EMPIRICAL SEISMO-ACOUSTIC STUDIES FOR CALIBRATION AND IDENTIFICATION CAPABILITIES AT INTERNATIONAL MONITORING SYSTEM ARRAY SITES

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ABSTRACT

Location and identification of small- to intermediate-magnitude seismic events utilizing regional waveforms will be critical to the success of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Mine-related seismicity has been detected and located by the prototype International Data Center (PIDC). Identification of mine-related events is important for purposes of calibration as well as avoiding false alarms. We report on the development of a portable seismo-acoustic technology that can be utilized for characterizing and constraining a physical understanding of the seismo-acoustic signals generated by these man-made sources. This instrumentation is also used to gather information necessary for calibration of location procedures. The instrumentation and procedures are being tested in the western United States where mine-related events are detected and located using the three regional arrays, TXAR, PDAR, and NVAR.

Portable instruments that are deployed at regional distances consist of a Refraction Technology 72A 6-channel 24-bit high-resolution seismograph interfaced with a Refraction Technology 114 remote access computer, which allows modem access of the data. Seismic sensors include Geotech S-13, Guralp CMG-3T and Streickheisen STS-2. In addition to three-component seismic instrumentation at each regional site, a three-element infrasound array with approximate 100-m station spacing will be deployed. The infrasound gauges are the Chaparral Physics Model 2 with flat response from 10 s to 300 Hz.

Close-in (10 m to 10 km) seismic, acoustic, and video instrumentation will be deployed in cooperating mines for purposes of quantifying shot times to within 0.1 s and shot location to within 100 m. These data will also be critical to the constraint of physical processes that accompany the mining explosions and are important in the generation of regional seismic and infrasonic signals.

Two preliminary experiments have been undertaken for purposes of calibration and source constraint.

The first experiment consisted of two cast blasts at the Peabody Western Coal Company Black Mesa mine near Kayenta, Arizona. The origin of the sequence of explosions (1.57 and 1.61 million pounds of ANFO/Emulsion mix) occurred at 21:07:31.36 UTC on 24 March 1999 and 21:10:38.69 on 25 March 1999. The precise origin time and location allows the classification of this event as a GT0 Ground Truth Data Base (GTDB) event. The event was recorded at several regional stations as well as the IMS array in Wyoming (PDAR). By using the two casts, the back-azimuths and phase velocities for a small range of back-azimuths at PDAR have been calibrated. Traditional Fourier filtering and beaming techniques could not extract analyzable signals out of background seismic noise from the NVAR and TXAR arrays. This most likely results from the propagation paths through the highly attenuating Basin and Range (NVAR) and Rio Grande Rift structures (TXAR).

The second experiment consisted of a reconnaissance visit to the Phelps Dodge Copper Mine in Morenci, Arizona. Mining operations at this mine as well as mines in Tyrone, New Mexico, and Chino, New Mexico, were reviewed. Preliminary information of shooting practices was exchanged and compared to regional observations at the three western U.S. arrays. Regional observations of hard rock fragmentation explosions from these mines were observed at TXAR but not NVAR and PDAR. The variability of these signals is attributed to the complex propagation paths in the western U.S. and illustrates that event identification may often rely on single-station analysis. A simple M pulse, similar to observations from cast blasts, characterizes near-source acoustic signals from delay-fired explosions.

Key Words: seismo-acoustic, mine seismicity, infrasound

OBJECTIVES

The International Monitoring System (IMS) is being developed to detect and locate seismic events down to small magnitudes. Seismic and infrasonic signals associated with mining explosions are detected at the smallest magnitudes. These events must be characterized as distinct from a nuclear explosion, possibly detonated in an evasive manner. Measurements made by SMU at TXAR suggest that the ability to observe infrasonic signals may be useful in developing ground truth data bases of mining explosions (Sorrells, Herrin and Bonner, 1997). However, questions remain as to how explosion source design, seasonal wind variations, and other factors affect seismo-acoustic propagation at regional distances. The objectives of our current study include: (1) Refinement of the physical models of mining explosions and the generation of regional seismic data; (2) Development of a comprehensive data base of acoustic and infrasonic measurements from a variety of types of mining explosions for which the explosive parameters are well known; (3) Investigation of a new approaches for utilizing combined seismic and infrasonic data sets for event location and identification; (4) Development of a procedure for calibrating problematic monitoring regions will be established; (5) Quantification of mining practices in the western US that might produce signals observable by the IMS.

