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Title: MINE SEISMICITY AND THE COMPREHENSIVE NUCLEAR TEST BAN TREATY

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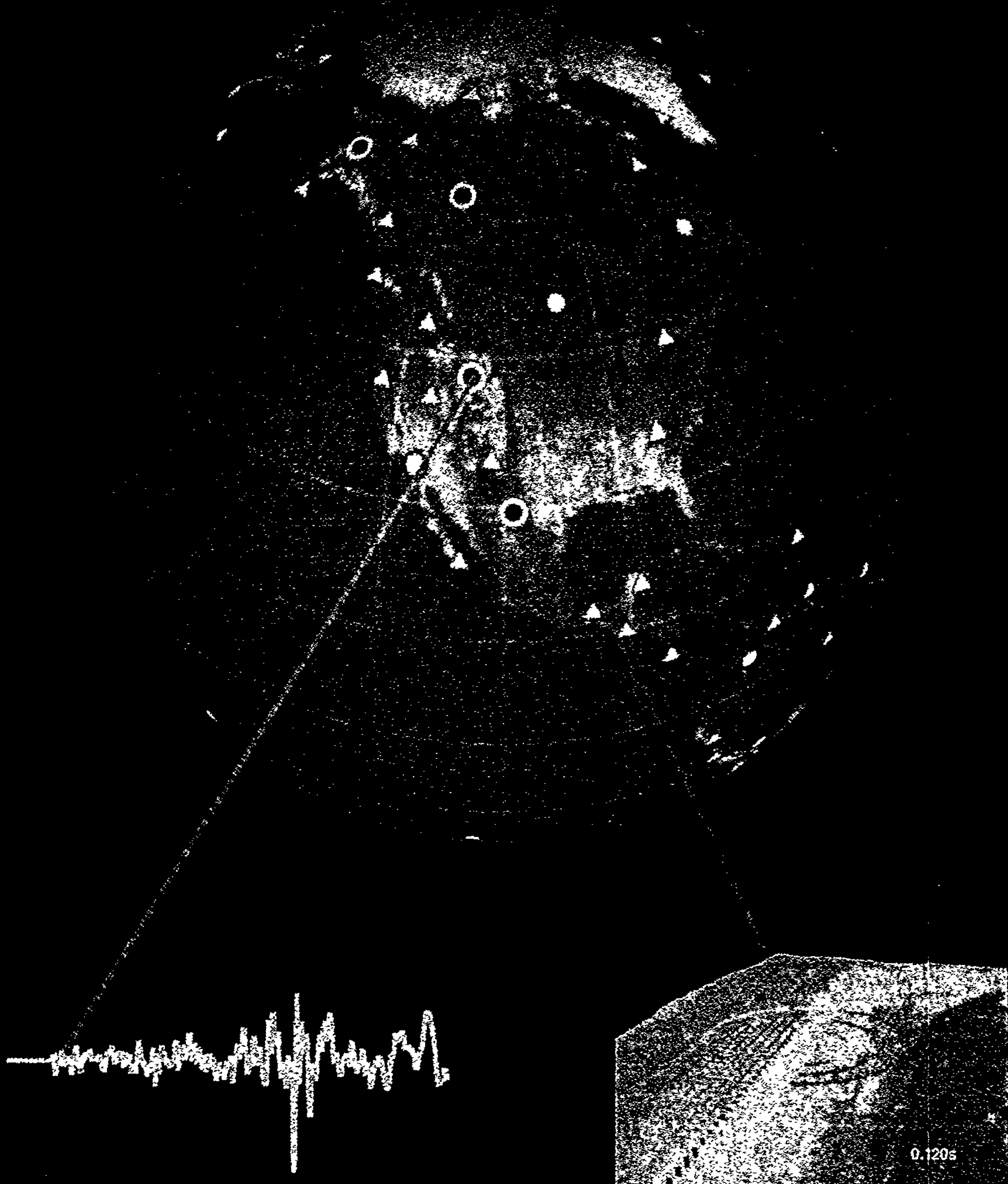
MINE SEISMICITY AND THE COMPREHENSIVE TEST BAN TREATY



PREFACE

This document was prepared by a Working Group of representatives from Government, Industry, and National Laboratories, under the sponsorship of the Department of Energy's (DOE) Office of Non-Proliferation and National Security. The Working Group represents the disciplines of explosives engineering, mining, and seismology. Its members are:

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The Working Group prepared a draft report in March of 1997. The DOE requested a review of that draft by the National Research Council (NRC) of the National Academy of Sciences. The NRC assembled a committee with the following members:

Thomas O'Neil, Cleveland-Cliffs Inc., Cleveland, OH (Chair)
Thomas Ahrens, California Institute of Technology, Pasadena, CA
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Michael Karmis, Virginia Polytechnical Institute and State University, Blacksburg, VA
William Leith, U.S. Geological Survey, Reston, VA
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John Wiegand, Vibronics, Evansville, IN
Zavis Zavdoni, Kennecott Utah Copper Corporation, Salt Lake City, UT

The NRC committee delivered its report on July 7, 1998. It contained several recommendations. First and foremost it placed emphasis on reducing the ambiguity of the mine signals, as opposed to reducing their visibility. It was indicated that this could be achieved through a combination of improvements in the CTBT monitoring capabilities of the U.S. scientific community, and of voluntary measures on the part of the U.S. mining industry such as providing data on their large blasts and their seismically ambiguous ground failures. The report also cautioned against advocating changes in U.S. mining practices which could be onerous to the industry. Finally, the committee stated its opinion that, in the end, there would only be a few U.S. mines which may be potential sources of CTBT false alarms.

The DOE Working Group is very grateful for the comments from the NRC review, and has drawn upon them in producing this final document. The Working Group will cooperate with trade associations such as the National Mining Association and the Institute of Makers of Explosives, and professional societies such as the Society of Mining Engineers and the International Society of Explosives Engineers to disseminate the results of this study and to promote a continued partnership between Government and Industry to eliminate the potential for CTBT false alarms coming from mining operations in the U.S. and overseas.

EXECUTIVE SUMMARY

The Potential Ambiguity of Seismic Signals from Mines

Surface and underground mining operations generate seismic ground motions which are created by chemical explosions and ground failures. It may come as a surprise to some that the ground failures (coal bumps, first caves, pillar collapses, rockbursts, etc...) can send signals whose magnitudes are as strong or stronger than those from any mining blast.

A verification system that includes seismic, infrasound, hydroacoustic and radionuclide sensors is being completed as part of the CTBT. The largest mine blasts and ground failures will be detected by this system and must be identified as distinct from signals generated by small nuclear explosions.

Seismologists will analyze the seismic records and presumably should be able to separate them into earthquake-like and non earthquake-like categories, using a variety of so-called seismic discriminants. Non-earthquake essentially means explosion- or implosion-like. Such signals can be generated not only by mine blasts but also by a variety of ground failures. Because it is known that single-fired chemical explosions and nuclear explosion signals of the same yield give very similar seismic records (Figure 2.1), the non-earthquake signals will be of concern to the Treaty verification community. The magnitude of the mine-related events is in the range of seismicity created by smaller nuclear explosions or decoupled tests, which are of particular concern under the Treaty (Figure 1.4). It is conceivable that legitimate mining blasts or some mine-induced ground failures could occasionally be questioned. As noted in the Appendix, a special provision of the Treaty entitled Consultation and Clarification was designed to address such questionable events in an unobtrusive way. Information such as shot time, location and design parameters may be all that is necessary to resolve the event identity. In rare instances where the legitimate origin of the event could not be resolved by a consultation and clarification procedure, it might trigger on On-Site Inspection (OSI). Because there is uncertainty in the precise location of seismic event as determined by the International Monitoring System (IMS) (Figure 1.3), the OSI can cover an area of up to 1000 squared kilometers. In active mining districts this area could include several different mining operations. So, an OSI could be disruptive both to the mining community and to the U.S. Government which must host the foreign inspection team. Accordingly, it is in the best interest of all U.S. parties to try and eliminate the possible occurrence of false alarms. This can be achieved primarily by reducing the ambiguity of mine-induced seismic signals, so that even if these remain visible to the IMS they are clearly consistent with recognizable mining patterns. Reduction in the seismic visibility or size of the seismic signal would be welcome, as well.

What Can Be Done About False Alarms

The elimination of false alarms will take a joint effort between the scientific community, mainly seismologists, and mine operators.

What the seismologists can do:

- they can improve their methods to discriminate between signals from earthquakes and explosions. This work is on-going.
- they can apply their models for collapse events, to separate collapse-generated seismic records from explosion-like signals. Such models have been applied successfully to some U.S. case histories.
- they can improve the accuracy of event location. This work is also on-going. It can be helped greatly by industry providing specific times and locations of their blasts, as well as by improvements in the procedures and interpretation for location by the International Data Center.

- they can provide resources to the industry to help establish seismic "fingerprints" of specific mine operations. Several such studies already have been conducted in the U.S (Chapters 2 and 3). More work is desirable to better characterize the U.S. signals, as well as to better understand the signals from foreign operations.

***What industry can do*:**

- it can provide information to the IMS community about blast events (date, precise time, location, pattern, yield), above some threshold to be determined as a function of mine-specific visibility. This information would minimize false alarms. The CTBT already encourages the advanced notification of shots of 300 tons or more, as confidence-building measures.
- provide advanced notice of controlled engineered ground failures, such as in a recent case history of pillar removal described in this report.
- provide ground truth concerning expected but uncontrolled ground failures, such as first caves in longwall coal mines.
- generally cooperate in providing prompt information on events identified by the IMS, that appear to originate from a mine.
- engage in joint seismic calibration of specific mining activities with scientists and engineers from the CTBT community. Several such projects have been completed and are illustrated in this report.

None of the above suggestions and recommendations is expected to add significant cost to mining operations, while providing the benefit of protecting the industry from false alarms. The joint calibration efforts with industry could also involve some of the industry's foreign operations to help validate seismic models in other countries and to better understand signals from overseas.

On rare occasions, industry may consider adjusting its operating practices at specific locations where the seismic ambiguity is not reduced by other measures. These adjustments may include better timing control of blasting delays as well as enhanced ground control practices.

Report Organization and Follow-Up

This report presents details of the CTBT and its implications for the mining industry in Chapter 1. Chapter 2 addresses the aspect of visibility and ambiguity due to chemical mining explosions. Some case studies that have involved cooperation between industry and the National Laboratories are used as illustration. Chapter 3 similarly focuses on ground failures. Joint calibrations of ground failures also are described, and conclusions drawn regarding signal ambiguity and potential remedial actions. Chapter 4 focuses on procedures designed to minimize the ambiguity of signals from mining events at regional distances. The final chapter includes a set of conclusions and identifies a number of outstanding issues..

The dissemination of these ideas and the exchange of information and experience between the mining and CTBT communities is very important. This information will provide support to CTBT monitoring that will lead to increased capabilities for event location and identification. These data will also minimize false alarms and possible OSIs.

1.0 INTRODUCTION AND MOTIVATION

1.1 Statement of the Problem

The Comprehensive Test Ban Treaty (CTBT) prohibits the detonation of any nuclear explosion as described in its basic obligations:

> *Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control.*

It was accepted for signature at the United Nations in September of 1996 and immediately signed by the United States. The CTBT has now been signed by 150 nations and ratified by 21. It awaits ratification by the United States. Pertinent details of the Treaty can be found in Appendix A.

A unique component of this Treaty is the inclusion of an International Monitoring System (IMS) that provides data for assessing compliance. This system includes seismic, infrasound, hydroacoustic and radionuclide sensors distributed around the world continuously relaying data to an International Data Center (IDC). These data will be made available to each state party for analysis. Suspect events identified with these data or other data available to a state party can be used to generate a request by the Executive Council of the CTBT Organization for either consultation and clarification on the nature of the event or an On-Site Inspection (OSI). An OSI would include the deployment of people and equipment to the suspected site for the purposes of gathering additional information and resolving the nature of the source of the signals.

Initial detection, location and identification of underground, contained explosions will rely upon observations from the seismic component of the IMS. Seismic observations alone are unable to distinguish between large single-fired chemical and nuclear explosions (Denny, 1994). A 1 kiloton (kt) fully tamped nuclear explosion produces a seismic magnitude near 4 (Murphy, 1996). Detonating the explosion in a cavity can significantly reduce the amplitude of the seismic wave and its resultant magnitude. This motivates interest in signals of smaller magnitudes. Possible sources of these smaller seismic signals come from surface and underground blasting, and from underground mine failures. The latter can be massive pillar failures (planned or accidental), coal mine bumps, first caves in longwall coal mines, or rockbursts in hard rock mines. The seismic magnitude of mining explosions rarely exceed magnitude 4.0 while those from collapses or rock bursts can be as large as 5.0 or greater. Currently, mining explosions are triggering the Prototype of the International Monitoring System.

Unambiguous identification of mining events using seismic observations from the IMS provides a mechanism for avoiding false alarms under the Treaty. One purpose of this report is to highlight the fact that signals from some mining operations will be observed by the IMS. Techniques developed for uniquely identifying mining explosions will be reviewed. Finally, cooperative measures to circumvent misidentification of mining events are suggested.

In this chapter the components of the IMS are described. Results from the Prototype IMS are used to illustrate that mining explosions will be observed by the IMS. The magnitude or size of seismic waves from nuclear explosions and mining explosions is established.

1.2 The International Monitoring System (IMS)

Since the Treaty prohibits nuclear explosions underground, in the atmosphere, and in the oceans, a number of monitoring technologies are required. The first IMS component and the most relevant to mining operations is the seismic network.

Verifying international compliance with the CTBT requires the ability to detect and identify small clandestine underground nuclear tests. These signals will need to be discriminated from a background of earthquakes, mining and construction activities and noise from wind and ocean waves. For the large events, detected around the world, identification is fairly straightforward (OTA, 1988) and the number of background signals, mainly earthquakes, is manageable. Large events produce seismic signals that can be observed at teleseismic distances (2000 to 9000 km) by many stations.

As one considers smaller and smaller tests, the number of background earthquakes and man-made signals greatly increases. The reduced amplitude seismic signals from these events are only observed at a few sites relatively close to the source. These small events are primarily observed at regional distances (200 to 2000 km). These considerations contributed to the design of the seismic component of the IMS. As indicated in Figure 1.1, the seismic network consists of 50 primary and 120 secondary seismic stations distributed around the world. The primary stations continuously transmit data to the International Data Center while data from the secondary stations can be retrieved when needed. The primary seismic stations in the United States are Pinedale, Wyoming; Lajitas, Texas; and Mina, Nevada.

The ocean environment is monitored with 11 hydroacoustic stations. Sixty infrasound and 80 radionuclide stations will provide data for possible atmospheric nuclear explosions. These components of the IMS are also included in Figure 1.1.

The data from the monitoring stations will be transmitted to the International Data Center (IDC) via National Data Centers (NDCs) of member countries. The IDC will analyze the data and make results (such as an event bulletin which includes lists of event times, locations and sizes) available to all member countries. The IDC will also redistribute all raw data to the NDCs. Individual member countries may re-analyze the data in any way they wish and may raise a question with the CTBT Organization concerning a suspicious event.

The CTBTO will initiate an OSI if evidence is strong that a nuclear test may have been conducted. Initiation of an OSI will require a positive vote from 30 of the Executive Council's 51 members and therefore will be difficult to initiate, thus making the occurrence of an OSI a rare event.

1.3 Results from the Prototype International Monitoring System (PIMS)

In preparation for entry into force of the CTBT, a Prototype International Monitoring System (PIMS) and complementary Prototype International Data Center (PIDC) have been operated. Although this system does not include the full complement of stations illustrated in Figure 1.1, there are many stations currently transmitting data to the PIDC. These data are being used to locate events around the world that are reported in a bulletin. The events in this bulletin provide a preliminary look at the numbers and locations of events in the US that might be associated with mining operations. Figure 1.2 shows locations of 87 mine related seismic events (white circles) located within or near the US during a two-year period. These events are identified as mine-related by the US NDC analysts through comparison of PIDC, US NDC, and United States Geological Survey (USGS) catalogs.

Included in the map are locations of non-coal (crosses) and coal (red circles) in the United States (data provided by William Leith, USGS). The proximity of the PIDC event locations to the mapped coal mines suggests that mine related seismic events may be attributable primarily to surface coal operations in the US. The preponderance of events in Wyoming is directly related to the existence of the primary seismic array near Pinedale, Wyoming. These events were determined without the benefit of data from the primary seismic array in Mina, Nevada. Thus, one may assume that the installation of this seismic resource in early 1999 would provide more mine related events in the western U.S. These data suggest that mining explosions will be detected and located by the PIDC. It becomes important to then identify these events as distinct from a possible clandestine nuclear explosion.

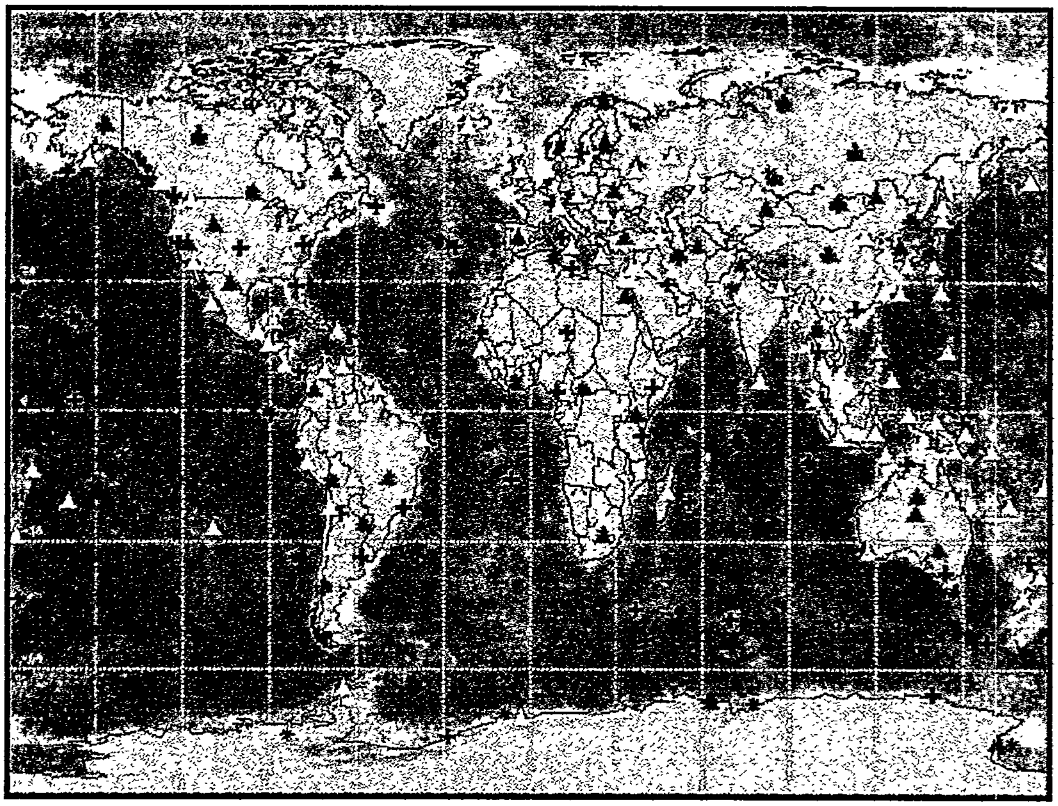

Figure 1.1: Seismic (triangles), infrasound (stars), hydroacoustic (circles) and radionuclide (pluses) stations making up the International Monitoring System

Precise locations provide the opportunity to associate a particular event with a mine. Such an association with complementary data from the mine such as blast design parameters could be useful in resolving the identification of a questionable event. PIDC locations of blasts in the Powder River Basin illustrate that current locations are not accurate or precise enough for this association. Figure 1.3 shows locations of a number of events and their associated error ellipses. One can see that individual locations cannot be associated with a single mine (squares in figure). In many cases the error ellipse includes many mines. The size of the error ellipses and the bias in the locations are a reflection of inadequate knowledge of the seismic velocity structure in this region as well as of the station coverage for a particular location. Empirical calibration of the travel times using events with known spatial and temporal location can reduce these uncertainties, improving association with a particular mine.

1.4 Size of Nuclear Explosions and Mining Events Observed by the IMS

The size of an explosion, earthquake, or collapse that generates a seismic signal is usually measured in terms of its seismic "magnitude". The magnitude scale is proportional to the logarithm of the peak seismic wave amplitude, normalized to a reference distance. Because this peak amplitude can be measured on different types of seismic waves, several different seismic magnitude scales have evolved. While this proliferation of magnitude scales may seem confusing, it has played a key role in identifying the source of the seismic waves, as will be discussed in Chapter 2.

Figure 1.2: Seismic events (white circles) in the continental US located by the PIDC from July 1995 and June 1997 that have been determined by the US NDC to be mine-related. Active coal mines (red circles) and non-coal mines (black crosses) are from a data base supplied by William Leith of the USGS.

One of the most common magnitude scales is the Richter or "local" magnitude scale M_L. As its name implies, this scale is used to measure the size of events at local or near regional (<1000 km) distances from the seismic station. While this is the oldest magnitude scale and it can measure even the smallest seismic events, it does have some drawbacks. First, the event must be fairly close to the seismic recording stations. Second, because the scale is a local one, and is strongly affected by local propagation effects or geology, it is often difficult to compare events with local magnitudes determined in, say, the western U. S with those determined in the eastern U.S. and be sure that the events are really of similar size.

Other magnitude scales have been developed for seismic waves that travel teleseismic (>2000 km) distances. The body wave magnitude, m_b, measures the amplitude of the first arriving P waves with a period near 1 second. The surface wave magnitude, M_s, measure the amplitude on the longer period, later arriving seismic waves that travel along the surface of the earth. Both of these teleseismic magnitudes have the advantage that they can be measured at stations around the globe for the larger events, and thus events in different parts of the U.S. or the world can be more easily compared. The disadvantage is that because the wave must travel a long distance before being measured, M_s and m_b of small events typically with m_b less than 3.5, cannot be determined. These three magnitude scales M_L, m_b and M_s are designed to give very similar magnitudes for earthquakes.

