UTILIZATION OF SEISMIC AND INFRASOUND SIGNALS FOR CHARACTERIZING MINING EXPLOSIONS

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ABSTRACT

This empirical study is designed to quantify mining explosions as sources of seismic and infrasound signals. The study focuses on the Western US, where a variety of different types of mining operations exist, ranging from surface coal cast blasting to hard rock fragmentation blasting in porphyry copper mines. The study is extended to the taconite mines of the Mesabi Range of Minnesota. Newly installed instrumentation, including in-mine equipment for ground truth as well as regional seismo-acoustic deployments to complement existing resources in the region, is a key component of the study. In-mine monitoring is ongoing at the Morenci Mine in Arizona and the Tyrone Mine in New Mexico. The seismo-acoustic station at Ft. Hancock, Texas, and the infrasound upgrade to Tucson, Arizona, and WUAZ will also be illustrated.

Data from this study have been used to address coupling and source characterization issues for both seismic and infrasound signals. The seismic coupling of large-scale cast blasts in Wyoming, copper fragmentation blasts in Arizona and New Mexico, and taconite fragmentation blasts in Minnesota are compared. For all these event types, there is no relation between total explosive yields and peak amplitude either in the mine or at regional distances. A series of contained, single-fired explosions of varying yield was conducted in the coal mine. At regional distances these events, in contrast, show a definitive magnitude-yield relation that follows the relationship for nuclear explosions. These data and an extensive modeling exercise suggest that the complete characterization of the delay firing process, including a spall contribution, can explain the regional observations.

Acoustic data from within the mine indicate that a relation exists between total explosive weight and peak acoustic amplitudes. At regional distances, under optimum wind conditions, approximately 25% of Morenci Mine shots are observed out to 500 km. The shots that are observed are among those with the largest total explosive yield conducted at this mine.

The acoustic data from within the mine can be used in developing ground truth. Unlike coal cast or taconite blasts, Morenci Copper Mine often shoots several explosive patterns within a short time interval (less than 5 s). The in-mine acoustic data can be used as ground truth to identify the occurrence of those complex explosive events and contribute to the interpretation of the accompanying regional signals.

KEY WORDS: Seismo-acoustic, mining, discrimination, infrasound

OBJECTIVE

This study focuses on seismic and infrasound signals from the following three types of mining operations:

Coal overburden casting (Black Thunder, WY) where explosions are designed to remove overburden to expose coal;
Rock fragmentation for copper recovery (Morenci, AZ) where moderate sized explosions are designed to break the rock for further processing; and
Rock fragmentation in hard rock for iron recovery (Minntac, MN) where large-scale explosions are used to pulverize the taconite for further processing.

Each mine has distinctive blasting practices that are reflected in regional seismic and infrasound signals that are illustrated in this paper.

This paper reports work in four areas:
1. Quantification of coupling of energy from mining explosions into regional seismic waves;
2. Development and constraint of physical models of mining explosions that are applicable to regional seismic signals;
3. Quantification of coupling of energy from mining explosions into infrasound signals; and
4. Characterization of seismic and infrasound signals from a number of unusual sources. Data from the three types of mining explosions listed earlier were used in developing these four work areas.

RESEARCH ACCOMPLISHED

Seismic Coupling

In all three types of mining operations, peak amplitude of regional seismic signals is independent of the total explosive weight (Figure 1 coal cast blasts, Figure 2 taconite (iron) fragmentation, and Figure 3, right, copper fragmentation blasts). In-mine peak amplitudes are also independent of total explosive weight (Figure 3, left). A series of contained, single-fired explosion experiments with total explosive weights from 5,000 to 50,000 lbs. was conducted in the coal mine to further investigate coupling. Regional phase amplitudes of P_n, P_g and L_g increase with a power law relation to total explosive weight (Figure 1, $\sim W^b$).

