AN ANALYSIS OF LOW FREQUENCY SEISMIC SIGNALS FROM LARGE MINING BLASTS

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ABSTRACT

The worldwide standard mine blasting practice involves a cascade of shots which are used to effectively fracture the rock. It is well established that this delay-fire shooting practice causes interference of the individual wavefields that will introduce artifacts (such as spectral modulations) into the regional seismic wavefield that can be diagnostic indicators of blasting and therefore useful for discriminating these events from earthquakes and nuclear tests. Source intershot delay times are typically on the order of 35 msec and therefore the most obvious interference effects are seen at 30 Hz or above. As the standard IMS station samples at 40 Hz, and because of rapid attenuation of high frequencies during propagation, these artifacts will not commonly be seen under typical CTBT monitoring conditions. This paper explores low-frequency (0.1 to 10 Hz) signals produced by the most important - the largest - mining blasts.

Kiloton class mine blasts are not uncommon in numerous regions worldwide such as Wyoming, Kentucky and, at least historically, the Kuzbass mining region in Russia. Our focus has been on large cast blasts in the Powder River Basin in Wyoming and in the Kuzbass. A recent regional experiment in Wyoming has produced evidence that large cast blasts commonly produce spectral modulations at frequencies from 1 to 10 Hz. Source modeling of these extremely complex events does not reproduce the exact spectral character but indicates the modulations are due to long inter-row delays and source finiteness. Recordings of instantaneous calibration shots exhibit no such modulations and indicate this spectral character should be useful for distinguishing these events from nuclear tests at IMS stations.

The experiment also provided further evidence that these events produce unusually large surface waves between 2 and 10 s. Physical modeling of these events indicates that the surface waves are due mainly to the extended source duration and to a lesser extent to the slap-down of spalled material. Recordings made at 9.1° exhibit both the spectral modulations and surface waves and attest to the utility of these signals for characterizing these events using the IMS.

Recordings of large blasts in the Kuzbass mining region exhibit significant spectral modulations below 20 Hz however surface waves are not routinely produced by these events.

Key words: Spectral modulations, attenuation, surface waves, remote source characterization

OBJECTIVE

To develop high- and low-frequency seismic techniques to characterize mining explosions and discriminate these events from single explosions and earthquakes. The focus is on mining explosions that detonate as planned and on mining explosions which contain significant detonation anomalies. Our focus has been on spectral modulations and surface waves that will commonly propagate beyond near-regional distances to stations in the IMS monitoring network. We use physical modeling to identify the source processes that give rise to these signals.

This paper summarizes our research on low-frequency signals produced by significant (> 1 kT) mining explosions in Wyoming. We also report preliminary results from our analysis of Altai-Sayan mine blasts and earthquakes recorded since January 1, 1995 by the IMS seismic station ZAL near Zalesovo, Russia.

RESEARCH ACCOMPLISHED

Wyoming Kiloton-class Blasts

We have focused on blasts in Wyoming for several reasons. The largest blasts in the Powder River Basin (PRB) coal mining trend in NE Wyoming (Figure 1) delay fire several million pounds of ANFO to fracture and to displace near-surface rock to expose the coal seam. IMS seismic stations occasionally detect these cast blast events. Blasts in this area are carefully documented and have been the subject of several studies (incl. Stump and Pearson, 1997; Stump et al.,

