A COMPARATIVE TEST OF SEISMIC DISCRIMINANTS FOR MINING EXPLOSIONS

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

University of California at San Diego[1], Southern Methodist University[2]

Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. DE-FC52-03NA99511[1], DE-FC52-03NA99510[2]

ABSTRACT

Seismic event identification can be viewed as a task to separate a collection of events into classes that could include earthquakes, single-fired explosions (nuclear or chemical), mining explosions, and underground mining collapses or rock bursts. Historical event identification based upon teleseismic data focused upon the simpler task of separating earthquakes and explosions. This approach was adequate for large events observed at teleseismic distances because there are few mining explosions, mining collapses and rock bursts large enough to be observed. The development of a robust seismic monitoring network, including high performance regional arrays has provided the opportunity to observe small-to-moderate size events that include many manmade sources. This transition in instrumentation and monitoring interest motivates this study to quantify event identification procedures focused upon mining explosions as separate from contained, single-fired explosions. A recent review of mining explosion tools has illustrated the vast array of tools available for this task (Stump *et al.,* 2002). The tools developed for this identification task should ideally be applicable to mining regions around the world. Broad application of tools requires an assessment of regional propagation path effects and a linkage of the identification procedures to the physical processes that accompany the mining explosion. We are studying mining explosions and their accompanying regional seismic waves in two regions in order to accomplish these goals. The first region is the continental United States (U.S.). We believe that this region is critical to the study because (1) significant ground truth information already exists; (2) a mixture of delay-fired and contained single-fired explosions either already exist or are planned; (3) multiple, high-performance regional arrays (PDAR, NVAR, TXAR) already exist; and (4) the U.S. can be divided into two distinct regions of propagation path — high attenuation in the west and low attenuation in the east. The second region of study is another area of significant mining activity, the Altai-Sayan in Russia. Ground truth information in this region is not as robust but is being expanded under this study. The tools developed in the U.S. will then be applied to data obtained for the numerous large-scale explosions in this region. A preliminary assessment of blasting in this region accompanied by seismograms has already been completed.

OBJECTIVES

To reach our primary goal of testing an integrated suite of discriminants in mining regions in the United States and Russia, we have a number of objectives each year. In the first year our objectives are as follows:

- Assembly and delivery of U.S. database.
- Identification of foreign region for study. Identify mine clusters in the foreign region.
- Develop contacts in foreign region for ground truth. Initiate communication with local seismologists, mining officials, and Russian authorities before a site visit. Develop a collaborative relationship with members of the nuclear monitoring and mining communities in Russia.
- Code development.

Objectives for the second year are as follows:

- Test integrated suite of discriminants on data from U.S. mining regions.
- Assembly and delivery of foreign database. We plan an initial dataset of 500 events recorded by five stations in the International Monitoring System (IMS) and the Ground Station Network (GSN), with detailed ground truth data on several mine blasts.
- Assessment of the U.S. results and modification of the tools based on initial testing.

Objectives for the third year are as follows:

- Test integrated suite of discriminants on foreign database.
- Assessment of testing of foreign database.
- Delivery of techniques and software.

We are currently in year 1. As will be described in the next section, we are ahead of schedule in some areas and are now working on some tasks originally planned for year 2. We believe that code development, originally to be completed in year 1, will not be completed until the first quarter of the second year of our contract.

HISTORICAL PERSPECTIVE

There is an unprecedented need to reliably discriminate mining explosions from nuclear tests, earthquakes and other mining related events. The crux of our effort is to determine if regional seismic data can reliably characterize mine blasts and reliably separate them from these other event types. Mining explosions are the most enigmatic among the large number of low magnitude-events. All mining events occur at shallow depths, and therefore a simple depth discriminant will never separate these events from nuclear tests. Like nuclear tests, mining blasts are detonated at a chosen time and place. It has been well documented that single-fired chemical explosions cannot be distinguished from nuclear explosions using seismic observations (Denny, 1994; Stump *et al.,* 1999). Fortunately, large-scale, single-fired chemical explosions are rare. Large-scale chemical explosions are used in the mining industry but most often with delay-firing thus introducing a spatial and temporal difference from concentrated, single-fired explosions. Because this latter type of explosion is very common, it will be necessary to identify the unique characteristics of seismic waves associated with this event type.

Although numerous mine-blast discriminants have been tested, some with notable successes (e.g., Baumgardt and Ziegler, 1988; Harris, 1991), so far no single technique has been globally reliable or transportable. Given the high cost of misidentification, no one technique is satisfactory. If there is a panacea for this problem, it may lie in the use of an integrated package of discriminants, particularly if the physical reasons for the failure of a single discriminant can be documented and understood. We have seen that the complexity of the mining explosions themselves and further complexity introduced by seismic wave propagation to the receivers cause the performance of generic discriminants to be regionally dependent. To date, there has been no operational test of an integrated discriminant package for identifying mine blasts. There is a clear need to develop, implement, test, and interpret such a discriminant package, possibly regionally tuned. The physical basis of these discriminants must be understood in order to interpret their performance under different conditions. This effort is built around extensive experience in blasting supported with ground truth information intended to provide these physical interpretations. For instance, L_g blockage along certain paths can move earthquakes into explosion populations, or long source durations from some types of mining explosions may provide efficient excitation of intermediate period surface waves, unlike a concentrated charge.

