Interface waves propagating along tensile fractures in dolomite

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Abstract. Elastic interface waves have been observed in induced tensile fractures in dolomite rock cores. Multiscaling wavelet analysis distinguishes the interface wave from bulk shear waves, quantifies the interface wave spectral content, and determines the arrival time of the peak energy. The dominant seismic energy is concentrated in the slow interface wave, with little or no detectable energy in the fast wave. As the stress across the fracture increases, the slow interface wave velocity increases, and the frequency of the spectral peak shifts to higher frequencies. The shear dynamic specific stiffness of the fracture was calculated from the peak energy arrival time as a function of stress.

Introduction

Discontinuities in rocks, such as faults, joints, and fractures, often dominate the hydraulic and mechanical properties of rock masses. Discontinuities are beneficial for water, oil and gas production, because they are highly conductive and therefore aid production. Conversely, these discontinuities are detrimental for hazardous waste isolation because they provide pathways for the escape of contaminated fluids. Locating and characterizing fractures is important for the successful exploitation of energy sources as well as for the protection of the biosphere from hazardous materials. Seismic techniques are often used to locate fractured zones in rock masses. However, seismic data may be difficult to interpret because of wave conversions that occur at interfaces and discontinuities. Converted wave modes may inhibit direct interpretation of the received signals because the source of the conversion is not always evident. Because the existence of interface waves has not been taken into account in seismic data interpretation, it is important to understand how non-welded interfaces, such as fractures and joints, give rise to interface waves and what information about the properties of fractures can be extracted from these waves.

Interface waves have been described theoretically (Pyrak-Nolte and Cook, 1987) and have been demonstrated to exist in idealized artificial fractures in aluminum (Pyrak-Nolte et al., 1992). While interface waves clearly exist in such a homogeneous system, rocks are composite materials that contain voids/pores and structural features (e.g. bedding planes) that can strongly scatter energy. Because interface waves are sensitive to material properties (seismic impedance, fracture stiffness, etc.), and source parameters (signal frequency), it is important to demonstrate that interface waves can be detected in fractures in rock. Here, we report the observation of elastic interface waves propagating along induced fractures in Dolomite rock cores. In addition, multiscale wavelet and theoretical analyses are used to extract the fracture specific stiffness as a function of stress.

Experimental Method

Interface wave measurements were performed on induced tensile fractures in solid cylinders of Dolomite, 5 cm in diameter by 4.8 cm in length. The seismic properties of the solid cores were measured before mechanically inducing tensile fractures in them. Measurements of amplitude and velocity for two polarizations of shear wave ($S_\perp$ and $S_{||}$) were made as a function of stress (0 to 8.3 MPa) on the intact sample. On the intact cores, the shear wave polarization oriented perpendicular to the plane along which the fracture would be induced is noted as $S_\perp$ and the shear wave polarization parallel to the plane along which the fracture would be induced is noted as $S_{||}$. Stress was applied normal to the plane along which the fracture would be induced. Measurements were made on the intact sample to determine the effect of stress on the bulk shear velocities ($S_\perp$ and $S_{||}$), and to determine whether the samples exhibited seismic anisotropy. Figure 1 shows the experimental setup used for these experiments.

Seismic transducers (Etalon Inc.) containing piezoelectric elements with a resonant frequency of 1 MHz were mounted straddling the center line on the faces of the core. The input pulse to the transducers (for both intact and fractured samples) consisted of a 300 V spike with a 0.4 μs duration and a repetition rate of 100 Hz (Cober Pulse Generator Model 505). The received waveforms were digitized (LeCroy 9314L oscilloscope) and stored on a computer for analysis. Arrival times were read to within 0.01 microseconds.

After characterization of the intact core, a tensile fracture was induced in the samples using a technique similar to Brazil-testing (Jaeger & Cook, 1979). The induced fracture spanned the diameter of the core and ran parallel to the long axis. With

