

PREPARING FOR THE 2006 ALASKA PERMAFROST EXPERIMENT

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ABSTRACT

The objective is to measure the effect of ice in rock on the seismic coupling of explosions. This study is motivated by discrepancies in modeling Soviet explosions at their arctic test site at Novaya Zemlya. In support of the Alaska field experiment, we have used the damage mechanics model developed by Ashby and Sammis (1990) to interpret laboratory data on the strength of frozen rock (Sammis and Biegel, 2004). In this model the increase in rock strength as a function of decreasing temperature is explained by the increase in the flow strength of ice asperities in the cracks as the temperature drops. Since the flow stress in ice is also strain dependent, we expect frozen rock to reach its low-temperature strength limit at the high strain rates in an explosion source region, even though its temperature is not very far from the freezing point. However, if the ice temperature is too near 0°C, then this strain-rate-dependent strengthening may be limited by pressure melting, a phenomenon we explore in this paper. The elasticity model of O'Connell and Budianski (1974) was used to calculate the increase in the elastic moduli caused by ice in the cracks (Sammis and Biegel, 2005). We have used the "equivalent elastic medium model" for an explosive source developed by Johnson and Sammis (2001) to explore the effect of an increase in both elastic stiffness and compressive strength on the amplitude of far-field seismic radiation. We found that an increase in the elastic moduli produces a decrease in the far-field amplitudes, as does an increase in the coefficient of static friction and the consequent increase in compressive strength. Our conclusion is that an explosion in frozen rock should have a smaller apparent yield than the same explosion in rock at temperatures above the freezing point and that the effect should be larger in limestone than in granite, although these effects can be reduced by pressure melting at rock temperatures near 0°C.

OBJECTIVES

The objectives of this research program are to accomplish the following:

1. Build the micromechanical damage mechanics developed by Ashby and Sammis (1990) into source models for underground explosions.
2. Use this model to explore the influence of site effects such as rock type, groundwater saturation, permafrost, and depth of burial on the seismic signature generated by the explosion.
3. Use this model to help interpret laboratory measurements and field experiments.
4. Explore the possibility that secondary radiation generated by the damage contributes to the regional seismic phases.

RESEARCH ACCOMPLISHED

Introduction

The Soviet test site at Novaya Zemlya at 73° north latitude lies well above the Arctic Circle. Rock at this site is probably below the freezing point of water to a considerable depth. Permafrost thickness is greatest in non-glaciated polar regions like Siberia, where a record depth of 4,900 feet to the permafrost base has been reported. Permafrost thickness in arctic Canada has been estimated to exceed 3,000 feet, and in arctic Alaska it may exceed 2,000 feet. The question has therefore arisen as to how frozen water in cracks and pores might affect the seismic signature of an underground explosion.

Sammis and Biegel (2004) interpreted uniaxial compressive and tensile strength data on frozen rock from Mellor (1973) using the micromechanical damage model developed by Ashby and Sammis (1990). In this model, sliding on preexisting cracks in rock induces additional fracture damage and ultimate failure. The effect of ice in the damage model is to increase the effective coefficient of sliding friction on the preexisting cracks, thus inhibiting the generation of new damage and strengthening the rock. In addition to strengthening, the damage model was also able to explain some of the subtler phenomenology in the frozen rock data, such as the differences between porous and crystalline rock and the progressive strengthening observed to occur as the temperature was lowered from 0°C to -150°C. A second effect of ice in cracks in rock is to increase the elastic moduli by sealing small cracks and shortening longer cracks by ice bridging.

Sammis and Biegel (2005) used the “equivalent elastic medium source model” developed by Johnson and Sammis (2001) to investigate the effects of frozen water in the cracks of crystalline rock on the seismic radiation from an underground explosion. They found that an increase in the elastic moduli produces a decrease in the far-field amplitudes. This was not surprising because it is well known that the apparent yield of an explosion decreases as the inverse of the shear-wave velocity in the source rock. An increase in the coefficient of static friction in the cracks, and consequent increase in compressive strength, also reduces the amplitude of the far-field seismic radiation. Their conclusion was that an explosion in frozen rock should have a smaller apparent yield than the same explosion in rock at temperatures above the freezing point, and that the effect should be larger in limestone than in granite.

