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CHALLENGES FOR MINING EXPLOSION IDENTIFICATION UNDER A COMPREHENSIVE TEST BAN TREATY: QUANTIFICATION OF THE PROBLEM AND DISCUSSION OF SYNERGETIC SOLUTIONS

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MASTER

CHALLENGES FOR MINING EXPLOSION IDENTIFICATION UNDER A COMPREHENSIVE TEST BAN TREATY

*Quantification of the Problem and Discussion of Synergetic Solutions**

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1. MOTIVATION

Seismic networks provide the primary technology for monitoring compliance with a comprehensive test ban treaty. The design goal of the network is the identification of possibly clandestine explosions detonated below the earth's surface and possible in the oceans. Complementary technologies such as infrasonic, hydroacoustic and radionuclide (particulate and noble gases) monitoring supplement the seismic monitoring covering explosions in the atmosphere and oceans. Seismic sources that will produce detectable signals will be both natural and man made in origin. Naturally occurring events include earthquakes, many of which are beneath the oceans or deeper than it is possible to drill, and volcanic eruptions. Accurate locations of such events to depths of beyond 10 km precludes consideration of these events further. Man made or induced events include the great range of different applications of conventional explosives for mining and excavation, rock burst and collapses associated with underground mining operations and induced earthquakes associated with the injection of fluids into the crust, often in secondary oil recovery. Each of these different man made sources are shallow enough in depth that simple locations will not be sufficient to identify the source type (this also holds for shallow earthquakes). The rest of event identification relies on distinguishing features of the seismic waveforms, possibly in conjunction with other monitoring technologies, for source identification. This paper will focus upon problems or ambiguities that can arise in the identification process for chemical explosions. The recent Non-Proliferation Experiment has focused attention upon the problem of distinguishing with seismic measurements a contained nuclear explosion from a chemical explosion. The number of ambiguous events identified by a monitoring system can only be quantified through the testing of a monitoring system such as the Group of Scientific Experts Technical Test 3. Procedures for minimizing such events and developing an information/experience base to decrease ambiguities with time is needed. This problem approach could include the utilization of supplementary data, active experiments and international information exchanges or fact finding visits.

2. KEY QUESTIONS TO BE ADDRESSED

A. How many mining explosions produce seismograms at regional distances that will have to be detected, located and ultimately identified by the National Data Center (NDC)? What are the waveform characteristics of these particular mining explosions?

Mining explosions that produce relatively large magnitudes ($m_b > 2.5$) are of most concern in the nuclear explosion monitoring program particularly when considered in conjunction with a decoupling scenario. There have been few systematic studies of the relationship between total explosive yield in mining explosions and regional magnitude, thus it is difficult to assess the possible size of the mine monitoring problem. In addition to the total size of the mining explosion, the mining practices used to detonate the explosions and rubblize the rock are known to affect regional seismograms. It has been proposed that all mining explosions over a given magnitude should be pre-announced further motivating the establishment of the relationship between magnitude and yield for the mining blasts. Bob Blandford (AFTAC) has completed a preliminary study of the relationship between yield and regional magnitude in Scandinavia. This study of events around magnitude 2.5 seems to indicate that there is no relationship between magnitude and explosive yield as shown in Figure 1.

