

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

SOURCE PHENOMENOLOGY EXPERIMENTS IN ARIZONA

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ABSTRACT

During the summer of 2003, Weston Geophysical, Southern Methodist University, the University of Texas at El Paso, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory formed a consortium to quantify the differences between contained single-fired chemical explosions (a surrogate for nuclear tests) and delay-fired mining explosions. We designed, detonated, and recorded ten single-fired explosions at a copper mine in southeastern Arizona and nine single-fired explosions in the northeastern Arizona coal mining district. Delay-fired mining explosions at each mine were also recorded. The single-fired explosions ranged in size from 91 to 15,000 kg. The purpose of these experiments was to examine the source functions of single- and delay-fired explosions and to quantify near-source phenomenology and its role in the generation of shear waves observed at regional distances. A diverse set of instruments were deployed including high-g accelerometers within the nonlinear zone, high-frequency velocity instruments to document the transition from near source to regional, and broadband portable instruments to supplement permanent regional seismic stations. In addition, detailed refraction surveys were conducted in and around the source region to constrain local material properties. The refraction data document the effects of weathering in both the granitic (copper) and sedimentary (coal) rocks in and around the sources. Accelerometer data characterize the failure of the near-source materials in spall. High-frequency velocity instruments in the 1 to 100 km range capture the generation of strong shear arrivals, in addition to *P* waves, and their development into surface waves. The near-source and local data have extensive azimuthal coverage and have allowed the development of velocity and attenuation models for both test sites, as well as moment tensor inversions, which are being completed. The broadband instruments record the regional propagation of the *P*, *S* (*Lg*), and *Rg* phases and allow examination of *S/P* discriminants for single-fired and mining explosions. Differences between the single-fired and delay-fired explosions are noted and linked to the extended source duration of the production mining explosions.

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OBJECTIVES

During the summer of 2003, Weston Geophysical, Southern Methodist University, the University of Texas at El Paso, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory formed a consortium to quantify the differences between contained single-fired chemical explosions (a surrogate for nuclear tests) and delay-fired mining explosions. The objectives of our project 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) completing moment tensor inversions for source properties, 5) performing discrimination between nuclear explosions, mining explosions, and earthquakes, and 6) determining whether regional signals from routine delay-fired explosions can be used to gauge anticipated signals from small nuclear explosions. We conducted the SPE at a coal (soft-rock) and copper (hard-rock) mine in Eastern Arizona because it allowed us to examine different propagation paths and geologic setting.

RESEARCH ACCOMPLISHED

Experiment Location and Design

We designed, detonated, and recorded ten single-fired explosions at a copper mine in southeastern Arizona and nine single-fired explosions in a northern Arizona coal mine. The single-fired explosions ranged in size from 91 to 15,000 kg. Delay-fired mining explosions at each mine were also recorded. We deployed a large range of instruments including high-g accelerometers within the nonlinear zone, high-frequency velocity instruments to document the transition from near-source to regional, and broadband portable instruments to supplement permanent regional seismic stations. We carried out detailed refraction surveys in and around the source region to constrain local material properties. Accelerometer data characterize the failure of the near-source materials in spall. High-frequency velocity instruments in the 1 to 100 km range capture the generation of strong shear arrivals, in addition to *P* waves, and their development into surface waves. Short-period, near-source, vertical-component sensors ("Texans") provide complete azimuthal coverage of the shots. Figure 1 shows the mine locations and stations deployed to record the explosions.

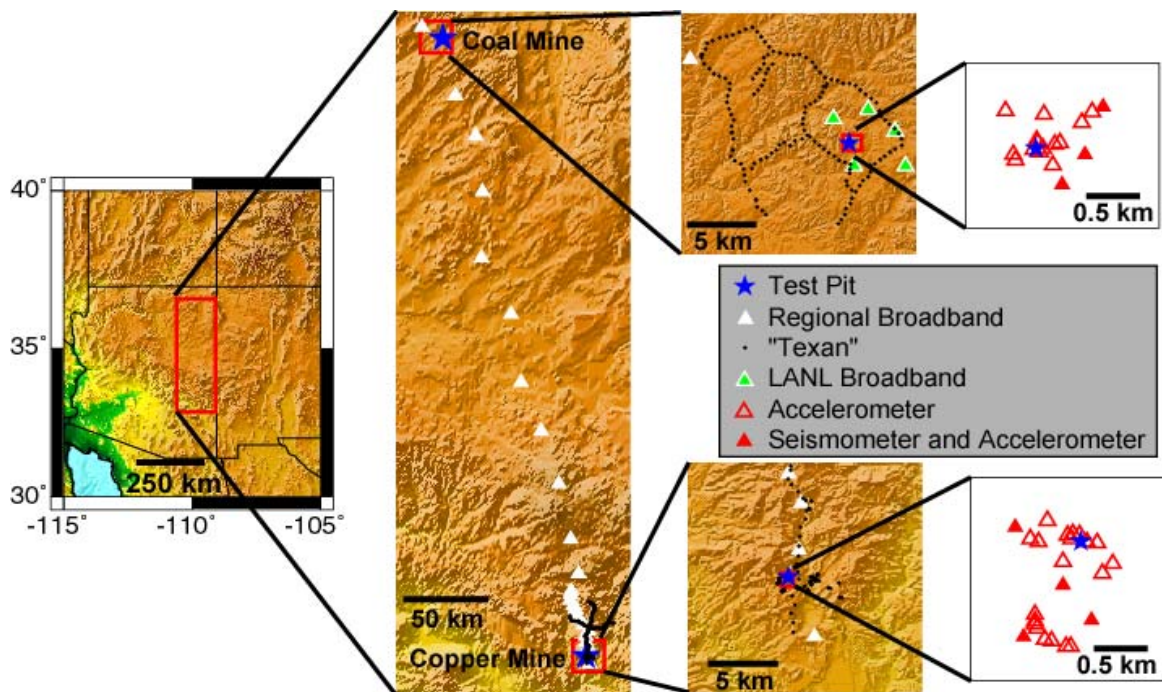


Figure 1. Location map for the SPE mines and stations deployed.

