POSSIBLE EFFECTS OF FROZEN ROCK ON EXPLOSIVE COUPLING

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ABSTRACT

Laboratory studies have demonstrated that frozen rock is significantly stronger than unfrozen rock, and it has been hypothesized that this increased strength can significantly alter seismically estimated yield. Weston Geophysical Corporation, University of Alaska at Fairbanks, and New England Research, Inc. formed a consortium to perform a field experiment to provide empirical data in order to test the hypothesis. The results of this experiment will aid the monitoring community in determining actual yield for explosions in permafrost regions.

The experiment is being conducted at a gold mine in central Alaska that has abrupt lateral boundaries in discontinuous permafrost. We are detonating a series of small, repeated explosions ranging in size from 2 to 800 lb of explosives at 20–30 m depth. We conducted laboratory tests on rock samples collected at the test site and found increased *P*-wave (primary wave) velocities when the rock temperature was decreased from +21°C to –12°C. The increase in *S*-wave velocities was even more significant.

The explosions are being recorded on a near-source network of 18 accelerometers and velocity seismometers along with a large array of seismometers at local distances. The mine is located near several stations of the Alaska Earthquake Information Center network and is within 100 km of the ILAR and ALPA seismic arrays, thus the explosions are being recorded by an extensive regional network.

Borehole temperature measurements at 10 m depth indicate frozen (–0.5°C) and unfrozen (1.5°C) rock within 300 m of each other. To examine the temperature at the planned depth of explosive emplacement, 50 m boreholes were drilled at the test site and indicate frozen (–0.2°C) with ice-filled fractures and unfrozen (0.1°C) rock at 30 m depth. A nearby shallow borehole located warmer unfrozen rock. We will locate the experiment explosive holes to achieve the largest possible temperature difference in the frozen and unfrozen rock. Time-dependent temperature logging indicates drilling has very little effect on the steady-state temperature regime and the experiment can be conducted shortly after the explosive boreholes are drilled. A shallow geophysical survey is being conducted to develop a high-resolution velocity profile of the test site. Borehole coring is also being conducted to examine the emplacement media's physical properties. To determine how the natural fracture field is modified by the explosions, we will obtain fracture orientation and extent from borehole cores before and after the detonations.

A broadband seismometer was deployed for 3 months approximately 12 kilometers from active blasting at the gold mine. Examination of waveforms from the blasting shows large signal-to-noise ratio body and surface waves. This data is aiding in the experiment design and providing background noise levels. Teleseismic earthquakes recorded at this station are being used to generate receiver functions for constraining the lower crustal velocity structure and Moho depth.

OBJECTIVES

Weston Geophysical Corp., the University of Alaska at Fairbanks, and New England Research, Inc., have formed a consortium to conduct the Frozen Rock Experiments (FRE) in central Alaska to characterize the variations in ground motion scaling and coupling for explosions in frozen and unfrozen rocks. The experiment is helping to quantify the variations in estimated seismic yield of explosions in frozen rock due to changes in coupling. The consortium is detonating and recording the explosions on a large array of near-source and local stations deployed specifically for the experiment. The data is also being recorded on permanent regional stations of the Alaska Earthquake Information Center (AEIC) network and nearby ILAR and ALPA seismic arrays. In the final phase, we will analyze the data to quantify the source function variations for equal yield explosions detonated in frozen and unfrozen rocks.

RESEARCH ACCOMPLISHED

Experiment Background

A critically important aspect of nuclear test monitoring is yield estimation. United States monitoring agencies must be able to accurately estimate yields for nuclear explosions detonated in regions of monitoring concern. If frozen-rock emplacement conditions create a circumstance favorable for biased yields, data must be available such that any bias can be accounted for when the yield is estimated. Prior studies (Mellor, 1971) have established that frozen-rock properties are considerably different from unfrozen-rock properties. Moreover, it has been hypothesized that these altered properties may be sufficient to cause significant variations in seismic coupling, which in turn, significantly alters seismic yield estimates.