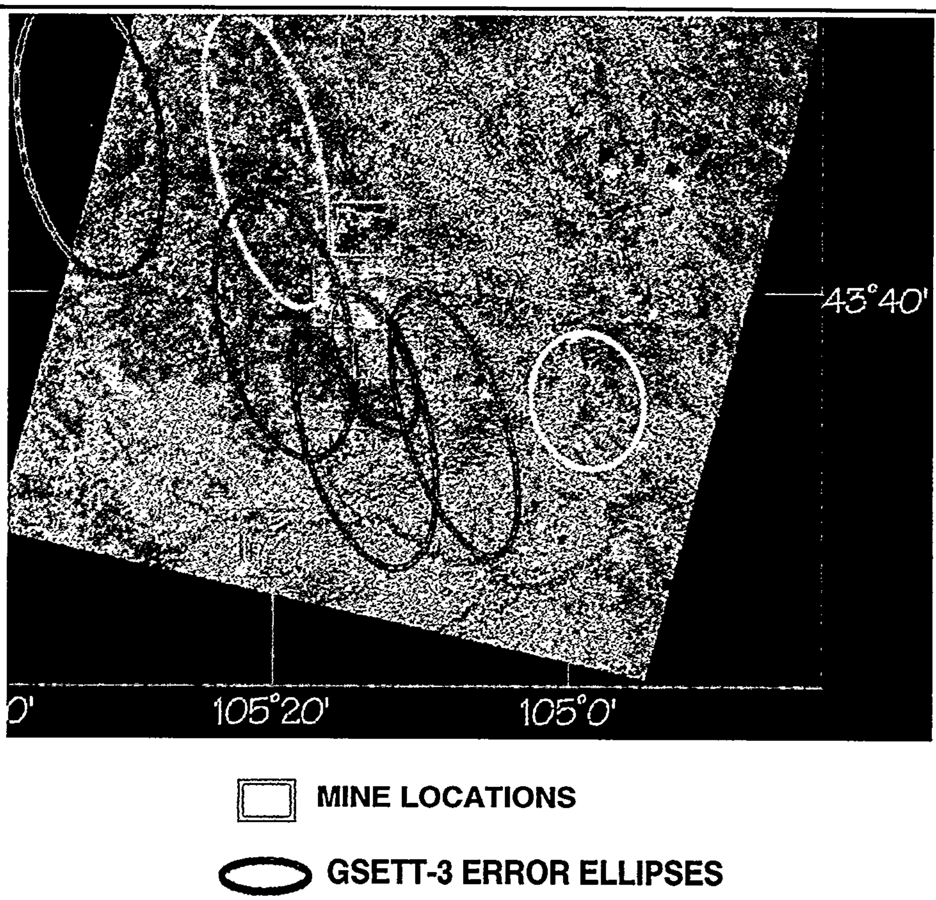

Figure 1.3: PIDC events located in the southern Powder River Basin compared to SPOT imagery and known locations of the events in coal mines in the region. The ellipses represent the error estimates for the locations. The squares are the spatial locations of individual mines.

A typical magnitude-yield curve for contained nuclear explosions in well-coupled material is reproduced in Figure 1.4 (Murphy, 1996). The yield is described as the equivalent mass of conventional explosives (TNT) in kilotons. A fully coupled 1 kiloton explosion (~ 2,000,000 lbs of TNT equivalent) will produce a teleseismic magnitude (m_b) of about 4. As discussed in Chapter 2, results from the Prototype International Monitoring System suggest that mining explosions are generating events with local magnitudes (M_L) ranging from the low 2's to the low 4's. Comparison of regional and teleseismic magnitudes can be problematic as noted earlier, but this result confirms that some small number of mining explosions will have magnitudes of similar size to small nuclear explosions especially if decoupling of the explosion is considered.

1.5 Identification of Ambiguous Mining Events

The PIMS results suggest that a small number of mining explosions will appear in the bulletins. These bulletins will include the approximate locations of the events in space and time. It will be up to each state party to identify the event as an earthquake, a mine related event or a possible clandestine nuclear explosion. The identification tools for mine related events will be discussed in Chapter 2. The data from some events will not allow a unique identification in a limited number of cases and as already noted seismic data alone cannot distinguish between a large, single-fired chemical and nuclear explosion (Denny, 1994). In order to resolve these conflicts, a number of measures are included in the Treaty. Consultation and clarification (Appendix A) is a process by which countries can ask one another for information that might help resolve a questionable event. In the case of questionable mining event, the information requested might be a simple as the shot time, location and design parameters.

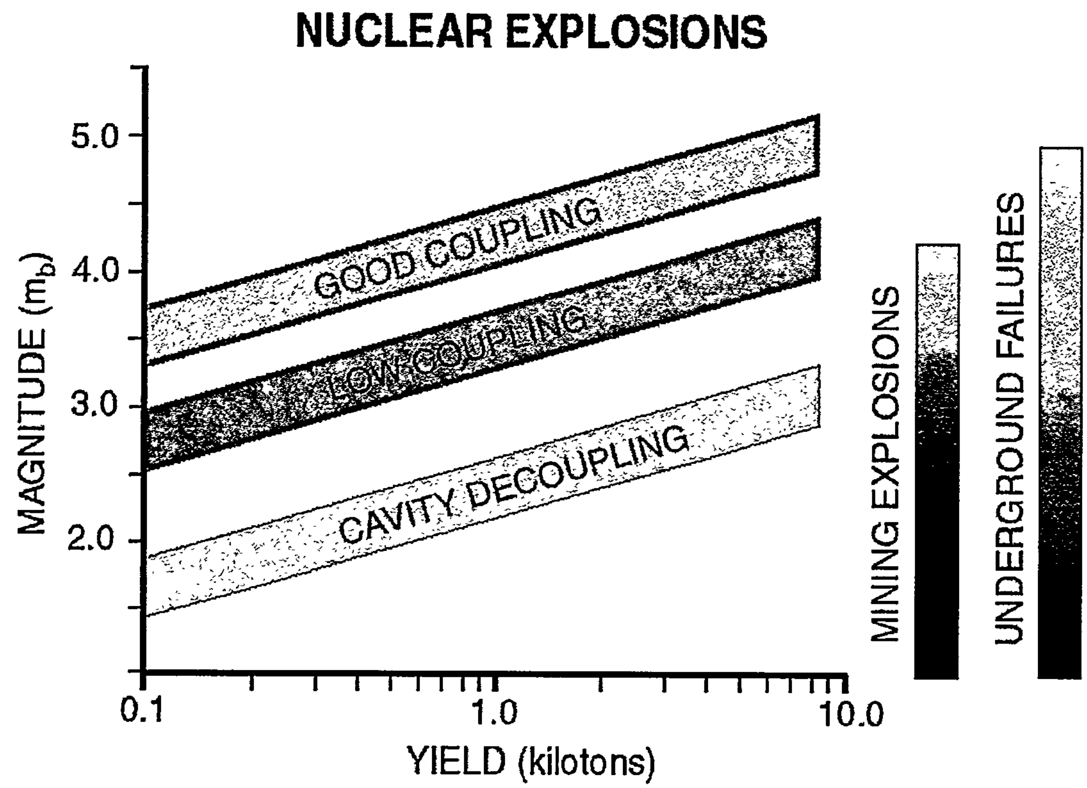

Figure 1.4: Estimate of expected teleseismic magnitude for a contained nuclear explosion as a function of yield. The effect of material on signal strength as well as of decoupling is illustrated, after Murphy, 1996. The curves have bounds representative of different propagation path effects. A qualitative estimate of the relative numbers of mining explosions and underground failures is given to the right indicating that mining events above magnitude 4 are rare.

Confidence building measures are also included in the Treaty. These are actions that countries can take to avoid possible false alarms. Such measures provide for the exchange of information that will help with calibration of the monitoring system. They include the release of times and locations of larger mining explosions. Single-fired chemical explosions conducted for the purposes of calibrating the types of signals expected can also be conducted by cooperating countries.

If data from all these measures fail to resolve a questionable event, then it might in unusual circumstances lead to an On-Site Inspection. The sole purpose of an OSI is to determine whether or not an ambiguous event detected on the basis of IMS data has been a nuclear explosion carried out in violation of the basic obligations under the CTBT. The OSI will be conducted in accordance with the regulations set by the Treaty and should be completed in the least intrusive manner possible, consistent with the effective and timely accomplishment of its mission. The suspected member country should comply and facilitate all the inspection activities, as described by the Treaty.

The types of inspection to be conducted are still to be determined and most likely will depend on the type of violation being investigated. A study by Zucca *et al.* (1996) has reviewed the underground nuclear explosion phenomenology and the types of observations that may be put to use. In the CTBT (United Nations General Assembly, A/50/1027), inspection techniques include position finding from the air and at the surface, visual and video observation, radioactivity level measurement at and below the surface, environmental sampling and analysis of solids, liquids and gases, passive seismological monitoring for aftershocks, resonance seismology and active seismic surveys to search for underground anomalies, magnetic, gravity and ground penetrating radar mapping for underground cavities, and drilling to obtain radioactive samples.

2.0 MINING EXPLOSIONS

2.1 Types of Mine Explosions

The use of explosives still remains the most economical means of rock breakage and/or dislodgment of in-situ mine material (Table 2.1). Current blasting techniques and mine explosions in the U.S. mining industry are quite varied, encompassing an extremely broad range of applications:

- surface coal operations
- underground mining (metallic ores and non-metallic minerals)
- open-pit operations (metallic ores and non-metallic minerals)
- quarrying operations (aggregate, coyote blasts)
- construction operations (surface, underground and tunneling)
- reclamation
- specialty industries (farming, graveyards, post holes, ponds, demolition, etc.)
- petroleum industry (pipelines, exploration, well stimulation)

Table 2.1. Typical Explosive Use and Shot Size for Various Blasting Operations in the U.S.

Operation	Hole Diameter (cm)	Hole Depths (m)	Explosive Quantity/ Hole (kg)	Total Explosives Per Shot (metric tons[1])
Surface Coal*	16.5-31.1	9.1-91.5	100-8000	Up to 500+
Open Pit	20.3-44.5	9.1-22.9	100-4000	Up to 500+
Underground Mining (Large Blocks)	6.4-20.3	7.6-91.5	10-3500	Up to 500+
Oil shale	11.4-20.3	15.2-91.5	100-2000	Up to 150+
Dredging	10.2-16.5	19.8-30.5	100-500	Up to 130+
Quarrying	7.6-16.5	7.6-61	10-1500	Up to 130+
Construction	3.8-16.5	1.5-19.8	1-350	Up to 45+
Reclamation	7.6-16.5	1.5-3	1-40	Up to 22+
Specialty (farming, graveyards, post holes)	3.8 - 16.5	0.9-6.1	0.5-77	Insignificant

Explosive Density is assumed @ 1.20 g/cc

*The largest surface coal cast blast shots in the U.S. have used up to 3.600 metric tons (8 million pounds) of ANFO at the Thunder Basin Coal Company, Black Thunder Mine in Wyoming

The degree to which a particular mining explosion may be observed by stations of the IMS depends on the amount of explosives detonated and the way in which it is detonated in space and time. It may also be dependent, to a degree, on hole diameter, bench height, explosive quantity per hole, number of holes fired per delay interval, and the material properties of the ground around the explosion. Coyote blasting, which can involve the simultaneous detonation of moderate to large amounts of explosives, is not considered here since it is a very rare blasting practice in the U.S.

[1] In the rest of this text, metric tons will be referred to simply as "tons".

although it would be quite likely to be observed by the IMS and have characteristics like a single-fired explosion. Typical explosive use and shot sizes for various blasting operations are listed in Table 2.1. Blasting operations listed in the first three catagories (surface coal, underground and open-pit operations) have the highest potential for being observed by the regional seismic stations of the IMS. This fact is consistent with the strong correlation of events from the PIDC with coal operations in the U.S. (Figure 1.2).

2.2 Regional Seismic Signals Produced by Mining Explosions

2.2.1 Seismic Signals from Concentrated Chemical and Nuclear Explosions

In order to set the stage for why mining explosions are of interest in the CTBT context, we first compare regional seismic signals from single-fired (simultaneously detonated) nuclear and chemical explosions. In 1993, the Department of Energy conducted a large (~ 1 kiloton TNT equivalent) contained, single-fired chemical explosion in the same region of the Nevada Test Site where contained nuclear explosions had been detonated (Denny, 1994). A regional seismogram (> 100 km) from the chemical explosion is compared to a seismogram from a near-by nuclear explosion in Figure 2.1.

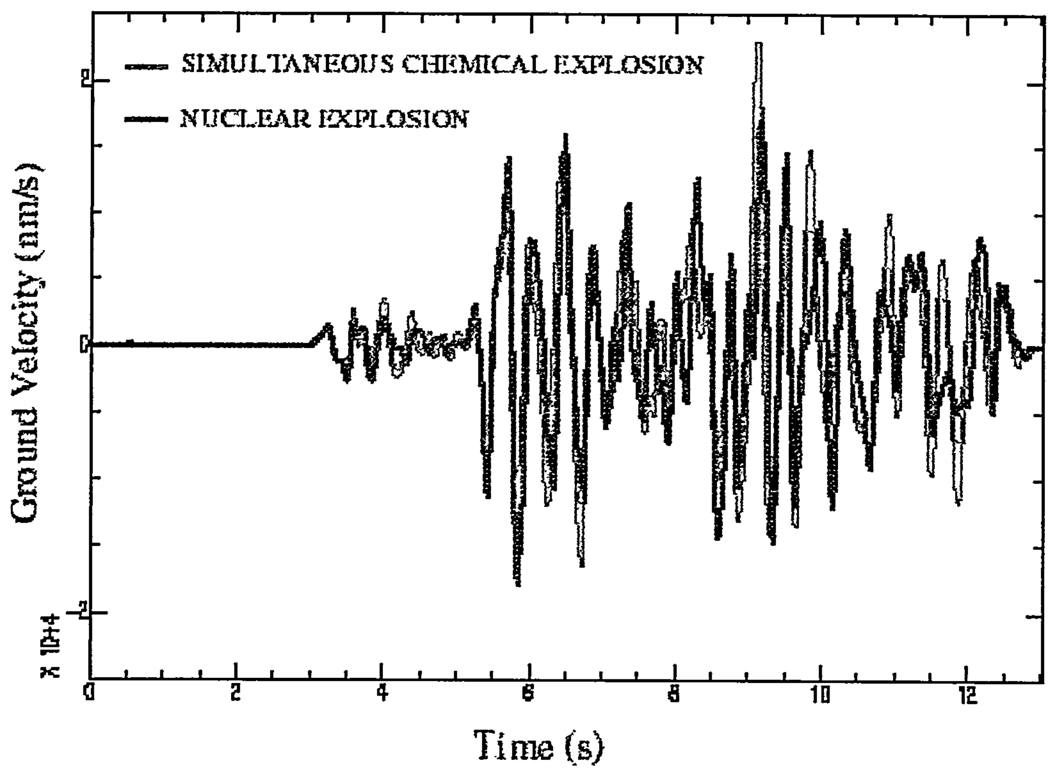

Figure 2.1: Comparison of the P energy at regional distance (station MNV) from a large simultaneous chemical explosions (NPE) and a near-by nuclear explosion.

The waveforms from these two sources are indistinguishable. Seismic data at near-source distances are consistent with regional data, suggesting that contained nuclear explosions cannot be distinguished from contained chemical explosions that are simultaneously detonated. Mining and construction explosions that have characteristics similar to large, simultaneously detonated chemical explosions could be problematic in the context of monitoring a CTBT.

2.2.2 Seismic Signals from Surface Coal Cast Blasting

Some of the largest operations in the blasting community involve the emplacement and detonation of explosives to cast overburden rock and expose shallow coal seams (Stump *et al.,* 1995). In one of the largest surface coal mines in the world (The Thunder Basin Coal Company, Black Thunder Mine), nearly 68,000 tons (150,000,000 lbs.) of explosives are used annually. The large cast shots occur about 25 times a year and use about 1.4 to 1.8 kilotons (3 to 4 million lbs.) of ANFO. However, some shots have used as much as 3.6 kilotons (8 million lbs.). These explosions are designed to cast material into an accompanying pit, exposing coal at depth. A single cast blast can include hundreds of boreholes each with as much as 4.5 tons (10,000 lbs.) of explosives, depending on overburden thickness. The sequence in the shooting pattern is often complex. Explosions nearest to the free face are detonated first followed by subsequent rows behind. Explosive arrays can include as many as 7 to 9 individual rows. There can be as many as 100 or more boreholes in a row and so the explosions in a single row are also delay-fired to reduce near-source ground motions in the mine and surrounding facilities.

Figure 2.2 is a model of the P wave energy generated by a typical cast blast, in this case with over 700 boreholes, 8 rows deep and in excess of 2 kilotons (4,500,000 lbs.) of explosives. The

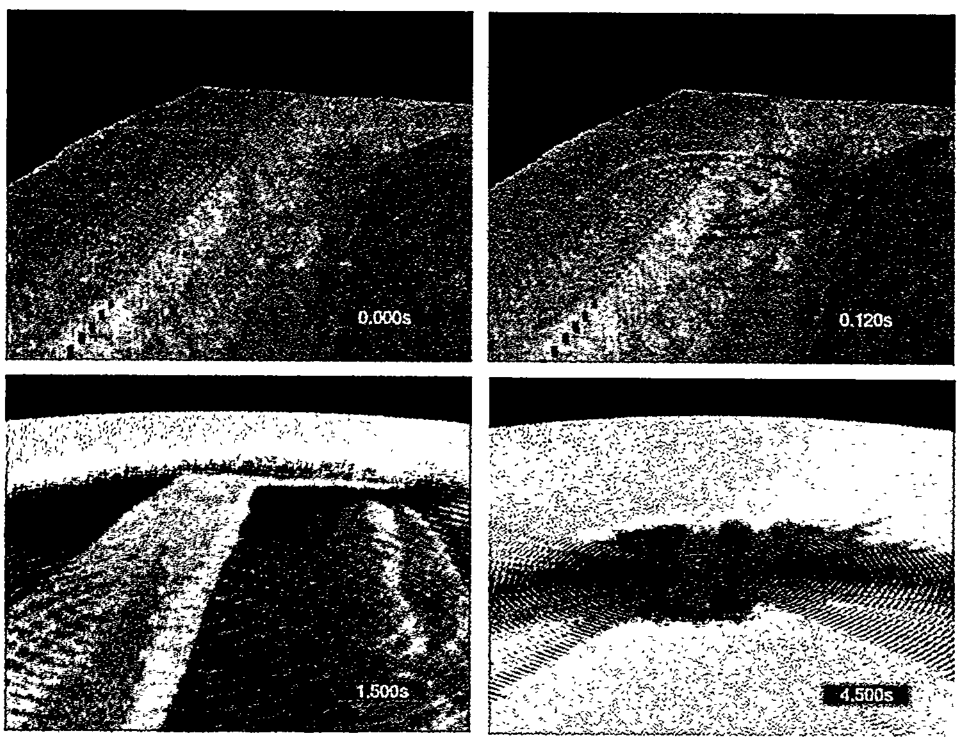

Figure 2.2: Four images of a large cast blast. Each borehole generates an expanding red ring that propagates (and turns yellow) at the compressional velocity of the material. These images illustrate the continuous radiation and long duration of this type of explosive source. Time from shot initiation in each image is denoted in the lower right corner.

delays between rows (125,300,500,700,900,1000,1200,1400 ms) and between shots in a row (35 ms) produce a total shot duration in excess of 4 seconds. The complex shot timing pattern results in a long source duration producing distinctive regional signals compared to a single-fired explosion. As long as the individual explosions in this mining application are fired in the continuous fashion depicted in Figure 2.2, they can be distinguished from single-fired explosions. In addition to the effects of the long source duration, cast blasts move material into the pit of the mine. A number of researchers (McLaughlin *et al,* 1993) have suggested that this secondary source effect will also produce distinguishing source signatures at regional distances.

2.2.3 Seismic Signals from Open Pit Fragmentation Explosions

Explosions designed to fragment hard rock for mineral excavation and recovery form a second subset of possible types of explosions that may have to be identified. One common practice in conducting these types of explosions is millisecond delay firing to enhance fracturing at a free face and reduce ground motions in the near-source region. Figure 2.3 contains two video and two

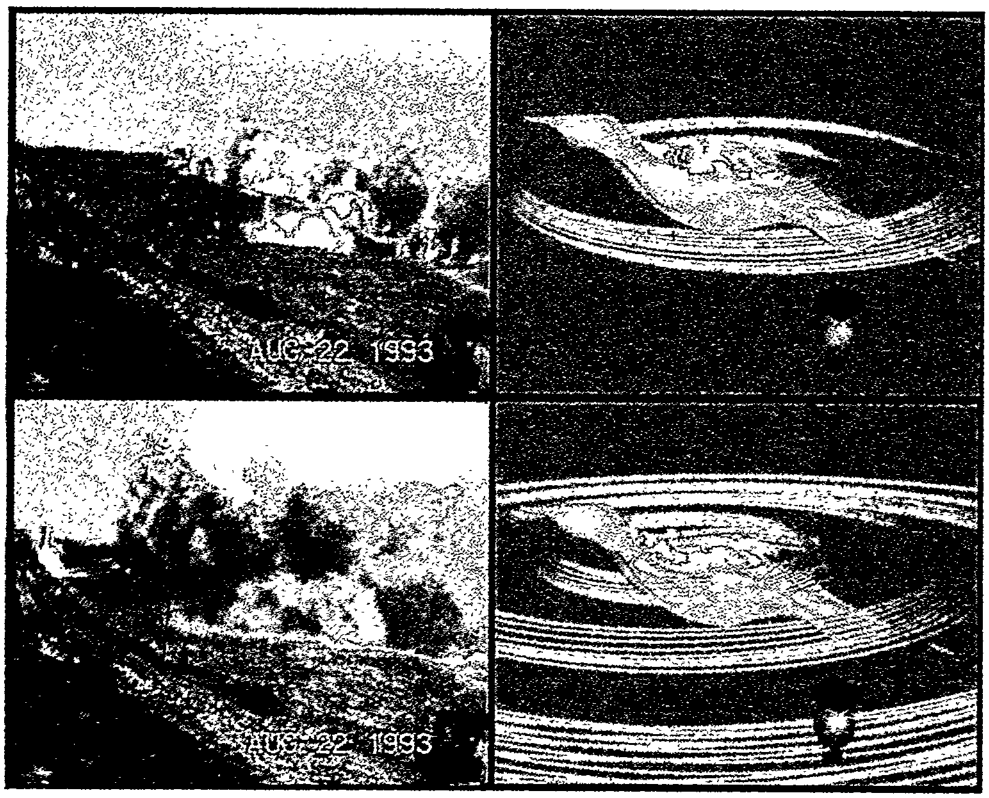

Figure 2.3: Two video (left) and two model (right) images for a fragmentation explosion in a Molybdenum mine in southern Russia. The explosions in each row detonate simultaneously, producing rings of impulsive compressive energy from the explosion. Compressive energy is modeled as blue and acoustic energy as yellow in the images. Detonation of individual boreholes (blue spheres) is represented as each borehole turns red at shot time. A seismometer is depicted in the lower left corner of the model.

model frames from such an explosion in a molybdenum mine in southern Russia. In this case, each row of explosions is simultaneously detonated starting with the row of explosions that is closest to the face. As the model documents, the resulting seismic energy (blue rings in figure) contains impulses of energy from each row followed by the more slowly expanding acoustic energy (yellow rings). At regional distances the banded nature of this sequence provides a good discriminant from a simultaneously detonated explosion (Hedlin *et al.,* 1989, 1990; Chapman *et al.*, 1992). As long as the detonation sequence is precisely controlled, these types of explosions produce well defined signals that can be distinguished from a simultaneous shot. Leith *et al.* (1996) have reported relatively large explosions (~1,000,000 lb.) that have been detonated in this manner in surface iron mines in Russia. In these instances, when there are many explosions in a single row, the size of ground motions in the near-source region and regionally can be quite large and possibly problematic.

Recent work in these mines has employed more complex delay designs where some type of echelon patterns are observed to reduce near-source and regional amplitudes. Implementation of such patterns with precisely controlled delays will again produce regional signals that possess a unique character and thus enable identification. The effect of imprecise detonators on the ability to identify such sources will be addressed in a later section. Smith (1989) reports on the characteristics of regional seismic signals from large mining explosions in the Mesabi Iron Range in northern Minnesota. This empirical study suggests that the effects of the delay pattern in the shooting can be used for event identification if frequencies at least as high as 35 Hz are observable. Observation of signals at these frequencies was made at a distance of 380 km from the sources. Jarpe *et al.*, 1996, have monitored explosions from within an open-pit gold mine in Nevada some of which do and some do not produce regional seismic signals characteristic of delay firing.

