CORRELATING NEAR-SOURCE ROCK DAMAGE FROM SINGLE-HOLE EXPLOSIONS TO SEISMIC WAVES

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ABSTRACT

We have conducted the Vermont Damage Experiment in central Vermont during July 2008. Five single-hole explosions with yields ranging from 61.5 to 122 kg were detonated in homogeneous, low fracture density granite. The centroid depths for the explosions ranged from ~8 to 13 meters. Explosives with different velocities of detonation (VOD), including black powder (0.53 km/sec), heavy ANFO (4.8 km/sec), and COMP B (8.1 km/sec) were detonated to relate the VOD to seismic wave generation and extent of damage in the source region. The purpose of this paper is to present the analysis of pre- and post-shot corings and borehole imaging in order to relate the microscopic and macroscopic damage caused by the explosions to the frequency-dependent differences in seismic wave generation.

Examination of the ground surface after the blasts found no radial fractures produced by the COMP B explosions, while there were large fractures with displacement from the heavy ANFO and Black Powder shots. Examination of the cores showed few native fractures in the pre-shot medium. Post-shot core was fragmented in the vicinity of the shot point, while intervals above the emplacement depth had less fragmentation. Large scale induced fractures developed for only short distances below the shot points. Blast induced disking of the core was observed in each of the post-shot cores. In addition, visual observation of the post-shot cores showed gross changes in appearance in the vicinity of the working point. The native rock is bluish gray, while the rock recovered near the blasts is lighter colored than the rock outside the working point. The change in appearance is likely due to shattering or crushing of the grains. Density of the rock in the vicinity of the shot points decreased after the blast with a corresponding increase in porosity. Laboratory measurements also show significant changes in rock properties due to blast damage, with higher permeabilities, lower resistivities and acoustic velocity reductions of greater than 20%.

Over 120 seismic stations were deployed to record the explosions at distances between 5 m and 30 km. Analysis of the seismic waves showed distinct differences in amplitudes between the three shots of the equal yields, with the heavy ANFO and COMP B producing larger seismic waves than the Black Powder at frequencies greater than 10 Hz. The slower VOD explosives (e.g., ANFO and Black Powder) produced larger amplitudes than the COMP B at frequencies below 8 Hz.

For the next phase of this study, we will continue to quantify the bulk properties, density, and porosity of the rocks before and after the explosions. We will also evaluate the geophysical properties of the rock at varying stress levels. Intact pieces of core recovered from additional post-shot core holes will also be systematically analyzed to identify distinct damage zones, and define their lateral extent. The variations in these properties at the micro-scale will be combined with macro-scale studies of near source damage by ground penetrating radar (GPR) to image the entire fracture regime. The objective of these studies will be to determine the elastic and effective cavity radii for the explosions as well as motion on the fractures and asymmetries in the damage from the explosions, and relate them to the near and far field seismic responses.

OBJECTIVES

Two of the proposed mechanisms for *S*-wave generation involve processes related to the damage and deformations caused by the explosions. Nonlinear effects in the immediate vicinity of the explosion causes rock damage that can effectively generate shear-waves provided that asymmetries exist in the damage pattern (Johnson and Sammis, 2001; Bykovtsev, 2007). A second proposed mechanism is damage and failure in an inverted conical region above an explosion. Media within the cone deform, fail, or exhibit driven block motions, as envisioned by Masse (1981). The failure in this cone has been modeled with moment tensor representation as a compensated linear vector dipole (CLVD) source (Patton et al., 2005).

Unfortunately, there is a paucity of detailed damage characterization studies from explosions easily available to test these two models of *S*-wave generation. Weston Geophysical Corp. (WGC) and New England Research, Inc. (NER) collected a unique dataset of damage characteristics from explosions in hard, crystalline rock during July 2008. The one year pilot study, called the New England Damage Experiment (NEDE), involved the detonation of five small (61.5 to 122 kg) chemical explosions in relatively unfractured, homogeneous Barre granite in Vermont, USA. Barre granite has been a worldwide standard for homogeneous, low fracture-density granite in commercial, monument, and industrial settings. The emplacement granite was characterized before and after the experiment using borehole cores and acoustic imaging. The explosions were designed with variable velocities of detonations (VOD ranging from 0.53 km/sec to 8.1 km/sec) in order to fracture the rock differently, thus leading to possible variations in *S*-wave generation. The preliminary conclusions from the pilot study (see Leidig et al., 2009):

- Larger amplitude *S*-waves were generated from shots using Black Powder and ANFO (VODs < 5 km/sec) than with COMP-B (VOD~8.1 km/sec);
- No meso-scale surficial damage was observed from the COMP-B shots, whereas large radial cracks with vertical movement were observed from Black Powder and ANFO shots with equivalent yields and source depths;
- Moment tensor inversions indicate a possible CLVD component to the explosions; and
- Meso-scale damage observed in post-shot cores was asymmetrical and had variable characteristics depending on the type of explosive detonated.