Sammis and Biegel (2004) have noted that an increase in low-temperature uniaxial strength is related to the ice in the initial pores and cracks. The ice increases the apparent coefficient of sliding friction on these initial cracks. Since the strengthening is strain-rate dependent, for nuclear explosions the full strengthening should occur in a small range near 0°C. This is important given that our experiment test site region has frozen ice in the cracks at temperatures of –0.5°C.

Sammis and Biegel (2005) successfully approximated the stresses around the 1993 NPE explosion. They found that increasing the static friction and reference strain, which simulates ice-filled cracks, each caused more rock damage at greater distance from the explosion and an increase in radial crack length. For the increased static friction case, there was actually less damage at very close-in distances. In addition, increasing the seismic velocity and/or rock strength caused reduced seismic amplitudes in the far-field for explosions in frozen rock, which would result in an underestimated yield.

Experiment Location and Design

We chose to conduct the experiment north of Fairbanks, AK (Figure 1) because that region contains discontinuous permafrost, with frozen and unfrozen rock in close proximity. Farther north, it is difficult to find unfrozen rock and farther south, it is difficult to find frozen rock. In addition, this area is also in close proximity to permanent regional seismic stations and allows for relatively easy placement of near-source and local instruments to record the experiment.

A series of repeated explosions will be detonated within 300 m of each other in frozen rock and unfrozen rock. These explosions will include shots of 200, 400 (two are planned), and 800 lb of ammonium nitrate fuel oil (ANFO). The emplacement depth is designed to approximate a nuclear-scaled depth of burial for a fully contained and confined explosion. This allows all rock damage to be confined to frozen or unfrozen rock, depending on the location of shot.

High-g accelerometers and broadband and short-period seismometers will be deployed at near-source and local distances to record the explosions. Accelerometers will be placed within 5 m of the explosions. The instruments will provide complete azimuthal coverage and span the distance to the permanent regional seismic network of the Alaska Earthquake Information Center (AEIC). High-speed and resolution videographic data will be recorded to verify the explosions detonate as planned and are fully confined and contained.