2.3 Number and Size of Regional Seismic Signals

2.3.1 The Number of Regional Seismic Signals from Mining Explosions

The number of explosions and the total explosive usage have been estimated by a number of authors for U.S. Figure 2.4[2] is based on an extensive study by Richards *et al* (1992) and included the analysis of total explosive usage in the U.S., a percentage of which were seismically monitored by Vibra Tech Engineers. Superimposed on these total U.S. estimates are two, single-mine studies, one at The Black Thunder Coal Mine(Stump *et al*, 1996b) and the second at The Barrick Gold Mine (Jarpe *et al*, 1996). At the surface coal mine, two types of explosions are regularly detonated. The first are the large cast blasts each of which includes in excess of several million lbs. of explosives. The second type are smaller coal shots designed to fracture the coal to facilitate excavation. The two types of blasts follow two distributions, the first from the fragmentation shots 3,000 to 300,000 lb. and the second above 1,000,000 lbs. Similarly for the hard rock fragmentation shots, the yields range from 3,000 to 200,000 lbs. The fragmentation shots are consistent with the U.S. estimates by Richards. It appears that this data set underestimated the number of large cast shots.

The number of mining explosions estimated in Figure 2.4 suggests that many events may trigger the International Monitoring System. Practically, the methodology of delay firing these explosions greatly reduces the size of the regional signal and thus minimize the mine visibility.

2.3.2 The Size of the Regional Seismic Signals From Mining Explosions

Table 2.2 lists events from the PIMS which are located in the Powder River Basin of Wyoming and their accompanying magnitude estimates. Although it is thought that M_L is biased high, most of the reported magnitudes are above 3.0. One cast shot, 1 August 96, has an estimate for both magnitudes with M_L =4.5 and m_b = 4.0 (teleseismic phases observed at a number of stations). This event is one of the largest and comparison of the two magnitude estimates is consistent with

[2] The original figure used units of lbs. They have been retained for this discussion.

bias in the M_L estimate discussed earlier. Comparison with the magnitude-yield curves for nuclear explosions (Figure 1.4) suggests that a 1 kiloton nuclear explosion detonated in good coupling material would produce a signal of similar magnitude. A nuclear explosion as large as 10 kilotons in low coupling material would also produce a signal of the same size.

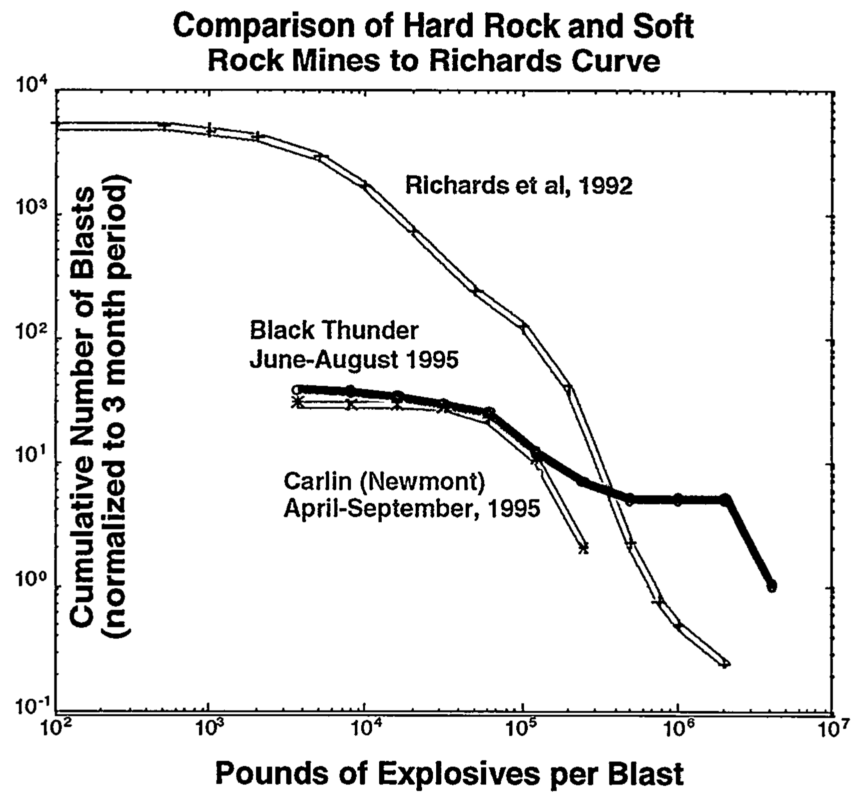

Figure 2.4: The cumulative number of explosions (scaled to three months) as a function of total explosive weight for the U.S. as estimated by Richards *et al,* 1992 (green). Actual number of explosions in three month periods for a large surface coal mine (purple, Stump *et al,* 1996b) and a surface gold mine (blue, Jarpe *et al,* 1996).

Table 2.2: Mining Explosions from the Powder River Basin detected and located by the seismic subsystem of the Prototype International Monitoring System along with local (M_L) and teleseismic (m_b) magnitude estimates (listed by increasing magnitude).

Date	Time	Latitude	Longitude	# of Phases	M_L	m_b	Teleseismic (> 20^0)
1996/05/15	22:03:18.8	44.62N	105.97W	7			
1996/04/29	22:53:32.0	43.47N	105.32W	8			
1996/03/30	00:10:24.9	43.53N	105.37W	5			
1996/01/12	19:33:44.1	43.98N	105.49W	4			
1995/07/07	17:54:16.7	44.54N	105.91W	4			
1995/05/20	20:50:52.7	44.10N	105.28W	9			
1995/05/06	17:04:40.6	44.17N	105.42W	11			
1995/04/24	21:19:05.7	44.30N	105.44W	17			
1995/04/13	20:05:31.9	43.86N	105.33W	10			

1995/03/20	21:32:31.4	43.97N	105.21W	11			
1995/03/17	20:37:27.4	43.56N	105.13W	7			
1995/03/02	22:42:10.0	44.61N	105.84W	9			
1995/02/24	17:38:10.5	44.26N	105.33W	12			
1995/02/16	19:43:28.4	44.48N	105.41W	15			
1995/02/12	22:31:45.1	43.07N	104.87W	5			
1995/02/11	22:23:55.6	43.79N	105.54W	5			
1995/02/11	22:12:38.5	44.27N	105.74W	9			
1995/02/11	20:18:35.4	43.56N	105.23W	5			
1995/01/26	23:43:42.9	43.64N	105.32W	5			
1995/01/01	20:37:52.5	44.23N	105.44W	9			
1996/04/09	22:57:57.8	43.72N	105.34W	7	2.6		
1996/03/11	23:01:06.5	44.54N	105.62W	7	2.8		
1996/03/01	19:03:11.6	44.53N	105.72W	7	3.1		
1995/12/28	23:03:22.1	43.90N	106.36W	8	3.3		
1995/07/25	17:38:21.3	44.60N	105.84W	7	3.3		
1996/01/20	21:38:16.0	43.75N	105.4W	8	3.5		
1995/12/17	20:54:18.2	44.78N	106.37W	6	3.5		
1996/04/24	22:01:44.6	44.05N	105.4W	8	3.6		
1996/02/13	23:03:03.6	44.34N	105.59W	9	3.6		
1996/01/26	23:56:51.7	44.06N	105.41W	8	3.6		
1996/02/02	21:08:35.6	44.44N	106.2W	4	3.7		
1996/01/16	19:07:25.7	43.94N	105.47W	9	3.7		
1996/04/12	23:49:07.9	44.28N	105.15W	9	3.8		
1996/04/05	20:13:59.0	43.77N	105.34W	10	3.8		
1996/02/27	00:01:06.8	44.19N	105.31W	10	3.8		
1996/02/15	00:20:23.2	44.24N	105.37W	14	3.8		
1995/12/11	22:04:51.5	44.32N	105.52W	10	3.8		
1996/06/16	19:05:19.7	44.41N	105.33W	9	3.9		
1996/05/13	22:14:58.8	43.50N	105.13W	11	3.9		
1996/05/08	00:02:09.7	43.70N	105.2W	9	3.9	3.9	yes
1996/04/13	23:06:54.8	43.41N	104.92W	7	3.9		yes
1996/03/18	23:40:39.5	44.07N	105.34W	9	3.9		
1996/03/11	20:13:36.9	43.61N	105.22W	12	3.9		yes
1996/02/24	00:28:24.8	44.20N	105.35W	14	3.9		
1996/01/14	23:17:47.5	43.01N	104.13W	12	3.9		
1996/05/15	23:54:02.8	44.20N	105.35W	14	4.0		
1996/04/02	23:05:52.7	44.23N	105.35W	12	4.0	3.5	yes
1996/02/13	21:03:42.7	43.53N	105.16W	5	4.0		
1996/01/10	21:10:40.3	43.72N	105.26W	10	4.2		yes
1996/08/01	19:33:06.8	43.72N	105.25W	13	4.5	4.0	yes
1996/07/22	20:40:33.9	44.20N	105.68W	9	4.5		
1995/06/29	23:51:42.2	44.38N	105.32W	7	4.6		
1995/07/18	19:47:42.4	43.58N	104.98W	12	4.7	3.6	yes
1995/06/19	21:38:25.9	44.09N	105.35W	11	4.7		yes
1995/07/07	16:42:37.3	43.70N	104.74W	5	5.3		

Material property data from explosions detonated in different types of geological materials suggest that the amount of gas-filled porosity can have a big effect on the size of the near-source and regional seismic signals (Murphy, 1996). Figure 1.4 illustrates coupling differences as large as an order of magnitude. Mining explosions, as illustrated, are rarely detonated simultaneously, often emplaced in relatively incompetent near-surface layers and designed to fracture and cast the materials in which they are detonated. All these characteristics result in a reduction in amplitudes relative to a contained, single detonation. Careful consideration of each of these effects will reduce the visibility of the seismic signals from mining explosions at regional distances.

In order to illustrate the consistent imprint the blasting practice has on the regional signals, we compare peak P and L_g amplitudes (phases most commonly observed at regional distances) for a single-fired explosion, a group of cast blasts and coal fragmentation explosions (explosions detonated in the coal designed to fracture the material). The results are shown in Figure 2.5.

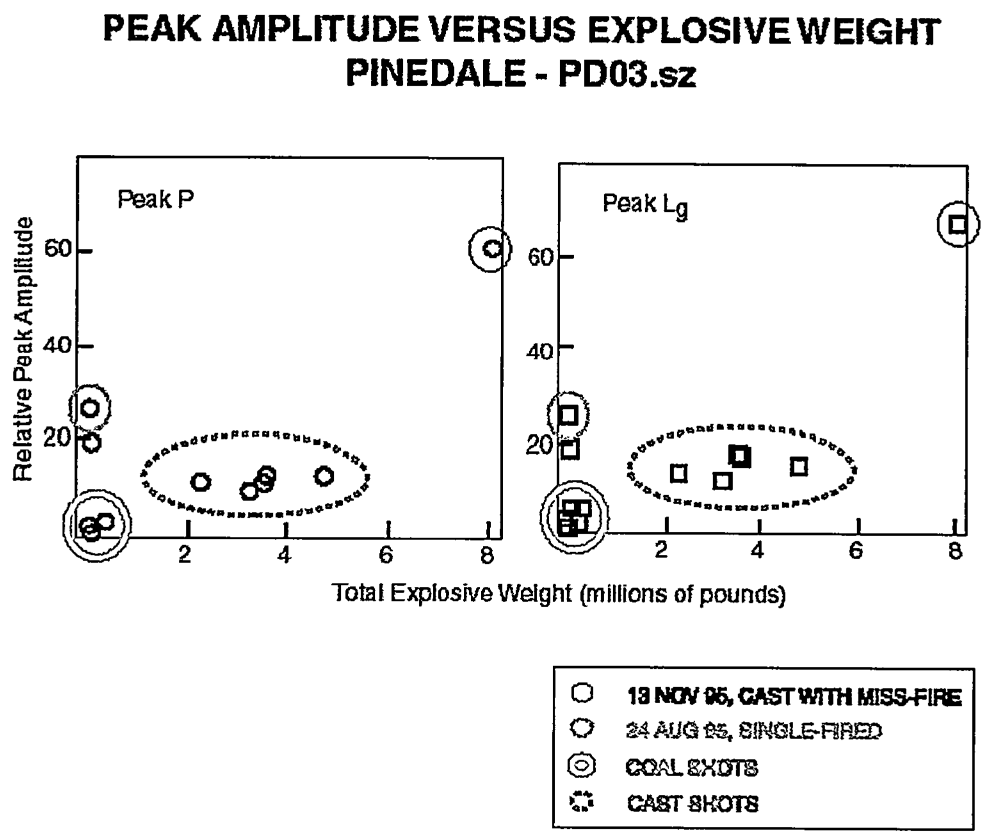

Figure 2.5: Peak RMS (high pass filtered at 0.8 Hz) P and L_g amplitudes at the regional station PDAR for different types of mining explosions from a single surface coal mine. Cast shots are circled in pink, coal shots in green and a single shot in blue. The event circled in red is an abnormal cast shot.

For both the P and L_g phases, the coal fragmentation shots have the smallest amplitudes, nearly an order of magnitude or more smaller than the single-fired 18.1 tons (40,000 lbs.) shot, despite including shots with total yields as large as 90.7 tons (200,000 lbs.). Five of the cast shots, spanning yields between 0.9 and 2.3 kilotons (2,000,000 and 5,000,000 lbs.) also have peak amplitudes slightly smaller than the single shot. The peak amplitudes from these five cast shots show little dependence on total explosive yield. This is also consistent with the mining practice of extending the time duration of the larger explosions, thus maintaining constant peak amplitudes in the near-source region and, by implication, at regional distances as well.

There is one cast shot which has peak amplitudes 5 times bigger than any of the others. We will return to this event in a subsequent discussion. Its detonation was not as designed, with a shot timing anomaly leading to large amplitudes at regional distances.

Results presented in this section support the contention that in-mine blasting practices have a strong imprint on the regional signals. The different types of explosions used in these illustrations came from a single mine and illustrate the difficulty in establishing good magnitude-yield curves for mining explosions without knowing the details of the local blasting practices. The fact that the amplitudes for a particular type of blast are close to one another despite spanning large ranges in yield illustrates that under normal mine circumstances ongoing practices that are designed to control in-mine motions will be reflected in regional signals. By implication, problematic blasting practices from the perspective of the mine operator will also be a problem in regional CTBT monitoring as these events can be large and with anomalous signal character, possibly similar to waveforms from a small nuclear explosion.

2.4 Identifying Events from Regional Seismograms

Even if a mining explosion produces large amplitudes, the identification of the signal as that from a mining explosion, distinct from a nuclear explosion, precludes any CTBT verification problem. This section reviews characteristics of the seismic waves from earthquakes, mining explosions, and single-fired explosions that can be used to identify the source. Mining practices that produce regional seismic signals that unambiguously identify these types of events are highlighted.

2.4.1 Separating Explosions from Earthquakes.

There are a number of established techniques to identify explosions and discriminate them from earthquakes, particularly when the events are large enough to be recorded at teleseismic (>2000 km) distances. Large magnitude seismic events which generate detectable surface waves can be identified by well established techniques such as the ratio of surface magnitude (M_s) to body wave magnitude (m_b) called the M_s:m_b discriminant (OTA, 1988).

When the event is less than magnitude 4, the surface wave signal may be masked by background noise, even at distances as short as a few hundred kilometers. In this case, other techniques such as short period ($f > 0.5$ Hz) seismic discriminants at regional distances (<2000 km) must be applied (e.g. Pomeroy *et al.*, 1982). The techniques or algorithms that use combinations of seismic measures to separate or discriminate explosions from earthquakes are called "discriminants".

These regional discriminants have been applied to earthquakes and underground explosions in several regions of the world including the Nevada Test Site (NTS where many nuclear explosions were detonated) in the western United States (e.g. Bennett and Murphy, 1986; Taylor *et al.*, 1989; Walter *et al.*, 1995). The location of some western U.S. seismic events and the stations that recorded them are shown in Figure 2.6. Also illustrated are typical earthquake and explosion high-frequency seismograms. Note the difference in the relative amplitude of the seismic phase labeled L_g. Some of the most useful and effective discriminants are based on the ratio of the amplitudes of seismic P phases (P_n or P_g) to those of seismic S phases (S_n or L_g). The amplitude of this P/S "phase ratio", after filtering the seismogram to include only high frequency energy, is one of the most successful discriminants (e.g. Dysart and Pulli, 1990; Baumgardt and Young, 1990; Kim *et al.* 1993; Walter *et al.* 1995; Taylor, 1996). Another recent discriminant technique fits a line to the amplitude ratio of P_g/L_g versus frequency and is effective since explosions tend to have steeper slopes (e.g. Goldstein, 1995). Figure 2.7 shows an example of these two discriminants, which when plotted, separate the earthquakes and explosions into two groups.

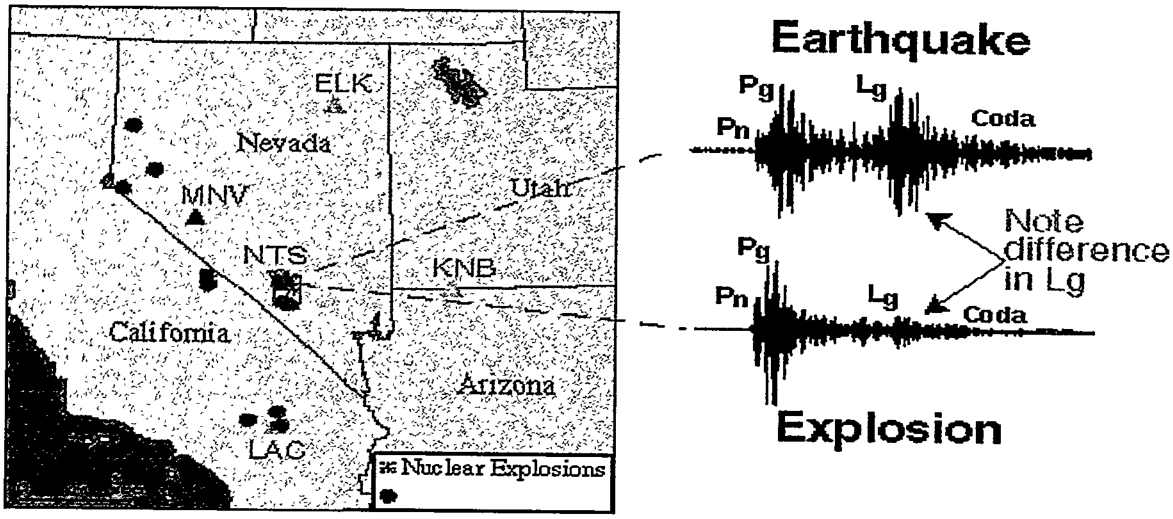

Figure 2.6: Seismic waves generated by an earthquake and an explosion near the Nevada Test Site recorded at the station MNV. Both seismograms are filtered to emphasize the high frequencies (6-8 Hz) since explosions can generally be separated from earthquakes based on their relatively lower amplitude L_g waves (adapted from Walter, 1996).

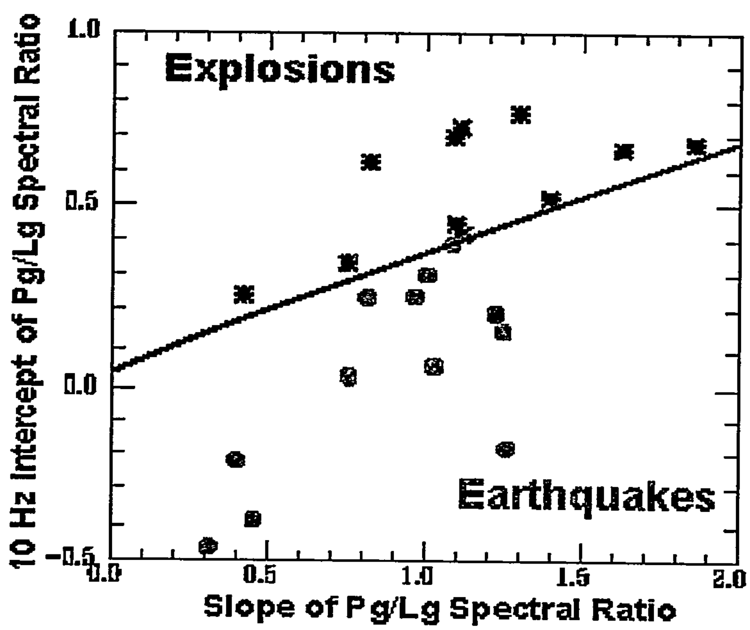

Figure 2.7: Example of a method of separating explosions from earthquakes. The vertical axis is a discriminant based on the amplitude of P_g/L_g (Walter *et al.*, 1995). The horizontal axis is a discriminant based on the slope of the P_g/L_g spectral ratio (Goldstein, 1995) (adapted from Walter, 1996).

2.4.2 Identifying Mine Blasts

Mine blasts are explosions of course, but unlike most nuclear tests they are normally made up of many small explosions spread out in both time and space to more effectively fracture rock. This can lead to modulations in the frequency content of the event that can be used to identify some delay-fired type mine shots and distinguish them from concentrated blasts (Baumgardt and Ziegler, 1988; Stump and Reamer, 1988; Smith, 1989; Hedlin *et al.,* 1989; Chapman *et al.,* 1992). These modulations show up as peaks and troughs in the spectral amplitude that are related to interference between waves emanating from the individual shots. These peaks and troughs create bands in the spectra that persist through the duration of the seismic signal. An example of this apparent banding for a delay-fired event is shown in the spectrogram plot at the top of Figure 2.8. Earthquakes do

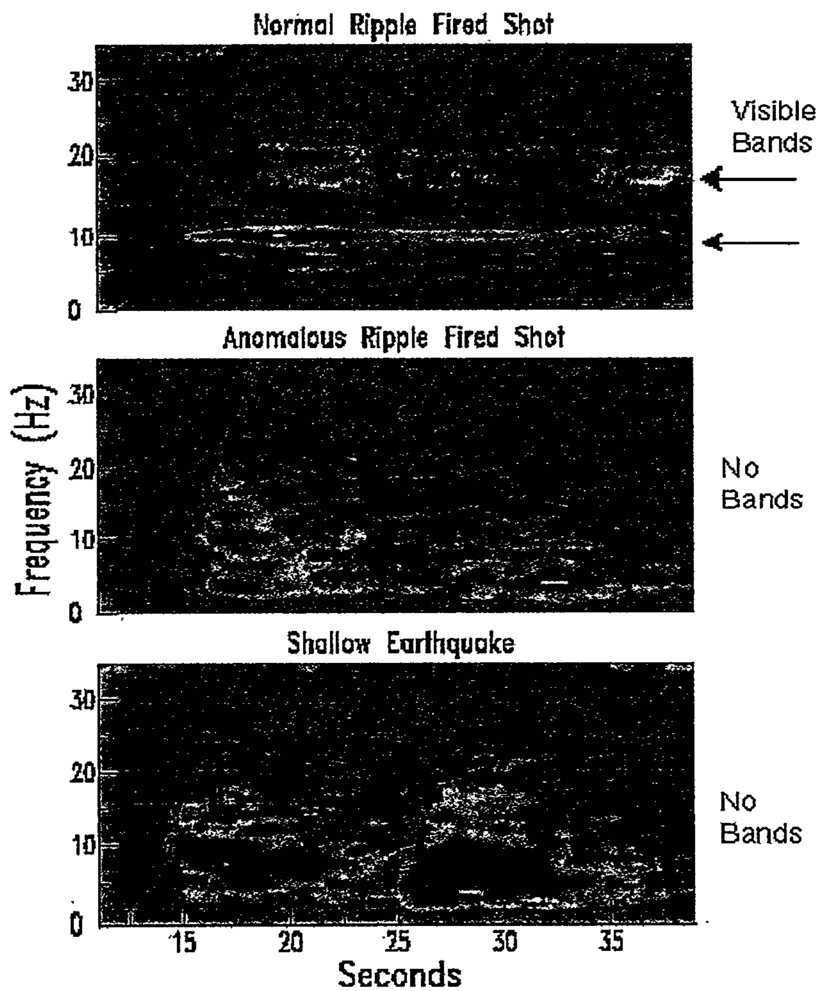

Figure 2.9: Mining explosions utilizing time delays can produce distinctive signatures. These spectrograms represent seismic wave amplitudes in color as a function of frequency and time of the recorded signal. Millisecond delay firing of the multiple explosions in some mining explosions results in peaks and troughs caused by the interference of the seismic waves from the many individual shots. These peaks and troughs persist through the signal, creating the bands visible in the top plot. If the delay times used in the explosion are either short, irregular, complex or non-existent (coyote blasts) the banding disappears (middle plot). Earthquakes do not show banding (bottom plot). (adapted from Jarpe *et al.,* 1996).

not generate this banding (bottom Figure 2.8) and thus banding can be used to identify delay-fired explosions (Hedlin*et al.,* 1990; Wuster, 1990). The techniques are not perfect however. If the explosion delays are very short, very irregular, complex, or the recording bandwidth is narrow (perhaps from losses during wave propagation) the mine blast may not show banding (middle Figure 2.8). If the mine explosion is not delay-fired (such as a coyote blast) then this technique is ineffective and the event may look seismically similar to an underground nuclear test (Denny, 1994).