The objectives of the current project will include microscopic evaluation of fracturing that occurred during the loading and unloading processes of the explosions. An objective will be to develop a physical model of the non-linear deformation that these rocks incurred. The results will be compared with a macroscopic evaluation of the fracturing from the explosions, which will be completed with additional borehole coring measurements (we only have three post-shot cores currently) as well as ground penetrating radar (GPR) studies to image the fractured regime. The objective of these macro-damage studies will be to determine the elastic and effective cavity radii for the explosions as well as motion on the fractures and asymmetries in the damage from the explosions. Finally, we will combine the results from the damage evaluation with the observed seismic data to examine possible models for differences in the observed *S*-wave generation from the explosions. In the remaining pages, we discuss our research plans and include initial results of the rock damage analysis.

RESEARCH ACCOMPLISHED

Mapping Explosion Damage Using GPR

The cores obtained thus far have provided us with a preliminary assessment of localized damage from three of the NEDE explosions. Observation of surface cracks immediately after the shots showed that the COMP B explosions did not generate radial cracks that reached the surface while the Black Powder and Heavy ANFO shots did (Figure 1). In order to obtain a comprehensive image of the 3D distribution of damage (e.g., cavity and elastic radii), we are conducting a GPR survey (July 2010) to map the large scale aspects of the damage. The objective will be to map the entire test bed and use the resulting data to determine the locations of additional coreholes near Shots 4 and 5.

Figure 1. Radial crack formation from the Black Powder Shot 1 (left) and the Heavy ANFO Shot 2 (right).

Drill Additional Cores

After GPR has imaged the damaged zone to beyond the inelastic radius for the NEDE explosions, we will use the resulting maps to locate additional coreholes. During the first year of the project, an expanded study will concentrate on Shot 4, the 121 kg ANFO shot. New coreholes will be drilled radially outward from the working point, parallel to the rift plain; three coreholes are planned. At least one hole will also be drilled normal to the rift plane. In this way, we should be able to determine whether the intrinsic anisotropy has any effect on the shape of the damage surfaces. During Year 2, similar coreholes will be drilled and studied for Shot 5, the 122 kg COMP B shot. Borehole imaging via optical and acoustical televiewer logs will also be performed in the new coreholes. This will allow for a greater ability to delineate the types and extent of damage, and will assist in determining the overall geometry of the damage. Comparisons of the results of these two shots will help characterize the effects of VOD on the changes in rock mass within the inelastic zone.

Laboratory Analysis of Damaged Barre Granite

Bulk Properties. Data will be collected on additional sections of the pre-shot core, as well as characterization of all post-shot core. We expect that there will be a variation in bulk density and porosity with depth. The spatial variation in porosity will be an initial indication of the degree of damage experienced by the sample due to the detonation of the explosions. Initial analyses show the post-shot porosity increases by a factor of 2-2.5 near the working point of the explosions, and the post-shot permeability can increase by a factor of 8–10 (Figure 2).

Velocities. Compressional- and shear-wave velocities will be measured parallel and normal to the rift plane on all core at ambient conditions. This includes completion of the study of the existing core collected in 2008 and all additional core required to complete the characterization of the damage zones associated with the shots previously detonated at the Barre quarry. Figures 3–6 provide some of the results of the initial velocity analysis completed on our current pre- and post-shot cores.

Geophysical Properties at Stress. Velocity, permeability, and electrical resistivity will be measured on specimens from selected intervals along the core. NER has developed a technique to invert the velocity, permeability, and resisitivity data, as well as image analysis of thin sections, to obtain a pore structure (PSI). For these specimens, we anticipate that the pore spectrum will be fairly simple and be comprised mostly of low aspect ratio (10^{-3}) cracks. By looking at both pre-shot and post-shot specimens, we will be able to determine how the crack length and crack density has changed due to the detonation and how these parameters vary as function of position with respect to the working point. We will model the changes in the length and density of microcracks on specimens collected radially outward from the working point in order to further assist in characterizing the geometry of the damage.

