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Title: REGIONAL OBSERVATIONS OF MINING BLASTS BY THE GSETT-3 SEISMIC MONITORING NETWORK

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REGIONAL OBSERVATIONS OF MINING BLASTS BY THE GSETT-3 SEISMIC MONITORING SYSTEM

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The cessation of testing of any nuclear explosive devices in all environments is the goal of the Comprehensive Test Ban Treaty. In order to assure compliance with such a treaty, an international monitoring system has been proposed. This system will include seismic, infrasound, hydroacoustic and radionucleide monitors located throughout the world. The goal of this system is the detection of any nuclear test. In preparation for this treaty, a series of monitoring system tests, focusing primarily on seismic observations, have been undertaken. The most recent of these tests, Group of Scientific Experts Technical Test Three (GSETT-3), provides valuable data for assessing future monitoring systems. During the course of this experiment, seismic events associated with earthquakes, nuclear explosions and mining explosions have been recorded. This presentation will discuss the numbers and types of mining explosions triggering the system, in a particular area. Possible implications for the mining industry will be explored.

1. The Comprehensive Test Ban Treaty and Seismic Monitoring of Explosions. The United States has been participating in the international negotiation of a Comprehensive Test Ban Treaty. The purpose of the treaty is to provide an international framework under which all nations can agree to stop the testing of nuclear explosions. These negotiations have culminated in the opening of the CTBT for signature under the auspices of the United Nations. President Clinton signed the Treaty on 24 September 1996. It awaits ratification by the US Senate.

The Treaty not only calls for the cessation of all testing but implements a monitoring network and accompanying On-Site Inspection procedures to assure that the Treaty is abided by all nations. The monitoring technologies that are included in the treaty are designed to detect a nuclear explosion in any environment and include seismic (50 primary and 120 auxiliary stations), infrasonic (60 stations), hydroacoustic (6 hydrophone and 5 T-phase) and radionuclide (80 stations) sensors distributed throughout the world (CD/NTB/WP.330/Rev.2, 14 August 1996). These sensors and the accompanying data would then become a part of the International Monitoring System (IMS) with the collation, analysis and dispersal of the resulting data and data products by an International Data Center (IDC).

Mining explosions generate both ground motion and acoustic energy that have some characteristics similar to small nuclear explosions, thus the proposed monitoring system may detect, locate and characterize some mining explosions. In order to gain practical experience with the seismic component of worldwide monitoring, a series of empirical tests in the gathering, exchange and analysis of seismic data have been conducted under the auspices of the Conference on Disarmament in Geneva. These tests have been titled the Group of Scientific Experts Technical Tests (GSETT) with the most extensive and recent test, GSETT-3. Results from these experiments provide some idea of the types and numbers of mining events that will be detected under a CTBT monitoring system. This report highlights some of the results of these tests and the associated mining activities.

A representative example of the proposed seismic monitoring components of the IMS is shown in Figure 1. The network is divided into two components, Primary and Auxiliary. The 50 Primary would continuously transmit data to the IDC and are represented by circles in Figure 1. Auxiliary stations (120 total) would only provide data upon request based upon signals observed by the Primary stations. A seismic event, possibly from a mining explosion, could then be located, its size determined and its cause assessed using these data. Similar networks accompany each of the other monitoring technologies.

