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Title: MINING INDUSTRY AND US GOVERNMENT COOPERATIVE RESEARCH: LESSONS LEARNED AND BENEFITS TO MINING INDUSTRY

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MINING INDUSTRY AND US GOVERNMENT COOPERATIVE RESEARCH:
Lessons Learned and Benefits to the Mining Industry

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ABSTRACT

Since 1994, various mines in the US have cooperated with research scientists at the Los Alamos and Lawrence Livermore National Laboratories to address issues related to verification of the Comprehensive Test Ban Treaty (CTBT). The CTBT requires that no country may conduct any nuclear explosion in the future. While the CTBT is a significant step toward reducing the global nuclear danger, verifying compliance with the treaty requires that the monitoring system be able to detect, locate and identify much larger numbers of smaller amplitude seismic events than had been required previously. Large mining blasts conducted world-wide will be of sufficient amplitude to trigger the monitoring system at the lower threshold. It is therefore imperative that research into the range various blasting practices employed, the relationship of yield to seismic magnitude, and identification of anomalous blasting results be performed. This paper will describe a suite of experiments funded by the Department of Energy and conducted by the Los Alamos and Lawrence Livermore National Laboratories in cooperation with the US mining industry. Observations of cast blasting, underground long wall generated coal bumps, stoping, and explosively induced collapse of room and pillar panels will be presented. Results of these dual use experiments which are of interest to the mining community will be discussed. These include 1) variation of amplitude of seismic energy at various azimuths from cast blasts, 2) identification of the extent of back failure following explosive removal of pillars, and 3) the use of single fired shots for calibration of the monitoring system. The wealth of information and discovery described in this paper is a direct result of mutual cooperation between the US Government and the US Mining Industry.

COMPREHENSIVE TEST BAN TREATY

The Comprehensive Test Ban Treaty (CTBT), after many years of negotiation, was opened for signature September 24, 1996 and has been signed by 143 nations. It awaits ratification by each signatory. The Treaty bans all nuclear explosions and includes a verification system to

monitor compliance. The International Monitoring System (IMS) includes a worldwide network of instruments to detect seismic, infrasound, hydroacoustic and radionuclide signals (Figure 1).

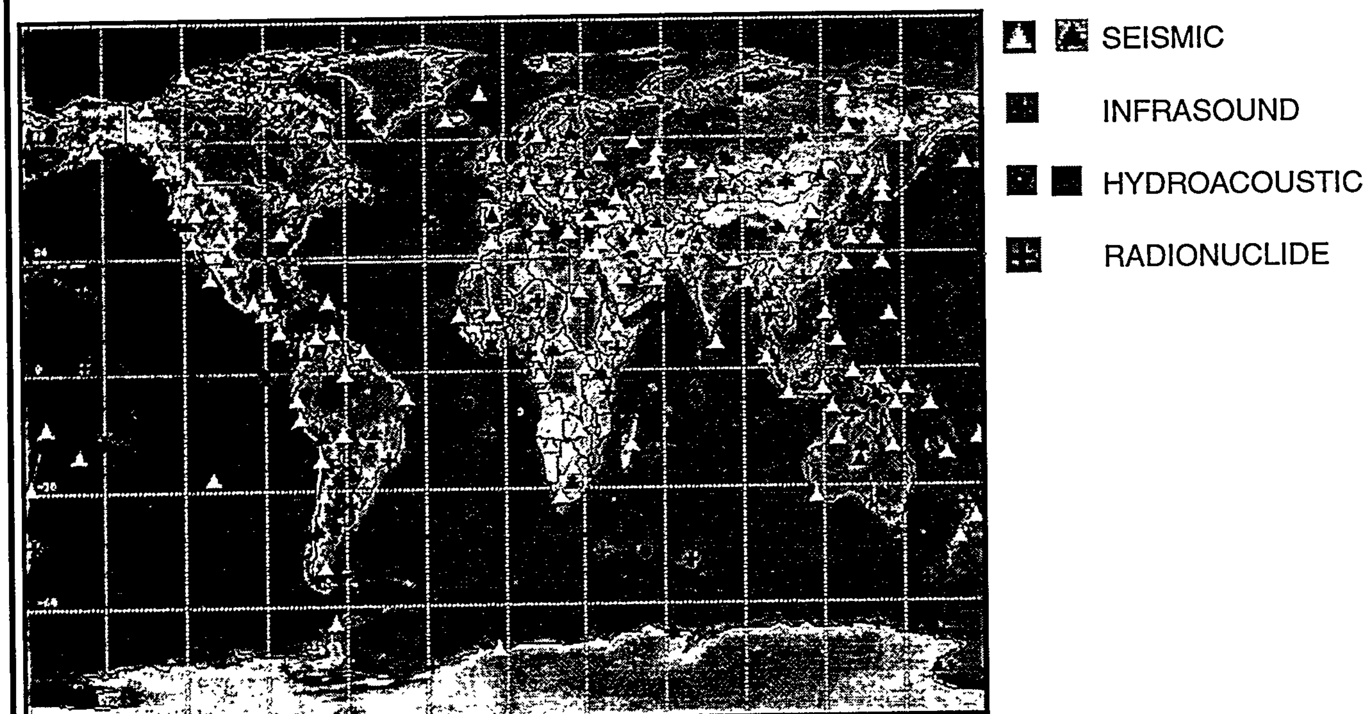

Figure 1: Seismic, infrasonic, hydroacoustic and radionuclide station locations that are to be part of the International Monitoring System.

Mining activities world-wide can generate seismic events which might appear as treaty-prohibited explosions. It is important to understand the signals generated from mining sources so that they can be identified and eliminated from consideration. The mining industry generates seismic signals from surface and underground blasting, and from underground mine failures. Seismic magnitudes of the largest mine collapses have exceeded 5.0 (equivalent to the signal from a 10 kiloton contained nuclear explosion), but more commonly, mine-related events range from magnitude 3.0 to 4.0 (the larger equivalent to the signal from a 1 kiloton contained nuclear explosion) (Figure 2).

A Prototype International Monitoring System has been in operation since 1995. Mining events have consistently triggered this system providing empirical evidence that mine related events will have to located and identified in order to assure that the monitoring system is operating effectively. Figure 3 demonstrates the number of events from one mining district, the Powder River Basin of Northeastern Wyoming, that are triggering this system.

