DISCRIMINATION OF SMALL EVENTS USING REGIONAL WAVEFORMS: APPLICATION TO SEISMIC EVENTS IN THE US AND RUSSIA

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ABSTRACT

Historically, event identification has focused on the task of separating earthquakes and explosions. This approach was adequate for large events observed at teleseismic distances since there are few other types of manmade sources large enough to be observed. However, with the availability of high-quality regional data, smaller events (m_b 3.5 and below) that include many manmade sources are observed. The present challenge of seismic-event identification now includes the task of categorizing not only earthquakes and single-fired explosions (nuclear or chemical), but also mining explosions, underground mining collapses, and rock bursts.

In order to investigate smaller, mining-related events, we have assembled a comprehensive database of earthquakes and mining events. This database consists of events in both the United States (US) and Russia and includes ground-truth data for several different kinds of mines (iron, copper, and coal in the US and coal in Russia). The US portion of the database comprises 128 stations (which include broadband three-component stations as well as regional short-period arrays, such as the Pinedale Seismic Array [PDAR]). The station distribution within the United States allows for good azimuthal coverage around three mining districts in Wyoming, Minnesota and Arizona. Nearly 72,000 waveforms were collected for 800 mining events and 400 earthquakes. The Russian portion of the database includes approximately 17,000 waveforms from five stations for 830 mining events and 260 earthquakes. The mining events were identified seismically by the Siberian Branch of Geophysics and co-locate well with known coal mines within the Altai-Sayan region of Russia. Additionally, through cooperation with Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL), we have access to many additional prior events in both Russia and the US.

We have been using this extensive database to develop discrimination tools that specifically consider the physical processes that accompany mining explosions and what makes them unique from earthquakes and other types of explosions for categorization purposes. In order to test the tools, we focus on mining events in the Powder River Basin of Wyoming as well as nearby earthquakes. The discrimination tools we are currently testing, both individually and combined, include magnitude and distance corrected (MDAC) amplitude ratios, time-varying spectral analysis, and infrasound. Ultimately, we hope to incorporate cluster analysis and M_S:m_b in order to generate a combined discriminant, which confidently and effectively identifies small mining events.

OBJECTIVES

During the past year we have made progress on three key tasks. These include: (1) Development of a comprehensive ground-truth database; (2) Quality review of a subset of data for testing discriminants; and (3) Identification and testing of discriminants.

Development of a comprehensive ground truth database. In order to characterize the source mechanism of mining related events against a large background of natural seismicity, a ground truth database of different types of mine blasts in varying geological regions is essential. Additionally, this data should be supplemented with earthquake data that span a range of magnitudes and depths. Finally, such a database should utilize the NNSA Knowledge Base schema to allow for easy integration with other NNSA database products. We present the results of our database development that meet these standards.

Quality review of a subset of data for testing discriminants. A high-quality training dataset is necessary to apply discriminants and understand their behavior before extending their use to a larger dataset. The training dataset should feature mining events and earthquakes of different sizes consistently recorded at various regional stations, with well determined magnitudes and regional phase arrival times. We have chosen to build a training dataset for events recorded at the Pinedale Seismic Array, PDAR. This allows us to determine discrimination techniques that fully utilize the capabilities of small, regional arrays. Focusing on (coal) mining events recorded at PDAR allows us to apply our techniques to the coal mining regions of Russia.

Identification and testing of discriminants. Various types of discriminants have been successful at characterizing certain types of mining events in various regions (Stump et al., 2002). Determining a set of discriminants that confidently identify mining events from other types of events, regardless of blasting practice employed and the geological structure surrounding the mine, is critical. To address this problem, we are initially investigating three discriminants: amplitude ratios, time varying spectral estimation, and presence of infrasound.

RESEARCH ACCOMPLISHED

Development of a Comprehensive Ground Truth Database

We have focused on database development in two main regions: the United States (US) and Russia. In the US, we have obtained ground truth data from three mining districts that employ different mining practices to accommodate the extraction of a variety of materials. The first is the Powder River Basin in northeast Wyoming. This region has active surface coal mines. Contact with mines in the area has provided a catalog of 295 mining events for which we have approximate origin times, blast types, and approximate yields. The second mining district, in southeast Arizona, features porphyry copper where mining explosions are used to fracture rock for ore extraction. Through collaborative experiments with the mines, a catalog of 129 mining events has been derived and features detailed information on origin time, yield, and shot geometry (number of holes, shot delay time, and hole locations within mine). The third district comprises the taconite mines of northwestern Minnesota. Collaboration with local mines has yielded a catalog of 379 events featuring origin time, location within the mine, yield, shot delay times, and number of shots per blast.

