CHARACTERIZING FRACTURE DAMAGE AT FROZEN AND UNFROZEN SITES IN THE ALASKA FROZEN ROCK EXPERIMENT AND ITS EFFECT ON SEISMIC RADIATION

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ABSTRACT

In order to assess the effect of ice on seismic coupling of explosions in frozen rock, a consortium of Weston Geophysical, New England Research, and the University of Southern California planned and executed a field experiment near Fairbanks, Alaska. Chemical explosions between 200 and 350 lbs were detonated at two sites: one in a dry schist above the water table and the other in a saturated frozen gneiss. The most significant difference between the seismic radiation from the two sites was the generation of more high frequency energy at the frozen site resulting in a higher corner frequency and, therefore, a smaller elastic radius. Explosions at the two sites were modeled using the Johnson-Sammis (2001) non-linear model that includes the Ashby-Sammis (1990) damage mechanic. This damage mechanics requires an estimate of the initial damage at each site, which we obtain by combining the seismic velocities measured by Weston Geophysical with the laboratory ultrasonic velocities measured in samples of the two source rocks by New England research. Using the self-consistent theory developed by O'Connell and Budiansky (1974), the ultrasonic data were used to find the undamaged moduli. These undamaged moduli were then used together with the seismic data to estimate the initial damage at the frozen and at the unfrozen sites. The lower value of initial damage found for at the frozen rock site, when used in the source model, predicted a smaller elastic radius and higher frequency seismic radiation than did an equivalent calculation using the higher value of initial damage found at the unfrozen site, in agreement with the field observations. The lower value of initial damage found at the frozen rock site is also consistent with the field observation that explosions at the frozen rock site produced larger fragments.

OBJECTIVE

In order to assess the effect of ice on seismic coupling of explosions in frozen rock, a consortium of Weston Geophysical, New England Research, and the University of Southern California planned and executed a field experiment near Fairbanks, Alaska. Chemical explosions between 200 and 350 lbs were detonated at two sites: one in a dry schist above the water table and the other in a saturated frozen gneiss. The objective of the work described here is to combine the seismic P and S wave velocities measured in the field with ultrasonic velocities measured in the laboratory to estimate the initial fracture damage at each site. We wish to test the hypothesis that the dry schist above the water table has a higher value of initial damage than does the saturated frozen gneiss, and that this higher value of initial damage results in a larger elastic radius and lower corner frequency as observed in the field experiment.

RESEARCH ACCOMPLISHED

During the past year, we have collaborated with Weston Geophysical and New England Research in the interpretation of data from the Alaska frozen rock experiment conducted by Weston Geophysical during the summer of 2006. Our working hypothesis has been that ice in the cracks of the source rock produced significant stiffening and strengthening that affected the seismic coupling, which led to the smaller apparent size.

In the Alaska experiment, seismic radiation from chemical explosions in dry schist (above the water table) was compared with explosions having the same yield, but set off in a frozen gneiss. The primary result, shown in Figure 1, was that the spectral levels of radiation from both sites were comparable, but the corner frequency of radiation from the frozen rock site was higher. This higher corner frequency would lead to the erroneous conclusion that the explosion in frozen-rock was smaller.