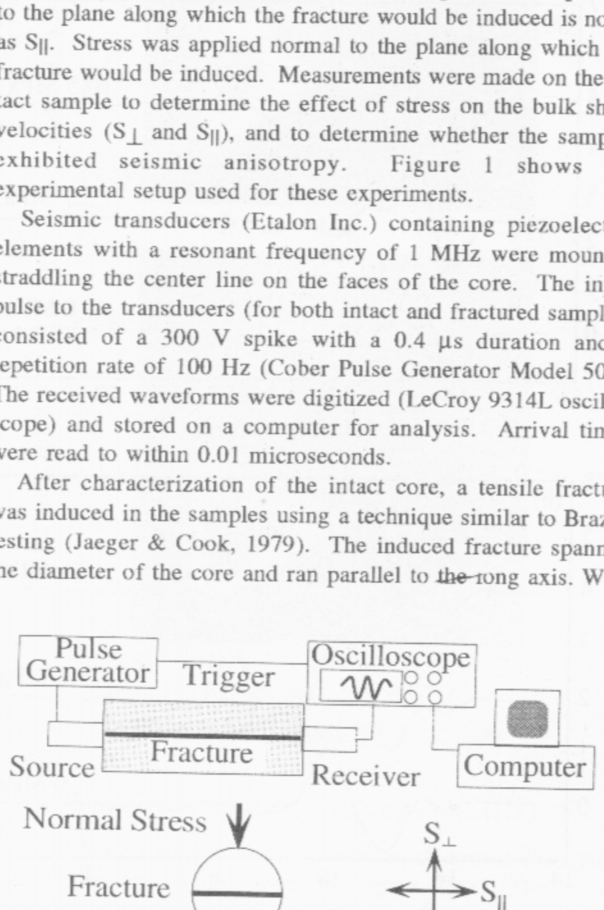

Figure 1. Experimental set-up for measuring interface waves on rock cores. The shear wave polarizations ($S\perp$ and $S_{||}$) are oriented with respect to the fracture plane (solid line).

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the seismic transducers straddling the fracture, measurements of $S_{||}$ and $S_{\perp}$ wave amplitudes and velocities were made as a function of stress (0 MPa - 10.51 MPa). Stress was applied normal to the fracture plane, along the same line as for the measurements made on the intact sample.

Experimental Results

Effect of Stress

Stress did not affect the arrival time of the bulk shear waves ($S_{||}$ and $S_{\perp}$) propagating through the intact sample. The received waveforms for the intact sample for two different polarizations are shown in Figures 2A and 2B. From measurements of first arrival times, the velocities of the $S_{\perp}$- and the $S_{||}$ waves were 3298 m/sec ±2 m/sec, and 3285 m/sec ± 2 m/sec, respectively.

On the fractured sample, the $S_{||}$-wave was not affected by applying stress across the fracture (Figure 2A). However for the $S_{\perp}$-wave (Figure 2B), as the stress across the fracture was increased, there was a shift in the main peak of the waveform by 0.60 μs towards earlier arrival time. There was also a change in phase around the shear-wave arrival of 14.93 μs. Both a fast and a slow wave have been shown to exist along a fracture (Pyrak-Nolte and Cook, 1987, Pyrak-Nolte et. al. 1992, Gu, 1994). However, only the slow wave was discernible on the received waveforms.

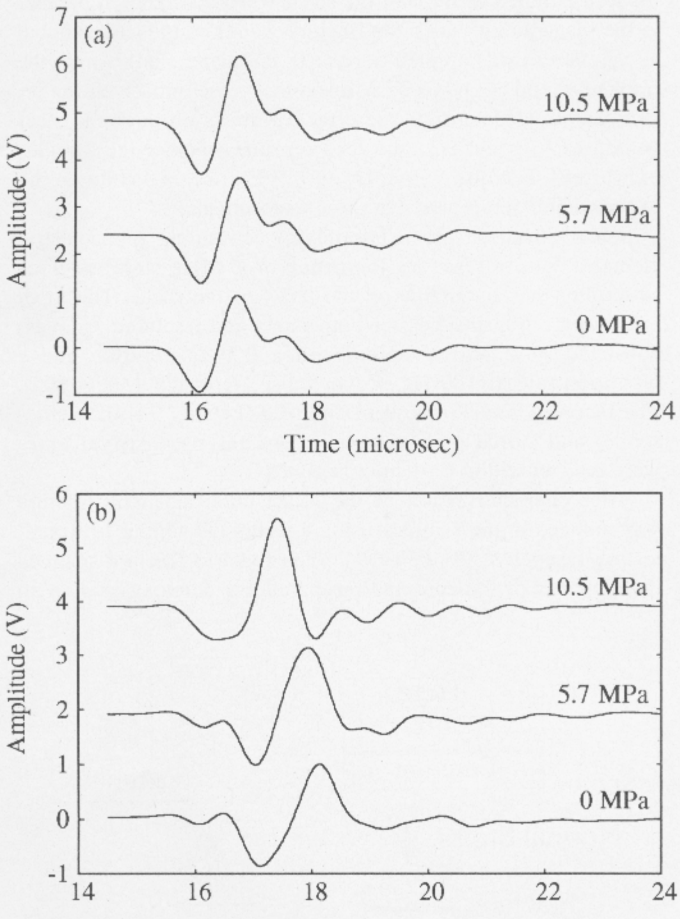

Figure 2. (a) Shear waveforms ($S_{||}$) propagated through fractured rock as a function of normal stress. (b) Shear waveforms ($S_{\perp}$) propagated through fractured rock as a function of normal stress.