The mining data have been supplemented with earthquake data as closely co-located as possible to each of three mining districts. In the Powder River Basin, catalogs derived from the University of Utah, the Montana Bureau of Mines and Geology, and the United States Geological Survey, preliminary determination of epicenters (USGS PDE) feature 213 earthquakes ranging in size from M_L = 2.0 to M_L = 4.9 at depths ranging from zero to 27 km, where most of the events are concentrated in the upper two to three km of the crust. The 87 earthquakes in the Arizona region were obtained from the USGS PDE and range in size from M_L = 2.5 to M_L = 5.5 at depths identified as upper- to mid-crustal (one to ten km). Finally, 119 earthquakes in the Minnesota mining region were obtained from the Canadian Geological Survey's earthquake bulletin. They range in size from M_L = 1.1 to M_L = 4.7 and are identified as mid-crustal (depths fixed at either five or 18 km). Figure 1 illustrates both the earthquakes and explosions gathered for the US portion of the study.

Data were obtained for these events via the Incorporated Research Institution for Seismology (IRIS) and the US National Data Center (NDC). A total of 128 unique stations from a range of both permanent network (e.g., Global Seismic Network [GSN]) and temporary deployments provide high-quality broadband and short-period data with good azimuthal coverage around the three mining districts of interest. For the Powder River Basin events, 38 seismic stations (which include PDAR) have recorded data for some or all of the events in the dataset. In the Arizona district, 41 seismic stations have recorded data for some or all of the events. Finally, in the Minnesota district, 58 stations provide data for some or all of the events. This comprehensive station coverage has provided nearly 72,000 waveforms comprising the US portion of the dataset. Figure 2 shows the station coverage in the US.

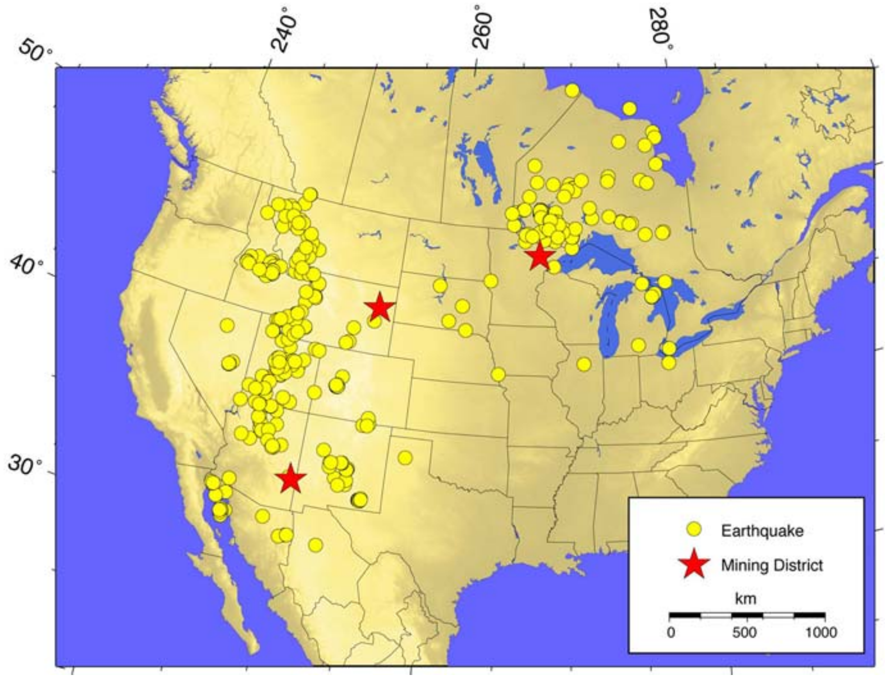

Figure 1. Earthquakes and explosions in the US portion of the database. Mining events in each of the three districts are initially given a single location, causing them to plot at a single point.

