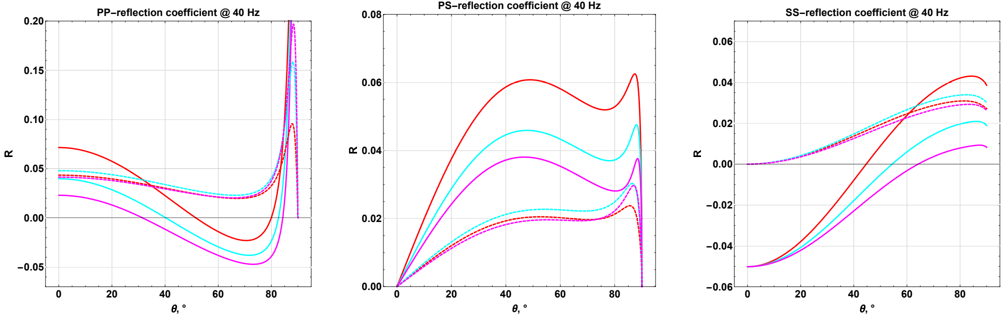

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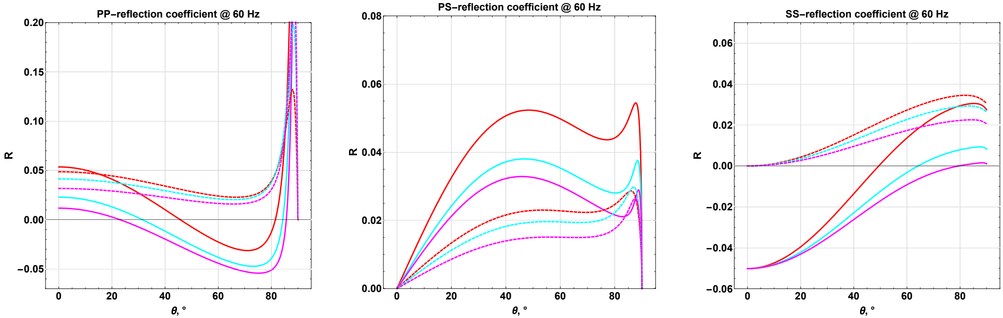
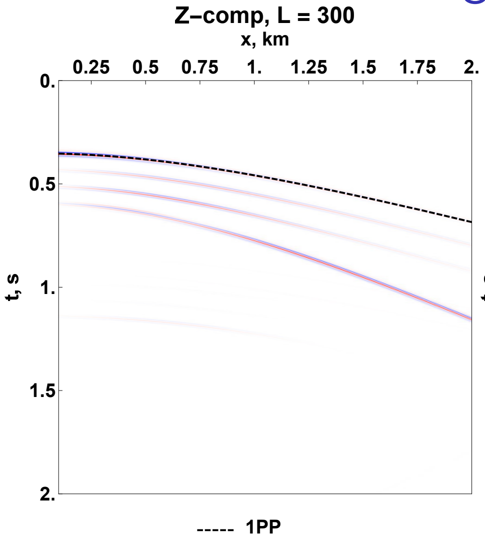
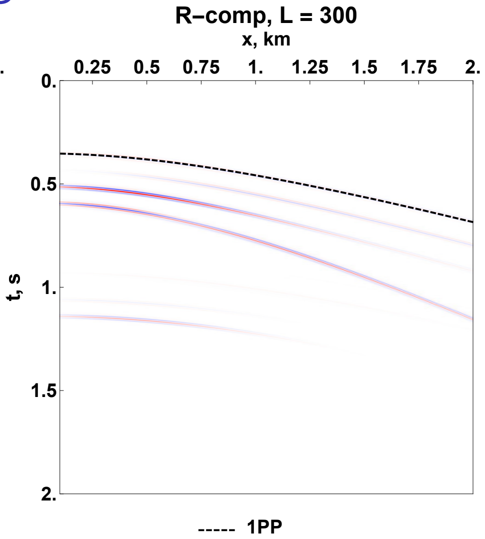