In order to test these ideas, an initiative has been launched to detonate identical chemical explosions above and below the permafrost layer in Alaska to see if the expected differences in seismic coupling are observed. There is some concern that temperatures in the permafrost hole are only -0.2°C which because of an interaction between the water and minerals, may not be cold enough to form ice in the cracks. There is also some concern that ice this near its melting temperature may not significantly strengthen the rock. We address the latter concern in this report by showing that significant strengthening should occur near 0°C at the high strain rates in the nonlinear region of an explosion. We begin with a brief review of the mechanical effects of ice in the cracks of crystalline rock and then present a simulation of an 800 lb explosion at a depth of 20 m in hard rock.

The Mechanical Effects of Ice in the Cracks of Crystalline Rock

When water in the cracks of crystalline rock freezes, it affects the mechanical properties in two ways: (1) it increases the elastic moduli, and (2) it increases the strength. Both effects can be understood in the context of the micromechanical damage mechanics developed by Ashby and Sammis (1990).

The Effect of Ice on Elastic Properties

In the Ashby and Sammis (1990) damage mechanics, the size and density of fractures in crystalline rock are characterized by a single parameter called damage. The initial damage, before loading, is defined as

$$D_0 = \frac{4}{3} \pi (a \cos \chi)^3 N_V \quad , \quad (1)$$

where a is the half-length of the cracks, N_V is the number of cracks per unit volume, and χ is an angle describing their orientation (see Figure 1).

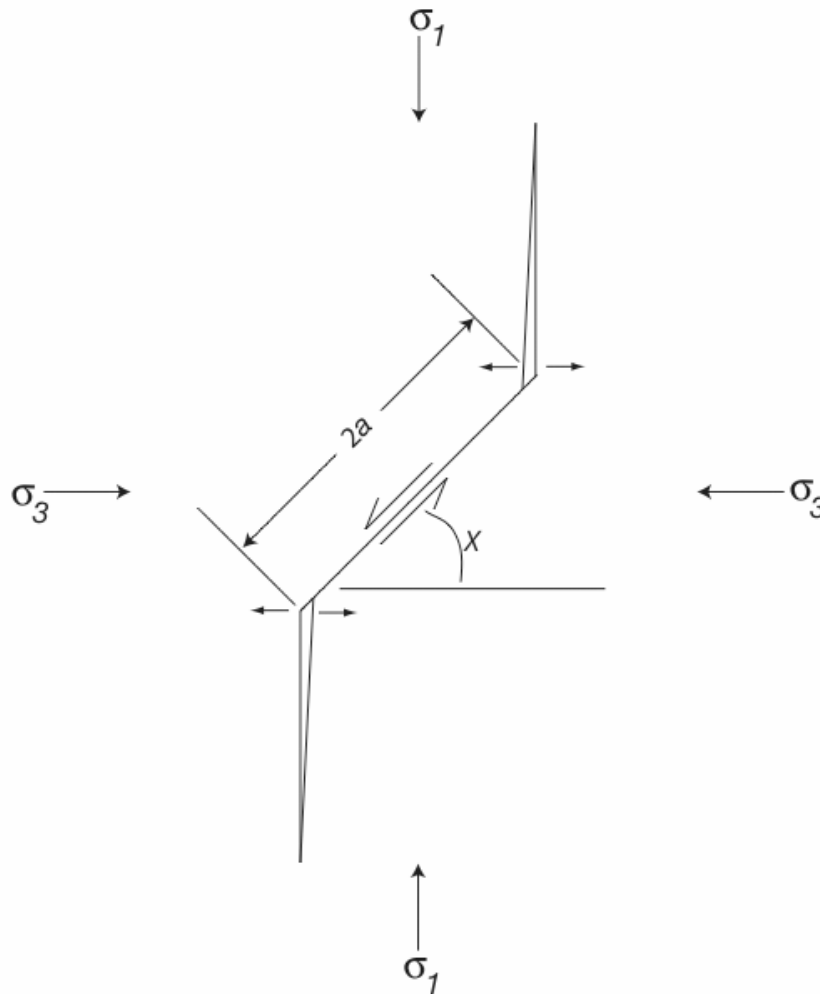


Figure 1. Crack geometry used in the Ashby and Sammis (1990) damage mechanics. Sliding on an inclined crack of length $2a$ nucleates tensile wing-cracks at its ends. Interaction between such cracks in an array of N_V cracks per unit volume leads to failure and fragmentation.