RESEARCH ACCOMPLISHED

Seismic and Acoustic Instrumentation Design

SMU has developed a portable seismo-acoustic instrumentation capability that can be deployed from close-in around the source out to regional distances. The purpose of the instrumentation is to provide a characterization of the initiation and development of the seismic and acoustic/infrasonic wavefields from mining explosions. This data will be used in quantifying these sources as seen at IMS Primary and Auxiliary stations. The data is intended to provide constraints on physical models of the source processes and the associated signal propagation. These models provide the mechanism for the interpretation and understanding of similar signals observed at IMS stations in other parts of the world which might not be directly accessible. Additionally the source studies will provide the physical basis for development of regional discriminants that can be transported to new regions. This approach builds on expertise and results developed by groups at SMU, LANL, UC San Diego, DSWA and AFTAC (Hedlin *et al*., 1999; Stump *et al.*, 1999) over the last several years. The systems have been tested and are ready for deployment in Fall '99.

Included in the instrumentation is special purpose near-source acoustic instrumentation and video documentation that includes accurate time. The acoustic instrumentation development for quantifying close-in signals follows the work of Bob Reinke at DSWA. The introduction of the time stamp to video is new in our field but has been previous implemented by videographers so that multiple cameras can be correlated on frame by frame basis. In this application a video camera with accurate time can provide source location and timing information.

Experiment Design

SMU has established a working relationship with the blasting engineers of the Phelps Dodge mines of western New Mexico and eastern Arizona and these mines have agreed to allow us on-site access to monitor their explosions. Experimental design is centered around the key IMS array TXAR, with complementary data from either NVAR and PDAR (Figure 1). These deployments of portable instrumentation have four goals:

(1) Close-in seismic, acoustic and video instrumentation of a number of different types of mining shots during the experiment. Mining engineers at Phelps Dodge are already cooperating with SMU providing shot time and characterization data. This data will provide empirical quantification of actual delay times, degree of confinement, material cast, and acoustic venting. The acquisition of geophysical and geological site characterization information around a limited number of shots will be needed for constraint of the resulting source models. Material cast into the pit (when appropriate), pit geometry and explosive array configuration can result in azimuthally varying radiation of seismic data. An azimuthal array of instruments at 10 to 20 km from the explosions is planned to assess these effects during the experiment.

(2) Development of a prototype of a system that could be deployed in a mining region for six months for the purposes of obtaining high frequency ground truth information. The mining district in SE Arizona and SW New Mexico has several active mines including Morenci, Tyrone, Chino and Santa Rita. This

configuration is similar to many mining districts in the world where a number of source locations might provide regional signals.

(3) Dial-up seismic stations will be deployed in this region. Queries of these portable instruments will be triggered by near-real time analysis of the TXAR data stream. A simple phone call to the data logger will retrieve the data. Cellular phones can be used in conjunction with the portable instrumentation for this purpose. This portable installation will allow the approach to be assessed with possible application to other mining regions.

(4) Critical to the interpretation of the signals at the permanent IMS arrays is a quantification of the regional signals as they propagate to these distances and beyond. Both seismic and acoustic instruments will be deployed along a radial to TXAR and beyond. The seismic instruments will include three-component broadband instruments while the each acoustic installation will consist of three acoustic sensors with pipe/hose arrays in a small array. We anticipate that 5-10 such stations will be deployed and data acquired over a 2 to 3 month time period.