Los Alamos National Laboratory and Livermore National Laboratory began a cooperative research program with the U. S. Mining Industry in 1994. This program was designed to address important mine related issues associated with the CTBT. This research has provided results which are mutually beneficial to the mining and monitoring communities. Ground motions observed at regional distances have been shown to be highly correlated with mining practices and ground motions in the mine. Mining practices which result in increased productivity, improved safety and minimized in-mine ground motions also produce smaller and unambiguous regional seismic signals.

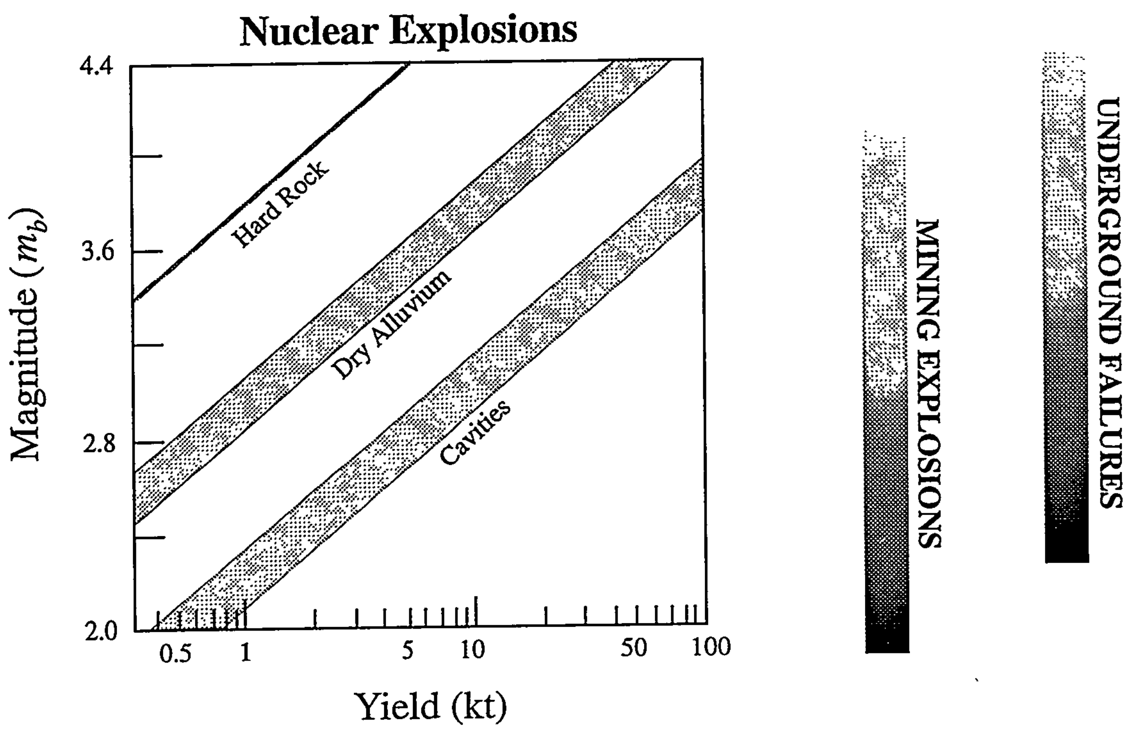

Figure 2: Estimate of magnitude for contained nuclear explosions detonated in different environments is shown to the left (after Hannon, 1985) and estimates of the corresponding magnitudes (right) of mining events.

This paper provides an overview of the cooperative activities that have been undertaken during this research program. Emphasis is placed on results from the research that are of interest to the mining community. We begin with a discussion of the types of cooperation that have been undertaken. This is followed with results from analysis of mining explosions and underground collapses. Finally, the utility of small scale calibration sources in quantifying mining sources is discussed.

COOPERATION WITH INDUSTRY

The key to successful identification of mining events at the International Monitoring System is documentation of the cause and effect relationship between mining practices and the characteristics of the resulting signals. In order to establish this relationship, a number of cooperative experiments and data exchanges with industry have been undertaken. Two of these studies are reported in these proceedings (Martin, 1997; Anderson, Stump and Wiegand, 1997). Others are documented in the Proceedings of the Thirteenth Annual Symposium on Explosives and Blasting Research, ISEE (Pearson, Stump and Martin, 1997; Stump, Martin, Gross, Pearson and Anderson, 1997; Stump and Pearson, 1997).

Cooperative experiments have been designed and implemented that benefit both the mines and the monitoring community. The goal of this work has been to document near-source phenomenology and relate it the resulting far field signals. The relationship between this phenomenology and the signals provides the basis for establishing methodologies for either reducing the size of these signals to such a level that they are of little or no concern or providing procedures for identifying the source as a mine related event. The strong focus on phenomenology provides the opportunity to address issues of interest to the mining industry, such as the development of new and/or improved diagnostics of blasting performance, as well as the quantification of spatial and temporal effects of engineered collapses.