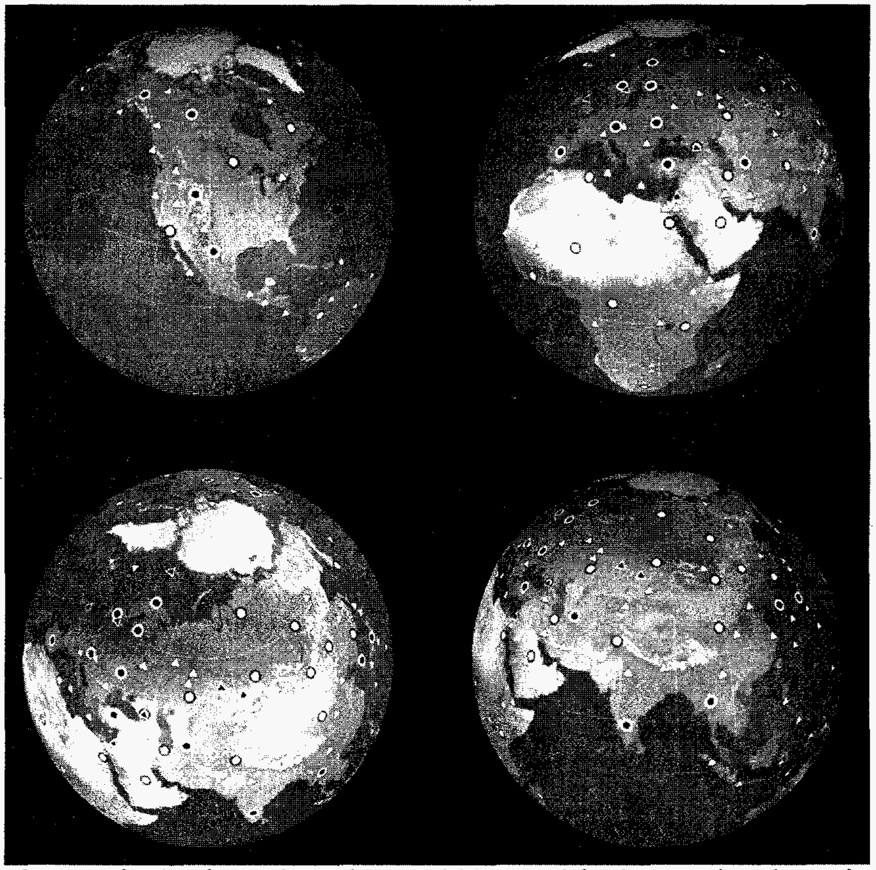

Figure 1: An example of a set of seismic stations that could be used for international monitoring of a CTBT. Primary stations are represented as circles and Auxiliary stations are represented as triangles.

Seismic stations such as those illustrated in Figure 1 will regularly record signals from naturally occurring earthquakes as well as man-made events such as those associated with mining operations. This paper will illustrate, through example, the characteristics of these signals and their relationship to operations in the mines.

2. Examples from Tests of Prototype Monitoring Systems, GSETT The Group of Scientific Experts (GSE), as noted earlier, has studied issues associated with the development of a monitoring system for the CTBT. As part of these studies they have conducted a series of three tests (GSETT-1 through GSETT-3) to quantify monitoring issues. In this paper we have used results from GSETT-2 and 3 to explore the types, sizes and numbers of signals that might be expected from mining explosions.

Results from GSETT-2 data analyzed for a seismic array in Texas illustrates that mining explosions produce seismic signals that will be observed. These observations will likely be made only at relatively close distances from the seismic station. Typically, seismic signals are classified according to the distance that they have traveled. Seismic waves that have traveled several thousand to tens of thousands of kilometers are characterized as teleseismic waves because they have traveled through the mantle of the earth. Events that generate teleseismic observations at these great distances are of relatively large events (greater than magnitude 4). In the left hand side of Figure 2 is a summary of the teleseismic events detected at the Lajitas array in Texas during GSETT-2. As the plot demonstrates these large events occur randomly in time.

Seismic waves that travel hundreds to over a thousand kilometers are classified as regional seismograms because they travel primarily in the earth's crust. Events that are only observed regionally are generally smaller than those observed teleseismically since the amplitude of the seismic disturbance decays as it propagates. The right part of Figure 2 illustrates the regional GSETT-2 triggers at Lajitas. It is interesting to note that these smaller regional events occur primarily Monday through Friday and during working hours, suggesting that they are man made. This data suggests that a number of these regional signals may be associated with mining operations, in this case near surface coal extraction in Northern Mexico.