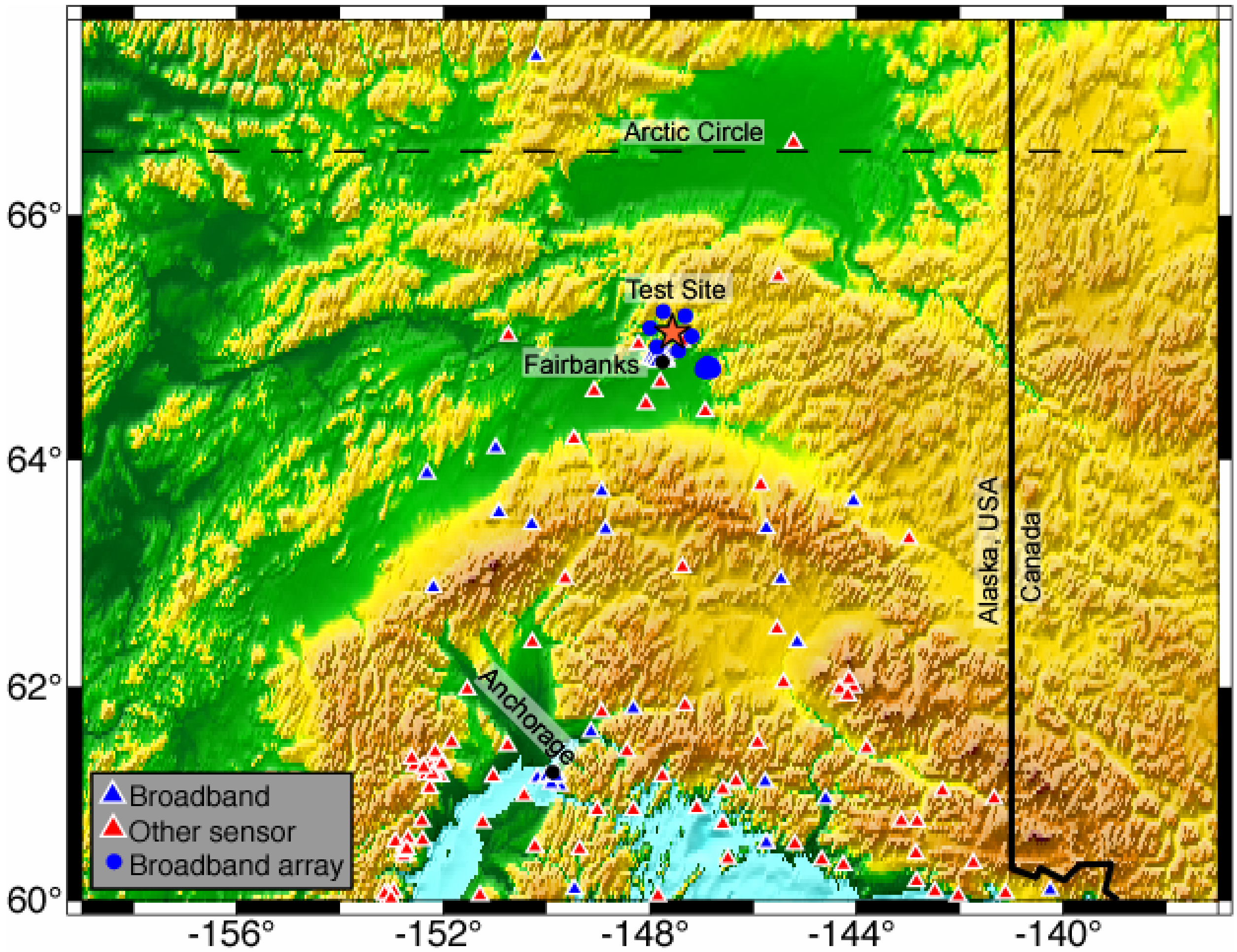


Figure 1. Location map of the test site region (star) and nearby seismic stations.

Temperature Profiles

Existing permafrost monitoring wells were logged to verify the test site contained sufficient quantities of frozen rock. This logging indicates frozen rock around –0.5°C (Figure 2). We drilled two 50 m boreholes to locate frozen and unfrozen rock in close proximity on our test site. Temperature measurements from these holes are shown in Figure 3 (left and center). The unfrozen rock borehole is located in marginally unfrozen ground, but logging of another nearby shallow borehole located a warmer unfrozen zone. The frozen rock hole is below 0°C between approximately 10 to 50 m depth. Temperature measurements were taken shortly after drilling so the values may have a slight variation above steady state due to drilling disturbance. Time-dependent temperature logging in the unfrozen well indicates the drilling disturbance is minimal though.

These four boreholes indicate our test site has discontinuous zones of frozen and unfrozen rock. In order to locate the best sites to conduct the experiment, we need to find the coldest and warmest regions. To accomplish this, we will conduct a 2-dimensional DC resistivity tomography of the test site before choosing the locations for the explosive boreholes. Temperature logging of the explosion boreholes will be conducted before loading them with explosives. We will require at least –0.4°C, with visible ice in fractures, for the frozen site and +1.0°C or greater in the unfrozen site before conducting the explosions.