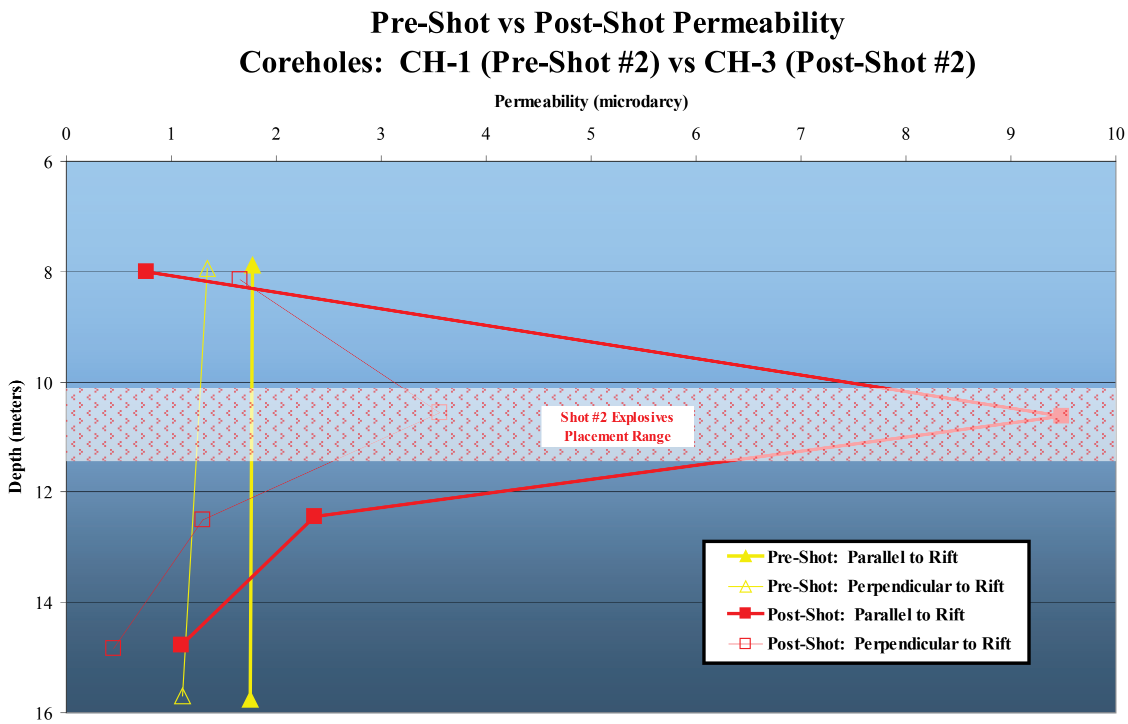

Figure 2. Permeability observed in pre- (yellow) and post-ANFO shot (red) cores parallel (solid symbols) and perpendicular (open symbols) to the rift in the Barre Granite.

Figure 3. Barre granite core that has been partitioned every 5 degrees in order to determine the fast and slow directions of the anisotropy or "rift."

