Estimation of fracture compliance based on time delays inferred from full-waveform sonic log data

Zhenya Zhou[(1)], Eva Caspari[(2)], Nicolas D. Barbosa[(1)], Andrew Greenwood[(1,2)], and Klaus Holliger[(1)]

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Introduction

- Fractures significantly influence the mechanical and hydraulic properties of rocks. As such, they have impacts on a wide range of human activities, such as geothermal energy production, CO_2 sequestrian, and nuclear waste storage, and, hence, their characterization is of interest and importance.
- Seismic methods possess the potential to estimate mechanical fracture properties, notably, fracture compliance (Bakku et al., 2013).
- Here, we propose to estimate normal fracture compliance from refracted P-waves observed in full-waveform sonic data. Three different methods are tested numerically on pertinent scenarios.
- Finally, the methods are applied to a full-waveform sonic data set acquired by standard continuous logging in the Bedretto Underground Laboratory situated in the crystalline basement of the Gotthard massif, Central Swiss Alps (http://www.bedrettolab.ethz.ch/home/).

Methodologies for fracture compliance estimation

When a seismic wave propagates across a fluid-filled fracture, its amplitude is diminished and its travel time is increased, which, in turn, provides the information required for characterizing fracture compliance (Barbosa et al., 2019). In this work, we propose a method for compliance estimation based on travel time delays. The fracture-related phase time delay is given by (Möllhoff et al., 2009)

$$t_{ph}(\omega)=\frac{1}{\omega}\arctan\left(\frac{\omega\rho v Z}{2}\right), \quad (1)$$

and the group time delay by (Pyrak Nolte, Cook, and Myer 1987)

$$t_g(\omega)=\frac{\frac{2}{\rho v Z}}{(\frac{2}{\rho v Z})^2+\omega^2}, \quad (2)$$

where ρ and v are density and P-wave velocity of the intact host rock, respectively. Z is the normal fracture compliance and ω is the angular frequency. In the frequency domain, the phase and group time delay can also be expressed as (Papoulis 1962)

$$t_{ph}(\omega)=\frac{\Theta(\omega)}{\omega}, \quad (3)$$

$$t_g(\omega)=\frac{d\Theta(\omega)}{d\omega}. \quad (4)$$

By rearranging the above equations, the fracture compliance can be estimated as

$$Z(\omega)=\frac{2\tan(t_{ph}\omega)}{\omega\rho v}, \quad (5)$$

$$Z(\omega)=\frac{4t_g}{[1\pm\sqrt{1-4{t_g}^2\omega^2}]\rho v}. \quad (6)$$

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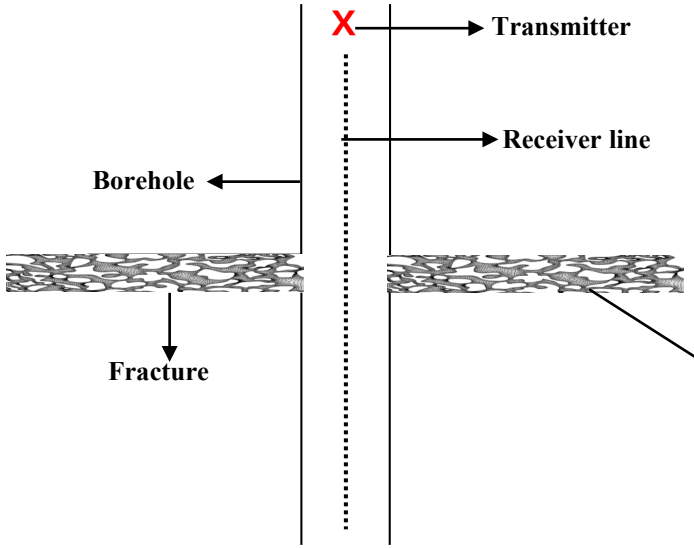
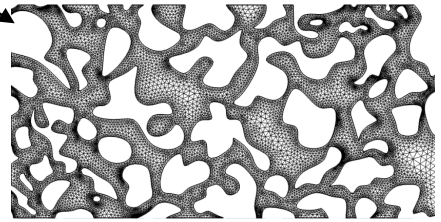
Numerical simulations of full-waveform sonic data

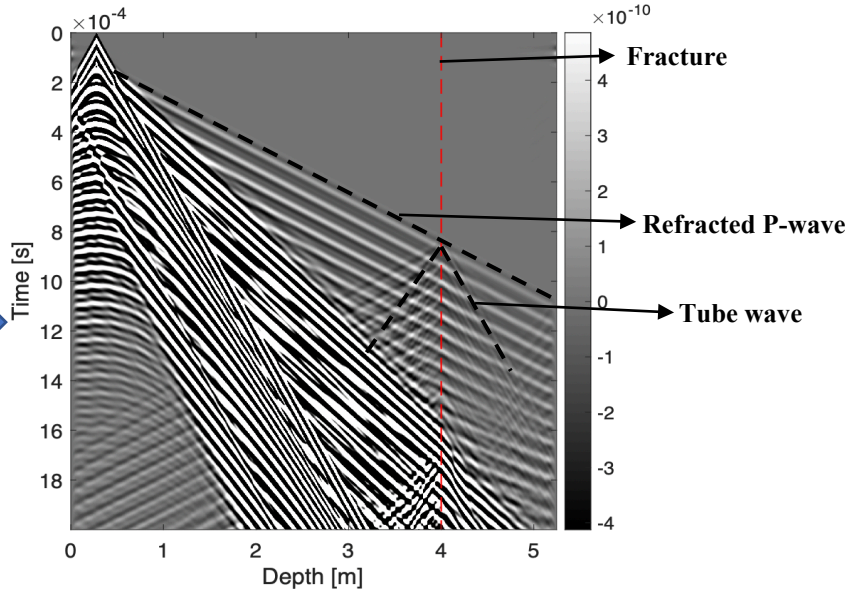
Schematic illustration of a borehole intersecting a fracture