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Source Phenomenology Experiments at a Coal Mine in Northern Arizona

The explosions at the coal mine in northern Arizona consisted of two fully confined and seven unconfined single-fired chemical explosions recorded on many of the stations shown in Figure 1. Additionally, a database of 18 mining production shots was also recorded by the broadband stations in the mine and at regional distances. Two of the unconfined shots were detonated in a topographic bench next to a free face. An example of an unconfined ~ 7 -ton explosion detonated at a depth of 20 meters is shown in Figure 2. Our research on this important dataset has focused on the following areas:

1. Developing velocity and attenuation models of the Black Mesa basin and Colorado Plateau for moment tensor inversion,
2. Quantifying shear-wave generation from the single-fired explosions,
3. Examining the effects of confinement on explosion amplitudes and radiation patterns, and
4. Developing discriminants based on the observed differences between single-fired chemical and delay-fired mining explosions.

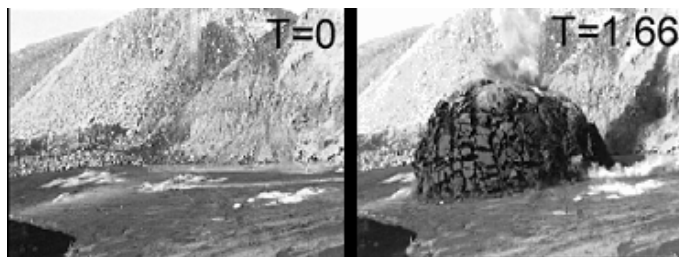


Figure 2. Images from northern Arizona SPE shot 4 taken just before detonation and 1.66 seconds after. This underburied shot lifted a dome of shattered rock more than 10 meters high.

Velocity and Attenuation Structure. We developed a detailed velocity and attenuation structure in order to complete moment tensor inversions and waveform modeling. For the northern Arizona coal mine, we used shallow refraction data to resolve the explosion test bed P -wave velocity and layer thicknesses. We also used 130 “Texans” at distances less than 15 km and the regional broadband stations to study the P -wave velocity structure of the upper crust (Figures 3a and 3b). Moment tensor studies also rely heavily on an adequate description of the shear-wave velocity structure, thus we considered ground roll (Figures 3c and 3d) and Rg inversion studies (Figures 3e and 3f) for S -wave velocity structure of the test pit region and upper crust. We also performed a joint inversion of surface wave dispersion and receiver functions using the software of Herrmann (2002) to constrain the structure in the middle and lower crust. Finally, a Q_β model for the upper crust was developed from observed Rg attenuation on the Texan and broadband datasets (Bonner *et al.*, 2004).

Shear-Wave Generation. One of the research objectives of this study was to quantify the possible sources of explosion-generated shear waves. Our preliminary studies aimed at accomplishing this goal have been in identifying S -waves on our datasets and examining the spectral ratios for the S -waves for the various blasts. The northern Arizona SPE shots generated significant shear-wave motion as evidenced in Figures 4a and 4b. On the vertical-component Texan recordings (Figure 4a), the P -wave and Rg arrivals are easily identified and are traveling at apparent velocities of 2.7 km/sec and 1 km/sec, respectively. There are additional arrivals that we delineate on the figure as possible S -wave arrivals. The apparent velocity for the phase is approximately 1.8 km/sec; however, we note that tracing the arrival times of this phase back to the origin results in ~ 1 second of offset in the origin time of this phase. Some may want to attribute this delay to near-source scattering while others may argue the delay is caused by secondary source effects (e.g., spall or CLVD). It may take a detailed analysis of the prominent Love waves (Figure 4b); including an examination of any Love-wave phase delay, to determine the source of the SPE shear-wave arrivals. It is interesting to note that the largest amplitude Love waves are not associated with the largest yield explosions, but instead are observed on the blasts in the topographic bench next to an unconfined free face.

Local Comparisons of Delay-Fired Mining Explosions vs. Single-Fired Chemical Explosions. There are numerous physical and chemical differences between nuclear and mining explosions. Perhaps the most obvious difference is that one involves a nuclear reaction and the other is a chemical reaction, which for our study involved Ammonium Nitrate Fuel Oil (ANFO) explosives. The 1993 NPE chemical kiloton explosion at NTS established that single-fired contained chemical explosions could be used directly as surrogate nuclear tests for the purposes of calibrating regional discriminants (e.g. Walter *et al.*, 1995), and that it would be very difficult to differentiate

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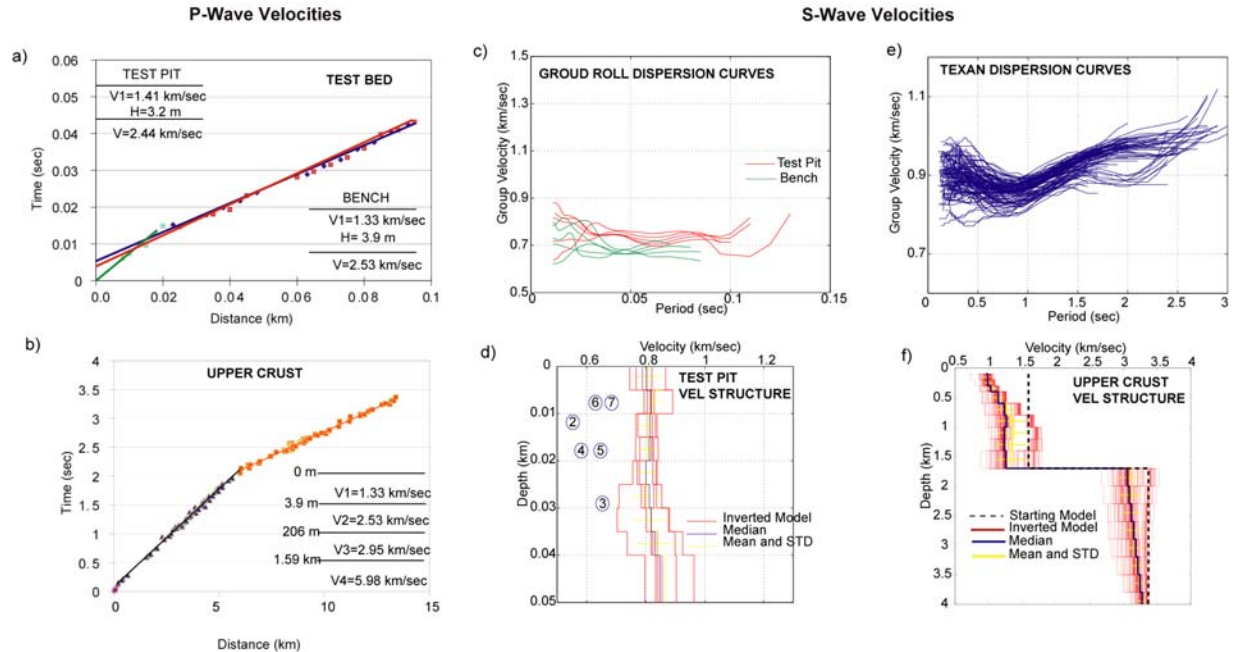