Common-shot gathers @ 50 Hz





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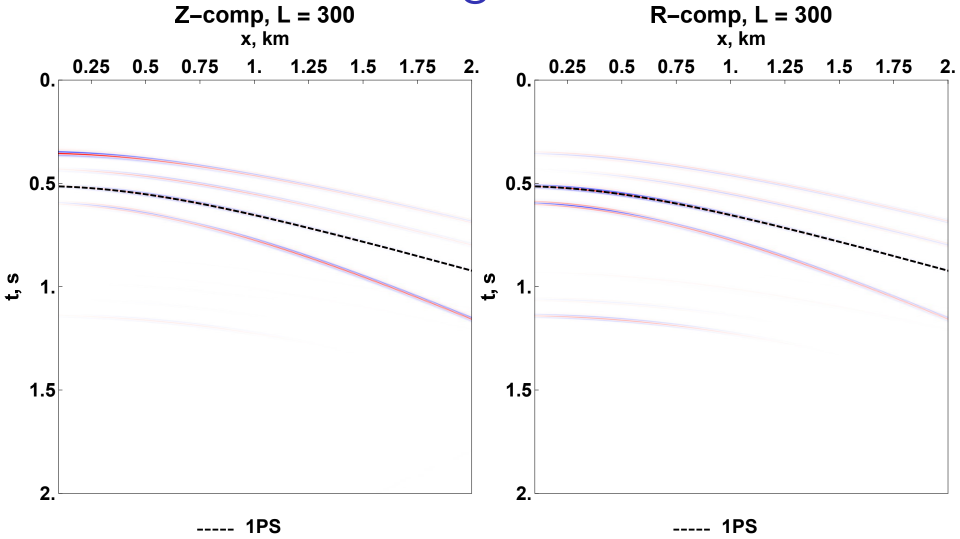

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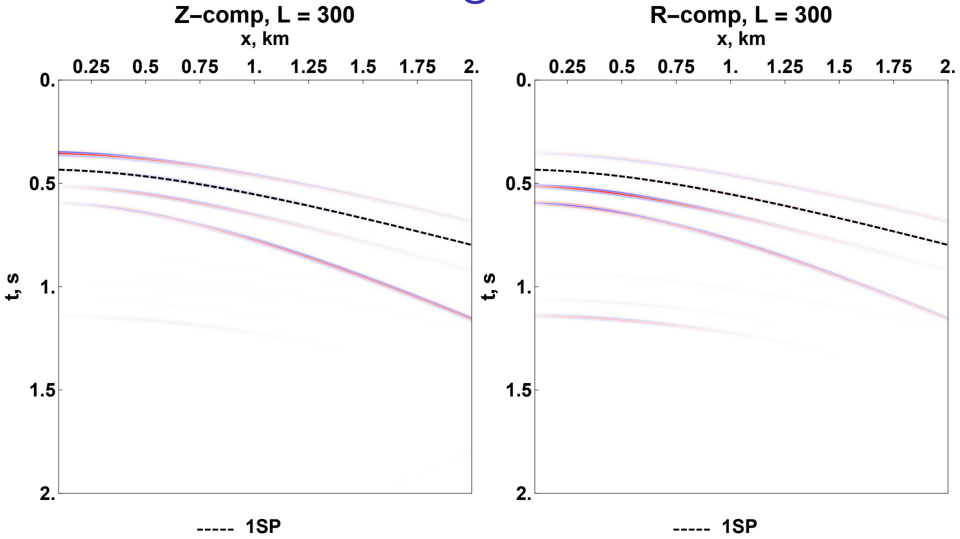

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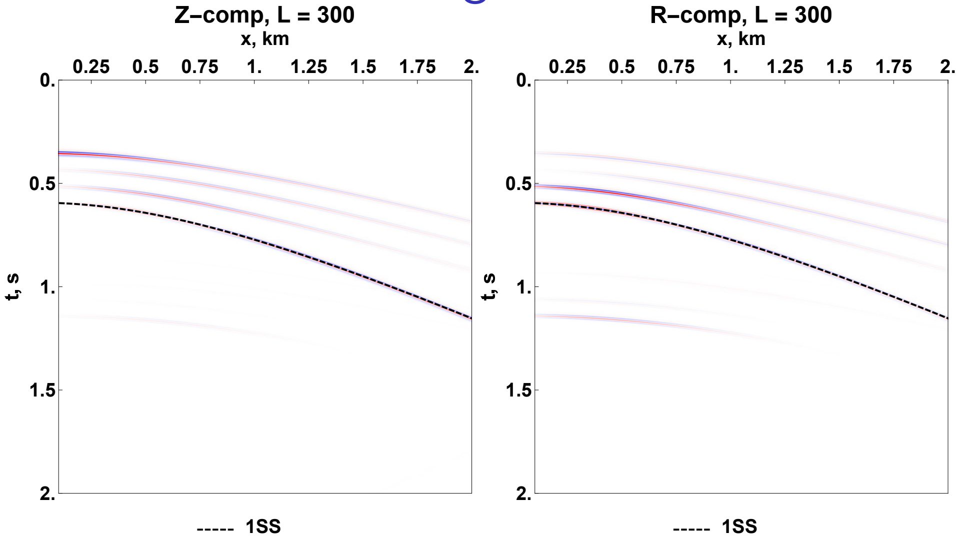