Poroelastic equations



Synthetic full-waveform sonic data



- Poroelastic approach with fractures being represented **as highly compliant, porous, and permeable** features embedded in a much stiffer and much less porous and permeable matrix.
- Full-waveform sonic data is simulated using a finite difference solution of the **poroelastic equations** (Sidler et al., 2014).

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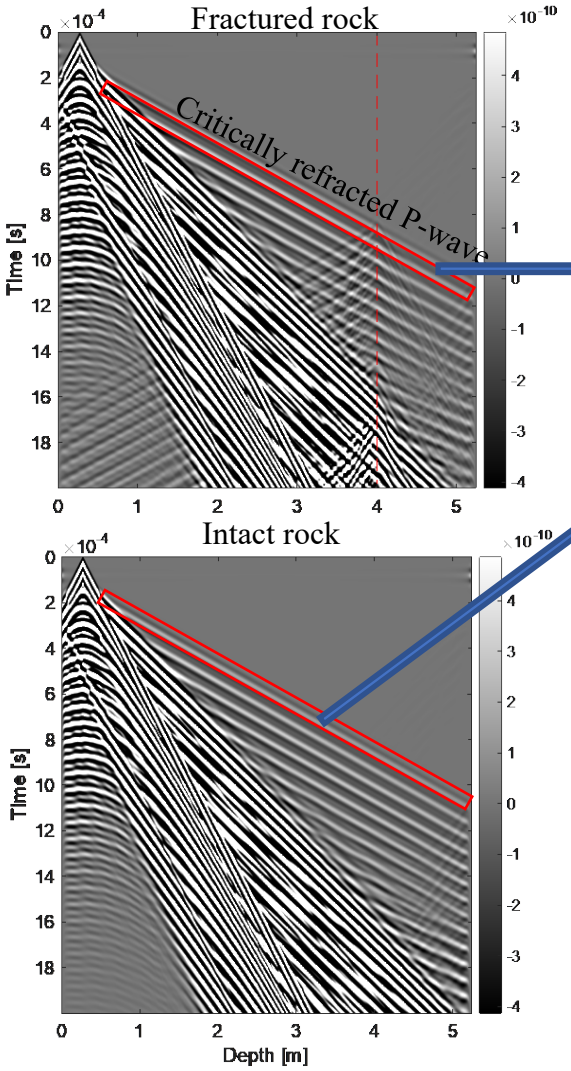
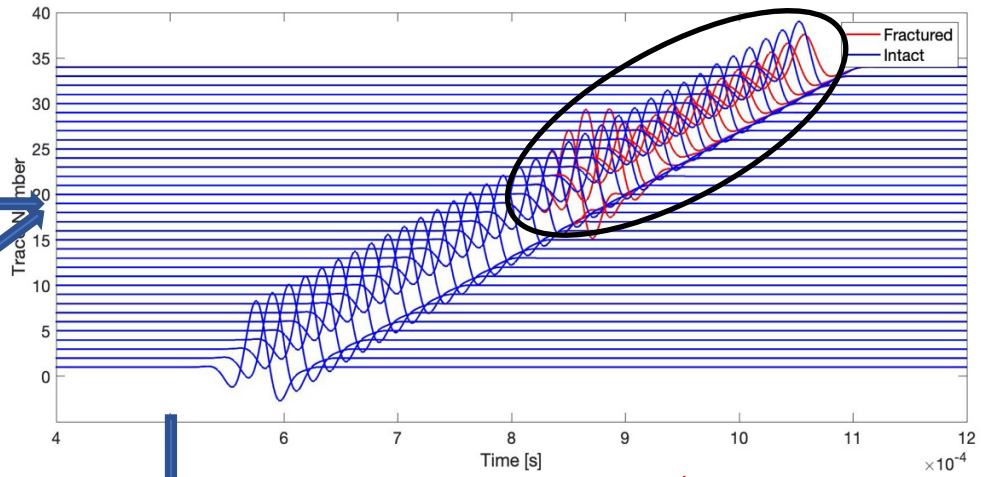
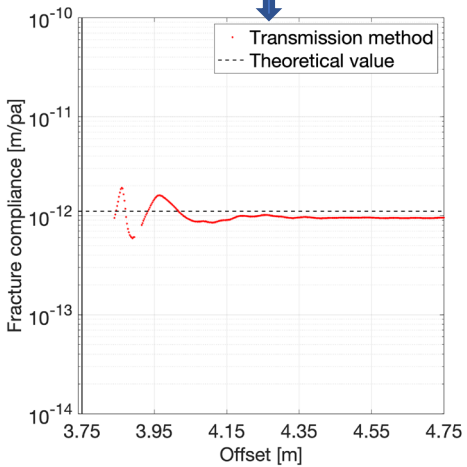
Estimation of fracture compliance from synthetic data



Time windows



Smaller amplitude and later arrival in fractured rock.



$$T(\omega) = e^{-\ln\left(A^{int}/A^{fra}\right) + i\omega\delta t}$$

$$Z(\omega) = \frac{2(1-T)}{iT\omega I}$$ (Barbosa et al., 2019)

T: transmission coefficient.
Z: normal fracture compliance.
δt: time differences in fractured and intact rock.
A: amplitudes for intact (blue) and fractured (red) rock.

