A SUITE OF DISCRIMINANTS FOR GROUND-TRUTH MINING EVENTS IN THE WESTERN U.S. AND ITS IMPLICATIONS FOR DISCRIMINATION CAPABILITY IN RUSSIA

Marie D. Arrowsmith[1], Stephen J. Arrowsmith[2], Brian W. Stump[1], and Michael Hedlin[3]

Southern Methodist University[1], Los Alamos National Laboratory[2], and University of California San Diego[3]

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ABSTRACT

The problem of identifying mining events has become an important one given the deployment of regional seismic stations in monitoring areas of interest, particularly in countries where mining efforts are significant to the economy. As with other types of regional events, signals from mining events are influenced by the propagation path and local site and receiver effects. Unique to mining explosions, however, are the complex source functions that are representative of the complicated firing sequences and spatial extent utilized in engineering blasts. Many factors contribute to the source function, including grid spacing, inter-row and inter-shot delay times, borehole depth, yield per hole, material casting, and total yield. During this four year study, we have developed a comprehensive database of ~150,000 waveforms featuring ~2500 mining events and ~1300 earthquakes. This database covers mines in the U.S. and in Russia; we have focused analysis on two regions: events associated with coal mines in Wyoming and regional earthquakes of the Western U.S., as well as mining events and nearby earthquakes in the Altai-Sayan (AS) region of Russia. Due to extensive collaboration with the largest coal mine in Wyoming and the nation, we have detailed shot information for ~1000 mining events, classified into six distinct blast types. We have limited information for events in the AS region based upon contacts with the AS Seismological Expedition.

We have applied three discriminants to data from 11 stations and one array in the Western U.S. The first discriminant, time-of-day (TOD), assesses the time an event occurs. In general, for our dataset, mining events occur between 9:00 am and 6:00 pm local time, while earthquakes are randomly distributed with respect to time. The second discriminant, amplitude ratios (AR), exploits spectral differences between regional phases due to source type. For the Western U.S dataset, results for Pg/Lg (6–8 Hz) are highly station centric. The largest type of mining events (cast blasts) shows some separation from earthquakes that are within distances of < 250 km from the mine; however, as the earthquake dataset expands spatially, discrimination performance degrades. The application of a 1D path correction improves results slightly, but due to dominating propagation effects, path calibrations are necessary to optimize this discriminant. The third discriminant, time frequency (TF), capitalizes on the unique spectral signature of ripple-fired mining events as a function of time. This discriminant separates the larger types of blasts at all stations. Smaller blasts presumably do not discriminate because of the shorter shot durations. We use a statistical method called classification and regression trees (CART) to combine these discriminants. CART yields an intuitive decision grid for classifying events based on the discriminant value for each of the three discriminants. In the AS region, we calculated these same discriminants at two stations for ~260 mining events. TOD results are similar to those in the Western U.S in that presumed mining events fall within working hours. The AR discriminant (Pg/Lg [6–8 Hz]) shows significant overlap of the earthquake and explosion population. Certain events do separate, but we have no information on what makes these events unique, if anything. Similar results are seen for the TF discriminant—there is overlap of populations, and although certain events can be identified as explosions, we cannot assess the reasons why we observe the overlap. We do not know if the discriminant itself fails, or if the majority of our data points are from smaller shots that have shorter durations. These unanswered questions illustrate the need for detailed ground-truth information. Future studies of mining event discrimination, particularly where large datasets are to be acquired, should involve a heavy degree of cooperation with mine operators in order to address ambiguities such as those identified in the AS study.

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OBJECTIVES

Data Quality Control

As discussed in previous proceedings (e.g., Arrowsmith et al., 2007), we have developed a database of earthquakes and mine blasts at three mines in the U.S. and in the Altai-Sayan, Russia. We have continued our efforts in examining the extensive set of waveforms and include results from additional stations which have been analyst reviewed.

Testing and Evaluation of Discriminants on a Large Dataset

We have identified three discriminants that can be easily applied to a large seismic catalog. The TOD discriminant characterizes events based both on typical working hours of mining operations and co-location with known mines. We have continued investigating amplitude ratios, using feature selection methods to identify potentially successful combinations. The time-varying spectral estimation method, described in detail in Arrowsmith et al. (2006), has also been applied to the dataset at multiple stations. We test the benefits and limitations of each discriminant on data in the U.S. and apply the results to data in Russia.

Combination of Discriminants

In order to build upon the performance of the individual discriminants, we utilize a discriminant combination method—CART—to assess the results obtained at individual stations and for the entire analyst-reviewed dataset.

RESEARCH ACCOMPLISHED

Ground-Truth Database of Mining Explosions

Nearly ~150,000 waveforms comprise our dataset, consisting of ~2500 mining events and ~1200 earthquakes. In order to analyze discriminant performance, we have focused on a smaller portion of the large database, concentrating on the Black Thunder coal mine in Wyoming. Black Thunder is in a region of high mining activity known as the Powder River Basin (PRB); 40.6% of all U.S. coal production occurs in the PRB. Black Thunder is the largest producer in this region (and in North America), having produced 92,653,250 tons of coal in 2006 (Energy Information Administration, 2007). We have a working relationship with Black Thunder and thus have access to very detailed ground-truth data. This area is interesting to study because upper crustal seismicity in the region is distributed in several geologic environments, allowing us to investigate the role of path effects on the discriminants. We have concentrated our efforts on 11 stations and one array distributed azimuthally around the mine; each station has recorded hundreds of events, including many mining blasts (Figure 1).