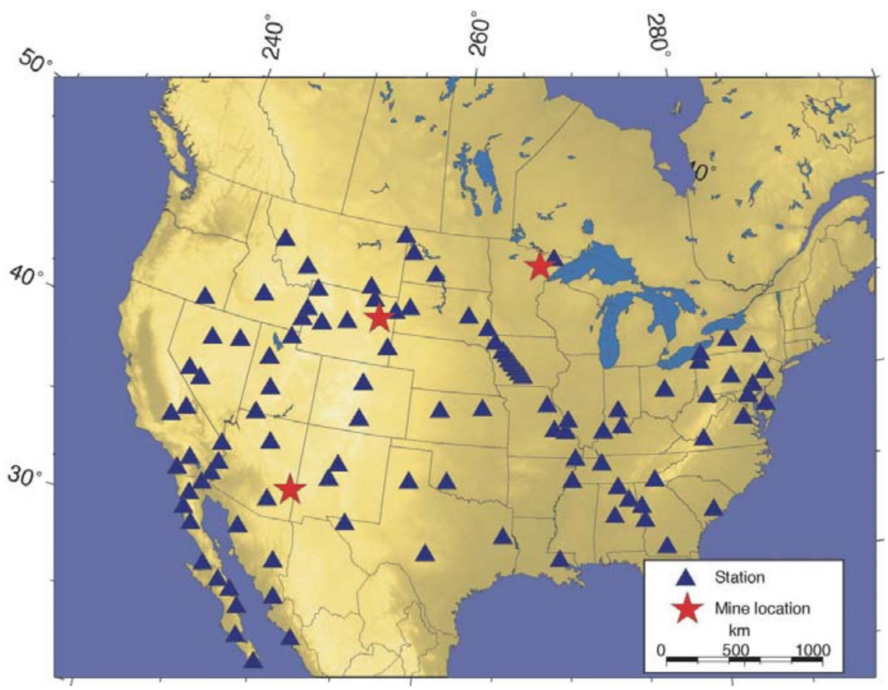

Figure 2. Station coverage for the US portion of the database. There are a total of 128 unique stations; several of the stations recorded data for more than one mining district.

Collaborative efforts with the Siberian Branch of the Russian Academy of Sciences Institute of Geophysics ("The Institute"), as facilitated by Vitaly Khalturin, has yielded a catalog of mining explosions and nearby earthquakes in the Altai-Sayan mining district in the Kuzbass region of Russia (Hedlin et al., 2004). The Institute administers the Altai-Sayan Seismological Expedition (ASSE) network; data analysts at The Institute use seismic location information from this network as well as blasting logs provided by local mines to quantify events as either mine blasts or earthquakes. Their efforts have resulted in the compilation of a catalog of 833 mining events and 263 earthquakes. Little information is known about the mining events, other than their co-location with active coal mines in the area. Magnitude estimates have been determined by The Institute and converted to approximate m_b measurements. These range in size from m_b = 3.1 to m_b = 3.8. The earthquakes range in magnitude from m_b = 3.1 to m_b = 5.6. Data were obtained for these events via IRIS and the PIDC for five stations in the Altay-Sayan area, which amounts to approximately 16,500 waveforms. Figure 3 illustrates the station coverage and events collected for the Russian portion of the database.

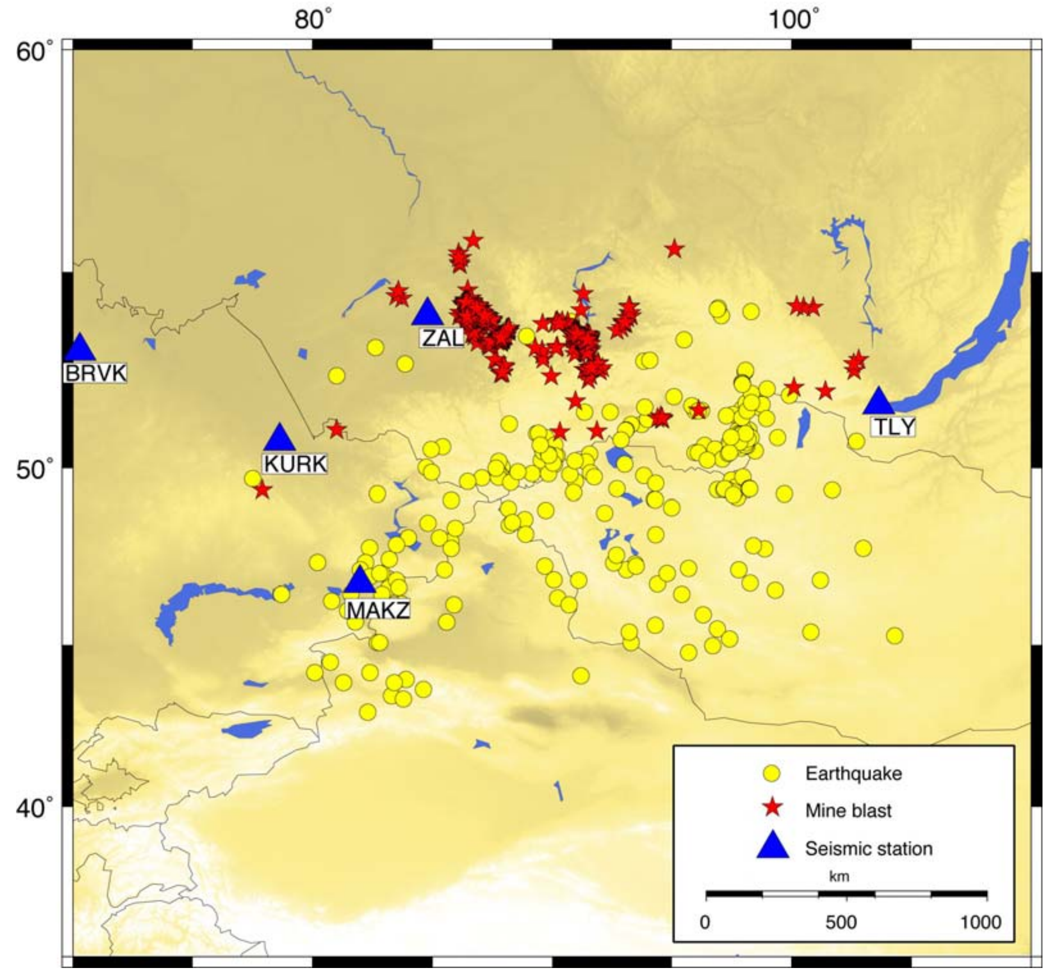

Figure 3. Earthquakes and explosions in the Russian portion of the database. The five stations for which data were obtained are also shown.