Ground Truth Data Collection

Black Mesa Mine, Northern Arizona

During the past year, we have collected ground truth data and site specific information from the mining regions that will be monitored for this study. The first of these studies was carried out at the Peabody Western Coal Company Black Mesa mine near Kayenta, Arizona. The purpose of the experiment was to investigate the utilization of in-mine multiple sensor data (seismic, acoustic and video) in constraining important blast related phenomena. A second goal of the experiment was the establishment of the relationship between these source processes and seismic and infrasound data recorded at regional distances (100-1000 km). The casts occurred at 21:07:31.36 UTC on 24 March 1999 and 21:10:38.69 on 25 March 1999. The 24 March event had an explosive yield of 1.57 million pounds of ANFO/Emulsion mix as compared to 1.61 million pounds for the 25 March event.

A third goal of this experiment was to use these cast blasts as GT0 events for the calibration of the IMS arrays TXAR, NVAR, and PDAR (Table I and Figure 1). Both cast blasts were recorded at PDAR while no data from either event was recorded at TXAR. The regional phases *Pg* and *Lg* were recorded for the 24 March 99 event at NVAR, but the low SNR inhibits any attempts at calibration. No phases were recorded at NVAR for the second cast on March 25. A possible reason for the lack of analyzable signals at NVAR and TXAR is a result of the small size of the events. This can not explain the lack of good SNR data at NVAR since the array-to-source distance is only 30 km greater than PDAR, where *Pn*, *Pg*, *Lg*, and *Rg* were recorded with significant SNR. An alternate explanation is related to the propagation path through the Basin and Range, a broad region of extension characterized by a thin crust (~30 km) and highly-attenuating mantle (Koch and Stump, 1995). We feel that the thin, inhomogenous crust in the Basin and Range acted to attenuate *Lg* propagation. In addition, the low-velocity upper mantle beneath the Basin and Range attenuated *Pn* propagation as well. A similar explanation can explain the lack of signals at TXAR as a result of the Rio Grande Rift structure of central New Mexico. The cold, thick crust and upper mantle that comprises the Colorado Plateau and adjacent provinces along the source-to-array path to PDAR provides an excellent medium for the propagation of *Pn*, *Pg*, *Lg*, and *Rg*. In fact, *Rg*, fundamental mode, short-period Rayleigh waves, with a dominant period of 4 seconds was recorded at PDAR from both events and can be seen in Figure 2. The preliminary results of the calibration of PDAR using these GT0 events is presented in Table II. Results thus far show that the observed *Pn* backazimuths are 11 degrees off from the true azimuth, while the observed *Lg* azimuths only slightly deviated from the true great circle path (approximately 1 degree). Incoming *Rg* at PDAR is refracted by more than 18 degrees towards the southeast possibly around the Uinta Mountains. In addition to the IMS array data, regional seismic recordings of the cast from various networks were studied for phase comparison and travel time calibration. Using this data, we have observed significant dipolar radiation patterns in the *Rg* generated from both explosions that may be related to the direction of casting during the shot (Figure 3).

	March 24		*March 25*	
Station	Distance (km)	Back-Azimuth	Distance (km)	Back-Azimuth
PDAR	697.9	186.1	698.2	186.2
NVAR	731.3	104.5	730.2	104.5
TXAR	1014	323.5	1014.7	323.4

Table I. Array-to-source backazimuths for the Black Mesa shots.

24 March 1999	25 March 1999
Parameter: Observed **(True)**	
Pn arrival: 21:09:10.4	*Pn* arrival: 21:12:17.8
Lg arrival: 21:10:57.6	*Lg* arrival: 21:14:07.2
Lg-P (sec): 107.19	*Lg*-P (sec): 109.40
Distance (km): 703.4 **(697.9)**	Distance (km): 717.2 **(698.2)**
Pn BAZ: 174.6 **(186.1)**	*Pn* BAZ: 174.8 **(186.2)**
Pn Phase Vel: 8.1 **(8.1)**	*Pn* Phase Vel: 7.8 **(8.1)**
Lg BAZ: 187.9 **(186.1)**	*Lg* BAZ: 185.7 **(186.2)**
Lg Phase Vel: 4.1	*Lg* Phase Vel: 4
Rg BAZ: 168.5 **(186.1)**	*Rg* BAZ: 166.7 **(186.2)**
Rg Phase Vel: 3.4	*Rg* Phase Vel: 3.5

Table II. Preliminary results of the calibration analysis of the PDAR array using the Ground Truth Database Events from Black Mesa, Arizona.