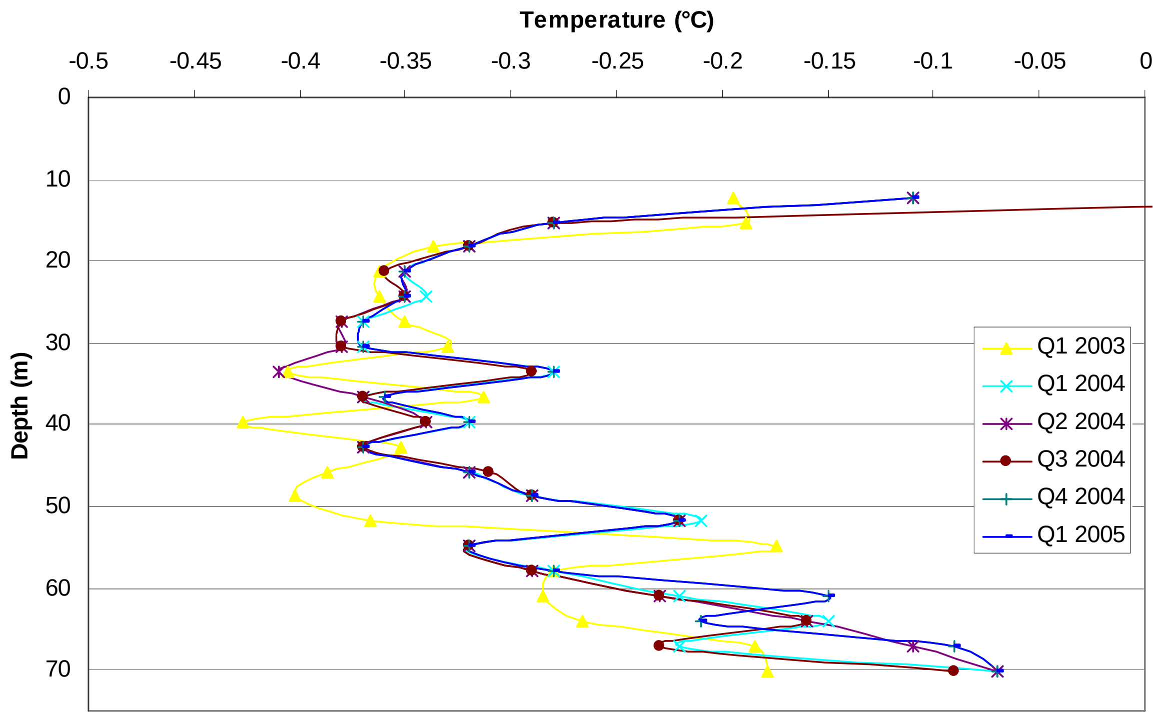


Figure 2. Temperature logs acquired from a permafrost monitoring well near the frozen rock test site. These logs allow us to examine the steady-state temperature profile.