The effect of ice in the inclined crack in Figure 1 is to either totally immobilize it, thus reducing N_V in Eq. (1), or, if saturation is not total, to form ice bridges, thus reducing a in Eq. (1). The net effect of both is to reduce the initial damage D_0 .

The elastic moduli of rock are extremely sensitive to D_0 . Figure 2, from O'Connell and Budiansky (1974), shows the effect of changing D_0 on the P and S wave velocities in dry and water-saturated rock. Note that the x-axis in Figure 2 is $\epsilon = N \langle a^3 \rangle$, where N is the number of cracks per unit volume and a is the half-length of the crack.

Comparison with Eq. (1) shows that ϵ can be written in terms of the initial damage as

$$\epsilon = \frac{3}{4\pi} \left(\frac{1}{\cos \chi} \right)^3 D_0 \approx 0.68 D_0 \quad (2)$$

The effect of freezing water in the cracks is to move to the left (toward lower damage) on the curves in Figure 2. This will produce an increase in elastic wave velocity. The effect is larger for S waves than for P waves in saturated rock.

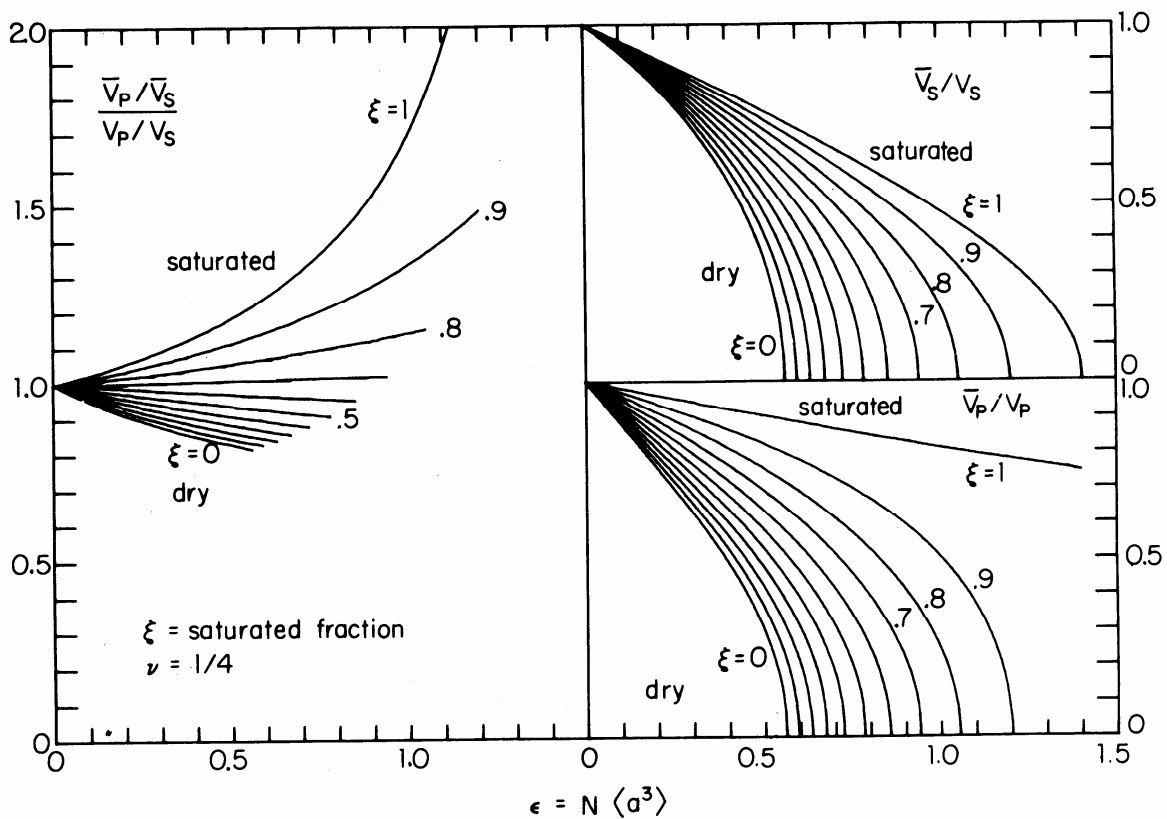


Figure 2. The effect of fractures on the elastic wave velocities in wet and dry rock (from O'Connell and Budiansky, 1974). The crack density parameter ϵ is closely related to the damage parameter in the Ashby and Sammis (1990) damage mechanics, differing only by a constant. See Eq. (2).