Figure 3. Data and models used to constrain the SPE test bed in northern Arizona. a). First arrival data from a 20-channel seismic refraction profile completed in the test bed and topographic bench. b). First arrival data for 130 “Texan” recordings used to develop a velocity model of the upper crust. c). Group velocity dispersion curves from ground roll observed on the 20-channel seismograph system. d). Inversion of ground roll dispersion curves for test bed shear-wave velocity structure. The explosion depth is indicated by the respective shot number on the plot. e) Short-period, fundamental-mode Rayleigh wave (R_g) group velocity dispersion curves for 130 Texan recordings. f). Inversion results for the R_g dispersion curves.

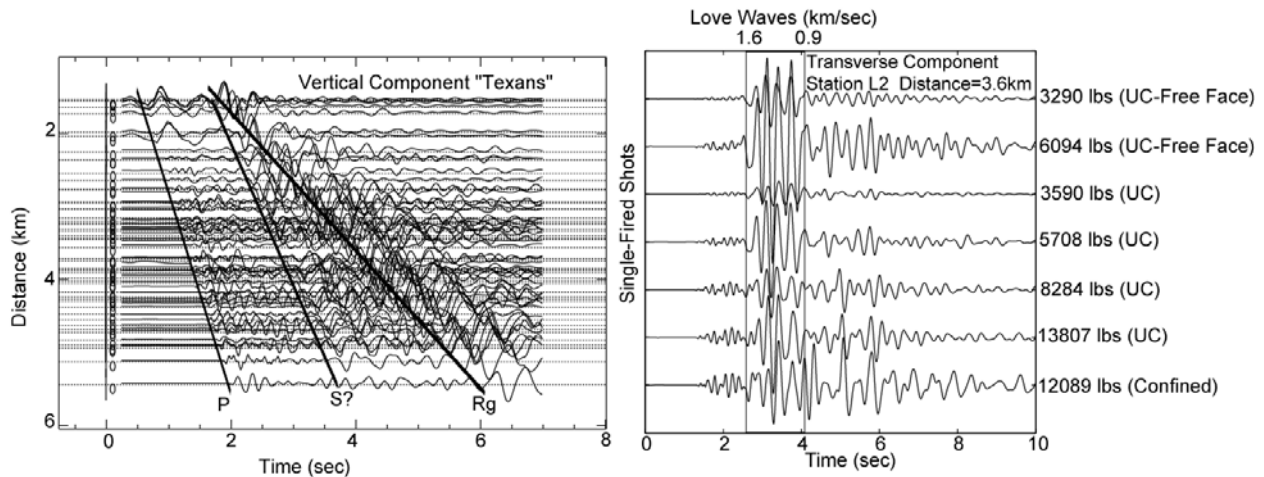


Figure 4. Shear-wave arrivals from the SPE shots in northern Arizona. a). Record section of “Texan” recordings showing P , R_g , and a possible S -wave arrival. b). Transverse component recordings of 7 SPE explosions at a single broadband station showing large amplitude Love-wave arrivals.

between the two types of explosions based on seismic data alone. Another important difference between nuclear and mining explosions is that mining explosions are rarely detonated simultaneously. For example, a typical mining explosion observed at regional distances may contain over 400,000 lbs. of ANFO; however, it may be detonated over a period of 2-4 seconds. The effect of this “delay-firing” technique is to fracture the rock as required for the

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mining operations while limiting ground vibrations in order to prevent damage to nearby structures. A final difference between the two explosions involves confinement. Underground nuclear explosions are often buried beneath several hundred meters of rock to ensure that the explosion is fully confined (e.g., minimal surficial effects from the explosion) and fully contained (no leakage of radioactive gases). Most mining explosions are detonated next to both vertical and horizontal free surfaces, resulting in significant surficial damage to the rocks, thus they are unconfined and uncontained.

The effects of delay-firing on local recordings of production shots are evidenced in Figure 5. The median velocity spectrum of five production shots (delay-fired yields ranging from 6.5 to 280 tons) recorded at local distances of 3.6 ± 0.6 km show increased 0.3 to 2 Hz energy in both the vertical and transverse components when compared to the median spectrum for the seven SPE shots (single-fired yields ranging from 1.5 to 7 tons) recorded at a distance of 4 km. We note that the peak magnitude of the ground motion for the SPE and production shots are very similar; however, at this distance the peak ground motion for the SPE shots is a *P*-wave, while it is *Rg* and Love-waves for the production shots.

