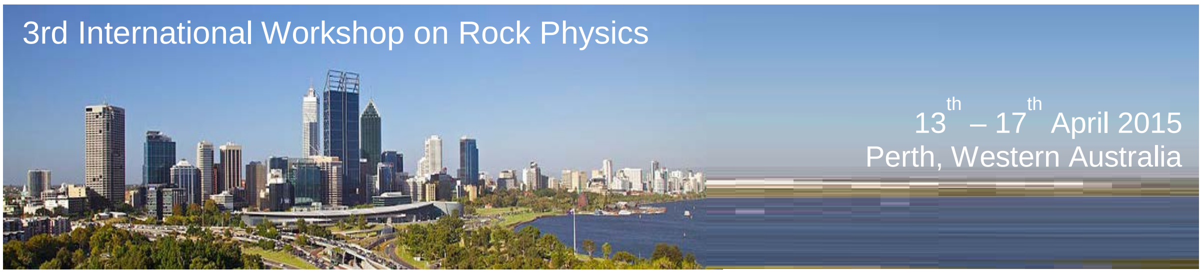

Laboratory evidence for Krauklis wave resonance in fractures

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Summary

A Krauklis wave is a unique seismic wave mode because it can lead to resonance effects in fluid-filled fractured rocks. A numerical study demonstrating that body waves are capable of initiating Krauklis waves illustrates that the initiation depends significantly on the incident wave mode (P-wave or S-wave) and fracture orientation. Here we present a laboratory study that simulates similar conditions as in the numerical experiments of a homogenous medium (i.e., Plexiglas) containing a single well-defined fracture. We record the signals obtained from propagating ultrasonic waves along a sample without a fracture and samples with a fracture with different inclination angles of 30°, 45°, and 60°. The experimental results of an incident S-wave indicate that the presence of the fracture leads to resonance effects in the recorded seismic coda at frequencies lower than the dominant source frequency, i.e. at approximately 0.1 MHz. By comparing numerical and experimental results we aim to identify relationships between the recorded seismic signal and the fracture properties (e.g., geometry, orientation, fluid type).

Introduction

The Krauklis wave is a unique guided seismic wave mode, which is bound to fluid-filled fractures and propagates along such fractures. It is expected to be able to resonate in the fracture and hence emit seismic signals with a signature frequency. This resonant behavior should lead to strong frequency dependence for seismic body waves, enabling the identification of Krauklis wave-related signals in the coda of recorded seismograms (Korneev, 2008). Aki et al. (1977), Chouet (1988), and Chouet (1996) used this resonance behavior to show the potential of volcanic eruption forecasting by recording long period volcanic tremor signals, which provide information of the state of fluid in the subsurface. The characteristics of Krauklis waves might be one of the keys to reveal properties of fluid-bearing fractured rocks.

Korneev (2009) suggested that Krauklis waves might be an important phenomenon to understand the observed frequency-dependent and nonlinear behavior of fluid reservoirs. Several theoretical studies have derived analytically the dispersion behavior of Krauklis waves in infinitely long and straight fractures (e.g., Korneev, 2008). Frehner and Schmalholz (2010) state that the resonance behavior of Krauklis waves in fractures should be incorporated into effective medium theories in order to obtain more realistic models for fractured rocks. However, purely analytical methods cannot handle realistic fracture geometries or finite-length fractures. Therefore, we combine numerical modeling results with laboratory experiments to visualize fracture-related effects on seismic wave propagation in reservoir rocks. Frehner and Schmalholz (2010) demonstrated that Krauklis waves can be detected as a converted body wave as a result of scattering at the crack tips. Moreover, Frehner (2014) employed a 2D finite-element model to demonstrate that both P- and S-waves are capable of initiating Krauklis waves. The initiation of Krauklis waves strongly depends on the incident angle and on the incident wave mode (P- or S-wave). The study shows that incident S-waves initiate larger amplitude Krauklis waves than P-waves. As a result, S-waves may carry more information about fractures such as fracture orientation or fluid content. The following laboratory study focuses mainly on the case of an incident S-wave. The numerical setup of Frehner (2014) provides the guidelines for our laboratory investigation.

Laboratory measurements

A cylindrical Plexiglas sample (120 mm length, 25 mm diameter) containing a single fracture (Figure 1a) is selected as the ideal material to mimic the simplified numerical setup. A 0.1 mm thick fracture is manufactured by cutting the sample at a given angle, milling on one side a 0.1 mm deep, 25 x 15 mm elliptical hole, and fusing the two pieces back together with chloroform (Figure 1a, b). Chemically fusing the Plexiglas with chloroform leads to an isolated fracture without interfaces around the fracture. Following this procedure, we created samples with fractures at 30°, 45°, and 60° inclination angle. We employ the ultrasonic pulse transmission method (source at position 1; receiver at position 2 in Figure 1a). The P-wave transducers are screwed embedded in the Plexiglas sample; the S-wave setup is slightly different due to the transducer's configuration. Figure 1c illustrates the experimental setup for P-wave and S-wave acquisition.