Figure 4 gives a statistical summary of the data we have collected thus far. In addition to the database we have developed, we have also integrated data collected by both LLNL and LANL for various projects. To complement our US dataset, Bill Walter and his colleagues at LLNL have provided us with their Western US database featuring earthquakes, mining related events, and nuclear explosions recorded at the Nevada Test Site (NTS) (Walter et al., 2003). To complement our Russian dataset, Julio Aguilar-Chang at LANL has provided us with an additional 12,700 waveforms recorded at 57 stations for 552 events in the Altai-Sayan area.

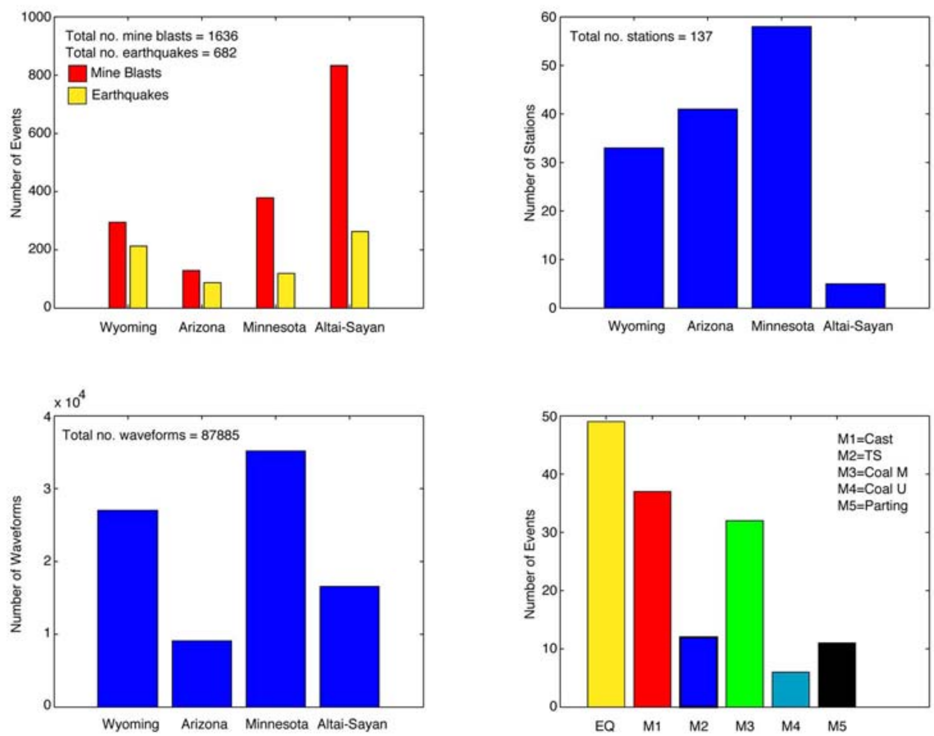

Figure 4. Summary of the US and Russian database. The top left graph illustrates the total number of mine blasts and earthquakes in the dataset for the four mining regions (Wyoming, Arizona, and Minnesota in the US and the Altai-Sayan in Russia). The top right graph shows the number of stations for which we have collected data. The bottom left graph shows the total number of waveforms collected for each of the four regions. Finally, the bottom right figure summarizes the types of events (see Table 1) featured in the subset database we are using for initial analysis (Powder River Basin, Wyoming).

Quality Review of a Subset of Data for Testing Discriminants

In order to begin testing of discriminants on small, mining-related events, we have chosen to focus on a subset of the larger database collected. We have reviewed over 300 events recorded at the PDAR in Wyoming. PDAR is 367 km from one of the largest coal mines in the Powder River Basin for which we have detailed ground-truth data. These data includes origin information as well as information about the blast types utilized by this mine (Table 1). It may be necessary to include additional event types, for example blast anomalies where a significant portion of the blast array detonates simultaneously.

Table 1. Blast types for a large coal mine in the Powder River Basin, Wyoming.