Technical Issues

The review by Stump et al. (2002) illustrates that there are a number of questions that remain to be solved for effective identification of mining explosions around the world. These questions have played an important role in both motivating this effort and influencing the design of the research we will carry out.

What is the linkage between the physical effects accompanying mining explosions and the observed regional waveforms? A number of physical processes are important in how mining explosions generate seismic energy and include both the spatial extent of the multiple boreholes and the complex detonation pattern in time of these boreholes. These characteristics have been related to complex spectral interference patterns as well as the relative generation of long- and short-period energy. These physical contributions to the waveforms are in some sense dependent upon the style of blasting employed at a particular mine. Ultimately, this understanding of the relationship between blasting practices and regional discriminants will provide a basis for assessing discriminant performance in other regions of the world if some information is available on mine-blasting style.

Why are individual discriminants that are successful in one region subject to failure in another? Separation of physical processes accompanying mining explosions and regional propagation path effects will be critical to the assessment of this question. This problem can only be approached through a physical understanding of the source, possibly supported by empirical observations and ground truth, and an assessment of regional path effects. We will focus on the physical understanding of the source and the collection of ground truth and rely upon the National Nuclear Security Administration (NNSA) regional characterization effort to help assess path effects.

Can a set of integrated regional discriminants provide the basis for identifying or classifying mining explosions at regional distances? The review of techniques for identifying mining explosions at regional distances has illustrated the failure of individual discriminants either because of source or propagation path variations. We intend to test the proposition that a suite of tools properly applied and physically interpreted can provide robust identification.

Can regional seismic data, including array data, beyond 5^o be used to reliably discriminate mining explosions? In four of the world's major mining regions, the Altai-Sayan, the Powder River Basin, Morenci in Arizona, and Minntac in Minnesota, there is one seismic station within 2^o–4^o of the mines with additional stations at considerably farther distances. This means that many of the regional observations for these small events may be at great regional distances with the accompanying reduced amplitudes and limited bandwidth. The practical test of the proposed discriminants in a number of mining regions will provide experience with the effects of such station coverage on identification performance.

How important are anomalous blasts in the identification process? Mining blasts that do not detonate as planned can produce regional waveforms that are impulse as when a large number of the explosive boreholes detonate simultaneously. This type of blast is rare but has been observed and thus with the observed equivalence of seismograms from single-fired chemical and nuclear explosions could be problematic. The systematic analysis of a large number of mining explosions in a number of different parts of the world will allow us to assess the importance of this problem.

RESEARCH ACCOMPLISHED

In this section we describe our preliminary work to develop an integrated suite of discriminants. We use the United States as a control because we have experience in monitoring in this area, can readily obtain ground truth information, and can include data from contained single-fired explosions. Ground-truth data are an essential for any study of seismic discriminants. This dataset will prove invaluable to test the operational effectiveness of an integrated identification package in Russia where less is known about the sources and the paths to the stations.

<u>**Assembly of U.S. Database**</u>

We see the U.S. as a logical test-bed for the suite of discriminants because of the high quality of ground truth in this area. Our initial focus is in three areas for which ground truth is under development. The first is the area surrounding the Powder River Basin in northeast Wyoming. This region has active surface coal mining activities. Contact with local mines is providing ground truth information on recent cast blasting. We have gathered data for approximately 300 mining explosions recorded at the seismic and infrasound arrays in Pinedale, Wyoming (PDAR/PDIAR). The mining explosion database is being supplemented with earthquakes in Utah, Wyoming, Montana, and Idaho also recorded at PDAR/PDIAR. Future plans include expanding the database to include data from other regional stations. A companion study (Zhou et al., 2004*)* has analyzed the intermediate period surface waves generated by blasts in this region and applied a variant of the M_S:m_b discriminant to the data with some success. A series of contained, single-fired explosions (Stump et al. 2004), will provide an additional comparison.

The second focus area of our U.S. study is the porphyry copper mines of southeast Arizona where mining explosions are used to fracture rock for copper extraction. A database of mining explosions is being developed for this region as well. We intend to incorporate seismic and infrasound measurements from within one of the mines in the region to supplement the ground truth database. This database currently consists of 229 events for which ground truth information, including in-mine seismic and acoustic observations are available. A summary of this in-mine database is given in Figure 1a, which shows the peak ground motion and acoustic measurements and Figure 1b, which illustrates one of the shot patterns. A trip to the mine during January provided the opportunity to retrieve data from the in-mine recording system. The data-acquisition systems were placed in trigger mode so that additional ground truth could be recorded.