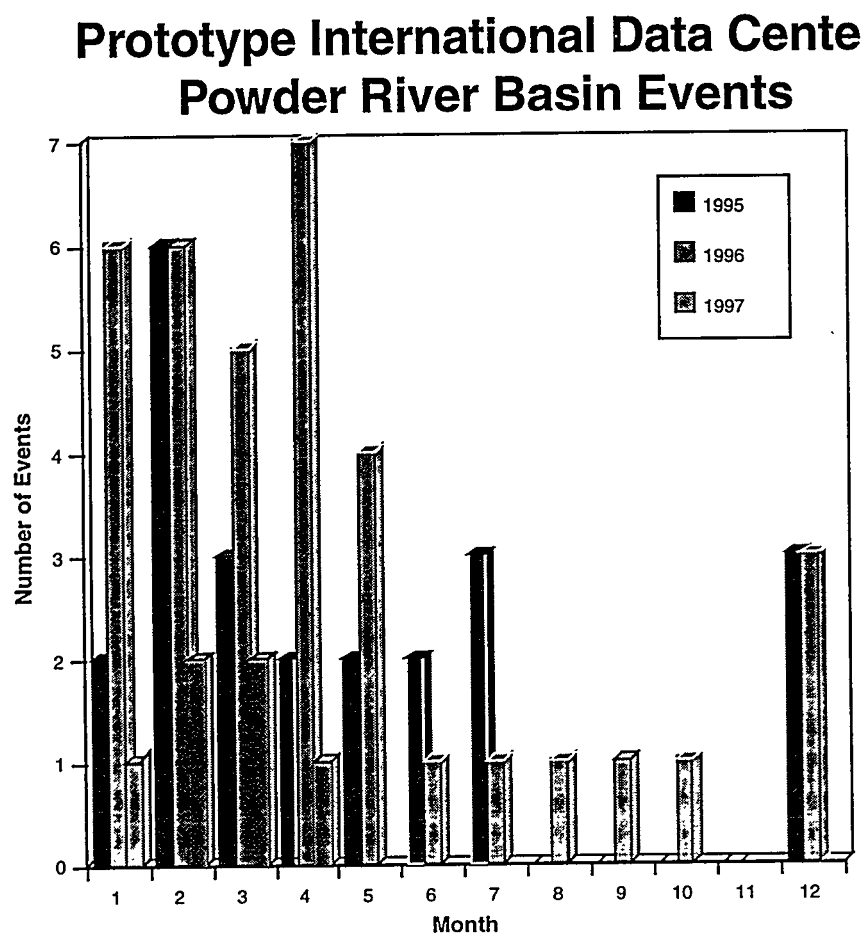

Figure 3: Events from the Powder River Basin that are triggering the Prototype International Monitoring System.

The design of these experimental studies has been driven by the needs of both the mining and monitoring communities. Typical measurements made within the mines have included high speed film and video, ground velocity and acceleration, acoustic and velocity of detonation. Three dimensional topography, subsurface geology and design blasting patterns have often been supplied by the mines. Data from the Prototype Monitoring System has been acquired as well. The integration and visualization of these different data sets has provided the key to the interpretation of the mining practices. Figure 4 illustrates on such integration where the design shot pattern for a large cast blast is superimposed on the three dimensional structure. Each successive frame is at a later time and represents the propagation of the compressive seismic energy away from each of the individual boreholes in the shot pattern.

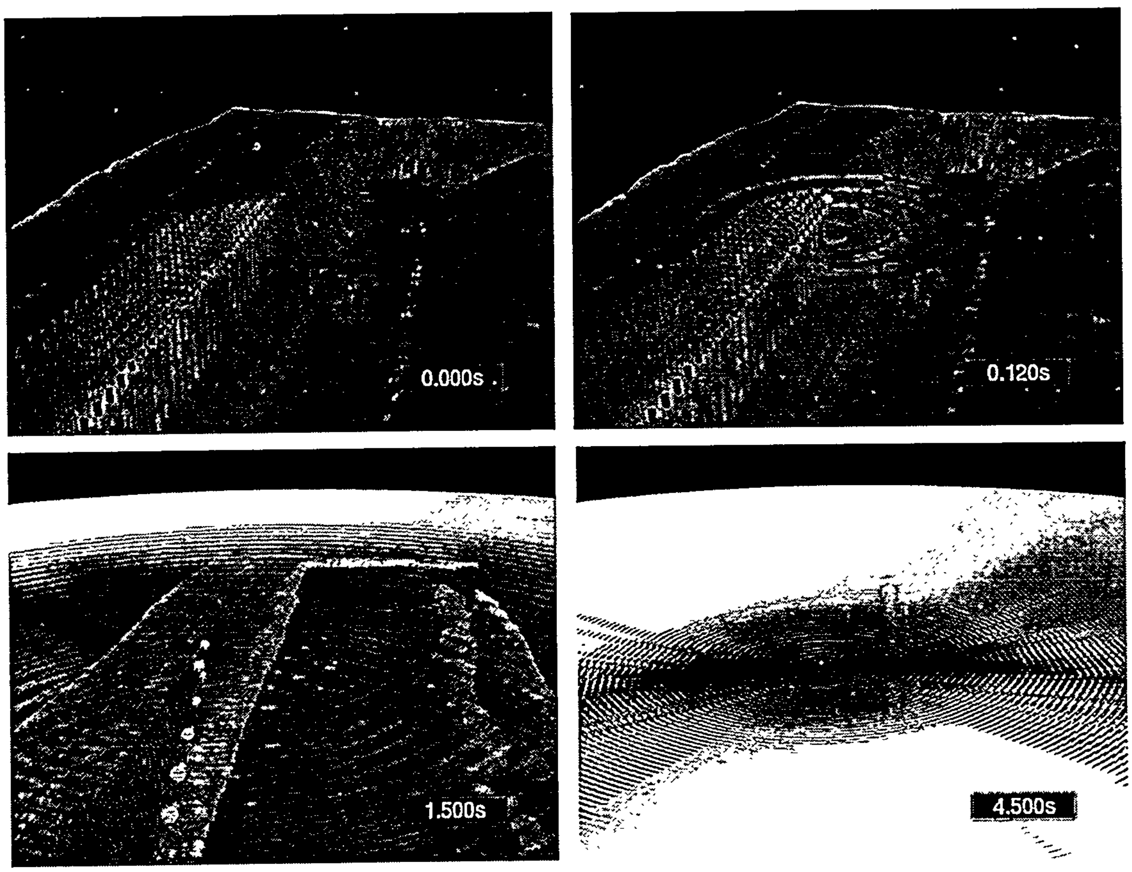

Figure 4: Four images of a large cast blast. Each borehole generates an expanding red ring that propagates (and turns yellow) at the compressional velocity of the material. These images illustrate the continuous radiation and long duration of this type of explosive source. Time from shot initiation in each image is denoted in the lower right hand corner.

MINING EXPLOSIONS

Blasting operations in surface coal, open-pit operations, and underground operations have the highest potential of being detected at regional seismic stations of the IMS. Seismic visibility increases proportionally as a function of hole diameter, bench height, explosive quantity per hole, number of holes fired per delay interval, the ground response to the explosion, and the total amount of explosive detonated per unit space and time.

Mining explosions are rarely detonated simultaneously, often emplaced in relatively incompetent near-surface layers and designed to fracture and/or cast the materials in which they are detonated. These characteristics result in a reduction in amplitude relative to a contained, single detonation. Comparison of contained single-fired explosions to large delay-fired cast blasts in the same geology suggests coupling differences between the two source types that are frequency dependent. Coupling differences as small as a factor of 10 (contained shot more effective coupling) at long periods and as great as a factor of 100 at high frequencies have been observed. Figure 5 compares seismic signals from a contained single-fired explosion and a large cast shot. Signals recorded in the mine and at a regional seismic monitoring station are included. The single-fired, contained explosion consisted of 40,000 lbs of explosive emplaced in eight boreholes while the cast shot included 4,738,230 lbs in 704 boreholes.

