# POSSIBLE EFFECTS OF FROZEN ROCK ON EXPLOSIVE COUPLING

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## ABSTRACT

Weston Geophysical Corporation, University of Alaska at Fairbanks, and New England Research, Inc., have formed a consortium to test the effects of explosions in frozen rock. 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. Our consortium is planning a series of explosive tests to determine the seismic variations between detonating explosives in frozen and unfrozen rock. The information derived from the proposed research will provide a thorough test of the hypothesis. It will also provide important results for application in regions where explosions can be detonated in permafrost conditions.

The experiment will be conducted near Fairbanks, Alaska, where abrupt lateral boundaries on discontinuous permafrost exist. For a proper assessment of amplitude variations, the shots need to be in close proximity to effectively remove path effects. We will detonate a series of small, repeated explosions ranging in size from 2 to 500 lbs. of explosives. The explosives will be placed at approximately 20–30 m depth in regions of frozen and unfrozen rock and will be recorded on a near-source network of 18 accelerometers and velocity seismometers. Scaling studies have been conducted to determine the proper distance for recording stations and expected ground shaking. Over 120 seismometers will be deployed between 1 and 15 km from the explosions. Several stations of the Alaska Earthquake Information Center network are in close proximity and AFTAC's ILAR and ALPA seismic arrays are within 100 km; thus, the explosions should be recorded by an extensive regional network.

Initial 10-m borehole temperature measurements indicate frozen (-0.5°C) and unfrozen (1.5°C) rock can be found within 300 m of each other. A refraction velocity survey will be conducted across the test site prior to blasting. Immediately following this, the explosive boreholes will be drilled and temperature logged, and then the frozen rock experiments will be conducted.

## 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 will help quantify the variations in estimated seismic yield of explosions in frozen rock due to changes in coupling. The consortium has spent the previous year planning the experiment and in the next phase will detonate and record the explosions on approximately 150 near-source and local stations deployed specifically for the experiment. The data will also be recorded on permanent regional stations of the Alaska Earthquake Information Center (AEIC) network and nearby Air Force Technical Applications Center (AFTAC) 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 alter 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 near 0°C. This is important given that our experimental test site region has frozen ice in the cracks at temperatures of -0.5°. It may be necessary to use nonlinear modeling using the damage mechanics models proposed by Sammis and Beigel (2004) and Ashby and Sammis (1990) to effectively model the amplitudes for explosions detonated in frozen rock.

### Experiment Location

We will conduct the experiment near Fairbanks, AK (Figure 1) because that region contains both frozen and unfrozen rock. Temperature logging in 10 m wells has found 2° C unfrozen rock approximately 300 m from -0.5° C frozen rock. Figure 2 shows temperature profiles of a monitoring well in permafrost near the test site. The data indicates the ground is frozen between 15 and at least 70 m depth. This area is also well located to permanent regional seismic stations and will allow for relatively easy placement of near-source and local instruments to record the experiment.

### Explosion Design

In planning the FRE explosions, we considered local vibration requirements. In addition, it is critical that the explosions be fully confined and rock fracturing be contained to completely frozen or unfrozen rock, depending on the type of shot. Every attempt will be made to use a charge depth equivalent to a typical scaled depth for nuclear tests if possible. Drilling and temperature logging will be conducted immediately prior to the tests to determine the thickness of the frozen and unfrozen rock and to ensure we use the proper charge weights and emplacement depth. Initial analysis indicates using a maximum charge weight of 500 lbs. of ammonia nitrate fuel oil (ANFO) and an emplacement depth of 20–30 m. These values will be refined after final temperature logging of the site. Table 1 lists the planned shots of the experiment. We will detonate a series of explosions with increasing charge weight to observe the variations between frozen and unfrozen explosions as a function of yield. The frozen and unfrozen explosions will be detonated within 300 m of each other to minimize effects of the travel path and emplacement medium.