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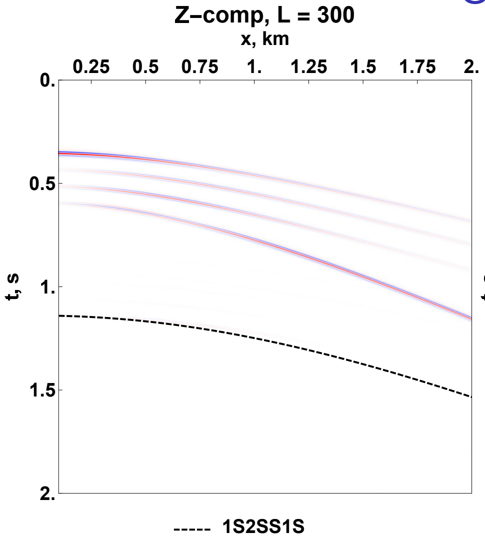

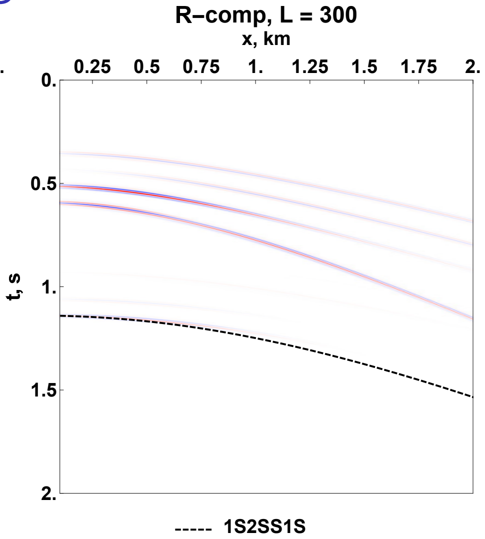

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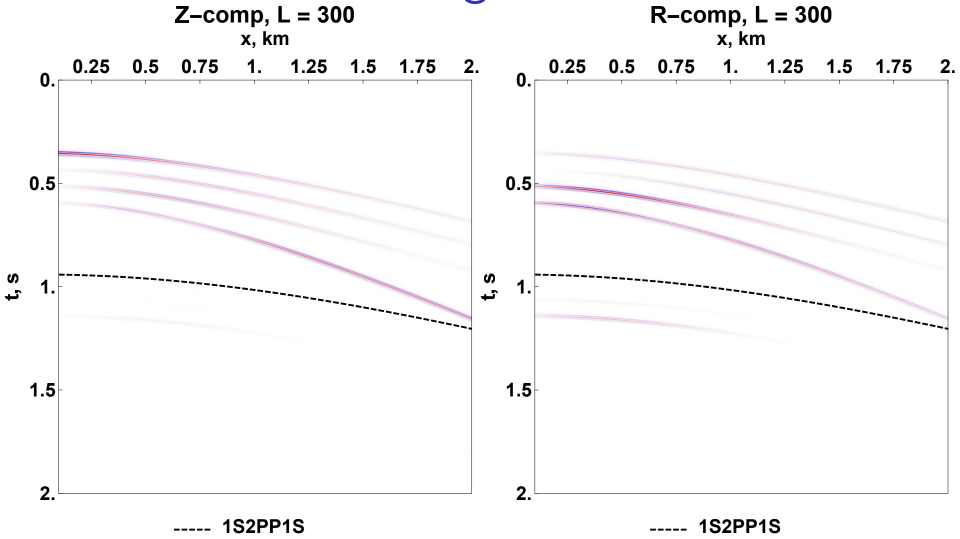