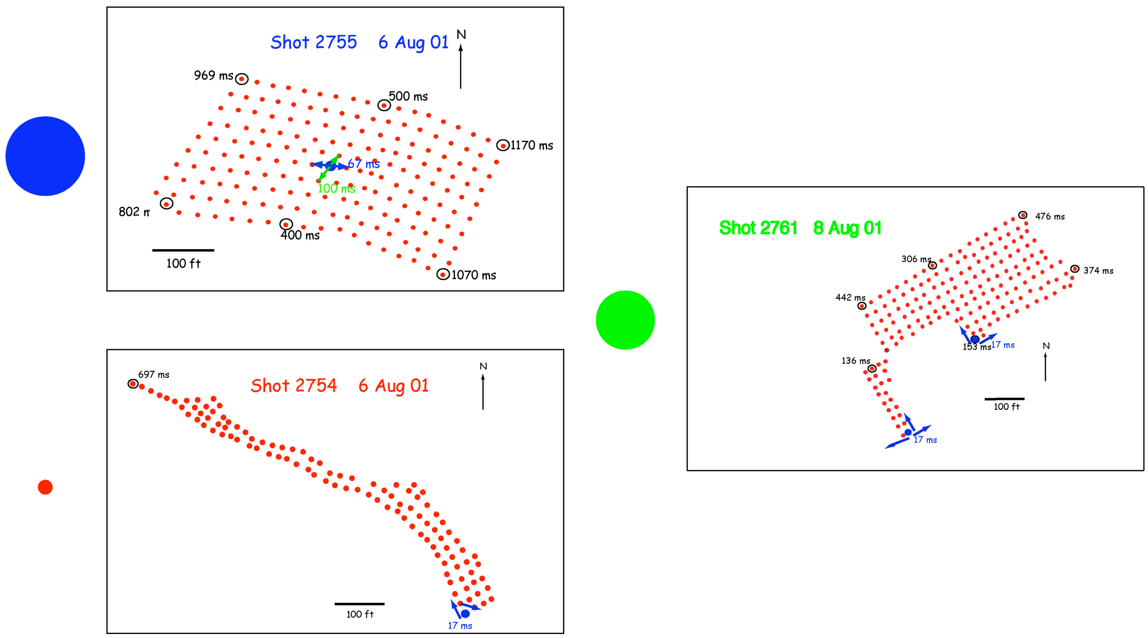

Figure 1a: Three example shot patterns from the southeastern Arizona ground truth database. The radius of the circle next to each pattern is proportional to the size of the blast with the largest, 348,070 lb. As noted in the figure, the largest shot (blue) uses much longer delay times than the other two shots.

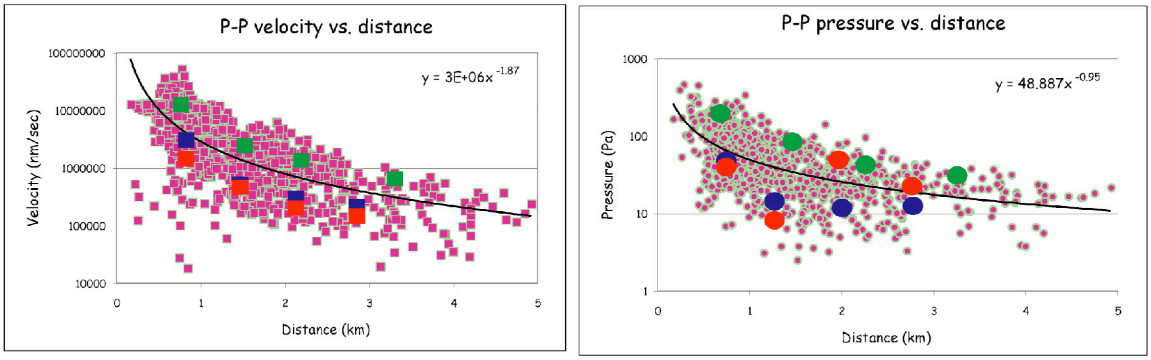

Figure 1b: Summary of the southeastern Arizona mining ground truth database. In-mine seismic and acoustic measurements from 229 explosions are summarized. The measurements for the three shots diagramed in Figure 1a are superimposed. The largest shot (blue) does not have the largest amplitudes either in-mine or at regional distances as a result of the longer delay times between individual shots. This information will be valuable in assessing the discriminants.

This area is the location of one of the two sites of a series of single-fired explosions conducted as part of the Source Phenomenology Experiment (Leidig et al., 2004). Data from these single-fired explosions and delay-fired explosions conducted during the experiments will be critical to our understanding of mining-explosion performance. Two record sections comparing a single-fired and delay-fired explosion are reproduced in Figure 2.