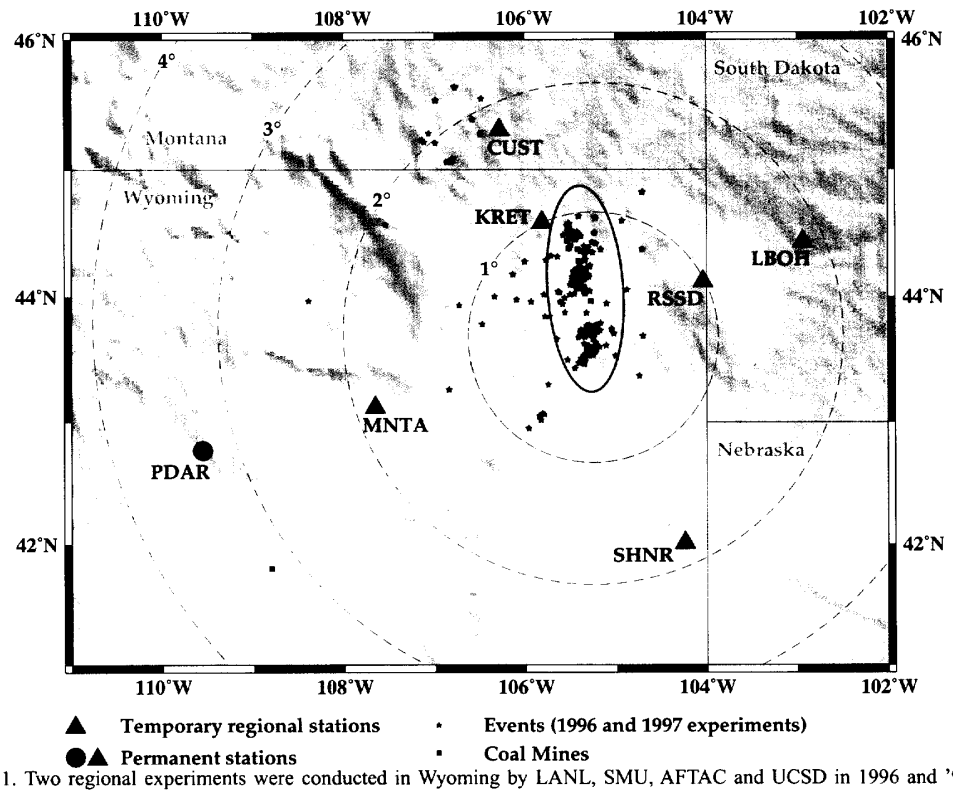

Figure 1. Two regional experiments were conducted in Wyoming by LANL, SMU, AFTAC and UCSD in 1996 and '97. Four broadband seismic stations (3-component STS2's) were deployed in a ring surrounding the Powder River Basin (PRB) at a range of 200 km from the Black Thunder coal mine. A fifth station (KRET) was deployed at a range of 100 km. Permanent seismic stations are located at PDAR and RSSD. Infrasound sensors were deployed at MNTA. Mining explosions detected by the temporary seismic stations during 49 days in 1996 and 1997 are plotted and correlate well with known mines. The slight northward bias is likely due to the 1D model. The oval indicates approximate limits of the PRB.

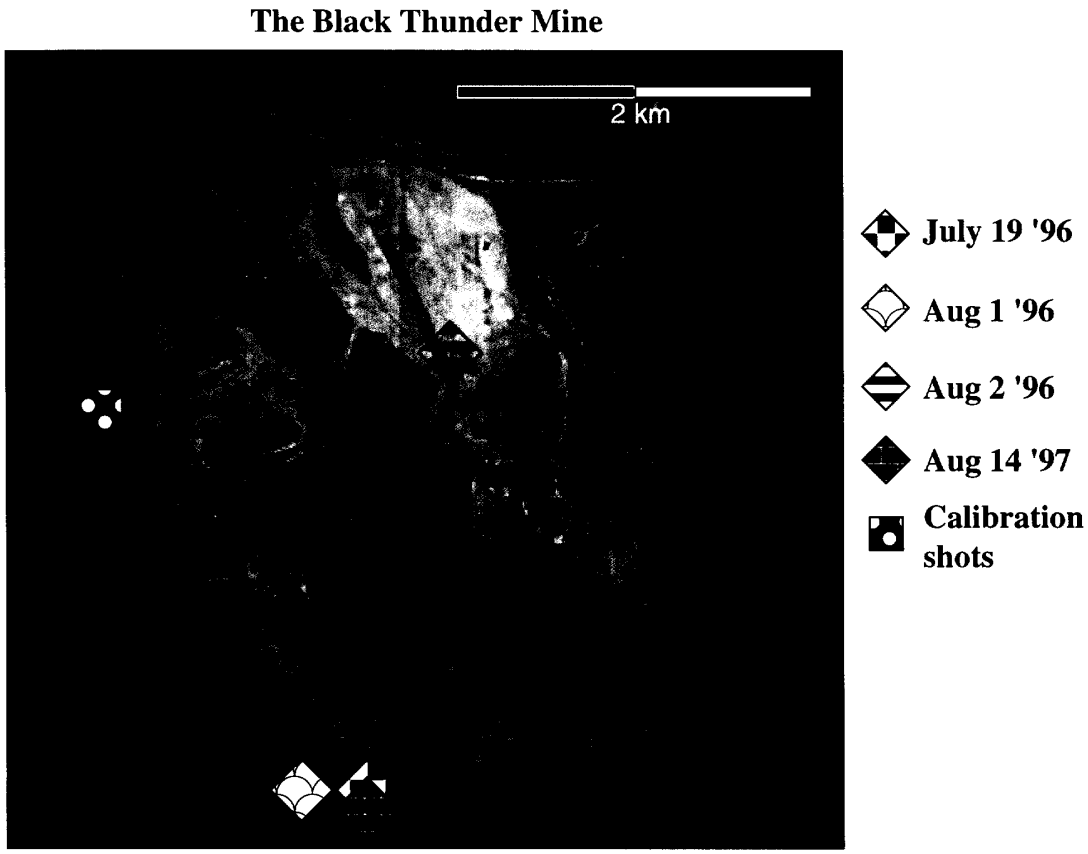

Figure 2. A satellite photo of the Black Thunder Coal mine in Wyoming. The symbols give approximate locations of the major events considered in this paper. The 1996 and 1997 experiments produced recordings of 4 significant cast blasts in the Black Thunder coal mine. The July 19, Aug 1.96 and Aug 14.97 blasts occurred at the west end of the south pit. The west end of the Aug 1 blast is believed to have detonated simultaneously. In the July 19, Aug 1, Aug 2 (all 1996) and Aug 14 (1997) cast blasts 4.5, 2.5, 2.8 and 7.0 million pounds of ANFO were detonated. The two largest calibration tests involved 12,000 and 16,000 pounds of ANFO.

1998). Shot specifications are readily available and thus these events can be modeled and used to better understand how large mine blasts can be distinguished from all other seismic events.