Blast Type	Description	Min Yield (lbs)	Max Yield (lbs)
Cast Overburden	Overburden is casted and removed into adjacent empty pit.	300,000	2,500,000
TS Overburden	Blasts in overburden material to be excavated by shovels loading into trucks.	100,000	600,000
Coal – Main	Blasts in the main coal seam, which is 60 - 70 ft in thickness.	20,000	200,000
Coal – Upper	Blasts in the upper coal seam, which is 10 ft in thickness.	2000	10,000
Parting	Blasts of waste material layer between the upper and lower coal seam, ranging from 0 to 40 ft in thickness.	200	500

Of the events reviewed in the Wyoming region, there were 98 mine blasts that could confidently be associated with the origin and location information in the database and that generated enough signal to be seen at PDAR. Additionally, there were 49 earthquakes that generated sufficient signal to be recorded at PDAR. The bottom right graph in Figure 4 summarizes the number of different blast types contained in the subset database. Earthquake locations relative to the mine location and to PDAR are shown in Figure 5.

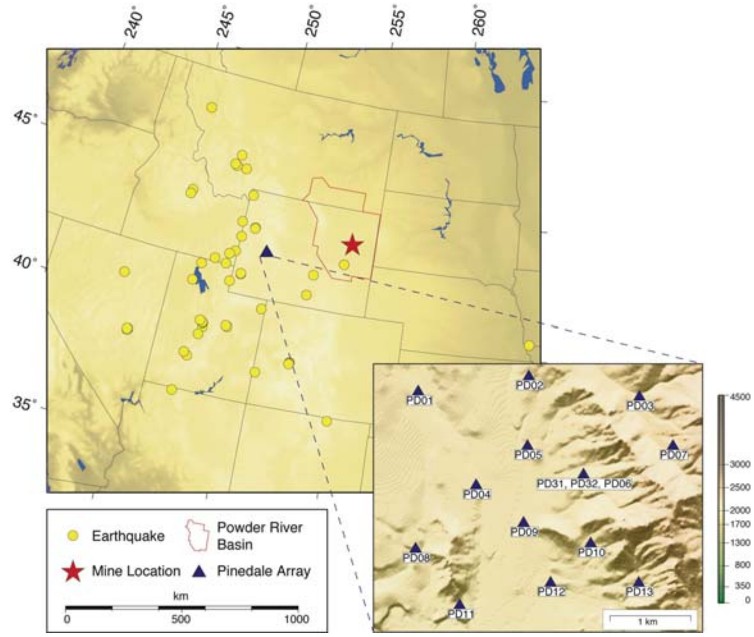

Figure 5. The subset of data used for testing the discriminants, illustrating earthquakes recorded at PDAR for the period 01/04 through 01/05 and the geometry of PDAR.

<u>Identification and Testing of Discriminants</u>

Amplitude Ratios using MDAC Corrected Amplitudes

Amplitude ratios have been used to successfully discriminate earthquakes from single-fired explosions, and discrimination power is greatly enhanced when path and source corrections are applied. We apply these same tools to mining explosions. In order to characterize the behavior of phase, spectral, and cross-spectral ratios for the types of events (Table 1) recorded at PDAR, we employ the use of the MDAC procedure. This procedure removes magnitude and distance trends in regional phase amplitudes using an earthquake source model and allows for maximum flexibility in the later construction of discriminants (Taylor et al., 2002). Using a velocity model determined by Prodehl and Lipman (1989) for the northern Rocky Mountains, regional phases (P_n, P_g, and L_g) were picked on elements of PDAR. Root mean square amplitude measurements were made using the frequency-domain procedure outlined in Hartse (2001) in six frequency bands commonly used for discrimination (0.5-1.0 Hz, 1.0 -2.0 Hz, 2.0-4.0 Hz, 4.0-6.0 Hz, 6.0-8.0 Hz, and 8.0-10.0 Hz). Because the MDAC procedure corrects for differences in source size, an estimate of m_b is necessary before applying the corrections. We have used the m_b(Pn) formula for the Western US, as described in Denny *et al.* (1987) to calculate magnitudes for each of the events in the subset, which range from m_b = 2.5 to m_b = 4.5.

The results of applying the MDAC corrections using parameters unique to the Western US are shown in Figure 6. Historically, high frequency Pg/Lg has been used to discriminate mine blasts (Stump et al., 2002). For the set of events featured here, that discriminant does not appear to be successful. Examination of selected waveforms shows great variability in both the earthquake and explosion populations in terms of relative Pg/Lg. The large variation in relative amplitudes for the mine blasts suggests that more study is needed to quantify how and why similar source types (e.g., cast blasts) are seismically different. Variations in the earthquake relative amplitudes due to path effects may be an indication that calibration studies are needed to improve the results of amplitude discrimination in this region. Examination of other ratios yields similar variability trends, although the Pn(1-2 Hz)/Pn(6-8 Hz) discriminant (Figure 7) shows promise in discriminating cast blasts (red) from earthquakes (yellow).