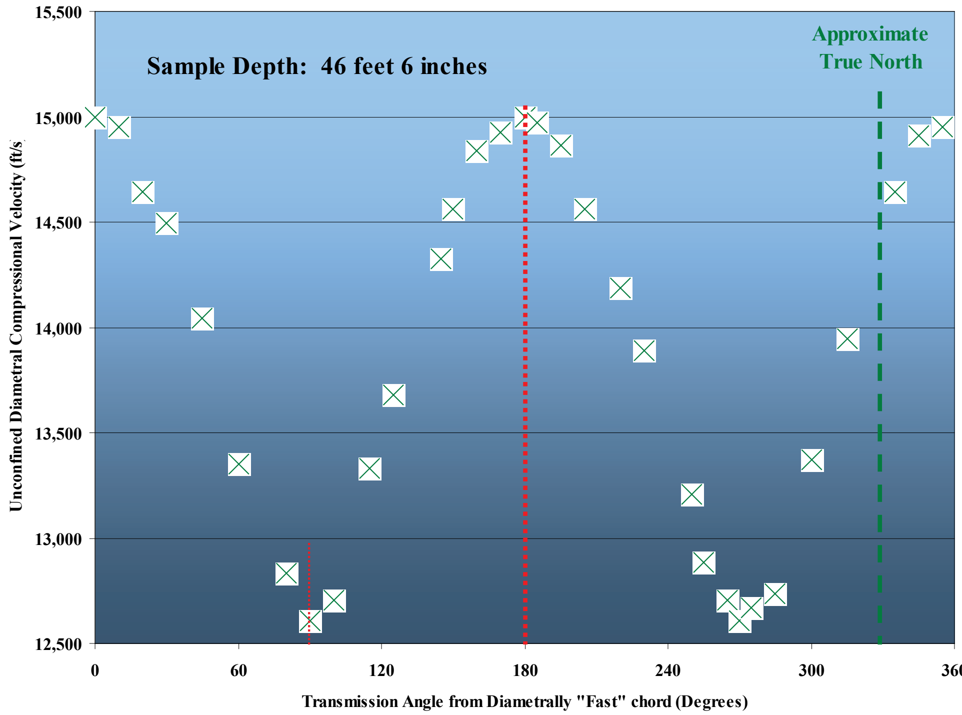

Figure 4. ***P*-wave velocities (in feet per second) for undamaged Barre granite core at a depth of 46 feet and 6 inches. The fast direction was found to be 30 degrees east of true North.**

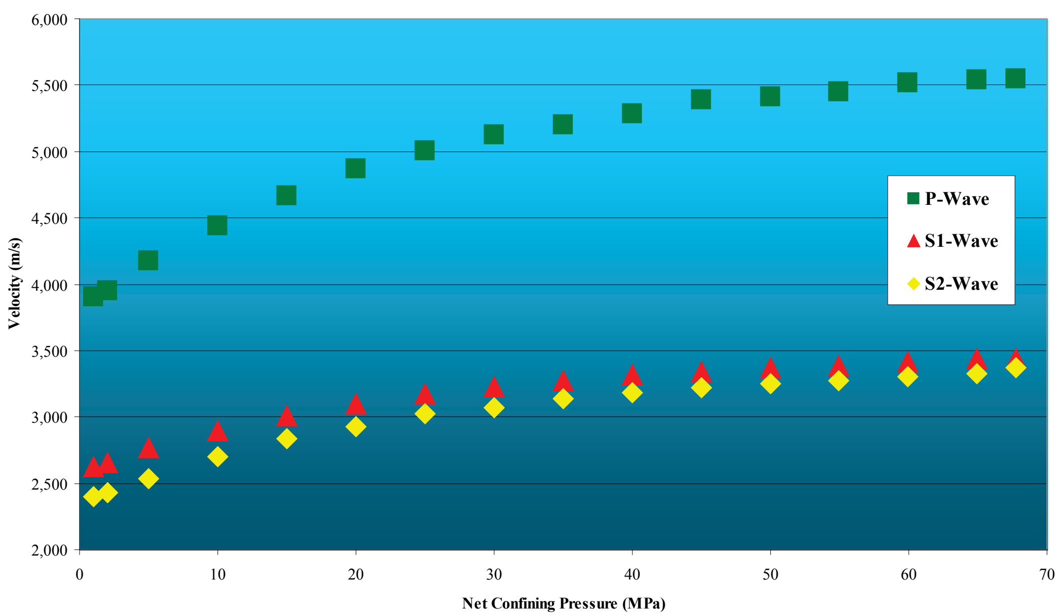

Figure 5. Ultrasonic *P*- and *S*-wave velocities as a function of confining pressure for Barre granite.