- We will compare fracture compliance estimated by the above transmission method with those obtained by the time delay methods (Eqs. 5 and 6).

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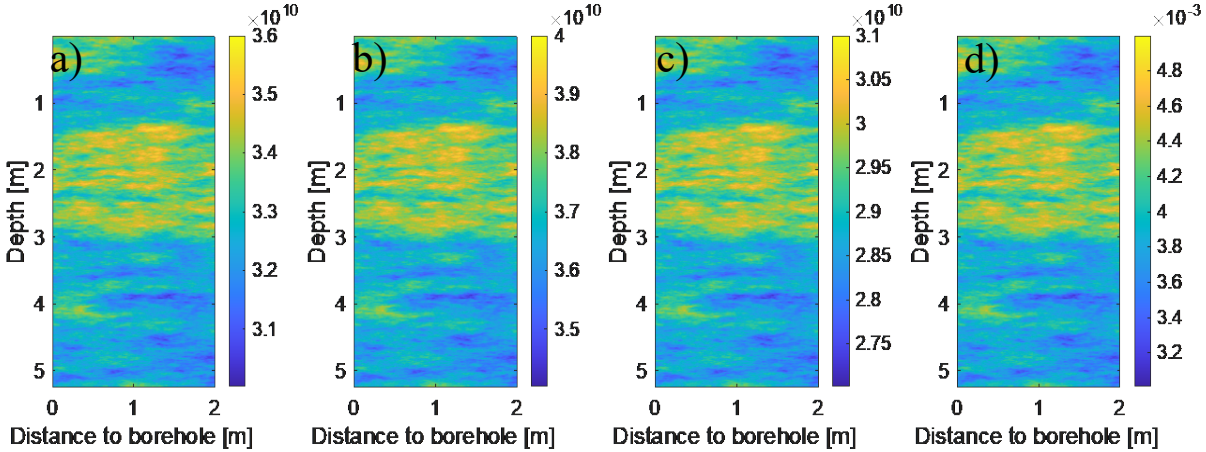
- In our study, the refracted P-wave in the intact rock is used as the reference signal for the computation of the fracture compliance, which avoids corrections for geometrical spreading.

- The time delay (Eqs. 5 and 6 on slide 1) and transmission methods (Barbosa et al., 2019) are tested on synthetic full-waveform sonic data sets for different properties of the intact host rock:

1. Homogeneous host rock (material properties corresponding to mean values in Table 1)

2. Inhomogeneous, quasi-fractal host rock model with a Gaussian distribution of the physical properties shown in the figures a) through d).



a) dry frame bulk modulus; b) solid grain bulk modulus; c) dry frame shear modulus; d) porosity of frame

Table 1. Physical properties of the background rock, fracture and fluid

Physical property	Background		Fracture
-	Mean value	Standard deviation	-
Dry frame bulk modulus [GPa]	33	3	0.056
Dry frame shear modulus [Gpa]	29	2	0.033
Porosity [-]	0.004	0.001	0.6
Solid grain bulk modulus [Gpa]	37	3	37
Solid grain density [Kg/m^3]	2730	0	2730
Fluid bulk modulus [Gpa]	2.25	0	2.25
Fluid density [Kg/m^3]	1000	0	1000
Fluid viscosity [Pa s]	0.001	0	0.001
Aperture [mm]	-	-	5
Fracture tortuosity [-]	-	-	2.2
Fracture length [m]	-	-	Infinity
Normal compliance [m/Pa]	-	-	1.11×10^{-12}

