

PLANNING SOURCE PHENOMENOLOGY EXPERIMENTS IN ARIZONA

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ABSTRACT

Our consortium continues to plan a series of source phenomenology experiments at coal and copper mines in Arizona. The purposes of the experiments are to examine the source of single- and delay-fired explosion generated shear waves, to quantify the energy partitioning in regional seismic phases from different types of explosions, and to quantify the differences between contained single-fired chemical (a surrogate for nuclear tests) and delay-fired mining explosions in mines located in different lithologic and tectonic regimes.

During the first year of this project, we have planned the explosions to be conducted at each mine. Scaling relationships for single-fired explosions will be examined by detonating single-fired shots of 3.5- and 7-tons in confined and unconfined (i.e. blasting near a free face in the mine) settings. We will also examine the effects of scaled depth of burial by detonating confined 7-ton shots at depths of 20 and 40 meters. Additional tests, such as a 14-ton shot detonated during a delay-fired production shot, are also planned. In addition to shot planning, we have collected databases of near-source and regional waveforms for routine blasts at both mines. These data have been supplemented with shot records from the mine engineers and scaling relationships have been studied. Finally, we have designed the near-source, local, and regional station deployment configuration. The explosions will be recorded by near-source velocity of detonation recorders, videographic equipment, and an array of accelerometers optimally positioned for moment tensor inversion. At local and regional distances, the experiments will be recorded by a linear profile of 25 broadband seismic stations. The experiments are planned for August and September, 2003.

OBJECTIVES

Weston Geophysical, Southern Methodist University, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the University of Texas at El Paso have formed a consortium to quantify the differences between contained single-fired chemical (a surrogate for nuclear tests) and delay-fired mining explosions in mines located in different lithologic and tectonic regimes. We have built upon ongoing cooperation with the US Mining Industry (Heuze *et al.*, 1999) and previous studies (Bonner *et al.*, 2003; Stump *et al.*, 2002) that have collected data from routine delay-fired explosions from mines across the US. In order to span the range of production mining techniques and *in situ* materials while maintaining a consistent set of regional stations, we have designed a series of single-fired explosions in the northeastern Arizona coal-mining district (cast blasting, parting, and coal shots) and in the southeastern Arizona copper mining district (hard rock fragmentation). The objectives of our shot designs include: 1) defining the fundamental source physics that govern energy partitioning among regional seismic phases, 2) identifying possible sources of *S*-wave generation for different types of explosions, 3) determining the effects of depth of burial, yield, and containment on the source function for contained chemical explosions, 4) performing discrimination between nuclear explosions, mining explosions, and earthquakes, 5) completing moment tensor inversions for source properties, and 6) determining whether regional signals from routine delay-fired explosions can be used to gauge anticipated signals from small nuclear explosions (Figure 1).