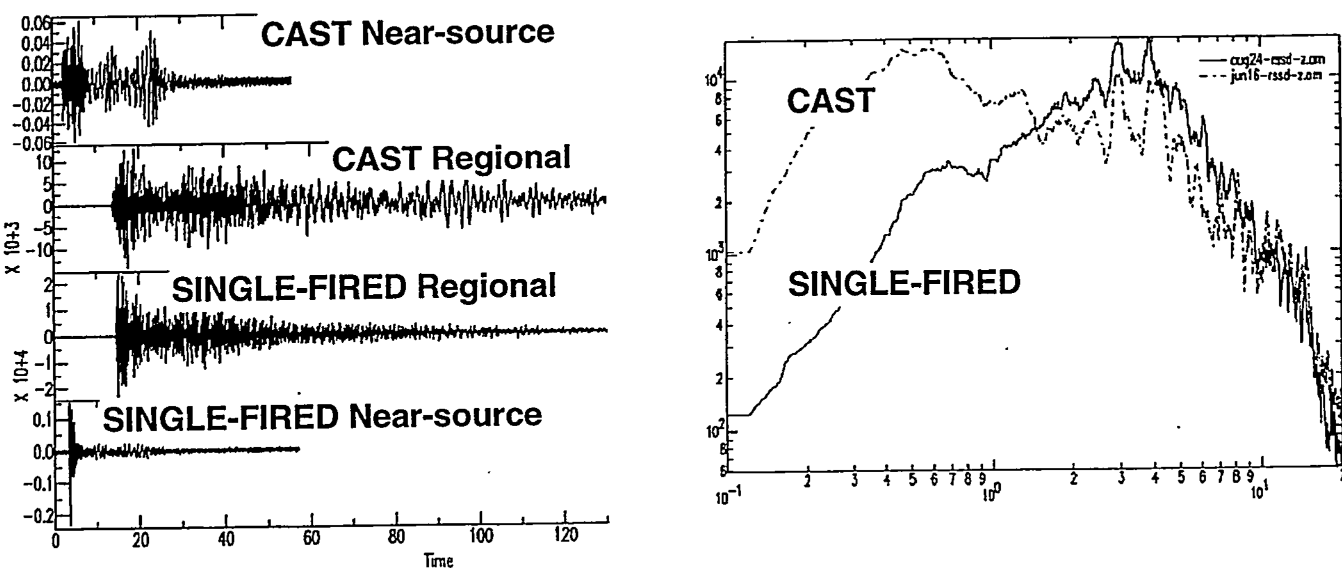

Figure 5: Comparison of in-mine (near-source) and regional (>100 km) seismograms from a contained single-fired explosion and a large cast shot (left). Despite the large differences in total explosives (single-fired - 40,000 lbs. and cast - 4,738,238 lbs.) the comparisons of the spectra from the regional signals (right) indicate that the single-fired explosion couples more high frequency energy than the cast blast.

Coupling of seismic energy at both local and regional distances may not be the same at all azimuths. Mining explosions with their large spatial extent and delay-firing provide the mechanism for enhancing azimuthal variations over a single-fired contained explosion. Quantification of these effects from a monitoring perspective may provide a diagnostic for mining explosions. Determination of these effects in the near-source region can provide a basis for understanding focusing of seismic energy on critical structures in and around the mine property. An empirical quantification of these effects was undertaken as part of the experimental program and has been reported by Pearson, Stump and Martin, 1997. Figure 6 illustrates the degree of azimuthal variability in transverse ground motion observed from a typical cast shot. In this case the material to the north of the pit was reclaim while that to the south was unmined. It is quite apparent that the reclaim experienced significantly reduced ground motions from this cast blast.