Field Experiments

The results in the present study came from recordings made by temporary seismic stations deployed in 1996 and 1997 at near-regional distances from the PRB (Figure 1). The field experiment was a collaborative effort with B. Stump (SMU/LANL), C. Pearson (LANL) and V. Hsu (AFTAC). The experiment was funded by LANL under the contracts 1973USML6-8F and F5310-0017-8F. The analysis was a collaborative effort involving these scientists and X. Yang (LANL). The results are reported in detail in Hedlin et al., (1999). The events of greatest interest to us occurred in the Black Thunder mine and are depicted in Figure 2. The largest cast mine blast occurred in the south pit and involved 7 million pounds of ANFO. The 1997 experiment produced records of this event and several instantaneous calibration shots that ranged in yield from 5000 to 16000 pounds.

The regional experiments were conducted to examine the dependence of low frequency (10s to 10 Hz) signals from the large mine blasts on range and azimuth. Previous studies (incl. Stump and Pearson, 1997, Anandakrishnan et al., 1997) found significant surface waves produced by the cast blasts in recordings made by the Pinedale seismic array

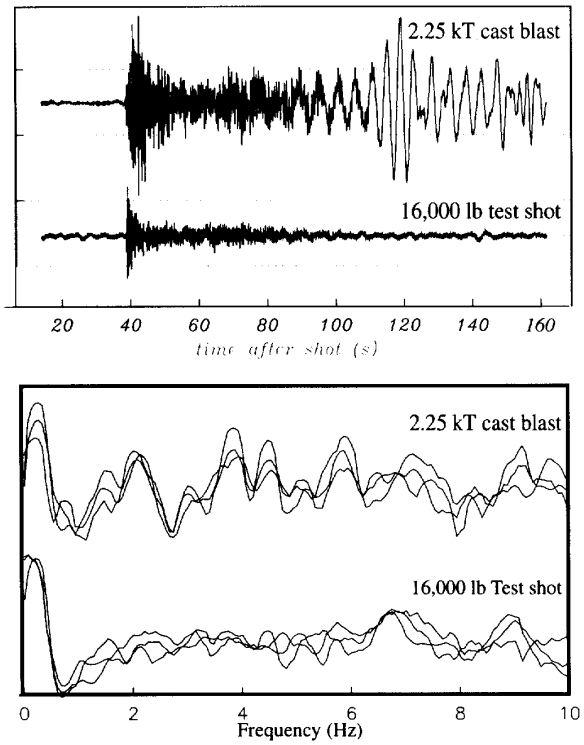

Figure 3. In the upper panel we show unfiltered vertical component recordings of the July 19, 1996 Black Thunder cast blast (top trace) and a 16,000 calibration shot made at CUST (Figure 1). In the lower panel we show spectra taken from the 3 components recorded at CUST. The cast blast is the only event that produced a significant surfae wave and clear spectral modulations below 10 Hz.

(PDAR; Figure 1).Stump (personal communication) found evidence for weak spectral modulations at high frequency at local distances from these events. The absence of strong modulations that normally are produced by millisecond delay-fired events such as these is likely due to source effects (e.g. shot scatter) and propagation losses.

As reported in earlier papers (Hedlin, 1998a,b; Hedlin et al., 1999) the regional recordings indicate that these events produce very energetic surface waves and significant spectral modulations below 10 Hz (Figure 3). These signals were recorded by all stations in the regional network and were seen as far away as the IMS station ULM at a range of 9.1°.

The utility of the surface waves for characterization of the mine blasts is suggested by Figure 4. In this figure we display peak amplitudes in two frequency bands , 1 to 10 Hz and from 2 to 10 s, of signals produced by the cast blasts and instantaneous explosions and recorded by the stations in the outer ring of the regional network. We plot single station amplitudes and unweighted network average amplitudes. The body waves produced by the calibration shots and the cast blasts are not markedly different with the exception of the August 1, 1996 cast event which has elevated body wave amplitudes due to the unplanned near-simultaneous detonation of a portion of the shot grid. The time-domain feature that clearly separates the two event types is the surface wave amplitudes. The calibration shots produced no mid-period surface waves above noise whereas significant surface waves were produced by each of the cast blasts.

Physical Modeling

To give these basic observations a physical basis we turn to synthetics. The synthesis of extraordinarily complex mining explosions has become relatively easy given the early work of Barker et al. (1990, 93) and McLaughlin et al. (1994) and recent work by X. Yang who has modified the linear elastic algorithm of Anandakrishnan et al. (1997) and packaged it into an interactive MATLAB package (MineSeis; Yang, 1998). The algorithm assumes the linear superposition of signals from identical single-shot sources composed of isotropic and spall components. Both shooting delays and location differences among individual shots are taken into account in calculating delays of the superposition, although the Green s functions are assumed to change slowly so that a common Green s function is used for all the single shots. We used a reflectivity method to calculate the Green s functions. A 1-dimensional velocity model was used (Prodehl, 1979; Anandakrishnan et al., 1997).