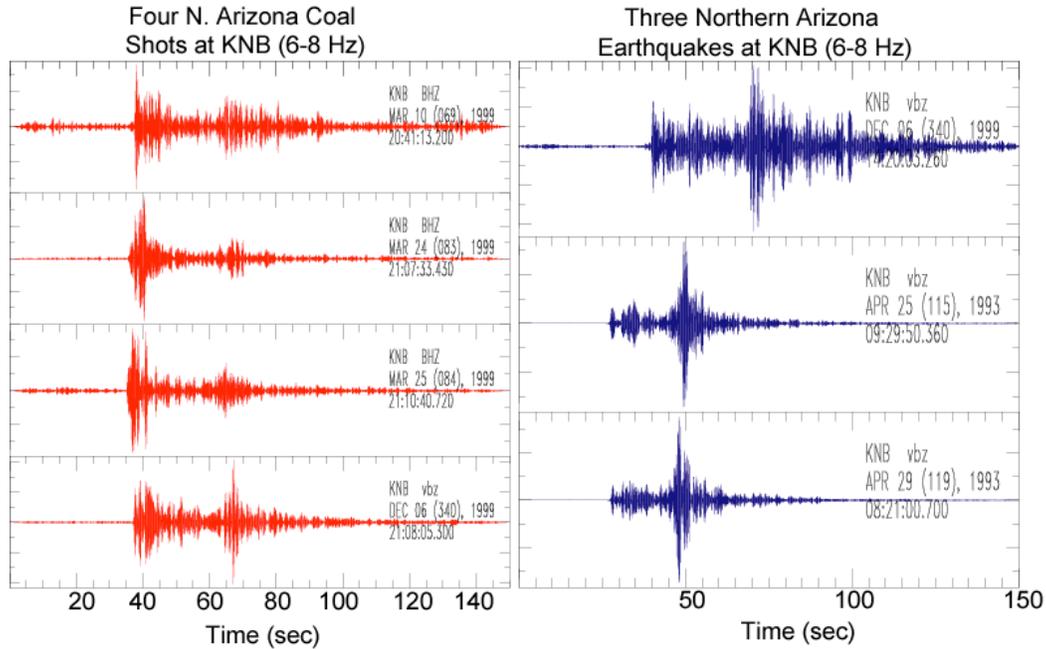


Figure 1. Examples of coal mining cast blasts and earthquakes in northern Arizona. An objective of the source phenomenology experiments is to examine mine blast and earthquake discrimination, in particular, the generation of *S*-waves from single- and delay-fired explosions.

During the initial year of this project, we have designed this series of explosions by 1) determining the characteristics of seismicity produced from routine production shots at both mines, 2) negotiating with mine engineers to design regionally recordable explosions that were within safety and production requirements at both mines, and 3) siting near-source, in-mine, and regional station arrays in order to record the data necessary to achieve the experiment objectives.

RESEARCH ACCOMPLISHED

Experiment Location

We proposed to conduct this source phenomenology experiment in Arizona (Figure 2) for multiple reasons. First,

the region. Second, by choosing copper and coal mines for the explosions, we could accomplish an objective of examining the differences in signals generated in hard and soft-rock settings, while maintaining a consistent set of regional stations. Finally, the two mines chosen also provide us with an understanding of the effects that different propagation paths may have on regional phase partitioning. At the request of the mining companies, we have withheld the mine names from this manuscript and refer to them as either Coal or Copper (as shown in Figure 2).

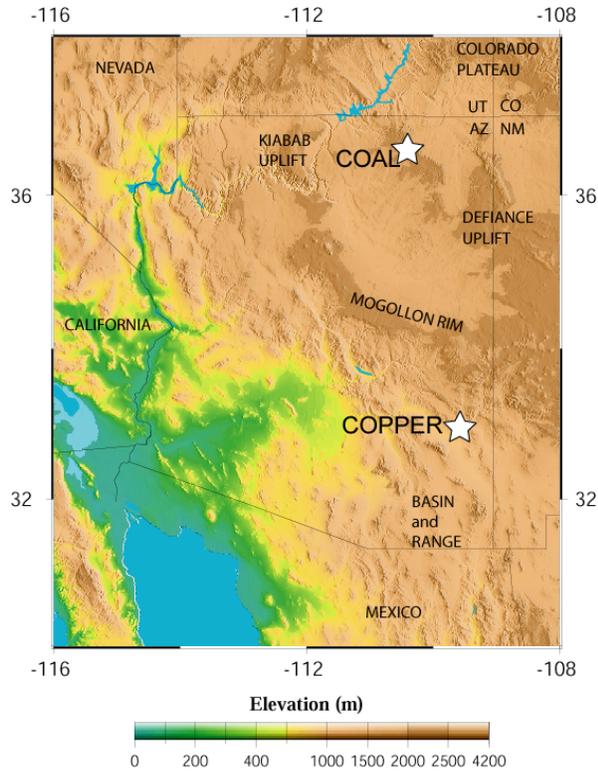


Figure 2. Topographic map of Arizona showing the locations for the proposed source phenomenology experiments. The soft rock coal mine is located in the structurally simple Colorado Plateau geophysical province, and the hard-rock copper mine is in the structurally complex southern extensions of the Basin and Range province.

Experiment Implications from Regional Seismograms of Routine Production Blasts

We have developed detailed shot databases for each mine that consist of local and regional seismic data, detailed blasting reports obtained from mine engineers, and in some cases videographic and ground-truth data. We have used the data to examine variations in routine blasting procedures and to predict the regional seismic amplitudes expected from the single-fired explosion series.

Copper. In the following paragraphs, we summarize some of the types of data and illustrate the effects of routine blasting practices on the regional seismograms from the copper mine (Figure 2). Two distinct types of delay patterns are currently used at the copper mine and are illustrated in Figure 3. Larger shots, over 250,000 lbs., utilize relatively long delay times between holes in a row (67 ms) and between rows (100 ms) resulting in long duration shots (Figure 3, left). Smaller shots utilize shorter delay times typically between 17 and 35 ms producing much shorter shot durations (Figure 3, right).