Morenci Mine, Southeastern Arizona

Another array calibration study was carried out for the IMS arrays using explosions from the open-pit Phelps-Dodge Morenci copper mine in southeastern Arizona. On 18 May 1999, we visited the mine to learn about blasting practices and shooting schedules. During the visit, we installed temporary seismic, acoustic, and videographic instrumentation to record five fragmentation shots. The seismic and acoustic recordings of each are shown in Figure 4, while the an image from the video of a fragmentation shot at a similar coal mine is shown in Figure 5. Two of the fragmentation shots were detonated simultaneously and were separated by less than 600 m. Careful comparison of the near-source P-waves from these shots illustrates significant differences. In particular, the P waves from the multiple event produces a simple impulsive P wave while the other shots yielded P waves more representative of their delay pattern. At our recording distance of 6 km, we were unable to separate the two explosions using the P wave records. We were able to separate the two explosions using the acoustic recordings which show each blast is characterized by a simple M shaped pulse. The shape of this pulse is similar to observations from cast blasts and will be the focus of our future research efforts aimed at learning how a simple M shaped pulse convolves with the atmosphere to create complex acoustic signals at regional distances. We observed no acoustics for these events at TXAR due to the zonal wind direction during the experiment.

Regional observations of the fragmentation explosions from these mines were observed at TXAR but not NVAR and PDAR. The variability of these signals is attributed to the complex propagation paths in the western US and illustrates that event identification may often rely on single station analysis. Results of the TXAR back-azimuth and phase-velocity calibration for these events are shown in Table III.

	Pn Phase Vel	*Pn* BAZ	*Pg* Phase Vel	*Pg* BAZ	*Lg* Phase Vel	*Lg* BAZ
MEAN	8.2	294.7	6.9	317	3.6	305.3
STD	0.3	7.5	0.0	2.3	0.1	5.5
TRUE	8.1	305.9	6.1	305.9	3.5	305.9
RESIDUAL	0.1	-11.2	0.8	11.1	0.1	-0.6

Table III. Phase velocity and back-azimuth calibration results for *Pn*, *Pg*, and *Lg* for the 18 May 99 fragmentation shots at Morenci, AZ.

Additional Calibration Explosions

Explosions were conducted at the Phelps Dodge Tyrone mine as part of the DEEP PROBE experiment in August 1995. The parameters for the explosions are shown in Table IV. The explosions were detonated simultaneously underwater and were recorded at TXAR (Figure 6) and used as Ground Truth Database events. The results of back-azimuth and phase velocity calibration of these explosions are shown in Table V.

Date	Latitude	Longitude	Time	Size (kg)
09 Aug 95	32.6324	32.3878	11:00:00	16329
17 Aug 95	32.6324	32.3878	11:00:00	16000

Table IV. Shot point information for the DEEP PROBE sources at Tyrone, NM.

09 August 1995	17 August 1995
Parameter: Observed **(True)**	
Pn arrival: 11:01:19.85	*Pn* arrival: 11:01:19.78
Pg arrival: 11:01:35.62	*Pg* arrival: 11:01:35.50
Lg arrival: 11:02:44	*Lg* arrival: 11:02:43.87
Distance to TXAR: 578.8 km	Distance to TXAR: 578.8 km
Pn BAZ: 297.5 **(307.8)**	*Pn* BAZ: 298.9 **(307.8)**
Pn Phase Vel: 8.8 **(8.0)**	*Pn* Phase Vel: 9.3 **(8.0)**
Pg BAZ: 302.5 **(307.8)**	*Pg* BAZ: 302.8 **(307.8)**
Pg Phase Vel: 7.1 **(6.0)**	*Pg* Phase Vel: 7.2 **(6.0)**
Lg BAZ: 310 **(307.8)**	*Lg* BAZ: 310.2 **(307.8)**
Lg Phase Vel: 3.7 **(3.4)**	*Lg* Phase Vel: 3.7 **(3.4)**

Table V. Data for regional calibration of the TXAR array using the Ground Truth Database Events from Tyrone, NM.