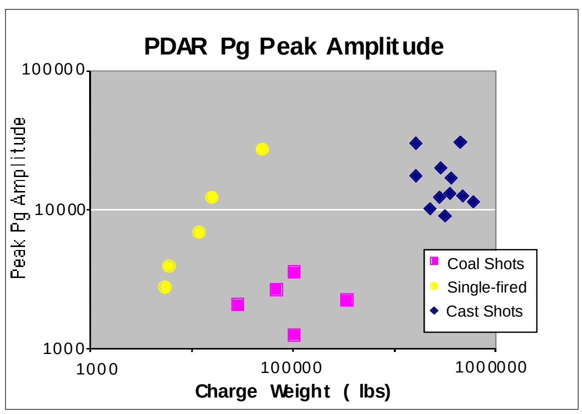


Figure 1: Peak P_g amplitudes observed at array element 03 of PDAR (360-km range) from contained single-fired explosions, delay-fired cast blasts and delay-fired coal shots

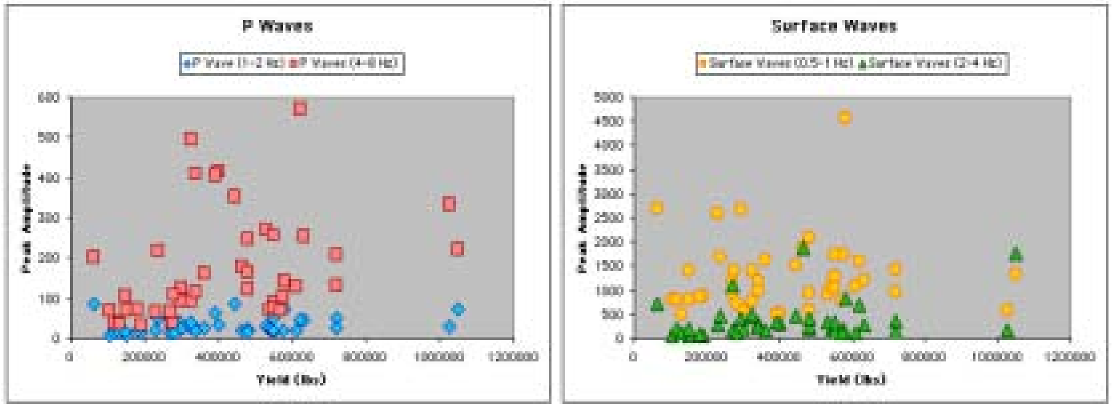


Figure 2: Peak P and R_g amplitudes observed at EYMN (Ely, Minnesota) from taconite fragmentation explosions approximately 110 km to the southwest of the station.

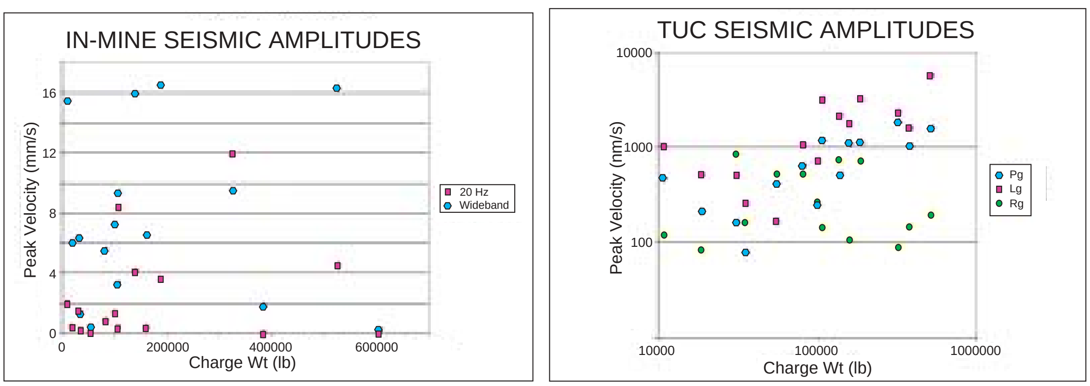


Figure 3: Peak amplitudes of in-mine recordings at Morenci are compared to total amount of explosives used in copper fragmentation blasts (left). Peak P_g, L_g and R_g amplitudes observed at the regional station TUC plotted against total amount of explosives used in the Morenci copper fragmentation explosions (right).