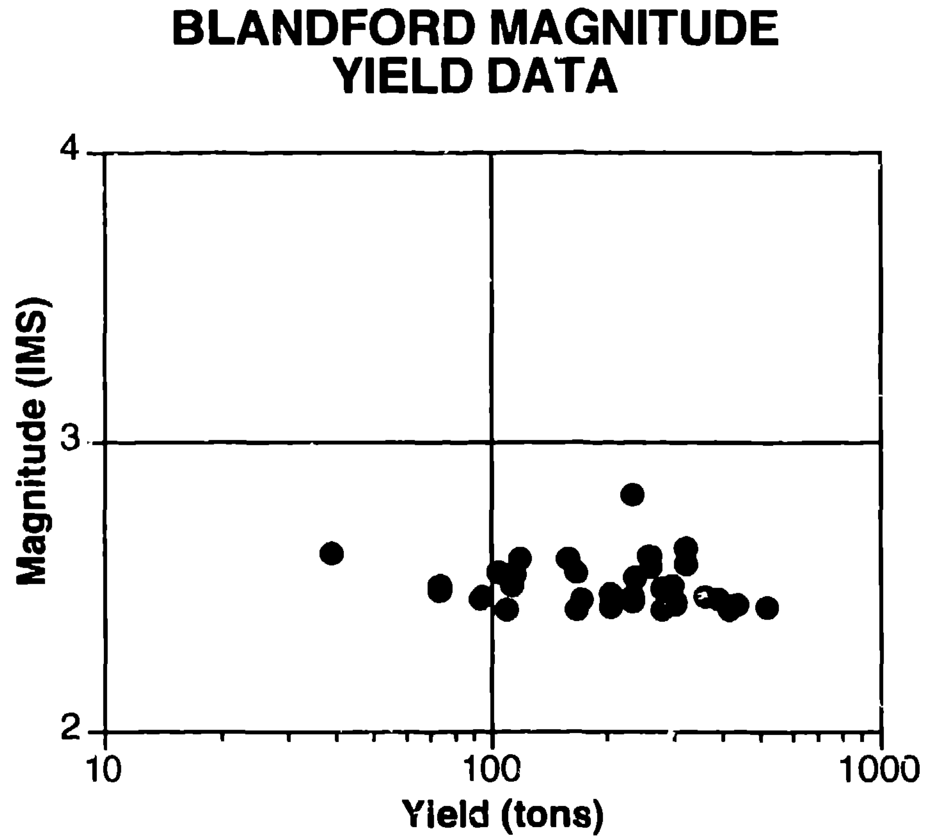


Figure 1: Magnitude-Yield Plot for Mining Explosions in Scandinavia

This plot of magnitude versus mining explosion yield appears flat although there is significant scatter at any particular yield. Supplementary data about these blasts such as the blasting pattern or the material in which the blasts were detonated is needed.

In order to illustrate the importance of near-source information in interpreting such plots, we have produced a plot of L_g amplitude around 1 Hz at the LLNL regional station ELK from NTS explosions with total yield less than 500 tons, similar to the size of the blasts in Blandford's study (Figure 2).

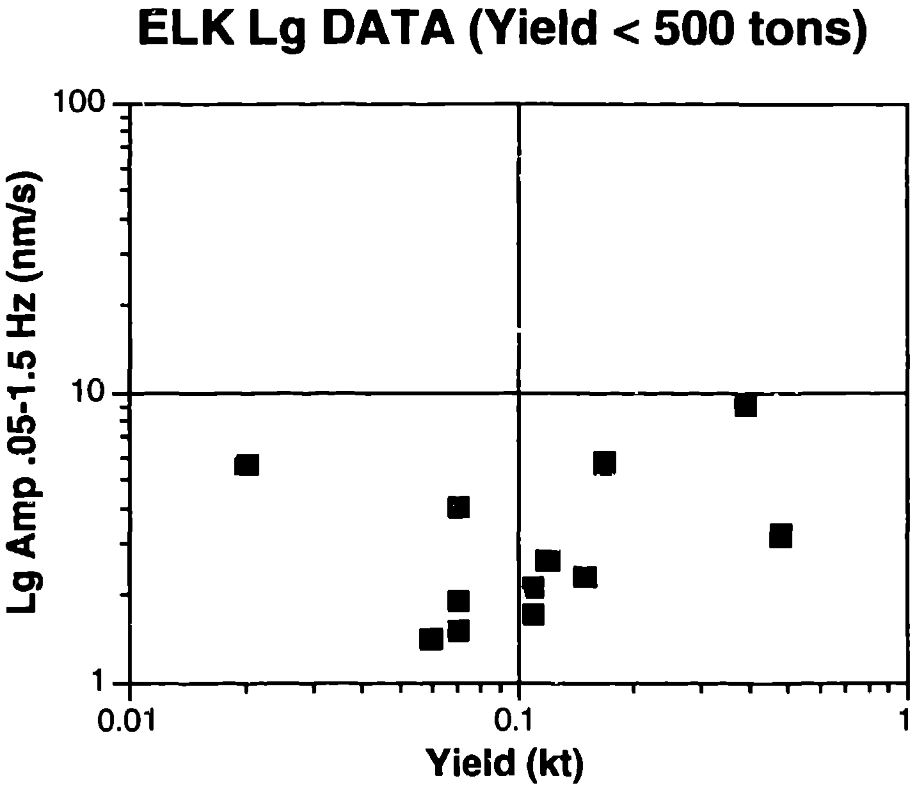


Figure 2: Log of L_g Amplitude Centered at 1 Hz (ELK) Versus Yield for NTS Explosions With Yield Less Than 500 Tons

This data set also shows a good deal of scatter over the range of interest and little change in amplitude with increasing yield. Extensive magnitude-yield studies at NTS using broader yield ranges and accounting for material properties around the explosions as well as explosive configuration have shown strong yield effects.

