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14. ABSTRACT

We are currently conducting a one-year feasibility study to determine the most efficient way to characterize the damage from an explosive source and to identify the source(s) of shear wave generation. We hope to quantify crack nucleation and growth (Ashby and Sammis, 1990) as an S-wave generation mechanism in the far-field (Sammis, 2002) and to map the cone of damage (Patton et al. 2005; Stevens et al. 2003) above a source, modeled by a compensated linear vector dipole (CLVD). This study is being conducted at a quarry in Barre, Vermont, in a granite body that has a low fracture density and typically forms large blocks used for monuments.

In this study, we are detonating five small (< 200 lb) explosions at depths of approximately 9, 12, and 17 m each separated by at least 20 m so the damage zones do not overlap. We plan to use two different types of explosives in order to provide different fracturing in the rocks. An ammonium nitrate fuel oil (ANFO)-Emulsion mixture with a slow velocity of detonation (VOD) should produce larger length cracks while a molecular explosive with a high VOD should produce a large rubble zone near the borehole and cracks of smaller lengths.

We are quantitatively and qualitatively defining the damage around the source using coring, cross-borehole seismic tomography, and borehole televiewers before and after the explosions. We will also deploy a large network of accelerometers and seismometers from 5 m to 30 km from each blast. These stations will include near-source (<1 km) accelerometers and short-period seismometers that will record the physical characteristics of the primary seismic pulse created by the explosions. We will also deploy two linear arrays of intermediate and short-period sensors in order to track the P- and S-waves energy partitioning from the explosions with hopes of relating the observables back to the variation in damage caused by the explosions. The explosions are planned for July 2008.

15. SUBJECT TERMS

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We are quantitatively and qualitatively defining the damage around the source using coring, cross-borehole seismic tomography, and borehole televiewers before and after the explosions. We will also deploy a large network of accelerometers and seismometers from 5 m to 30 km from each blast. These stations will include near-source (<1 km) accelerometers and short-period seismometers that will record the physical characteristics of the primary seismic pulse created by the explosions. We will also deploy two linear arrays of intermediate and short-period sensors in order to track the P- and S-waves energy partitioning from the explosions with hopes of relating the observables back to the variation in damage caused by the explosions. The explosions are planned for July 2008.

OBJECTIVES

Two of the proposed mechanisms for S-wave generation involve secondary processes related to the damage and deformations caused by the explosions. First, outside the cavity radius, there is a "shell" of fragmented rock. Sammis (2002) theoretically showed that the integrated effect of the nucleation and growth of the fractures in this shell can generate secondary seismic waves as large as the P-waves from the explosion itself.

A second proposed method is the CLVD, which is an elastodynamic equivalent of a conical source. In this case, it is an inverted cone with apex at the detonation point (Patton et al., 2005). Media within the cone deforms and fails as a result of tensile stresses caused by the downgoing shock wave reflected off the free surface. Spallation is an obvious example of such failure. Driven block motions at depth, as envisioned by Masse (1981), is another example that may have greater significance for seismic wave generation.

A problem for researchers trying to relate damage to S-wave generation is a paucity of detailed, readily available, damage-characterization data from explosions. Weston Geophysical Corporation and New England Research, Inc. plan to detonate small chemical explosions in relatively unfractured, homogeneous Barre granite in Vermont, USA. Barre granite has been a worldwide standard for homogeneous granite in commercial, monument, and industrial settings. The focus of the experiment will be to quantify the damage caused by these explosions and to provide a unique dataset that should have important ramifications for models of P- and S-wave generation from explosions in hard rock in areas of monitoring interest.