The scaling parameters (the b in $W^{b)}$ determined for these chemical explosions were 0.84 (–0.14) for P_n, 0.84 (–0.09) for P_g, and 0.91 (–0.08) for L_g. These b values are in close agreement with the scaling relations of Vergino and Mensing (1983) for P_n waves from nuclear explosions in Nevada. This comparison of contained, single-fired explosions with standard mining explosions suggests that delay-firing, casting and fragmentation are responsible for the independence of peak regional and close-in amplitudes and total amount of explosives.

Seismic Modeling

Following Anandakrishnan et al (1997) and Yang s (1998) implementation in MATLAB,¤ an equivalent elastic source model for the mining explosion was used to develop regional synthetic seismograms. The source model components shown in Figure 4 include: (a) explosion; (b) vertical spall; and (c) horizontal spall. The purpose of modeling was to investigate why peak regional amplitudes are insensitive to total explosive weight in delay-fired explosions (Figures 1-3) and how mid-frequency surface waves (2-12 s) are generated from large-scale cast blasting.

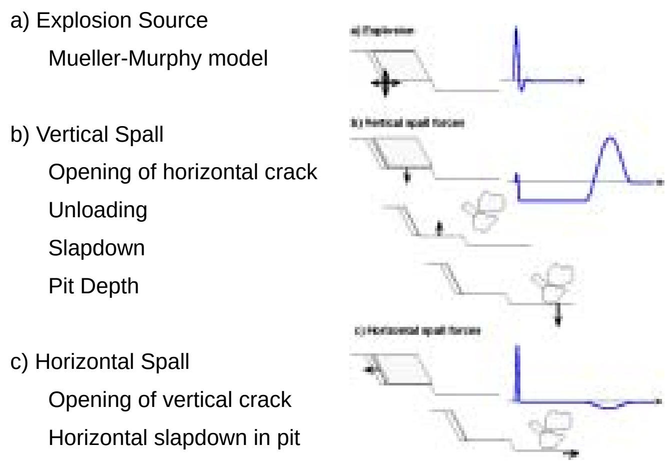


Figure 4: The three components of the equivalent mining explosion source model are represented pictorially. They consist of (a) the directly coupled energy from the contained explosion modeled as a Mueller-Murphy source function, (b) vertical spall due to the tensile failure of near-surface materials and (c) horizontal spall accompanying cast blasting when overburden is cast horizontally into a pit.

In addition to the three-source components, the temporal and spatial finiteness of the explosive array is included in the model. Collaboration with the three mines used in the study provided the necessary information to model the source and generate synthetic seismograms.

Hetzer (2000) investigated the effect of delay firing at the Taconite Mine in Minnesota (Minntac). The mine provided shot details that could be incorporated into the source model (Figure 4). Hetzer set total spall mass, one of the important parameters in the model, as equal to the mine's report of total mass of rock blasted. This same technique was applied to large-scale coal cast blasts in Wyoming. Figure 5 plots the average spall mass per hole versus the average charge weight per hole for the Minntac data (open triangles) and the single cast blast data point. Spall scaling relations developed for nuclear explosions (Viecelli, 1973; and Sobel, 1978) are included in the figure for comparison. The Minntac data relation falls between the Sobel and Viecelli scaling models and is consistent with the coal cast data (red star). This empirical spall scaling relation was used in the mining explosion source model.