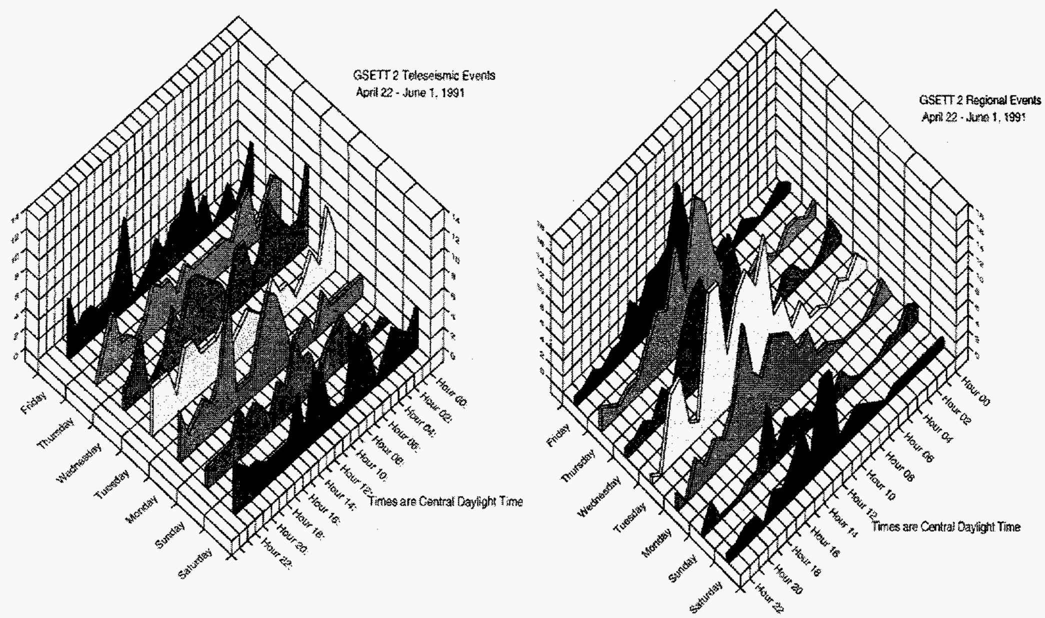

Figure 2: Teleseismic (left) and regional (right) GSETT-2 events from the regional array at Lajitas, Texas. Note that regional events occur primarily Monday through Friday and over a limited number of hours during the work day (0600 to 1500 hours local time) suggesting that these events are dominated by mining activity. Figure supplied by Eugene Herrin and Jesse Bonner, Southern Methodist University.

GSETT-3 included a greater number of seismic stations, continuous transmission of data and more detailed analysis of the data than GSETT-2. This experiment and the resulting data products allow further insight into the numbers and types of mining explosions that might be detected by regional seismic stations. Figure 3 summarizes 52 seismic events located in the Powder River Basin in northeast Wyoming during the time period 1 January 95 through 1 June 96 by GSETT-3. The locations and times of these events suggests that they are explosions associated with coal mining in this region. The percentage of these events that were detected by individual regional seismic stations in North America is represented by the height of the bar at each of the operating station locations (The circles and triangles in the figure represent both operating and planned stations). The strong effect of the earth's crust and upper mantle (as well as station quality) on the range of signal delectability is reflected in this figure. The majority of the events are detected by stations to the north where the propagation path is relatively efficient while fewer events are detected to the south and southwest of the Powder River Basin where the decay of the seismic amplitudes is more rapid and thus the signals fall below local background noise at shorter distances. This result illustrates that the number and size of mining explosions that will be detected will depend on both the regional geology and wave propagation as well as the locations of the seismic stations in each region.