RESEARCH ACCOMPLISHED

Pre- and Post-Shot Characterization

We are currently implementing a three-phase experimental field project at a granite quarry in Vermont. Figure 1 shows a schematic of the planned experiment. First, the test-site rock rheology and fracture distribution will be thoroughly characterized through a series of boreholes drilled near the shot-point borehole. Next, a series of explosions at depths of burials ranging from approximately 9 to 17 meters will be detonated at the test site. Finally, post-deformation alterations to the *in situ* rock properties will be measured in order to provide a quantitative and detailed description of the rock damage caused by the explosions.
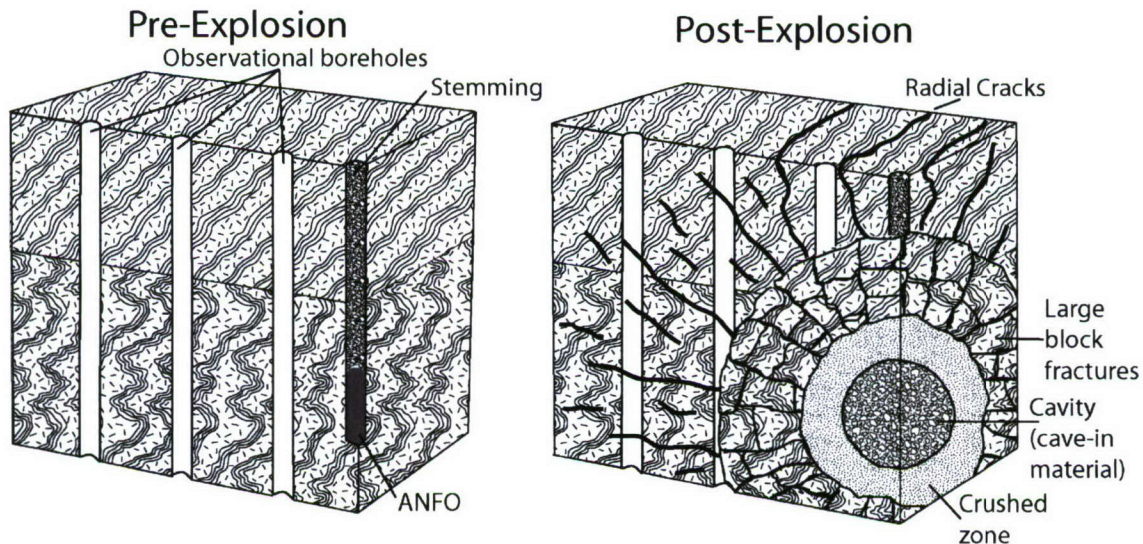

Figure 1. Schematic of proposed experiment. A series of observational boreholes will be cored and logged to provide geotechnical data (left) before explosives are detonated (right). The boreholes will be cleared and re-logged. The information gained would be used to determine the characteristics of each damage zone.

In-situ Velocities. An in-situ seismic velocity model will be developed using traditional seismic refraction and/or cross-borehole seismic velocities. Crosshole seismic surveys are used to obtain in situ properties of rock strata. Often used as part of a comprehensive geotechnical investigation, the crosshole seismic survey yields valuable information as to the strength and cohesiveness of the underlying bedrock, information that is critical to characterizing the pre- and post-shot media. We plan to drill two 4" boreholes on opposite sides of two explosion boreholes at the test site. These holes will be cased with PVC pipe and then a crosshole seismic velocity analysis conducted to measure the time for horizontally traveling P- and S-waves to travel from a source hole to a receiver hole. After the explosion, we will conduct another round of crosshole imaging to quantify the change in P- and S-wave velocities as a result of the explosions. Figure 2 provides a modeled crosshole response for our planned explosions.
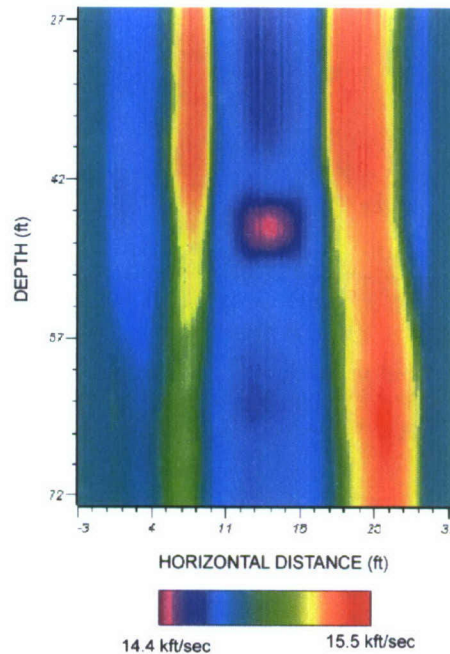

Figure 2. Modeling the predicted response of an 1-m diameter rubble filled void (1200 fps) surrounded by a 1-m crushed zone (8500 fps) in a homogeneous 15,000 fps block. The observation holes are located 15 feet from the blast hole and the blast is located at a depth of about 40 feet. A geophone spacing of one-foot and a shot spacing of 2-feet are adequate to image the explosion effects.