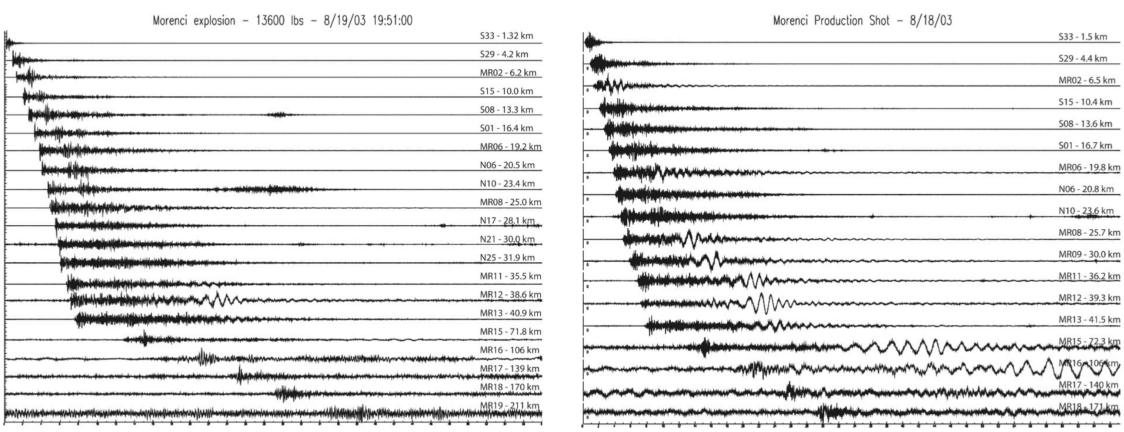

Figure 2: Regional record sections from a single-fired (left) and delay-fired (right) explosion detonated at one the southeastern Arizona copper mines.

The third area of focus is the Taconite Mines in Minnesota. Cooperation with one of the mines in the area provides shot information on each of the shots. The ground truth database currently consists of 472 events. The information provided includes the details of the shots in terms of the total amount of explosives, the number of shot holes, and the environmental conditions. The environmental conditions include the local wind speed and direction at shot time that may be important in understanding the accompanying infrasound signals. Figure 3 illustrates the type of data that is being gathered and the relatively large size of these blasts in Minnesota. We intend to visit the mine this summer for additional ground truth information.

In order to begin building the U.S. database of relevant seismic data, we contacted Dr. William Walter at Lawrence Livermore National Laboratory. Dr. Walter and his colleagues have assembled a database of seismic events featuring nuclear and mining explosions, as well as earthquakes, for the western U.S. (Walter et al., 2003). Dr. Walter agreed to distribute to us a copy of this database once his research team had finished making arrival onset picks and performing waveform quality control. He will be in contact with us once this occurs so that we may make arrangements for transferring the data.

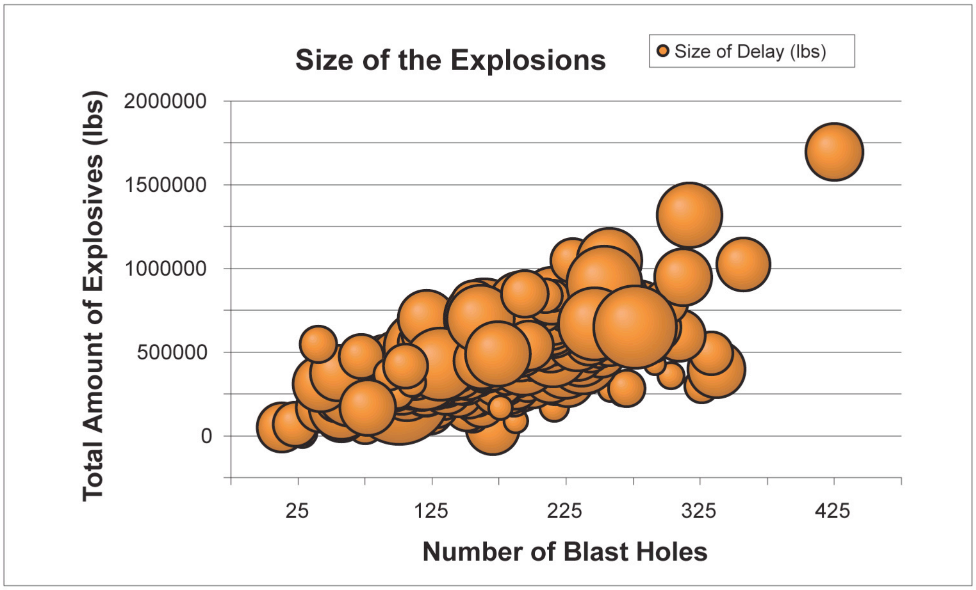

Figure 3. Summary of the Minnesota ground truth database. The largest explosion exceeds 1,500,000 lbs and consists of 425 individual blast holes.