Through cooperation with Black Thunder, we have obtained basic information such as origin time and blast types utilized by this mine for approximately 1000 events. We have additional detailed ground-truth data for 98 of these events, which includes information such as delay times between shots and rows, amount of explosive used, and number of rows in each blast. Jimeno et al. (1995) describe many of these parameters in detail and how they are applied to the blasting process. Additionally, we have records at two stations (RSSD and PD31) of seven single-fired explosions at Black Thunder that were collected as part of experiments in 1995 and 1997 (Stump et al., 2003). Of the various types of blasts in Figure 2, cast blasts are the largest and most likely to be observed at regional distances. In this type of blast, overburden above the coal seam is moved into an adjacent pit. Anandakrishnan et al. (1997) describe this process: an array of up to 1000 individual boreholes is filled with 5000 to 10,000 lbs of material and delay fired over several seconds. The explosive array is parallel to the free face of the mine and the time-delay procedure ensures that material closest to the free face is cast into the pit before subsequent rows are detonated. As much as 20 to 30 % of the overburden is cast into the pit and the remainder is dug with a dragline to expose the coal. At Black Thunder, overburden ranges from 100 to 230 feet in thickness and consists of unconsolidated sedimentary facies. There are four active pits at Black Thunder and four draglines are utilized to remove material that has been cast blasted. The “Truck Shovel” (TS) overburden explosions are similar to the cast blasts but material is cast such that it can be excavated with large truck shovels and hauled off. The coal shots are used to fracture the coal after it has been exposed so that a shovel can remove it and load it into haul trucks. Parting shots are used to remove small amounts of material between the two main coal seams currently being excavated. The latter two explosion types are generally small in total explosive charge and shorter in time duration.

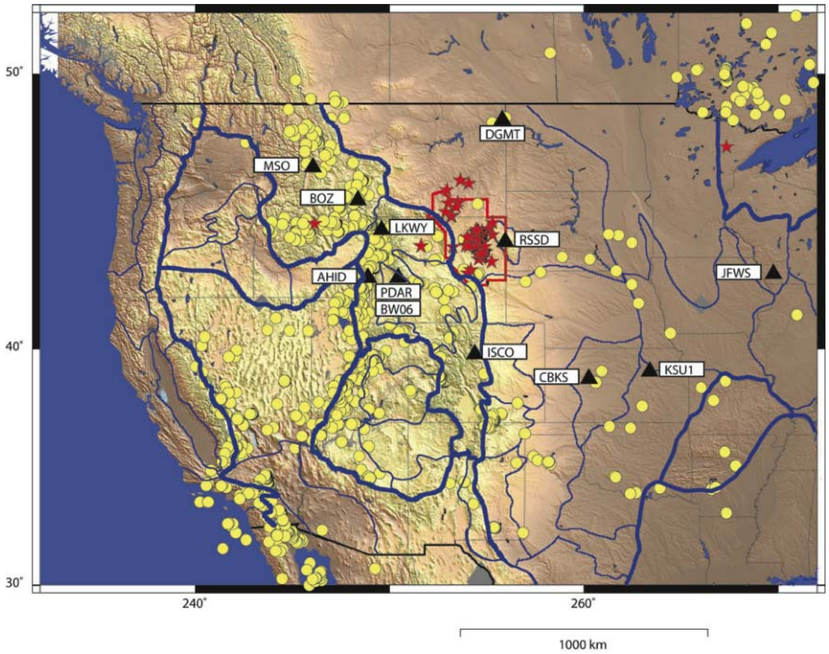

Figure 1. Data featured for discrimination analysis. Earthquakes (yellow circles) and mining events (red stars) are interspersed throughout the Western U.S. and Interior Plains. Seismic stations (black triangles) used in the analysis are distributed around the main mining region, the Powder River Basin (red outline). Superposed on the high-resolution background topography are outlines (blue) of the major (thicker lines) and minor (thinner lines) geologic provinces of the U.S. Only sub-provinces within the Western U.S. and Interior Plains are shown.

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
Cast (Electric Delay)	Delays are controlled by electric delay detonators		
Cast (Long Delay)	Interrow delay times are 300 seconds		
TS Overburden	Blasts in overburden material to be excavated by shovels loading into trucks.	100,000	600,000
Extraction	Blasts in the main coal seam, which is 60 - 70 ft in thickness or in the upper coal seam, which is 10 ft in thickness.	2,000	200,000
Parting	Blasts of waste material layer between the upper and lower coal seam, ranging from 0 to 40 ft in thickness.	200	500