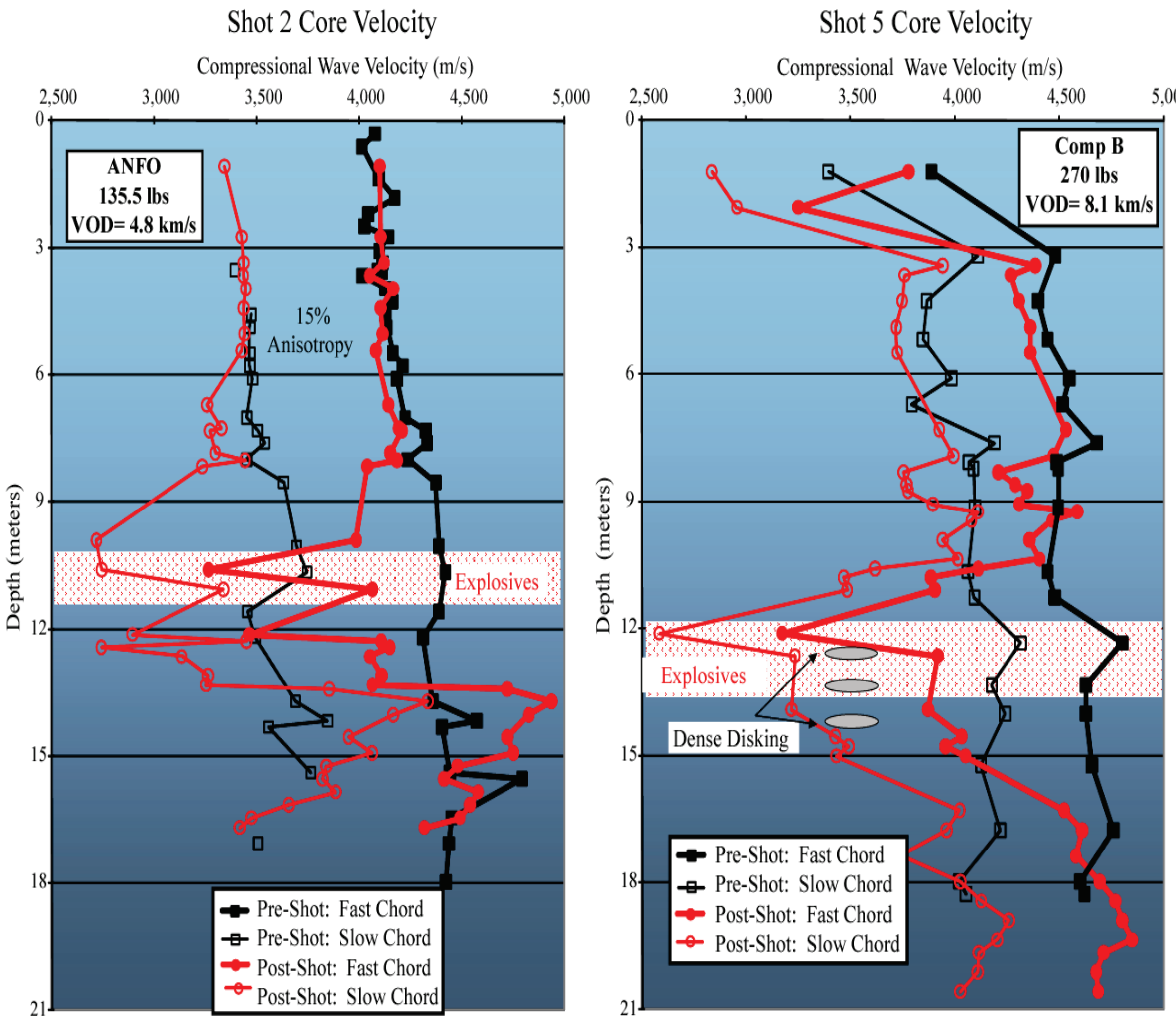

Figure 6. (Left) Velocity data from cores extracted before and after the 61.5 kg (136 lbs) ANFO shot. Because of the rift plane in the Barre granite, there are both "fast" (measured parallel to the rift plane) and "slow" (perpendicular) chords or directions. (Right) Velocity data from cores extracted before and after the 122 kg (269 lbs) COMP B shot. These plots show significant reduction in the seismic wave velocity caused by micro-scale damage from the explosions.

PSI: Pore Structure Inversion – Overview. Details of the pore structure of a rock control many fundamental rock properties including fluid transport, electrical resistivity, seismic velocities, and rheology. While direct imaging of the pore structure of individual cores can provide great insight into physical understanding of a given core, most practical applications involve cases of limited observations. NER's pore structure modeling yields a pore structure of a sample based on measured core scale properties.

The approach is based on the idea that a limited but diverse set of observations provides sufficient constraint to say something meaningful about the pore structure. Simultaneously satisfying observations of a variety of core scale properties can be a powerful constraint because each of the properties is linked to the pore structure in a different way. A schematic illustration of the modeling is shown in Figure 7. The method starts with an assumed generic topology, for which we have adopted a disordered network of tubes connecting nodal pores. Using measurements of velocity, porosity, permeability, resistivity, and compressibility, a description of the pore structure is found, which simultaneously satisfies each of the constraints. Image analysis of the thin section is used to constrain some of the free parameters. The model output is a shape spectrum, describing the smoothest distribution of the throat shapes (for granites, low aspect ratio cracks) and sizes that is consistent with the constraints and model assumptions.