These time delays create additional complexity in the radiated seismic energy when compared to a contained, single-fired explosion. One simple way of modeling this complexity is with an impulse time series like that shown in Figure 3 (middle). At regional distances the seismic data are relatively band-limited by the earth filter, so it is important to look at the constructive and destructive interference introduced by the source delay times and total shot duration. The theoretical spectra from three explosion designs, two short delay time events (green and red) and one long delay shot (blue) are compared in the frequency domain in Figure 4.

In the 1 to 10 Hz band, typical of the regional data, the short delay time shots produce the largest amplitudes despite the fact that they have the smaller total charge size. This theoretical result is in strong contrast to that expected from single-fired explosions where models and data indicate consistent scaling relations between the total amount of explosives and peak amplitude of regional and teleseismic waves. Seismic instruments were deployed in the mine and at regional distances to document these blast-timing effects; these are discussed in the next two sections. These same instruments will be utilized in our source phenomenology experiments.

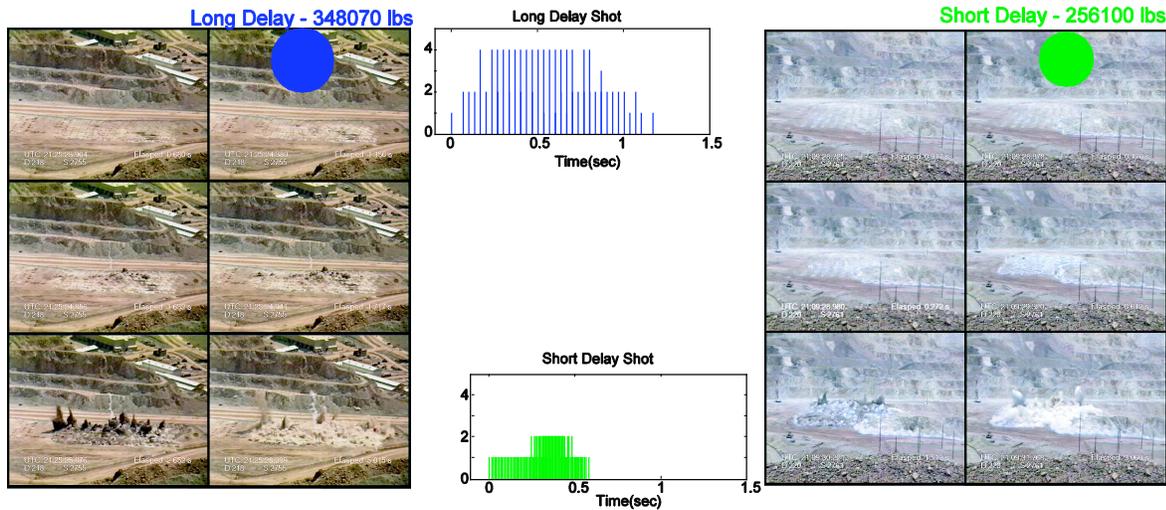


Figure 3. Two types of blasting are used in the mine. The first (top) are blasts with total explosive weights of over 250,000 lbs. and long time-delays between shots (67- 100 ms). The smaller shots (bottom) are detonated over a shorter total time interval with shorter delays (17-35 ms).