To model the July 19 cast blast we used a blast report issued by the Black Thunder Mine. The blast consisted of 7 rows and a total of 620 decked shots with a total yield of 4.5 million pounds. In a decked shot, more than one charge is detonated in the same hole. In this event, each hole contained two charges separated by 50 to 200 msec. Although the number of shots in each row varied from 85 to 93, for simplicity we assumed each row had 89 shots and that each decked shot had a total yield of 0.0033 kt. We assumed that all rows were spaced by 9.1 m and that all adjacent shots in the same row were 10.4 m apart. Intershot delays were 35 msec, interrow delays ranged from 200 to 275 msec. We assumed each decked shot spalled 20 kt of material that was cast at an angle 10° above the horizontal and fell 20 m. Sobel (1978) estimated that 9.6 x 10^9 kg of material is spalled by each kt detonated. In our experiment, each decked

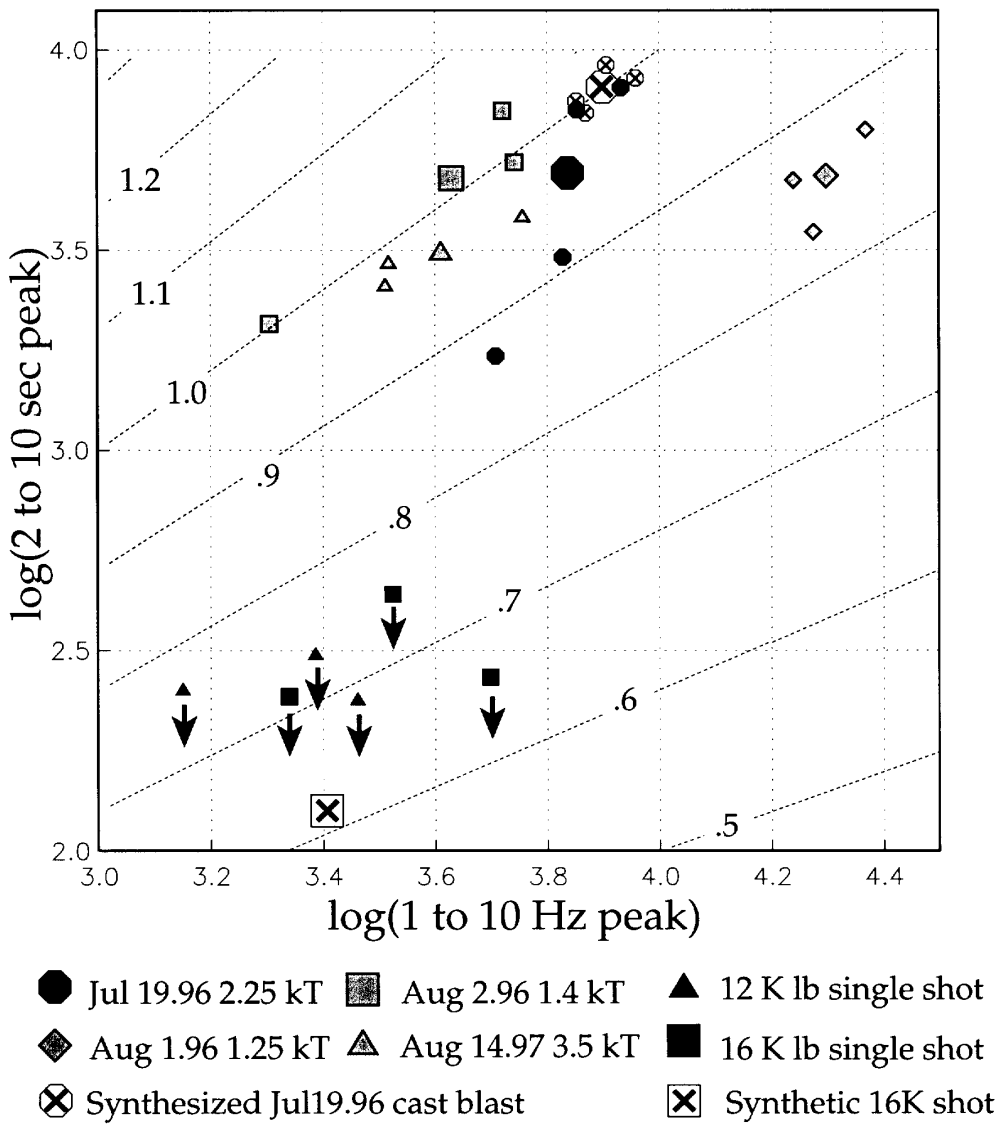

Figure 4. A comparison of 2 to 10 second surface wave and 1 to 10 Hz P wave peak amplitudes using recordings made at a range of 200 km by MNTA, CUST, LBOH & SHNR (Figure 1). All events occurred in the Black Thunder coal mine. Each trace is filtered, converted to an envelope and adjusted downward by an amount determined by pre-onset noise. Above are displayed the logarithms of the individual station peak amplitudes. The large symbols represent the network average for each event. Each labeled curve indicates a constant ratio of surface wave to *P* wave amplitude [*i.e.* log(2to10s peak)/log(1to10Hz peak)]. As expected the calibration shots yield essentially no surface wave energy above noise. The downward arrows indicate that the maximum *P* wave amplitude is well constrained but the surface wave amplitude lies below noise. For this reason, no network averages are displayed for these events. The Aug 1.96 cast shot appears as being somewhat explosion-like due to the sympathetic detonation. The sympathetic detonation greatly boosted P wave amplitudes but left the surface waves untouched. Unadjusted amplitudes are plotted as all stations are at the same range from the mine. We also display peak amplitudes from a synthetic version of the July 19 cast blast and from a synthetic 16,000 pound calibration shot. The energy partitioning from the synthetic events is in agreement with observations.

shot had a total yield of 0.0033 kt and thus the Sobel relation gives ~31 kt of spalled material. For the July 19 Black Thunder event we found this figure yielded surface waves that were more energetic than those that were recorded and so we reduced the spall figure to 20 kt. This discrepancy can be due to the incomplete conversion of spalled kinetic energy into seismic or to inadequacy of the velocity model.