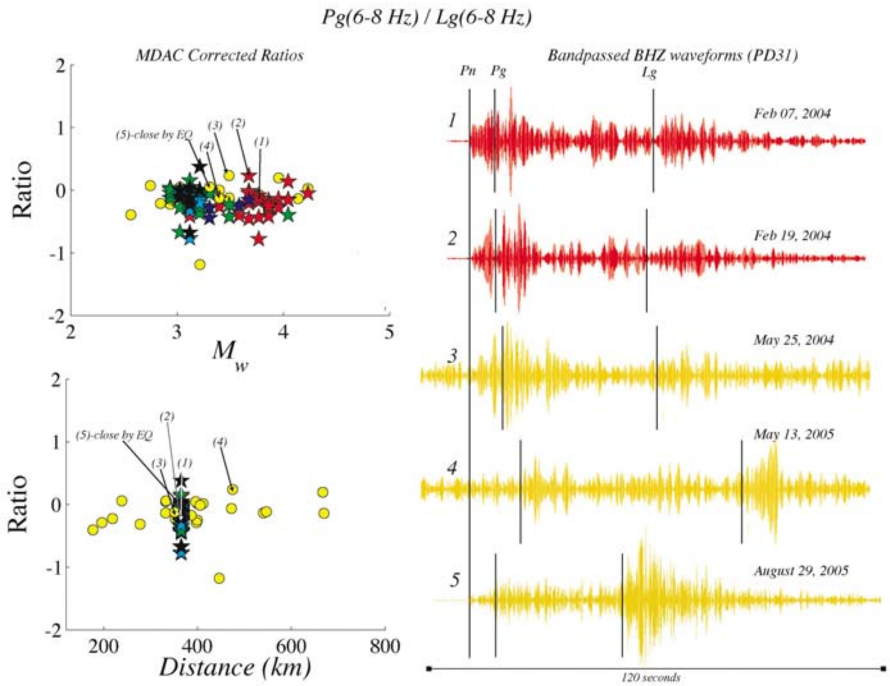

Figure 6. High frequency Pg/Lg discriminant values as a function of Mw and distance. Selected waveforms are shown for two cast blasts (red) and three earthquakes (yellow). Events passing an SNR of 2 for Pn and Pg and 1.3 for Lg are shown. Each point is colored by event type using the scheme in Figure 4.

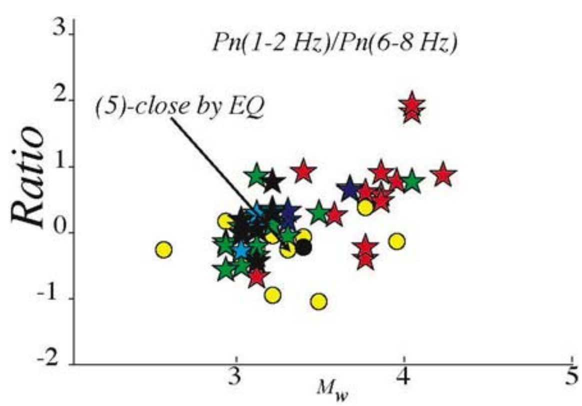

Figure 7. Pn(1-2 Hz)/Pn(6-8 Hz) ratio, which is a promising discriminant for Wyoming cast blasts.

Time-Frequency Discriminant

The time-frequency discriminant is based on spectrograms of recorded events. The discriminant exploits the fact that delay-fired mine blasts exhibit time-independent spectral modulations (Hedlin, 1989). Such spectral modulations are thought to be caused by either the dominant inter-shot or inter-row time spacing, or by the duration of the entire set of blasting depending on the individual delays and bandwidth of the observational data.

Figure 8 illustrates the time-frequency discriminant methodology using an example delay-fired mine blast. For each event, a spectrogram is computed for every component of each sensor that recorded it. The spectrograms are computed in time windows that begin at the first arrival (Pn or Pg) and extend through the Lg wave coda. Each spectrogram is reduced to binary form by filtering each spectral estimate with two running-average filters that comprise different window lengths, and then differencing the two filtered spectra (Figure 8). Locally high and low spectral values are then replaced 1 and 0 respectively and then the mean is removed.