Location				
	Pit	**Cut**	**Section**	**Loc. Code**
	North	22	West	N22W
Explosives				
No. Holes	132		**Delay Time**	**Quantity**
No. Rows	4		9 ms	70
Hole Diameter	12.25 in		200 ms	66
Burden	48 ft		500 ms	66
Spacing	27 ft		800 ms	66
Avg. Hole Depth	188.1 in		1100 ms	66
			Total Delays	653
Shot Type	Cast OB			
Avg. Stemming Depth	35 Drill Cuttings			
Type	**Qty**	**Weight (lb)**		
SoftLoad		1,114,700		
1-lb Primer	264	264		
Det Cord	32,000			
Lead In (50' 100 ms)	1			
Total Explosives Used		1,114,964		
Max Charge per 8 ms Delay (lb)		10,302		

Miscellaneous	
Temp	41 deg
Cloud Cover	Pt Cloudy
Wind Speed	6 mph
Wind Direction	WNW

Inter-row delay times (ms)

Cast Blasts	TS Overburden	Coal Extraction	Parting
300	**300**	300	**42**
	200	200	
	42	42	
	60	**35**	
		7	

Inter-shot delay times (ms)

Cast Blasts	TS Overburden	Coal Extraction	Parting
9	20	42	**42**
	17	35	17
	9	17	9
		9	

Total shot Duration (ms)

	Cast Blasts	TS Overburden	Coal Extraction	Parting
min	1044	424	18	72
max	1854	1638	1400	672
mean	1296	936	318	301

Figure 2. Types of ground-truth data obtained from Black Thunder. Top panel describes types of shots the mine performs (color code will be used throughout the paper). Bottom, left panel describes a cast overburden shot pattern. Bottom, right panel summarizes timing information used for the different types of shots (bold numbers indicate the mode).

Discrimination of Mining Events in the Western United States

Time-of-day and location

Using the entire U.S. event catalog, we followed the method described in Mackey et al. (2003) to visually examine the dataset based on TOD and event location. By clustering events into 1º x 1º bins, we observe the mining regions we have cataloged (in Arizona, Minnesota, and Wyoming) are predominantly daytime events; in other parts of the U.S., mixed daytime and nighttime events are seen. We also investigated the Western U.S. event catalog as a function of time-of-day and event type. Events categorized as mining events are constrained to working hours (roughly between 7 am and 6 pm), with the majority of events occurring between 11 am and 4 pm. One exception is an event occurring at hour 24, local time. Reviewing the ground-truth record for this blast shows that an origin time was not recorded by the blaster; a default value of 0:00:00 local time was noted in their records. The earthquake case shows a random distribution of events occurring both seasonally and as a function of TOD, which is an expected result. This discriminant, while simple, can be quite useful as a preliminary measure for categorizing or verifying events, particularly when the location and TOD characteristics are used together.

Amplitude Ratios

We reviewed and picked data from the 11 stations and the array shown in Figure 1 prior to measuring regional phase amplitudes. Due to poor signal-to-noise ratio (SNR), there were insufficient mining blast data from KSU1, JFWS, and LKWY to be used in the amplitude analysis. We used the magnitude and distance amplitude corrections (MDAC) methodology to make source and 1D path corrections and improve discrimination performance (Walter and Taylor, 2002).

We use the Mahalanobis distance, a multivariate statistical approach, to determine the best discriminant at each station. The Mahalanobis distance weighs the distance between two populations based upon the population variability. Using a feature selection method developed by Dr. Steven Taylor, we pre-selected 12 discriminants and determined the best amplitude ratio based upon the highest Mahalanobis distance. This analysis was performed for four cases: all earthquakes and all mining explosions; all earthquakes and only cast blasts; earthquakes within 250 km of Black Thunder and all mining explosions; and earthquakes within 250 of Black Thunder and only cast blasts. Results for all stations are shown in Figure 3.

Station	Quakes All Mining	Quakes Cast Blasts	Quakes (250 km) All Mining	Quakes (250 km) Cast Blasts
AHID	Pn(6-8)/Lg(6-8) 0.4715	Pn(6-8)/Lg(6-8) 0.4715	Pg(6-8)/Lg(6-8) 17.8398	Pg(6-8)/Lg(6-8) 17.8398
BOZ	Pn(4-6)/Pn(1-2) 1.5441	Pn(4-6)/Pn(1-2) 1.6742	Pn(6-8)/Lg(6-8) 66.5964	Pn(6-8)/Lg(6-8) 63.0015
BW06	Pg(6-8)/Lg(1-2) 0.5346	Pg(6-8)/Lg(1-2) 0.8541	Pg(6-8)/Pg(1-2) 53.2668	Pg(6-8)/Lg(6-8) 36.7874
CBKS	Pn(4-6)/Lg(4-6) 0.8514	Pn(4-6)/Lg(4-6) 0.7638	Pn(4-6)/Lg(4-6) 8.1918	Pn(4-6)/Lg(4-6) 6.8957
ISCO	Pg(4-6)/Pg(1-2) 0.9749	Pg(4-6)/Pg(1-2) 1.0498	Pg(4-6)/Pg(1-2) 9.4969	Pg(4-6)/Pg(1-2) 9.4507
MSO	Pg(6-8)/Pg(1-2) 1.5064	Pg(6-8)/Pg(1-2) 1.5064	Pg(4-6)/Pg(1-2) 6.0025	Pg(4-6)/Pg(1-2) 6.0025
PD31	Pn(4-6)/Pn(1-2) 0.3442	Pn(6-8)/Lg(6-8) 0.5673	Pg(6-8)/Lg(1-2) 6.0651	Pg(6-8)/Lg(1-2) 4.3922
RSSD	Pg(6-8)/Lg(6-8) 21.3163	Pg(6-8)/Lg(6-8) 23.2469	Pg(6-8)/Lg(6-8) 285.8222	Pg(6-8)/Lg(6-8) 123.7424

Figure 3. The top discriminants at the nine stations used in the analysis. The top value in each column is the amplitude ratio and bottom value is the Mahalanobis distance for that discriminant.