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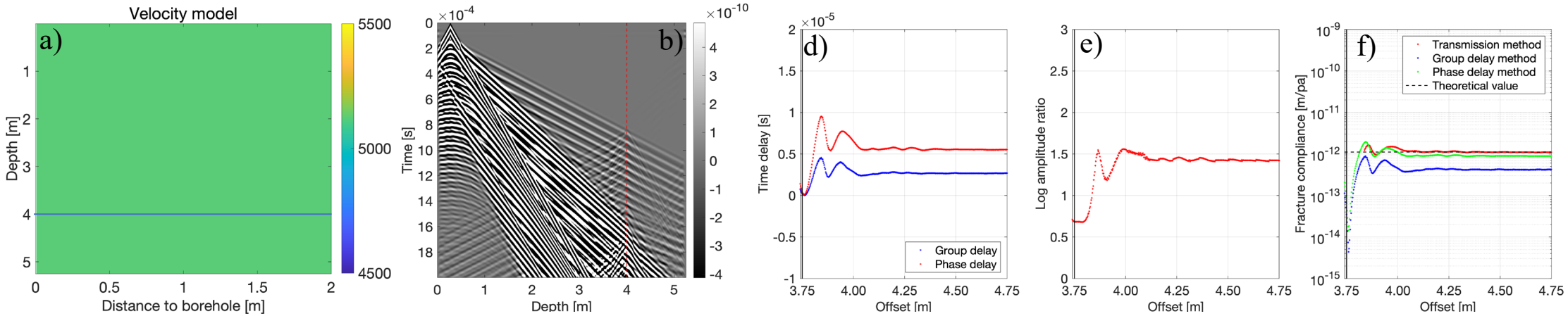
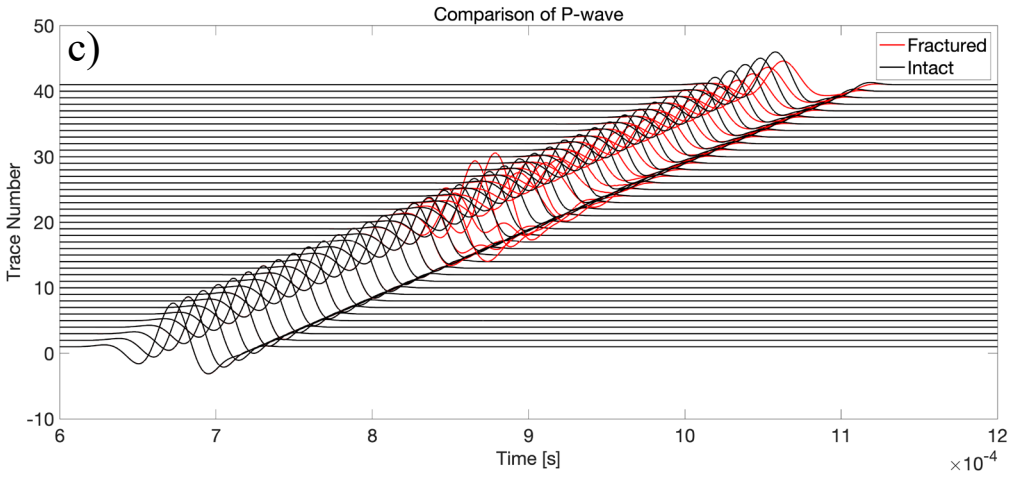
Homogeneous host rock





a) Velocity model (5200m/s) of a homogeneous host rock with a fracture at 4.0 m depth.
b) Synthetic seismogram based on poroelastic equations.
c) Comparison of refracted P-waves extracted from synthetic data for the intact (black) and fractured rock (red).
d) Group (blue dots) and phase time delay (red dots) from refracted P-waves shown in figure c).
e) Amplitude ratio of refracted P-waves for intact and fractured rock.
f) Normal fracture compliance estimated by transmission (red dots), group time delay (blue dots), and phase time delay (green dots) methods. Horizontal black dashed line indicates theoretical fracture compliance that is computed as the ratio between the fracture aperture and the saturated P-wave modulus of material filling in fractures.

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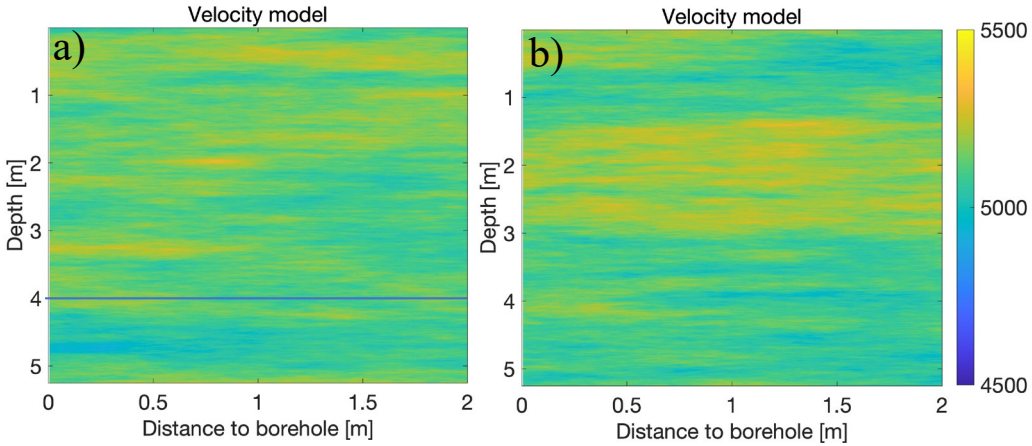
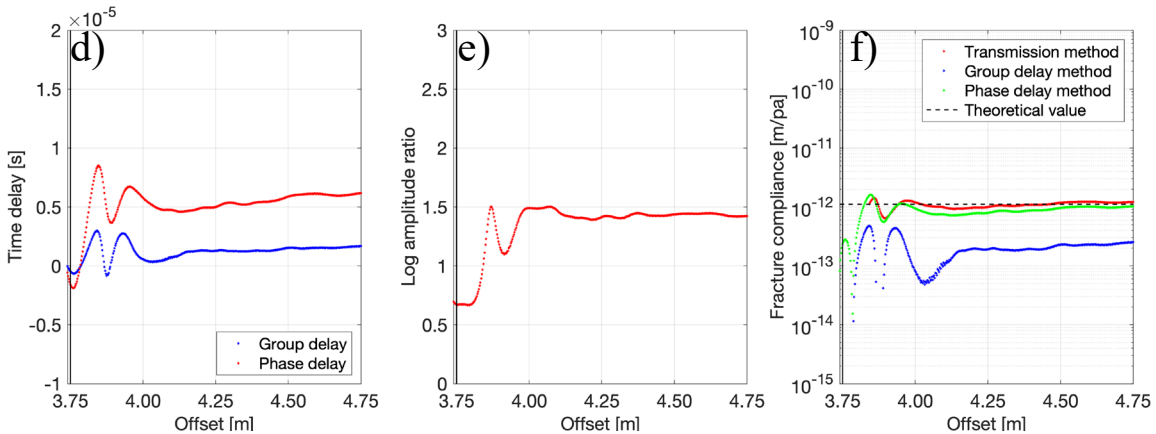
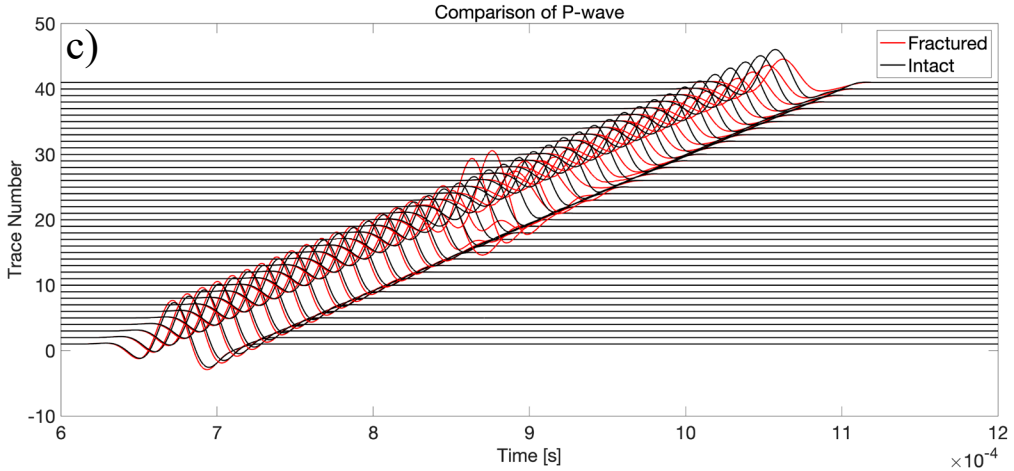
Inhomogeneous host rock