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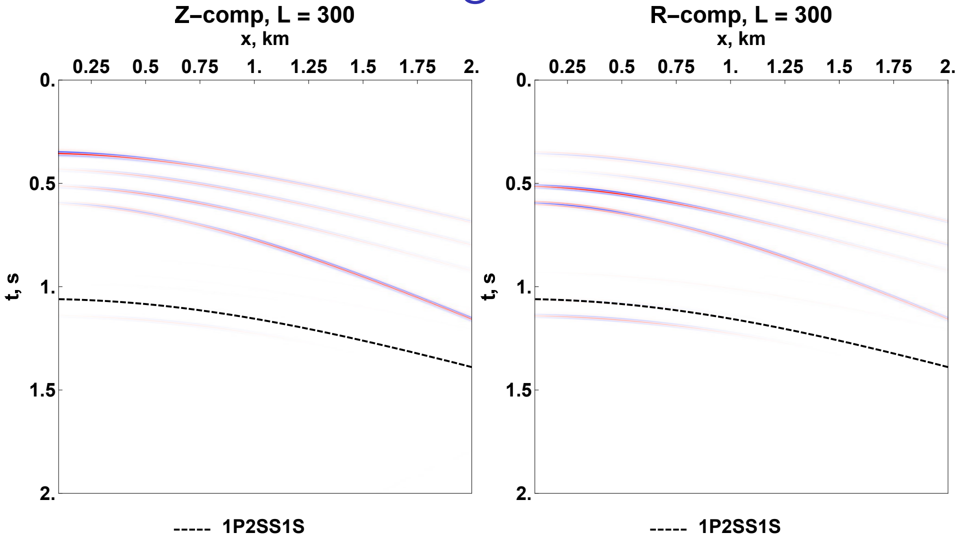
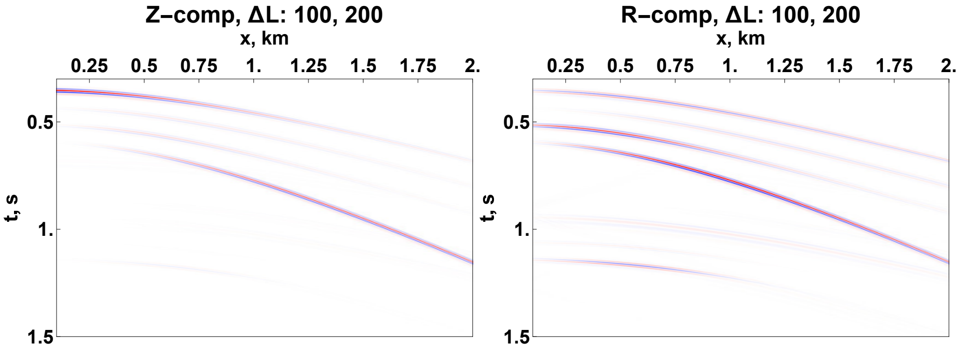


CSG differences



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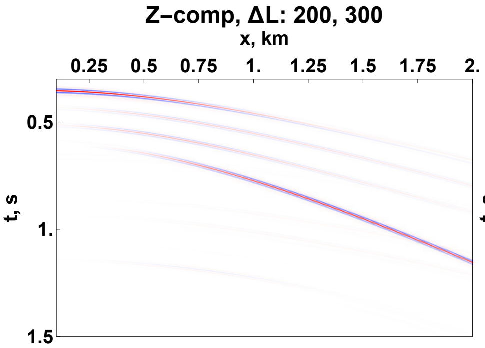