**Table 1. Planned Frozen Rock Experiment Explosions**

| Shot Number | Charge Weight (lbs.)* | Charge Depth* (m) | Rock Condition |
|---|---|---|---|
| 1 | 100 | 20 | Frozen |
| 2 | 200 | 25 | Frozen |
| 3 | 500 | 30 | Frozen |
| 4 | 100 | 20 | Unfrozen |
| 5 | 200 | 25 | Unfrozen |
| 6 | 500 | 30 | Unfrozen |

*Initial planning. Actual weight and depth may vary to comply with regulations and rock conditions.

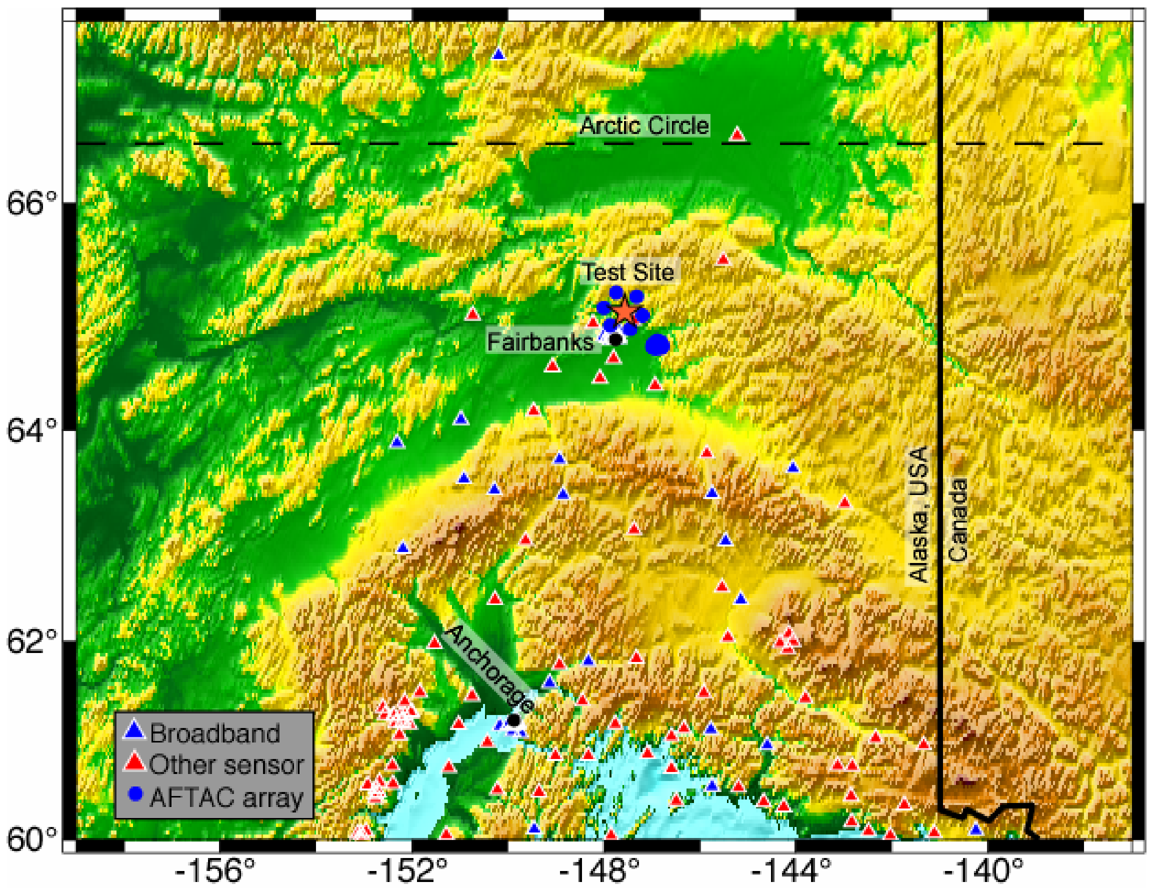


**Figure 1. Location map of the test site region (star) and nearby seismic stations.**

**Station Deployment**

We will deploy approximately 150 seismic stations within 15 km of the test site. These sensors include high g accelerometers, vertical component Texans, short-period seismometers, and broadband seismometers. Over 400 sensors of different types are permanently deployed across Alaska. An accelerometer will be placed within 5 m of each explosion to acquire an accurate origin time. In order to determine the proper station distance for the remaining stations, we examined signal quality from the Source Phenomenology Experiment (SPE) in September 2003 (Bonner et al., 2005) and modeled expected ground shaking for the FRE. The planned shot sizes for the FRE are approximately an order of magnitude smaller than the SPE shots, yet the SPE explosions, including the 233 lbs.

calibration shot, provide a guide to determine the proper explosion to station distance and prevent damage to nearby structures.