The best performing discriminants varies between stations, particularly in the performance metric (e.g., Mahalanobis distance). In general, high-frequency to low-frequency P/S ratios show the best performance, but there are deviations between stations. Additionally, Pg/Lg (6-8 Hz), which has been shown to be successful in other regions, is successful for some stations. Figure 4 shows this discriminant at all stations. As a result of low SNR at high frequencies for some stations, there is a lack of data points at stations, which makes a definitive conclusion about this discriminant difficult. Events that do discriminate from close-by earthquakes are predominantly cast blasts; smaller shots merge into the earthquake population. Despite some of the promising results seen at several of the stations for some of the events, the results are very station-centric. The application of MDAC does provide better separation, but we believe the diversity of regional geology (see Figure 1) is imprinted on the discriminant values.

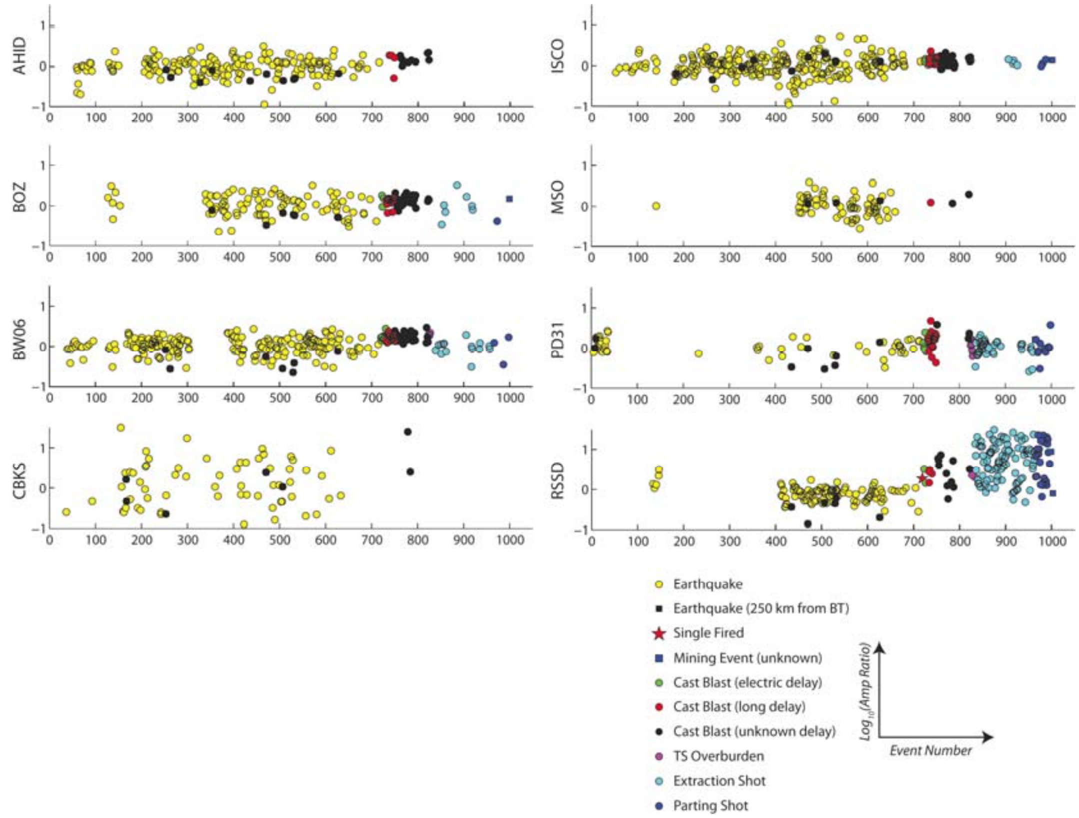

Figure 4. MDAC corrected log (Pg/Lg [6-8 Hz]) discriminants (RSSD has not been corrected, as mining events are located before the crossover distance and the MDAC methodology is not applicable for events in this region). Data are plotted as a function as event number.

Time Varying Spectral Analysis

For this discriminant we use an algorithm that has been developed for identifying delay-fired mining explosions (Arrowsmith et al., 2007). The discriminant measures the extent of time-independent spectral banding in each waveform in windows that begin at required first-arrival picks. Time-independent spectral banding, which consists of regularly spaced peaks and troughs in the frequency domain, is typically produced by delay-fired mining explosions and reflects periodicities in the nature of the source. In contrast, earthquakes and single-fired explosions do not typically contain a periodic source component. The characteristic function for time-independent spectral banding is the cepstrum of the 2D binary spectrogram, which measures periodicity in the spectral content of the waveform as a function of time. Thus, a binary spectrogram can be reduced to a single discriminant value, hereafter referred to as the cepstral mean.