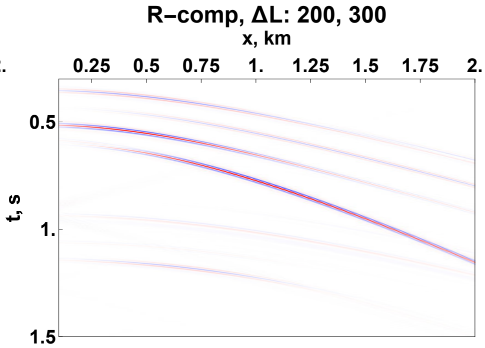

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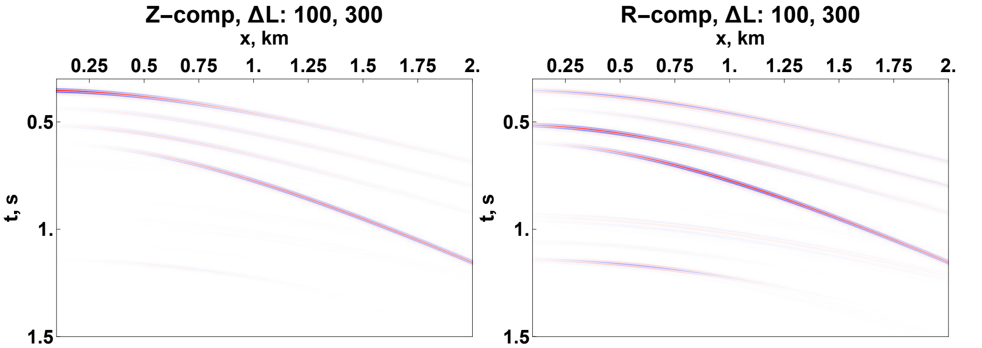
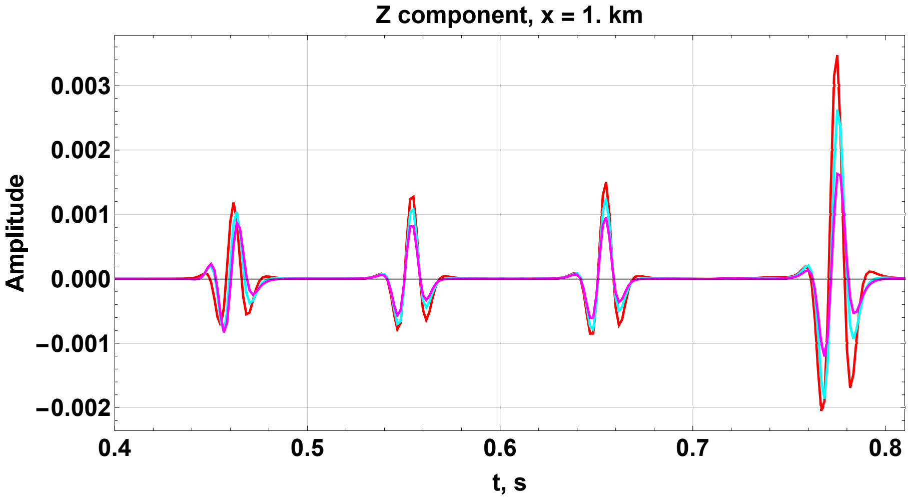


Traces at $x = 1$ km



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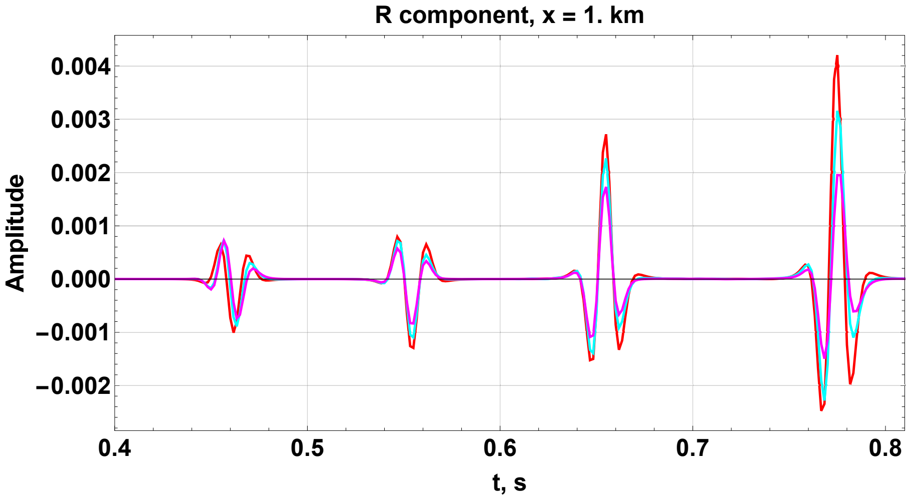