The Effect of Ice on Strength

Sammis and Biegel (2004) used the Ashby and Sammis (1990) damage mechanics to explain measurements by Mellor (1973) of the uniaxial strength of saturated rock as a function of temperature from 20°C to -197°C. They found that Mellor's data for the compressive strength (replotted here as Figure 3) could be fit by the Ashby-Sammis model if the coefficient of friction in the sliding cracks is temperature dependent. The required temperature dependence is shown in Figure 4. Sammis and Biegel (2004) then showed that a simple Bowdin and Tabor (1950, 1964) asperity model consisting of a combination of rock and ice asperities could explain the temperature

dependence of the coefficient of static friction in Figure 4, using the known temperature dependence of the creep strength of ice.

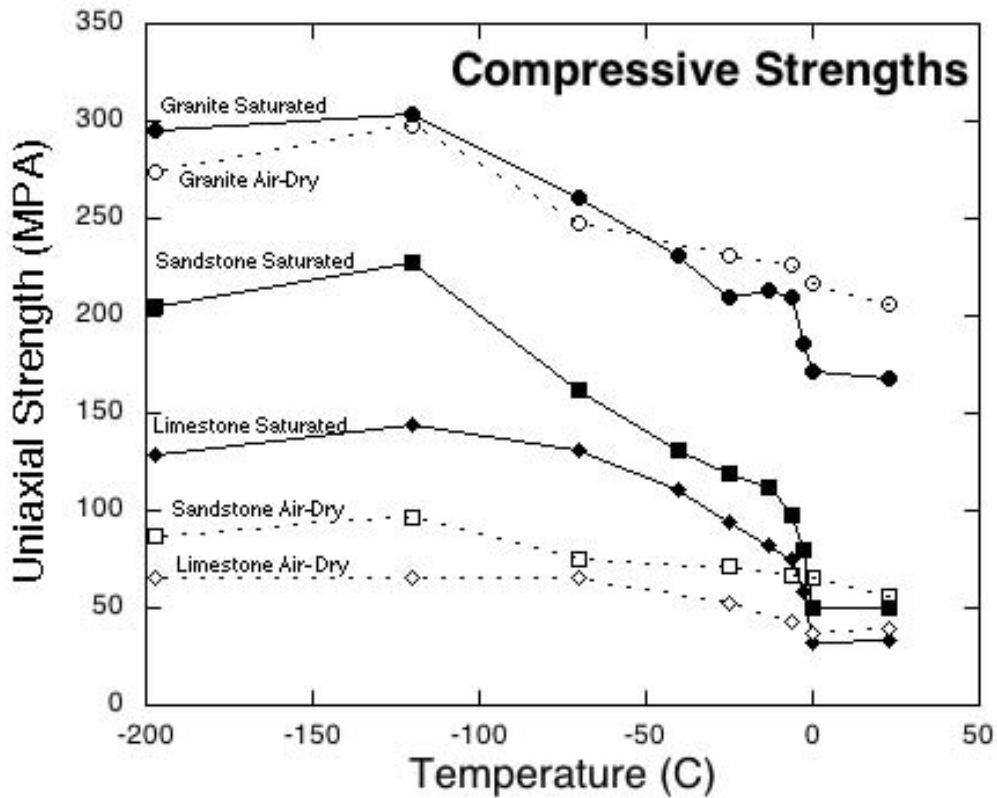


Figure 3. Strength of granite, limestone, and sandstone in uniaxial compression at low temperatures from Mellor (1973). Note that the strengths of saturated and air-dry granite samples are nearly the same at all temperatures, indicating that the thin cracks in granite are saturated under air-dry conditions (from Sammis and Biegel, 2004).