2.4.3 Fingerprinting a Specific Mine

When seismic events are planned or known to occur at a specific mine, ground truth (specific information obtained at the mine), can be used to determine the event type for each of the seismically recorded events. These known waveforms can then be compared with subsequent events occurring at that same mine using a waveform correlation technique (e.g. Harris, 1991). If the new events are similar to the known event, there will be a high degree of correlation, and the new event will be identified as the same type as the old. If
the waveforms look different, then the event either did not occur at the mine or had a very different source mechanism. For a large mine, covering a big area, a number of well distributed known waveforms will be required to identify subsequent events with confidence.

2.4.4 Infrasonic Signals from Mining Explosions

Infrasonic monitoring is an old but powerful technique for monitoring atmospheric nuclear tests. A review of this technology is presented by Simons (1996). The IMS includes a 60-station infrasonic monitoring network (Figure 1.1). Recent studies have shown evidence that mining explosions (and theoretically, mine collapses) register very large and characteristic signals at infrasonic stations (Sorrells *et al.*, 1997). The 06 June 1996 Black Thunder Mine cast shot near Gillette also registered clear signals at the newly-installed 4-element infrasonic array at AFTAC's Pinedale Seismic Research Facility (PSRF). Extended observations of infrasonic signals at PSRF (Hsu and Stump, 1997) show that propagation of infrasonic signals are more efficient in the westward direction in summer months and in the eastward direction in winter months as a result of seasonal wind patterns. The infrasound results are shown in Figure 2.10. One of the biggest differences between a possible nuclear test and a mining explosion is that in all likelihood the nuclear test will be conducted underground to eliminate or minimize the release of radioactive materials or gas into the atmosphere. This means that nuclear explosions should have a much smaller and possibly different acoustic signal from a surface mining explosion that produces strong acoustic signals. Much work remains to be done in assessing the utility of combined acoustic and seismic data sets for identifying mining explosions, but preliminary work suggests a possible additional tool for source characterization.

2.4.5 Anomalous Blasts and Regional Seismograms

Anomalous blasts that detonate large amounts of explosives at the same time could trigger regional seismic stations providing signals similar to those from a contained nuclear explosion. They can occur in both surface and underground operations from:

- direct and indirect lightning strikes
- sympathetic detonations whereby a large number of holes or sections of a shot fire prematurely and instantaneously
- accidents from improper use of explosives
- operator errors and/or inexperience in designing and hooking up the shot sequence

Sympathetic detonations can result from a host of reasons: poor explosive, primer and initiator performance; massive ground shifts; high amplitude shock, pressure, and gas and heat migrating through discontinuities into an undetonated borehole.

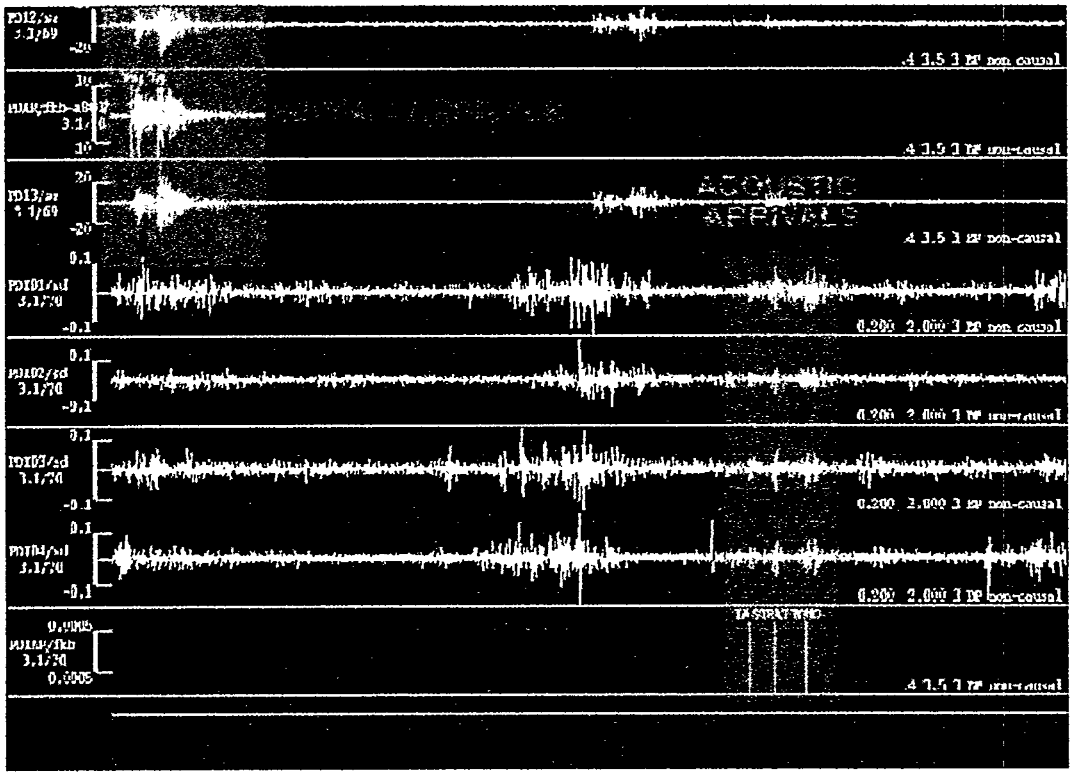

Figure 2.10: Three-component seismograms (top 3 traces) are compared to infrasonic records (the next 4 traces) for 6 June 1996 cast shot at the Black Thunder Mine, Wyoming. All records are from AFTAC's PSRF about 360 km west of Gillette. The 3 vertical bars in the bottom box indicate predicted infrasonic signal arrival times. The prediction matches very well with real arrivals. Frequency-wave number analysis indicates that the infrasonic signals come from direction of Gillette. Figure provided by Sgt. Jon Creasey of AFTAC.

Anomalous blasts as recorded by regional seismic signals may be problematic. Figure 2.11 compares near-source (~10 km) vertical seismograms from a well executed cast blast (top), a simultaneous explosion (second) and two anomalous explosions in which as much as a half million pounds of explosives were simultaneously detonated.

The large impulsive nature of the single fired explosion and the even larger impulse buried in the 13 Nov event illustrates how such abnormal effects can adversely affect in-mine ground motions. The event with the largest regional P and L_g amplitudes in Figure 2.5 is the 13 Nov cast blast. Figure 2.11 also compares the near-source and regional seismograms from the first three explosions. Amplitude and wave shape comparisons at the regional station illustrate how similar to the single shot the anomalous cast blast appears, except for being significantly larger in amplitude. Thus the event was problematic both in the near-field and at regional distances. Minimization of abnormal blasting practices such as those just illustrated will improve operations within the mine while reducing questions from a monitoring perspective. In the abnormal blast used to illustrate this point, the problem was linked to a possible sympathetic detonation, as the stress waves from explosions early in the detonation sequence outran the source timing.

Not only simultaneous detonations, but bad timing of a delay-fired explosion can be problematic by possibly reducing spectral banding used to identify such mining explosions (Figure 2.9). This spectral banding is dependent upon the actual detonation times of the explosions matching the nominal times. The simultaneous, sympathetic detonation of a large amount of explosives shown earlier is an example of a case where the nominal times did not match the actual detonation times. A more subtle but equally problematic departure of the initiation system from design is illustrated in Figure 2.12.

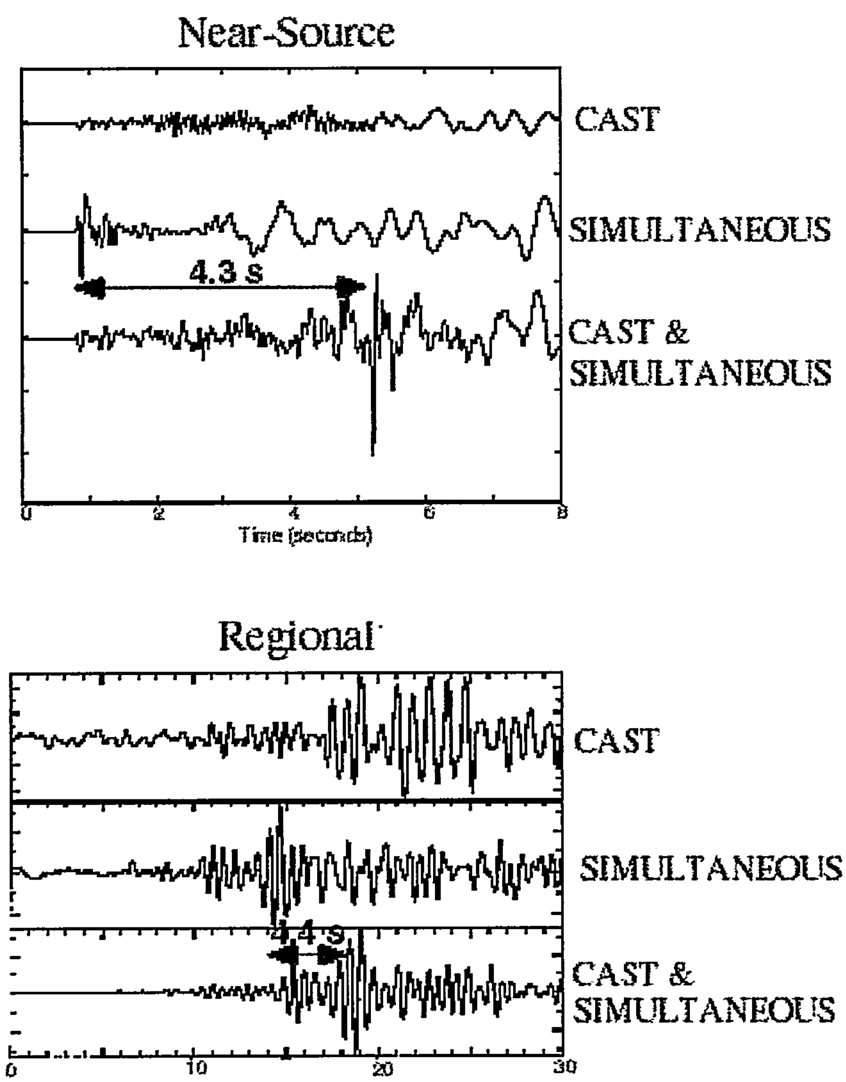

Figure 2.11: In the top portion of the figure near-source seismograms (~10 km) are compared from a good cast shot (16 June 95) a simultaneous, contained shot (24 Aug 95) and two problematic cast shots (13 Nov 95). In the lower section of the plot regional seismograms (>300 km) are compared from these sources.

In this case (Stump *et al*, 1996a), velocity of detonation measurements and high speed film were used to quantify the exact detonation time of sixteen explosions in a four-by-four explosive array. The design and actual detonation times are reproduced in the figure. The constructive and destructive interference in the frequency domain is modified by the scatter in detonation time, for example the spectral hole near 4 Hz (blue arrows in figure) is not as deep and the one at 9 Hz (red arrows) is nonexistent for the actual detonation time series. Thus, identification of this mining explosion using spectral banding would be a more difficult task because of the scatter in the actual detonation time series. In this example, no two explosions are planned to detonate concurrently and the overall pattern is quite complex, making the resulting waveforms quite sensitive to relatively small variations in detonation times of the individual explosions.

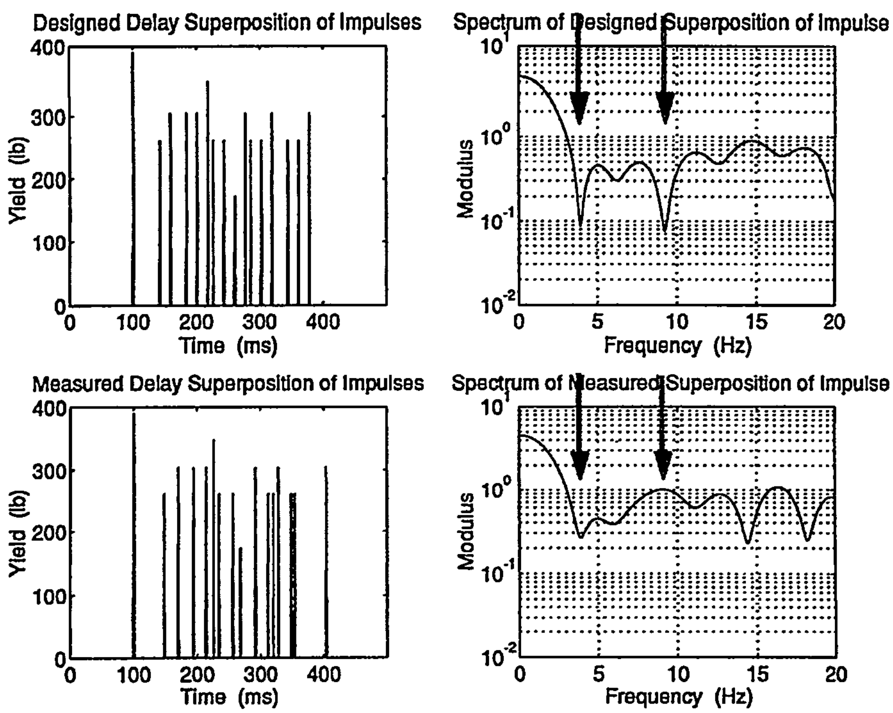

Figure 2.12: Design (top) and measured (bottom) shot times (left column) and resulting source spectra (right column) for a typical mining blast. Blue arrow denote the design spectral holes at 4 Hz and 9 Hz with comparison to the spectra from the actual shot times.

3.0 GROUND FAILURES IN UNDERGROUND MINES

3.1 Types of Ground Failures

Some ground failure is a normal part of many mining operations. However, the seismic signals emanating from large failures may subject mines to scrutiny under a CTBT. For example, longwall coal mines, room-and-pillar mines, block caving operations, and shrinkage stoping operations can create large openings which can then collapse and send out regional seismic signals.

Underground mine failures may be categorized for convenience in the following fashion:

- planned failures which are controlled: an example would be the blasting out of existing, stable pillars, to create a mass of rock rubble which may be leached in situ. This was the case of the recent such blast at the Copper Range Company's White Pine Mine (Phillips et al., 1996).
- planned failures which are not controlled: a typical example would be the initial and subsequent caving behind a new longwall in coal. This collapse is a natural part of the mining method but its timing and areal extent usually are not controlled. Such events were monitored seismically at the Twentymile Mine in Colorado (Walter et al., 1996). Another example would be the induced collapses in block caving operations, such as activities at the Henderson mine in Colorado (Smith et al., 1995).
- unplanned failures (clearly uncontrolled) which include:
  - pillar failures in coal, metal, and nonmetal mines
  - violent ground failures in coal mines, known as coal bumps
  - violent ground failures in hard rock mines, known as rockbursts.

In the U.S. there are relatively few underground mine failure events that have well-documented ground motions. Partly, this is a result of the efforts of local seismic network operators to keep their catalogs of earthquakes "pure" for the purposes of doing earthquake hazard and other tectonic studies. For this reason, known mine blasts and mine collapses are often either knowingly discarded or not identified as such. U.S. government agencies that regulate mines and mine operators have a wealth of data on observed damage in mine collapses but since their focus is on safety they do not normally collect information on seismic magnitude. Another reason for the lack of documentation is the confusion between whether damage in a mine is the result of, or the cause of seismic waves. When the seismic locations and mechanisms are ambiguous, this confusion has not been resolved for many mine-related events. The combined analysis of mine damage data with seismic information such as magnitude, focal mechanism, and discrimination behavior should be actively pursued.

3.2 Regional Seismic Signals Produced by Ground Failures

3.2.1 Seismic Signals From Cascading Pillar Failures

Some of the largest mining-associated seismic signals are due to accidental failures in large room-and-pillar mines (e.g. Pechmann et al., 1995, Taylor, 1994). These events have been termed cascading pillar failures by Zipf (1996). Those giving regional signals above M_L 3.5 in the U.S. and overseas, in the past two decades, are summarized in Table 3.1.

Table 3.1 Characteristics of Cascading Pillar Failures in the U.S. and Overseas with Magnitude Exceeding 3.5, for the Period 1981-1995, (after Zipf, 1996)

Date	Location	Mine Type	Collapse Area (m^2)	M_L	m_b	References
5/14/81	UT	Coal	~22,500	3.5	4.0	Taylor (1994) Patton and Walter (1994)
3/13/89	Germany	Potash	~6,000,000	5.6	5.4	Knoll(1990) Bennett et al (1994)
1/21/93	UT	Coal	15,000	3.6	3.4	Boler et al. (1997)
3/12/94	NY	Salt	40,000	3.5	3.6	Zipf (1996)
2/3/95	WY	Trona	~2,000,000	5.2	5.3	Pechmann et al. (1995) Swanson and Boler (1995)

The events in Germany and Wyoming showed M_L in excess of 5.0. At these large magnitudes, the events are easily detected teleseismically under a CTBT monitoring system. Their shallow depth relative to that of earthquakes, and their unusual mechanism, can cause them to look somewhat more like explosions than earthquakes, when using the most robust of the teleseismic identification techniques, M_s:m_b. The sheer size of these events and speculation that they could be induced has led to supposition that a treaty evader might claim that an explosion was a collapse or might conduct a clandestine explosion simultaneously with an induced collapse with the intent of hiding the explosion in the overall event coda (Heuze, 1995). For these reasons massive pillar collapse events should be considered candidates for false alarms under a CTBT. The case of the Solvay, WY, collapse offers an example of the ambiguities that may arise.

The February 3, 1995, collapse of the Solvay trona mine near Green River, Wyoming (M_L=5.2, m_b=5.3; Ms=4.6) was recorded all over the world (see Pechmann et al., 1995; and Swanson and Boler, 1995). During the collapse, the entire southwest quadrant of the mine, an area of approximately 2 squared kilometers, failed without warning. In the initial days after the Solvay mine damage, there was confusion as to whether the mine collapse was the cause or the result of the seismic event. Inexact seismic locations indicated that the seismic waves and damage to the mine were related but it was not clear immediately whether an earthquake had induced damage in the mine or whether the collapse itself had generated the seismic waves. Seismic analysis of the all dilatational first motions of the seismic waves and a comparison of calculated waveforms to the actual data showed the collapse itself had generated the bulk of the seismic energy (Pechmann et al., 1995). This conclusion was also supported by an investigation of the seismic and rock mechanics properties of the mine by Swanson and Boler (1995). Based on mine surveys, the surface above the collapse area subsided about 90 cm. However, from a CTBT verification point of view, it is interesting to note that no surface expression of that subsidence could be noticed either by walking on the ground surface or from aerial photography performed in October 1995 and again in October 1996 (Heuze, 1996, 1997).

An aspect of pillar collapses that warrants further examination is the potential relationship between the area of the collapse and the seismic magnitude of the signal. Table 3.2 seems to show a trend of proportionality between the two parameters. The collapses in Germany and Wyoming covered one hundred times more area than the smaller events and their signals also were about one hundred times stronger. If additional data can be obtained from failures in the range between the two extremes it may help verify whether the explanation given for a particular seismic event in terms of an area of pillar collapse is consistent with the (small) database of such occurrences.

3.2.2 Seismic Signals from Coal Bumps

Coal bumps signals can be very conspicuous. For example, the magnitude of the March 11, 1995, event in Table 3.1 was 4.2, and the signal was recorded by seismic stations as far away as Africa and Australia. Records from several large coal bumps in Kentucky indicates they have very similar seismic source characteristics to the pillar failures. Given that the damage observed in the mine can be quite different for these two types of events, more work is needed to understand the precise mechanism of the failure generating the coal bump signals. The example of the Gentry Mountain event illustrate the potential ambiguities arising from coal bumps.

The May 14, 1981 Gentry Mountain, Utah mine collapse was seismically identified by Taylor, 1994. Previously, the event had been listed in seismic catalogs as an earthquake. In the late 1980's a study of regional seismic discriminants was performed in the Western U.S. (Taylor et al., 1989) with many seismic events. It was noted that one "earthquake" consistently plotted with the explosions. Upon checking with the mine operators, Taylor found that the event was associated with a large collapse in a coal mine. By modeling the event, Taylor (1994) was able to show that the collapse was responsible for the seismic signal observed. In another Western U.S. discrimination study (Patton and Walter, 1993, 1994), this mine collapse was also found to group with the explosions. As discussed by Taylor (1994), these types of events would likely be false alarms under a CTBT because their seismic characteristics are explosion-like and they group with explosions for a number of regional discriminants.

3.2.3 Seismic Signals from Rockbursts

In the U.S., the deep mines of the Coeur d'Alene district have been the source of numerous rockbursts (Blake, 1984; Whyatt et al, 1996). Elsewhere in the world other very deep hard rock mines show similar occurences (Young, 1993).

Ryder (1988) suggests that the mining-induced-seismicity in hardrock mines falls into at least two categories, namely, crushing-type and shearing-type events. The crushing-type events are associated with the compressive failure of large volumes of highly stressed rocks, whereas the shearing-type events result from sudden catastrophic movements on structural features such as faults and other geologic discontinuities or else actual shear rupture within the rock mass. Research shows that the majority of the mining induced seismicity in hardrock mining is of the shearing-type and that the largest rockbursts (magnitude in excess of 5) historically have been related to shear motion on faults affected by the mining (Gibowicz, 1990, 1993). These events appear as earthquakes and would not cause false alarms.

However, rockbursts also can appear as implosional or explosional events (Wong and McGarr, 1990) and thus become of concern under CTBT verification. There is also a remote chance that such events could be engineered to mask clandestine explosions (Heuze, 1994).

Empirical studies of rockbursts (Bennett et al., 1994 and 1995) including events from the deep (2-3 km) gold mines in South Africa suggest that some rockbursts may produce surface wave magnitudes (M_S) that are as much as one unit smaller than body wave magnitudes (m_b). This would make them appear to be explosions, using the traditional M_S: m_b discriminant. Recent work (Bennett et al., 1996) supports the utilization of high-frequency regional P and L-waves$_g$ for discrimination of some rockbursts.