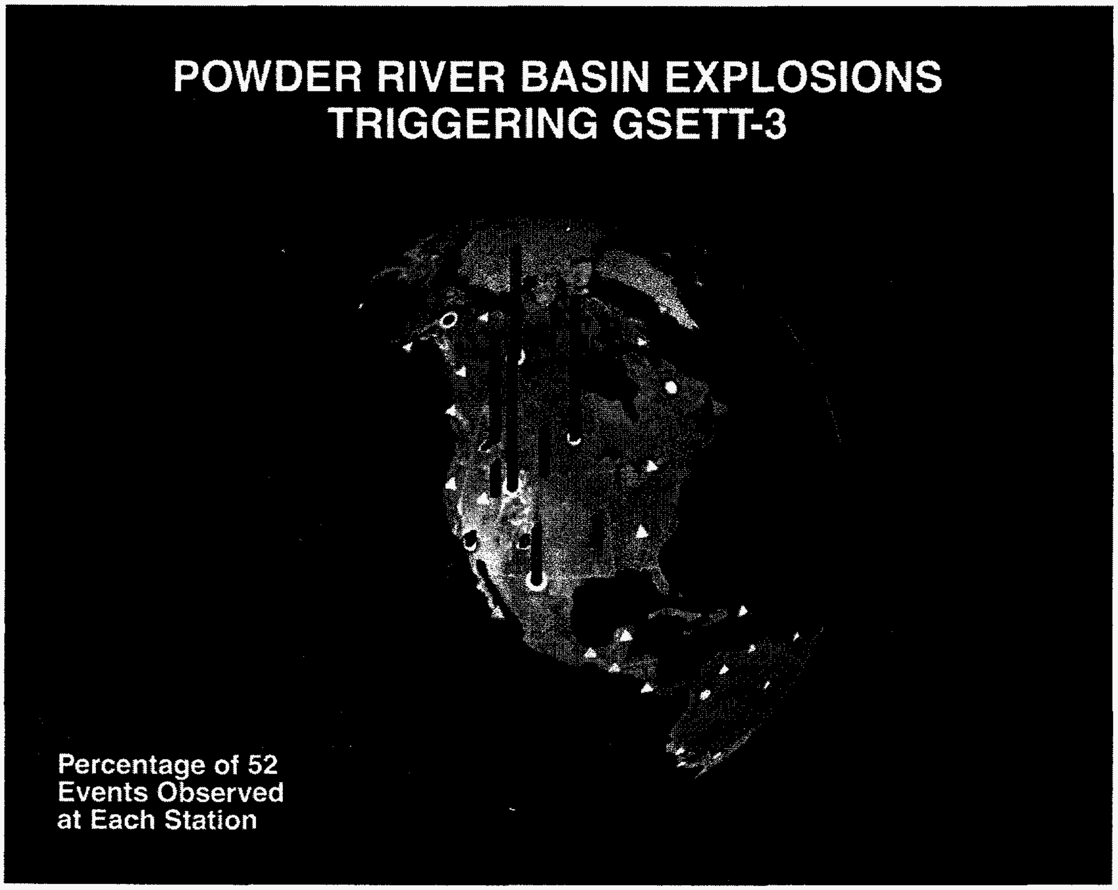

Figure 3: Mining explosions from the Powder River Basin of Wyoming and Regional Seismic Signals Detecting these Explosions

The fifteen months of activity represented in Figure 3 suggests that in an active mining region such as the Powder River Basin, as many as several events per month might be expected.

Event location is very important in the assessment of the seismic data. Utilization of the arrival times of multiple seismic phases at a single seismic station, relative arrival times at an array of closely spaced seismometers, and observations at multiple stations are used to determine the origin of the events in space and time as well as some assessment of error in the estimates. Location information can be used in the assessment of the probable cause of the seismic disturbance. Figure 4 focuses on the GSETT-3 events from the southern portion of the Powder River Basin where a number of event locations and their accompanying error ellipses have been plotted over a SPOT satellite image of this region. The outlines of five active mines in the region are also included in the figure. Thanks to a cooperative program with the Black Thunder Coal Mine (arrow in the figure), the seven events displayed in Figure 4 were identified as originating from this operation. It is interesting to compare the quality of the locations of the events with the outline of the mine. The events are all close to the mine although the error ellipse for the events do not all include the mine property. This result indicates that in an active mining region, event locations will in many cases associate an event with a mining region but possibly not with a single mine. Cooperative programs such as that which has been undertaken with the Thunder Basin Coal Company provide the opportunity for assessment of these issues. Further, with known source locations, calibration of the monitoring system and thus minimization of possible confusion between a signal from a large mining explosion and a small nuclear explosion is possible.