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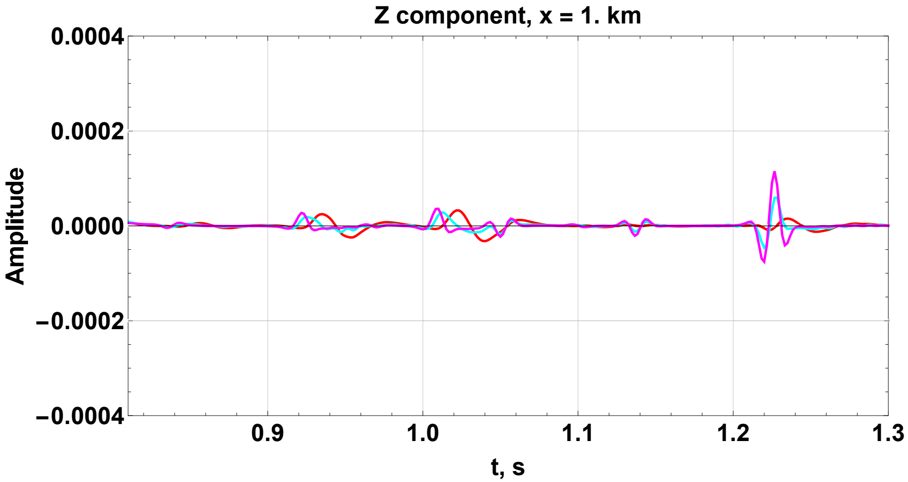

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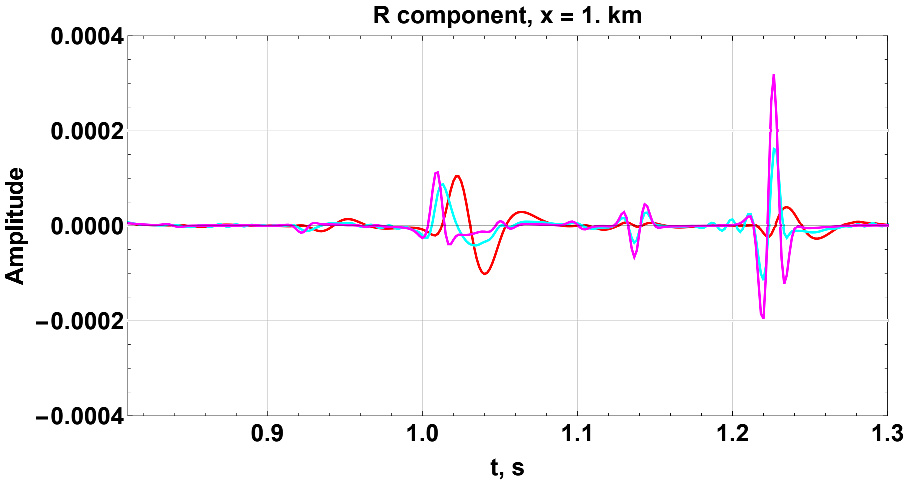
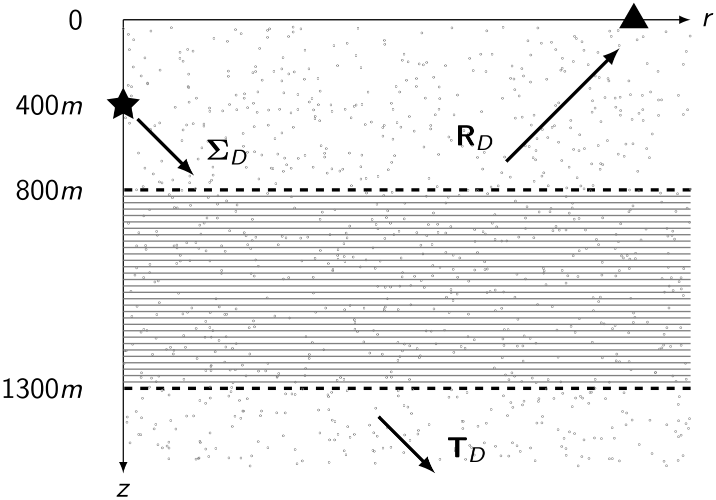
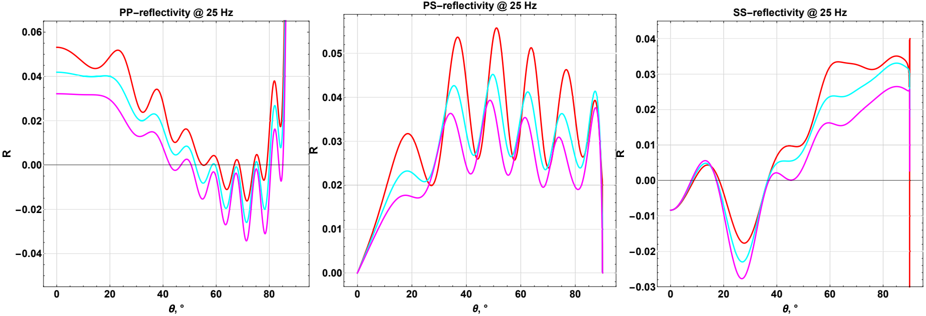