CONCLUSIONS AND RECOMMENDATIONS

This paper represents the initial reconnaissance for our field based study that will attempt to understand the physics of seismic and acoustic sources from hard rock fragmentation blasts. As part of this study, we will also examine the propagation of the signals from these blasts to regional distances in an attempt to develop ground truth databases for IMS array calibration. We have used explosions in the western United States to acquire calibration data for TXAR and PDAR for various azimuths at regional distances. The data shows large azimuth and phase velocity deviations that must be explained through additional data acquisition and modeling. Our results show that various propagation characteristics for physiographic provinces such as the Basin and Range and Rio Grande Rift will often create the need for single array location and identification, thus increasing the need for additional calibration and ground truth database development in the western United States. Our results thus far show that the Phelps Dodge Morenci mine is the optimum mine for use in the initial phase of the project. This is based upon our working relationship with the blasting engineers at the mine who have agreed to cooperate in the study. Based upon the variability observed in the seismic recordings of Morenci fragmentation shots at the IMS arrays, we have decided to study seismic and acoustic propagation to TXAR for the first phase of this study. This phase will begin in the Fall of 1999 when zonal winds are favorable for the path from Morenci to TXAR.

ACKNOWLDEGMENTS

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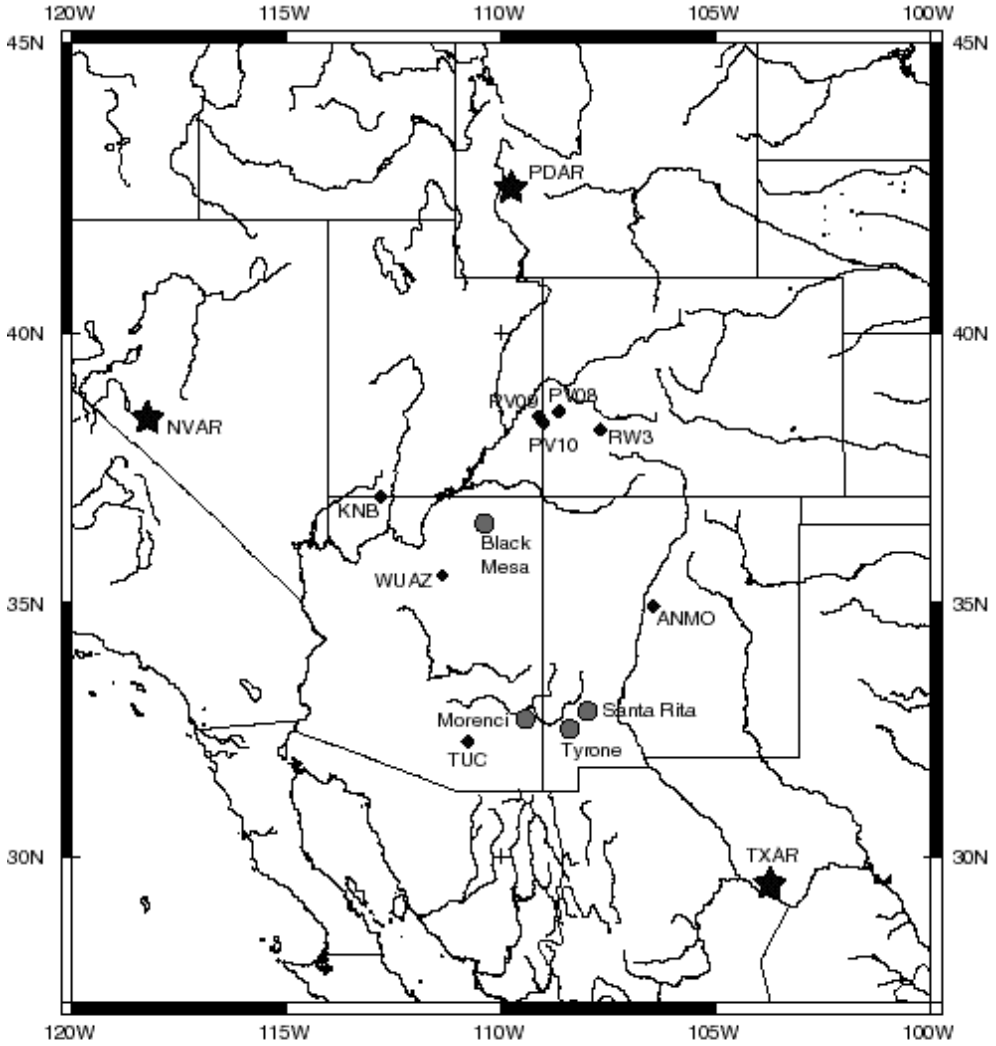