Mine monitoring experiments might be designed to provide information similar to that found to be necessary to quantify yield effects at NTS. Thus conventional explosive source coupling could be placed on a consistent basis with the nuclear explosion data.

Bill Leith (USGS) has begun a preliminary analysis of regional magnitudes from mining explosions in the US. He finds that one or two m_b 3.5 events per week may occur in this region with many more events at lower magnitudes (Table 1).

Blast data that could be obtained from the U.S. National Network and Telemetered Network stations (operated by the U.S. Geological Survey) for a two-day period. The period chosen was Thursday and Friday (UTC), April 7 and 8, 1994.

Locations for 16 explosions:

Date/Time (UTC)	Lat	Long	Mag	Location
07 Apr 04:05:30.5	39.46 N	111.27 W	1.7 MD	west of Price, Utah
06:49:01.8	39.31 N	114.84 W	2.9 MD	Ely, Nevada
07:23:54.9	39.66 N	111.24 W	1.7 MD	west of Price, Utah
16:03:35.3	39.45 N	111.21 W	1.7 MD	west of Price, Utah
16:13:51.3	31.44 N	108.71 W	2.5 ML	east of Douglas, Arizona
18:53:45.6	41.89 N	110.76 W	-2.0 ML	Kemmerer, Wyoming
19:07:58.5	38.09 N	80.80 W	2.9 LG	northeast of Beckley, WV
→ 19:21:15.1	41.79 N	109.27 W	3.5 ML	north of Rock Springs, Wyoming
22:47:01.1	46.80 N	122.82 W	3.0 MD	Centralia, Washington
08 Apr 17:06:04.2	40.52 N	112.17 W	2.2 MD	Bingham Canyon (Tooele), Utah
18:20:37.8	37.17 N	81.99 W	1.9 LG	southwestern West Virginia
20:09:33.9	40.56 N	112.17 W	1.9 MD	Bingham Canyon, Utah
21:33:38.3	36.41 N	110.25 W	2.3 ML	Black Mesa (Kayenta), Arizona
21:48:37.3	46.82 N	122.84 W	2.3 MD	Centralia, Washington
22:38:30.6	40.23 N	112.20 W	2.2 MD	Bingham Canyon area, Utah
23:49:30.5	38.97 N	111.38 W	1.9 MD	southwest of Price, Utah

Table 1: Partial List of USGS Identified US Mining Blasts

As noted in this table, there are several different regional magnitude measures reported. Comparison of the diffeent event magnitudes and relation to explosive yield and characteristics thus becomes problematic. These magnitude measures need to be linked to the common teleseismic m_b scale in order to assess the effects of blasting practices.

These results are supported by a similar study conducted in Australia and reported to the Conference on Disarmament on June 10, 1994. Unfortunately, again little or no information has been collected to identify the source characteristics of the mine blasts that produce the largest regional signals. Both these studies illustrate the need for quantitative information about the blasts possibly gathered at the site of the explosions.

B. Can discrimination techniques based on empirical studies be placed on a firm physical basis so that they can be applied to other regions where we have little monitoring experience? With this information, can evasion capabilities be assessed in a region?

A number of discriminants have been suggested for mining explosions including the relative excitation of P and S phases, fundamental mode surface wave generation and spectral scalloping. The physical cause of these different discriminants are probably a result of the proximity of the sources to the free surface, the exact spatial and temporal characteristics of the ensemble of explosions in the blast and the rubblization of the near-surface materials by the explosions. None of the discriminants have been found to work in all environments and under all blasting conditions, in fact in most cases little is known about the processes in the source region.

There is strong evidence for great variability in blasting practices around the world. Figure 3 illustrates this point with four video frames from a large mining blast in Southern Russia. One can see the effects of the unstemmed holes and resulting large air blast signal.