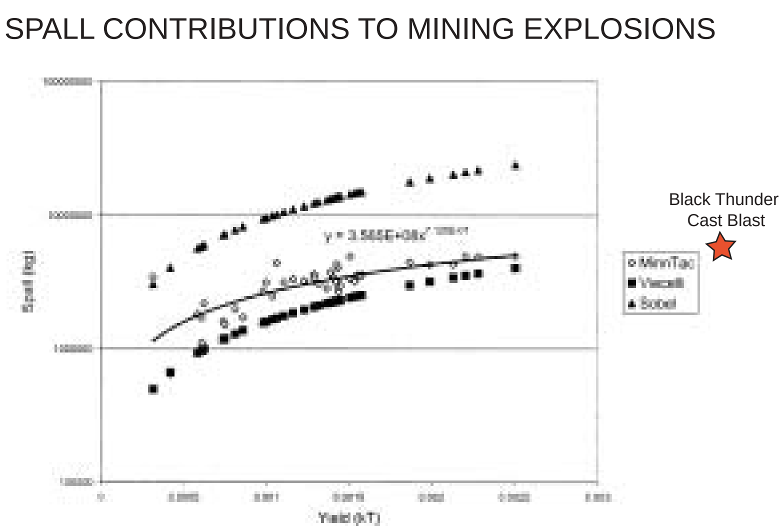


Figure 5: Spall mass (per hole) for the taconite hard rock explosions (open diamonds) and a single coal cast blast (star) were estimated from blasting logs. These empirical estimates from mining explosions are compared to the Viecelli and Sobel spall mass scaling relations developed for underground nuclear explosions.

Near-regional observations from the Minntac fragmentation blasts were made at EYMN approximately 110 km to the NE of Minntac near Ely, Minnesota. These observations provide the basis for the empirical and modeling studies of Hetzer (2000) and are summarized here. The shots ranged from 63,000 lbs to 1,050,000 lbs total explosive weight. Peak body (P_g) and surface wave (R_g) amplitudes showed little relation to total explosive weight (yield) as shown in Figure 2. The previously described source model and a regional propagation model were used to produce synthetics for the Minntac taconite fragmentation blasts. The models replicate the independence of regional signal peak amplitudes to total yield and replicate the order of magnitude scatter in amplitudes for a given yield. The modeling suggests that the average individual charge weight in the explosive array may control the absolute amplitudes of the regional phases. The observed body wave peak amplitudes in the 2-4 Hz band are plotted against average charge weight per hole in Figure 6 (solid symbols) and indicate a slight increase in peak amplitude with increasing single hole yield. For nine of the shots in the observational data set peak amplitudes on synthetic seismograms were compared with observations. The model amplitudes (open circles) are compared to the observations in the 2-4 Hz band in Figure 6 and replicate the increase in peak amplitude with increasing charge weight per hole. The synthetics also replicate the scatter in the peak amplitude values for any given average charge weight.

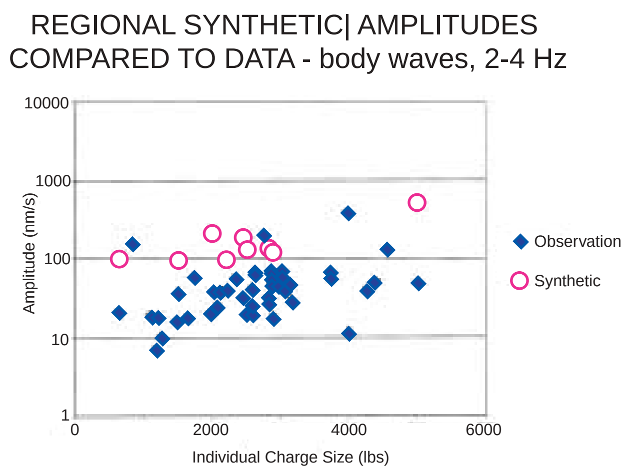


Figure 6: The mining explosion source model (Figure 4) was used to produce synthetics for a distance and crustal velocity model appropriate for EYMN. Synthetics were produced for a number of mining explosions of different average charge weight per borehole. Peak amplitudes of the synthetics are compared to the observations from the same explosions.

A second modeling exercise was completed for the large-scale cast blast associated with the coal mines in Wyoming. Peak P_g, P_n and L_g amplitudes from these blasts show little relation to total explosive yield as well (Figure 1). These large, one to eight million lbs, explosions use many boreholes and as a result have long time durations. They are designed to cast the overburden and so material is moved horizontally and then drops vertically into a pit. As demonstrated in Figure 7 (left), these events generate significant regional surface waves in the 2 to 12 s band. From the surface wave dispersion analysis, a regional velocity model was developed and combined with the above mining source model to produce the synthetic regional surface waves (Figure 7, right). This study suggests that a long duration source in combination with a large-scale casting operation can generate the mid-period surface waves observed with this coal mine.