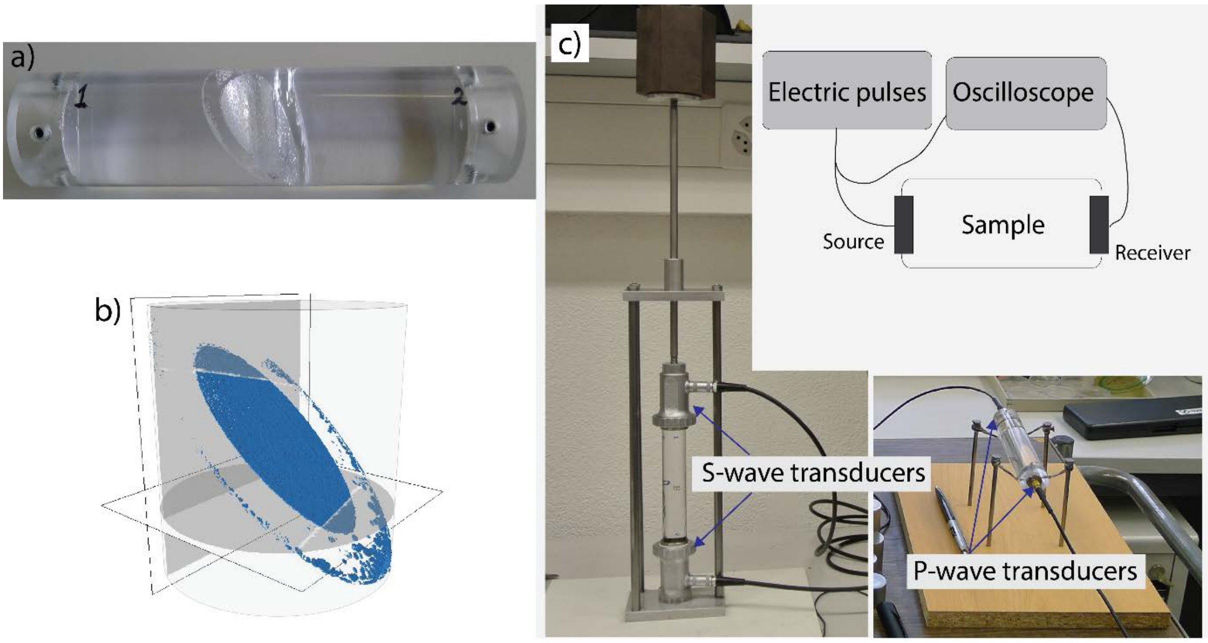

Figure 1. a) Plexiglas sample (120 mm length, 25 mm diameter) with manufactured elliptical fracture (25 x 15 mm, 0.1 mm thickness, 45° inclination angle) for P-wave acquisition. b) Segmented micro-CT scan of the same sample (transparent grey) containing the manufactured fracture (blue). c) Left: S-wave acquisition setup. The sample is placed between the S-wave transducers under a custom-made presser with a metal weight, which enhances the coupling between the sample and the transducers. Bottom right: P-wave acquisition setup. The sample is hung on top of two cotton wires to obtain the smallest possible contact surface between the sample and the means of suspension, minimizing the contact effects. The P-wave transducers are screwed embedded in the Plexiglas sample. Top right: For both setups, one transducer is connected to the electric pulser (source) and the other is connected to the oscilloscope (receiver).

Results & Discussion

Figure 3 displays the receiver spectra for an S-wave source with 1 MHz source frequency for the intact sample and for fractured samples with 30°, 45°, and 60° inclination angles. The general patterns of the receiver spectrum are similar for all four experiments. However, a fracture-related attenuation can be identified at around 0.1 MHz for all three different inclination angles. The receiver spectrum for the case of 45° fracture inclination reveals the largest attenuation as compared to the cases of 30° and 60° (Figure 3). Figure 4 presents the spectrograms of the receiver data. The presence of the fracture induces elevated amplitudes at low frequencies in the coda after the first arrival (150 µs onwards, Figure 4 b, c, d). The spectrogram for the case of 45° fracture inclination exhibits relatively larger amplitude around 0.1 MHz (200 µs, Figure 4 c) as compared to the cases of 30° and 60°. This fracture-related effect is very narrow-banded (around 0.1 MHz) and decays relatively slowly. Therefore, we interpret this effect as a resonance in the fracture.

There are differences between the numerical setup (Frehner, 2014) and the laboratory setup, such as the source and receiver positions, the fluids inside the fracture, and the source frequency range. Despite the different setups, our preliminary laboratory results coincide with the published numerical results (Frehner, 2014) where we expect the largest influence of the fracture in the case of an incident S-wave at an inclination angle of 45°.

Conclusions & Outlook

Our laboratory results show that the presence of the fracture leads to possible resonance effects at approximately 0.1 MHz, which we interpret to be caused by Krauklis waves. Our ongoing laboratory experiments might demonstrate a relationship between the measured resonance effect (frequency and decay of resonance) and fracture properties (length, aperture, orientation, fluid content).