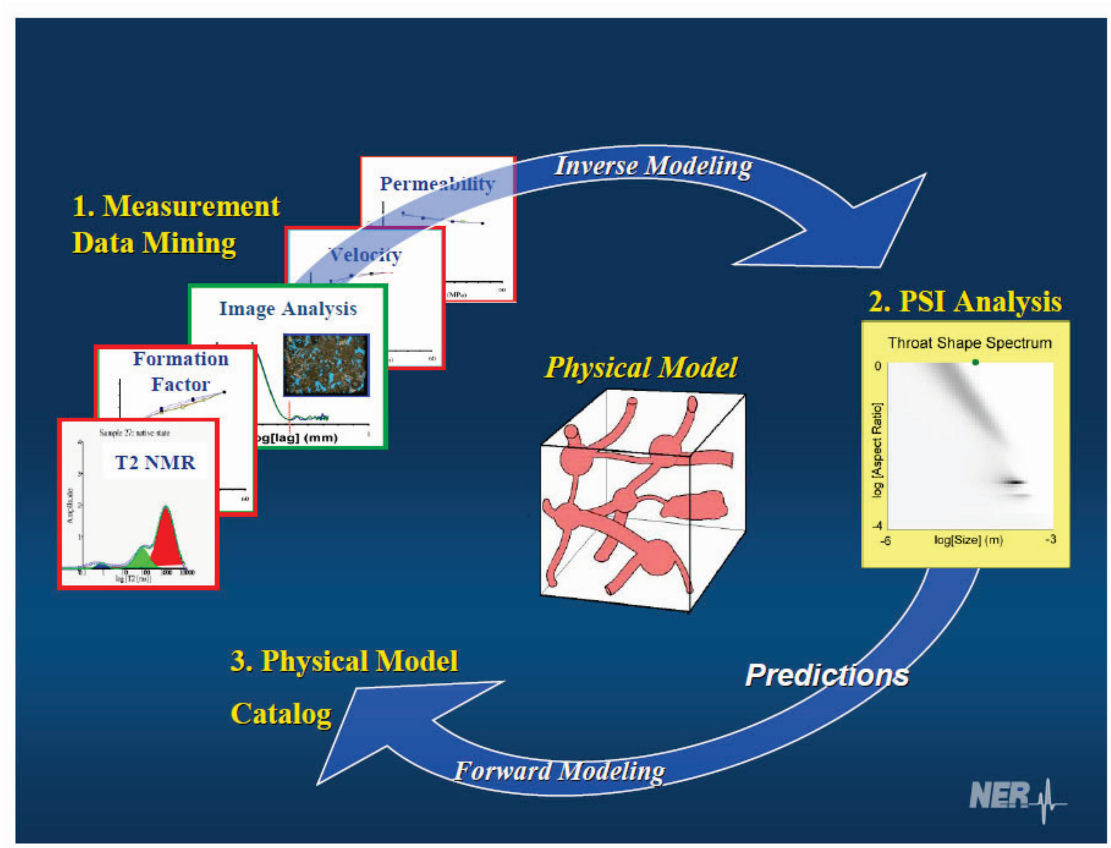

Figure 7. Schematic representation of the pore structure inversion to be performed on Barre granite pre- and post-shot core.

Fragmentation Analyses. In addition to quantifying the variation in microcrack damage in the intact pieces of core recovered from the post-shot core holes, the degree of fragmentation and the size of each fragment need to be systematically analyzed. The specific interests will be the size and shape of each fragment. In this way, it will be possible to determine the amount of granulation occurring between the fragments, and again determine this as a function of position in each of the post-shot coreholes. Presently, this effect has only been documented photographically (Figure 8).

Figure 8. Examples of meso-scale damage observed in cores above the working explosion point.

Identification of Damage Zones. Most models assume that there is a series of concentric shells with varying degrees of damage ranging from the cavity outward to the inelastic radius. The shape of each of these specific zones is not known. In this study, we will integrate collected data to determine the variations of the damage zones surrounding the working point

Testing the Damage Mechanics Model Against the Observed Seismic Data

The shape of the damage zone (e.g., inelastic and cavity radii) and the determination of whether the zones of increasing damage are concentric or variable as a function of depth need to be quantified in order to model the energy distribution throughout the source region. Furthermore, the variations may also occur radially. Note that the rift zone introduces fairly strong anisotropy into the site. The anisotropy may affect the shape of the damage zones in the horizontal plain. Once the data are complete, then the active data modeling, either using the Sammis (2002) model or the CLVD model will be tested.