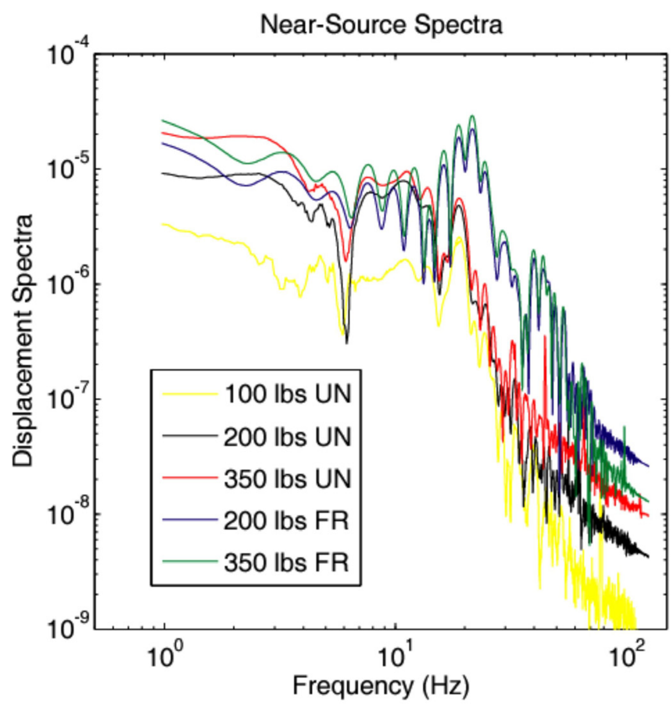

Figure 1. Displacement spectra for explosions in unfrozen dry schist (UN) and frozen gneiss (FR). Note the spectral peak and higher corner frequency for shots at the frozen site. (Figure courtesy of Jessie Bonner at Weston Geophysical).

In order to make a quantitative interpretation of this result, we wish to model the Alaska explosions using the Johnson and Sammis (2001) source model. This model incorporates the Ashby and Sammis (1990) micromechanical damage mechanics, which we have previously shown gives a good description experimental data for the temperature dependence of strength in frozen crystalline rock (Sammis and Biegel, 2004, 2005). The basic idea is that ice in the cracks strengthens the rock and increases its elastic stiffness by reducing the initial damage D_o.

In the Ashby and Sammis (1990) formulation, the initial damage D_o is defined as

$$D_o = \tfrac{4}{3}\pi N_V \langle a \rangle^3 \qquad (1)$$

where N_V is the number of cracks per unit volume and $\langle a \rangle$ is the average radius of these cracks which comprise the initial damage. When water in the cracks freezes, it immobilizes some of them, reducing N_V thereby lowering D_o. Ice bridges in longer cracks reduce their effective radius a, also reducing D_o.

Our hypothesis is that frozen rock has a smaller D_o than does unfrozen rock. In our source model, this results in less explosion-induced damage in the frozen rock, and a higher corner frequency – as observed.

We use the theory developed by O'Connell and Budiansky (1974) to estimate D_o from the seismic velocities measured by Weston Geophysical at each field site. Figure 2 from their paper shows the ratios $\bar{v}_P / v_P$ and $\bar{v}_S / v_S$ as functions of a crack density parameter, which they define as $\varepsilon = N_V \langle a \rangle^3$ and which is simply related to D_o in equation (1) as

$$D_o = \tfrac{4}{3}\pi \varepsilon \qquad (2)$$

The quantities $\bar{v}_P$ and $\bar{v}_S$ are velocities in the fractured rock, while v_P and v_S are velocities in the unfractured rock.

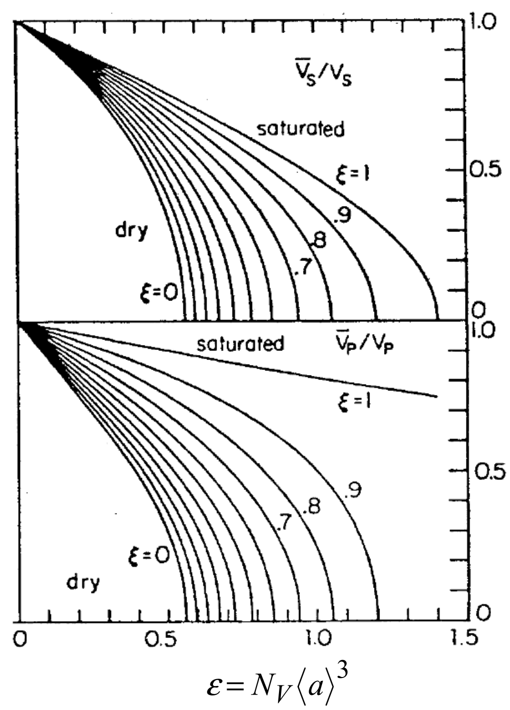

Figure 2. Decrease in velocity with increasing fracture parameter ε. Velocities in the damaged rock, $\bar{V}$, are scaled by the velocities in undamaged rock V. (From O'Connell and Budiansky, 1974).

In order to use Figure 2 to find the crack density parameter ε (and hence the initial damage D_o) from the seismic velocities ($\bar{v}_P$ and $\bar{v}_S$) at each test site, we need to know the un-fractured velocities (v_P and v_S) for the source rock at each site (the schist and the gneiss). These we estimate using the ultrasonic velocities measured in laboratory samples of each rock type by New England Research (NER).