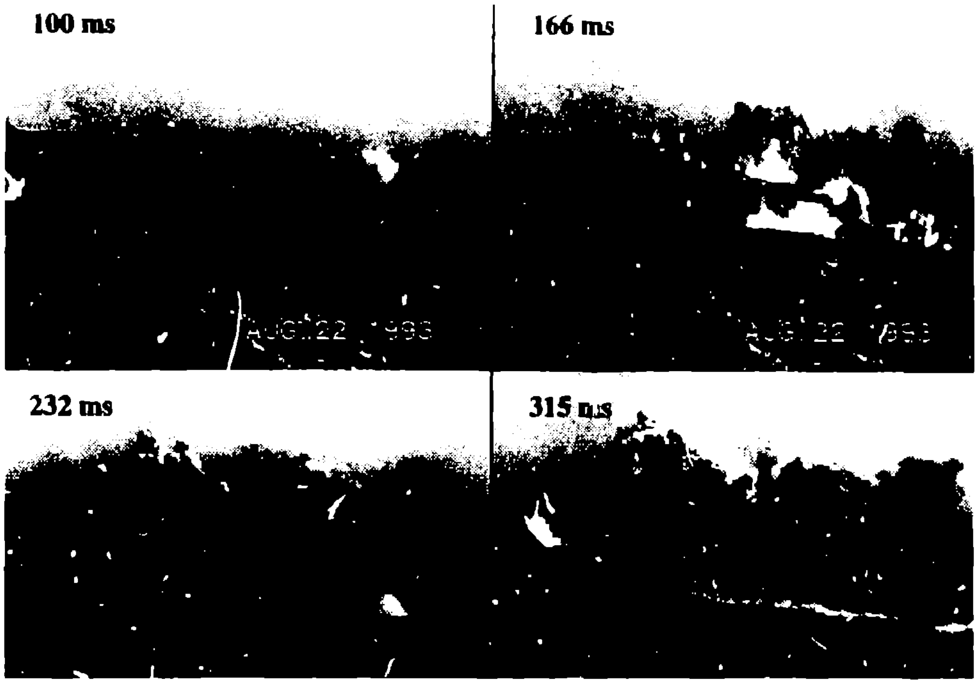
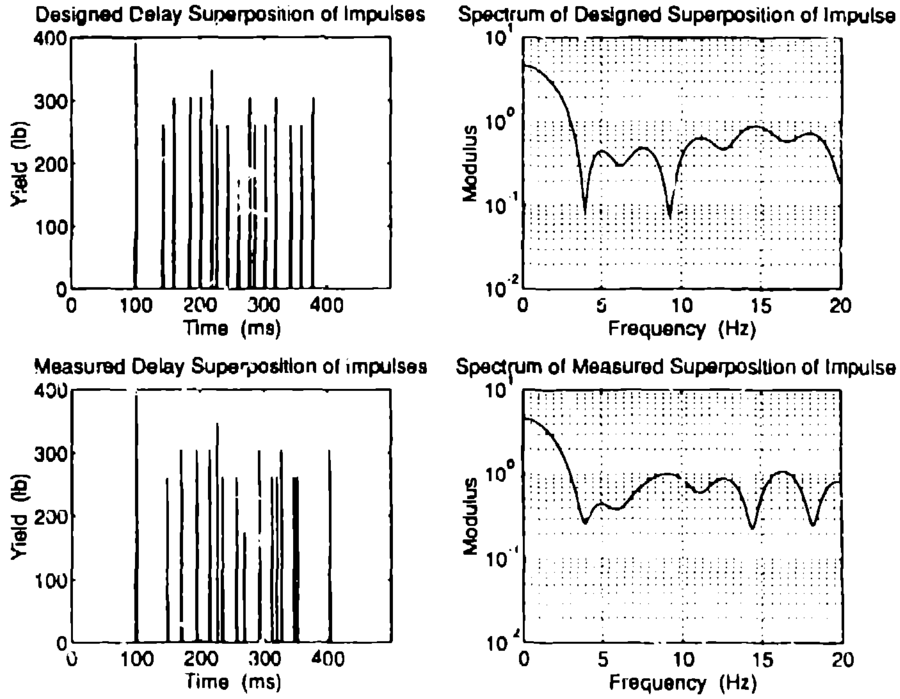