Identification of foreign region

One of our primary goals for the first year was to identify a foreign region for study. We have selected the Altai-Sayan (A-S) mining trend near Novosibirsk, Russia. The A-S mining region is one of the largest and most active in the world. The 500 km long Altai-Sayan mining trend is located in a Paleozoic folded terrain just north of the Mongolian Altai and the Tien Shan. This is clearly a key area for monitoring research. This active mining trend is monitored by single stations and arrays in the IMS and the GSN as well as stations in the regional Altai-Sayan Seismological Expedition (ASSE) network (Figures 4 and 5) and offers a great range of mine blasts (e.g., explosive yield, shot patterns). Some ground-truth data was obtained from this region in the past, and we expect more detailed information in the future. One key to this analysis is identification of mine clusters in the Altai-Sayan trend. We have identified 8 clusters of mines in this trend (Figure 5). The clusters have been defined using event locations obtained by the ASSE network. We will seek more information about the mines in these clusters during our site visit (next section).

Development of contacts in Russia — Site Visit

With the target region selected, we have arranged for a site visit to Novosibirsk, Russia, and a mine in the Altai-Sayan mining trend in August, 2004. We believe that significant progress in this area will come with us working directly with experts from the Novosibirsk area. Dr. Khalturin has discussed the site visit with Dr. Vladimir Pergament, Head of the Mining Blasts Seismic Effects Laboratory of Magnitogorsk State Technical University. Dr. Pergament has agreed to work with the U.S. team during their site visit. Hedlin, working with Vitaly Khalturin, has contacted Dr. Alexander Fedorovoch Emanov, Head of the Altay-Sayans Experimental Methodological Seismic Expedition and Dr. Victor Sergeevich Seleznev, Head of the Siberian Geophysical Survey about this visit.

In August of this year, the entire team from Southern Methodist University (SMU) and the University of California at San Diego (UCSD) will travel to Novosibirsk for meetings with local seismologists and mining experts. We have several objectives in making this trip. First, we intend to establish a collaborative relationship with our counterparts in this area. Extensive discussions to date indicate that there are many areas of mutual interest relating to the monitoring of mining activity. Once common ground has been discussed in detail, our goal is to prepare for a detailed study of mine blasts in the A-S trend for the next 2 years. Historically, there has been limited ground truth data from this region. The information we have had access to in the past is typically lacking in detail. When detailed information about a blast is provided, it hasn't been possible to authenticate it. We will seek detailed ground-truth data for several large mine blasts that will occur during the next 12 months. We also seek general information about mining along the A-S trend—the types of mining techniques, the types of material recovered, etc. We will also visit a coal mine in the Kuzbass region to observe a mine blast and to prepare to record a ground truth blast in that mine in 2005. We will inquire about gaining access to data from the 17-station ASSE Network (Figure 5).

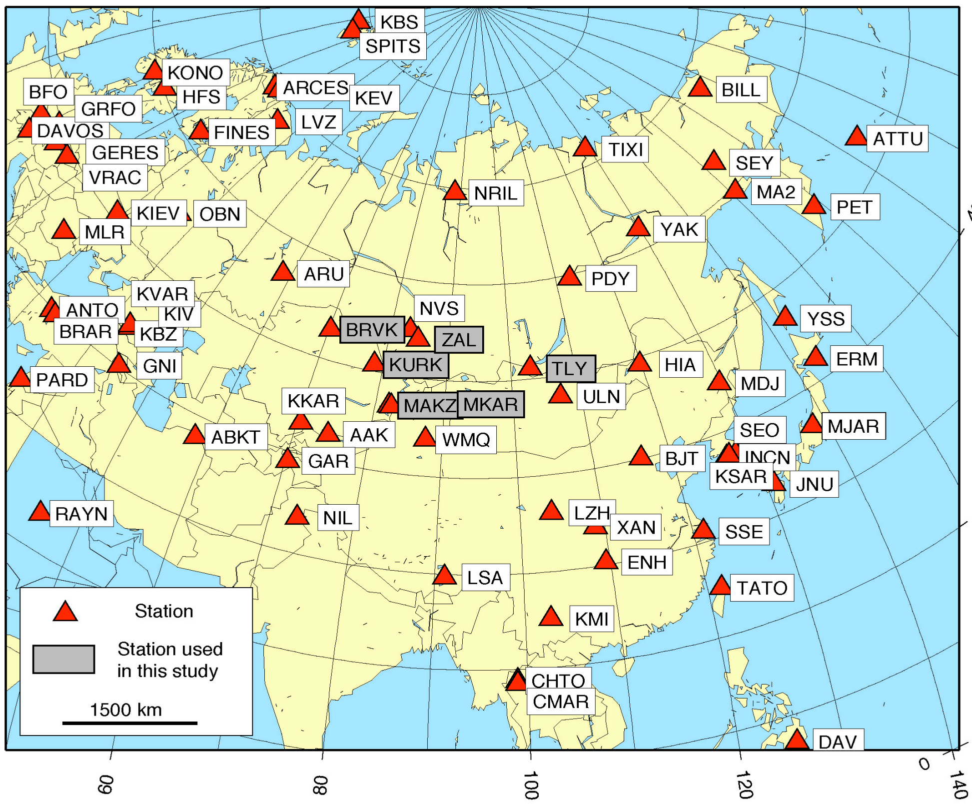

Figure 4. Seismic station coverage in Asia. The stations included in this study are highlighted.