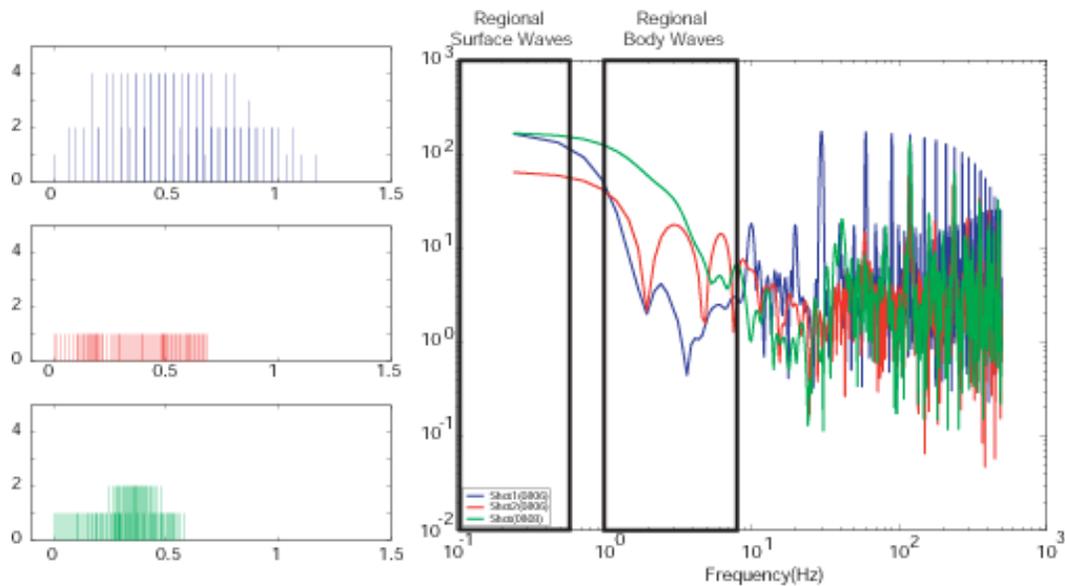


Figure 4. Comparison of predicted spectral levels from the impulse time series for a long-delay shot (blue) and two short delay shots (red and green). The long delay times result in substantial decrease in peak amplitudes in the 1-10 Hz band relative to the short delay shots.

Regional seismic stations high signal-to-noise ratio signals from typical mining explosions at this copper mine. For example, during July and August of 2001, nearly 1/3 of all events in the USGS Mining Database came from this mine. It is interesting to examine the events that appear in the USGS mining seismicity database. The vast majority

mine. It is interesting to examine the events that appear in the USGS mining seismicity database. The vast majority of events in this database are generated by short-delay shots, which close-in data suggests will produce the largest amplitudes at regional distances. This blasting practice effect is illustrated by comparing the total yield for the blast with the P , Lg , and surface wave amplitudes recorded at TUC (Figure 5). Variations in coupling and blasting delays for these explosions cause wide variations in the regional P and Lg amplitudes versus yields; however, the surface wave amplitudes generally increase with increasing yield. The blasts with the longer downhole delays (green stars), with yields of 350,000 and 500,000 lbs, have surface wave amplitudes typical of 150,000 and 100,000 lbs. short delay shots (red and yellow stars).

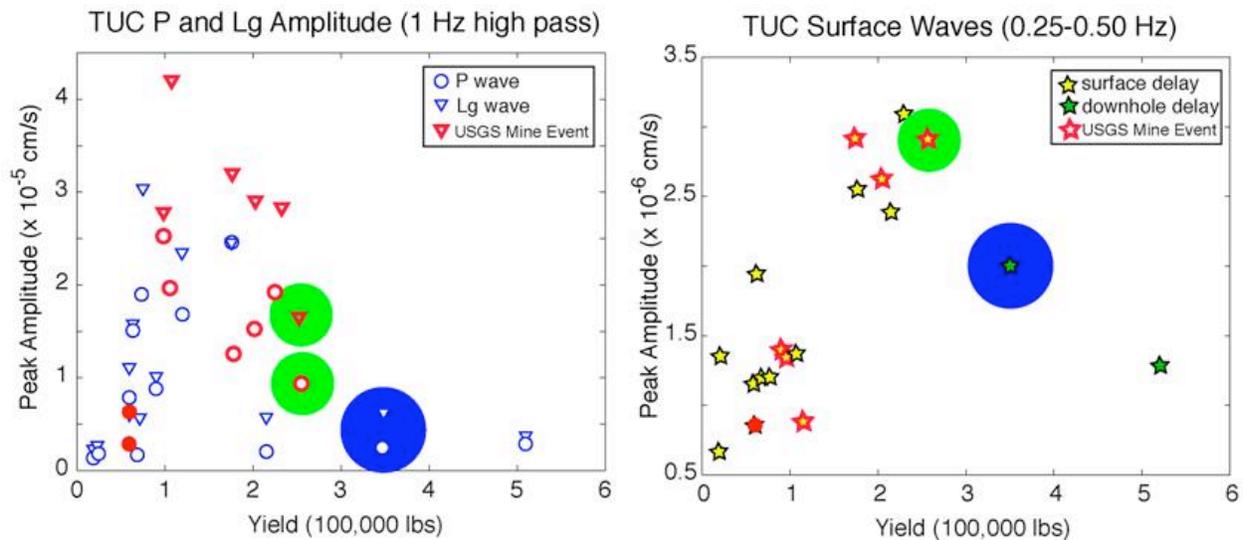


Figure 5. Comparison of observed regional P and Lg (left) and surface wave (right) amplitudes versus yield for short- and long-delayed copper mining explosions.

These in-mine and regional observations have been compiled in the shot database and have been used in the design of the source phenomenology experiments. For example, the strong effects of source timing on near-source and regional amplitudes and waveform complexity has led us to employ velocity of detonation recorders (VODRs) and electronic blasting detonation systems to better characterize the source. We also recognize that both P and S waves are observed in-mine thus helping us design our near-source seismic network. In addition, the regional data from these explosions suggest that we can reliably record the larger single-fired explosions at distances of 1000 km or less. Finally, the shot database highlights that the key to success for any study of mine blast seismicity is cooperation with the mining engineers and ground truth within the mine.