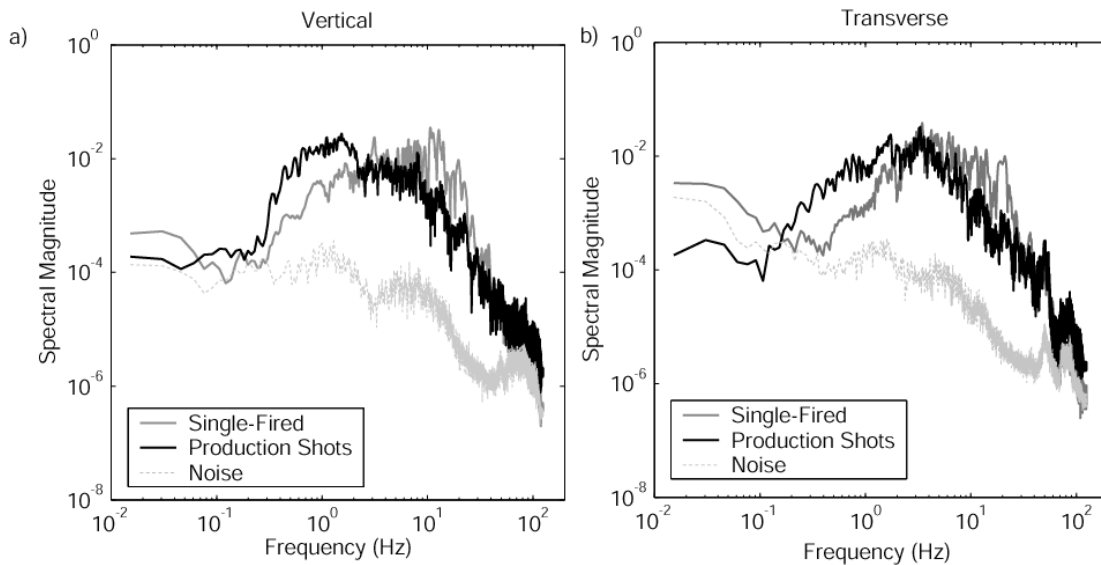


Figure 5. Spectral comparisons of delay-fired mining explosions and single-fired SPE shots. a). Median vertical component spectra for 5 production shots (black), 7 SPE shots (medium gray), and 7 pre-event noise estimates (light gray). b). Median transverse component spectra for same series of explosions and noise.

We have also examined the effects of confinement on the amplitudes recorded from the SPE experiment. As an example of this analysis, Figure 6 presents spectral ratios of Shot 3 to Shot 4 as recorded on the inner ring of the Texan network (see Figure 1). Shot 3 was a ~ 6-ton explosion detonated at 30 meters depth that was fully confined while Shot 4 was a ~ 7-ton explosion at 20 meters depth that was unconfined (see Figure 2). We used the Mueller and Murphy (1971) source to account for the differences in yield and depth of burial, and then simulated explosion synthetics in the velocity model described earlier. We formed the Shot 3/Shot 4 synthetic spectral ratio of the *P*-waves in five different frequency bands. The synthetic spectral ratios are plotted as solid black lines in the center of each plot in Figure 6. The observed spectral data in the same frequency bands are plotted as dots. The results show that at 1-2 Hz, 2-4 Hz, and 4-8 Hz, the observed *P*-wave ratios for Shot 3/Shot 4 are much larger than those predicted by the Mueller-Murphy sources. This is caused by lack of confinement (which videographic data confirms), improper shot detonation, or both. The degree to which the observed ratios differ from the theoretical ratios is dependent upon corner frequency effects, as by 8-15 Hz, the observed and theoretical ratios are similar. It is also interesting to note that the ratios are generally not circular (although the 8-15 Hz plot comes close), demonstrating that the unconfined Shot 4 and confined Shot 3 sources are different. Further analysis of the northern Arizona SPE data allowed us to calculate a set of “decoupling” factors, which quantify the amplitude decrease caused by lack of confinement. These decoupling factors vary widely over all frequency bands, and are frequency-

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dependent with the largest decoupling factors occurring in the lower frequency bands (0.5 to 4 Hz). The decoupling factors are 1.1 to 4.8 for *P*, 1.1 to 4.3 for *S*, and 1.2 to 10.1 for *Rg*.

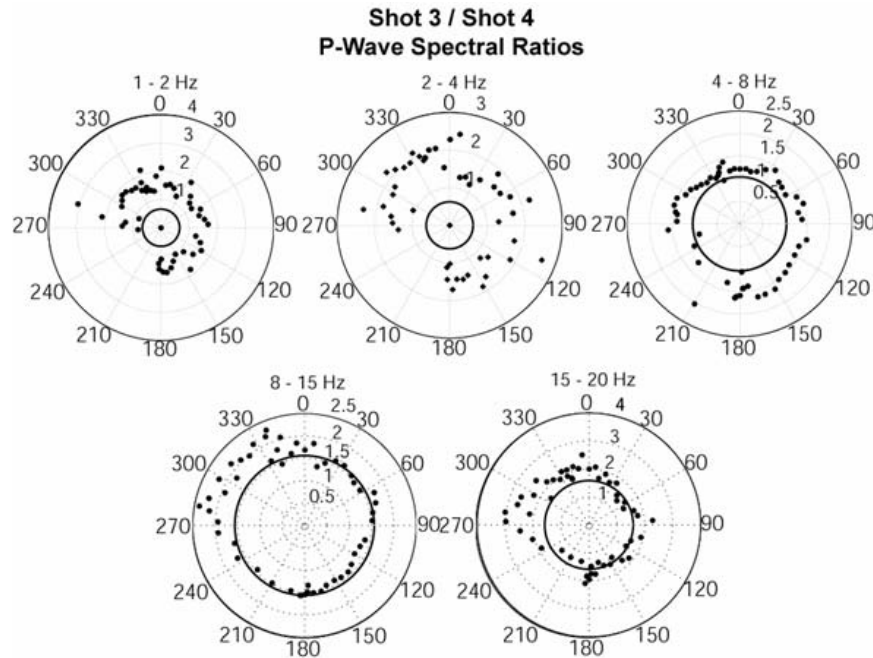


Figure 6. Shot 3 / Shot 4 plots showing theoretical (circles) and observed (dots) spectral ratios for *P*-waves in 5 frequency bands. Energy increases radially outward.

Single-Fired vs. Mining Explosion Spectral Amplitude Discriminant. We developed a regional station technique to discriminate between SPE single-fired chemical explosions and normal delay-fired mining explosions using spectral amplitude ratios of the *P* and *Lg* phases. The discriminant utilizes the equation:

$$D = \left[\frac{P(h) * Lg(h)}{P(l) * Lg(l)} \right]^2$$

where *P*(*h*) and *Lg*(*h*) are the average *P* and *Lg* amplitudes, respectively, between 4 and 8 Hz, and *P*(*l*) and *Lg*(*l*) are the average *P* and *Lg* amplitudes, respectively, between 0.5 and 1 Hz. Figures 7 and 8 plot the spectral amplitude of the *P* and *Lg* phases, respectively, of the SPE single-fired explosions and a closely located delay-fired mining explosion. The other delay-fired explosions have very similar spectra to the shown delay-fired explosion. The high frequency spectra have larger amplitudes than the low frequency spectra for the single-fired explosions, while the delay-fired explosions have the opposite relationship. The results of applying the above discriminant to explosions from the coal mine are shown in Figure 9. There is a clear separation between the two types of explosions. Initial results indicate the discriminant does not work for very large single-fired explosions such as nuclear explosions and the NPE due to the increased surface wave energy below 3 Hz.