Assembly of Russian Database

The Altai-Sayan trend is a natural laboratory for the study of mine blast identification tools. The trend includes several significant clusters of mines (Figure 5). Seismic-station coverage in the Altai-Sayan mining trend and surrounding region is indicated by Figures 4 and 5. The 3-component IMS station ZAL is located between ~100 km and 500 km from these clusters. This site has been recording data since day 346, 1991. The IMS array (MKAR) lies ~6° from most mines in the trend, and began delivering data on day 319, 2000, in a test phase; MKAR was certified as a primary IMS array in January 2002, and subsequent data are available through the International Data Center (IDC). Other IMS stations, KURK, TLY, BRVK, are not yet established; however, the Incorporated Research Institutions for Seismology (IRIS) GSN stations are operating at these sites and providing data for this study. Additional 3-component data from GSN station MAKZ , located southwest of the mining trend, serves as a surrogate for MKAR for the time prior to certification as an IMS array. All stations lie to the west, east, and south within ~1,000 km of the trend. We are presently developing a database of 500 mining events recorded at these stations in the IMS and the GSN.

The large numbers of events in each cluster identified in Figure 5 should prove useful in testing event correlation techniques (e.g., Harris, 1991) and in testing any other discriminant evaluating the performance of the event identification tools as a function of event location.

An essential component of this database will be ground truth data. A key goal of our site visit is to arrange for the collection of detailed ground-truth data from the mines in the A-S region. We have limited ground truth information for several thousand mine blasts that occurred between 1997 and 2001.