Borehole Core Analysis. A series of borehole cores have been recovered from the test site. Figure 3 shows an example of a 2.5-m section of core from the test site. The section core had to be broken with the coring machine due to a lack of natural fractures. The core samples are currently being studied using the AutoScan technology at New England Research, Inc. AutoScan has a capability of measuring permeability, electrical resistivity, and compressional and shear-wave velocity as a function of position on the core (Figures 4 and 5). After the explosions, additional core will be drilled through the shot point and at points just inside and outside the predicted cavity radius (e.g., Figure 1). The combination of the pre-and post-shot core data will allow us to test the spatial distribution of damage due to different boundary conditions.

Figure 3. Section of core (2.5 meters in length) consisting of homogeneous granite with low fracture density from the test-site location.
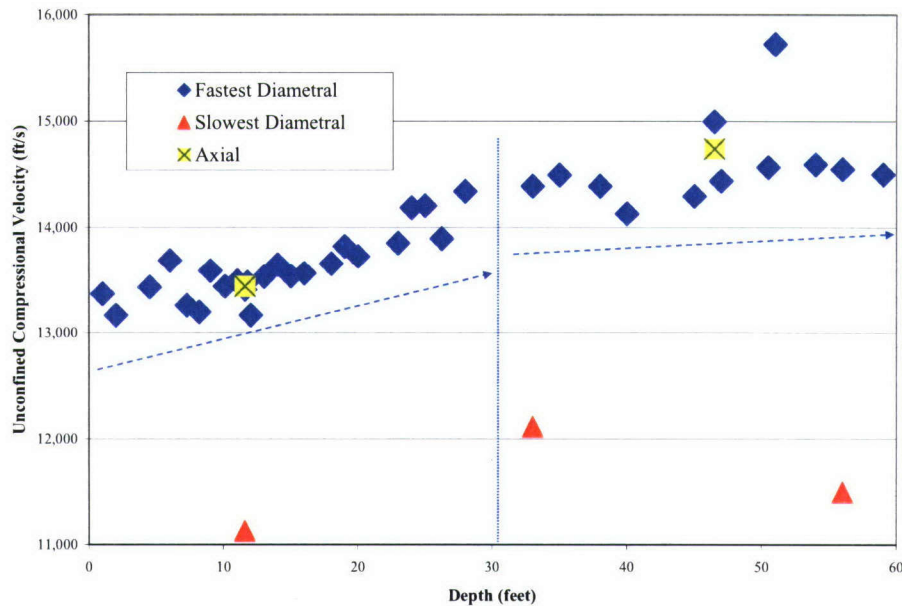
Figure 4. Compressional wave velocity (feet per second), as a function of depth, in the corehole at the proposed location for Shot 2. Velocity increases with depth, and there appears to be a change in slope at approximately 30 feet. The increase in compressional velocity with orientation, at a single depth, can approach 25 percent.
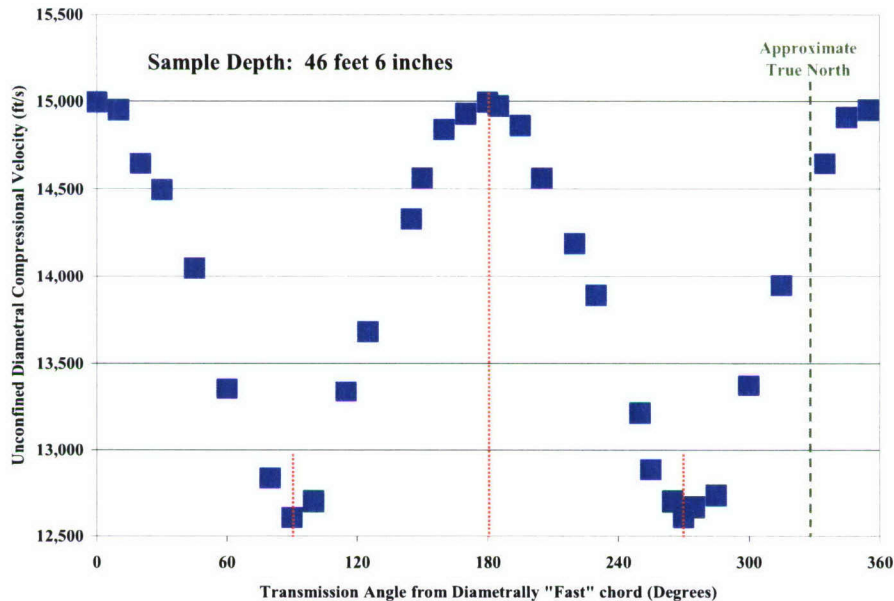