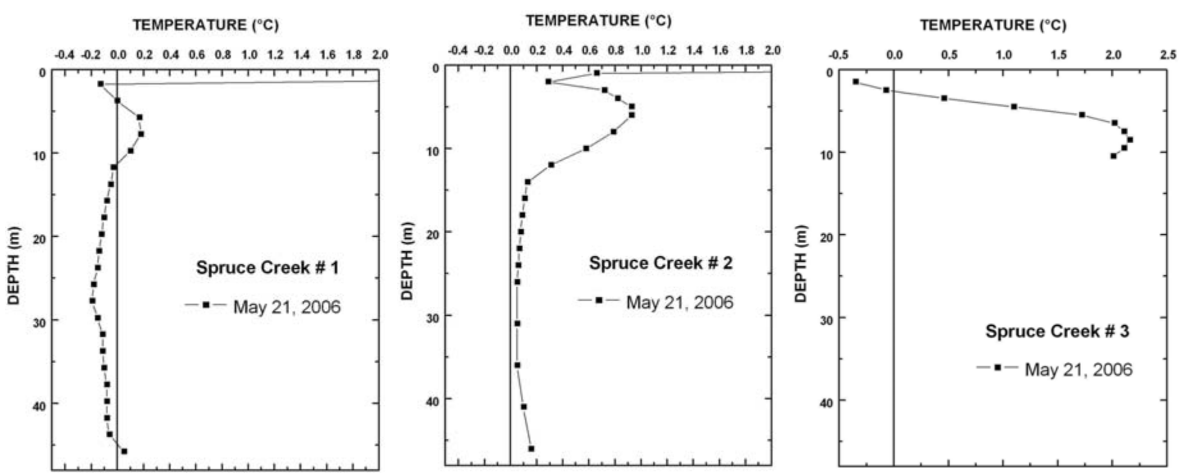
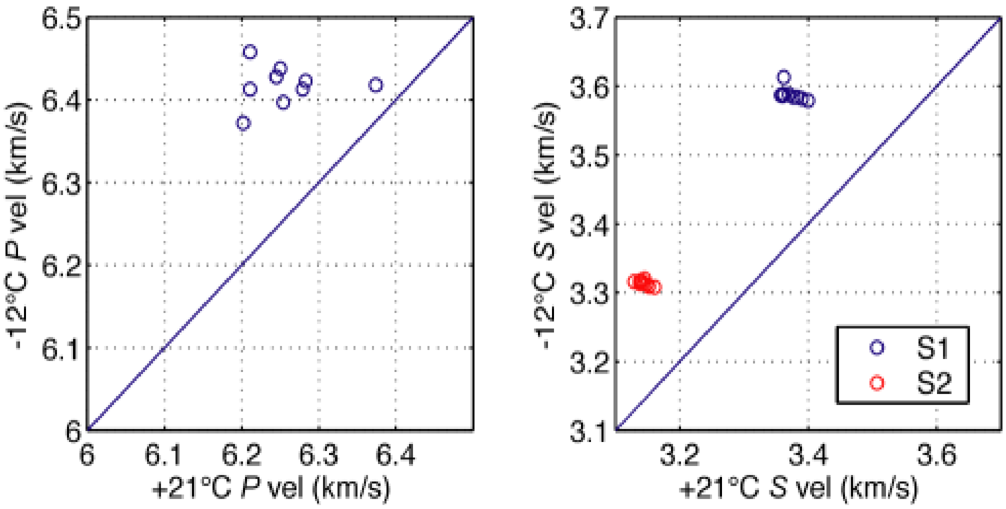


Figure 3. Temperature profiles of the test site from our initial characterization. We drilled two 50 m boreholes and located frozen rock (left) and unfrozen rock (center) sites in close proximity. A fourth borehole on the test site (right) located warmer rock for the unfrozen tests.

Test Site Rock Properties

Laboratory testing of rock samples collected at the test site indicates both *P*- and *S*-wave velocities increase when saturated rocks are frozen at –12°C. Figure 4 plots the results for *P* velocity on the left and the results for *S* velocity at two different confining pressures on the right. Velocities increase by 3%–5% in the frozen samples. Sammis and Biegel (2005) determined that an increase in velocity related to ice-filled cracks would decrease observed seismic amplitudes causing a smaller estimated yield.



+21ºC *P* vel (km/s) +21ºC *S* vel (km/s)

Figure 4. Empirical laboratory results comparing the *P*- (left) and *S*- (right) wave seismic velocities of frozen and unfrozen rocks collected at the test site.

A series of preliminary experiments are being conducted to determine the elastic moduli, strength, and coefficient of friction in frozen and unfrozen rock samples. Coring of the explosive boreholes before and after the explosions will provide rock samples from the explosive emplacement depth. Laboratory tests will then be conducted on these samples. Shallow seismic refraction experiments are being carried out across the test site to develop a velocity and structure profile. A DC resistivity tomography survey is being conducted to map the extent of permafrost across the test site. This will also aid in locating the explosive boreholes in the coldest and warmest rock at the test site.

Local Mining Explosions and Earthquakes

A broadband seismometer was deployed for three months less than 1 km from the test site. The station recorded nearby delay-fired mining activity and earthquakes, including a number of small local events. A map of the local events recorded is shown in Figure 5. Open pit delay-fired mine blasting designed to fracture the hard granitic rock occurred 12 km to the east-southeast of the station and forms a cluster of events. Small earthquakes or other man-made events (ML<2) at local distances were also recorded and make up the rest of the events in the plot. Body and surface-waves from the local events were well recorded by this station even for the smallest events. The station will record the experiment blasts for a direct comparison of local earthquakes and single-and delay-fired explosions.