As a first step, we will focus on predicting the fracture orientation from the recorded receiver signals by further quantifying the differences between the spectrograms for the three different fracture orientations. The major part of the spectrum is not concentrated at the source frequency (1 MHz) due to the material attenuation of Plexiglas. We plan to counter this loss by repeating the measurements using a reduced sample length. Further on, we plan to measure a wider range of inclination angles and dimensions of the fracture. Eventually, we will employ natural samples, which are more representative of natural fractured reservoirs.

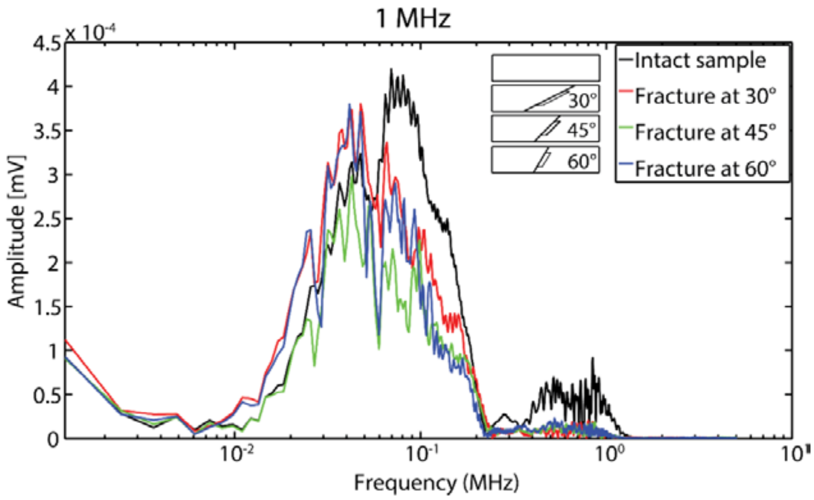

Figure 3. Receiver spectra for experiments with a dominant S-wave source frequency of 1 MHz for the intact sample and fractured samples with a fracture inclination angle of 30°, 45°, and 60°.

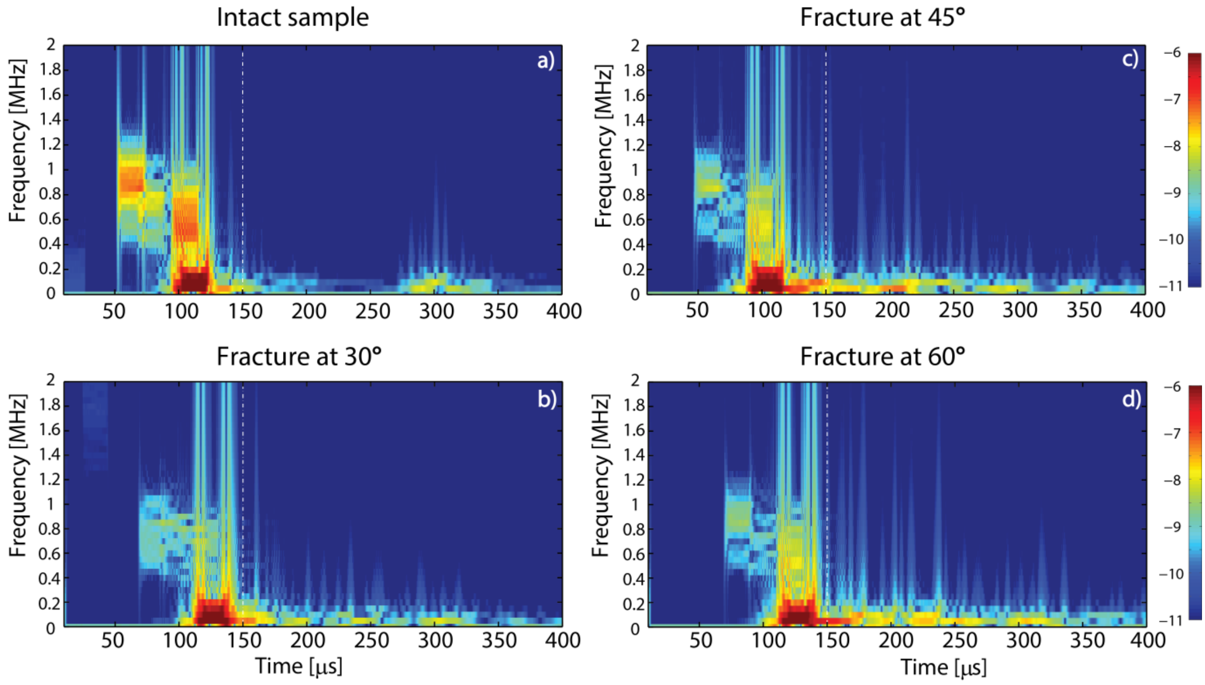

Figure 4. Spectrograms of receiver time signals generated by an S-wave with a source frequency of 1 MHz propagating through the intact sample (a) ,and fractured samples with a fracture inclination angle of 30° (b), 45° (c), and 60° (d), respectively.

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