Figure 5. Diametrally transmitted compressional wave velocity (in feet per second), as a function of chord orientation, in a core specimen recovered from a corehole at the Shot 2 location. The "Fast" chord is considered to define the orientation of the strike of the rift plane in the Barre granite. The strike of the rift plane appears to be oriented at approximately N30°E at this site, and it is considered to be near-vertical. The fastest compressional wave velocity is 19 percent greater than the slowest in this specimen.

Borehole Televiewer Analysis. An optical or acoustic televiewer will be lowered in each borehole to obtain the fracture density, magnitude, and orientation. The acoustic televiewer transmits and records ultrasound pulses reflected off the borehole wall. The optical televiewer simply records a 360° picture of the borehole wall. Figure 6 shows images from an optical and acoustic televiewer of fractures in a borehole at our test site. Below 14.6 feet, there were only three rank-2 fractures, which are intermediate fractures that are distinct and continuous around the borehole with little or no apparent aperture. These fractures occurred at 21.1 (shown in Figure 6), 39.6, and 50.8 feet. Given the proposed depth of the explosion at this borehole location (12 meters or 39 feet), we may choose to detonate the explosives at a shallower depth to avoid this fracture. There was only one rank-3 fracture (e.g., major fractures that are distinct and continuous around the borehole with apparent aperture) in the imaged borehole, occurring at a depth of 7.7 feet.
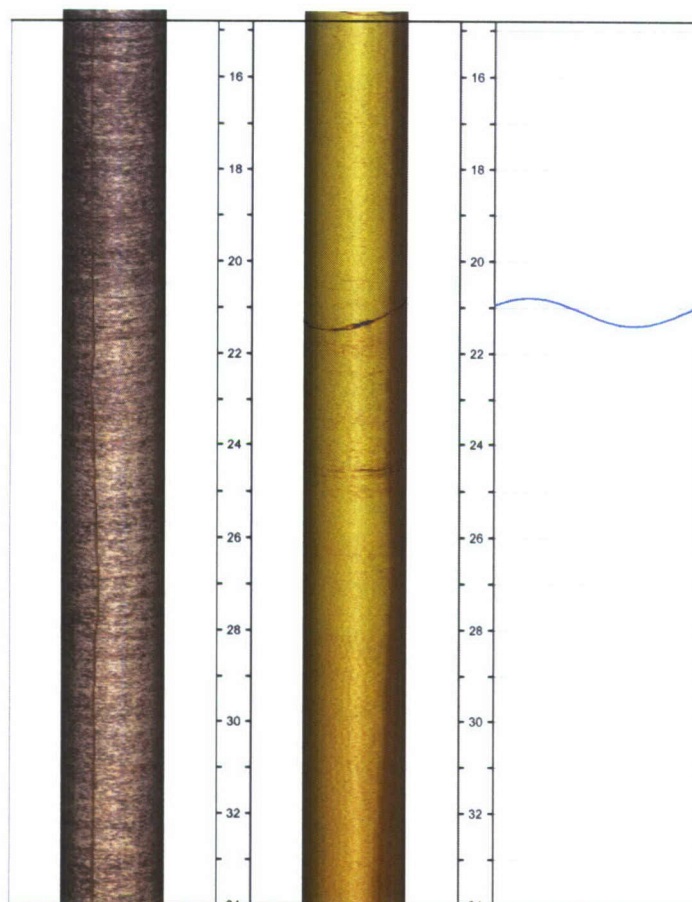

Figure 6. Optical televiewer (left) and acoustic televiewer (middle) images of a portion of a borehole at the test site. In the section shown here, only one Rank-2 fracture was observed (right, at 21 feet).

Post-Shot Characterization. After the test site has been completely characterized, the explosions will be conducted (see next section). Following detonation, we will re-open any boreholes that caved in or were damaged during the blasts, and the test-site physical properties will be examined again to determine the extent of the damage. New cores will be extracted for analysis. As shown in Figure 1, the borehole spacing will be devised to try and measure the radius of the cavity, pulverized rock, fragmented rock, and radial cracks. The televiewer will return images of the damage in each zone and quantify slip amounts along pre-existing and newly developed fractures. Surface mapping of faulting and radial cracks will be completed.