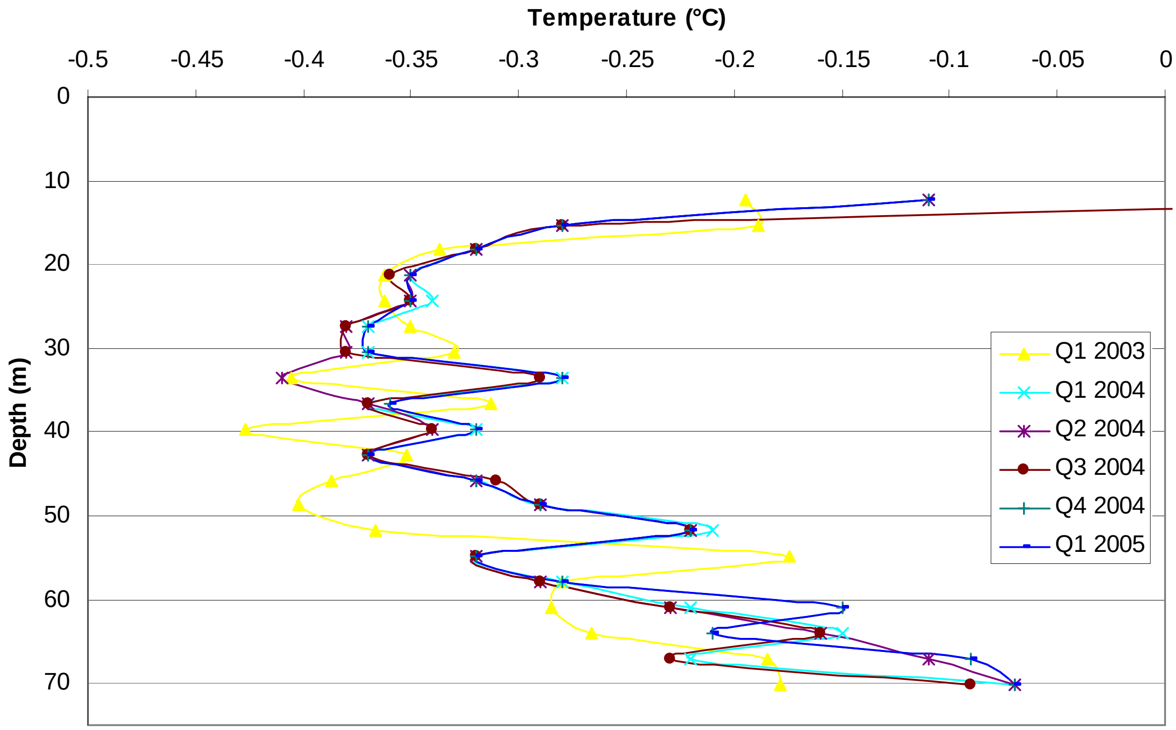


**Figure 2. Temperature logs of a permafrost monitoring well near the frozen rock test site.**

**Peak Velocity.** In order to determine the amount of shaking expected, we followed the analyses of Stump (2003) for the SPE project. The peak velocities for different shot sizes and distances were calculated using models developed by various published authors (summarized in Leidig, 2004). The Fuis et al. (2001) model with distance scaling was chosen as the most realistic based on observations from the SPE data. The peak velocity equation is

$Log(v) = -1.9277Log(r) – 0.3411 (Log(r))^2 + 0.8119 Log(w) – 3.1249$, where v is velocity, r is distance, and w is charge weight.