Coal. The shot database at the coal mine (Figure 2) consists of regional recordings of 22 routine blasts with blasting logs for each event. Our analysis of the data from these events has shown strong azimuthal surface wave radiation patterns from cast blasts (Bonner *et al.*, 2003) and variable relationships between yield and regional amplitudes for cast blasts and parting shots. The regional data in Figure 6 are plotted against the total yield of the explosion as well as the maximum amount of explosives that will detonate within an 8 millisecond (msec) time window. For cast blasts, which are designed to fragment and throw the overburden off coal seams, we determined power law increases in amplitude with yield (for both total and max per 8 msec), with correlation of at least 65%. However, for the parting shots, which are designed to fracture the material above coal seams, we do not observe similar scaling relationships. Further, we determined that the lowest total shot weight with measurable P and Lg amplitudes was 111,641 lbs (delay-fired) and the lowest yield per 8ms is 1253 lbs. Therefore, all of the planned shots will have yields between 7,000 and 56,000 lbs of explosives.

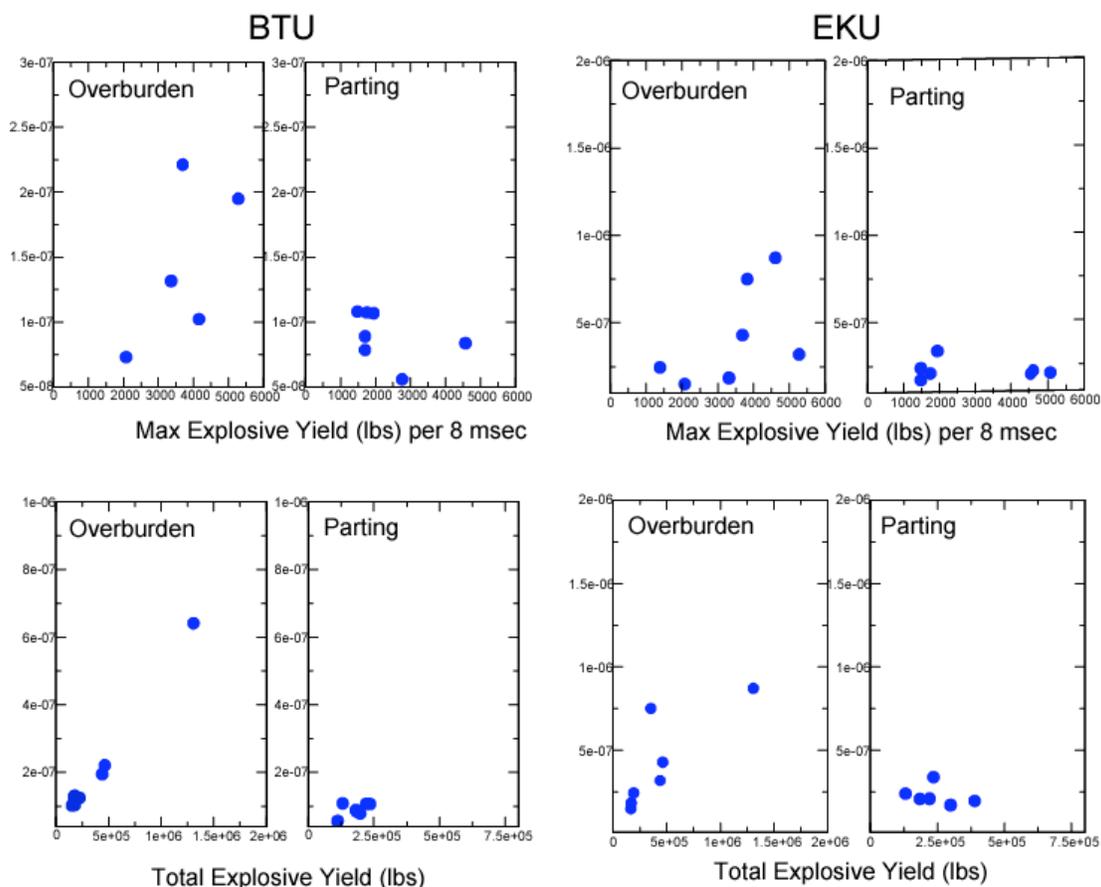


Figure 6. *P* amplitudes (BP 1 to 2 Hz) from coal cast and parting blasts measured at the regional seismic stations BTU (left) and EKU (right) as a function of maximum detonated yield per 8 msec as designed (upper) and total designed yield (lower).