Explosion Design

Personal safety and structural integrity are the most important factors to consider when designing any explosion experiment. This damage experiment at the granite quarry in Vermont presented new challenges for design primarily due to two structures located less than 1 km from the proposed test site. The first is a cell phone tower located ~200 meters from the blast site, and the second is the vertical face high-wall of the active granite quarry (Figure 7) located ~550 meters from the blast site. Preliminary estimates of peak particle velocities (PPVs) from a fully-confined, 400-lb explosion were slightly above the United States Bureau of Mining vibration limits (USBM RI8507) at the cell tower and slightly below the regulations at the high wall.

Figure 7. Near-vertical face of the Vermont granite quarry hosting the explosion experiments. The face shown here is less than 600 meters from the proposed test site. The face must not be damaged by vibrations from the planned explosions. All explosions will be conducted after work hours when quarry personnel are not in the pit.

We attempted to locate another test site that was at a greater distance from the critical infrastructure in order to detonate the 400 lb explosions. We located a site at an abandoned aggregate quarry pit more than double the distance from the cell phone tower and quarry free face. Coring operations commenced at this site in early May 2008 only to determine that the granite was unsatisfactory for our planned experiments. The granite had a higher fracture density than the original test site (hence, it was being used for aggregate rather than monument stone), and we cored into a large schist xenolith. The desire for greater homogeneity of the emplacement media and fewer fractures led us to return to the former site and evaluate detonation yields that would provide acceptable vibration limits at the two critical structures.

We predicted the PPVs for our explosions using the mining industry standard formula of

$$\text{PPV (in/sec)} = K \times SD^A \qquad\qquad (1)$$

where A is an attenuation term that typically varies between -1.6 and -1.8, and SD is called the "scaled distance" and is defined by

$$SD = \frac{D}{\sqrt{W}} \qquad (2)$$

where D is distance and W is the explosive yield. K is a site vibration modifying factor for confinement, which varies from 24 for under-confinement to 605 for completely-confined. We used Equations 1 and 2 and K=605 to estimate the PPVs for 200-lb and 400-lb explosions at the cell tower and quarry face (Figure 8). The results show that the predicted PPVs for the 400-lb explosion are slightly above the USBM R18507 limits at frequencies greater than 10 Hz for the cell phone tower. And because the USBM vibration limits are more restrictive for lower frequency data, both explosions are predicted to vibrate above the limits at frequencies less than 10 Hz.

We have detonated three (3) 200-lb fully confined explosions in different emplacement media as part of our previous experiments (Bonner et al., 2005; Leidig et al., 2007). We plotted the PPVs for these blasts at stations between 0.2 and 11 km in Figure 8. All of the PPV data for our 200-lb shots fall below the predicted PPVs, which is due in part to the conservative choice of K=605 for the predictions. The observed data and the predictions suggest that detonating 200-lb explosions at the original test site (e.g., the site with monument-quality granite) will generate PPVs at the cell phone tower and quarry wall that are below USBM industry regulations.
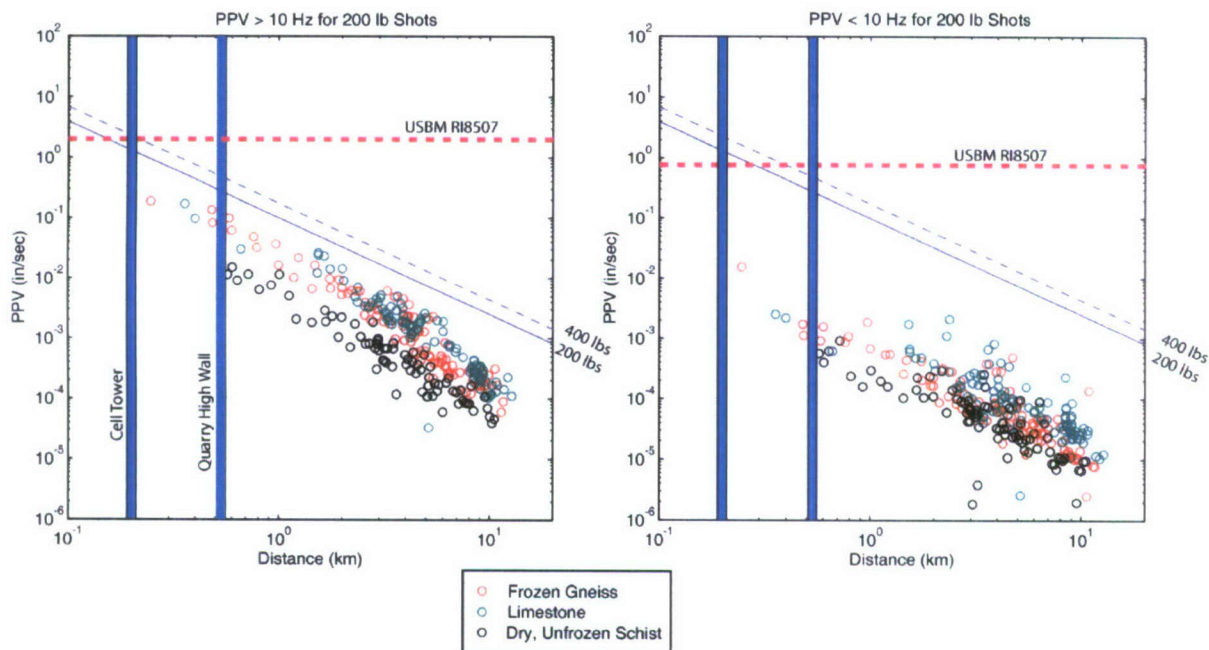