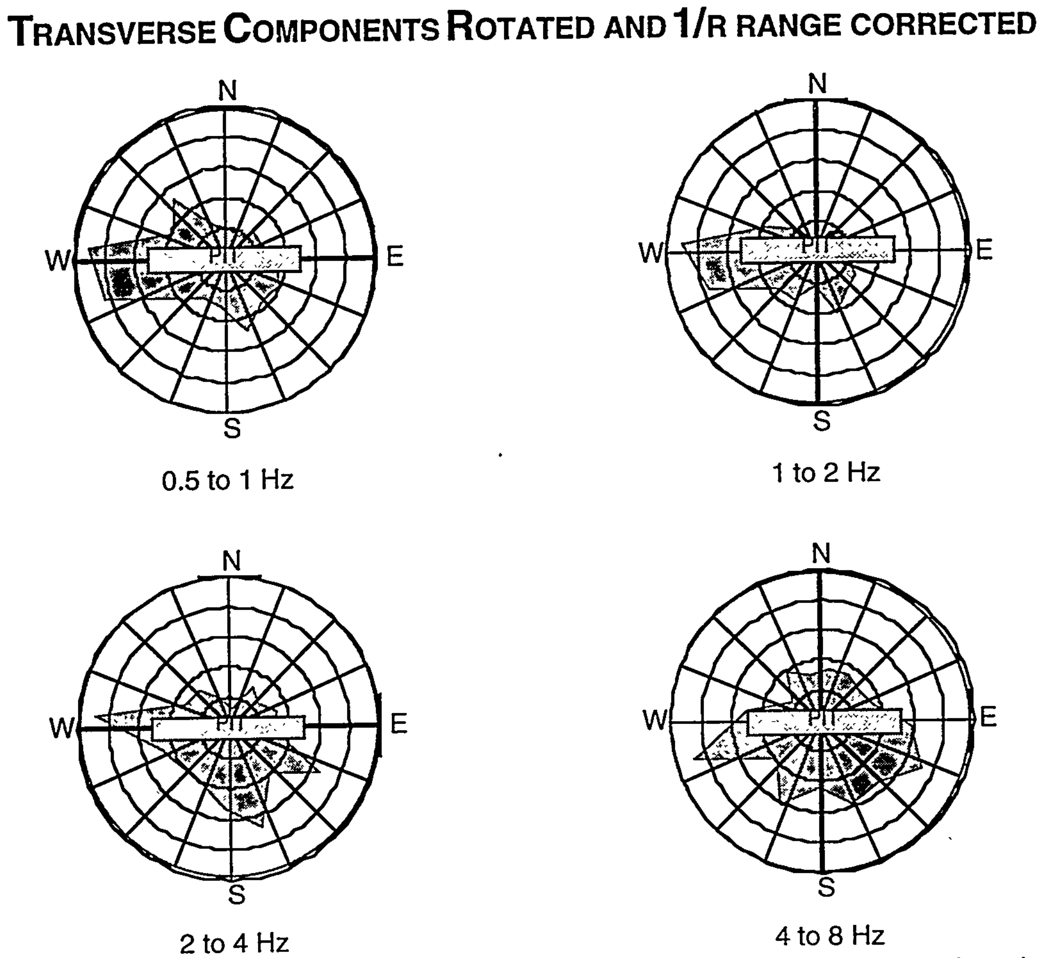

Figure 6: Azimuthal radiation of transverse energy in narrow frequency bands from a cast blast. The material to the north of the pit is reclaimed (slower and softer) and the material to the south has not been mined (faster and harder). These data, taken at 2.5 km from the explosion, illustrate how seismic energy is a function of material stiffness, pit orientation, and direction of shot propagation.

Integrated data sets from explosive sources can also be used to assess the coupling of seismic energy by explosive sources. Visualizations, animated in time, can be used to identify how the explosive sequence progressed and the effect on the amplitude of the near-source wavefield. Development of physical models of the blasting process can be used to help assess new blasting techniques. A variety of physical models of blasting are being developed that provide an improved and more comprehensive understanding of the physics, mechanisms and factors influencing mine-generated seismic disturbances. One illustration of these tools has been provided in Figure 4. A second example of combining different data sets is discussed by Anderson, Stump and Wiegand in this proceedings. In this case, video images of the blast are correlated with ground motion and acoustic data for interpretative purposes. This synergy of different data sets has proven useful for quantifying explosive performance. Figure 7 illustrates four frames from a cast blast illustrating the development of the explosion and the resulting seismic energy.

These synergy tools have been used to identify the simultaneous detonation of a large amount of explosives during a standard cast blast. Figure 8 is a visualization from another cast blast. The format of this figure is the same as that in Figure 7. This image is taken 4.467s into the blast. As indicated by the vertical bar passing through the ground velocity records (RTZ), at the instant of this image there is a very large pulse of seismic energy resulting from the simultaneous and accidental detonation of a number of boreholes of explosive. The synergy of these data sets illustrate this effect. Movies (to be shown at the meeting) of this process allow the correlation of the strong seismic (and acoustic) signal with the movement of a significant portion of the pit free face.

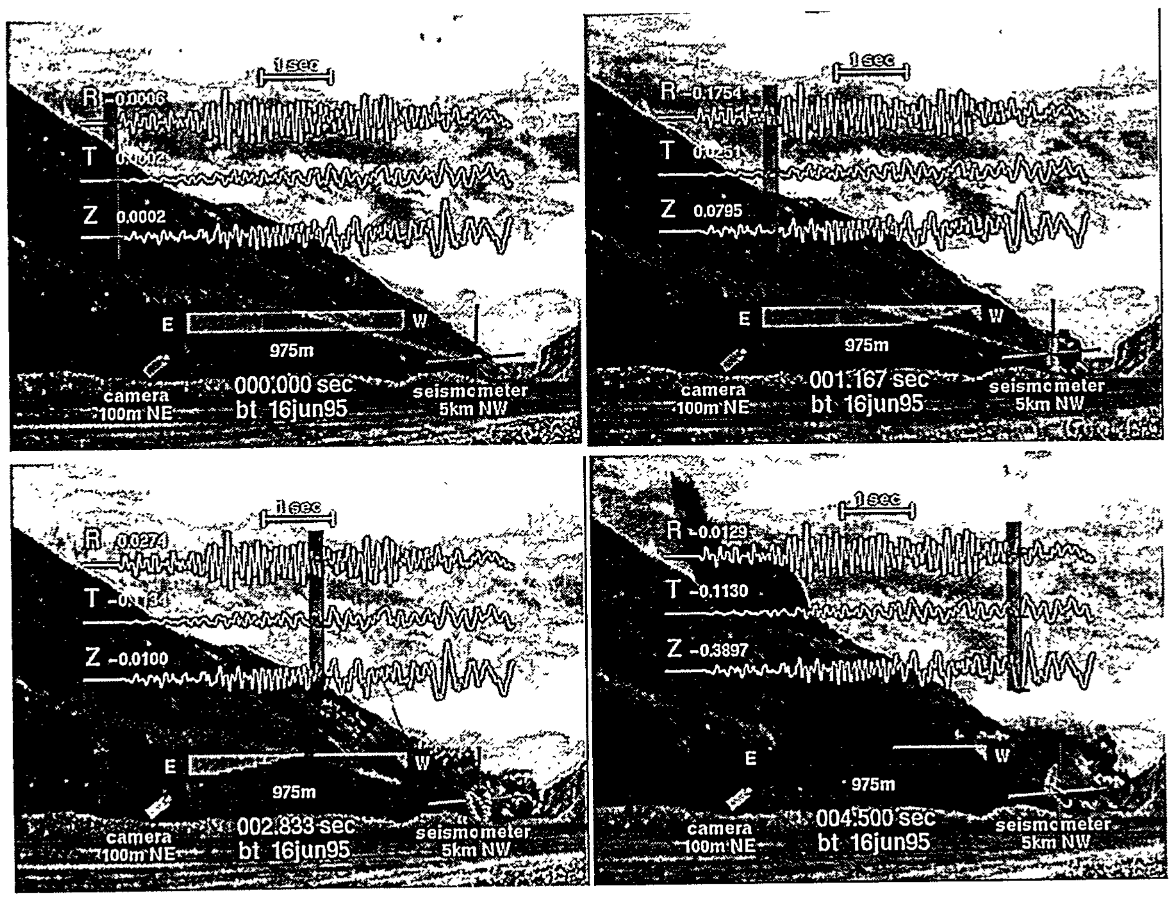

Figure 7: Four images from a large cast shot. Combined with the video images and time synchronized are the radial (R), transverse (T) and vertical (Z) ground velocities. In the lower center portion of each image, the design shot pattern is mapped with the individual boreholes changing from white to dark at shot time. The three-component particle motion is represented in the lower right hand corner of each image.