3.2 Number and Size of Regional Seismic Signals from Ground Failures

For CTBT verification purpose we will assume that events of magnitude above 3.5 may be picked up by the IMS. We show in Table 3.2 such occurrences in the U.S. in the past two decades. The events listed are a subset of many more mine seismic events recorded in this country, most of which would not be of concern regarding CTBT verification. The table indicates that:

- several regions throughout the United States (AL, ID, KY, NY, UT, VA, WY) have created mine seismic signals visible at regional scales
- several mining methods have been involved

- coal mines were by far the most frequent sources of such signals
- One specific mine accounted for the majority of the IMS-relevant events in the past five years. This particular mine is now closed, but coal mining will continue in the same local geologic environment.

The relatively small number of events per year shown in the Table should not be a source of complacency. Even a single false alarm, potentially leading to an OSI, would create a significant burden on the industry and the U.S. government.

A large amount of recent additional information regarding the various types of mine failures as well as their associated seismicity can be found in Gay and Wainwright, 1984; Fairhurst, 1990; Young, 1993; Chase et al., 1994; Iannacchione and Zelanko, 1995; Maleki et al., 1995; and Whyatt et al. 1996.

Table 3.2: Examples of U.S. Mining Seismic Events, Non-related to Explosions, with Magnitude Exceeding 3.5, for the Period 1981-1996.

Date	Location/Mine	Ml	mb	Remarks
5/14/81	Gentry Mountain, UT	3.5	4.0	Pillar failures in coal
5/7/86	Jim Walters Resources #4, AL	3.6	4.2	Coal bump
4/14/88	Buchanan #1, VA	4.0		Coal bump
4/10/89	Buchanan #1, VA	3.6	4.3	Coal bump
5/23/91	East Mountain, UT	3.6	3.5	Coal Bump
7/5/92	East Mountain, UT	3.7	4.0	Coal bump
7/11/92	East Mountain, UT	3.0	3.9	Coal bump
1/21/93	Book Cliffs, Soldier Canyon, UT	3.6	3.4	Pillar failures in coal
3/12/94	Retsof, NY	3.5	3.6	Pillar failurs in salt
8/16/94	Lucky Friday, ID	4.1		Rockburst
10/5/94	Lynch 37, KY	3.6		Coal bump
10/15/94	Lynch 37, KY	3.6		Coal bump
1/19/95	Lynch 37, KY	3.7		Coal bump
1/30/95	Lynch 37, KY	3.7		Coal bump
2/3/95	Solvay Minerals, WY	5.1	5.2	Pillar failures in evaporites
3/11/95	Lynch 37, KY	4.0	4.2	Coal bump
10/25/95	Lynch 37, KY	4.2		Coal bump
4/19/96	Lynch 37, KY	3.7		Coal bump
5/4/96	Lynch 37, KY	3.7		Coal bump

3.4 Identifying Ground Failures from Regional Seismograms

There are two approaches to resolving the ambiguities: the seismic fingerprinting of specific mines and the use of seismic discriminants which compare the signals from a particular location to those of many other events.

3.4.1 Seismic Fingerprinting

An example of fingerprinting based on existing records is shown in Figure 3.1. The seismic records of events occuring several months apart at the Lynch 37 coal mine in KY are very similar. This would reduce the ambiguity of the source of these events.

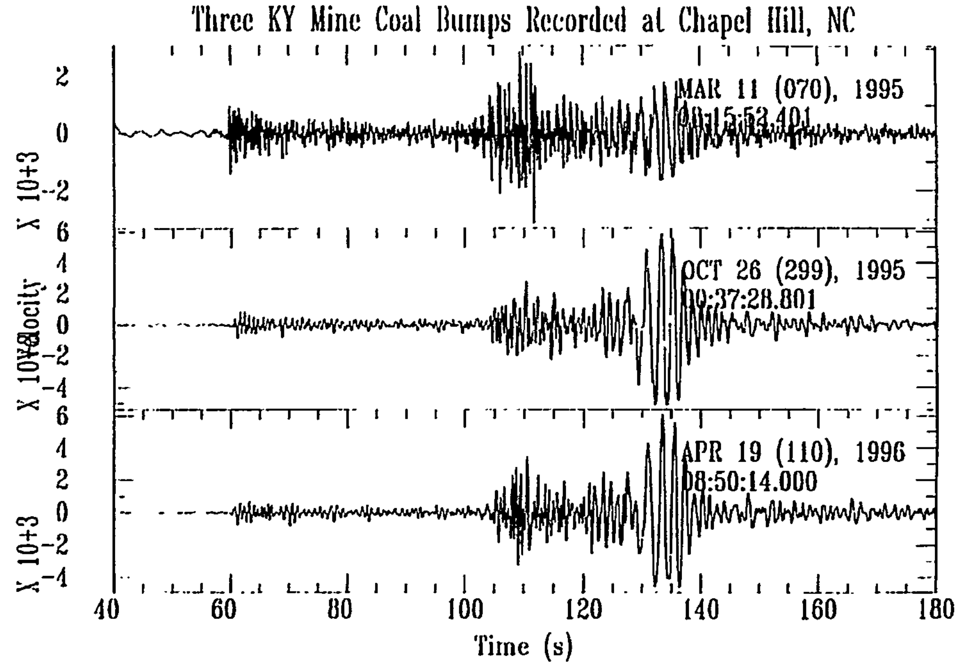

Figure 3.1 Seismic records from three coal bumps from the Lynch 37 coal mine, KY, recorded at Chapel Hill, North Carolina.

3.4.2 Seismic Discriminants

The seismic point source mechanism for collapses (a closing tension crack, or block falling under gravity), is different from the double couple in earthquakes and the spherical expanding sphere for explosions. Mine seismicity from uncontrolled sources (e.g. rockbursts, coal bumps, mine collapses) can also look different than either earthquakes or explosions. Mine tremors with a large implosional component such as a collapses have some unique discriminant behavior. If the collapse is large enough, the long period wave forms can be compared with calculated wave forms to identify the event (Walter, 1996). This kind of waveform comparison to determine source mechanisms has become routine for earthquakes but is just starting to be applied to mine tremors.

It is expected that collapses can have different excitation of P and S waves than do earthquakes or explosions (e.g. Walter and Brune, 1993). Studies that have applied algorithms that discriminate earthquakes from explosions to known collapse data show that these events belong in their own category (Bennett et al., 1994; Taylor, 1995; Walter, 1995). Figure 3.2 shows four different regional seismic discriminants applied to western U.S. earthquakes explosions and mine collapses. Using the traditional M_s:m_b and its variations such as M_0:m_b (Patton and Walter, 1993, 1994) the collapses plot close to the explosions. On the other hand, using the regional P/S ratio discriminants the collapses look more earthquake-like.

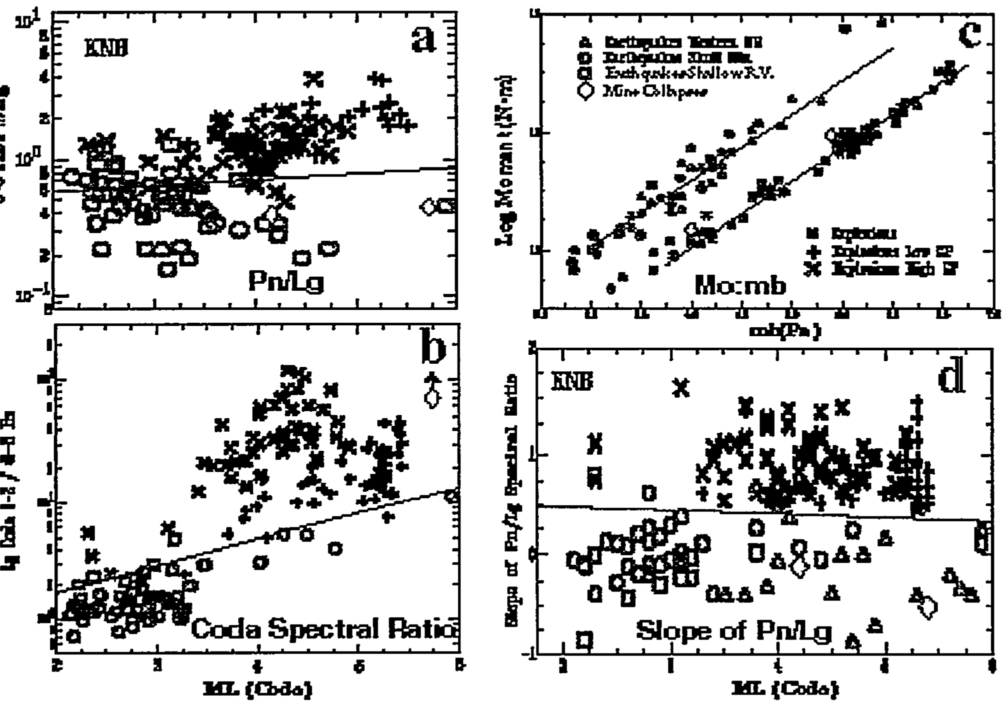

Figure 3.2: Collapses do not fall into either the earthquake or explosion categories when regional seismic methods to discriminate these events are applied. Four different discriminants are displayed. In (a) and (d) the Gentry Mountain and Solvay collapses look like earthquakes while in (b) and (c) they look like explosions.

The pattern of behaving like earthquakes for some seismic measures and like explosions for others might be exploited to uniquely identify collapse events. This is especially important for smaller collapses that cannot be identified by waveform modeling, first motion analysis, or inspection of the mine. However, the current number of known collapses which have been studied is very limited and more work needs to be done to define the seismic criteria for discriminating collapses from both earthquakes and explosions.

Next, we illustrate how the partnership between industry and the CTBT verification community can result in characterizing seismic signals from various types of mine failures and reducing their ambiguity.

3.5 Seismic Studies of Specific Underground Failures

These studies were designed to provide the seismic data to develop techniques for identifying ground failures. Similar work focused on IMS stations will provide the opportunity for fingerprinting specific mine operations. Well-developed fingerprints will reduce the ambiguity of signals from specific mines.

3.5.1 Planned and Controlled Failure by Pillar Rubblization

On September 3, 1995, the White Pine Mine, in Michigan, which is owned by Copper Range Company, conducted the first of a planned series of explosive removal of existing pillars. The purpose of this operation was to evaluate the effectiveness of pillar rubblization and roof collapse for planned in-situ leaching of copper ore from the rock mass. This type of seismic source is unique in that a large, delay-fired, explosive source was expected to be followed by collapse of the rock immediately above the explosion into the void created (Phillips et al.,1996).

The underground workings at the mine are extensive, with rough dimensions of 8 km by 9 km (Figure 3.3). Historically, some portions of the mine have collapsed "naturally"; they are denoted by dark black areas in the figure. The area in the north central portion of the mine has collapsed slowly over a period of many years. The area south west of the White Pine Fault failed catastrophically, producing a locally felt earthquake and extensive damage to underground mine structures (St. Don, 1995). The controlled collapse documented here is the first of its type in the White Pine mine.

Seventy-two (72) pillars with average dimensions of 6.1m by 12.2m were loaded with an average of 820 kg (1,807 lbs.) of explosive per pillar, for a total explosive source of 59 tons (130,068 lbs). A millisecond delay firing pattern, 325 milliseconds in duration, was used to minimize vibration effects at the surface and to propagate the collapse toward the unmined faces. Note that this test collapse was designed to be only 1/4 the size of future full scale panel blasts (St. Don, 1995). Figure 3.4 shows vertical velocity seismograms at the free surface directly above the explosion. It gives a relative measure of the seismic energy generated by the explosions in the pillars (red), by the failure of the pillars (green), and by the collapse (blue). The explosions are a factor of 100 times or more smaller than the signal generated by the collapse. This indicates that the primary signal observed from this type of event will be a result of the collapse not of the explosions.

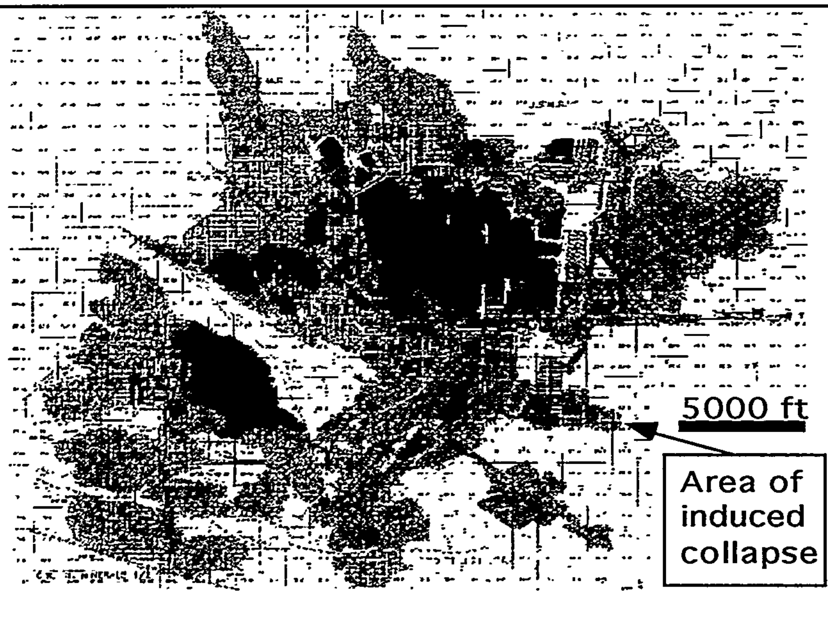

Figure 3.3: A plan view of underground workings at the White Pine Mine. Hatched areas indicate room and pillar mined areas while black indicates failed pillar areas. The failed area in the lower left quadrant was a catastrophic event which generated regional signals, in January 1989.

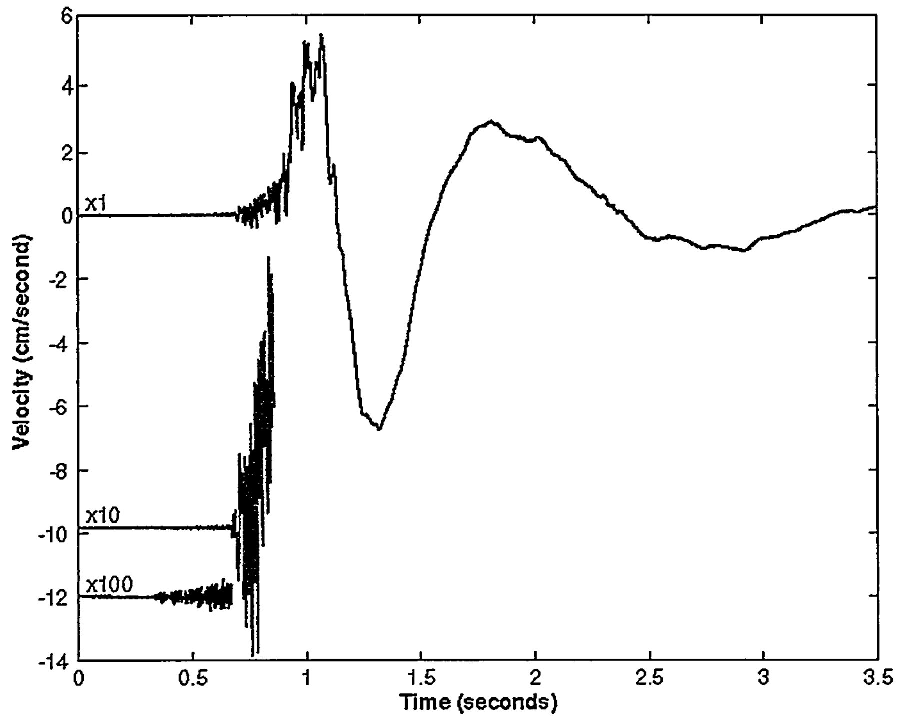

Figure 3.4: Vertical component velocity seismogram recorded at surface ground zero. The upper trace is the complete seismogram, dominated by the long period collapse (blue). The middle and lower traces are magnified by 10 and 100 times, respectively. The green middle trace shows pillar failure and the red lower trace shows the explosions in the pillars.

Regional seismograms of the White Pine induced collapse were recovered from stations at ranges from 200 to 1000 km. Figure 3.5 shows the vertical, North/South, and East/West velocities at station EYMN (range 202 km, azimuth 313 degrees) and their associated spectra. High signal-to-noise ratio body and surface waves are evident in the data which have been high pass filtered at 0.75 Hz. Coda lengths (150 s) indicated a magnitude (m_{bLg}) of 3.1 using a scale developed for New England (Chaplin *et al.*, 1980). This magnitude is an overestimate because Lg-coda attenuation is higher in New England than in north-central U.S. (Singh and Herrmann, 1983).

This study has shown that the explosively induced collapse of a panel in an underground room-and-pillar mine can generate seismic signals which will propagate to at least near regional distances. It has been reported that there are 50,000 pillars remaining at White Pine, containing over 450,000 tons (1 billion lbs.) of recoverable copper (Crawford, 1996). So, this mine could be visible to the IMS in the future if additional such collapses are performed. Near-source monitoring of the September 1995 collapse shows that the observed ground motions are consistent with a source model using an opening horizontal crack, the free-fall of a tabular region of the roof, and its impact on the floor (Yang *et al.,* 1998). This collapse source model has a large volumetric component similar in some aspects to that of a contained explosion.

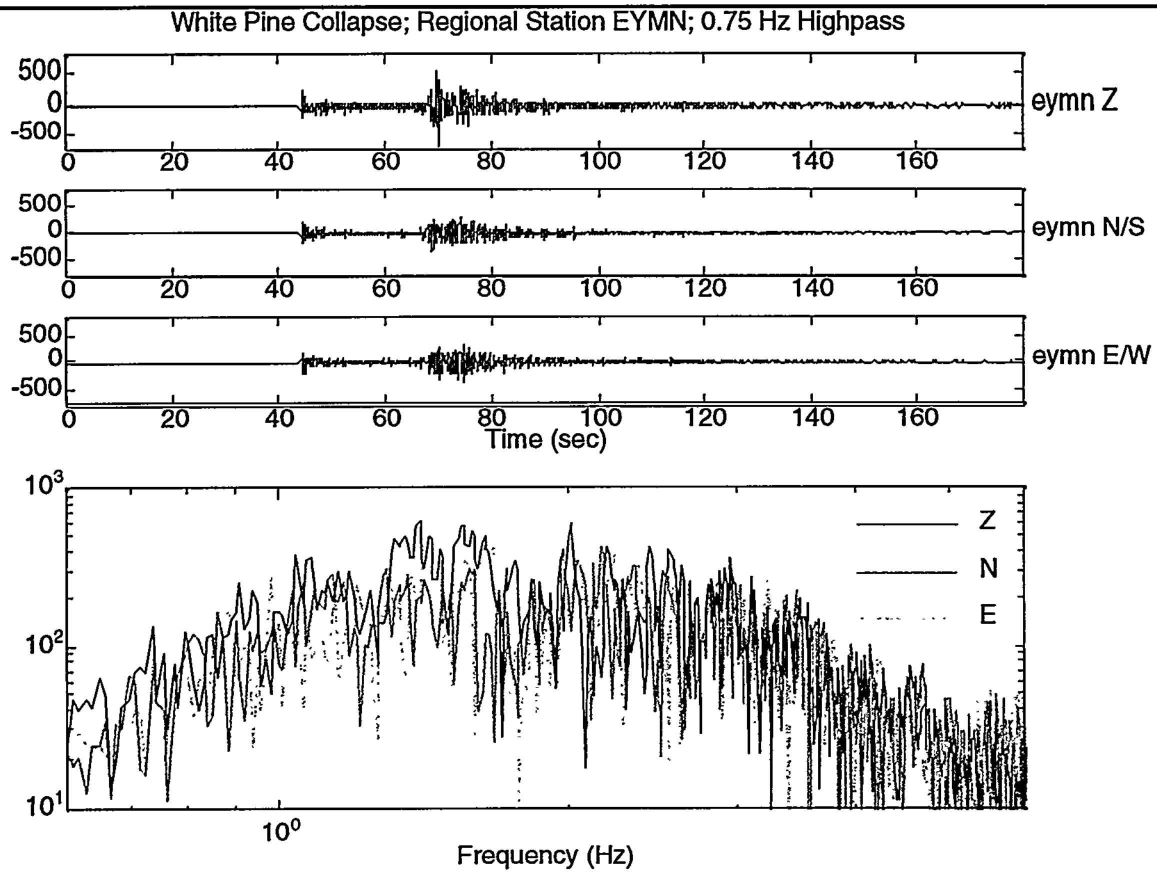

Figure 3.5: Three-component regional seismograms and spectra of the collapse event at EYMN (range 202 km), high pass filtered at 0.75 Hz. Full waveform spectra indicate that the vertical component is peaked between 1 and 2 Hz similar to on-site measurements.

3.5.2 Planned and Uncontrolled Failure in Longwall Coal Mining

To learn more about the seismic characteristics of longwall collapse events, a seismic monitoring experiment was designed and conducted in cooperation with the Cyprus Twentymile Coal Company at their Twentymile Coal Mine, in Colorado (Walter et al., 1996). The overall mine area is shown in Figure 3.6. This longwall mine held the world record for monthly underground coal production (534,557 tons in September 1994), and set a new world record during the experiment in September 1995. Eleven seismic stations were deployed covering the immediate vicinity of the mine and extending to a distance of roughly 100 km. All the seismicity associated with the mining of a new panel, beginning with the "first cave" of an estimated 25,000 m^2 roof panel, and continuing with the monitoring of aftershocks and subsequent collapses were recorded for about a 3-month period.