a) Velocity model of inhomogeneous host rock with a fracture at 4.0 m depth.
b) One stochastic realization of velocity model for inhomogeneous intact host rock.
c) Comparison of refracted P-waves extracted from synthetic data for in intact (black) and fractured rock (red). Reference data for intact host rock were generated by averaging synthetic seismograms generated for 7 stochastic realizations of the type shown in figure b).
d) Group (blue dots) and phase time delay (red dots) from refracted P-waves shown in figure c).
e) Amplitude ratio of refracted P-waves for intact and fractured rock.
f) Normal fracture compliance estimated by transmission (red dots), group time delay (blue dots), and phase time delay (green dots) method.

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- The comparison of the fracture compliances estimated from the time delay methods with the estimates from the transmission method, which takes time delays and amplitude decay into account, illustrates that the simpler and more robust time delay methods provide reasonable estimates.

- For the time delay methods, phase time delay produces a better compliance estimate than group time delay. One reason is that the group time delay is proportional to the derivative of the phase shift, while the phase time delay is directly proportional to the phase shift (see Eqs. 3 and 4 on slide 1). A more stable result for the group time delays might be obtained by performing the estimate in the time domain, as this would allow to avoid noise amplification in response to taking the derivative with regard to frequency (see Eq. 4 on slide 1). This will be the subject of future work.

- Both the transmission method and the simpler time delay methods work well not only in homogeneous host rock but also in an inhomogeneous environment.

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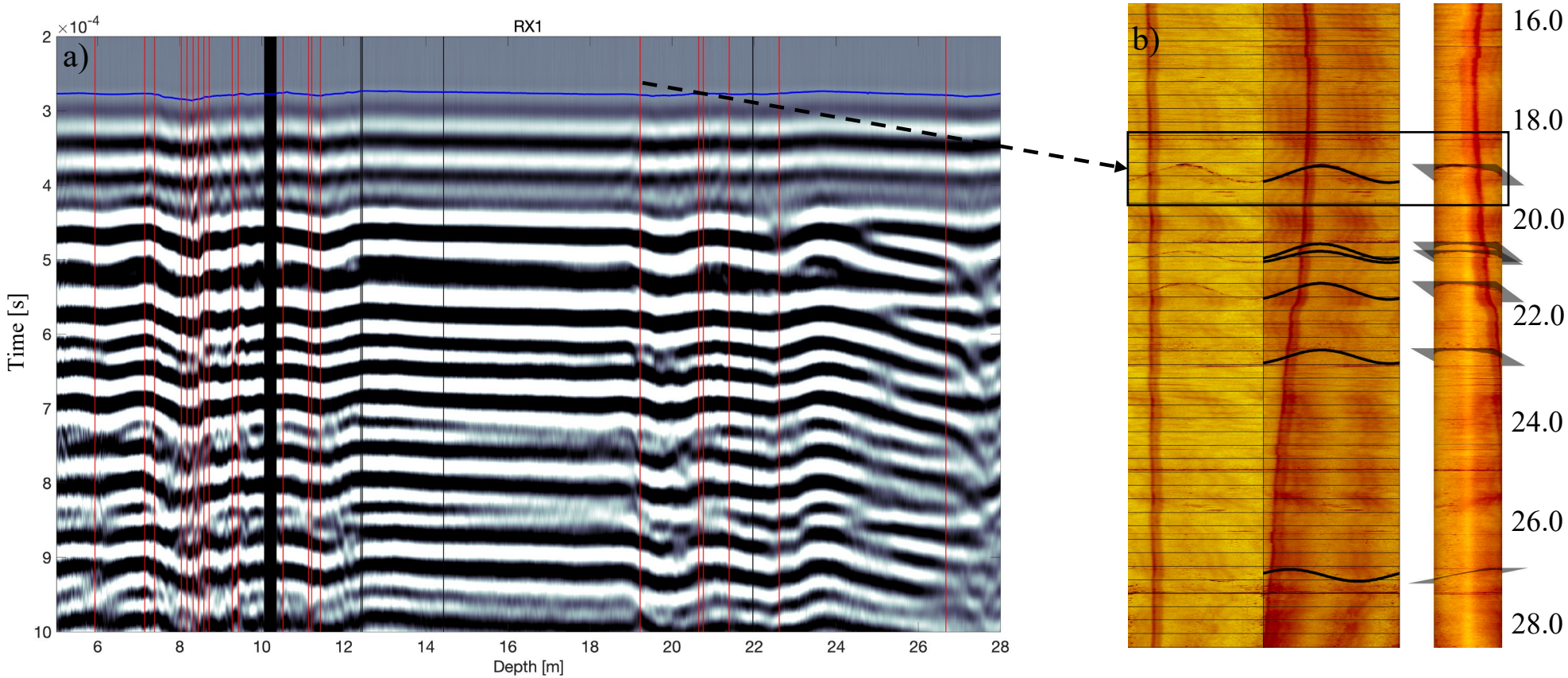
Field example: Full-waveform sonic data from a granitic environment