Experiment Design: Explosions

We negotiated with mine engineers at the coal and copper mines to design the source phenomenology experiment explosions. Table 1 shows the planned single-fired shots that will be detonated at the mines in August and September 2003. The final explosion plan is currently being considered for compliance with the Office of Surface Mining (OSM) regulations.

Table 1. Planned Source Phenomenology Experiment Explosions

| Shot Number | Tons ¹ | Explanation |
|-------------|-------------------|--|
| 1 | 28 | Shot to an open face with pre- and post-vibration monitoring |
| 2 | 14 | 14 ton shot to start a cast blast |
| 3 | 7 | Single-fired at 40 meters depth |
| 4 | 7 | Single-fired at 20 meters depth |
| 5 | 3.5 | Shot to buffer |
| 6 | 7 | Shot to buffer |
| 7 | 3.5 | Shot to open face |
| 8 | 7 | Shot to open face |

¹ Planned yield. Final yields to be determined based on in-mine vibration studies and OSM regulations.

Shots 1 and 2: Single-Fired Shots on an Open-Face of the Mine. One blast planned at the coal mine will be to detonate a single-fired shot to an open face of either 14 or 28 tons. The location of the shot will be on an active mine face. The blast cannot exceed acceptable ground vibration; thus, a pre- and post-blast survey of nearby structures in the mine will be required. The explosion yield may be reduced if damage to nearby structures is anticipated. Another blast will be a 14 or 28 ton single-fired blast during a routine cast blast to simulate the effects of sympathetic detonations on regional data, as well as to study the evasion scenario of hiding a nuclear explosion in a mine blast.

Shots 3 and 4: Depth of Burial Shots. At sites near the end of a production pit at the coal mine (Figure 7), we will detonate two single-fired shots of 7 tons (one shot at a depth of 20 meters and another at depth of 40 meters in confined rock). The location of these shots will be in a region that will not be mined in the future so that coal damage is not an issue. The planned location is within 300 to 400 yards of normal production shots at the mine. It is also at the required distance from uncontrolled structures such that pre- and post-blast surveys will not be required.



Figure 7. Proposed location of the depth of burial (DOB) shots (white star) near the J-19 pit of the coal mine.

Shots 5-8: Comparison of Confined and Unconfined Single-Fired Shots with Mine Blasts. At a location in a working pit (Figures 8 and 9), blasts of 3.5 and 7 tons will be detonated in the un-mined rock located at the base of the open pit. The blasts will be confined. Above these blasts, shots of 3.5 and 7 tons will be “shot to an open face” simulating unconfined conditions. Both shots will be located in pits where routine production shots occur thus allowing for an excellent comparison of the different types of explosions.



Figure 8. Proposed location of confined vs. unconfined single-fired shots in the J-21 pit of the coal mine. The blasts (stars) will be 3.5 and 7 tons single-fire shots.



Figure 9. The unconfined shots will be detonated in the light-colored rock (overburden) in the background, while the confined shots will be detonated in the rock (partings) comprising the lower level shown in this picture. The blastholes shown in this image are being shot to a buffer.

Predicting Regional Magnitudes. We used the Vergino and Mensing (1990) relationship:

$$\log_{10}(\text{Yield}) \sim 1.1 m_b(Pn) \quad (1)$$

to predict body wave magnitudes for the planned single-fired explosions. Our predictions are tied to the Non-Proliferation Experiment (NPE) shot (Denny *et al.*, 1997) of 1.07 kt that had an $m_b(Pn) = 4.14$. Since these relationships were developed for sources located in the Basin and Range, the predicted magnitudes (Table 2) will be most appropriate at the copper mine, located in the southern Basin and Range. Based on observations from the coal mine, we expect larger amplitudes for similar yield explosions as a result of more efficient propagation in the Colorado Plateau. The magnitudes may also vary with changes in confinement and different depths of burial.

Table 2. Predicted Magnitudes for the Source Phenomenology Experiment Explosions

| Yield (tons) | $m_b(Pn)$ |
|--------------|-----------|
| 3.5 | 1.9 |
| 7 | 2.2 |
| 14 | 2.4 |
| 28 | 2.7 |

Experiment Design: Stations

There are three distinct station deployments that will be completed for the experiments: 1) in-mine arrays, 2) near-source arrays, and 3) a regional profile. First, five stations will be deployed for the experiment duration in various locations within each mine. These stations will consist of broadband sensors (STS-2 and Guralp CMG-3Ts) operated continuously at high (>100 sample/sec) sample rates. The in-mine array at the copper mine has been deployed previously. The planned in-mine array in the coal mine is also shown in Figure 10.