Figure 8. Predicted and observed PPVs for explosions at frequencies greater (left) and less than (right) 10 Hz. Also shown are the USBM vibration limits, which are frequency dependent. The solid and dashed blue lines represent predicted PPVs based on Equations 1 and 2, while the circles are observed PPVs for three 200-lb explosions detonated during previous experiments in different emplacement media.

Figure 9 shows the predicted layout for the five explosions (Table 1) in an image taken from near the base of the cell phone tower. To further ensure the safety of our planned operations, we are detonating three "calibration" explosions. Shot 1 will be a 50-lb ANFO explosion, while Shots 2 and 3 will be 100-lb single-fired shots. The PPVs from these "calibration" explosions will be recorded on Instantel accelerometers at the cell tower, the quarry high wall (top and bottom), and the nearest residential structure. The Instantels will provide us with rapid PPVs that can

be compared to Figure 8 in order to ensure that our homogeneous, low-fracture density media does not behave contrary to Equations 1 and 2. If the PPVs from Shots 1–3 are at or below the predictions, we will then load and detonate Shots 4 and 5, which are planned 200-lb shots located as far away from the cell tower as possible while remaining within the test pit.
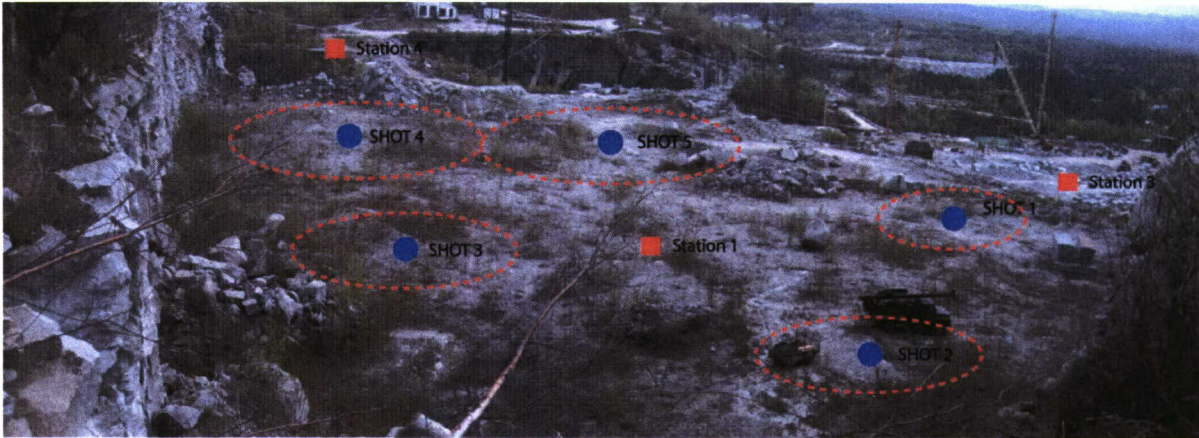

Figure 9. Image of the test pit showing the planned locations of the shots. The blue circle shows the shot point, the red circles show the predicted elastic radii for the explosions, and the red squares represent near-source stations. Shots 1-3 will be detonated first and the PPVs recorded at critical infrastructure to ensure that the 200-lb Shots 4 and 5 will be at or below USBM safety regulations.