The peak amplitudes of the point source and the July 19, 1996 cast blast synthetics at a range of 200 km have been calculated for the 4 outer stations in the regional network and are displayed in Figure 4 with the observed amplitudes from the recorded events. Despite the assumptions listed above, we found the surface and body wave amplitudes produced by the synthetic event were consistent with the recorded waves at MNTA and CUST. The other two stations (LBOH and SHNR) yielded broadly dispersed surface waves that had lower peak amplitudes in the frequency band from 2 to 10 seconds. This pronounced mismatch is not due to unmodeled source effects but results from the propagation of the energy through a crust that differs significantly from the 1-dimensional Prodehl model. The azimuthal dependence that is seen in the synthetics is due to source directivity.

Experiments in Varying Source Parameters

Although we have reproduced the relative peak amplitudes of body and surface waves generated by the July 19 cast blast, several important questions remain unanswered. We have yet to determine which of the many source parameters included in the model play a leading role in generating the energetic surface waves. We need to gauge the sensitivity of the observed signals to changes in source parameters and to assess the utility of these signals for source characterization. ANANDAKRISHNAN ET AL. (1997) considered the effect of changes in several source parameters on regional waveforms. In this paper, we conduct a similar exercise however we are most interested in how these changes affect the partitioning of energy between the surface and body waves. We focus on the frequency bands considered in Figure 4. We consider a broad suite of mine blasts. The blasts we synthesize are all the same as the presumed correct one reviewed in the previous section except one source parameter is allowed to vary while the others are held fixed. In turn, we vary the spalled mass, individual shot yield, and the duration of the blast. In a separate experiment we also allowed shot times to deviate from the planned 35 msec delays. All synthetics are calculated for CUST, the station located 200 km to the north of the mine.

We consider peak amplitudes in two filtered versions of the synthetic traces. We filter the synthetic traces between 2 and 10 s, and between 1 and 10 Hz and calculate the log of the peak amplitude in each trace. In Figure 5, we display the ratio of the peak amplitude in the low frequency trace to that in the high-frequency trace. We display the ratios obtained from synthetic events in which a significant source parameter has been varied between 2.5% and 500% of the standard value. The filled circles in Figure 5 represent the result of varying individual shot yield. This effect is seen to be relatively minor as varying the yield over more than 3 orders of magnitude (from 182 to 36,300 pounds) changes the body-surface ratio by ~ 10%. This ratio change results from variations in both the surface and body wave amplitudes.

Varying the spalled mass has the opposite effect. When the spalled mass is varied from 0.5 kt to 80 kt (from 2.5% to 400% of the standard) the surface-body wave ratio changes from ~ 0.9 to 1.13 (filled triangles in Figure 5). The change in this ratio results from the effect spalled mass has on the surface waves as the spalled mass is predominantly a source of low-frequency energy. Changing the spalled mass had little effect on the body wave amplitudes. Although the production of surface waves is reduced when essentially no material is spalled into the pit, the restricted blast still produces surface waves that are significantly more energetic than those produced by the single shot.

The most significant changes in the waveform result from variations in the total duration of the blast. To vary the blast duration we scaled both the number of rows and the number of shots in each row. The standard blast had 7 rows and 89 shots in each row and lasted a total of ~ 4.8 s. The largest blast grid we considered had 10 rows, each with 200 shots. The extended blast spanned ~ 9.5 s - ~ 200% of the actual duration and had a total yield of 14 million pounds. The reduced blast grids consisted of 5 rows, 50 shots per row; 4 rows, 40 shots per row; 3 rows with 30 shots per row; 2 rows with 20 shots per row and 1 row with 10 shots. To reduce the blast further we decreased the number of shots in the final row to 5 shots and then to 3. The duration of these reduced blasts ranged from 3.1 s (for the blast with 5 rows and 50 shots per row) to 70 msec (for the smallest blast). As we see in Figure 5, extending the blast beyond the standard one that was used on July 19 yielded essentially no change in the surface-body wave amplitude ratio. However reducing the scale of the grid has a significant effect on the partitioning of energy between surface and body waves. Reducing the scale of the blast has a modest effect on body-wave amplitudes but the surface waves are strongly dependent on this source attribute. The ratio drops most rapidly when the blast duration is reduced below 2/10 of the actual duration