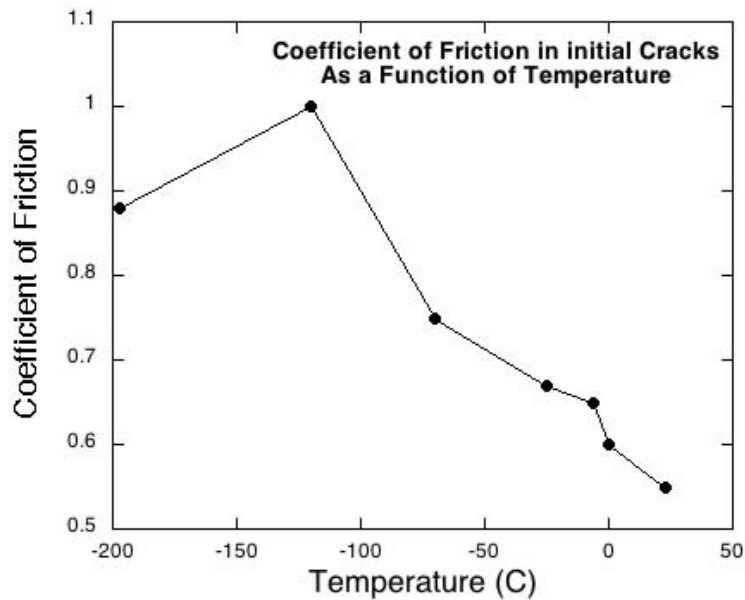


Figure 4. Coefficient of friction on starter cracks required if the damage mechanics model is to explain the increase in compressive strength at low temperatures in Figure 3 (from Sammis and Biegel, 2004).

The Effect of Strain Rate on the Strength of Frozen Rock

The effect of strain rate on the strength of frozen rock is illustrated by the deformation-mechanism map for ice in Figure 5. Temperatures near melting are at the right edge of the map, where it can be seen that increasing the strain rate produces a significant increase in the flow stress. At an effective shear stress of about 10 MPa, this trend is reversed by the onset of pressure melting, which weakens the ice.