Figure 1. Locations of the mines where calibration events were recorded. Also shown are the locations of the IMS arrays PDAR, TXAR, and NVAR. Additional regional stations used in these studies are marked by small diamonds.

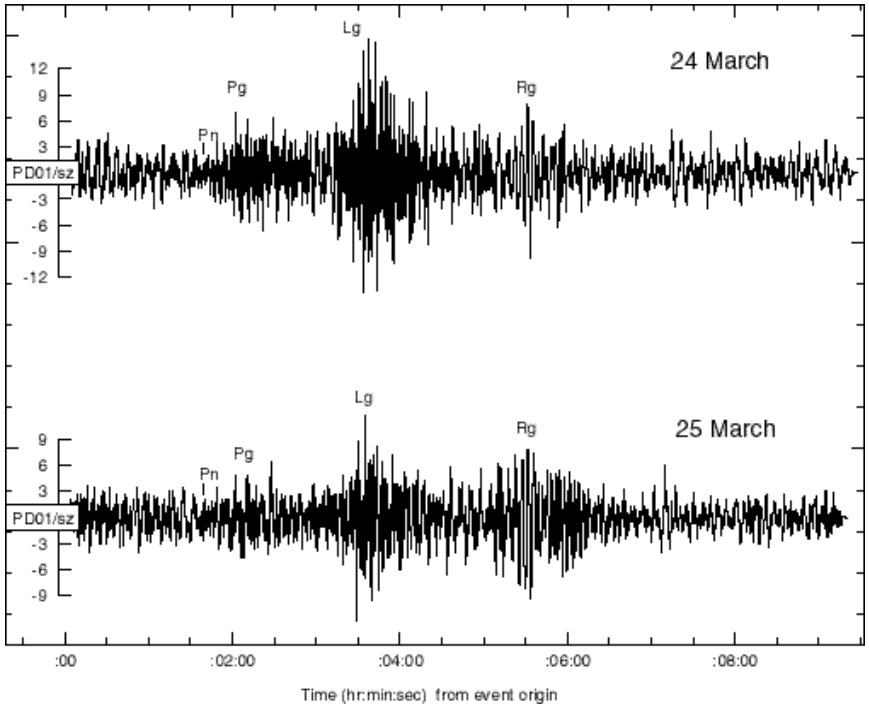

Figure 2. Unfiltered PDAR recordings of the Black Mesa cast blasts.