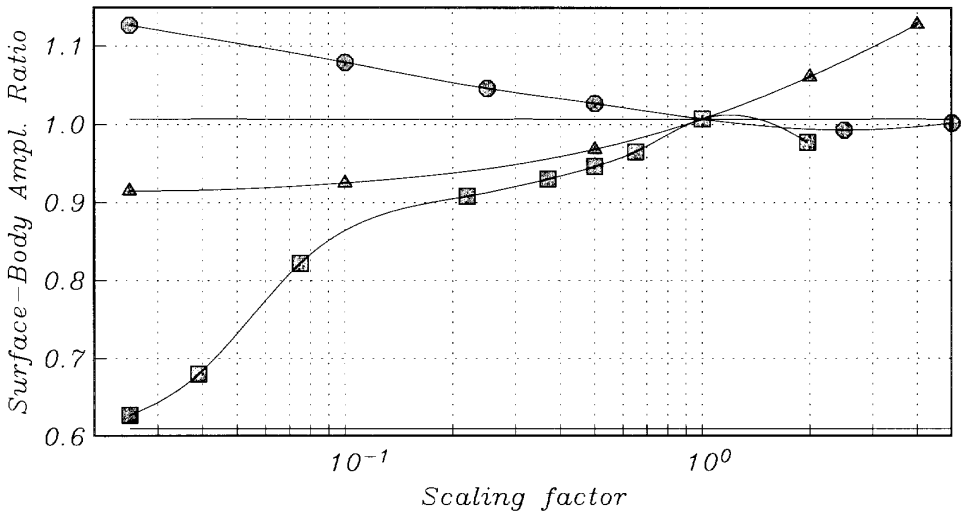

Figure 5. We display the surface-body wave ratios for a suite of blasts in which a single source parameter is varied while all others are held fixed at levels believed to be appropriate for the July 19, 1996 cast blast. The filled circles represent sources in which individual shot yield is varied from 182 to 36300 lb. The filled triangles represent blasts in which the spalled mass per shot is varied from .5 kt to 80 kt. The squares represent blasts grids that range from a single row with 3 shots to a 10 row blast with 200 shots in each row. Varying blast duration clearly has the most significant impact on energy partitioning. Only the severely restricted grid partitions energy like the synthetic 16,000 pound shot (represented by the horizontal line at a ratio of 0.61). All of these simulations assumed the subshots detonated exactly when planned.

(down to ~ 0.5 s from 4.8 s). The production of 2-10 s surface waves is reduced significantly when the blast duration is reduced below 2 seconds. When the blast duration extends much beyond 5 seconds, production of these surface waves is not increased substantially. Of all the blasts considered, just the brief blast resembled the single shot (which is represented by the horizontal line at a ratio of 0.61).

Spectral Modulations

The Wyoming events typically produce strong modulations that are independent of recording direction and time. These modulations are typically seen below 10 Hz and are seen beyond 9° from the source. Physical modeling by Hedlin et al. (1999) reproduces the general character of the modulations (the enhanced spectral roughness) however the fine details of the modulations has not been reproduced for any of the 4 events considered in this study. This is in spite of the fact that excellent shot information is available for the events. There are a number of reasons for the mismatch. Resonance is ever present and will cause additional spectral modulations. We know the spectral modulations we observe are not due to resonance as similar modulations are not seen in the spectra of instantaneous events (Figure 2). The modeling exercise has made a number of assumptions about the events. It is assumed that all shots have equal yield and adhere perfectly to the planned shooting times. Any deviations from the planned shot times will complicate the interference of the wavefields and will change the spectral modulations. If shot yield varies, and given variable coupling of the energy to seismic this is inevitable, the modulation pattern will be dominated by the few shots that have the largest effective yield.

The fine spacing of the modulations requires long delays at the source. We have concluded that these modulations result from long interrow delays (200 to 275 msec) and source finiteness (Hedlin et al., 1999).

Altai-Sayan events

The mines in the Altai-Sayan region in western Siberia produce 100 to 200 blasts each year with a magnitude of 3.5 or above (Khalturin et al., 1997). Of these, ~ 2 each year have a magnitude above 4.0 (Khalturin et al., 1997). This region includes the Kuzbass mine (~ 200 km SE of Novosibirsk) and the Abakan mine. These statistics rank this region as a leader in producing events that are detected by IMS stations (Khalturin et al., 1997). The mines are believed to be