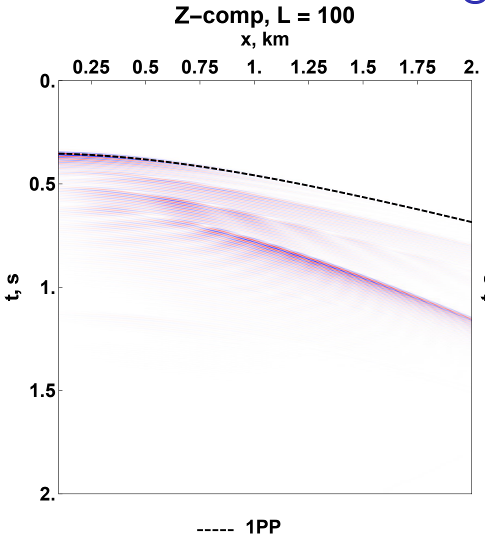
Fractured porous finely-layered media

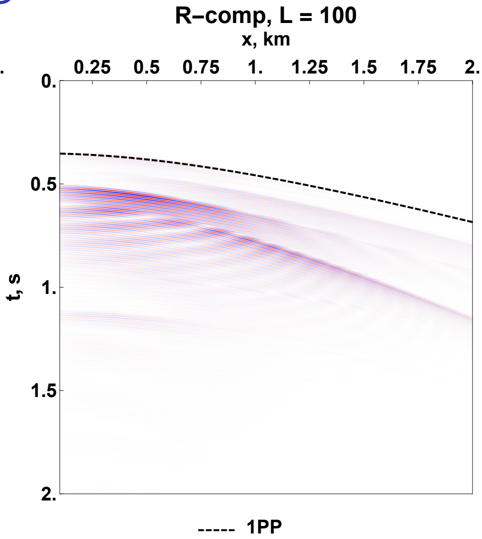


Reflection coefficients



Common-shot gathers @ 25 Hz





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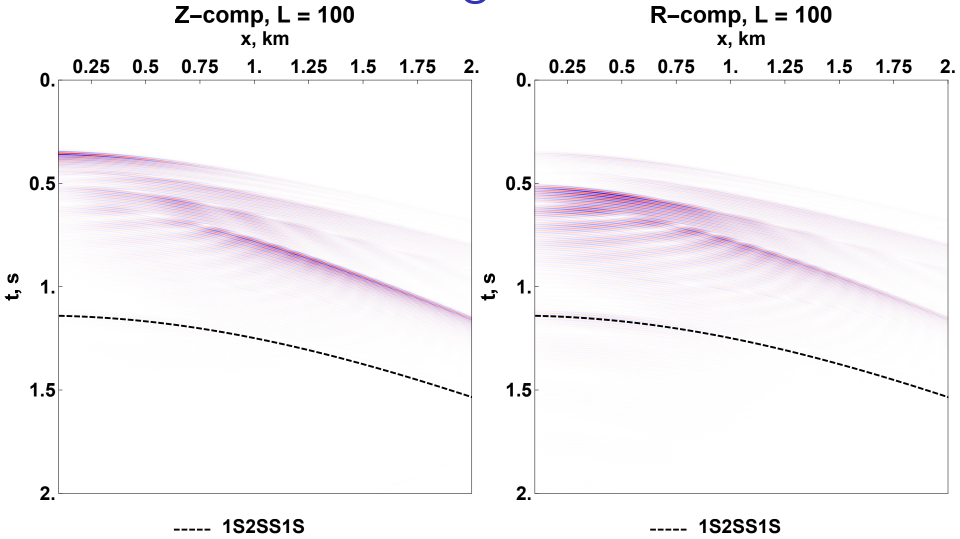
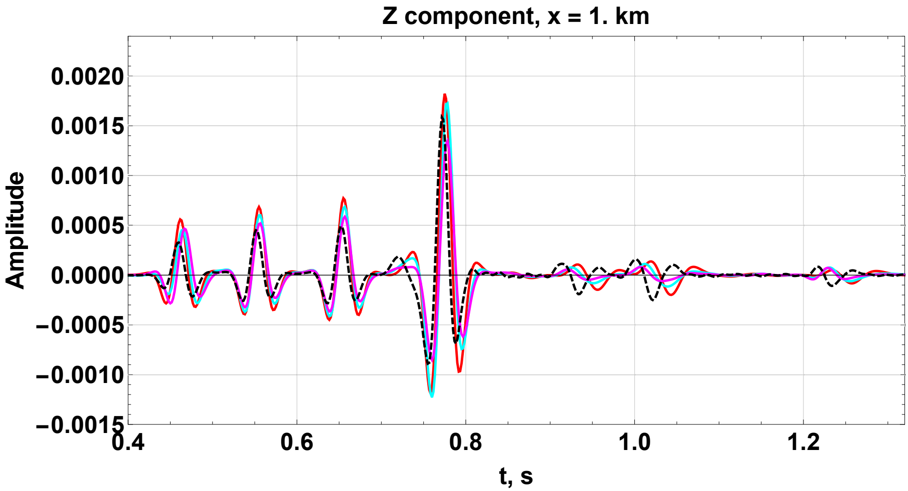