Table 1. Designed Explosions.

Shot	Projected Hole Depth (m)	Yield (lb)	Explosive Type
1	9	50	ANFO/Emulsion
2	12	100	ANFO/Emulsion
3	12	100	Composition B
4	17	200	ANFO/Emulsion
5	17	200	Composition B

Also shown in Figure 9 are the predicted elastic radii for the planned explosions based on a Mueller-Murphy (1971) source model (see Figure 10). In designing the experiment, we separated the explosions by 1.5x the elastic radii or greater with the exception of Shots 4 and 5. Before drilling the Shot 5 blasthole, we may attempt to move the explosion a few meters west and away from Shot 4; however, this could result in damage to the access road to the pit.

The reason for the redundancy in the two 100-lb calibration shots is because we will load and shoot the holes differently. Our objective is to determine the effect of damage on *S*-wave generation; thus we plan to try and fracture the rock differently. We will detonate two different types of explosions. The first will be an ANFO/Emulsion mixture that is typically used in the mining industry that has a velocity of detonation (VOD) of ~4 km/sec. The second type of explosive used will be a molecular explosive (e.g., TNT or Composition B) with a velocity of detonation of ~8 km/sec. The two explosives will behave differently when detonated in the boreholes. Singh (1993) found that higher VOD explosives do less damage, fracturing, and over-breakage than lower VOD explosives. This is caused by the higher VOD explosives powderizing the material near the borehole due to the rapid, enormous pressures. The powderized rock subsequently hinders secondary gasses from significantly driving long cracks. The mining industry considers these phenomena as well as cost and logistics when choosing ANFO/Emulsion as their typical blasting agent for rock fracturing. By conducting a 100-lb calibration explosion of each type of blasting agent, we will have data to ensure that the detonation of the higher VOD explosives does not behave anomalously with respect to Equations 1 and 2, which were developed mainly with ANFO/Emulsion explosions.
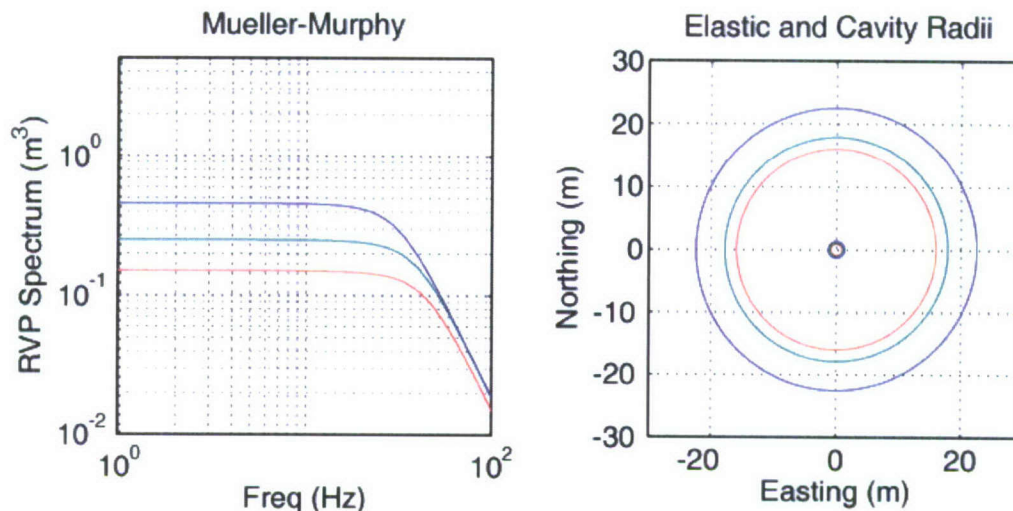
Figure 10. Estimates of the corner frequencies (left) and elastic and cavity radii (right) for 50-lb (red), 100-lb (green) and 200-lb (blue) explosions. The smaller circles with radii of approximately 1 meter represent the cavity radii while the larger circles are the elastic radii. Note that for chemical explosions, the cavity is actually a rubble or powderized zone.