The delay-fired event identification algorithm is applied to nine stations where a sufficient number of first-arrival picks were made. The resultant discriminants obtained for each station are shown in Figure 5. A common feature in the results is the clear separation between the large, delay-fired shots (cast blasts and TS overburden blasts) and the remaining event population (comprising earthquakes, extraction shots, and parting shots). The extraction shots and parting shots do not separate from the earthquakes, although there are a few exceptions. High values in the cepstral mean have been associated with inter-row delay times and total shot durations; inter-shot delay times are thought to not play a role since they are generally outside the bandwidth of the seismic observations. Figure 2 provides typical timing values for Black Thunder mining explosions. As expected, the larger blasts have the longest durations and larger inter-row delay times. Several of the extraction shots have longer durations and delay times, which may explain why there are outliers in the cepstral discriminant.

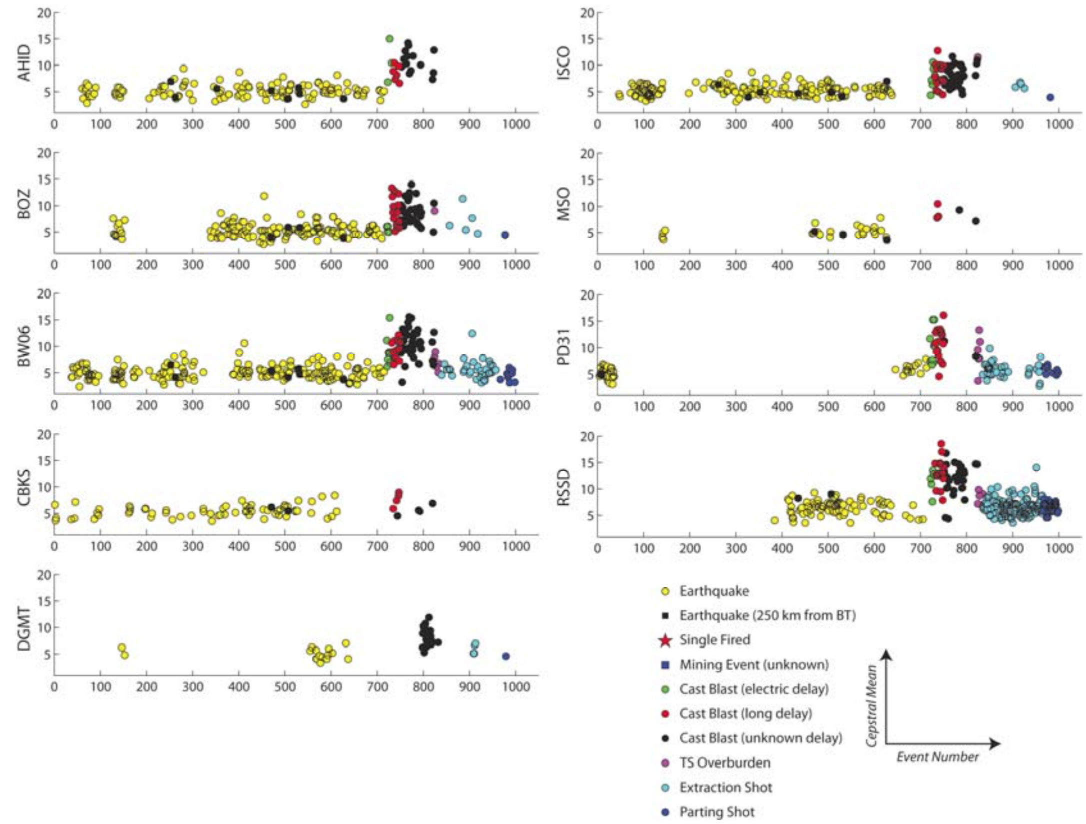

Figure 5. Cepstral mean discriminant values plotted as a function of event number.

CART Analysis

Combining discriminant measures has been shown to increase overall classification power; however, difficulty lies in combining multiple measures in a statistically sound way while accounting for problems such as missing data. In a comprehensive report, Dr. Dale Anderson and colleagues (1996) investigated eight classification methods for combining discriminants. After reviewing the methods using a comprehensive dataset of earthquakes and explosions, they found that CART met criteria related to treaty verification challenges; current discussions with Dr. Anderson about our dataset have also affirmed this method to be the most suitable for merging discriminant measures.