Thin lamination



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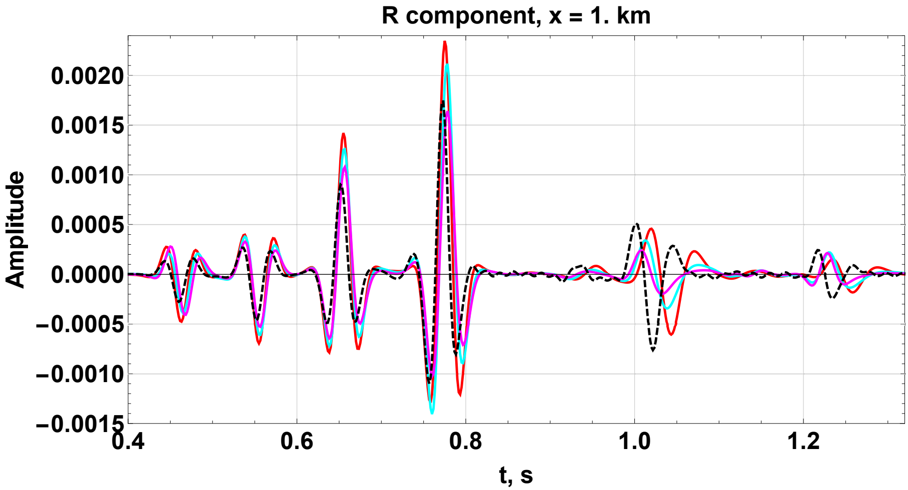

Discussion & Conclusions

- Reflectivity modelling. Practical albeit limited approach for complex models:
  - \+ Low-symmetry anisotropic frequency-dependent models,
  - \+ Partial response (e.g., PP-reflection),
  - \+ Source waveform independent,
  - \+ Multiple source formulations (e.g., force, moment tensor),
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  - – Effective models,
  - – Flat layers.
- Rock-physics model. Simple yet realistic:
  - \+ Multiple-scale inclusions,
  - \+ Multiple fluids,
  - \+ Calibrated to real rocks,
  - – No fracture interaction.

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- Modelling results.
  - + Fracture effects in seismic frequency band,
  - + Phase and amplitude effects,
  - + Can be confused with thin-bedding.
  - – Difficult to interpret.

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  - $+$ Fracture effects in seismic frequency band,
  - $+$ Phase and amplitude effects,
  - $+$ Can be confused with thin-bedding.
  - $-$ Difficult to interpret.
- Future research (besides more detailed analysis):
  - $\rightarrow$ Inversion for fracture parameters,
  - $\rightarrow$ Vertical fractures,
  - $\rightarrow$ Multiple fracture sets,
  - $\rightarrow$ Code release.

References

Chapman, M., 2003, Frequency-dependent anisotropy due to meso-scale fractures in the presence of equant porosity: Geophysical Prospecting, **51**, 369–379.

Kennett, B., 2009, Seismic Wave Propagation in Stratified Media, 1st ed.: ANU Press.

Ursin, B., 1983, Review of elastic and electromagnetic wave propagation in horizontally layered media: Geophysics, **48**, 1063–1081.