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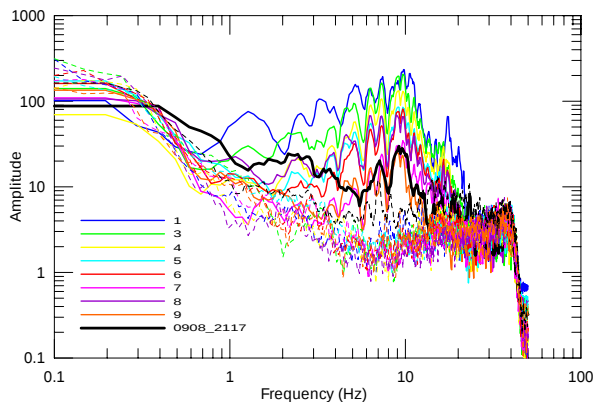


Figure 7. Vertical component *P* spectra of the single-fired shots and delay-fired production shot near the SPE test pit (heavy black line). Solid lines are the event spectra and dashed lines are pre-event noise spectra. Event and noise spectra have a 4-point smoothing applied.

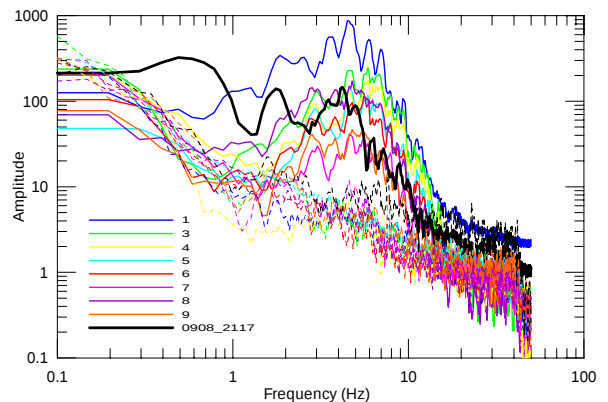


Figure 8. Transverse component *Lg* spectra of the single-fired shots and delay-fired production shot near the SPE test pit (heavy black line). Solid lines are the event spectra and dashed lines are pre-event noise spectra. Event and noise spectra have a 4-point smoothing applied.

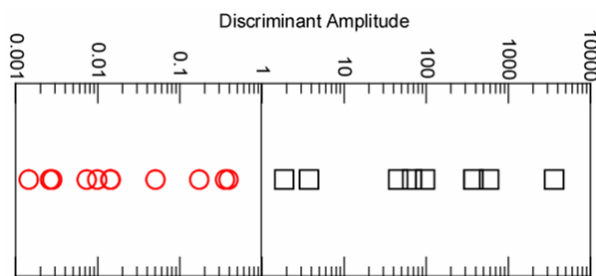


Figure 9. Single-fired (black boxes) vs. delay-fired (red circles) explosion discriminant results for the coal mine recorded at a regional station. A discriminant amplitude of 1 separates a single-fired from a delay-fired mining explosion.

Earthquake and Explosion (Chemical and Nuclear) Discrimination. Many seismic stations of monitoring interest have never recorded a regional distance nuclear test. Such tests were limited geographically mainly to the former test sites and temporally to the last century. Under the current global moratorium, the challenge to regional discriminant calibration is how to most effectively calibrate stations without nuclear test records. Many of these stations do record mining explosions and if clear physically based relationships between production mining explosions and nuclear tests were available, these events could be used to help calibrate regional discriminants.

We have started to examine the regional discrimination behavior of the SPE shots relative to normal production mining explosions, to natural earthquakes, and to previous nuclear tests at the Nevada Test Site. The analysis includes identifying and picking the onset arrivals of the regional phases *Pn*, *Pg*, and *Lg*, making amplitude measurements in a variety of passbands and then normalizing those measurements for the effects of source and path using the MDAC methodology (Walter and Taylor, 2002). LLNL has recently developed a sophisticated database oriented tool called RBAP (Regional Body-wave Amplitude Processor) that we use to complete the analysis. The tool allows interactive seismogram filtering, picking and phase window control needed for this analysis. We show in Figure 10 the results at KNB for six of the northern Arizona SPE shots (green diamonds) compared to a set of nuclear tests (red stars) and western U.S. earthquakes (blue circles). We find that the MDAC corrected SPE shots fall in the middle of the nuclear explosion population with very little variation due to the differing shot conditions. Thus for this particular discriminant at this station, the shots are good surrogates for nuclear explosions and the differences in depth of burial and single versus multiple shot have only a small effect on the discriminant measures. We are extending this analysis to other regional stations (e.g. ANMO, TUC, WUAZ) and other discriminants to more completely examine the discrimination relationship of these shots to production shots, earthquakes and nuclear tests.

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Source Phenomenology Experiments at a Copper Mine in Southeastern Arizona

The explosions at the copper mine in southeastern Arizona consisted of four fully confined and six unconfined, single-fired chemical explosions recorded on many of the stations shown in Figure 1. Seven mining production shots were recorded by the stations. Many of the production shots consisted of multiple explosive arrays detonated over an extended time interval. Three of the unconfined shots were detonated in a topographic bench next to a free face. Our research to date on this important dataset has focused on the following areas:

1. Empirical determination of velocity models in the mine and their spatial variation,
2. Examination of the effects of confinement and yield on explosion amplitudes at close-in, near-source, and regional distances, and
3. Quantification of shear-wave generation and propagation from the single-fired explosions using a mixed set of instrumentation.