a) Example of full-waveform sonic log data acquired from a short borehole in the Bedretto Underground Laboratory in Switzerland. Red and blue lines indicate fractures and first-arrivals of the refracted P-wave, respectively. Black vertical lines represent dead traces during the data acquisition.

b) Image from acoustic televiewer (ATV) logging from 16.0 to 28.0 m depth. The fracture circled by a black rectangle is our target for compliance estimation.

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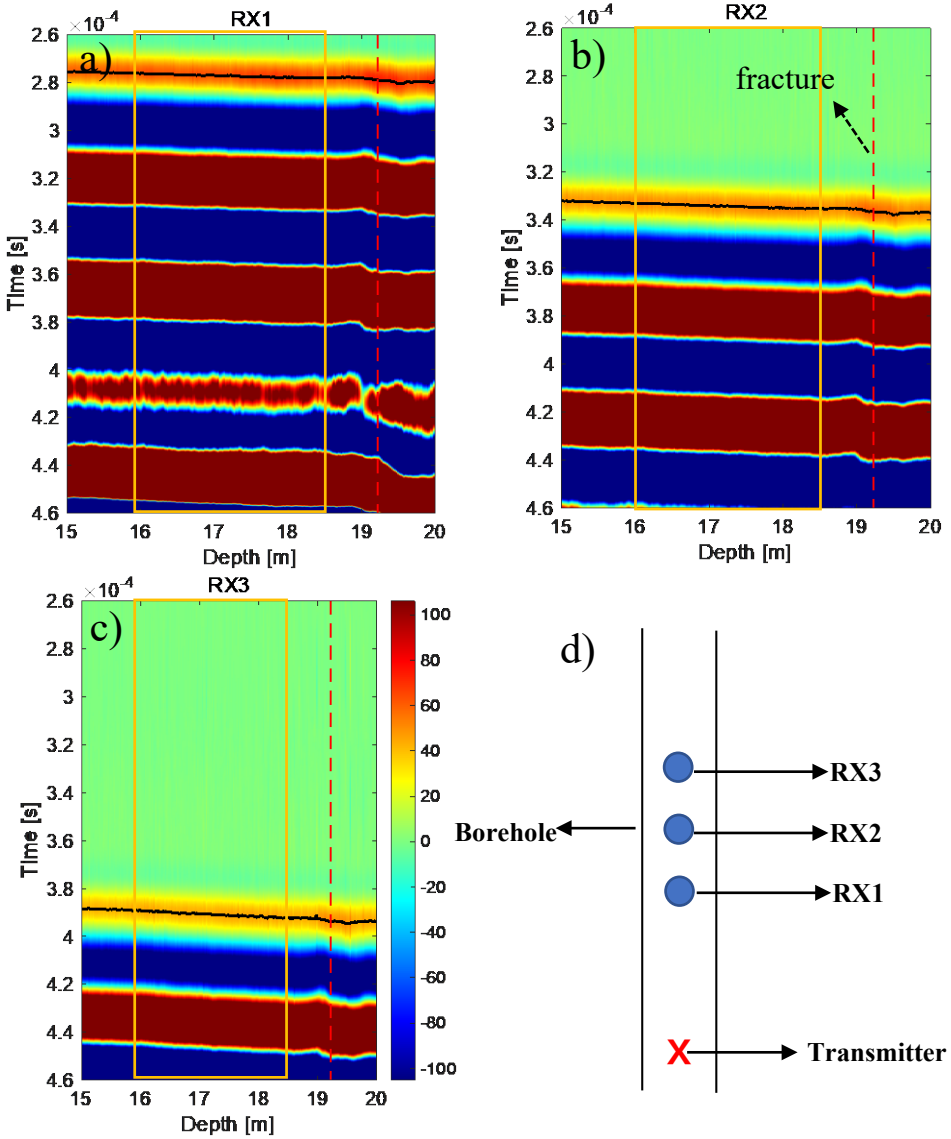
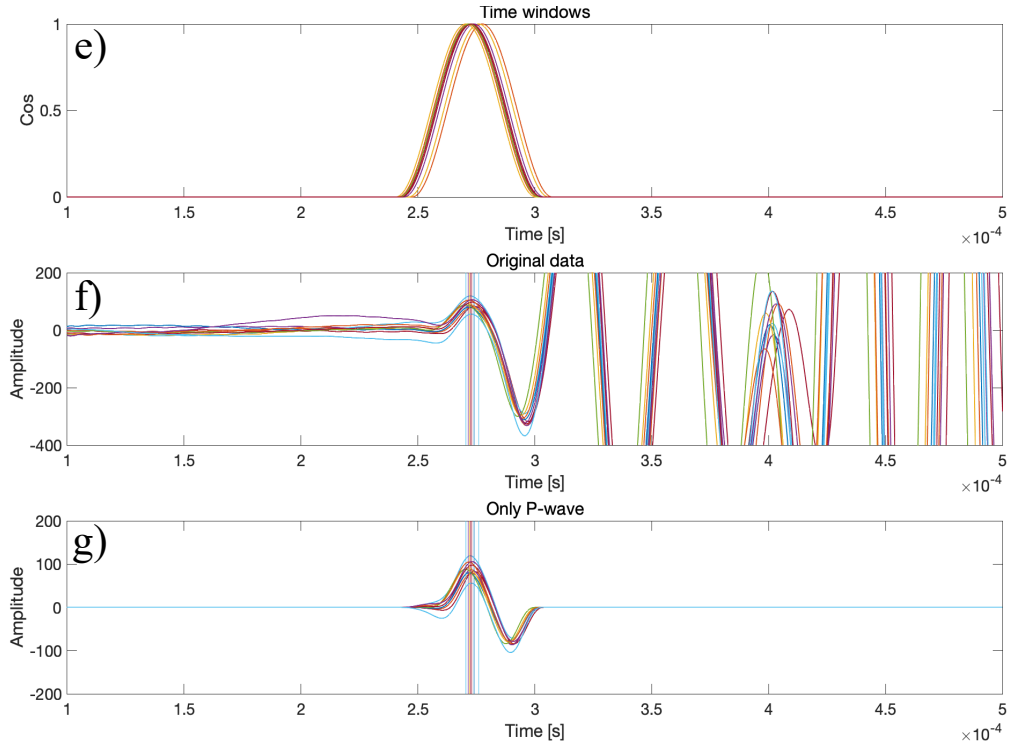