The second series of in-mine deployments will be a near-source array consisting of portable accelerometers within 200 meters of each shot. These sensors and systems, which will include Hi-8 videographic equipment with GPS timing, will be moved to the location of each single-fired or delay-fired explosion that we plan to instrument. Figure 11 shows the proposed configuration for the shots. The configurations were designed to achieve shot initiation data and to provide data for moment tensor inversions.

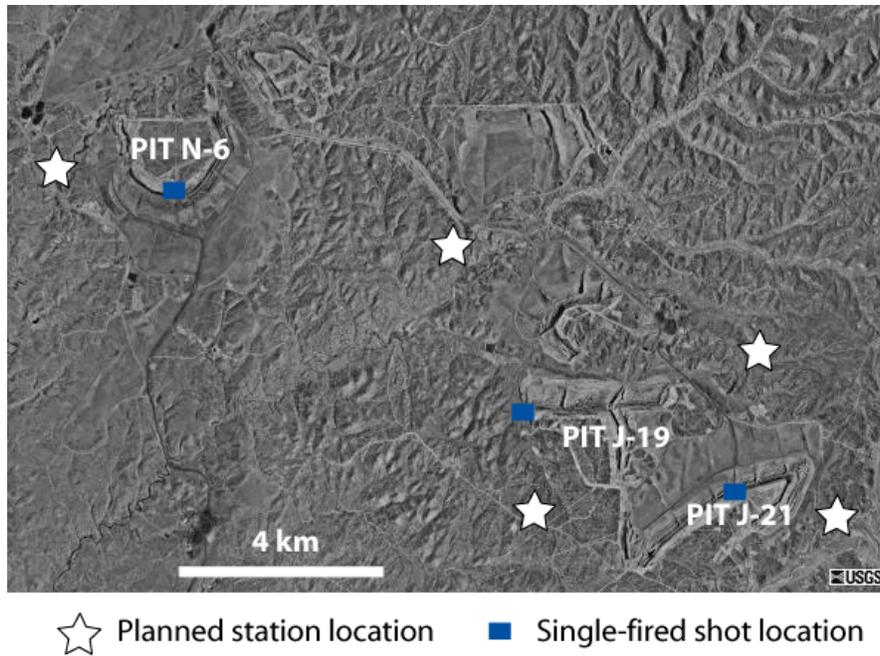


Figure 10. Planned in-mine seismic stations and experimental explosion locations at the coal mine.

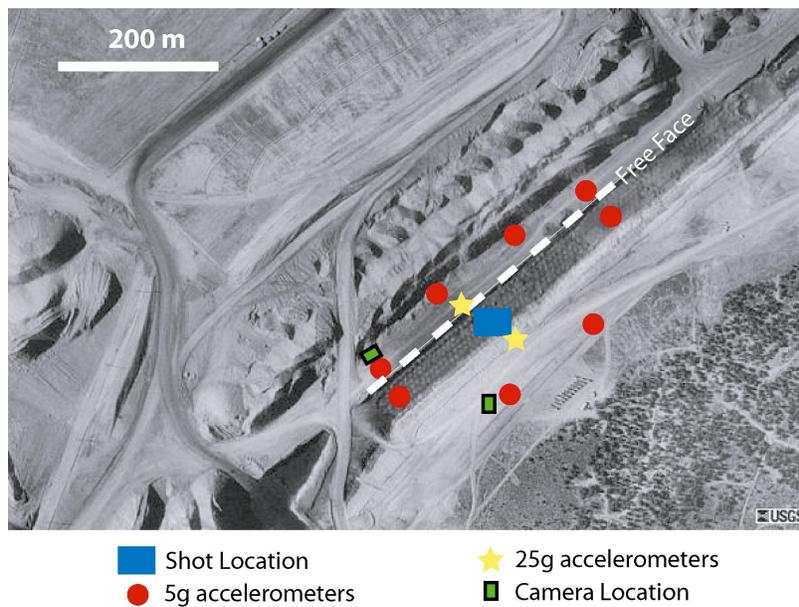


Figure 11. Plan for near-source instrumentation.

The final deployment will consist of a regional profile of broadband stations (CMG-40Ts) that will be placed along a line between the coal and copper mines. The red triangles in Figure 12 are stations that will remain deployed throughout the experiments at both the coal and copper mines, while the blue triangles are sites that will only be deployed during experiments at each mine and then re-deployed.