The Twentymile operation completely excavates the 3 meter (10 foot) high Wadge coal seam at a depth of approximately 350 m (1100 feet) underground in 244 m (800 foot) wide panels. The roof rock above the coal seam is supported by hydraulic shields in the immediate vicinity of the area of

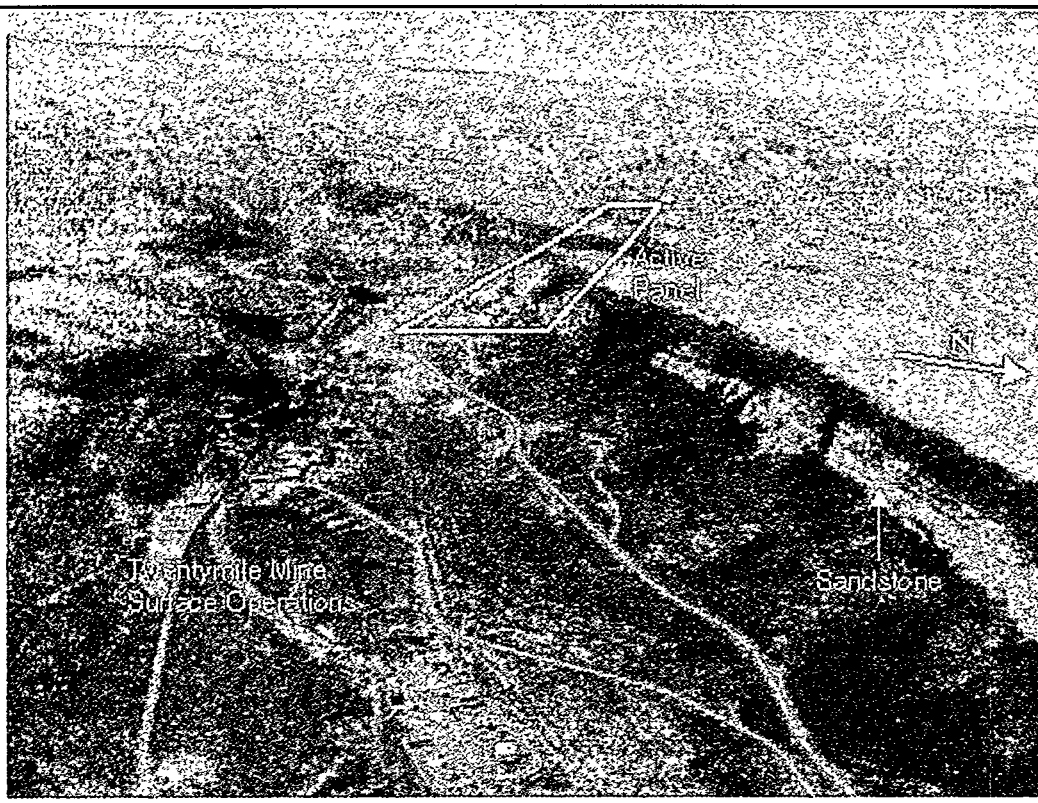

Fig. 3.6. Aerial photo of Twentymile Coal Mine area. A surface projection of the mining panel active during the seismic deployment is superimposed on the picture. The ground above the active panel 35W and previously mined panels to the north has subsided 1.4 m but this is not easily visible to the naked eye. On the other hand, the thick Twentymile sandstone layer, visible where it outcrops, has shown extensive response to the undermining, under the form of very conspicuous cliff failures (Figure 3.8). (Photo by François Heuze).

active mining. The longwall mining machinery moves forward as the coal is removed and the region behind the active face is allowed to collapse as shown in Figure 3.7. It is believed that the softer shale rocks collapse until reaching the more competent sandstone layers, which can support more weight. It is the failure of these sandstone layers that is believed to lead to the M≈2-3.5 seismic events which have been detected by the U. S. Geological Survey station 160 km away in Golden, Colorado. These seismic events do not cause significant air waves underground and do not generally impede the operation of the mine. After failure of the sandstone layers, the collapsed zone spreads up to the surface, where the ground above the region that has been mined eventually subsides (about 1.4 m - 4.5 feet). This surface settling tapers near the edges and is not easily detectable by the naked eye. On the other hand, the thick outcropping Twentymile Sandstone bed can exhibit significant distress due to the subsidence from underground mining. This has taken the form of substantial cliff collapses. The collapses due to the mining ongoing during this experiment are conspicuous on Figure 3.8. Such features would be noticeable in an aerial inspection.

During the experiment (August to November, 1995) hundreds of seismic events were recorded. The largest of these were recorded 640 km away at KNB in Utah. Having previously calibrated this station for magnitude (Mayeda and Walter, 1996) we were able to determine M_L(Coda) magnitudes for all the events. There were five events between magnitude 2 and 3 which are listed in Table 3.3 with their dates and times.

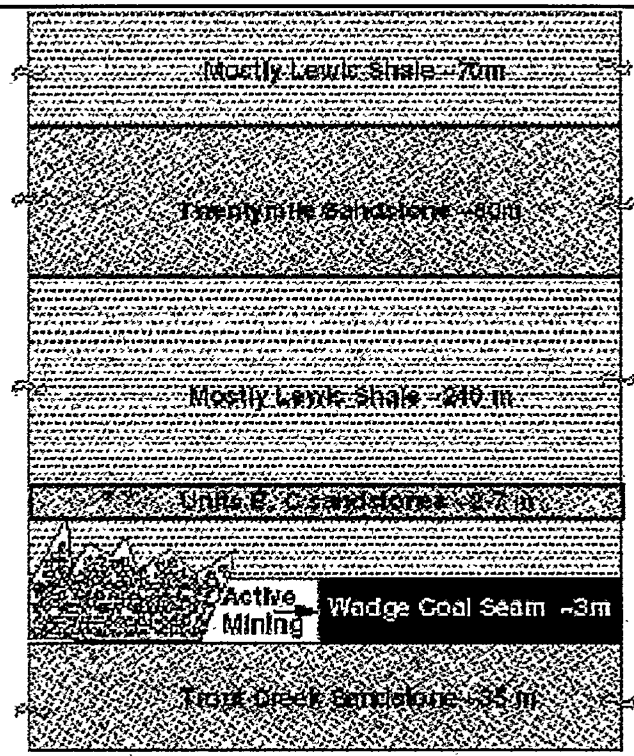

Fig 3.7 Simplified schematic cross section of Twentymile coal mine and some of the major rock units. The 3m (10 ft.) high Wadge coal seam is completely excavated within the mining panels and the weak shale rocks are allowed to collapse behind the advancing face of active mining. It is hypothesized that the roof rock collapses until it reaches the stronger sandstone rock layers which can support more weight before failure. It is believed that the failure of these sandstone layers, either units B, C or the thicker Twentymile sandstone layers is responsible for the largest seismic events. (Simplified from detailed cross-sections provided by Twentymile coal mine).

Table 3.3: Largest Events Recorded During the Longwall Coal Mine Experiment, Twentymile Mine, Colorado

Date	Time (UT)	M_L(Coda)
August 5, 1995	23:49:50.0	2.0
August 25, 1995	12:51:24.6	2.8
September 6, 1995	2:57:49.4	2.6
October 2, 1995	12:38:12.0	2.9
October 5, 1995	01:18:13.5	2.8

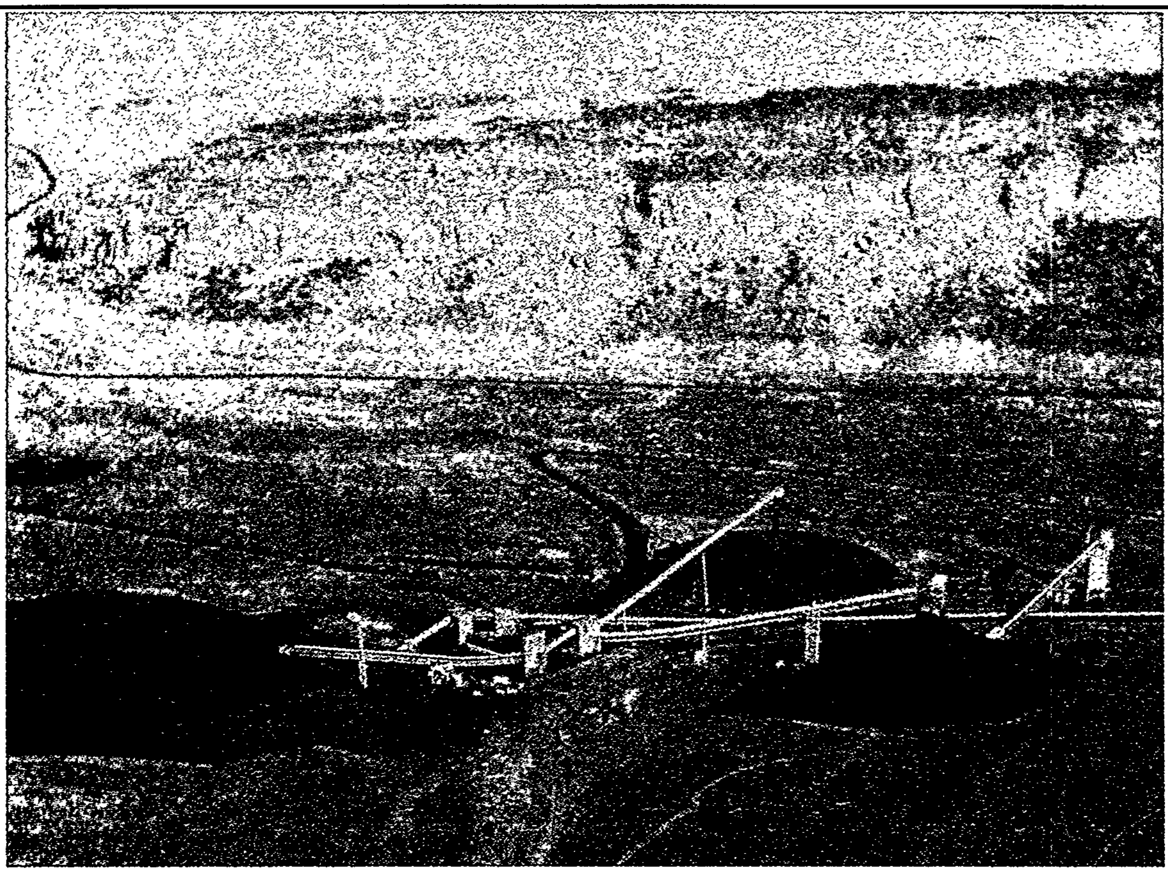

Fig. 3.8: Aerial photo of the cliff collapse in the Twentymile Sandstone outcrop due to the longwall mining of panel 35W, as confirmed in discussions with mine personnel. (Photo by F. Heuze)

The seismic records indicate they were shallow and occurred in or above the active mining panel. Seismometers on top of the mine indicated downward first motion consistent with either a shallow normal earthquake or a collapse mechanism (block collapsing under gravity). This first motion is not consistent with explosive sources or other simple types of earthquake mechanisms. As shown in Figure 3.9, a comparison of the seismic waveforms with calculated waveforms (e.g. Walter, 1995) indicates that the gravity-driven collapse model fits these large events better than a normal earthquake model. Thus the larger seismic events coming from the longwall mine have a similar point-source seismic mechanism to the larger accidental collapses described by Taylor, 1994, and Pechmann et al., 1995. Although these events have not been tested using seismic identification algorithms, we expect their behavior to be similar to the large unplanned collapses based on their shallow depth and collapse mechanism.

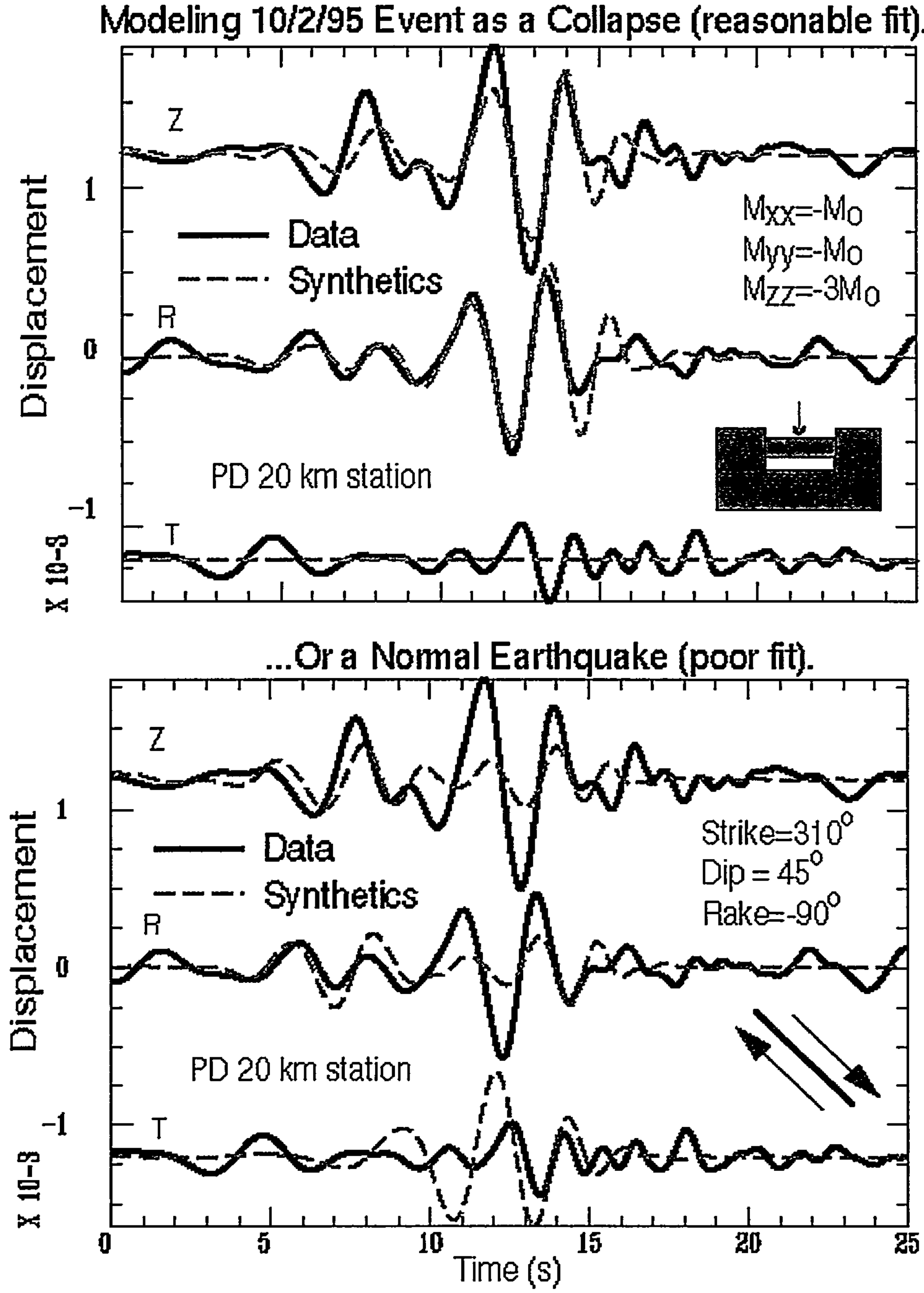

Fig. 3.9: Preliminary waveform modeling indicates that the point-source mechanisms for the largest events are more consistent with a gravitational collapse mechanism than a normal earthquake mechanism. This figure compares three-component, 2-5 s period fits of synthetic seismograms for both mechanism types to the data recorded at a station 20 km away towards Pinedale, Wyoming. (after Walter *et al.*, 1996).

3.5.3 Planned and Uncontrolled Failure by Block Caving

An experiment was conducted in cooperation with the Henderson mine of Cyprus Climax Metals Company, in Colorado (Smith et al., 1995). In the block caving process, the ore body is undermined and a cavity is created. Figure 3.10 shows a schematic of the layout at the Henderson mine. The ore body is contained within Red Mountain and is mined by block caving. Seismic signals are generated from both the undercut blasts and the subsequent caving events. Thirteen seismometers were deployed on Red Mountain surrounding the mine to record these seismic events.

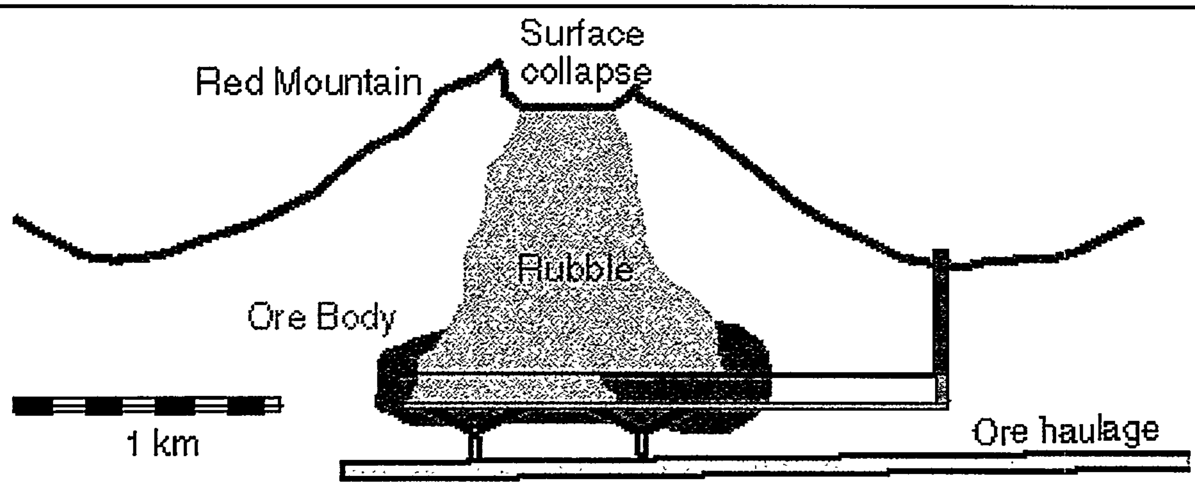

Fig. 3.10: Schematic of operations at the Henderson Mine, Colorado. The ore body, shaded purple, lies 1.5 km directly beneath the peak of Red Mountain. At successively deeper depths a mesh of tunnels are laid out in the ore body and explosions are used to initiate gravitational fracturing and collapse in the overlying ore. As the ore is extracted, the fractured rubble zone grows forming a subsidence crater at the surface. Extraction continues at each level until the ore is exhausted and then mining is initiated at the next deeper level. Ore is dumped down chutes for loading on a train (after Smith et al, 1995).

Both the undercut blasts and the caving events are quite small (M<2) and most likely would not be detected by the IMS. However, the caving process itself is quite similar to the chimney formation that occurs after underground nuclear explosions. In this case the roof of the cavity formed by the nuclear explosion falls-in to create a rubble zone that extends upward and may intersect the surface to form a crater. The seismic events associated with this process are anomalously deficient in high frequencies compared with similar sized earthquakes. As shown in Figure 3.11, the low-frequency seismic events from block caving have a very different character than the impulsive, high frequency seismograms from the undercut blasts. Note that the aftershock of the NTS explosion has a similar low frequency character to the caving event. Preliminary investigations reveals that there are two techniques to try and differentiate caving events from suspected aftershocks of a nuclear test. First, the block caving events are slightly more emergent than those observed at the Nevada Test Site (Smith et al, 1995) . Second, it is expected that accurate location of the events in the working part of the mine could also be used to confirm the legitimate mining origin of these events. There are few active block caving mines in the U.S., and their seismic signals usually are small.

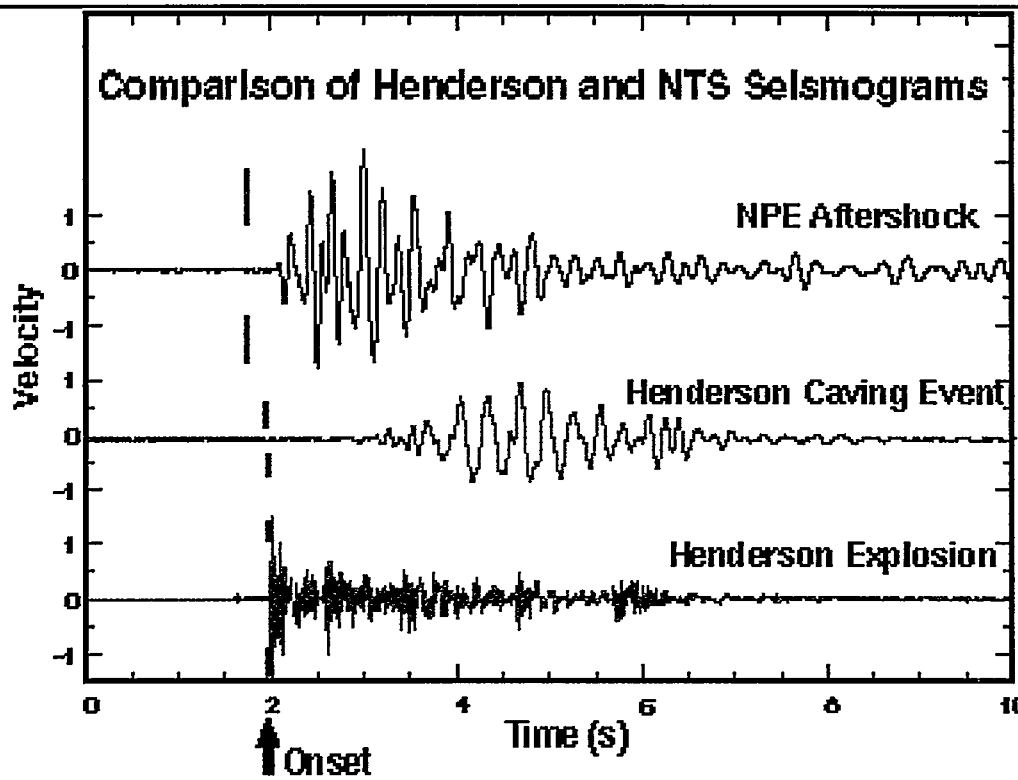

Fig. 3.11: Comparison of two seismograms recorded during field deployment of seismometers on Red Mountain above the Henderson, Colorado mine, with the seismogram of a chimney-forming event after the NPE, a large chemical explosion at the Nevada Test Site (NTS). The bottom two traces are seismograms generated by rock caving (green) and by an undercut blast to initiate caving (blue). The explosion shows an impulsive onset and high frequency energy. The caving event has a very emergent onset and lower frequency energy. The low frequency aftershocks that follow all underground nuclear explosions at NTS have some similarities to the Henderson Caving events. (after Smith et al, 1995)

4.0 VOLUNTARY MEASURES TO REDUCE THE SEISMIC AMBIGUITY OF MINE SIGNALS AT REGIONAL DISTANCES

To minimize ambiguity and false alarms, seismic data from mining operations must by their character allow their source to be clearly identified as distinct from nuclear explosions. In addition, we have shown evidence that procedures that reduce ground motions in the near-source region, of immediate interest to a mine operator, have similar effects at regional distances.

4.1 Measures Concerning Mining Explosions

Several suggested measures that can help achieve these objectives are described. They include trying to create spectral banding at regional distances, minimizing the occurrence of sympathetic detonations, implementing consistent blast patterns, and adjusting the design of blastholes such as with airdecks.

It is clear that most mines already try to optimize blast designs from the standpoints of production and fragmentation. If appropriate, the recommendations proposed here can be incorporated in a manner compatible with the economic objectives of the mines.

4.1.1 Creating Spectral Banding

One consequence of regular and repeatable delay patterns in a mining explosion is, under certain conditions, the introduction of spectral banding in regional seismograms (Figure 2.9). Since the bandwidth of seismic data at regional distances is typically limited to below 20 Hz, the identification of banding from delay patterns works best when the delays are long (~ 100 ms) and repeated. Spectral banding has also been observed at low frequencies (<5 Hz) and attributed to the total duration of the explosive source (Stump et al.,1999). One suggested way to achieve this banding is to design blasts with appropriate delays and to control the implementation of the design with accurate detonators.

The delay periods used in blast designs can significantly influence the vibration outputs in terms of the amplitude and predominant frequencies. Delays of up to and over 100 ms may be required in some areas to completely eliminate any cumulative seismic effects. The exact delay separation depends on the source function (i.e. explosive), explosive column length, distance from the source, geologic setting and the attenuation characteristics along the different seismic travel paths.

Blast simulations to predict vibration amplitudes and frequencies, based on the single hole signature analysis, assume that the detonators fire exactly at their rated nominal times. With pyrotechnic detonators this is not always possible. The accuracy of pyrotechnic detonators has in general been steadily improving. A comparison of nominal vs. measured delay times from an overburden explosion is given in Figure 2.12 which shows significant departures from design. In cases where the scatter of in-hole detonation times is great, spectral banding at regional distances may be degraded or destroyed making event identification using this characteristic difficult or impossible.

Precise, programmable electronic detonators hold promise in the control of blast induced ground vibrations by eliminating the inherent scatter in the detonator firing times while providing unlimited choice of delay intervals. It is anticipated that these new products may provide the opportunity to create seismograms with strong spectral banding and thus enhanced identification. Although they cost more than conventional ones, electronic detonators are being tested in the U.S. and overseas (Bosman et al., 1998; Chiappetta, 1998).