The classification tree considers each discriminant value, partitioning event types into homogenous regions. The process is iterative, and allows the tree to be branched or pruned based upon the number of discriminants, events, and probability levels achieved at each step in the iteration. We use a statistical software package called JMP, which has a CART module. In the example shown in Figure 6, a simple case from station RSSD is considered. Earthquake (blue) and cast blast (red) discriminant values are considered for three discriminants: TOD, Pg/Lg (6–8 Hz) amplitude ratio (Amp), and TF. Given the input data distribution assuming no discriminants are applied, the top-level box shows the probability of an event being an earthquake is 72% and 27% for a cast blast. The G^2 value is a measure of system entropy, and the goal throughout the tree-growing process is to minimize this value; the JMP routine allows us to do that by either maximizing the split statistic or maximizing the significance of the split. In the following example, we demonstrate the latter option. We can follow the tree based on whether we want to select explosions from the dataset (log(amplitude) $\geq$ 0.3925) or eliminate them from the dataset (log(amplitude) < 0.3925). For example, for the purpose of selecting explosions from background earthquakes, we choose the right path. This selects 53 probable events. The next best discriminant in this branch is TOD; by selecting events that have an hour greater than GMT of 18, we have a 97% probability of selecting a cast blast. Following the left branch of the tree, we can select events that are probable earthquakes and compare those against the values obtained in the right branch. The CART method provides a visually simple method of working with a number of discriminants, and can be tuned to handle additional discriminants (such as the presence of infrasound), as well as results for multiple stations.

Future work involves integrating data from all stations into a single blueprint that can be utilized for the different types of mining events seen in Figure 1, and applied to other regions.

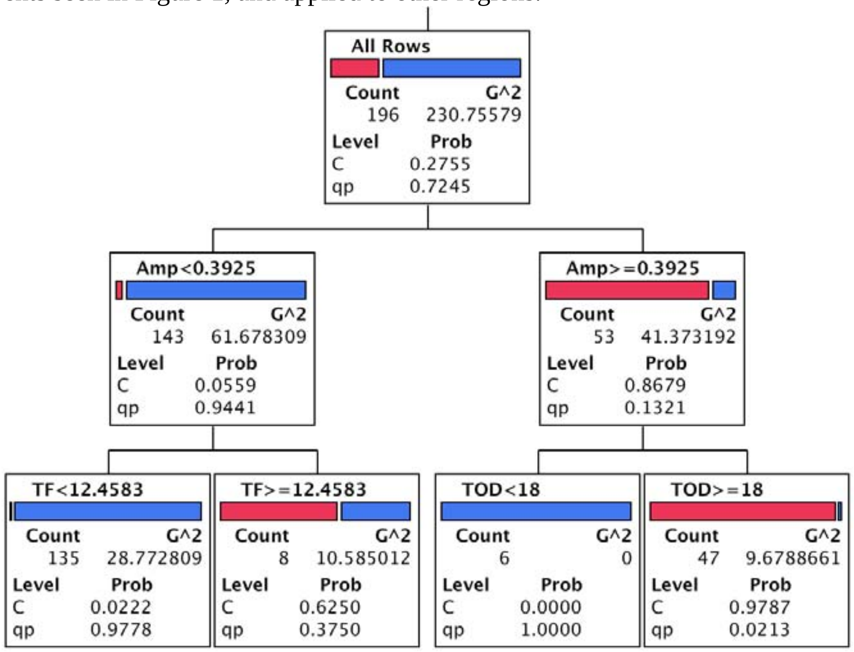

Figure 6. Sample CART tree for station RSSD output from JMP.

Addressing Discrimination in the Altai-Sayan, Russia

The AS (Figure 7) is an active mining region in Russia with numerous types of mines and quarries; approximately 40% of active surface coal mines in Russia are in the AS. The region also has a prevalence of natural seismicity due to the Asia-India collision zone to the south and the Baikal rift zone to the east. We have used this region to test the techniques developed in the Western U.S., as applied to a dataset where less is known about the ground-truth information from the mining explosions. The Altai-Sayans Seismological Expedition (ASSE) provided us with event lists (location, origin time, and m_b converted from Russian K class) of 263 probable earthquakes and 843 probable mining explosions. We were not provided the criteria for how ASSE seismologists categorized event types. We analyzed data from five seismic stations (ZAL, KURK, MAKZ, TLY, and BRVK) using the event catalogs provided to us by the ASSE.

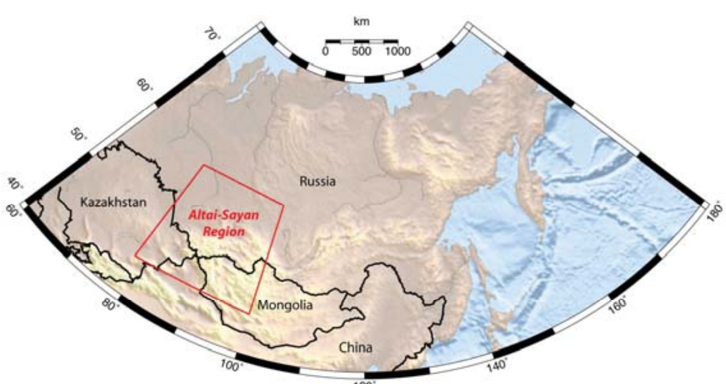

Figure 7. The Altai-Sayan region (red) is located western Siberia and encompasses portions of Kazakhstan, Mongolia, and China.

In a region where we have limited ground truth, one of the most important discriminants is the TOD information. Figure 8 shows the distribution of events with respect to month and hour for both mining explosions and earthquakes in the catalog. Mining events clearly occur during working hours, while the earthquakes exhibit no clear time-of-day dependence, providing confidence in the event bulletins supplied to us by the ASSE. These results also illustrate that TOD is not the sole criterion used by the ASSE in constructing the event bulletins, since the earthquakes occur also during working hours.