Figure 3: Four video frames from a large mining blast in Southern [illegible]



In order to assess the effectiveness of the discriminants and investigate ways in which the source characteristics could be controlled by the tester and thus used in an evasive regime, a physical understanding of the source is needed. The approach found to be successful in separating such physical processes in the case of large, single explosions was demonstrated during the recent Non-Proliferation Experiment with the combination of near-source and regional seismic observations. Figure 4 demonstrates how blasting processes (as determined in the near-source region) can affect regional discriminants, in this case spectral scalloping. The first spectra displayed in this figure (upper right) is that expected from the designed ripple-fired explosion (upper left) showing the characteristic spectral holes at 4, 10 and 20 Hz. The exact firing times of the individual explosions were experimentally determined with high speed photography and velocity of detonation measurements (lower left). The spectra from the actual detonation times is shown at the bottom right portion of the figure. The variability of the detonation times of the individual explosions destroys the spectral holes while maintaining the width of the low frequency lobe, representative of the total blast duration. This example illustrates that in this particular mining operation one would not expect the predicted spectral scalloping to work as a discriminant. Experiments which combine near-source and regional seismic observations as well as supplementary source information will allow the quantification of successful discriminants and determine the applicability of these tools in other environments.

C. Can large scale chemical explosions (possibly mining explosions) be used to calibrate source and propagation path effects to regional stations? Can source depth of burial and decoupling effects be studied in such a controlled environment?

Anomalous events will be of significant concern under a CTBT. The probability that such events might be a clandestine test will have to be assessed and communicated. Possible source or propagation path effects could be responsible for identifying an event as anomalous. The use of large, chemical explosions to *calibrate* propagation path effects (including depth of burial) could provide a mechanism for dealing with these unusual events.

3. EXPERIMENTAL IMPLEMENTATION METHODOLOGY

Quantifying mining blasts in terms of their characteristics and importance as sources of significant regional signals is the goal of this study. Experimental design is constrained by these goals and requires a combination of near-source and regional observations of different types in order to make an unambiguous assessment of the important source processes and their contribution to regional signal. The components of the experiment are described. A prototype experiment along with some implications are described in an available video, *The Physical Interpretation of Mining Explosions as Sources of Seismic Waves.*

Regional signals from these sources are the data that will have to be interpreted under an operative CTBT. These seismic signals form the foundation of the experiments. Unfortunately, the propagation paths to the regional stations at hundreds to thousands of kilometers can be quite complex and thus it is not always possible to unambiguously separate source from propagation effects. In order to facilitate this separation, the experiments have a near-regional and near-source instrumentation component to document the generation and propagation of the seismic energy. Figure 5 illustrates the near-regional instrumentation component.