4.1.2 Minimizing Anomalous or Sympathetic Detonations

Under certain conditions, sympathetic detonations within a large scale blast can be observed at regional seismic stations. These detonations are usually unpredictable, unintentional, and are difficult to identify without blast monitoring instrumentation directly on the shot. Anomalous blasts can occur in a single explosive within a hole, a row or rows of holes or a large section within the shot. As illustrated in Figure 2.5 and 2.11, sympathetic detonations have been documented empirically. They produce regional seismograms that have some characteristics similar to those of single-fired explosions. These type of events will be problematic in CTBT monitoring. It is important to minimize their occurrence.

4.1.3 Consistent Blasting Practices for Fingerprinting

Repeated explosions with similar shot patterns from an individual mine or a single pit within a mine generally exhibit similar characteristics when observed at regional distances (Figure 2.5). These results emphasize the importance in maintaining consistent shot patterns when possible. Further, sharing information about changes in shooting patterns and notice of possible sympathetic detonation would enhance the capability of fingerprinting individual mines in a region.

4.1.4 Reducing In-Mine Vibrations with Decking

As demonstrated earlier, reductions in near-source ground motions will have a similar effect at regional distances. This may put some mine blasts under the threshold of IMS visibility, thus completely eliminating any CTBT-related concerns. A possible way to effect such reductions, while achieving economic objectives, is by explosives decking. This technique, which has been extensively documented, is familiar to many mining operators in the U.S. and overseas (Melnikov and Marchenko, 1971; Mead et al, 1993; Davids and Botha, 1994; Terrett et al, 1995; Chiappetta, 1998).

4.2 Measures Concerning Pillar Collapses

There is a substantial amount of published research regarding the post-failure behavior of rocks, its implications regarding the stability of mine pillars, and the safe design of such pillars (Starfield and Fairhurst, 1968; Bienawski and Vogler, 1970; Heuze, 1970; Salamon, 1970; Wagner, 1974; Van Herdeen, 1975; Das, 1986; Abel, 1988). More recently, three different approaches have been summarized to control cascading pillar failures: 1) containment of failure, 2) prevention of failure, and 3) full extraction mining. They are described in Zipf, 1996.

Mine operators can draw from this large body of experience and from on-going additional work to prevent pillar collapses. Clearly, there are competing interests between economic factors (maximizing extraction) and safety factors. But, in the end, the control of such events will minimize signals observed by the IMS as well as improve mine safety.

4.3 Measures Concerning Rockbursts and Coal Mine

As stated by Salamon (1993), "human control over the occurrence of most rockburst-like events is, at best, tenuous." But much work continues to be done towards improving mine safety under rockburst or coal bump conditions.

Engineering methods for rockburst control address both the prevention of the events and the lessening of the damage. Preconditioning or de-stress blasting, as discussed by Blake (1984) and

Adams et al. (1993), has been proposed to reduce the stress concentrations leading to violent rock mass failure. Brady (1990) and Lightfoot (1993) discuss fluid injection for controlled fault slip. Dennison and Van Aswegen (1993) demonstrate a mine layout and mining sequence for extracting stopes near faults. The suggested method may decrease the risk of uncontrolled fault movement and the ensuing ground failure. Yi and Kaiser (1993) discuss a methodology to design rock support systems to resist rockburst damage. The approach assesses the damage potential from a likely rockburst event and then considers support strategies that economically survive the event.

Similarly for coal mine bump control, mining and prevention methods have been described by Rice (1934), Holland and Thomas (1954), Talman and Schroder (1955), Campoli et al. (1987), Pen and Barron, 1994, and Iannacchionne and Zelanko, 1995.

So, there is substantial information available to the industry to help control these failures and to reduce the likelihood of CTBT false alarms.

4.4 Cooperative Measures for Calibration

4.4.1 Types of Calibration - Event Location and Source Characterization

Key to the success of any monitoring system are the location and identification of the source of the seismic waves. In order to avoid problematic mining events, the location ability must be good enough to associate the sources with mines, and the identification must be good enough to show that the characteristics of the waveforms are consistent with normal mining activities. This section discusses procedures for calibrating or fingerprinting signals from known mines in order to minimize the impact of the monitoring system on mine operations, and to minimize false alarms.

Calibration for Event Location and Regional Travel Times

The first step in identifying a seismic event detected by the International Monitoring System is locating the source. An example of locations estimated by the prototype IMS was shown in Figure 1.3. The presumed IMS-based locations of mine blasts in the southern Powder River Basin of Wyoming were compared to the known locations of the explosions. In some instances the actual event location was not even contained within the formal error estimate. Bias in locations reflect local and regional variations in the travel time curves for a particular region, inadequate station coverage, or problems in depth determination. Thus, such bias can be location specific. An empirical approach to this problem is the use of events with known location and origin time to develop a set of corrections to the regional propagation model. Once these corrections are established through the analysis of a calibration event, the locations of all other events in the region of interest are improved.

For proper calibration, events whose locations are known to within 100 m and 0.10 s are desirable. These requirements can be met with typical Global Positions System (GPS) data and seismic recorders. This procedure can provide exact shot time and location for use in improving the locations derived by the monitoring system. Cooperation with active mines which regularly shoot explosives provides one source of events which can be used to help calibrate the location capability of the monitoring network.

Calibration for Event Identification

Once an event has been located, the type of source must be identified. The concept of fingerprinting a mine was introduced earlier. With good locations, the characteristics of the radiated seismic waves can be used to identify the blast type and possibly the mine from which the seismic waves emanated. This fingerprinting process or identification of particular blasts from a known mine provides the opportunity for avoiding questionable events under a CTBT. The instrumentation and source documentation procedures outlined in this section are one method of obtaining good fingerprints of a mine. Such documentation could be used to answer questions related to future events.

4.4.2 Information for Calibration

Blaster's logs can be used as a source of information on event time and location, for the purpose of calibration. Some of the largest mining shots have source dimensions in excess of a kilometer. These documents provide location to the nearest quarter section (0.65 km^2) and time to the nearest 5 or 10 minutes at best. Typically, safety issues within the mine control the exact shot time. Thus, the recorded explosion time is the blaster's best estimate, possibly with reference to his watch. These estimates do not meet the detailed level of calibration previously discussed.

Additionally, in an active mining region such as the Powder River Basin where individual mines shoot on a daily basis, it may not be possible to associate a particular regional signal with a single mine using a blasters log unless very precise documentation of the explosion detonation time is undertaken. Table 4.1 illustrates the problem, where on 11 Feb 95 there were three GSETT-3 events in the Powder River Basin in an approximate 2 hour period and two events within 11 minutes of one another. We were provided with the precise location of a large cast shot on 11 Feb 95. Typical of blaster's logs (this event was not documented with the calibration instrumentation), the shot time was given as some time around 2200. With this information, it is difficult, if not impossible, to know with which one of the three REB events on the 11th the ground truth information should be associated. Table 4.1 gives the location difference between each of these three REB events and the ground truth. Depending on which event is the one generated by the mine, quite different conclusions about the monitoring network performance can be reached. The proper association of a seismic signal with a particular blast may not be resolved using blaster's logs but can be performed with appropriate calibration instrumentation that provides empirically determined shot times and characteristics.

Table 4.1: Comparison of REB and Mine Locations

Date Time (GMT)	REB Lat	REB Long	MINE Lat	MINE Long	DIFF km
950126 234342.8	43.64	-105.32	43.68	-105.27	6
950211			43.64	-105.26	
201835.4	43.56	-105.23			9*
221238.4	44.27	-105.74			80*
222355.6	43.79	-105.54			28*
950317 203727.3	43.56	-105.13	43.64	-105.26	14
950718 1914742.4	43.58	-104.98	43.69	-105.26	25
960311 201336.9	43.61	-105.22	43.64	-105.26	5
960405 201359.0	43.77	-105.34	43.66	-105.27	14

The alternate approach to obtaining ground truth information for calibration/validation of a monitoring system is to use a set of simple portable instruments which could be deployed and operated by one or two people with a minimum of effort or impact on the mine. That would provide a cost effective methodology for calibration, using sources of opportunity such as those available in an active mining region.

4.4.3 Example Calibration System

The main design goals for the calibration system are that it must be deployable by one or two people in approximately one to two hours at a remote site. The minimum source information it must provide is the shot time and location of the event. Since a supplemental goal of the system is a quantification of the character of the source, in the case of surface explosions, information associated with the design of the blast and detonation of the explosions is useful. Video and acoustic measurements that supplement the primary seismometers are included for this purpose. The system should be able to run unattended for hours to days depending on the particular application. The requirement for unattended operation is to accommodate safety issues in the mine at the time of detonation. The ability to record data over a period of days (excluding video) provides the opportunity to use the system to monitor activity in a mine or mining district for an extended period of time with little or no intrusion on the commercial activities.

The data acquisition system should include six channels, with sample rates as high as 500 samples per second (0.002 s) and amplitude resolution of 24 bits. The high sample rate assures that the system is able to acquire high frequency data which will document the detonation times of delay-fired mining explosions and the 24 bit dynamic range data with the highest possible bandwidth. Example data loggers are pictured in Figure 4.1 in two mining operations. Time and location is provided to the data logger by a GPS clock, and the entire system is powered by a battery backed by a solar panel. This GPS, or possibly an additional handheld GPS, is used to determine the location of the explosion.

For the purpose of recording the near-source, three-component wavefield a 1 to 2 Hz velocity transducer has been found to be adequate. Two additional vertical geophones are deployed along a line towards the explosions at 10 to 20 m separation in order to determine the phase velocity of the first arriving P wave so that one can correct the arrival time of the first P wave at the observation point back to the explosion. Depending on the spatial separation between these geophones and the explosion, shot time estimates within one or two tenths of a second of the actual shot time can be obtained. A geophone on top of the initial explosion would provide a very precise detonation time at the expense of the loss of a geophone (~$50)

The sixth channel on the data logger is assigned to an acoustic gage. A simple instrument that is capable of recording these source signatures close-in at a modest cost has been developed by Reinke (1985). These data can provide near-source atmospheric signature information and are used in the supplementary task of source characterization.

The final component is a consumer-level Hi-8 video camera that captures 30 frames or 60 fields of data per second. One of these instruments is pictured in Figure 4.1 ready for documenting a large mining explosion in the Powder River Basin. Normally the camera is deployed at the same location as the seismometer and acoustic gage, so that the different source phenomena can be correlated for interpretation purposes. It is possible to deploy the camera at a different site if a special perspective of the blasting process is needed.

The system as described is simple to deploy. Practical experience with the installation of this equipment indicates that it can be installed in less than two hours by one to two people. It is completely self-contained, and thus requires no assistance from the mine in which the measurements are to be made. Even when the equipment is deployed at a location where the mine operators, for safety reasons, would not allow personnel at the time of detonation, the system can operate unattended. In an active region such as the Powder River Basin, the system can be deployed at a number of mines from several days to a few weeks to provide calibration data in a cost-effective manner.

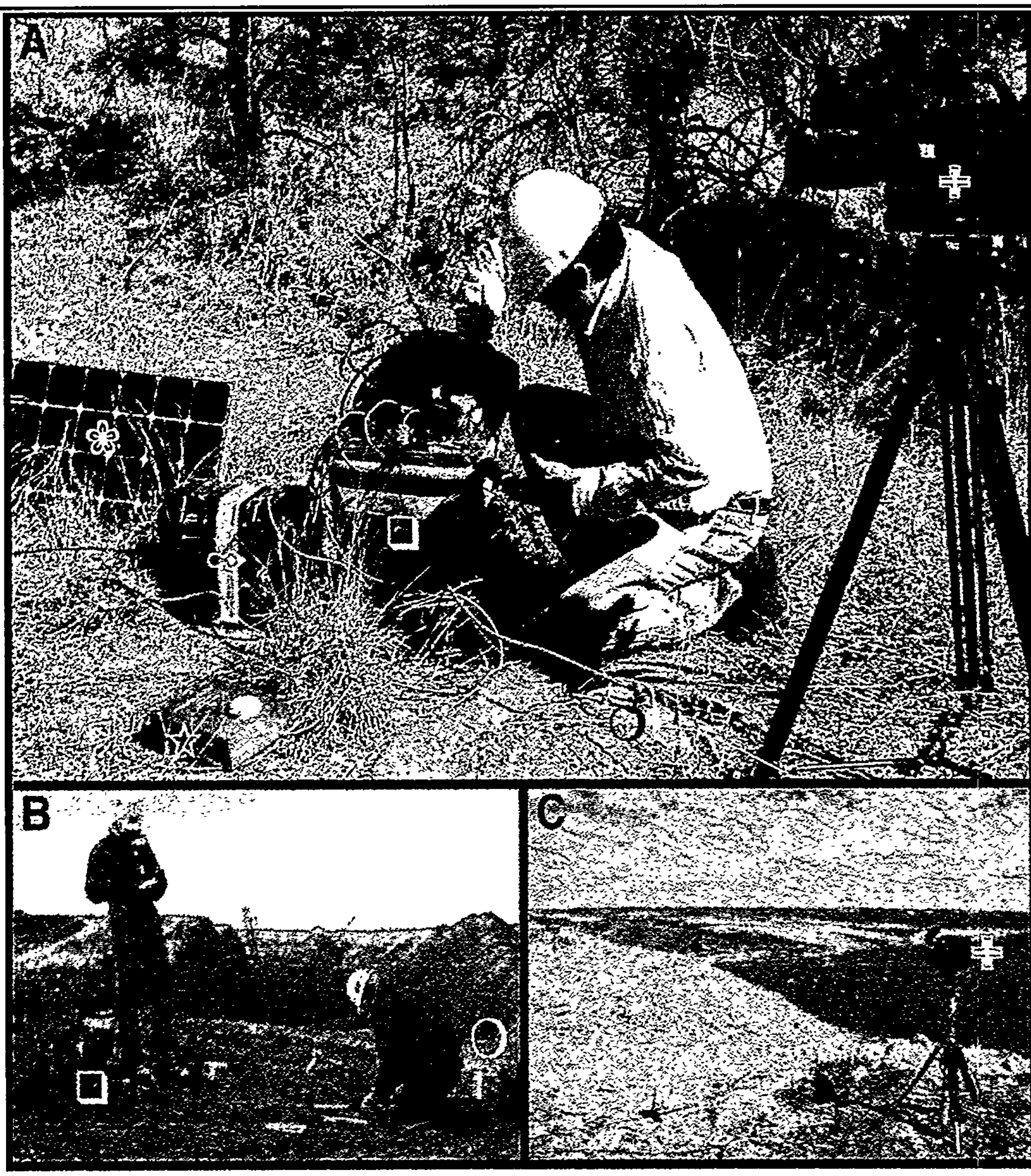

Figure 4.1: The data logger (❑) is attached to the velocity transducer (O) and the GPS receiver (☆). The camera (✙) is to the far right with battery (⚯) and solar panel (❀) to far left. B: Installation of the system in a mine just prior to a large cast blast. C: Hi-8 camera deployment prior to a large cast explosion.

5. SUMMARY

5.1 The Potential Ambiguity of Seismic Signals from Mines

Surface and underground mining operations including blasting and ground failure generate seismic ground motions. Ground failures (coal bumps, first caves, pillar collapses, rockbursts, etc...) can occasionally produce seismic signals whose magnitudes are as strong or stronger than those from any mining blast.

A verification system that includes seismic, infrasound, hydroacoustic and radionuclide sensors is being completed as part of the CTBT. The largest mine blasts and ground failures will be detected by this system and must be identified as distinct from signals generated by small nuclear explosions.

Seismologists will analyze the seismic records and presumably should be able to separate them into earthquake-like and non earthquake-like categories, using a variety of so-called seismic discriminants, Non-earthquake essentially means explosion- or implosion-like. Such signals can be generated not only by mine blasts but also by a variety of ground failures. Because it is known that single-fired chemical explosions and nuclear explosion signals of the same yield give very similar seismic records (Figure 2.1), the non-earthquake signals that have characteristics similar to a single-fired chemical explosion will be of concern to the Treaty verification community. The magnitude of the mine-related events is in the range of seismicity created by smaller nuclear explosions or decoupled tests, which are of particular concern under the Treaty (Figure 1.4) It is conceivable that legitimate mining blasts or some mine-induced ground failures could occasionally be questioned. As noted in Appendix A, a special provision of the Treaty entitled Consultation and Clarification was designed to address such questionable events in an unobtrusive way. Information such as shot time, location and design parameters may be all that is necessary to resolve the event identity. In rare instances where the legitimate origin of the event could not be resolved by a consultation and clarification procedure, it might trigger an On-Site Inspection (OSI). Because there is uncertainty in the precise location of seismic events as determined by the International Monitoring System (IMS) as shown in Figure 1.3, an OSI can cover an area of up to 1000 squared kilometers. In active mining districts this area could include several different mining operations. As such, an OSI could be disruptive both to the mining community and to the U.S. Government which must host the foreign inspection team. Accordingly, it is in the best interest of all U.S. parties to try and eliminate the occurrence of false alarms. This can be achieved primarily by reducing the ambiguity of mine-induced seismic signals, so that even if these remain visible to the IMS they are clearly consistent with recognizable mining patterns. Reduction in the seismic visibility or size of the seismic signal would be useful, as well.

5.2 What Can Be Done About False Alarms

The elimination of false alarms will take a joint effort between the scientific community, mainly seismologists, and mine operators.

What the seismologists can do:

- they can improve their methods to discriminate between signals from earthquakes and explosions. This work is on-going (see Chapters 2 and 4).

- they can apply their models for collapse events, to separate collapse-generated seismic records from explosion-like signals. Such models have been applied successfully to some U.S. case histories (see Chapter 3).
- they can improve the accuracy of event location. This work is also on-going. It can be helped greatly by industry providing specific times and locations of their blasts, as well as by improvements in the procedures and interpretation for location by the International Data Center (see Chapter 4).
- they can provide resources to the industry to help establish seismic "fingerprints" of specific mine operations. Several such studies already have been conducted in the U.S. (see Chapter 5). More work is desirable to better characterize the U.S. signals, as well as to better understand the signals from foreign operations.

What industry can do:

- it can provide information to the IMS community about blast events (date, precise time, location, pattern, yield), above some threshold to be determined as a function of mine-specific visibility (see Chapter 4). This information would help minimize false alarms. The CTBT already encourages the advanced notification of shots of 300 tons or more, as confidence-building measures.
- provide advanced notice of controlled engineered ground failures, such as in a recent case history of pillar removal described in this report (see Chapter 3).
- provide ground truth concerning expected but uncontrolled ground failures, such as first caves in longwall coal mines
- cooperate in providing prompt information on events identified by the IMS, that appear to originate from a mine.
- engage in joint seismic calibration of specific mining activities with scientists and engineers from the CTBT community. Several such projects have been completed and are illustrated in this report.

None of the above suggestions and recommendations is expected to add significant cost to mining operations, while providing the benefit of protecting the industry from false alarms. The joint calibration efforts with industry could also involve some of the industry's foreign operations to help validate seismic models in other countries and to better understand signals from overseas.

On rare occasions, industry may consider adjusting its operating practices at specific locations where the seismic ambiguity is not reduced by other measures. These adjustments may include better timing control of blasting delays as well as enhanced ground control practices.

REFERENCES

Abel, J.F. (1988), "Soft Rock Pillars", *Int. J. Min. & Geol. Eng.*, v. 6, pp. 215–248.

Adams, D.J., Gay, N.C., and Cross, M. (1993), "Preconditioning - A Technique for Controlling Rockbursts", *Rockbursts and Seismicity in Mines*, R.P. Young, ed., A.A. Balkema, Brookfield, VT.,pp. 29–34.

Baumgardt, D. R. and K. A. Zeigler (1988), Spectral evidence for source multiplicity in explosions: application to regional discrimination of earthquakes and explosions, *Bull. Seism. Soc. Am, 78,* 1773-1795.

Baumgardt, D. R., and G. B. Young (1990). Regional seismic waveform discriminants and case-based event identification using regional arrays, *Bull. Seism. Soc. Am., 80*, 1874-1892.

Bennett, T. J. and J. R. Murphy (1986), Analysis of seismic discrimination capabilities using regional data from western United States events, *Bull. Seism. Soc. Am.*, *76,* 1069-1086.

Bennett, T. J. , M. E. Marshall, B. W. Barker, and J. R. Murphy, (1994). Characteristics of rockbursts for use in seismic discrimination, PL-TR-94-2269, Phillips Laboratory, Hanscom AFB, MA (NTIS, Springfield, VA).

Bennett, T. J., M. E. Marshall, K. L. McLaughlin, B.W. Barker and J. R. Murphy, (1995). Seismic characteristics and mechanisms of rockbursts, *Proceedings of the 17th Annual Seismic Research Symposium*, 12-15 September 1995, PL-TR-95-2108, Phillips Laboratory, Hanscom AFB, MA, August 1995 (NTIS, Springfield, VA).

Bennett, T. J., M. E. Marshall, K. L. McLaughlin, B.W. Barker and J. R. Murphy, (1996). Seismic investigations of rockbursts, *Proceedings of the 18th Annual Seismic Research Symposium*, 4-6 September 1995, PL-TR-96-2153, Phillips Laboratory, Hanscom AFB, MA, July 1996 (NTIS, Springfield, VA).

Bieniawski, Z.T., and U.V. Vogler, 1970. Load-Deformation Behavior of Coal After Failure. Proc. 2nd Intl. *Congress on Rock Mechanics*, ISRM, Belgrade, **1**, #2-12.

Blake, W. (1984), "Design Considerations for Seismic Monitoring Systems", *Rockbursts and Seismicity in Mines*, N.C. Gay and E.H. Wainwright, eds., South African Inst. Min. Metall., Johannesburg, pp. 79–82.

Boler, F. M., S. Billington, and R. K. Zipf (1996)., Seismological and energy balance constraints on the mechanism of a catastrophic bump in the Book Cliffs coal mining district, Utah, USA, *Int. J. Rock Mech. Min. Sci., 34,* No. 1, 27-43, January 1997.

Bosman, H.G., Bedser, G., and Cunningham, C.V.B. (1998), "Production Blasting With Electronic Detonators at Peak Quarry", *Proc. 8th High-Tech Blasting Seminar,* Nashville, TN, July 20-24, pp. 93-119 (Blasting Analysis Int., Allentown, PA)

Brady, B.H.G. (1990), "Keynote Lecture: Rock Stress, Structure and Mine Design", *Rockbursts and Seismicity in Mines*, C. Fairhurst, ed., A.A. Balkema, Brookfield, VT, pp. 311–322.

Campoli, A.A., Kertis, C.A., and Goode, C.A. (1987), "Coal Mine Bumps: Five Case Studies in the Eastern U.S", U.S. Bureau of Mines *IC 9149*, 34 pp.

Chaplin, M.P., S.R. Taylor and M.N. Toksoz (1980). A coda-length magnitude scale for New England, *Earthquake Notes, 51,* pp. 15-22.

Chapman, M. C., G. A. Bollinger, and M. S. Sibol (1992). Modeling delay-fired explosion spectra at regional distances, *Bull. Seism. Soc. Am., 82,* 2430-2447.

Chiappetta, R. F. (1998), "Choosing the Right Delay Timing for the Blasting Application, Optimization and Maintaining Field Controls", *Proc. 8th High-Tech Blasting Seminar,* Nashville, TN, July 20-24, pp. 213-254 (Blasting Analysis Int., Allentown, PA)

Crawford, M. J. (1996). "Beam Me Down Scottie", *Mining Voice,* July-August, pp. 24-30.