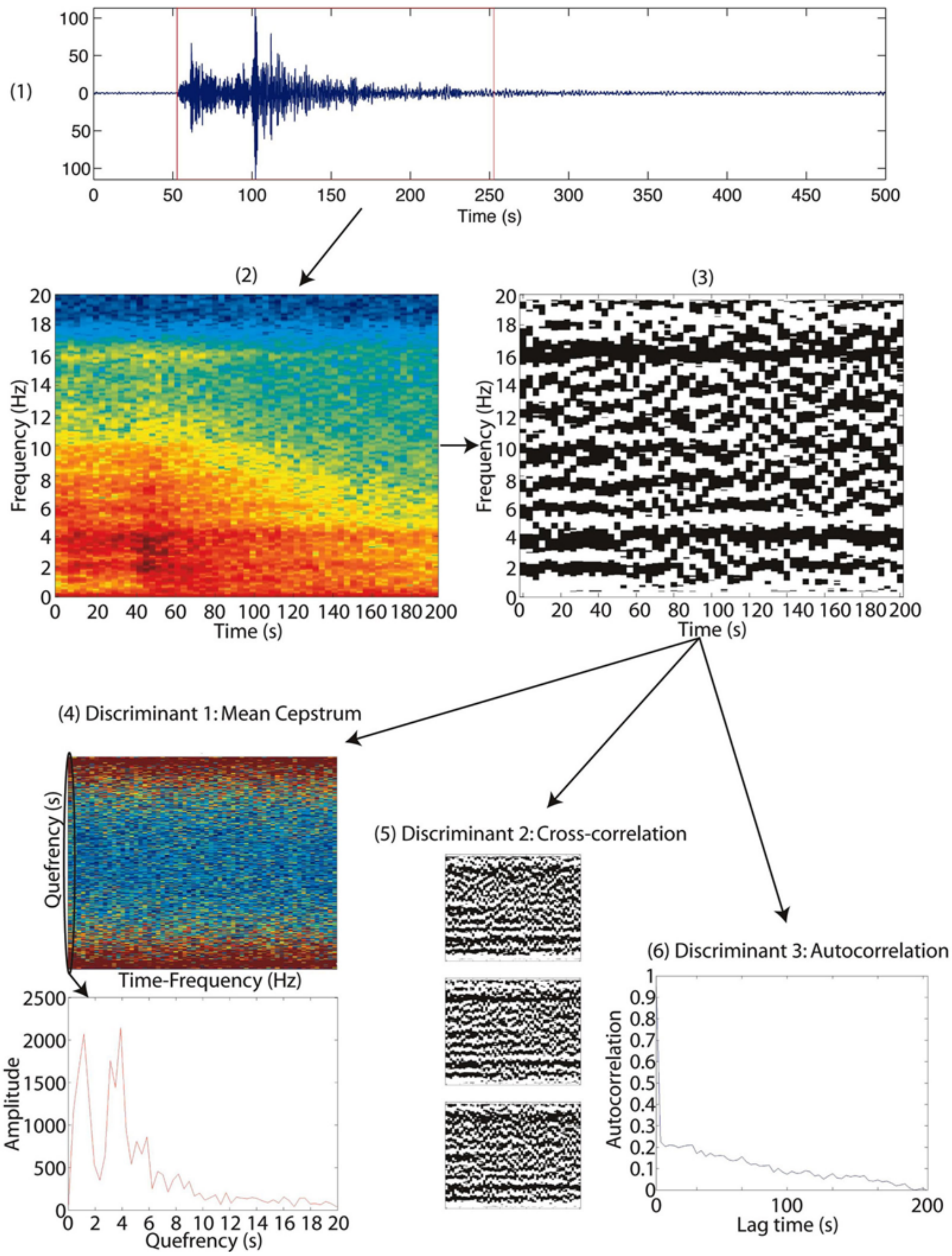

Figure 8. Flowchart that aids in explaining the time-frequency discriminant methodology using an example recording of a ripple-fired mine blast. (1) Input trace, with the red box showing the first arrival time of P energy through the Lg coda (window used for processing). (2) Spectrogram of input trace. (3) Binary spectrogram computed from input spectrogram in (2), showing clear evidence of time independent spectral scalloping. (4) 2D Cepstrum and 1D Cepstrum at zero time-frequency, showing clear evidence of cepstral peaks related to the time independent spectral scalloping. (5) Cross-correlation discriminant is computed using additional 2 traces of a 3-component recording. The additional 2D binary sonograms are shown to illustrate the clear correlation in spectral banding on the different components. (6) The autocorrelation is computed at a range of lag times and the mean is taken as a third discriminant.

Following Hedlin (1998) three different sets of discriminants are then computed, based on the binary spectrograms (Figure 8). The first discriminant is the mean cepstral value. This discriminant is evaluated by calculating the 2D cepstrum of each binary spectrogram and then retaining that part of the 2D cepstrum that reflects energy that is periodic in frequency but independent of time. For three-component seismometers the estimates from each of the individual components are stacked. This exploits the fact that cepstral structure should correlate on all 3 components for delay-fired mine blasts, but should be uncorrelated for earthquakes and single-fired mine blasts as long as a time independent spectral structure isn't acquired during propagation. A further two discriminants (Figure 8) exploit the fact that time independent spectral modulations should correlate on all 3 components (Cross-correlation) and that they should be time independent (Autocorrelation).