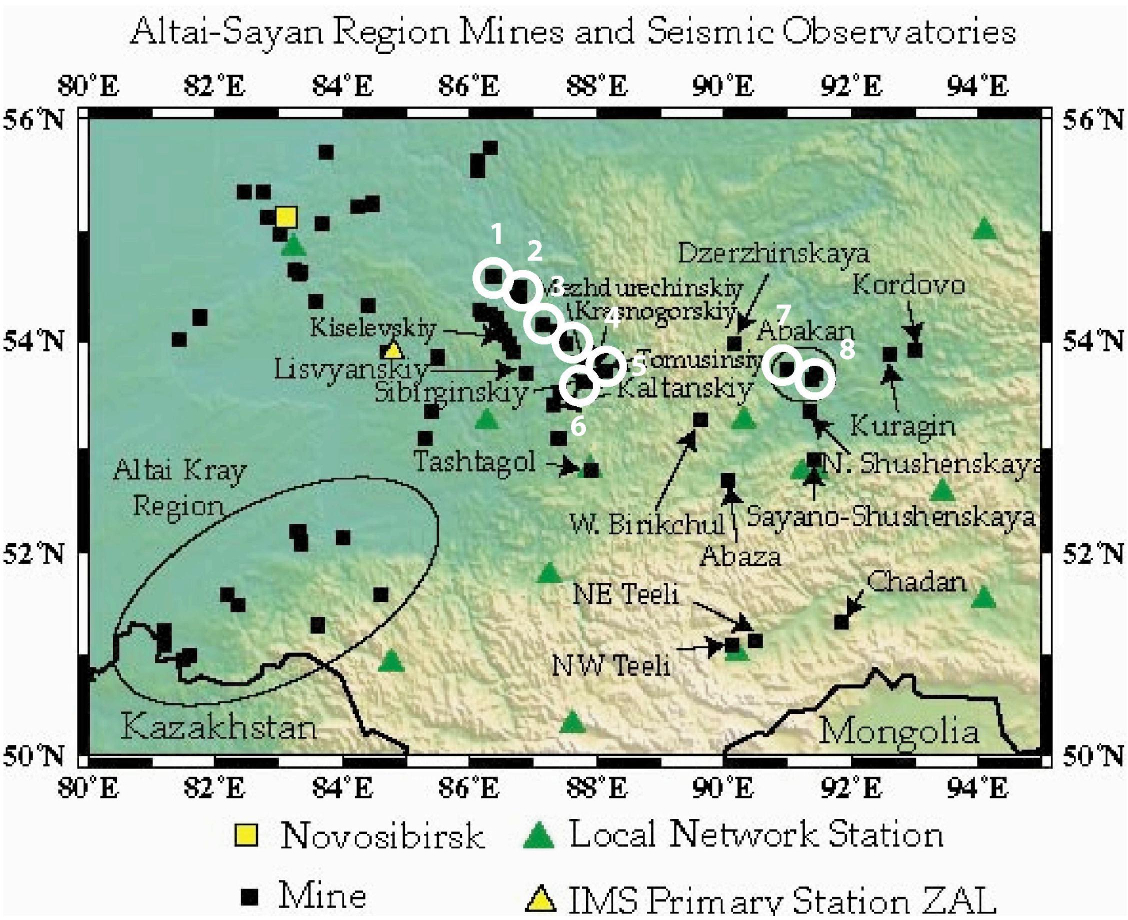

Figure 5. Mines in the Altai-Sayan region, stations in the Altai-Sayan Seismological Expedition regional network and the IMS (station ZAL). Eight clusters of mines/mining events are outlined.

__Code development__

Successful event identification employs analysis techniques using regional seismic data that identify characteristics for mining explosions that are distinct from those produced by contained, single-fired explosions and earthquakes. Special consideration is given to techniques that separate single-fired, contained explosions from delay-fired explosions typical of mining operations (Baumgardt and Ziegler, 1988; Smith, 1989; Hedlin et al.,1989; Chapman et al., 1992; Hedlin et al., 2002*)*. Procedures must minimize false alarms, the misidentification of a mining explosion as a contained, single-fired, possible nuclear explosion. A broad suite of discriminants has already been developed. Discriminants that we will include in our suite include the following:

- P/L_g at high and low frequency
- Surface Wave to Body Wave Amplitudes
- Time-varying spectral estimates
- Low-frequency modulations
- Correlation analysis
- Time-space clustering
- Acoustic and seismic signals

Our focus is to consistently test the complete list of identification tools and to judge the ultimate joint ability of these tools to separate mining explosions from single-fired explosions and earthquakes. Establishing the underlying physical basis of the tools is critical to developing a complete set of useable, portable, and extendable discriminants. Ground truth information is used to link the performance of individual identification tools to the physical processes accompanying the mining explosion. This information can be as simple as the source time and location but preferably includes details such as the individual borehole blast timing and explosive weight.

The application of multiple discriminants to single events means that some consideration of methods for combining the individual estimates must be considered. In our case, the use of ground truth information will be used to assess each discriminant and assess its contributions to the identification process. This will be based around the development of a physical understanding of discriminant performance with specific consideration of path and source contributions.

Through collaboration with Los Alamos National Laboratory (LANL), we intend to use regional discrimination methodology as described in Hartse *et al.* (1997) and associated computer codes developed by the Ground-based Nuclear Explosion Monitoring (GNEM) team at LANL. For example, the MDAC2 procedure removes magnitude and distance trends in regional phase amplitudes, allowing for maximum flexibility in the later construction of discriminants (Walter and Taylor, 2002). LANL also has developed feature selection codes that use the Mahalanobis distance metric as a measure for combining the best phase and spectral discriminants. We plan to tailor the discrimination work already accomplished at LANL for use on both the U.S. and Russian datasets.

Regional Ms:mb discriminant: Rong-mao Zhou (2004) has been developing a regional equivalent of the M_s:m_b discriminant. The procedure includes the determination of dispersion relations for intermediate period surface waves so that region-specific path corrections can be made to the observed surface waves. Preliminary application of the procedure to mining explosions in Wyoming and NE China suggest that large-scale, long-duration mining explosion may be identified as earthquakes.

Infrasound data: If techniques based solely on seismic data cannot provide an unambiguous classification of an event, infrasound data might be particularly useful. Surface blasts are known to generate large infrasonic waves, and propagation of these waves is particularly efficient downwind. Seasonal changes in stratospheric winds are well understood. As a result, it is known when IMS infrasound stations will be sensitive to mining activity. One example comes from the 8-element infrasound array at Pinon Flat in southern California. The array is ~400 km downwind of mines in eastern Arizona. The array at Pinon detects signals from mine blasts in Arizona during the summer season when the zonal stratospheric winds are to the west. We have detections from mines in the Kayenta and Morenci regions.

Integration: Ultimately rigorous methodologies for combining discriminants must be proposed and refined. We do not intend to develop such approaches as part of our research but take advantage of developments in this area by others. Specifically, we are interested in the preliminary work of Anderson and Taylor in this area. We have spoken to Dale Anderson at Pacific Northwest National Laboratory about coordinating our regional discrimination study of mining explosions with his development of methodologies for combining discriminants. He has expressed interest in communication and cooperation in this area. We feel that this cooperation will be critically important to the implementation of results developed during this research project.