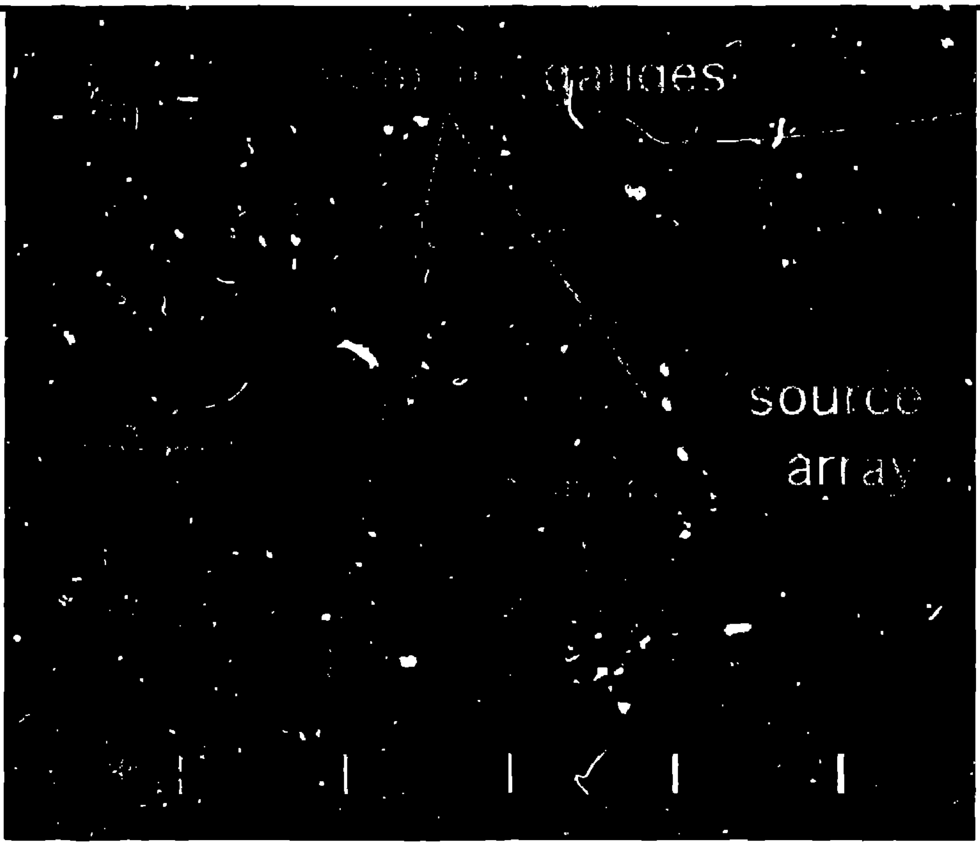
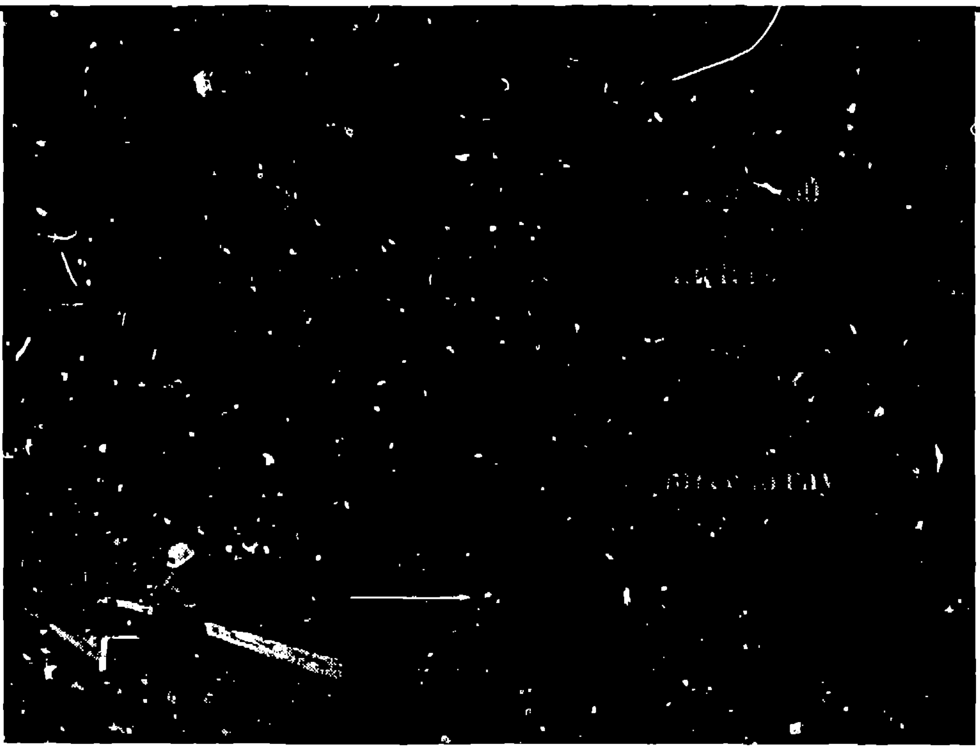


Figure 5: Near-Regional Instrumentation Plan



[illegible]

Velocity instruments with digital event recorders and GPS clocks are deployed to quantify the transition of the wavefield from what is labeled as the source array out to tens of kilometers. In addition to the seismic instrumentation, we have found it useful to use both Hi-8 video and high speed film to document the blasting practices, in particular the timing of the individual explosions. Zooming into the source array we find ourselves documenting the processes that are taking place in an area several hundred meters square as shown in Figure 6.

In order to complete a broad band characterization of the source processes at a distance with the least contamination from propagation path effects, an array of force-balance accelerometers is deployed around the source (the source consists of four rows of explosives, each with four cylindrical boreholes). In addition to the seismic instrumentation, the three-dimensional characteristics of the test bed is surveyed (in this example the structure is dominated by the vertical face of the mine wall).