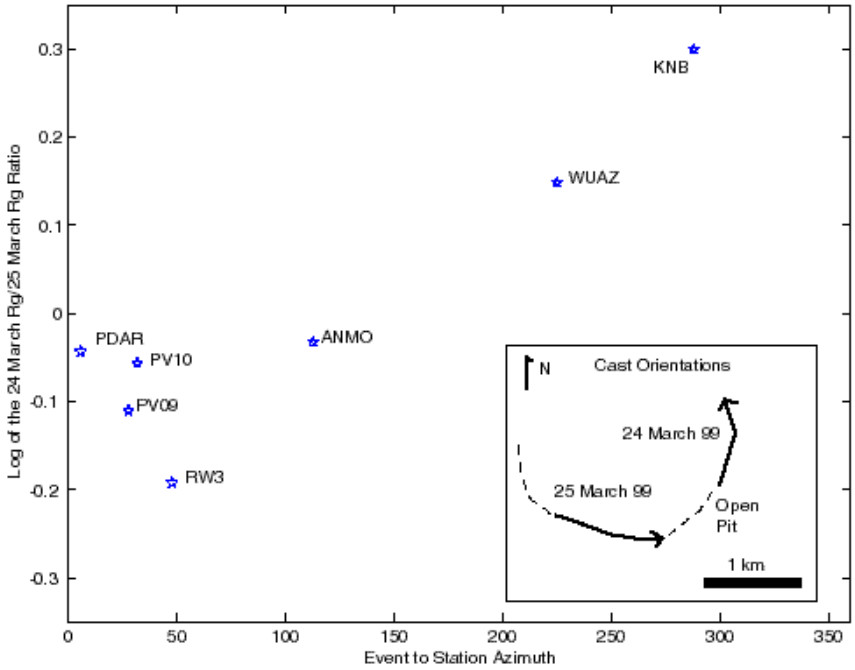

Figure 3. *Rg* ratios observed for the Black Mesa cast blasts. The ratios can be explained by dipolar radiation patterns oriented parallel to the direction of cast propagation. The solid arrows in the inset represent direction of detonation parallel to the free face.