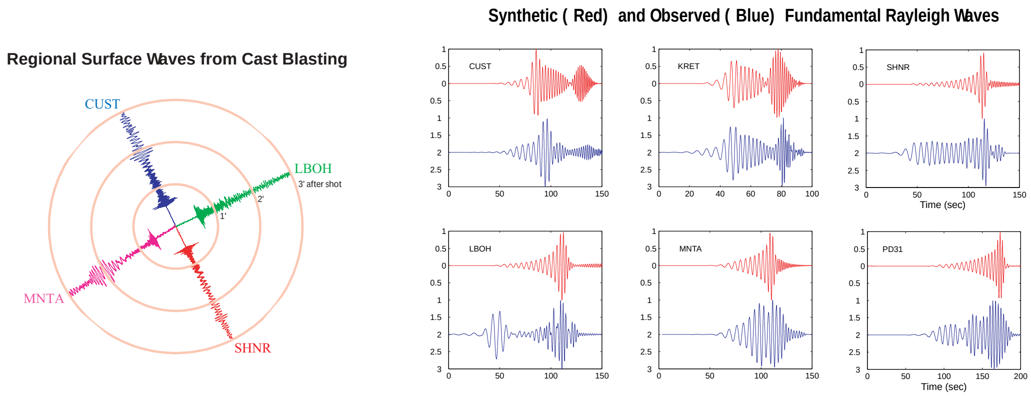


Figure 7: The mining explosion source model was also used to compute synthetics for the large-scale cast blasts. The focus in this modeling exercise is on the long period surface waves.

Infrasound Coupling

Infrasound signals have been reported to accompany mining explosions and may provide a source diagnostic (Sorrells et al, 1997; Hsu and Stump, 1997). Critical analysis of infrasound observations requires associated regional seismic observations and source information (such as blasting practices or designs). Coupling issues must be assessed, as well as models related to atmospheric propagation and source physics. Ground truth from the Morenci and Minntac mines provides source constraints. Preliminary results from Minntac (Figure 8 and Table 1) and Morenci (Figures 9 and 10) are illustrated below. Operations at both mines regularly generate seismic and infrasound signals.

Recorded infrasound data from Lac du Bonnet, Manitoba, were examined for Minntac-originated infrasound signals during August 2000 and November 2000. Four explosions were chosen for each time period. For detected signals, back azimuth estimates were within 5 degrees of the actual (Table 1). Signals included significant energy from 1/10 to several Hz (Figure 8). All explosions over 500,000 lbs generated detectable infrasound. The effects of seasonal winds on the infrasound propagation have not been taken into account.

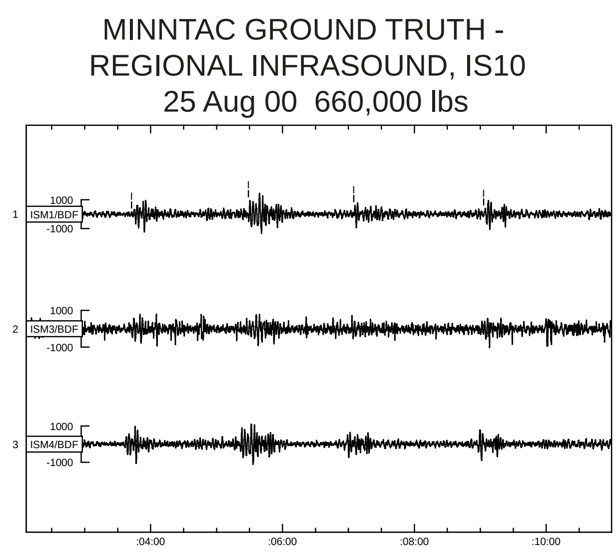


Figure 8: Example infrasound arrivals observed at IS-10, Lac du Bonnet, Manitoba, from a hard rock fragmentation blast at Minntac. Back azimuth estimates from these data were within 5 degrees of the ground truth location.