UNDERGROUND COLLAPSES

Underground collapses also generate seismic waves that can be used as diagnostics of the mining processes. Utilization of these data is especially effective when the collapse is controlled in time and space through the use of explosively induced collapses. Characterization of this type of mining source is of interest to CTBT monitoring due to its unique properties (Taylor, 1994; Walter *et al,* 1996) which include the controlled nature of the source in time, location, and magnitude, the fact that the source is located in an active region of underground mining, and the fact that natural collapses of large portions of this mine have occurred in the recent past. The operator's concern is with the characterization of the vibration induced by both the explosive and implosive components of the procedure, and with determination of the elevation to which chimneying of the roof progressed.

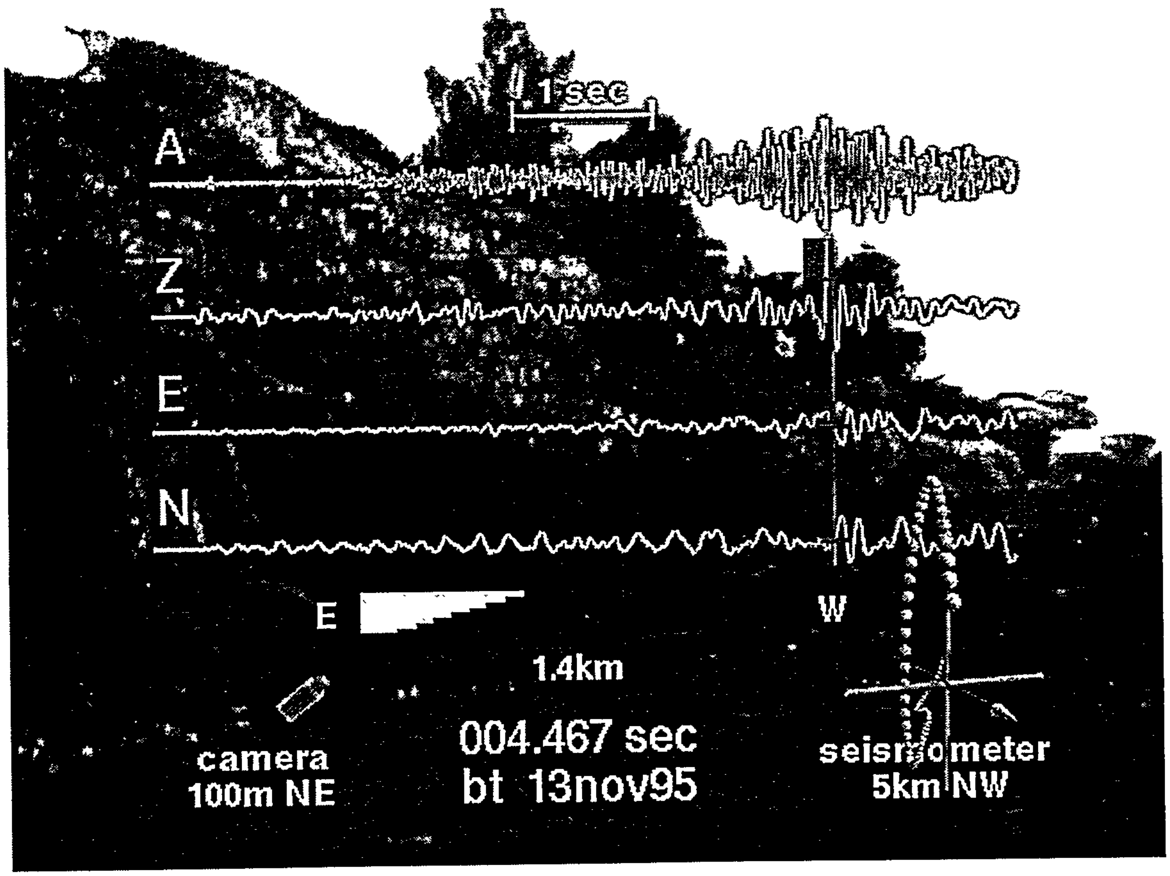

Figure 8: Single frame of combined video, ground motion (Z-vertical, E-east to west, N-north to south), acoustic (A) data along with a model of the design detonation pattern (following format of Figure 7). In this frame at 4.467 s the shot is over three quarters complete. The large amplitude at this time, vertical bar across all time traces, is a result of the accidental simultaneous detonation of a significant number of boreholes at the end of the shot pattern.

A series of tests in which explosives were used to remove pillars in an underground mining operation and induce a collapse were instrumented with a near-source seismic array. The primary purpose of this instrumentation was to quantify the blast, collapse and resultant seismicity that followed the collapse. The purpose of the mining operation was to evaluate the effectiveness of pillar rubblization and roof collapse for planned in-situ leaching of copper ore from the rock mass. This type of seismic source is unique in that a large, delay-fired, explosive source was expected to be followed by collapse of the rock immediately above the explosion into the void created (Phillips *et al.,*1996).

Since the primary purpose of the seismic array deployment was the quantification of the relative importance of the explosives and the following collapse in generating seismic energy as well as identification of the underground region affected by the collapse, twelve stations were distributed in azimuth and range out to approximately 1000 m. A thirteenth seismic station was located at a range of approximately 5 km (station 12), primarily to record the electrical shot break signal and secondarily to characterize the wave-field as it propagated away from the source region. Each station was instrumented with a six channel, Refraction Technology Model 72A-08 data logger which was continuously locked to GPS broadcast timing signals for adequate timing accuracy (< 1 millisecond). Three-component, 1 Hz, Mark Products Model L4-3C geophones were fielded at each station and a three-component, Terra Tech SSA-302 accelerometer was fielded at station 2.