For the schist source rock from the dry (un-frozen) site, NER measured P and S wave velocities under dry, saturated, and frozen conditions, at confining pressures ranging from 5 to 70 MPa. Table 1 summarizes the values at 5 and at 70 MPa - values at intermediate pressures vary monotonically between these limits.

Table 1. Ultrasonic data for schist source rock from the dry unfrozen site.

	P (MPa)	$\bar{v}_P$ (m/s)	$\bar{v}_S$ (m/s)	ν	v_P^* (m/s)	v_S^* (m/s)
Dry	5	4150	2800	0.082	5253	3294
	70	4750	3200	0.085	5723	3556
Saturated	5	5200	3000	0.25	5306	3261
	70	5450	3400	0.18	5561	3579
Frozen (-8C)	5	5800	3700	0.16		
	70	5700	3700	0.14		

*Unfractured reference velocities v_P and v_S found using ε_P and ε_S from Table 2.

The last two columns of Table 1 contain estimates of the un-fractured P and S wave velocities that were made using the calculations summarized in Table 2. In Table 2, values of $\frac{\bar{v}_P(sat.)}{\bar{v}_P(dry)}$ and $\frac{\bar{v}_S(sat.)}{\bar{v}_S(dry)}$ are calculated from the data in Table 1. Note that $\frac{\bar{v}_P(sat.)}{\bar{v}_P(dry)} = \frac{\bar{v}_P(sat.)/v_P}{\bar{v}_P(dry)/v_P}$ and that $\frac{\bar{v}_S(sat.)}{\bar{v}_S(dry)} = \frac{\bar{v}_S(sat.)/v_S}{\bar{v}_S(dry)/v_S}$ and that the ratios on the right hand side of these equations can be found as a function of ε in Figure 2 and are plotted explicitly in Figure 3. The values of ε in Table 2 were found using Figure 3 as indicated on the figure. Once ε was determined, the ratios $\bar{v}/v$ were found from Figure 2 and appear in the last four columns of Table 2. These ratios were used together with the measured seismic velocities to calculate the un-fractured velocities in the gneiss samples, which are give in the last two columns of Table 1. Note that the un-fractured velocities found by this method are very similar to the velocities measure in the frozen samples. This observation supports our assumption that ice immobilizes the fractures.

Table 2. Ultrasonic velocity ratios used to find fracture parameter ε in gneiss lab samples.

P (MPa)	$\frac{\bar{v}_P(sat.)}{\bar{v}_P(dry)}$	$\frac{\bar{v}_S(sat.)}{\bar{v}_S(dry)}$	ε_P	ε_S	$\frac{\bar{v}_P}{v_P}$ (dry)	$\frac{\bar{v}_P}{v_P}$ (sat.)	$\frac{\bar{v}_S}{v_S}$ (dry)	$\frac{\bar{v}_S}{v_S}$ (sat.)
5	1.25	1.07	0.18	0.16	0.79	0.98	0.85	0.92
70	1.15	1.06	0.13	0.15	0.83	0.98	0.90	0.95