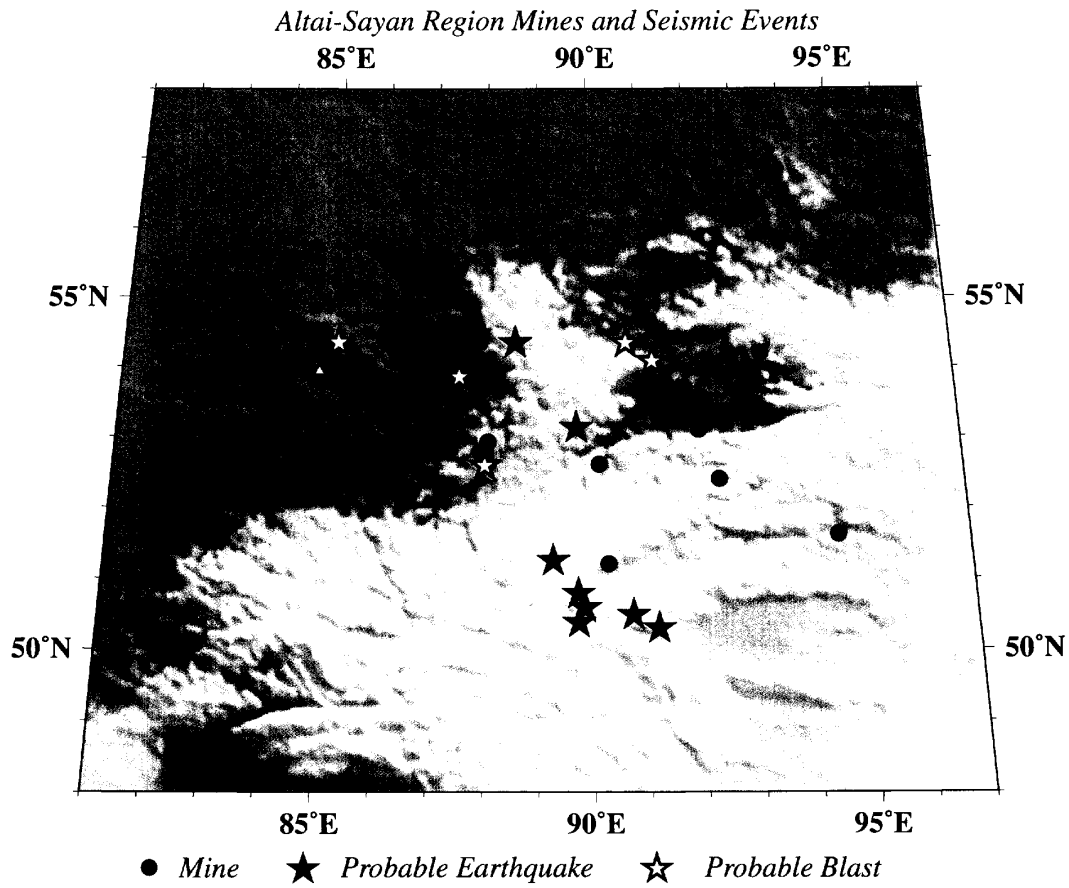

Figure 6. Altai-Sayan region mines, blasts and earthquakes. The event locations were taken from the REB catalog obtained from the PIDC web site www.pidc.org. Mine locations were taken from Khalturin et al. (1996).

extracting coal. The high magnitudes likely result from shooting entire rows of shots with no delay in each row (Paul Richards pers. comm.).

Despite having essentially no ground truth information we have examined events in this region to determine if the methods that appear to be effective in Wyoming also work here. What follows is a preliminary study of 14 events that were recorded at the IMS station ZAL from Jan 1, 1995 to July, 1999. Event and mine locations are shown in Figure 6.

Our preliminary study of events in this region has produced mixed results. In Figure 7 we display 2 to 10 second filtered vertical component records from the IMS station ZAL. Although the blasts shown here had magnitudes above 3.0, and are on par with the Wyoming blasts considered earlier, just one produced a significant mid-period surface wave. This event occurred at a range of 2.35° from ZAL and was assigned an mb of 3.6. Although definitive conclusions are not possible given the lack of detailed information about how these blasts were detonated it is likely that these events have high magnitudes due to the shooting of rows with no delays in each row. The absence of significant 2 to 10 second surface waves in most blasts suggests that the overall shot duration is < 2 seconds.

The mine blasts however do produce significant spectral modulations below 20 Hz (Figure 8). The modulations are typically spaced at ~ 5 Hz and suggest an interrow time spacing of ~ 200 msec.

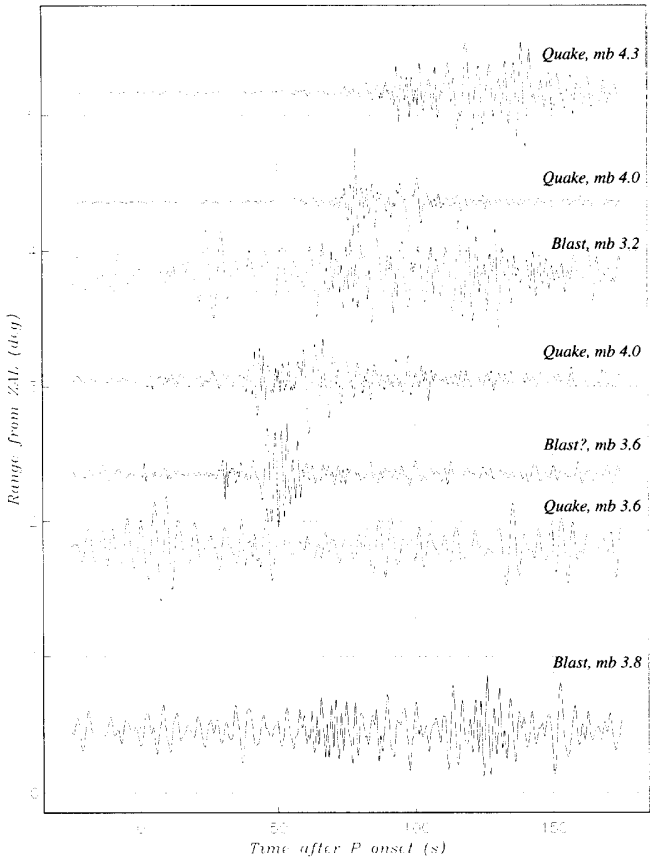

Figure 7. Vertical component (MHZ) recordings made by the IMS station ZAL near the Altai-Sayan mining region in western Siberia. The records have been filtered to 2 to 10 s. Two of three blasts shown here did not produce surface waves above noise in this band.