***S* Waves from Crack Growth.** Ashby and Sammis (1990) formulated a micro-mechanical model for the formation and growth of new fractures from pre-existing cracks under the compressive loading states representative of explosions. Their research has demonstrated that the growth of these fractures contributes to the generation of high-frequency seismic waves from explosions. The Ashby and Sammis (1990) micro-mechanical model has been incorporated into the non-linear explosion codes used by SAIC which have successfully modeled near-source data from the NTS (Rimer *et al*., 1998) and the Degelen Mountain Test Site (DTS; Stevens et al., 2003a).

Sammis (2002) showed that crack growth affects the source in two ways: 1) the increased damage weakens the rock by lowering the elastic modulus and 2) the growing fractures are secondary sources of seismic energy. By combining their micro-mechanical model with a stress field for explosions, they can estimate the growth and seismic moment tensor for each individual crack. While the moment may be small for each crack, integrating them over the entire source volume produces secondary waves that can propagate into the far field. Any asymmetries in the pre-existing shear stress or preferred orientation of the initial cracks can generate *S* waves. Preliminary examination of the post-shot cores for the NEDE does suggest that there were asymmetries in the cracks generated above and below these explosions.

***S* Waves from Spallation and Block Motions.** The presence of the Earth's free surface creates significant asymmetries in rock damage. Above the spherical region of the explosion, there is an inverted conical-shaped damage region with apex at the explosion point source (Masse, 1981). The material inside the cone deforms and fails as a result of tensile stresses caused by the downgoing shock wave reflected off the free surface. Spallation, which usually involves shallow, poorly-coupling geologic strata that open and close with no net displacement, is an example of such failure (Eisler and Chilton, 1964; Stump, 1985). Another example is driven block motions at depth, as envisioned by Masse (1981) and Blouin (1980, 1981). This source might be more important for seismic wave generation than spall if it involves permanent deformations and couples better into the Earth, since its centroid may be located in more competent rock at depths greater than spall.

The region inside the cone of deformation has been modeled extensively using a CLVD moment tensor representation (Knopoff and Randall, 1970). Stevens et al. (2003b) examined *Lg* generation at DTS using non-linear finite difference modeling. Their non-linear seismograms, which incorporate damage in the source region, showed abundant *S*-wave energy on regional distance synthetic seismograms that matched observed data. The researchers then observed they could match the data equally well just by considering an explosion point source plus a shallow point CLVD source.

The CLVD source may excite azimuthally-independent Rayleigh waves. Patton et al. (2005) showed that *Rg* spectra for chemical explosions at the Shagan Test Site could be modeled using a combined monopole explosion and CLVD source. The CLVD source in their study appeared to be more closely related to a driven block motion model envisaged by Masse than spall. *Rg* source amplitudes were consistent with *mb*(*Lg*) measurements at station MAK, as would be expected if near-field *Rg*-to-*S* scattering (Myers et al., 1999) plays a role in generating *S* waves observed at regional distances.

Preliminary research has determined that the amplitudes of M_{xx} and M_{yy} components of the NEDE moment tensors are approximately similar, while the amplitudes of M_{zz} components exceed the horizontals by almost a factor of 2, which could be caused by a CLVD source. We propose to use detailed velocity and attenuation models for this region (currently being developed) coupled with these explosion moment tensors to conduct numerical modeling of recorded near-source, local, and regional seismograms. We will use 1D, 2D, and 3D models, and include topography and stochastic properties of the media in order to quantify possible scattering effects. The goal of this modeling exercise is to determine how much of the local data can be traced back to source effects (e.g., moment tensors which appear to have a strong CLVD component) and what characteristics of the local and regional data are due to path effects.

CONCLUSIONS AND RECOMMENDATIONS

We believe that the datasets that will be obtained from this new study (e.g., meso and micro-fracture analyses, bulk properties under variable stress conditions, pore structure inversions, GPR mapping of meso-fractures, etc.) in conjunction with seismic data collected during the 2008 pilot study will provide the Nuclear Explosion Monitoring community with further data for the development of a more complete explosion source theory model, including *S*-wave generation.

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