Figure 10 focuses on the vertical velocity seismogram at the surface directly above the explosion (ground zero). It gives a relative measure of the seismic energy generated by the explosions in the pillars (bottom), the failure of the pillars (middle) and the collapse (top). The

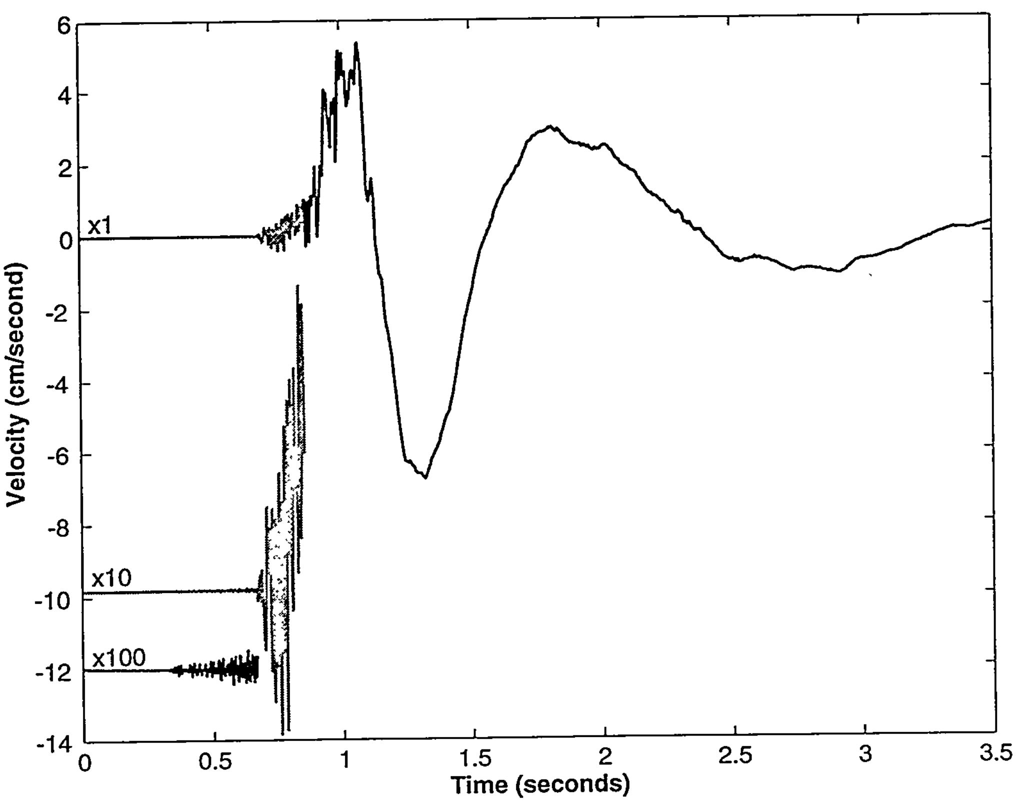

Figure 10. Vertical component velocity seismogram recorded at ground zero. The upper trace is the complete seismogram, dominated by the long period collapse. The middle and lower traces are magnified by 10 and 100 times, respectively. The middle trace shows pillar failure and the lower trace shows the explosions in the pillars.

explosions are a factor of 100 times or more smaller than the signal generated by the collapse, suggesting that the primary signal observed from this type of event will be a result of the collapse not the explosions.

Arrival time data at the free surface stations deployed for this experiment were measured an used to locate the aftershock activity that followed the collapse. It is believed that these locations provide a three dimensional image of the area of the mine affected by the collapse. A complete discussion of these results can be found in Phillips, Pearson, Edwards and Stump (1996). Plan and cross-section views of 135 aftershock locations are shown in Figure 25. These aftershocks were required to have 6 or more arrival times, largest error ellipsoid axis less than 50 m and RMS arrival time residual less than 7 ms.

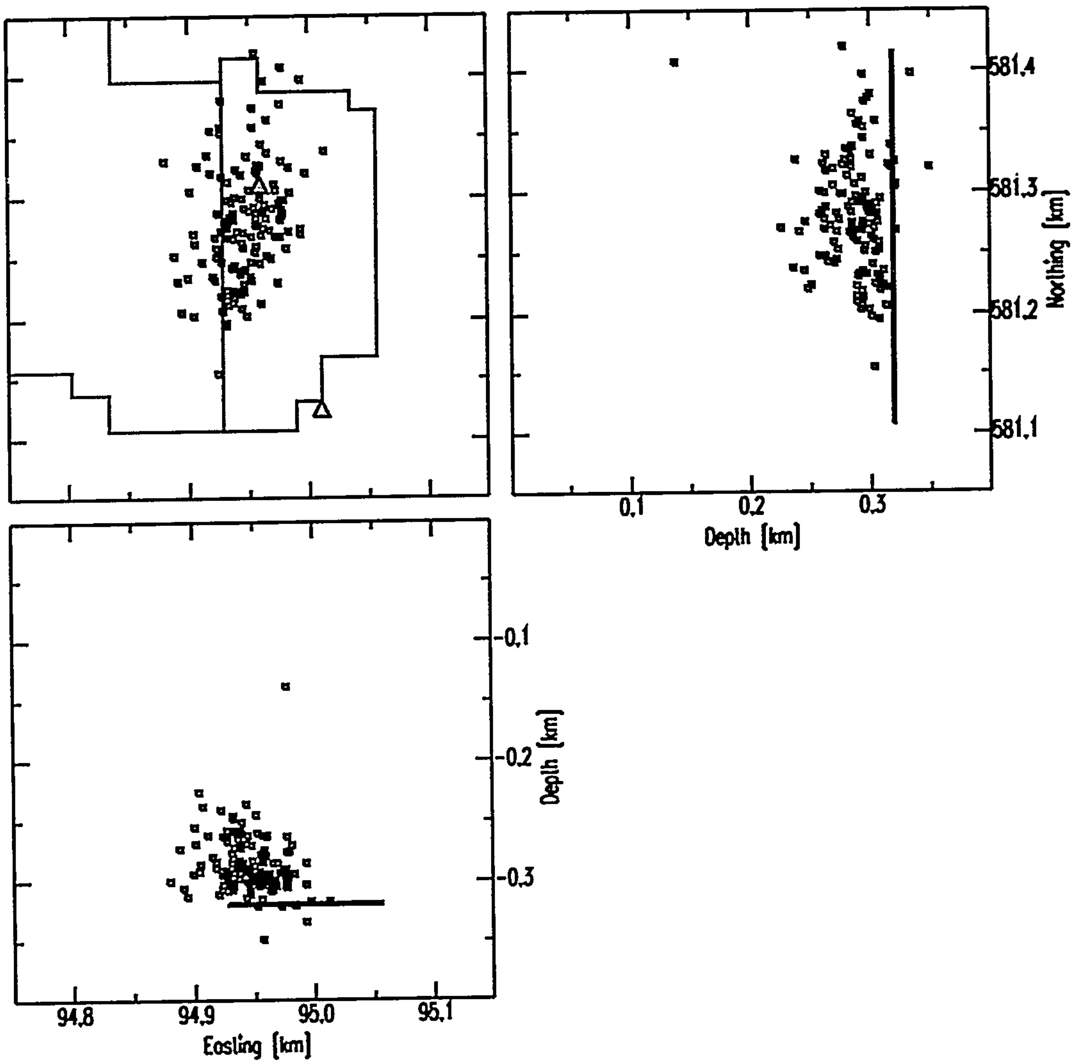

Figure 11. Map and cross-section views of aftershock locations. The heavy solid line in the map-view represents the room-and-pillar mined area, the thin line encircles the collapsed panel from the unblasted region. Triangles represent nearby stations