Figure 9 shows the mean cepstral values obtained for each class of event in the picked Wyoming dataset using the time-frequency discriminant method outlined above. We observe a clear separation between earthquakes (yellow) and the largest mining events (Cast blasts, red), with poorer separations for the smaller mining events. Similar results are obtained for the other two time-frequency discriminants: cross-correlation and autocorrelation. The methodology requires an a priori choice of a number of free parameters (e.g., filtering parameters for creating the binary spectrograms) and further work is required to train the algorithm to optimize the separation of earthquakes and each class of mine blasts separately. Although our initial results are very encouraging, different choices of filtering parameters for each class of mining event may result in an improved separation from earthquakes.

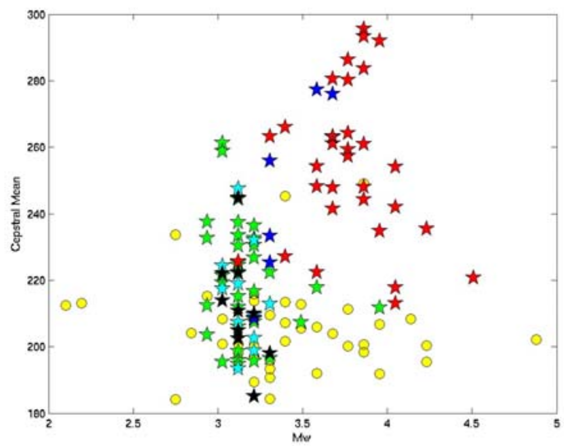

Figure 9. Mean cepstral value versus Mw for each event in the picked Wyoming dataset. Each point is colored by event type using the scheme in Figure 4.

Infrasound Discriminant

We will test using infrasound as an additional discriminant in Wyoming using Pinedale Infrasound Array (PDIAR) data. The premise behind this discriminant is that mine blasts are more efficient generators of infrasound than earthquakes, owing to their location on the free surface. Therefore, infrasound has potential to be an effective depth discriminant. For each event in the database, we will search for an associated infrasound signal with a consistent arrival time and backazimuth. Signal detection will be performed using the Progressive Multichannel Cross Correlation method. We will evaluate whether the presence (or absence) of an infrasound signal may then be used as a separate discriminant in our suite of discriminants.

CONCLUSIONS AND RECOMMENDATIONS

Using a subset of data in the Powder River Basin and surrounding area, we have tested two discriminants: amplitude ratios and time-frequency estimation. Initial results for the amplitude ratios show great variation in relative amplitudes for both earthquakes and mine blasts, making discrimination difficult using traditionally successful ratios (e.g., Pg/Lg (6-8 Hz)). Other ratios show better results, but further study is needed. Future work in this area will focus on gathering more information on individual blasts from the mines to ascertain conditions that lead to amplitude variability. Additional study on regional earthquakes will be useful to determine how path effects are influencing the outcome of this discrimination method. Initial results for the time-frequency method are very promising, showing good separation between cast blasts and earthquakes, as well as some of the smaller mining events. Future work in this area will focus on refining filtering parameters and using all array elements to improve discrimination performance. We will also determine how to optimally combine each of the discriminants in order to maximize performance. Figure 10 illustrates a first order look at how utilizing more than one discriminant can increase population separation (cast blasts [red] discriminate well from earthquakes [yellow]). Finally, we plan to extend our analysis to include data collected in the Altai-Sayan coal mining regions in Russia; that dataset allows for the opportunity to test the transportability of the discriminants utilized in the Powder River Basin.

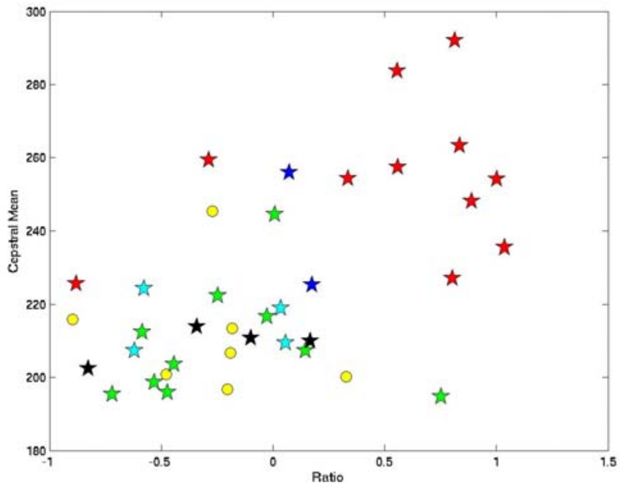

Figure 10. Combined results of the amplitude ratio discriminant featured in Figure 7 and the cepstral mean discriminant featured in Figure 9.

ACKNOWLEDGEMENTS

We wish to thank Steve Taylor at LANL for providing access to MDAC codes and data; Julio Aguilar-Chang at LANL for assembling additional data to supplement our database; Bill Walter at LLNL for giving us access to his Western US database; and the IRIS Data Management Center (DMC) for providing much of the data utilized in this study.

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