Refracted P-wave extraction



Figures a), b), and c) present a part of the recorded full-waveform sonic data shown on the previous slide for three receivers, respectively. Yellow rectangular area is chosen as intact background rock for reference trace calculation.

d) Schematic diagram of the logging tool.

e) Time window for refracted P-wave extraction from full-waveform sonic data.

f) Acquired unprocessed full-waveform sonic data.

g) Extracted refracted P-wave.

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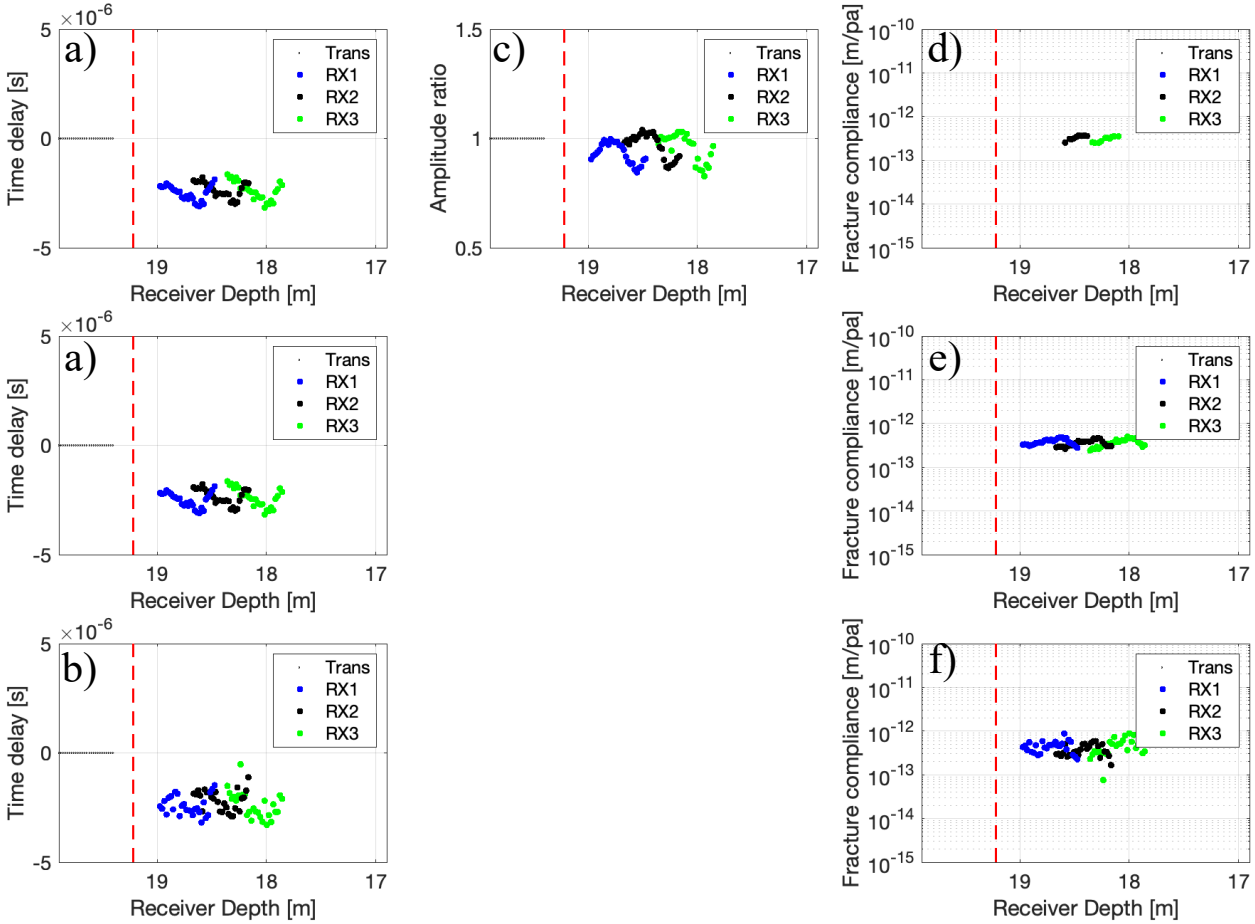
Results