CONCLUSION(S) AND RECOMMENDATION(S)

A key objective in nuclear monitoring is to find seismic-signal processing methods that have the potential to lower the thresholds at which detection, location, and identification functions can be performed without increasing false alarm rates to unacceptable levels. New techniques for discrimination, which make "significant improvement over current techniques" are of interest. We seek to address these issues as they relate to the monitoring of mining activity. It is well known that individual discriminants that have been found to be useful in some areas are often prone to failure in others and that one reason the discriminants fail is because the physics of signal generation at the source and propagation to the receiver are not yet well enough understood. We believe the solution to the problem posed by global mining activity lies in using all of these discriminants as an integrated package. We are developing this package, and will improve our understanding under what conditions the individual modules within the package will sometimes fail and use the package in a significant mining region in Russia. We have chosen to study the Altai-

Sayan mining in Russia under this second phase of our analysis because of the need to improve the U.S.'s ability to effectively monitor in this region.

ACKNOWLEDGEMENTS

Vitaly Khalturin (Lamont Doherty Earth Observatory) and Anna Titova (Siberian Geophysical Survey) for assistance with our work in Russia. Additionally, we wish to thank Steve Beil of Black Thunder Mine for providing shot times; Steve Taylor of LANL for facilitating access to codes; and Bill Walter of LLNL for sharing the Western U.S. dataset upon its completion.

REFERENCES

Baumgardt, D.R. & K.A. Ziegler, (1988), Spectral Evidence for Source Multiplicity in Explosions: Application to Regional Discrimination of Earthquakes and Explosions, *Bull. Seism. Soc. A., 78*, 1773-1795.

Chapman, M.C., G.A. Bollinger, & M.S. Sibol, 1992, Modeling Delay-Fired Explosion Spectra at Regional Distances, Bull. *Seism. Soc. A.,* 82*,* 2430-2447.

Denny, M. P., Editor, 1994, Proceedings of the Symposium on the Non-Proliferation Experiment (NPE): Results and Implications for the Test Ban Treaties, April 19-21, 1994, Rockville, Maryland, CONF 9404100, LLNL.

Harris, D.B., 1991, A Waveform Correlation Method for Identifying Quarry Explosions, *Bull. Seism. Soc. A.,* 81, 2395-2418.

Hartse, H., S. Taylor, W. Phillips, and G. Randall (1997), Regional Event Discrimination in Central Asia with Emphasis on Western China, *Bull. Seism. Soc. A.*, 87, 551-568.

Hedlin, M.A.H., J-B Minster, & J.A.O. Orcutt, (1989), The Time-Frequency Characteristics of Quarry Blasts and Calibration Explosions Recorded in Kazakhstan, USSR, *Geophys. J. Int.,* 99, 109-121.

Hedlin, M. A. H., B.W. Stump, D.C. Pearson & X. Yang, (2002), Identification of Mining Blasts at Mid- to Far-Regional Distances Using Low Frequency Seismic Signals, *PAGEOPH,* 159, 831-864.

Leidig, M. R., B. W. Stump, J. L. Bonner, C. T. Hayward, A. A. Velasco, D. F. Baker, H. Hooper, W. R. Walter, X. Yang, R.-M. Zhou, C. L. Edwards, M. D. Renwald, T.-S. Kim, M. McKenna and J. F. Lewkowicz, (2004), "Source Phenomenology Experiments in Arizona", in *Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring*, Orlando, FL (Sept. 21-23, 2004).

Smith, A.T., (1989), High-Frequency Seismic Observations and Models of Chemical Explosions: Implications for Discrimination of Ripple-Fired Mining Blasts, *Bull. Seism. Soc. A.,* 79*,* 1089-1110.

Stump, B. W., D. C. Pearson and R. E. Reinke, (1999), Source Comparisons Between Nuclear and Chemical Explosions Detonated at Rainier Mesa, Nevada Test Site, *Bull. Seism. Soc. A. 89,* 409-422.

Stump, B., M.A.H. Hedlin, D.C. Pearson, and V. Hsu, (2002), Characterization of Mining Explosions at Regional Distances, *Reviews of Geophysics, 40(4), 1011, doi:10.1029/1998RG000048.*

Taylor, S.R., A.A. Velasco, H.E. Hartse, W. S. Phillips, W.R. Walter, and A.J. Rodgers, (2002), Amplitude Corrections for Regional Seismic Discriminants, *PAGEOPH*, 159, 623-650.

Walter, W., K. Smith, J. O'Boyle, T. Hauk, F. Ryall, S. Ruppert, S. Myers, M. Anderson, and D. Dodge, (2003), *"*Improving the Fundamental Understanding of Regional Seismic Signal Processing with a Unique Western United States Dataset", in *Proceedings of the 25th Seismic Research Review - Nuclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. 1, pp. 486-494.

Zhou, R.-M., B. W. Stump and C. T. Hayward, (2004), "*M*s:*m*b Discrimination Study of Mining Explosions in Wyoming, USA and Qianan, China", in *Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring*, Orlando, FL (Sept. 21-23, 2004).