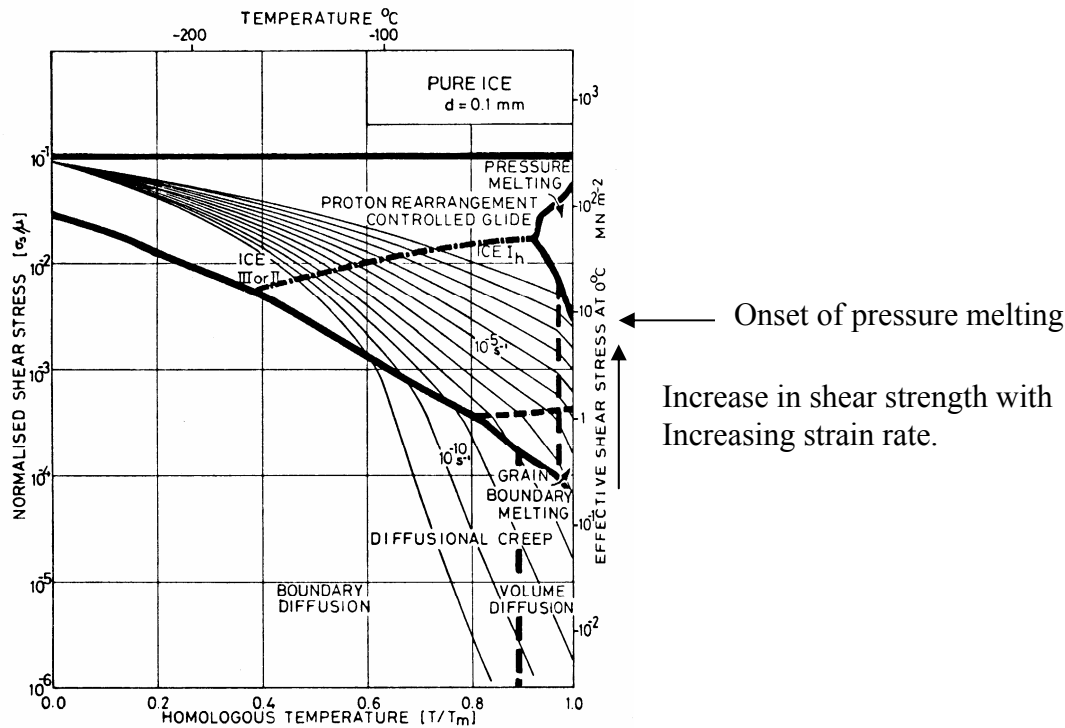


Figure 5. Deformation-mechanism map for ice. Note that increasing the strain rate by 5 orders of magnitude near 0°C increases the shear strength (effective shear stress) by a factor of 10. This increase in strength is limited by pressure melting that occurs at an effective shear stress of about 10 MPa (from Frost and Ashby, 1982).

The Effects of Ice in the Cracks of Crystalline Rock on Seismic Radiation from an Explosion

In order to model the effect of ice on the damage generated by an explosion and on the seismic radiation, we require the principal stresses generated by the explosion as a function of distance and time. This is made difficult by the existence of the nonlinear processes between the cavity radius and the effective elastic radius, beyond which the assumptions of ordinary linear elasticity are valid. Sophisticated computer codes have been developed that include hydrodynamic effects, shock waves, and nonlinear equations of state (see, for example, Rodean, 1971; King et al., 1989; Glenn, 1993; Glenn and Goldstein, 1994, for discussion and further references). We use here an approximate method to calculate the stresses surrounding an explosion that is based on the equivalent elastic method developed by earthquake engineers to model the nonlinear behavior of soils that occurs during strong ground motion. The central idea is to make the material properties a function of the stress in the outward propagating pressure pulse and then to adjust these material properties in an iterative process until the appropriate values are present at all distances from the source. In effect, the nonlinear stress-strain behavior is approximated by a series of linear relationships that

change with the level of stress. The present formulation, described by Johnson (1993), relates density and bulk elastic properties to the peak pressure and shear and anelastic properties to the maximum shear strain.

The details of this model are published in Johnson and Sammis (2001) and will not be repeated here. In that paper we modeled the 1 kt chemical explosion detonated in September 1993 as part of the Non-Proliferation Experiment (NPE) (see Denny, 1994). Last year Sammis and Biegel (2005) explored the effect of an increase in both elastic stiffness and compressive strength on the amplitude of far-field seismic radiation that would be expected if ice were present in the source rock of the NPE explosion. Both produced a decrease in the far field amplitudes. Our conclusion was that an explosion in frozen rock should have a smaller apparent yield than the same explosion in rock at temperatures above the freezing point and that the effect should be larger in limestone than in granite.

The Expected Effects of Ice in the Cracks of Crystalline Rock in the Proposed Alaskan Experiment

The question here is how much strengthening we can expect in the much smaller explosions planned for the Alaskan experiment. To explore this question, we simulated an 800 lb explosion at 20 m depth in crystalline rock in order to see whether the peak shear stresses (and associated strain rates) are large enough to significantly strengthen ice in the source region and whether they are high enough to induce pressure melting. The results are summarized in Figure 6.