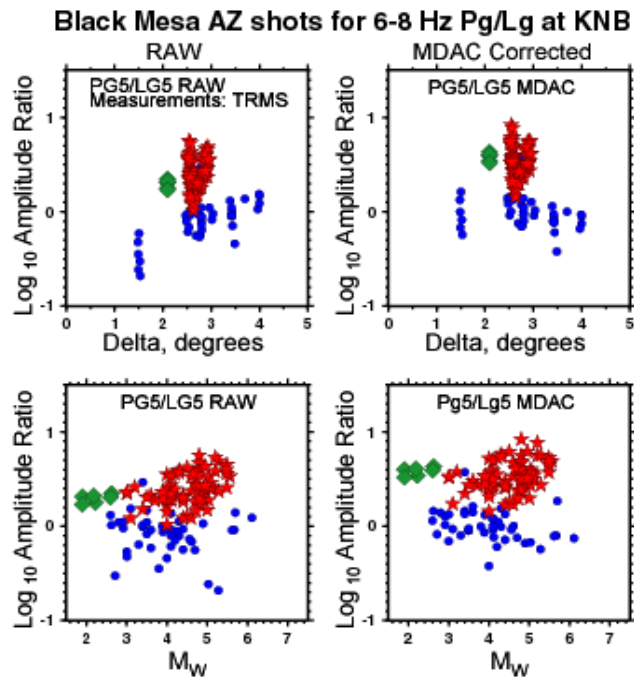


Figure 10. An example of six northern Arizona SPE shots (green diamonds) compared to Western U.S. earthquakes (blue circles) and NTS nuclear tests (red stars) at station KNB. Left-hand side shows the raw measurements as a function of distance (top) and magnitude (bottom). Right-hand side shows MDAC corrected measurements where magnitude and distance trends have been corrected, and earthquake data has near zero mean value. The MDAC values are based on the earthquake data only and then applied to the explosion data. Note that the SPE explosions fall right near the middle of the nuclear explosion values, indicating for this discriminant, they are reasonable surrogates for nuclear tests.

Development of a Velocity Model. A series of refraction surveys were conducted at the copper mine. The goals of the in-mine refraction study included: (1) Testing of procedures to gather shallow seismic survey data in a noisy mine environment; (2) Assessment of shallow (~ top 30 meters) velocity structure within the mine; (3) Determination of the variability of this structure both within an SPE test site and between different locations within the mine; (4) Determination of the relationship between the seismic structure and the test site geology. The test site where the SPE tests were conducted was one of those characterized.

Two orthogonal 300 foot lines of 40 Hz geophones were deployed at each site so that they crossed at the center. This geometry was employed to assess the three dimensional variation at each site. Sources were placed at each end of 30-geophone line. A Betsy seisgun was used as a set of sources at the surface for shallow structure, and a small explosive source at approximately 10-foot depth to resolve the deeper structure. Two benches of material have been removed between the time of the SPE and the refraction survey. The depth of the deepest blast conducted during the SPE was at 120 feet, close to the level of the refraction survey. The results from all the refraction surveys at North Coronado are summarized in Figure 11.

The north to south surveys produced a model with a very low velocity (1,900-2,200 ft/s) shallow layer (13-18 ft), an intermediate layer (~60 feet) with degraded velocity (8,000-10,000 ft/s) and finally the competent granite velocity (~15,000 ft/s). The length of the line and the size of the Betsy source made the imaging of the deepest layer difficult and so the estimate of its depth and velocity is the most uncertain. The structure along the west to east line is more complex,

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possibly reflecting the effect of a high-wall to the east. As indicated in Figure 11, the west end of the line produced a structure similar to the north-south line. As one moves towards the east the travel time indicates a significant decrease in the second layer velocity at the 180 foot offset. As indicated in the summary results in Figure 11, the Betsy source at the center of the east to west lines produced quite different models to the west and east of the center point with the model to east producing the much slower intermediate layer velocity, possibly showing the effects of the free face.

Refraction surveys from four sites across the copper mine, including the SPE location, have been analyzed. The models at all the sites produce evidence for a very thin, low velocity zone, possibly reflecting damage from explosions conducted in the bench above the surface. A second layer of greater thickness was also imaged with reduced velocities from competent granite. The fastest material, with velocities between 15,000 to 17,500 ft/s, was found at depths from 60 to 80 feet. All refraction surveys that were conducted away from the bench free face produced nearly plane layer models. Dips of 0.5 to 1.5° were observed. The refraction survey at North Coronado approached the free face along the bench. This refraction survey produced evidence of lateral velocity changes with the velocity slowing as the line approached the free face.

These velocity models will be the starting place for the development of propagation path models for the source inversion. They illustrate the range of materials and strengths in which the single-fired shots were detonated. These effects will have to be taken into account in assessing coupling and source characterization as a function of source depth and proximity to the free face. The next step is the utilization of the high-frequency surface waves for constraining the complementary shear structure.

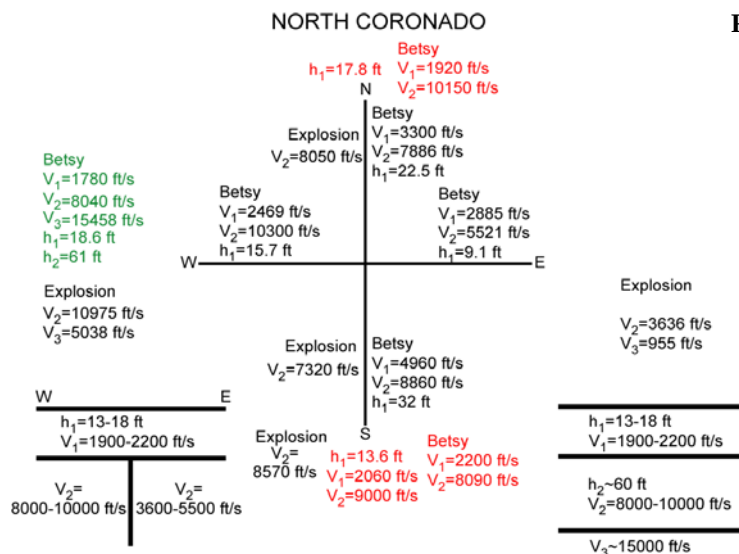


Figure 11. Summary of the refraction survey at North Coronado. The data suggests that there is some asymmetry in the structure. It also suggests that there is a lateral change in structure as one moves from west to east and approaches the free face where the velocity decreases in the intermediate layer as indicated in the model to the left. The model to the right is more representative of the structure away from the free face.