- Targeted individual fracture is marked by a red dashed vertical line at 19.1 m depth.
- Transmitter (small black dots) moves up from 19.9 to 19.4 m depth; the offsets for the three receivers are 0.91, 1.22, and 1.52 m, respectively.
- Note that we repeat the same plot of the phase time delay in the first and second row for illustration purpose.

a) Frequency-dependent phase time delay (nominal source frequency 25 kHz) of refracted P-waves between intact and fractured rock sections.

b) Frequency-dependent group time delay of refracted P-waves between intact and fractured rock sections.

c) Amplitude ratio of refracted P-waves (A^{int}/A^{fra}) at nominal source frequency.

Figures d), e), and f) show normal compliance estimates of the targeted fracture estimated by transmission (Barbosa et al., 2019), phase delay, and group delay methods, respectively.

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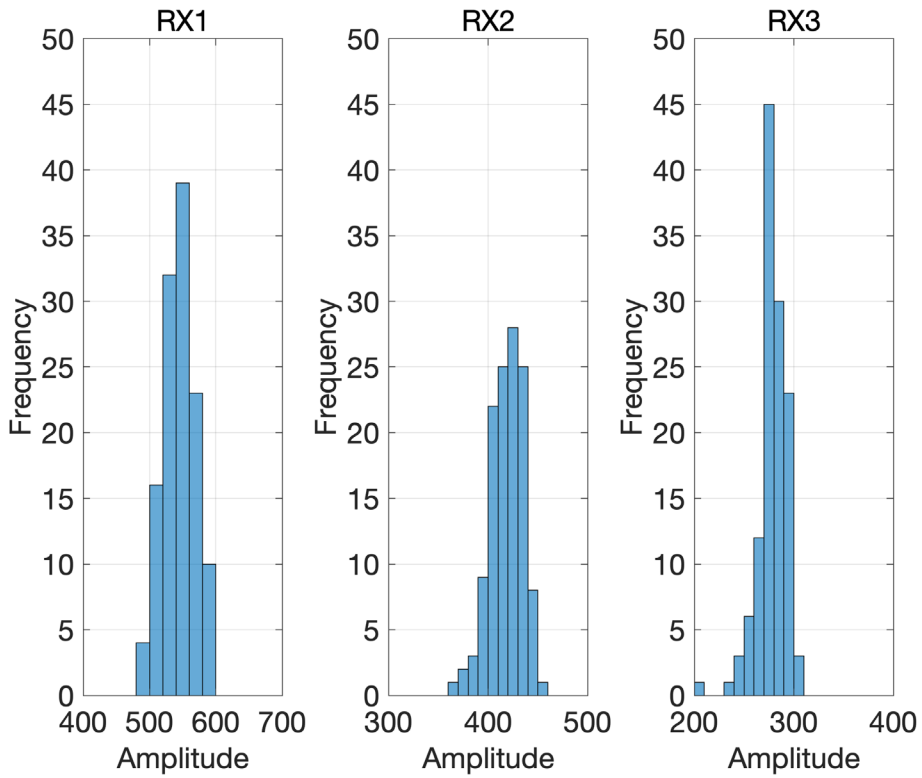
Discussion

- For the observed full-waveform sonic data, the transmission method for compliance estimation tends to be more sensitive to noise due to its reliance on the amplitude of data and their limited repeatability. This leads to an amplitude ratio (A^{int}/A^{fra}) smaller than 1 for some source locations (see figure d) on the previous slide).

- Histograms show amplitudes at the nominal source frequency for the refracted P-wave propagating across the intact rock section (yellow rectangular area on slide 9). The variability of the amplitudes is not negligible.

- The simpler time delay methods allow for a reliable estimation of fracture compliance in a noisy environment.

- The phase time delay method produces less scattered estimates than the group delay method. The latter might be more robust in the time domain, as this would allow to avoid the notorious noise amplification associated with the derivative of the frequency-domain expression.



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