The peak velocities were calculated and plotted in Figure 3 for 100, 200, 500, 1,000, and 5,000 lbs. shots. Our largest planned explosion is 500 lbs., though.

**Peak Acceleration.** Nearby structures and equipment can be damaged by large ground accelerations. Following Stump (2003), peak accelerations were calculated by multiplying the peak velocity by $2\pi f_c$, where $f_c$ is the corner frequency. Stump determined $f_c$ to be approximately 35 Hz for a 1,800 lbs. shot and then used a cube root scaling relationship for other shot sizes. The corner frequencies for the shot sizes used in the FRE study are listed in Table 2. In Figure 4, we plot the peak accelerations from the velocities plotted in Figure 3.

**Station Locations.** The appropriate station distances are listed in Table 3. Figure 5 shows an example of how we might deploy the broadband and Texan seismometers based on terrain accessibility, azimuthal coverage, and appropriate station to explosion distance. The near-source accelerometer and short-period instrument placement is shown in Figure 6. This configuration will allow us to extensively record both the frozen and unfrozen tests without having to redeploy stations between tests. Hundreds of permanent stations are already deployed at regional distances.

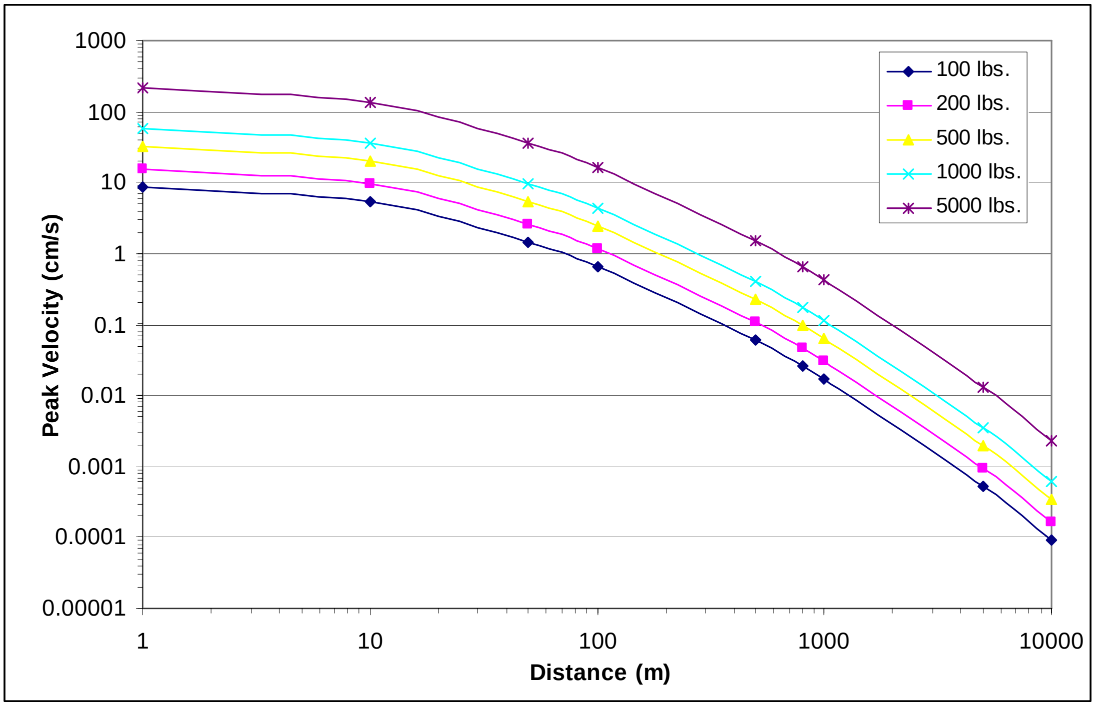


**Figure 3. The peak velocities calculated for shots of various sizes using the Fuis et al. (2001) model.**

**Table 2. Corner Frequency as a Function of Shot Size**

| Shot Size (lbs.) | Corner Frequency (Hz) |
|---|---|
| 100 | 91.7 |
| 200 | 72.8 |
| 500 | 53.6 |
| 1,000 | 42.6 |
| 5,000 | 24.9 |