Wavelet Analysis

Because the sample is short and the interface wave velocities range between bulk shear and Rayleigh wave velocities, the arrival time of the interface waves could not be easily discerned from the waveforms. The velocity of the interface wave is needed to determine the stiffness of the fracture. We applied wavelet analysis to the signal to determine the arrival time of the peak energy of the interface waves. Wavelet analysis, also known as multi-resolution analysis, uses a series of scaled and delayed oscillatory functions to decompose a time-varying signal into its non-stationary spectral components. Though similar to windowed Fourier Transforms, the advantage of wavelet analysis is that it maintains equal accuracy in both frequency and time space. A non-orthonormal Morlet (Morlet et. al., 1982) mother wavelet composed of a harmonic wave modulated by a Gaussian envelope is scaled and delayed to produce a set of daughter wavelets. The wavelet transform, as a function of scale and time delay, is obtained by integrating the time-varying signal over the daughter wavelets. A detailed description of the technique used in our analysis can be found in (Pyrak-Nolte & Nolte, 1995).

Wavelet analysis was performed on the $S_{\perp}$ and the $S_{||}$ waveforms measured for the intact sample. From the wavelet analysis, the peak in spectral energy occurred at 0.74 MHz, and arrived at 16.37 μs ($V_{S\perp peak}$ = 3089 m/sec) for the $S_{\perp}$ wave, and 16.50 μs ($V_{S||peak}$ = 3064 m/sec) for the $S_{||}$-wave. Figure 3 shows the wavelet spectrum for the $S_{||}$-wave for the fractured sample as a function of stress. No shift in arrival time or frequency content of the peak spectral energy was observed as stress across the sample was increased. This is consistent with the original waveforms (Figure 2A) which are very similar over the range of stresses studied. For the fractured sample, the peak in spectral energy occurred at 0.50 MHz, and arrived at 16.50 μs ($V_{S||peak}$ = 3064 m/sec). That is, $V_{S||peak}$ for the fractured sample was the same as that of the intact sample, indicating that for such a polarization, only the bulk shear wave was observed, with a reduced frequency at the spectral peak for the fractured sample (0.5 MHz as compared to 0.74 MHz for the intact sample)

Figure 4 shows the wavelet spectra for the $S_{\perp}$ waveforms for the fractured sample as a function of normal stress across the fracture. For this polarization, as the stress across the fracture was increased, the arrival time of the spectral peak decreased by 0.6 μs (from 17.833 μs to 17.233 μs). This decrease in arrival time is consistent with the behavior of interface waves as the stiffness of the fracture is increased (Pyrak-Nolte et. al., 1992). The high frequency lobe occurring at 16.37 μs (Figure 4A, shown with the blue arrow), is consistent with the arrival time of the bulk wave on the intact rock. The merging of this lobe with the lobe occurring around 18.233 μs (Figure 4A, shown with the red arrow) with increasing stress illustrates the change in energy partitioning between the interface waves and the bulk $S_{\perp}$ waves. Gu (1994) found numerically that energy partitioning between bulk shear waves and interface waves is a complicated function of fracture stiffness, signal frequency and material properties (seismic impedance). The wavelet analysis has enabled us to observe the energy partitioning between bulk and interface waves, and to extract quantitative values to use in the determination of the fracture specific stiffness.