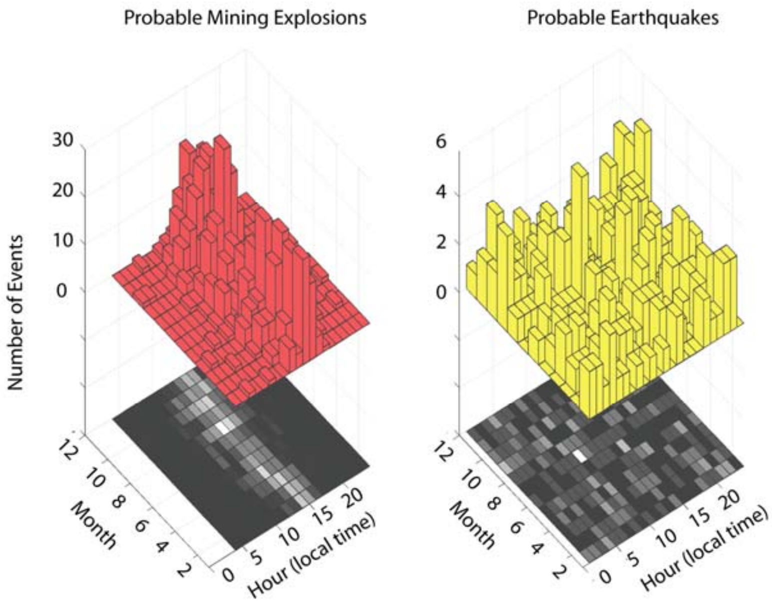

Figure 8. Time-of-day distribution with respect to month and hour of day for the dataset for both probable mining events (left) and earthquakes (right). Surface reflections of the histograms show trends, where lighter colors indicate larger numbers of events.

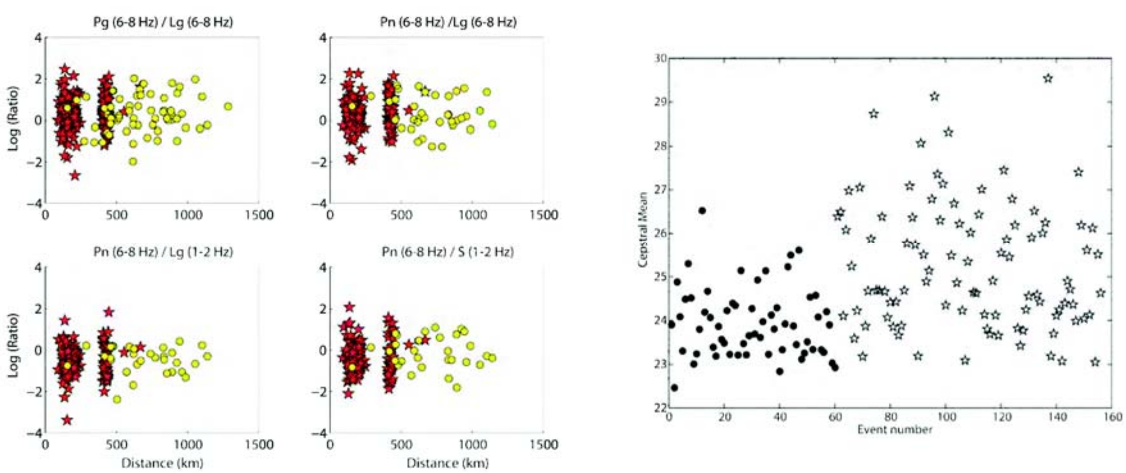

Figure 9. Four log(amplitude ratios) (left) as a function of distance at station ZAL. Amplitude ratios are not corrected since instrument response problems are known at this station; however it is the closest station to the mining region. Data were analyst-reviewed and events with SNR > 2 are shown. The cepstral mean for this dataset is shown at right.

Amplitude ratio discriminants (Figure 9) were not successful in separating waveforms from mining explosions from those generated by earthquakes in this region for multiple stations. There is large scatter in the explosion population (up to four log units), suggesting that different blasting types and timing patterns may be dominating the discriminant, since the propagation paths are very similar for each blast, although for certain discriminants the earthquake populations are similarly scattered; this phenomenon is seen for analyst-reviewed data of SNR quality at multiple stations. Without further ground truth, we cannot be sure what causes the failure of this discriminant. The time-frequency discriminant (Figure 9), which proved very successful in a multitude of geological regions within the Western U.S. and Interior Plains also does not work well in the AS region, again at multiple stations. Certain events have a high cepstral mean, and based upon the Western U.S. results, we can presume those are the largest blasts which emulate the cast or TS overburden shots we observe at Black Thunder. However, the majority of the mining events do not discriminate from the earthquakes and with a lack of information from the mines themselves, we cannot conclude definitively the reason why the discriminant behaves poorly.