Effect of Yield and Confinement. The effect of yield and coupling on the close-in accelerations (S1 ~0.5 km, Figure 12), near-source Texan seismograms (M1A8 ~ 1.5 km, Figure 13), and regional broadband seismograms (MR12 ~ 40 km, Figure 14) are documented. The left panel in each figure compares the effect of yield using the shots at twice normal depth of burial, including shots B4 (6800 lbs.), B6 (1700 lbs) and B10 (13600 lbs). There is a strong amplitude variation from the three shots, which is also reflected in the spectra. Close-in, near-source, and regional observations document similar scaling. Spectral comparisons illustrate the differences in the close-in accelerometers, Texan geophones (4.5 Hz corner), and broadband regional instruments. The close-in data for all three shots peak at 10 Hz or above, indicative of the source corner frequency. This source corner is obscured by propagation path effects at greater distances and motivates the determination of the path effects, in particular, attenuation effects in order to interpret the waveforms.

The right panel in each figure compares the effect of confinement on the seismic waveforms. All the shots contained 6800 lbs. of explosives. The data displayed include Shot B2 (shot at the free face), B4 (twice normal burial depth) and B5 (twice burden but normal burial depth). The detonation of B2 resulted in a significant amount of material at the free face being moved into the mine pit. B4 created a large crater. There was little permanent displacement at the surface following the detonation of B5. These significant free surface differences are not reflected in the seismic observations. As the three figures document, the waveforms are very similar for the three shots. The shot with the greatest depth does have the highest amplitudes with about a factor of two variations in peak amplitudes.

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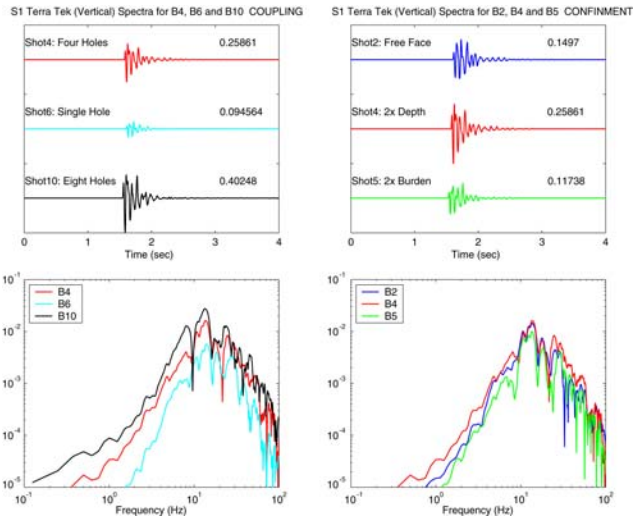


Figure 12. Close-in accelerograms from B4, B6, and B10 (left) and B2, B4, and B5 (right). Effect of yield is illustrated to the left and effect of confinement on the right.

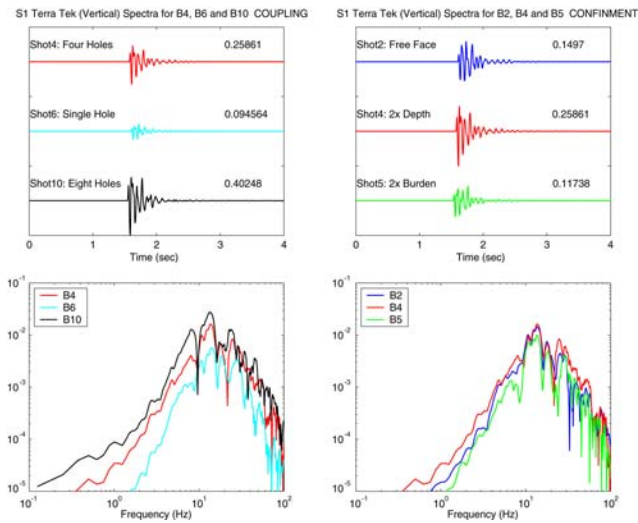
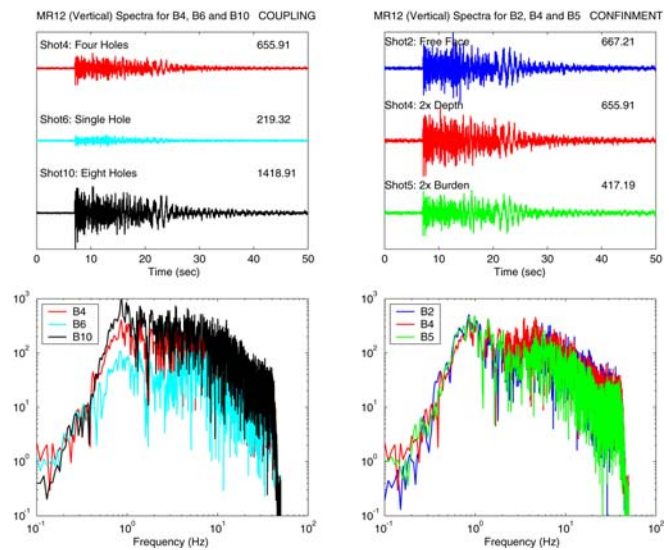


Figure 13. Near source Texan data from B4, B6, and B10 (left) and B2, B4, and B5 (right). Effect of yield is illustrated to the left and effect of confinement on the right.

Figure 14. Regional broadband data from B4, B6, and B10 (left) and B2, B4, and B5 (right). Effect of yield is illustrated to the left and effect of confinement on the right.



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Shear Generation and Propagation. One of the goals of these experiments was the quantification of generation and propagation of shear energy from the single-fired and delay-fired explosions. The shear energy includes both the direct shear arrivals and surface waves, R_g , at near-regional distances. In order to quantify these effects, a combination of Texans and broadband seismometers were deployed around the mine and along a profile to the north of the mine (Figure 1). The first step in the study was to assess the two types of instruments. Along the profiles to the north, there were co-located Texans (4.5 Hz nominal corner) and broadband Guralp seismometers (40T). The vertical component of broadband seismometers (Guralp 40T) was compared with collocated “Texans” to quantify the signal bandwidth. The broadband sensor has a 30 seconds natural period, 800V/m/s sensitivity and the short period Texans’ sensor has a 4.5 Hz low cut corner and 91V/m/s sensitivity. The instrument responses of these sensors were removed from the raw data. A Hanning window was applied for the noise and signal data segments followed by spectral estimation (Figure 15). It is found that the noise level of the broadband seismometer is greater at high frequency (> 7 Hz) than that of the short period sensor in some cases. Therefore, the data quality of short period sensors is better at high frequency.