Critical to quantifying the coupling of energy into the ground from the explosions and its propagation is an understanding of the near-source material properties. An important part of this material property determination is the completion of P and S refraction/reflection surveys of the test bed as indicated in Figure 7.

Figure 7: Test Bed Refraction Survey

Exploration sources for both P and S waves are used to couple energy into the near surface materials where the explosive will be detonated. Geophones are placed at close intervals to determine the velocities of the near surface materials and in some instances the dispersion of shallow surface waves.

4. MINE MONITORING RESULTS

VIDEO PROCESSING:
In order to assess the spatial and temporal effects of typical mining explosions, work has focused on the utilization of standard Hi-8 video recordings of mine blasts. Video records from the blasts are digitized utilizing a Galileo video capture card and a SGI Indigo 2. The nominal frame rate is 30 frames/s although each image is composed of two interlaced frames sampled 1/60 s apart. De interlacing of the signals provides 16.67 ms sampling of the blast.

Typically the camera is fielded close to the explosion in order to provide maximum resolution of source processes. As a result, the camera experiences ground motion strong enough to blur near-by objects. A procedure that utilizes distant fixed points in the image is introduced that separates the camera motion from the image. Near-source ground motions were recovered from these shots using standard velocity and acceleration gauges. Combining the ground motion data, camera motion, digital video images and relative time into a single visualization provides the opportunity for interpreting the relationship between source region processes and the resulting ground motions.

SINGLE SHOT ANALYSIS:
A number of single, cylindrical sources were detonated in order to begin the investigation of the differences between spherical and cylindrical sources and quantify the effect of the free face in front of the explosion on the radiated waveforms. The example displayed in Figure 8 records used emulsion explosives with a total weight of 653 lb. The burden was 18-22 ft and the depth of the borehole was 27 ft.

Figure 8: Ground Motion Recovered from the Camera (y/vertical, x/horizontal) and the Image of a Typical Mining Blast Designed to Cast Material

In order to quantify the source processes of such a mining explosion and correlate them with the ground motion field, the process steps described earlier were employed. Four frames from the explosion separated by 500 msec are displayed. The camera motion is given in the bottom center of each frame while the time of the image is represented by the vertical bar. These images along with those in the video emphasize the strong contribution of the direct shock from the explosion to the radiated wavefield. The actual ground motions recorded near the camera (Figure 8), despite the undamped nature of the camera tripod, are completed before any of the material cast into the mine impacts the mine floor.

MULTIPLE SHOT ANALYSIS:

A four by four array of cylindrical sources were ripple-fired using typical blasting materials and practices. Source measurements included high speed film, velocity of detonation, Hi-8 video, ground acceleration and velocity. These data are used to produce an integrated visualization of the source processes in Figure 9. These results are animated in the available video.

Figure 9: Combined effects of individual explosions detonation time (upper left), near-regional seismograms (upper right) and blast (lower center)

Because of the 500 ms downhole delays in each hole and the variances associated with these detonators, large differences between the designed and observed detonation times for each hole were documented (Figure 4). The spectral holes above 4 Hz that are predicted by the designed shooting pattern disappear for the actual pattern as a result. The only thing that remains similar between the design and actual shooting pattern is the total duration of the source. The second point that can be documented with the visualizations is the relative timing between the observed waveforms and the material response around the explosions. The impulse of the individual explosions can be seen in the P waves while the latter, longer period surface waves are complete before the cast or spalled material re-impacts. These images and those from the single explosion argue that the spalled or cast material has little contribution to the time domain representation of the near-source waveforms.

5. CONCLUSIONS

❶ **Need for magnitude-yield relations for mining explosions with link to US testing experience.**

❷ **Many different types of mining blasts. Need to assess impact on coupling and discrimination.**

❸ **Integration of multiple data types utilizing visualization tools provides means for assessing important processes in generation of seismic waves. Cast or spalled material has little contribution to near-source seismograms.**

❹ **The great variability of typical US detonators (with large downhole delays) leads to complex spectral effects. Total duration of shot is less affected.**

❺ **High frequency (> 5 Hz) spectral scalloping due to source detonation times is easily destroyed by typical US blasting practices in soft rock.**

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