MINNTAC GROUND TRUTH -
REGIONAL INFRASOUND DETECTIONS AT IMS10

Date	Yield (lbs)	Detection
17 Aug 00	545,932	Yes
23 Aug 00	550,000	Yes
25 Aug 00	660,000	Yes
30 Aug 00	500,000	Yes
14 Nov 00	425,000	No
15 Nov 00	380,000	No
21 Nov 00	275,000	No
28 Nov 00	810,000	Yes

Table 1: Ground truth data from two one-week time periods were used to investigate the detection of infrasound signals at IS10. Five out of eight of the blasts were detected.

Regional infrasound signals from 7 of 25 ground truth events at Morenci in February 2000 were observed at the Los Alamos infrasound array (Figure 9). Every observed explosion was over 100,000 lbs although not every large explosion was observed (Figure 10). The dominant energy in the infrasound signal was in the 1- to 3-Hz band. Back azimuth estimates using f-k analysis were within 5 degrees of the ground truth.

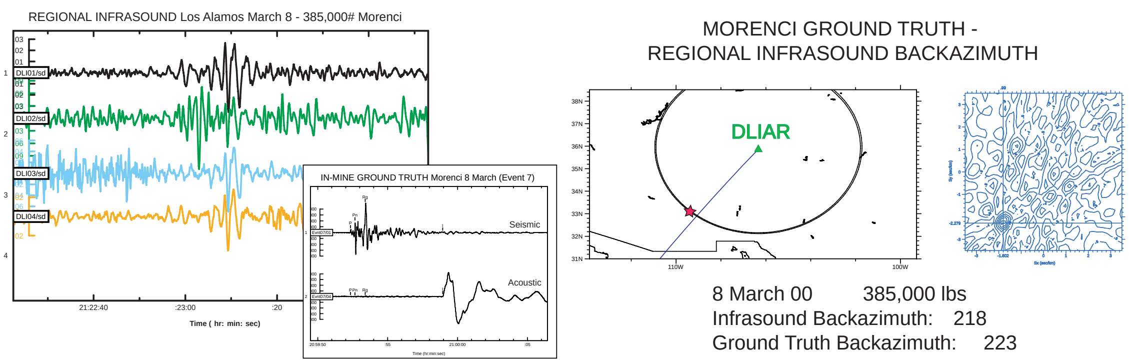


Figure 9: Mining explosions from the hard rock copper mines in southeastern Arizona generate infrasound signals as exemplified by the records from DLIAR in Los Alamos (left). Ground truth for this event was provided by close-in seismic and acoustic records of the blast (left, inset). Frequency-wavenumber estimates were used to make the backazimuth estimate shown to the right.

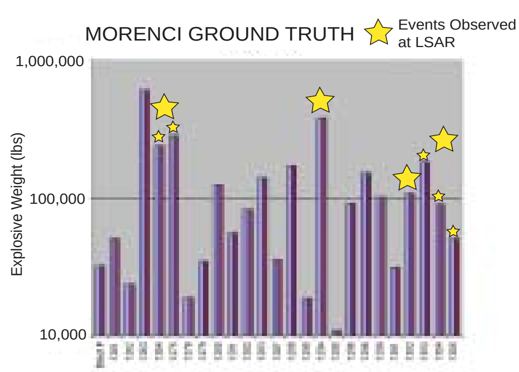


Figure 10: A number of the ground truth mining explosions from the copper fragmentation blasts in SE Arizona were observed at Los Alamos. Detected events were among the largest of the blasts.

Unusual Events

Close-in observations provide source constraints that can be used to interpret regional seismic and infrasound signals. An example of how in-mine monitoring can illuminate unusual blasting practices is provided by data recorded on a seismo-acoustic system that is deployed in the Morenci Mine. A three-component broadband seismometer and three acoustic gauges in a tripartite configuration have been installed in the center of the mine. The combined seismic and acoustic data set provides a quantification of daily blasting in the mine with little or no impact on the mining operation.

Analysis of this in-mine data set has illustrated that it is not uncommon for the blaster at this mine to detonate two or more explosive patterns within a few seconds. Such a blasting practice can produce complicated regional signals. In-mine seismic and acoustic records (top six waveforms) from two closely spaced patterns and the resulting complex regional seismograms observed at TXAR are reproduced in Figure 11.