Seismic Networks

We will record the explosions on an array of almost 160 accelerometers and seismometers. The near source instrumentation will consist of nine stations with high-g accelerometers and short-period seismometers within 1 km of the test site. One station will be installed in the middle of the explosions (Figure 11) to record the precise time of detonation and close-in phenomenology, such as spall, while the remaining close-in stations will be located to obtain complete azimuth coverage for moment tensor inversions. This array of sensors will be recorded at 500 samples per second.

Two linear arrays with a total of 19 three component seismometers and 120 vertical component geophones with "Texan" digitizers are going to be deployed to the northeast and southeast of the test site (Figure 11). The intermediate period seismometers will be installed at 3 km spacing with Texans placed along the same paths at 0.5 km spacing to increase sampling density. These sensors will record at 250 sps. The northeast array is oriented to follow the structural trend of the region, while the southeast array will lie oblique to the trend. Digital and analog video recordings will be made of the blasts to document any surface effects, although the explosions are designed to be fully contained and confined.

CONCLUSIONS AND RECOMMENDATIONS

Our experiment to quantify damage from explosions and its effect on S-wave generation is planned for 12–13 July, 2008.
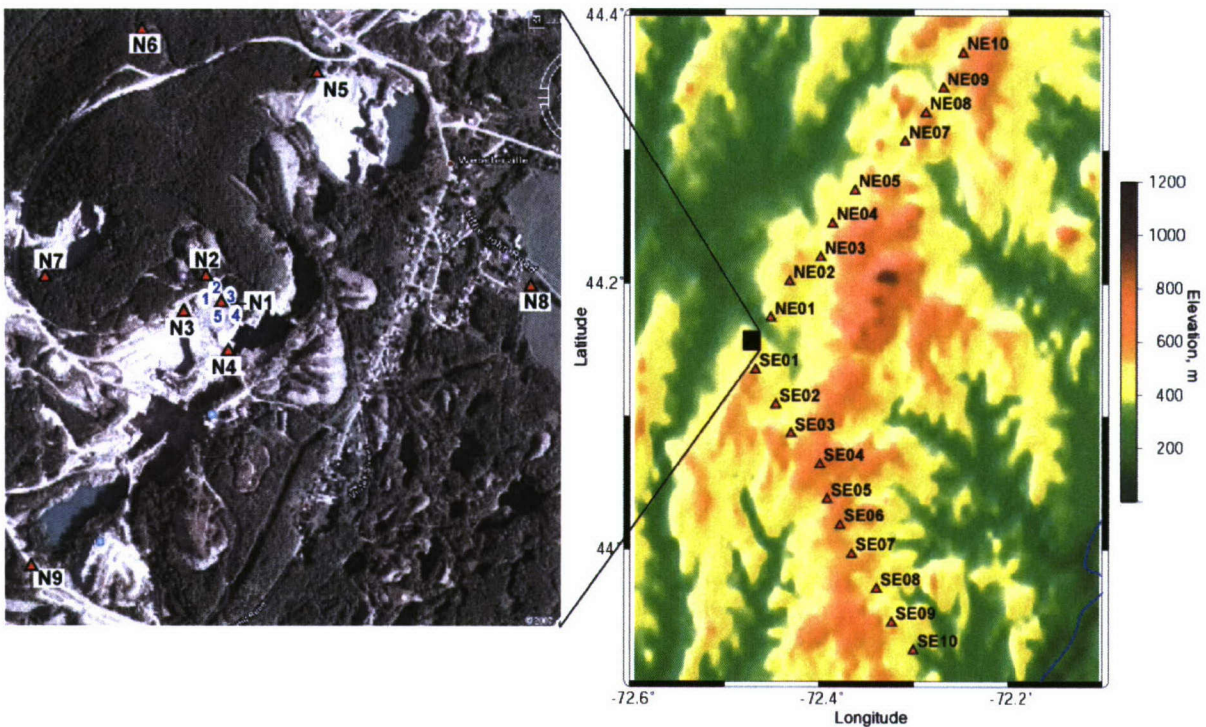
ACKNOWLEDGMENTS

Figure 11. Map of near source stations (left) relative to the explosions (blue numbers) and linear station arrays (right). The Texan sensors (not shown) will be placed along the path of the linear arrays to increase sampling density.

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