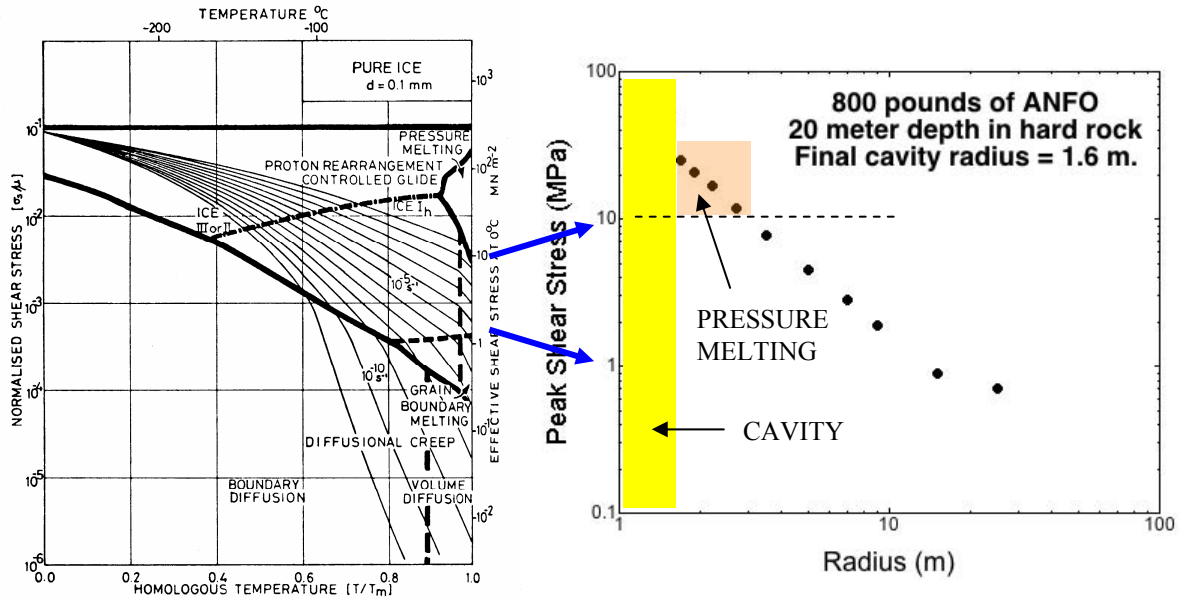


Figure 6. Simulation of 800 lb explosion in hard rock. Note that pressure melting is expected out to a radius of about 3 m and that significant strengthening should extend out to about 10 m.

The shear stresses are sufficiently high to cause pressure melting out to a radius of about 3 m and to significantly strengthen the ice out to a radius of about 10 m. We did not feed the new ice parameters back into the model and iterate to find a self-consistent solution, as we will do when we model the actual experiments. The objective here was simply to see if the peak shear stresses are sufficiently high to significantly strengthen the ice. They are.

CONCLUSIONS AND RECOMMENDATIONS

Inclusion of the mechanical effects of ice in the cracks of crystalline rock in the explosion source formulated by Johnson and Sammis (2001) has led to the following conclusions:

1. The increase in elastic wave velocities associated with ice in the cracks will decrease the seismic amplitudes in the far field, resulting in an apparently smaller yield.

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2. The increase in compressive strength caused by ice in the cracks will also decrease seismic amplitudes in the far field, also resulting in an apparently smaller yield.
3. Near 0°C, significant strengthening should occur at high strain rates in the nonlinear regime of an 800 lb explosion of the type planned for the Alaska experiment. However this increase is limited by the onset of pressure melting. The rock should be weak close to the detonation point, but strong farther out.

The following recommendations are based on the analysis in this paper and our previous analysis of the frozen rock data (Sammis and Biegel, 2004, 2005). Many of these recommendations may already have been implemented in Randy Martin's laboratory work to be presented at this year's SRR meeting.

1. The uniaxial data from Mellor (1973) should be supplemented with a full set of triaxial data in granite at low temperatures. Uniaxial data typically shows large experimental scatter, mostly because the strength is extremely sensitive to the initial flaw distribution in the absence of confining stress. A set of triaxial data would allow a more comprehensive assessment of the extent to which the damage model can represent the strength of rock at low temperatures.
2. The triaxial data set should be supplemented with measurements of the coefficient of friction as a function of temperature under saturated and air-dry conditions. These measurements can be made either on saw-cut samples as part of the triaxial set of experiments or in Jim Dieterich's double-shear apparatus at the United States Geological Survey laboratory in Menlo Park, California.
3. Both the triaxial measurements and friction measurements should be performed at different strain rates to further test the hypothesis that the strengthening is associated with ice asperities.
4. Seismic velocities should be measured in frozen and thawed rock at the same field location as part of any pending field study of explosions in frozen rock. The differences between the seismic velocities above and below the permafrost should lead to a constraint on the nature and density of the native fractures.
5. The equivalent elastic source model of Johnson and Sammis (2001) should be improved to make the nonlinearity depend explicitly on the damage. This nonlinearity is now given by an analytic approximation that depends on only the peak stress (or, equivalently, on the reference strain).
6. The issue of the actual freezing temperature of water in cracks in rock needs to be resolved, as does the amount of strengthening achieved by increasing the strain rate near 0°C. These issues are vital to the success of the pending field test where the permafrost temperature in the proposed hole is only -0.2°C.

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