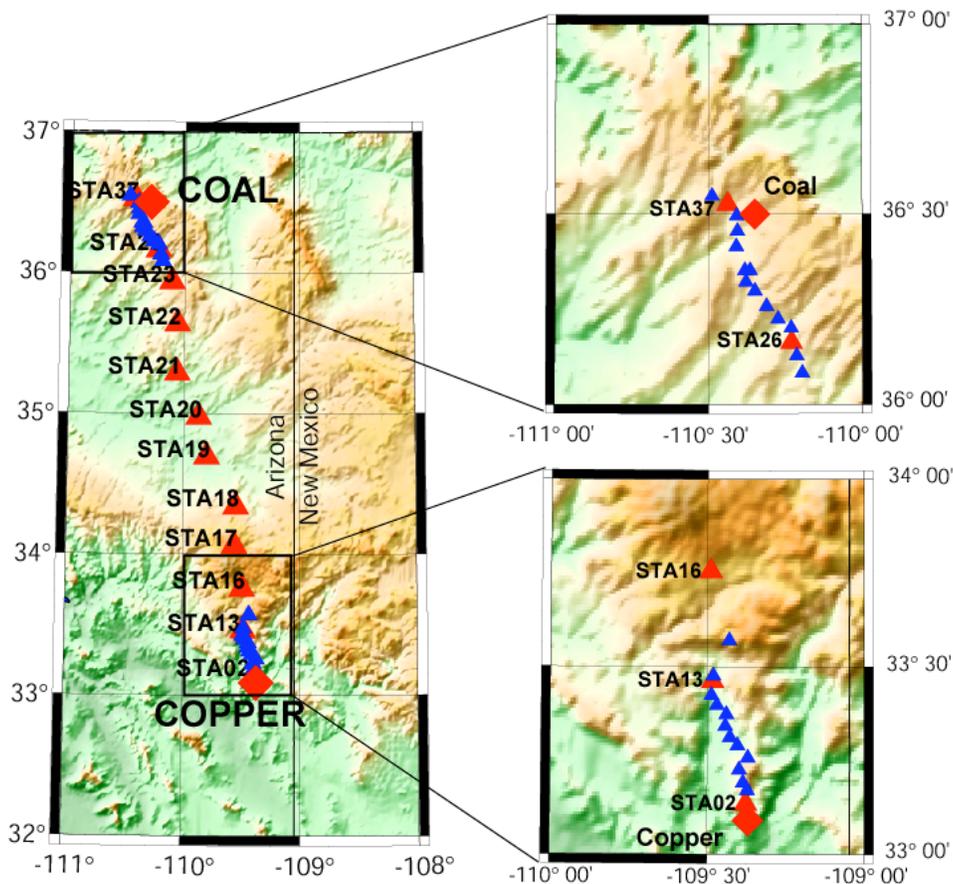


Figure 12. Stations for the regional profile between the coal and copper mines. The stations near the coal mine are located on Navajo reservation land are currently being negotiated.

CONCLUSIONS

We have designed a series of single-fired explosions at copper and coal mines in Arizona. The explosions will be conducted in August and September of 2003.

REFERENCES

- Bonner, J., D. C. Pearson, and S. Blomberg, 2003, Azimuthal variation of surface wave energy from cast blasts in northern Arizona, *Bull. Seism. Soc. Am.*, 93, 724-726.
- Denny, M. D., P. G. Goldstein, K. Mayeda, and W. R. Walter, 1997, Seismic results from DOE's Non-Proliferation Experiment: A comparison of chemical and nuclear explosions", In *Monitoring a Comprehensive Test Ban Treaty*, edited by E. S. Husebye and A. M. Dainty 355-364, Kluwer Academic Publishers.
- Heuze, F., B. Stump, F. Chiappetta, R. Hopler, V. Hsu, B. Martin, D. Pearson, W. Walter, K. Zipf, 1999, Mine Seismicity and the Comprehensive Nuclear-Test-Ban Treaty, Report of a working group from Government, Industry, and National Laboratories, Sponsored by the U.S. Department of Energy Office of Nonproliferation and National Security, *LA-UR-99-384* and *UCRL-ID-132897*.
- Stump, B.W., M.A.H. Hedlin, D.C. Pearson, and V. Hsu, 2002, Characterization of mining explosions at regional distances: implications with the international monitoring system, *Rev. Geophys*, 40RG000048.
- Vergino, E.S. and R.W. Mensing, 1990, Yield estimation using regional $m_b(Pn)$, *Bull. Seism. Soc. Am.*, 80, 656-674.