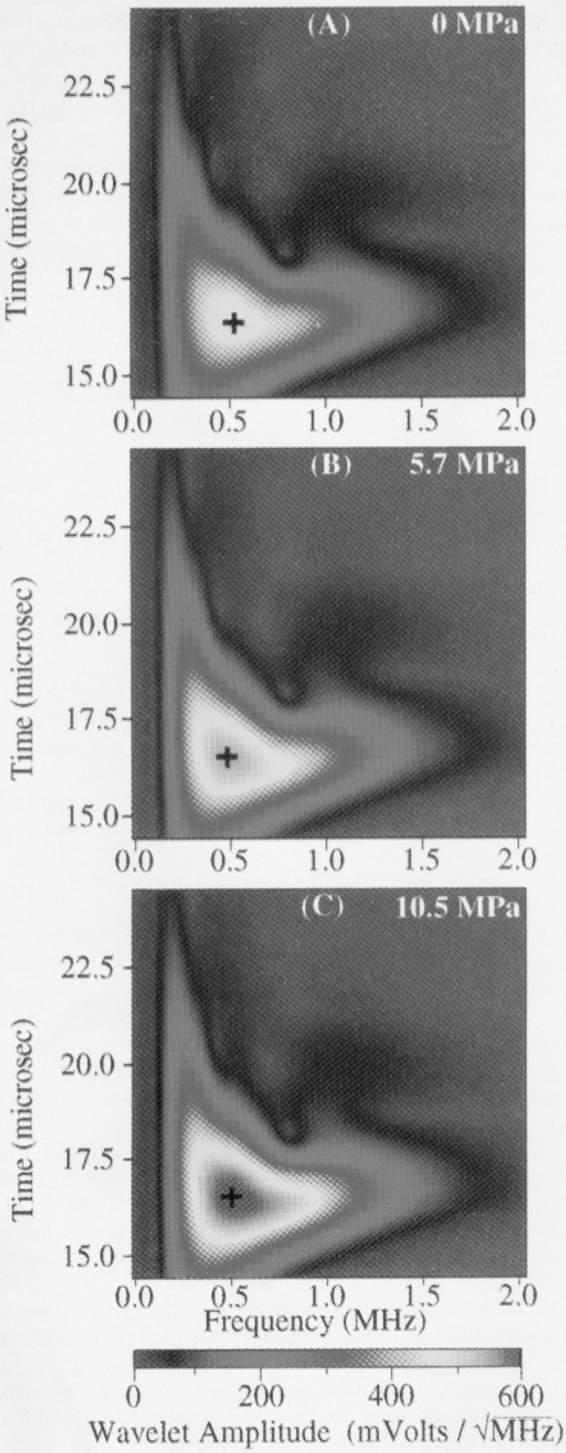

Figure 3. Wavelet transform as a function of normal stress for shear waveforms ($S_{||}$) given in Figure 2(a). The color indicates the strength of the transform. The cross-hair (+) indicates the peak of the transform that gives the arrival time and frequency of the dominant group energy.

›etermination of Dynamic Fracture Stiffness

›acture specific stiffness has been shown theoretically and ›mentally to depend on the contact area between the › of the fracture and the aperture distribution of the 'Bandis et. al., 1983, Brown and Scholz, 1985 and kins et. al., 1987 and 1990, Pyrak-Nolte et. al., 1990, Yoshioka and Scholz, 1989a, 1989b). Because fracture stiffness depends on the geometry of the voids in the fracture, it is implicitly related to the hydraulic properties of the fracture (Pyrak-Nolte et. al., 1995). Arrival times of the peak