CONCLUSIONS AND RECOMMENDATIONS

Although virtually all large mining blasts worldwide involve delay-firing, the fine details of how individual shots are delayed with respect to one another depends on the exact practical needs at each location. Shooting practice is highly variable and thus there is a very complex relationship between event magnitude and the kinds of seismic signals that will be produced.

In Wyoming, where millisecond shot delays are used with longer delays between rows and between decks, the large blasts (> 1 kt of explosives) routinely generate significant mid-period surface waves and obvious spectral modulations below 10 Hz. Physical modeling indicates that the surface waves are due mainly to the extended duration of these events. The modulations appear to be due to long interrow and interdeck delays and source finiteness.

Events in the Altai-Sayan mining region in western Siberia have similar seismic magnitudes but are otherwise markedly different. The occasional blast in this region produces significant 2 to 10 second surface waves. Most mine blasts produce significant spectral modulations spaced at ~ 5 Hz. Although we cannot make definitive conclusions regarding the sources due to the lack of ground truth data, we conclude that the spectral modulations are due to long (~ 200 msec) interrow delays. The lack of mid period surface wave energy indicates that most, if not all, mine blasts in this region have a duration of < 2 seconds.

Unannounced mining events that include significant simultaneous explosive energy releases are problematic for several reasons. Such blasts are unwanted by the mining community as these events have both reduced rock-fracturing efficiency and increased seismic efficiency. Some of these blasts will trigger the IMS and cause some to question whether the anomalous energy release was chemical in nature. Effective characterization techniques, which rely on remote IMS observations, will reduce the need for on-site inspections. Our preliminary analysis suggests that such events can be identified using spectral modulations and the relative strength of surface and body wave seismic energy. A fuller analysis of errant blasts will be the subject of a forthcoming paper.

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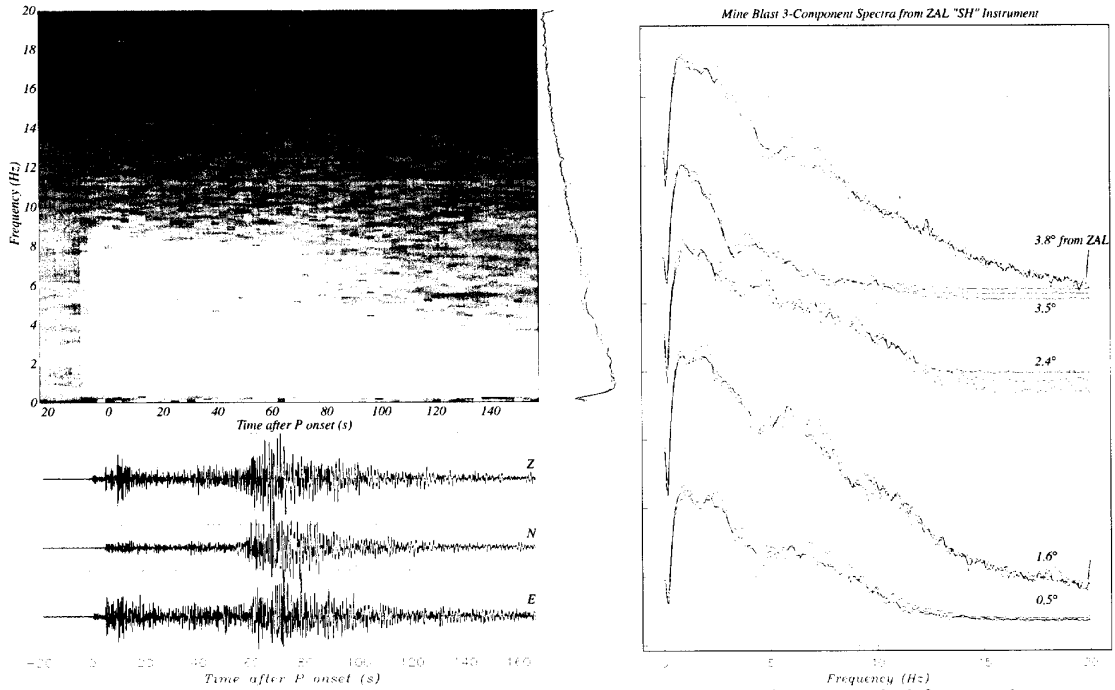

Figure 8. Altai-Sayan mine blasts routinely produce spectral modulaions below 20 Hz. The event on the left occurred at a range of 3.83° from ZAL. A clear spectral notch is present at 5 Hz. No modulations above noise are seen above 10 Hz. On the right we show five events believed to be mine blasts as a function of range. The event at 2.4° occurred during the day at one of the mines shown in Figure 6. The waveform has a sharp P wave onset however the classification of this event as a mine blast is questionable as only a weak spectral modulation can be seen. This event is also shown in Figure 7.

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