Das, M.N. (1986), "Influence of Width/Height Ratio on Postfailure Behavior of Coal", *Int. J. Min. & Geol. Eng.*, v. 4, pp. 79–87.

Davids, T. and Botha, B. F. F. (1994), "Mid-Column Air Deck Applications In Full-Scale Production Blasts", *Proc. 5th High-Tech Blasting Seminar,* New Orleans, LA (Blasting Analysis Int., Allentown, PA)

Dennison, P.J.G. and Van Aswegen, G., (1993), "Stress Modelling and Seismicity on the Tanton Fault: A Case Study in a South African Gold Mine", *Rockbursts and Seismicity in Mines,* R.P. Young, ed., A.A. Balkema, Brookfield, VT, pp. 327–336.

Denny, Marvin P., Ed. (1994). Proceedings of the Symposium on the Non-Proliferation Experiment (NPE): Results and Implications for Test Ban Treaties, April 19-21, 1994, Rockville, Maryland, CONF 9404100, Lawrence Livermore National Laboratory.

Dysart, P. S. and J. J. Pulli, (1990). Regional seismic event classification at the NORESS array: seismological measurements and the use of trained neural networks, *Bull. Seism. Soc. Am., 80,* 1910-1933.

Fairhurst, C., Ed. (1990), *Rockbursts and Seismicity in Mines,* Proc. 2nd Int. Symposium, Minneapolis, MN, June 8–10, 1998, 439 p, (A.A. Balkema, Brookfield, VT).

Gay, N.C. and Wainwright, E. H., Eds. (1984) *Rockbursts and Seismicity in Mines,* 363 p. (South African Institute of Mining and Metallurgy, Johannesburg).

Gibowicz, S.J. (1990), "The Mechanism of Seismic Events Induced by Mining", *Rockburst and Seismicity in Mines,* Proc. 2nd Int. Symposium, Minneapolis, MN, June 8–10, 1998, pp 3–27, (A.A. Balkema, Brookfield, VT).

Gibowicz, S.J., (1993) "Keynote Address: Seismic Moment Tensor and the Mechanism of Seismic Events in Mines", *Rockbursts and Seismicity in Mines,* R.P. Young, ed., A.A. Balkema, Brookfield, VT, pp. 149–156.

Goldstein, P. (1995) Slopes of P to S wave spectral ratios: a broadband regional seismic discriminant and a physical model, *Geophys Res. Lett.,* **22,** 3147-3150.

Harris, D. B. (1991). A waveform correlation method for identifying quarry explosions, *Bull. Seism. Soc. Am, 81,* 2395-2418.

Hedlin, M. A. H., J. B. Minster, and J. A. 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., J. B. Minster, J. A. Orcutt (1990), An automatic means to discriminate between earthquakes and quarry blasts, *Bull. Seism. Soc. Am., 80*, 2143-2160.

Heuk, F. R. (1990), "The Design of Room and Pillar Structures in Competent ???? Rock", Ph.D. Thesis, Univ. Calif. Berkeley, University Microfilms, Ann Arbor, MI.

Heuze, F.E. (1994), "Rockbursts as Opportunities for the Concealment of Nuclear Tests?", Lawrence Livermore National Laboratory, *UCRL-ID-116123*, 7 p, Jan.

Heuze, F.E. (1995), "Rockbursts and Coal Bumps as Opportunities for Evasive Nuclear Testing", Lawrence Livermore National Laboratory, *UCRL-JC-120945*, 12 p, Jan.

Heuze, F.E. (1996), "LLNL's Partnership with Selected U.S. Mines, for CTBT Verification: A Pictorial and Some Reflections", Lawrence Livermore National Laboratory, *UCRL-ID122577*, 40 p., Jan.

Holland, C.T. and Thomas, E. (1954), "Coal-Mine Bumps: Some Aspects of Occurrence, Cause, and Control", U.S. Bureau of Mines Bulletin 535, 37 pp.

Hsu, V. and B. Stump, 1997, Seismic and infrasonic arrays at Pinedale Seismic Research Facility (PSRF) Wyoming: Synergy of Infrasonic and seismic signals from miing explosions, abstract, *Seism. Res. Lett., 68,* 320.

Iannacchione, A.T. and Zelanko, J.C. (1995), "Occurrence and Remediation of Coal Mine Bumps: A Historical Review", in *U.S. Bureau of Mines SP 01-95*, pp 27–67.

Jarpe, S.P., Moran, B., Goldstein, P., and Glenn, L.A. (1996), "Implications of Mining Practices in and Open-Pit Gold Mine for Monitoring of a Comprehensive Test Ban Treaty", Lawrence Livermore National Laboratory, *UCRL-ID-123017*, Jan., 35 p.

Kaiser, P.K. (1993), "Keynote Address: Support of Tunnels in Burst-Prone Ground - Toward a Rational Design Methodology", *Rockbursts and Seismicity in Mines*, R.P. Young, ed., A.A. Balkema, Brookfield, VT, pp. 13–28.

Kim, W. -Y., D. W. Simpson, and P. G. Richards (1993). Discrimination of earthquakes and explosions in the eastern United States using regional high-frequency data, *Geophys. Res. Lett., 20,* 1057-1510.

Knoll, P. (1990). The fluid-induced tectonic rockburst of March 13, 1989 in the Werra potash mining district of the GDR (first results), *Gerl. Beitr. Geophysik, 99*, 239-245.

Leith, W., A. Spivak and L. Pernik, (1996), "Large Mining Blasts from the Kursk Mining Region, Russia, *Proceedings of the 18th Annual Seismic Research Symposium*, 12-15 September 1995, PL-TR-96-2153, Phillips Laboratory, Hanscom AFB, MA, September 1996 (NTIS, Springfield, VA).

Lightfoot, N. (1993), "The Use of Numerical Modelling in Rockburst Control", *Rockbursts and Seismicity in Mines*, R.P. Young, ed., A.A. Balkema, Brookfield, VT ,pp. 355–360.

Maleki, H., Wopat, P.F., Repsher, R.C., and Tuckman, R.J., Eds. (1995), "Mitigation of Violent Failures in Coal and Hard Rock Mines", *U.S. Bureau of Mines SP 01-95*, 355 p.

Mayeda, K. M., and W. R. Walter, (1996). "Source Parameters of Western U.S. Earthquakes: Moment, Energy, Stress Drop and Source Spectra from Regional Coda Envelopes", *J Geophys. Res.*, 101, 11,195-11,208.

McLaughlin, K. L., T. G. Barker, J. L. Stevens and S. M. Day, (1993), "Numerical Simulations of Quarry Blast Sources", *Proceedings of the 15th Annual Seismic Research Symposium*, 8-10 September 1993, PL-TR-93-2160, Phillips Laboratory, Hanscom AFB, MA, August 1993.

Murphy, J. R., (1996), "Types of Seismic Events and Their Source Descriptions", Husebye, E.S. and Dainty, A.M. (eds.), pp 225-246, Kluwer Academic Publishers, Dordrecht.

Office of Technology Assessment (1988). Seismic Verification of Nuclear Testing Treaties, OTA-ISC-361, *U.S. Government Printing Office*, Washington, D.C.

Patton, H.J., and W. R. Walter, (1993), "Regional Moment: Magnitude Relations for Earthquakes and Explosions", *Geophys. Res. Lett., 20*, 277-280.

Patton, H.J., and W. R. Walter, (1994), "Correction to "Regional Moment: Magnitude Relations for Earthquakes and Explosions", *Geophys. Res. Lett., 21*, 743.

Pechmann, J. C., W. R. Walter, S. J. Nava and W. J. Arabasz, (1995), "The February 3, 1995 M_L=5.1 Seismic Event in the Trona Mining District of Southwestern Wyoming", *Seism. Res. Lett., 66*, 25-34.

Pen, Y. and Barron, K. (1994), "The Role of Local Mine Stiffness in Pillar Bump Prediction", *Proc. 1st North American Rock Mechanics Symposium*, Austin, TX, June 1–3, pp 1017–1024 (A.A. Balkema, Brookfield, VT).

Phillips, S., D. C. Pearson, C.L. Edwards and B. W. Stump (1996). The White Pine Controlled Collapse Experiment, *LA-UR-96-2642*, Los Alamos National Laboratory, November.

Pomeroy, P. W., W. J. Best, and T. V. McEvilly (1982), Test ban treaty verification with regional data--a review, *Bull. Seism. Soc. Am., 72B*, 89-129.

Reinke, R. E. (1985). A Digital Microbarograph System, AFWL-TR-84-142, Kirtland AFB, NM 87117-6008, May.

Rice, G.S. (1934), "Bumps in Coal Mines of the Cumberland Field, Kentucky and Virginia—Causes and Remedy", U.S. Bureau of Mines *RI 3267*, 36 pp.

Richards, P., D. A. Anderson and D. W. Simpson, (1992), "A Survey of Blasting Activities in the United States", *Bull. Seism. Soc. Am., 82*, 1416-1433.

Salamon, M.D.G. (1970), "Stability, Instability, and Design of Pillar Workings", *Int. J. of Rock Mech. and Min. Sci,*. v. 7, pp. 613–631.

Salamon, M.D.G. (1993), "Keynote Address: Some Applications of Geomechanical Modelling in Rockburst and Related Research", *Rockbursts and Seismicity in Mines,* R.P. Young, ed A.A. Balkema, Brookfield, VT, pp. 297–310.

Simons, D.J., (1996), "Atmospheric methods for nuclear test monitoring", in Monitoring a Comprehensive Test Ban Treaty", Husebye, E.S. and Dainty, A.M. (eds.), pp 135-141, Kluwer Academic Publishers, Dordrecht.

Singh, S. and R. B. Herrmann (1983), Regionalization of crustal coda Q in the continental United States, *J. Geophys. Res.,* pp. 527-538.

Smith A.T., Schultz, C. and Zucca, J.J. (1995), "Aftershocks and On-Site Inspections Under a Test Ban: Progress Report", Lawrence Livermore National Laboratory, *UCRL-ID-122252*, 16 p, Sept.

Smith, A. T., (1993). Discrimination of explosions from simultaneous mining blasts, *Bull. Seism. Soc. Am, 83*, 160-179.

Sorrells, G.G., E.T. Herrin and J.L. Bonner, 1997, Construction of regional ground truth databases using seismic and infrasonic data, *Seism. Res. Letters, 68,* 743-752.

St. Don, D. A. (1995), "Copper Range Company - Solution Mining Study, Pillar Rubblization Project, 70-Pillar Blast", White Pine Mine Internal Report, 66 pages.

Starfield, A. and Fairhurst, C. (1968), "How High Speed Computers Advance the Design of Practical Mine Pillar Systems", *Eng. Mining Journal*, pp. 78–84, May.

Stump, B.W., M.A.H. Hedlin, D.C. Pearson and V. Hsu (1998), Characterization of Mining Explosions at Regional Distances, submitted *Reviews of Geophysics.*

Stump, B. W. and S. K. Reamer (1988), "Temporal and Spatial Source Effects from Near Surface Explosions", *10th Annual AFGL/DARPA Seismic Research Symposium*, Fallbrook, CA; Phillips Laboratory, Hanscom AFB, MA, 1988 (NTIS, Springfield, VA).

Stump, B.W., D. C. Pearson, R. L. Martin, P. E. Harben, C. L. Edwards, D. Baker, K. Kihara, K. Dalrymple, J. P. Lewis, D. Rock and R. Boyd (1995), "The Black Thunder Regional Seismic Experiment, 10 June - 19 September 1995", *LA-UR-95-3980*, Los Alamos National Laboratory, October.

Stump, B.W., D. P. Anderson and D.C. Pearson (1996a), "Physical Constraints on Mining Explosions - Synergy of Seismic and Video Data with Three Dimensional Models", *Seismological Research Letters, 67,* p. 9-24.

Stump, B.W., Pearson, D.C., Edwards, C.L., and Baker, D. (1996b), "Experimental Studies for Event Identification Calibration, and Evasion Assessment: A Progress Report", Los Alamos National Laboratory, *LA-UR-96-1187*, March.

Swanson, P.L. and Boler, F. M.(1995). "The Magnitude 5.3 Seismic Event and Collapse of the Solvay Trona Mine: Analysis of Pillar/Floor Failure Stability", U.S. Bureau of Mines, OFR-86-95, 82 pp.

Taylor, S. R. (1994), "False Alarms and Mine Seismicity: An Example from the Gentry Mountain Mining Region, Utah", *Bull. Seism. Soc. Am., 84*, 350-358.

Taylor, S. R., (1995), "A Review of Broadband Regional Discrimination Studies of NTS Explosions and Western U.S. Earthquakes", *NATO Advanced Study Institute on CTBT Monitoring*, Faro, Portugal, January 23 - February 2, 1995.

Taylor, S. R., M. D. Denny, E. S. Vergino, and R. E. Glaser (1989), "Regional Discrimination Between NTS Explosions and Western U.S. Earthquakes", *Bull. Seism. Soc. Am., 79*, 1142-1176.

Taylor, S. T., (1996). Analysis of high-frequency Pg/Lg ratios from NTS explosions and western U.S. earthquakes, *Bull Seism. Soc. Am., 86*, 1042-1053.

Van Heerden, W.L. (1975), "In Situ Determination of the Complete Stress-Strain Characteristics of Large Coal Specimens", *J.S. Afr. Inst. Min. and Metall., 75*, (8) 207-217.

Wagner, H. (1974), "Determination of the Complete Load-Deformation Characteristics of Coal Pillars", *Proc. 3rd Intl. Congress on Rock Mechanics*, National Academy Sciences, **V2B**, 1076-1081.

Walter, W. R. (1995), "Status Report on New Whole Waveform Discriminants, and Preliminary Results", Lawrence Livermore National Laboratory, *UCRL-ID-123227, 11p.*

Walter, W. R., and J. N. Brune (1993), "Spectra of Seismic Radiation form a Tensile Crack", *J. Geophys. Res. 98*, 4449-4459.

Walter, W. R., K. M. Mayeda and H. J. Patton (1995), "Phase and Spectral Ratio Discrimination Between NTS Earthquakes and Explosions Part 1: Empirical Observations", *Bull Seism. Soc. Am., 85*, 1050-1067.

Walter, W.R., Hunter, S.L., and Glenn, L.A. (1996), "Preliminary Report on the LLNL Mine Seismicity Deployment at the Twentymile Coal Mine", Lawrence Livermore National Laboratory, *UCRL-ID-122800*, 19p,Jan.

Walter, W. R., (1996). Identifying clandestine underground nuclear tests by their seismic signature, Lawrence Livermore National Laboratory, *UCRL-MI-123958, 3p.*

Whyatt, J.K., Williams, T.J., Blake, W., Sprake, K., and Wideman, C. (1996), "Mining-Induced Seismicity at the Lucky Friday Mine: Seismic Events, Magnitude ≥2.5, 1989–1994", report to Lawrence Livermore National Laboratory by U.S. Bureau of Mines, Spokane, WA, Sept., *UCRL-CR-125538.*, 165 p.

Wong, I.G. and McGarr, A. (1990), "Implosional Failure in Mining—Induced Seismicity: A Critical Review", *Rockburst and Seismicity in Mines*, Proc. 2nd Int. Symposium, Minneapolis, MN, June 8–10, 1998, pp 45–51, (A.A. Balkema, Brookfield, VT).

Wuster, J. (1990), "Discrimination of chemical explosions and earthquakes in central europe - a case study", *Bull. Seism. Soc. Am., 83*, 1184-1212.

Xiaoning Yang, B. W. Stump, W. S. Phillips, 1998. Source mechanism of an explosively induced mine collapse, *Bull. Seism. Soc. Am., 88*, 843-854.

Yi, X. and Kaiser, P.K. (1993), "Mechanisms of Rockmass Failure and Prevention Strategies in Rockburst Conditions", *Rockbursts and Seismicity in Mines*, R.P. Young, ed., A.A. Balkema, Brookfield, VT, pp. 141–148.

Young, R.T., Ed. (1993), *Rockbursts and Seismicity in Mines '93*, Proc. 3rd Int. Symposium, Kingston, Ontario, Canada, Aug. 16–18, 449 p., A.A. Balkema, Brookfield, VT.

Zipf, R.K. (1996), "Analysis and Design Methods to Control Cascading Pillar Failure in Room-and-Pillar Mines", *Milestones in Rock Engineering*, Z.T. Bieniawski, ed., (A.A. Balkema, Brookfield, VT), 1996, pp. 225-264.

Zucca, J.J., Carrigan, C., Goldstein, P., Jarpe, S., Sweeney, J., Pickles, W.L., and Wright, B., (1996), "Signatures of testing: On-site inspection technologies", in "Monitoring a Comprehensive Test Ban Treaty", Husebye, E.S. and Dainty, A.M. (eds.), P123-134, Kluwer Academic Publishers, Dordrecht.

APPENDIX: COMPREHENSIVE TEST BAN TREATY

A.1 Nuclear Testing

Nuclear Testing Since the detonation of the first nuclear device in southern New Mexico on 16 July 1945, at least four countries have joined the U.S. as nuclear nations i.e. Russia, Britain, France and China (Bolt, 1974). Testing has continued up until the present with the most recent series of underground nuclear test being conducted by India and Pakistan in 1998. After this test, China announced that it, like the other nuclear capable countries, would begin a self imposed moratorium on testing, thus setting the stage for the conclusion of negotiations on the CTBT.

Testing was conducted for these fifty plus years for a number of reason including (Office of Technology Assessment (OTA), 1988):

- development of new weapons systems
- reliability of weapons
- safety of nuclear devices
- maintaining high levels of technical expertise

Other issues associated with testing have been the effect that such practices have on the proliferation of nuclear technologies, the decreased or increased likelihood of war, and the effect of these weapons on world stability.

A.2 Comprehensive Test Ban Treaty, 1996

Because of concerns about the proliferation of nuclear weapons, a desire to continue the NPT, increasing costs of testing programs, changes in the world political situation, and increasing pressure from non-nuclear states, negotiations of a CTBT began again in January 1994 at the Conference on Disarmament (CD) in Geneva Switzerland and was opened for signature September 24,1996. The difference of this Treaty from those that proceeded it was that it bans all nuclear explosions, even underground.

Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control. (United Nations General Assembly, A/50/1027)

The Treaty will enter into force 180 days after the ratification of the Treaty by each of the countries listed in Annex 2 of the Treaty. These countries include: Algeria, Argentina, Australia, Austria, Bangladesh, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Democratic People's Republic of Korea, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran (Islamic Republic of), Israel, Italy, Japan, Mexico, Netherlands, Norway, Pakistan, Peru, Poland, Romania, Republic of Korea, Russian Federation, Slovakia, South Africa, Spain, Sweden,Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, United States of America, Viet Nam, Zaire. If all these countries have not ratified the Treaty three years after its deposit for signature then the Treaty Depositary shall convene a Conference of the States that have already ratified the Treaty. This Conference will discuss and decide what measures may be taken to complete the ratification process and facilitate the early entry into force of the Treaty.

In order to make the Treaty effective and assure that all nations would participate the Treaty includes a series of verification measures so that all Treaty participants can assure themselves that all other participants are adhering to the Treaty. A monitoring network is envisaged that would be able to detect and provide data on a nuclear explosion if it were to occur underground, in the atmosphere or in the oceans. The details of this verification scheme and the specifics of the monitoring network are described in the Treaty text which was adopted by the UN General Assembly, A/50/1027. A complete copy of the text is available on the World Wide Web. For example the DoE CTBT Research and Development homepage contains links to not only the Treaty but also to a current list of countries that have signed and ratified the document (see Appendix D).

A.3 Monitoring System

The monitoring system and verification provisions that are included in the current Treaty text (United Nations General Assembly, A/50/1027) take into account all possible nuclear testing environments. The monitoring system then will include seismic, infrasound, hydroacoustic and radionuclide monitors distributed throughout the world. The numbers and types of these instruments has been determined through scientific consultations with political decision makers during the course of the negotiations. The Treaty includes the following stations shown in Figure1.1:

Seismic
- 50 Primary Stations with continuous data transmission to the International Data Center (Annex 1, Table 1-A, A/50/1027)
- 120 Auxiliary Stations, data on request (Annex 1, Table 1-B, A/50/1027)

Infrasound
- 60 Stations (Annex 1, Table 4, A/50/1027)

Hydroacoustic
- 6 Hydrophones & 5 T-phase Stations (Annex 1, Table 3, A/50/1027)

Radionuclide
- 80 Stations (Annex 1, Table 2-A&B, A/50/1027)

A.4 Consultation/Clarification and Confidence Building Measures

In order to provide a mechanism for resolving questionable signals detected by the IMS that are not fully understood two intermediate actions are included in the provisions of the Treaty:

- consultation and clarification
- confidence building measures

Consultation and clarification is the process by which countries can ask another for information that might help resolve a questionable event. This process could include the exchange of data or information about a particular source that generated the signals.

Without prejudice to the right of any State Party to request an on-site inspection, States Parties should, whenever possible, first make every effort to clarify and resolve, among themselves or with or through the Organization, any matter which may cause concern about possible non-compliance with the basic obligations of this Treaty. (United Nations General Assembly, A/50/1027)

Confidence building measures are cooperative actions that can be taken by nations to improve the performance of the monitoring system and eliminate ambiguities that may develop in the interpretation of the resulting data. The following measures that might affect the mining industry are contained within the Protocols of the current draft of the Treaty (United Nations General Assembly, A/50/1027).

CONFIDENCE-BUILDING MEASURES

1. *Pursuant to Article IV, paragraph 68, each State Party shall, on a voluntary basis provide the Technical Secretariat with notification of any chemical explosion using 300 tonnes or greater TNT-equivalent blasting material detonated as a single explosion anywhere on its territory, or at any place under its jurisdiction or control. If possible, such notification shall be provided in advance. Such notification shall include details on location, time, quantity and type of explosives used, as well as on the configuration and intended purpose of the blast.*

2. *Each State Party shall, on a voluntary basis, as soon as possible after the entry into force of this Treaty provide the Technical Secretariat, and at annual intervals thereafter update, information related to its national use of all chemical explosives greater than 300 tonnes TNT-equivalent. In particular, the State Party shall seek to advise:*
   - (a) *The geographic locations of sites where the explosions originate.*
   - (b) *The nature of activities producing them and the general profile and frequency of such explosions.*
   - (c) *Any other relevant detail, if available, and assist the Technical Secretariat in clarifying the origins of any such event detected by the International Monitoring System.*

3. *A State Party may, on a voluntary and mutually-acceptable basis, invite representatives of the Technical Secretariat or of other States Parties to visit sites within its territory referred to in paragraph 1 and 2.*

4. *For the purpose of calibrating the International Monitoring System, States Parties may liaise with the Technical Secretariat to carry out chemical calibration explosions or to provide relevant information on chemical explosions planned for other purposes.*

Both of these mechanisms provide a means for resolving questions without relying on the more intrusive and costly OSI.

A.5 <u>On-Site Inspection</u>

The final step in resolving the identity of a problematic event detected by the IMS is the On-Site Inspection (OSI). The Treaty contains provisions for requesting an OSI if the data from the IMS suggests that an event has the character of a nuclear explosion.

An OSI will be a very costly endeavor as it will involve the mobilization, transport and support of a number of people and instruments from some type of international team. Instruments would probably be deployed to a suspect site so that further data could be gathered to definitely resolve the source of the signals detected by the IMS. Such a deployment could disrupt a facility or area for days to weeks. The frequency of such deployments will depend on experience with the monitoring system but practical consideration of the cost of such deployments means that they will be infrequent.