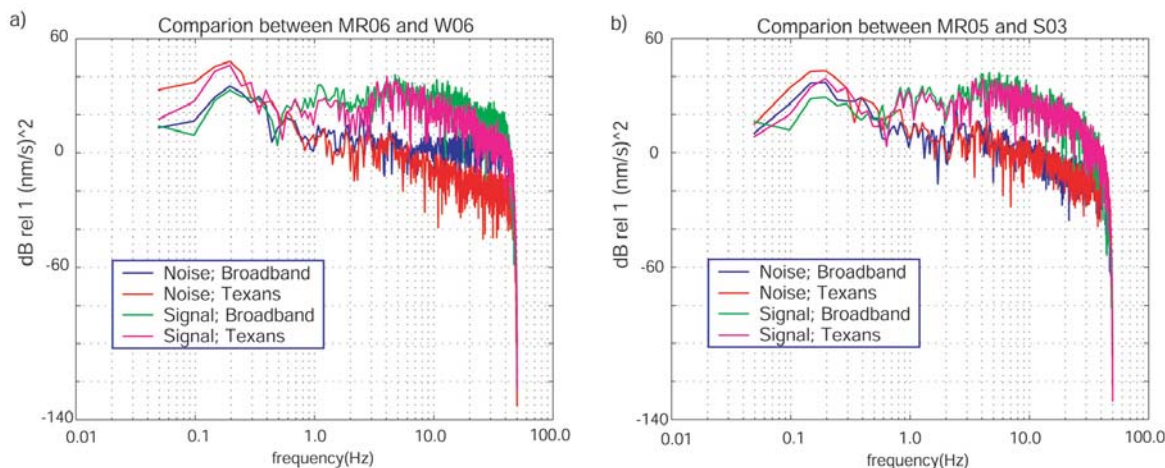


Figure 15. Spectral comparison between broadband CMG-40T and Texans after instrument correction. a). The noise level of the broadband (MR06) is higher than that of the collocated Texan (W06) at high frequency. b). The spectrum of the broadband (MR05) is identical with Texan (S03).

Based on this assessment, all the observational data along the line to the north of the mine was instrument corrected and a record section formed to assess shear wave generation and propagation path effects (Figure 16). Strong P , S and R_g phases are traceable back to the source. The R_g energy is strongest at the lowest frequencies (0.5 to 3 Hz). The P wave amplitudes are much larger than the shear amplitudes at high frequency, although, there is significant shear energy that is traceable back to the source. This data was used to estimate average P , S , and R_g velocities of 5.4 km/s, 3.0 km/s and 1.9 km/s respectively. Careful inspection of Figure 16 reveals that there is a break in the travel-time curve for P around 20 km, possibly indicative of upper crust structure.

These results illustrate the value of the Texans in both source and propagation studies from modest-sized explosions. The high-frequency content from the single-fired sources (> 0.5 Hz) and the increased high-frequency noise on some CMG-40T's makes the instrument-corrected Texan data very useful. Analysis of the delay-fired explosions may indicate the importance of the CMG-40T's since the longer duration source is expected to boost energy at the lower frequencies. The next step in this analysis is to explore the azimuthal radiation from these sources as was done at the northern Arizona coal mine. We also plan to explore the signals from the delay-fired shots using a similar analysis.

CONCLUSIONS AND RECOMMENDATIONS

The Arizona SPE experiments have resulted in an important dataset for the nuclear monitoring community. The 19 dedicated single-fired explosions together with multiple delay-fired mining explosions were recorded by one of the most densely instrumented accelerometer and seismometer arrays ever fielded, and the data have already proven useful in quantifying confinement and excitation effects for the sources. The results so far suggest that the single-fired explosions are surrogates for nuclear explosions in higher frequency bands (e.g., 6-8 Hz P_g/L_g discriminants). The datasets have also allowed us to develop a new discriminant to help separate small single-fired chemical and

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delay-fired mining explosions based on the decreased 0.5 to 1.5 Hz energy in the small explosions. And finally, we have shown that the SPE shots, together with the mining explosions, are efficient sources of S-wave energy, and our next research stage is to postulate the possible sources contributing to the shear-wave energy. This will be completed through moment tensor inversions that make use of the detailed velocity structure obtained for the two SPE test sites.

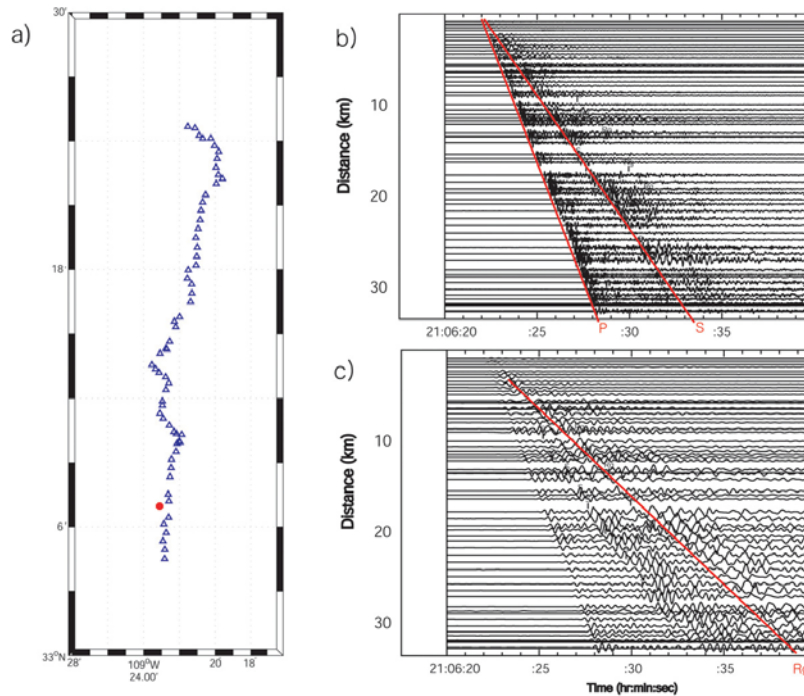


Figure 16. Texan record section from the fully confined single shot B10 (13,600 lb). The source (red dot) and station locations (blue triangles) are to the left. The record section in the upper right is filtered 0.7 to 20 Hz while that in lower right is filtered 0.5 to 3 Hz.

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