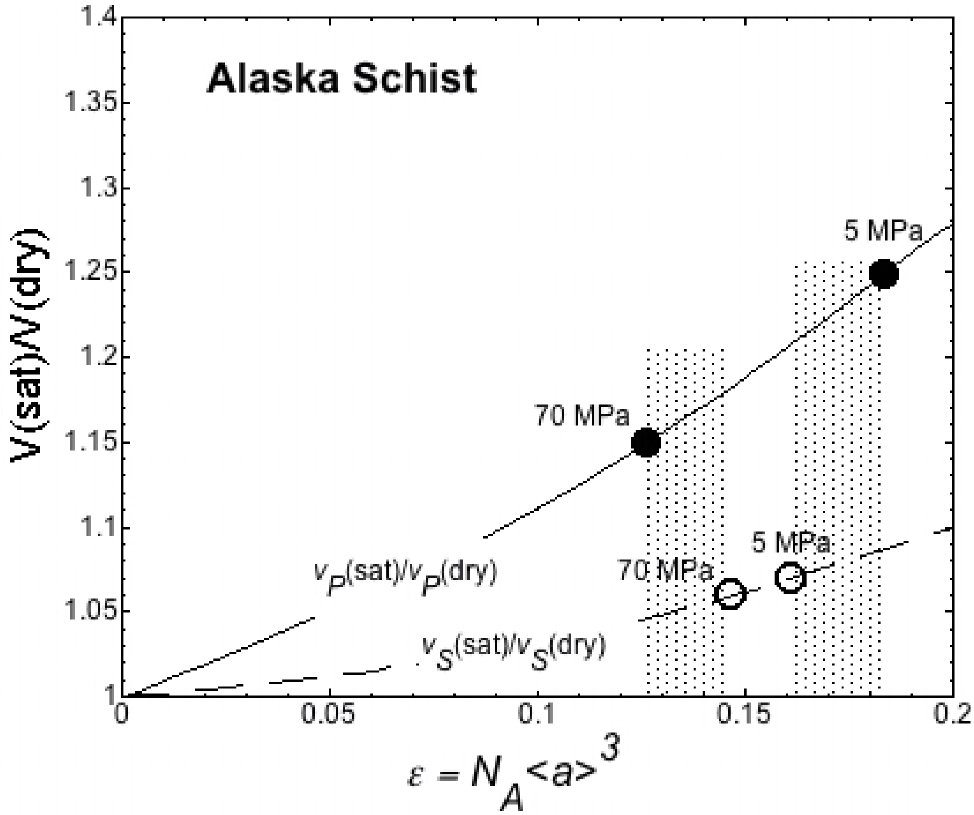

Figure 3. The ratio of saturated to dry velocities as a function of the crack parameter e. The curves were calculated from Figure 2. The points are ratios of the ultrasonic data for schist from Table 1. Note the decrease in crack parameter as confining pressure closes cracks.

For the gneiss source rock from the frozen site, NER measured P and S wave velocities under saturated and frozen conditions, also at confining pressures ranging from 5 to 70 MPa. Table 3 summarizes the values at 5 and at 70 MPa - values at intermediate pressures vary monotonically between these limits.

Table 3. Ultrasonic velocities for gneiss source rock from the frozen site.

	P (MPa)	$\bar{v}_P$ (m/s)	$\bar{v}_S$ (m/s)	ν
Saturated	5	5450	3050	0.27
	70	5550	3200	0.25
Frozen (-8C)	5	5800	3400	0.24
	70	5800	3450	0.23

Since no measurements were made under dry conditions, we can not use the same method we used to estimate the un-fractured velocities in the schist. However, based on the results for the schist, we can assume that the frozen velocities are a reasonable approximation to the un-fractured velocities.

Having estimated the un-fractured velocities v_P and v_S for both source rocks, it is now possible to estimated the fracture parameter at each test site. The seismic field velocities and implied fracture parameters at each site are summarized in Table 4.

Table 4. Ultrasonic velocities for schist source rock from the dry unfrozen site.

	$\bar{v}_P$ (m/s)	$\bar{v}_S$ (m/s)	ν	$\frac{\bar{v}_P}{v_P}$	$\frac{\bar{v}_S}{v_S}$	ε_P	ε_S	$\langle\varepsilon\rangle$	$\langle D_o\rangle$
Unfrozed Site	2700	1700	0.17	0.47	0.46	0.41	0.45	0.43	1.80
Frozen Site	3800	2400	0.17	0.66	0.65	0.28	0.35	0.31	1.30

Note that for both P and S waves, the fracture parameter ε, and the equivalent initial damage D_o, is larger at the unfrozen site, consistent with the hypothesis that ice reduces the fracture density in the source rock. When these values of D_o are used in the Johnson and Sammis (2001) source model, the unfrozen site has a larger elastic radius and lower corner frequency than the frozen site, as observed in the Alaska frozen rock experiment.

CONCLUSIONS AND RECOMMENDATIONS

The hypothesis that ice in cracks decreases the fracture damage is supported by a joint quantitative analysis of the seismic velocities at the frozen and dry un-frozen test sites in the Alaska frozen rock experiment and ultrasonic velocity measurements on lab samples from the two sites. The lower initial damage at the frozen site results in a smaller elastic radius and higher corner frequency as observed.

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