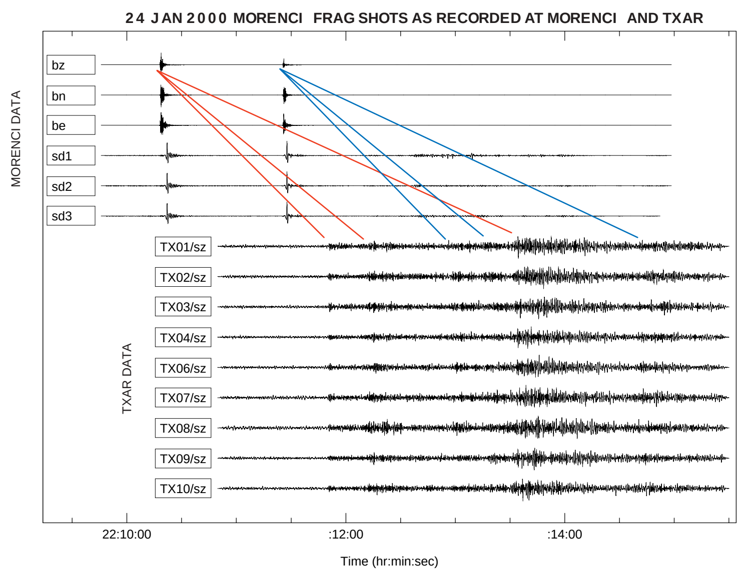
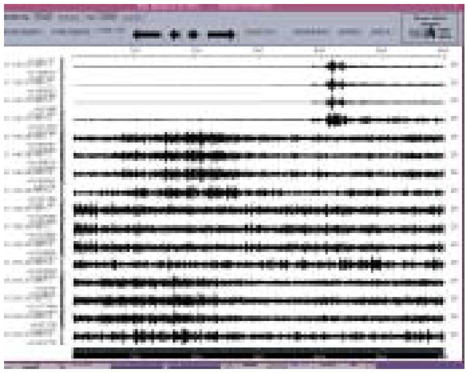


Figure 11: Seismic and acoustic instrumentation from within the cooper mine was used for ground truth. The upper six traces represent the three seismic and three acoustic gauges deployed in the mine. The bottom nine traces are the array elements of TXAR. The close-in seismic and acoustic signals document two mining explosions detonated over a short time period providing a complex regional seismogram.

Infrasound signals were recorded at the seismo-acoustic station outside of El Paso, Texas (Ft. Hancock) from the explosion and subsequent burning of a gas pipeline in New Mexico. Data from all three acoustic and one seismic sensor in the array are displayed in ten-minute segments (Figure 12). As documented by the data, the pipeline burned for over 40 minutes. Details of the infrasound signal are compared to near-source seismograms (Figure 13) illustrating that the complex nature of the explosion is reflected in the infrasound and seismic data. The gas pipeline explosion produced no regional seismic signals at the TXAR (Lajitas, TX) regional seismic array.

Natural Gas Explosion and Burn in New Mexico



T. Wallace

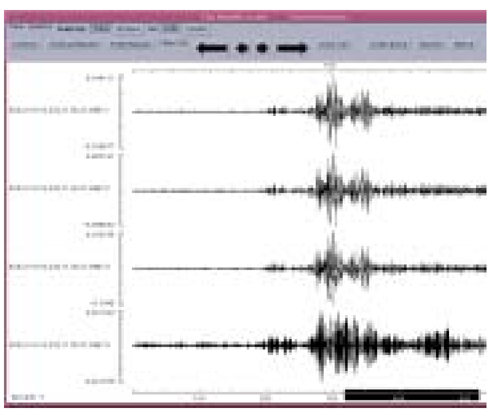
19 August 2000

180 km NE of site

No Seismic at TXAR

Figure 12: Infrasound (channels 1,2, 3) and seismic data (channel 4) from a seismo-acoustic station installed outside El Paso, Texas (Ft. Hancock). Each horizontal section represents 10 minutes of data. This seismo-acoustic signal that extends for over 30 minutes represents the explosion and burning of a natural gas line in New Mexico (photo: Terry Wallace, University of Arizona).

Natural Gas Explosion and Burn in New Mexico



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