**Table 3. Instrument Distances for the FRE**

| Instrument | Distance Range |
|---|---|
| 100 g accelerometer | < 20 m |
| 25 g accelerometer | 10 - 50 m |
| 1 g accelerometer | > 100 m |
| Texan seismometer | 1-12 km |
| Broadband seismometer | 1-100 km |

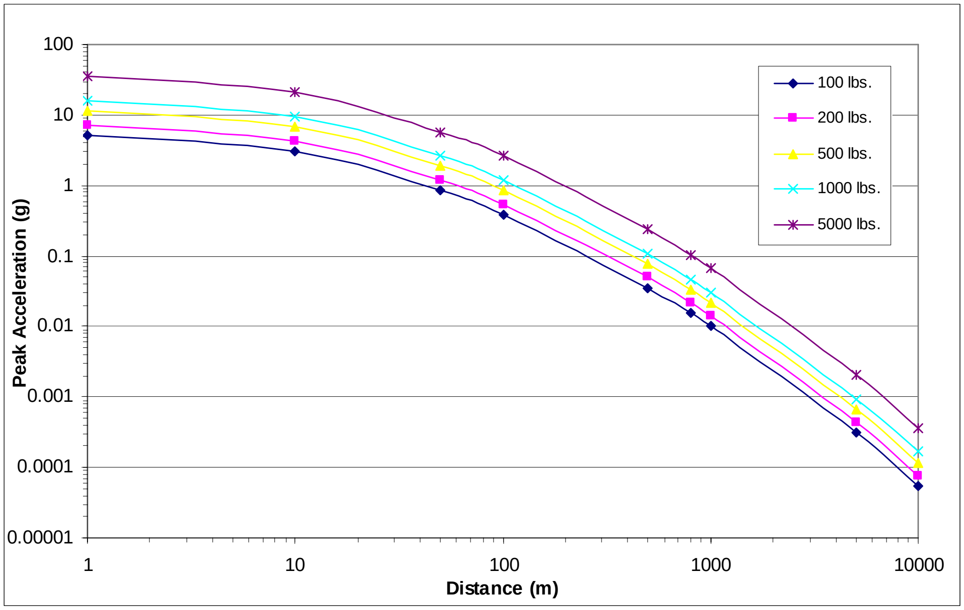


**Figure 4. The peak accelerations calculated from the Fuis et al. (2001) model for a range of shot sizes.**

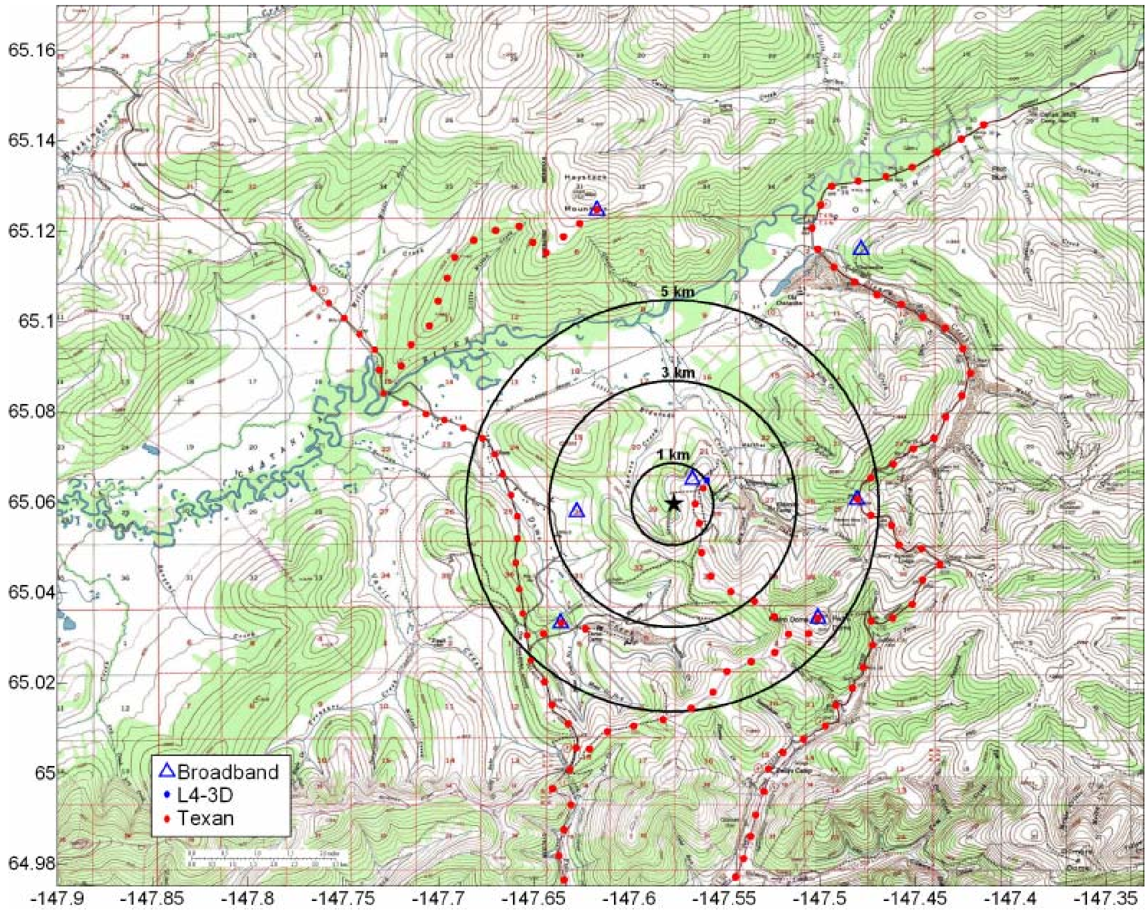


**Figure 5. An example station deployment map showing how we could deploy seismometers.**

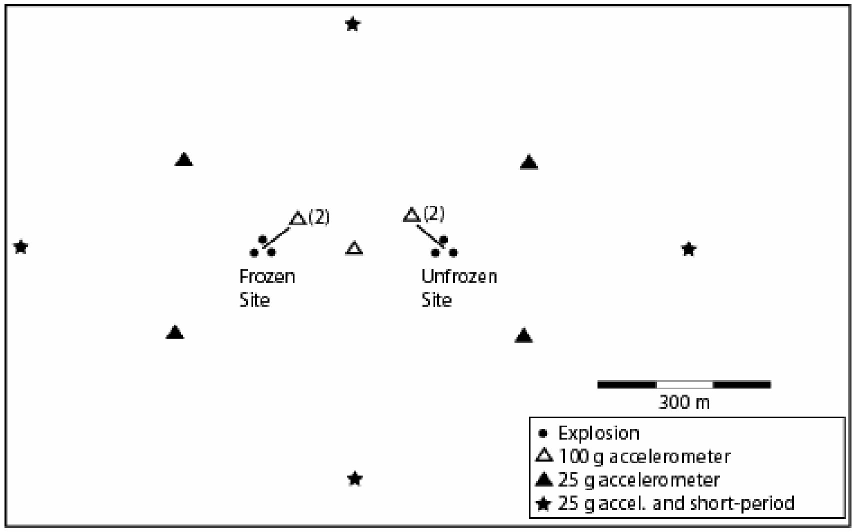


**Figure 6. Near-source deployment of accelerometers and short-period instruments to adequately record both the frozen and unfrozen explosions without redeploying the stations in between tests.**

## CONCLUSIONS AND RECOMMENDATIONS

A series of single-fired explosions will be conducted in Alaska to advance the understanding of phenomenology and estimated yield differences from explosions in frozen and unfrozen rock. We may choose to conduct the experiments in the spring of 2006 so that the frozen rock will extend closer to the surface and be as cold as possible. Upon completion of the testing, our consortium will analyze videographic and seismic data to quantify the variations from near-source to regional distances.

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