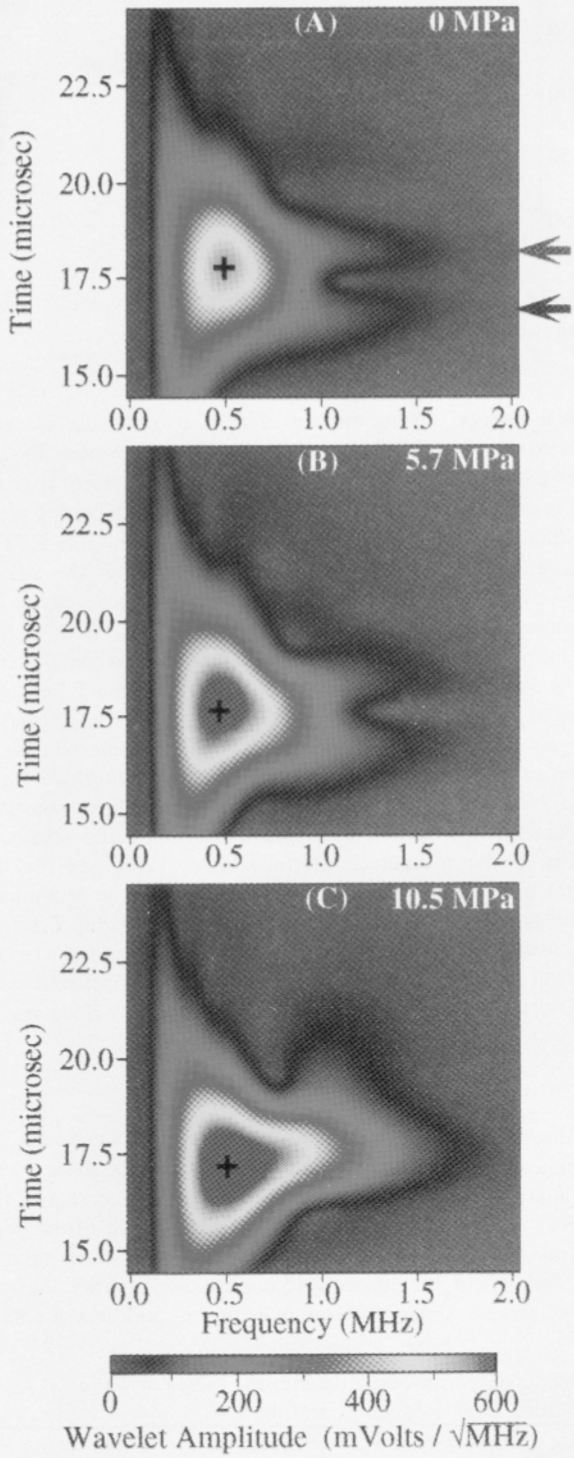

Figure 4. Wavelet transform as a function of normal stress for shear waveforms ($S_{\perp}$) given in Figure 2(b). The color indicates the strength of the transform. The cross-hair (+) indicates the peak of the transform that gives the arrival time and frequency of the dominant group energy. The two high frequency energy lobes occurring at 16.37 μs (blue arrow) and 18.233 μs (red arrow) illustrate the change in energy partitioning with increasing stress.

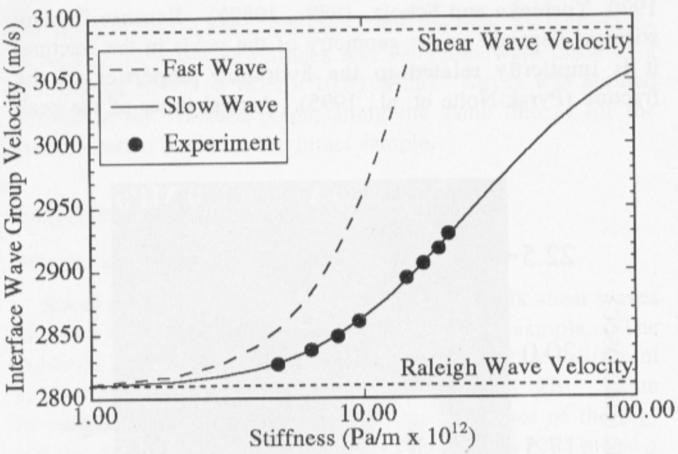

Figure 5. Theoretical and measured group velocity as a function of fracture specific stiffness.

spectral energy from the wavelet analysis for intact and fractured samples, and the theory for interface waves (Pyrak-Nolte and Cook, 1987) were used to fit fracture specific stiffness. Theoretical interface wave group velocities were generated using the measured parameters listed in Table 1. The measured intact velocities were determined from the arrival times of the spectral peak determined from wavelet analysis for the intact sample. The frequency and arrival time of the spectral peak for the fractured sample was used to calculate the interface wave group velocity, and was determined from the wavelet spectrum.

Figure 5 shows the experimentally measured interface wave velocities (closed circles) and the theoretical interface wave group velocities (solid curves). From the analytical solution, the only fittable parameter is the fracture specific stiffness. By fitting the measured interface wave velocities for the stresses used in the experiment, fracture stiffness is determined to vary between 6.0×10^{12} Pa/m and 2.0×10^{13} Pa/m. Fracture stiffness for the lowest stresses (0 to 4.9 MPa) could not be determined from the group velocities which is consistent with the theory that shows that the velocity of the interface waves are constant at low fracture specific stiffness.

Summary

Through multiscale wavelet analysis, we were able to distinguish the slow interface wave from the bulk shear wave. This analysis enabled us to quantify the spectral content of the interface waves, and to determine the arrival time of the peak spectral energy. The good fit between the experimental observation and the theoretical curves demonstrate that we have observed interface waves in rock. In addition, we have used the theoretical curves to fit specific stiffness to the fracture as a function of stress. Interface waves, and wavelet analysis exhibit great potential for characterizing fractures in rock. While the experimental geometry is not conducive to field application (i.e., spanning the ends of the fracture with sender and receiver), off-fracture generation of interface waves is possible, and would not require access to both ends of the fracture (Pyrak-Nolte and Roy, unpublished results).

Table 1. Experimentally determined values of wave velocities, peak frequency, and density.

Intact Compressional Wave Velocity	4040 m/s
Intact Shear Wave Velocity (S⊥)	3089
Frequency	0.49 MHz
Density	2700 kg/m^3

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