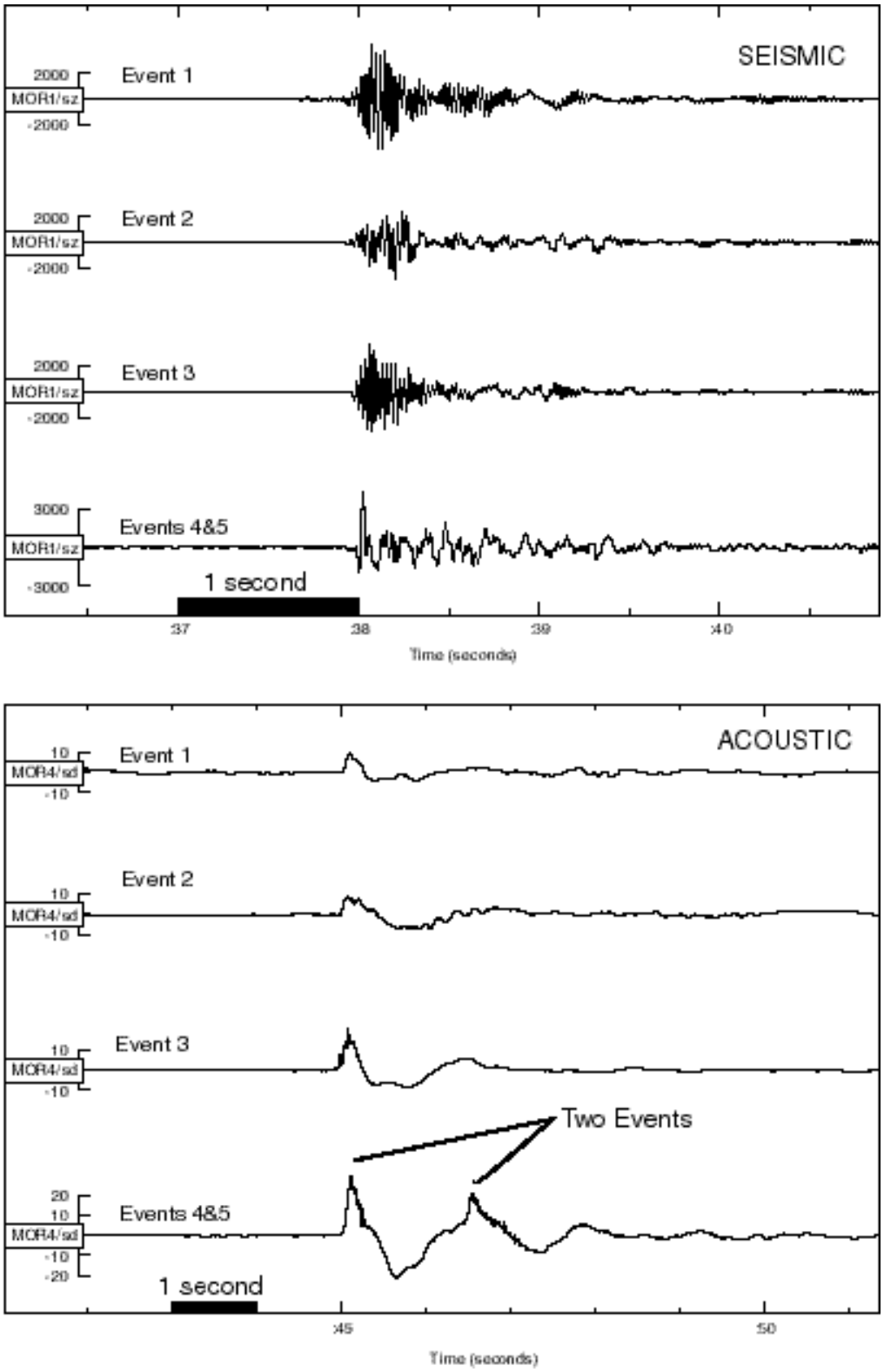

Figure 4. In-close seismic and acoustic monitoring of fragmentation blasts at the Phelps Dodge Morenci open pit copper mine on 18 May 99.

Figure 5. Image of a rock fragmentation blast at copper mine in the southwestern United States.

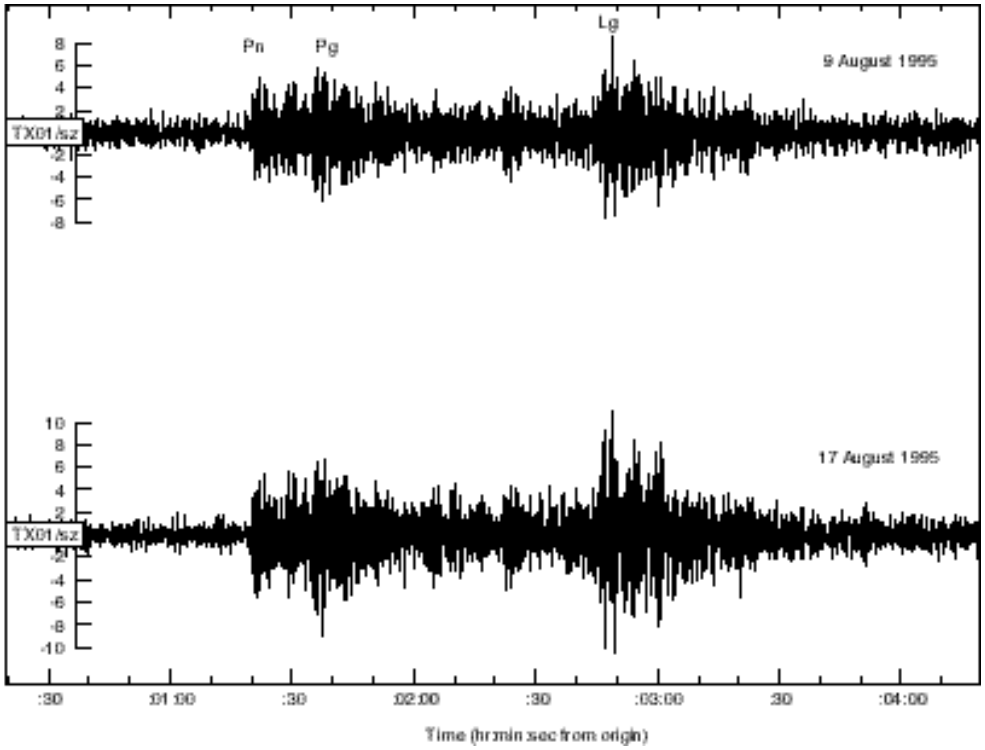

Figure 6. TXAR recordings of the Tyrone, NM DEEP PROBE explosions (BP Filtered 0.6 to 4 Hz).