Many regional and teleseismic earthquakes were also recorded. These events are being used in a joint surface wave dispersion and receiver function study to determine the crustal velocity structure of the area. Combining this model with the data obtained from the shallow seismic refraction and resistivity tomography will provide an extremely detailed model of the test site structure from the shallow sub-surface to the Moho depth.

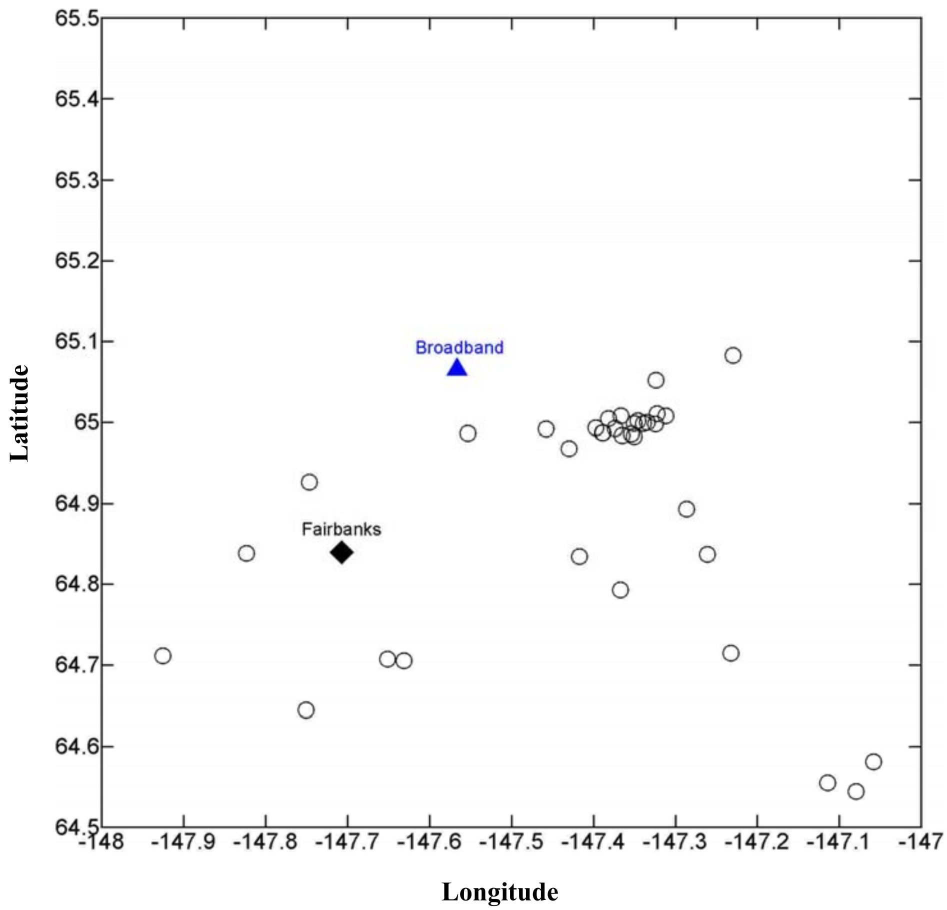


Figure 5. Location of the deployed broadband station (blue triangle) and nearby seismic events (black open circles). Mine blasts are clustered ESE of the broadband.

CONCLUSIONS AND RECOMMENDATIONS

A series of single-fired explosions is being conducted in Alaska the last week of August to advance the understanding of phenomenology and estimated yield differences from explosions in frozen and unfrozen rock. Sammis and Biegel (2005) concluded that estimated seismic yield will be reduced by increased seismic velocities and compressive strength of the explosive source rock related to ice-filled cracks. We plan to obtain empirical data to compare with their theoretical values.

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