CONCLUSIONS AND RECOMMENDATIONS

In the Western U.S., we have gathered a large set of mining explosions from a region with prolific blasting activity. Due to a working relationship with a mining operator, we have detailed ground-truth for the dataset, which is crucial for understanding the behavior of waveform-based discriminants. A simple discriminant, time-of-day, is useful for verifying the event catalog and shows that mining events that are clustered in certain regions are confined to working hours. Amplitude ratios, which have been useful in other regions (high-frequency P/S), show mixed results in the Western United States. A number of factors come into play for this discriminant. The results are very station-centric, suggesting that sensitivities due to regional geology affect the discriminants. Attenuation studies in the Western U.S. by Phillips and Stead (2008) show strong variations in Lg amplitudes with relation to detailed crustal structure, implying that simple 1D path corrections are likely inadequate for the broad region of our study. Additionally, different event types seem to yield different discriminant results, with the larger cast blasts performing better. This result is also true for the time-frequency discriminant. Larger blasts discriminate very well, and station location seems to play no role in the success of the discriminant, consistent with the fact that this discriminant is strongly related to the distinctive spectral shape resulting from the long source duration. Smaller blasts merge with the earthquake population for this discriminant, and as there are many small blasts in the dataset, it would be easy to assume the discriminant was not working if we did not have the additional explosion features summarized in Figure 1. Being able to constrain the type of shot, as well as other types of information on the blasting configuration is invaluable in assessing discriminant success. Early work using the CART methodology to combine discriminant information gives a valuable and easy to use tool for synthesizing the multiple results we have obtained and assess the importance of multiple discriminants in characterizing the data set. The complete assessment of this tool is an ongoing study.

Applying these discriminants to the Russian dataset, which has very limited ground truth, yields much less promising results. The best performance comes from the time-of-day discriminant, which shows that mining events are constrained to working hours. Event locations are clustered in areas of known active mines. Both amplitude ratios and time frequency discriminants are largely unsuccessful, but this does not imply discriminant failure, just that we lack sufficient information to properly assess the results we see. Given these findings, we suggest the following recommendations: any future datasets in which mining explosions are specifically to be acquired should involve intense collaboration with mining operators; due to the regional imprint seen in the Western U.S. amplitude ratio values, understanding and correcting for path requires having a high-quality, highly station-sampled dataset. These results further motivate the development of detailed regional attenuation maps that can be used to correct regional amplitudes prior to discrimination analysis. The deterioration of the amplitude ratio discriminants with range found in the Western U.S. illustrates this effect.

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REFERENCES

Anandakrishnan, S., S. R. Taylor and B. W. Stump (1997). Quantification and characterization of regional seismic signals from cast blasting in mines; a linear elastic model, *Geophys. J. Int.* 131: pp. 45–60.

Anderson, D.N, K. K. Anderson, D. N. Hagedorn, K. T. Higbee, N. E. Miller, T. Redgate, and A. C. Rohay, (1996),.Statistical Classification Methods Applied to Seismic Discrimination, *Pacific Northwest National Laboratory report PNNL-11192US*, pp. i–27.

Arrowsmith, M. D., S. J. Arrowsmith, B. Stump, and M. A. H. Hedlin (2007). Discrimination Capability for Mining Events in the Altai-Sayan Region of Russia and the Western United States, in *Proceedings of the 29th Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-07-5613, Vol. 1, pp. 531–540.

Arrowsmith, S. J., M. A. H. Hedlin, M. D. Arrowsmith, and B. W. Stump (2007). Identification of delay-fired mining events using seismic arrays: Application to the PDAR array in Wyoming, USA, *Bull. Seism. Soc. Am.* 97: pp .989–1001.

Arrowsmith, S. J., M. D. Arrowsmith, M. A. H. Hedlin, and B. Stump (2006). Discrimination of delay-fired mine blasts in Wyoming using an automatic time-frequency discriminant, *Bull. Seism. Soc. Am.*. 96: pp. 2368–2382.

Energy Information Administration (2007). Annual Coal Report 2006, United States Department of Energy, DOE/EIA-0584.

Jimeno, C. L., E. L. Jimeno, and F. J. A. Carcedo (1995). Drilling and Blasting of Rocks, A.A. Balkema, Netherlands, pp. 179–190.

Mackey, K. G., K. Fujita, L. V. Gounbina, B. M. Koz'min, V. S. Imaev, L. P. Imaeva and B. M. Sedov (2003). Explosion Contamination of the Northeast Siberian Seismicity Catalog: Implications for Natural Earthquake Distributions and the Location of the Tanlu Fault in Russia, *Bull. Seism. Soc. of Am.* 93: 737–746.

Phillips, W. S. and R. J. Stead (2008), Attenuation of Lg in the western U.S. using the USArray, *Geophys. Res. Lett.*, Vol. 25, L07307, doi:10.1029/2007GL032926.

Stump, B. W., D. C. Pearson and V. Hsu (2003), Source scaling of contained chemical explosions as constrained by regional seismograms, *Bull. Seism. Soc. Am.* 93: pp.1212–1225.

Walter, W. R. and S. R. Taylor (2002). A Revised Magnitude and Distance Amplitude Correction (MDAC2) Procedure for Regional Seismic Discriminants: Theory and Testing at NTS, *Lawrence Livermore National Laboratory UCRL-ID-146882*, pp. 1–13.