The aftershock plan view shows a distribution that fell short of the unmined faces of the mine by 50 m in places. However, the aftershocks lined up along the boundary between explosively collapsed and unaltered pillars on the western, open edge of the collapsed panel. The cross-section views show an aftershock zone just under 100 m thick, bottoming at mine level. In the cross-section view to the north, the distribution is asymmetrical, with the shallowest aftershocks falling closer to the open, western edge of the collapsed panel. These results illustrate the possible utility of aftershock locations in imaging subsurface mining operations.

CALIBRATION

Keys to the success of any monitoring system are the accurate location and positive identification of the source of the seismic waves. Empirical procedures are suggested for calibration or fingerprinting of signals from active mines in order to minimize the impact of the verification system on mine operations by minimizing false alarms. The approach to obtaining ground truth information for calibration/validation of a regional monitoring system is to use a set of simple portable instruments which could be deployed and operated by one or two people with a minimum of effort in the near-source region. This approach would provide a cost effective methodology for calibration, using sources of opportunity such as those available in an active mining region. Near-source data gathered by this calibration system can also be used to assess important source processes that lead to regional signals that will be detected by the International Monitoring System. A set of instrumentation that could be used for calibration procedures is illustrated in Figure 12. The instrumentation includes a video camera, seismometers, acoustic gauge and absolute timing and location information such as that provided by the Global Positioning System (GPS). In order to make the equipment effective, it can be deployed by one to two individuals in one to two hours and be left unattended at shot time and for extended periods of time.

Another form of calibration is the detonation of a single-fired (no delay), moderate sized (50,000 to 100,000 lbs.) contained explosion for empirical comparison to a typical mining explosion utilizing delay-firing. Data from this calibration event can then be used in comparison to the standard mining event for identification purposes. Figure 5 displayed data from such a comparison utilizing seismic data recorded on mine property and at one station of the permanent monitoring system. The single fired data from within the mine can also be used to assess timing and explosive performance during standard blasting operations as a pilot signal.

CONCLUSIONS

Physical understanding of how mine related activities generate seismic and acoustic energy is of interest to both the mining industry and the community responsible for monitoring the Comprehensive Test Ban Treaty. This mutual interest has provided the foundation for cooperative experiments designed to understand the physical processes that accompany mining blasts and collapses.

The synergy of data sets such as those provided by video, ground motion, acoustic and blast design characteristics has provided new constraints on mining phenomenology in both the above ground and underground mining environment. These new results have only come about as a result of close cooperation between industry, government, national laboratory and university. Programs such as these offer further benefit to these communities.

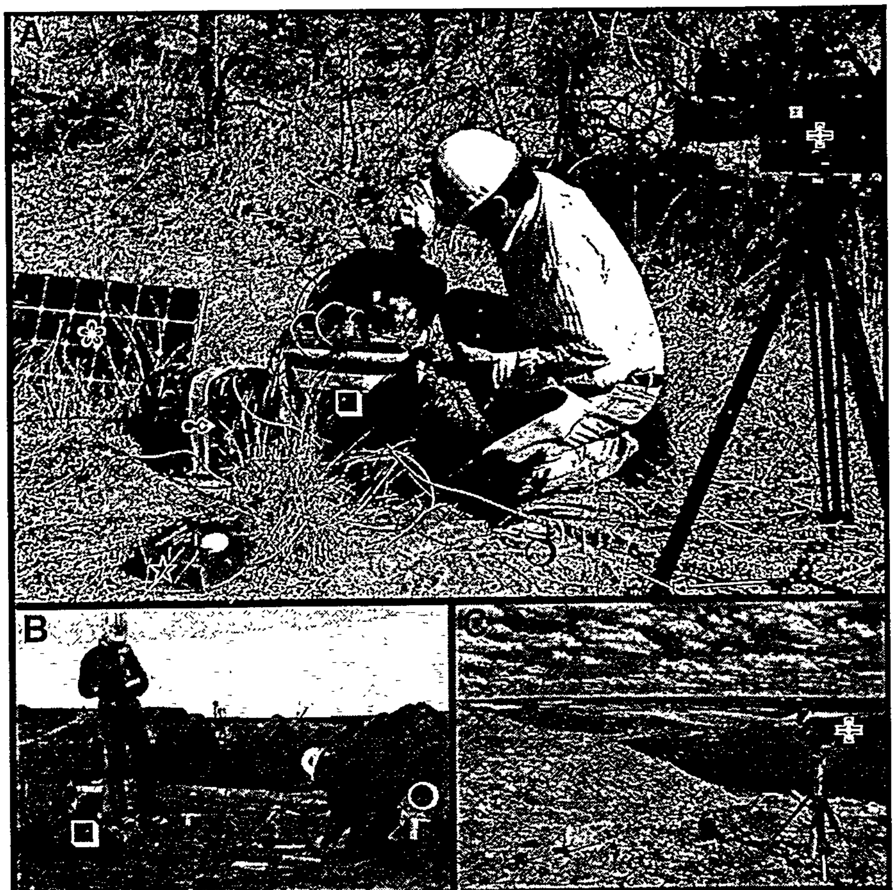

Figure 12: A: The data logger (❑) is attached to the velocity transducer (O) and the GPS receiver (☆). The camera (✙) is to the far right with battery (⚭) and solar panel (❀) to far left. B: Installation of the system in a mine just prior to a large cast blast. C: Hi-8 camera (Sony EVW-300) deployed prior to a large cast explosion.

ACKNOWLEDGMENTS

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