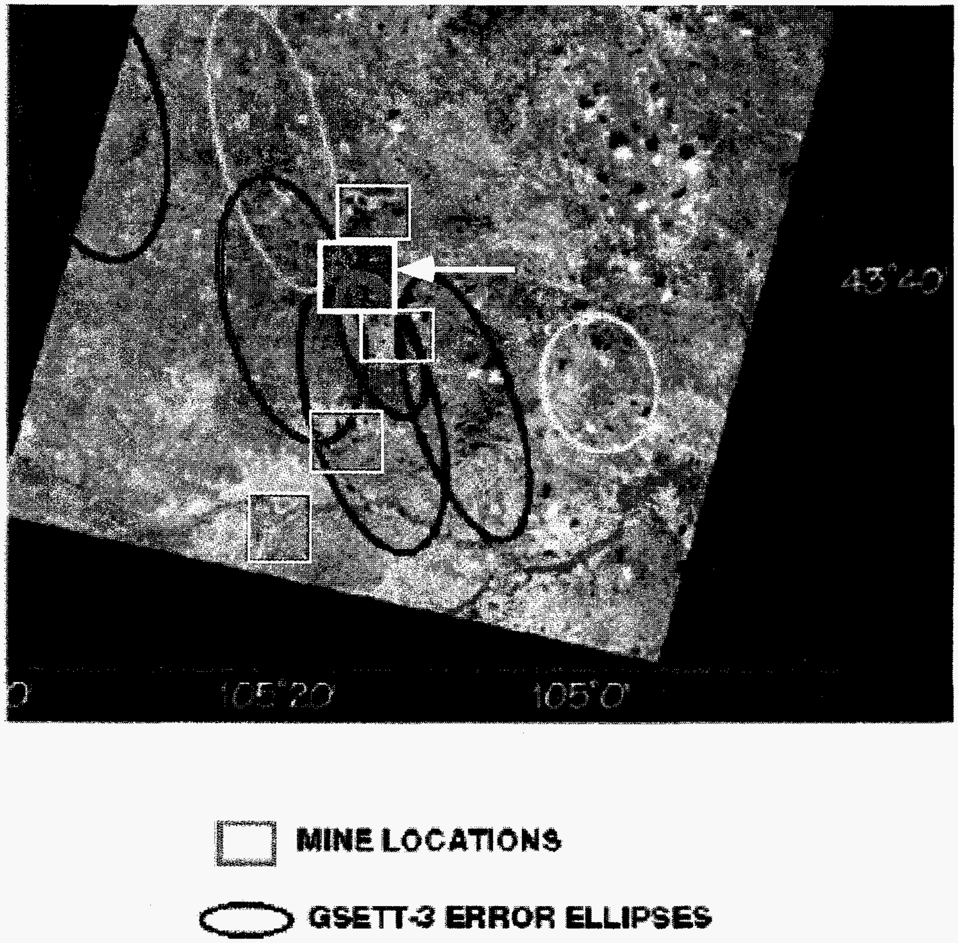

Figure 4: GSETT-3 events located in the Southern Powder River Basin compared to SPOT imagery and known locations of the events in coal mines in the region.

3. Size of Regional Signals from Explosions The expected seismic magnitude (logarithm of a distance corrected peak amplitude of seismic waves) from underground nuclear explosions is reproduced in Figure 5. This figure illustrates that the magnitude of the seismic energy is dependent on the material in which the explosion is detonated (hard rock to dry alluvium) as well as the way in which the explosion is emplaced with the possibility of decoupling in cavities. A 1 kiloton nuclear explosion (2,000,000 lb. of TNT equivalence) fully coupled produces a teleseismic magnitude of around 4.

During the GSETT-3 experiment, magnitude estimates have been made for many events, including mining explosions from the Powder River Basin. Table 1 contains a list of these estimates that range from the low 2's to the low 4's. As indicated in Figure 3, the majority of the observational data from the Powder River explosions are at regional distances and not at teleseismic distances from which the nuclear explosion magnitude-yield curves have been developed. As Figure 3 illustrates, there is a strong influence of the earth's crust and upper mantle on this regional wave propagation thus suggesting that there can be biases between regional and teleseismic magnitude estimates (M_L) making detailed comparisons between the results summarized in Figure 5 and the regional magnitudes in Table 1 difficult. Realizing possible bias in the regional magnitude estimates, these results suggest that the largest of the mining explosions may produce seismic signals comparable in size to some of the smallest nuclear explosions, particularly if decoupling is considered. This conclusion motivates the desire to understand the generation of the regional seismic signals from the largest of the mining explosions and to determine the characteristics of these signals that are unique to standard blasting practices thus allowing identification of these signals as resulting from standard mining explosions.

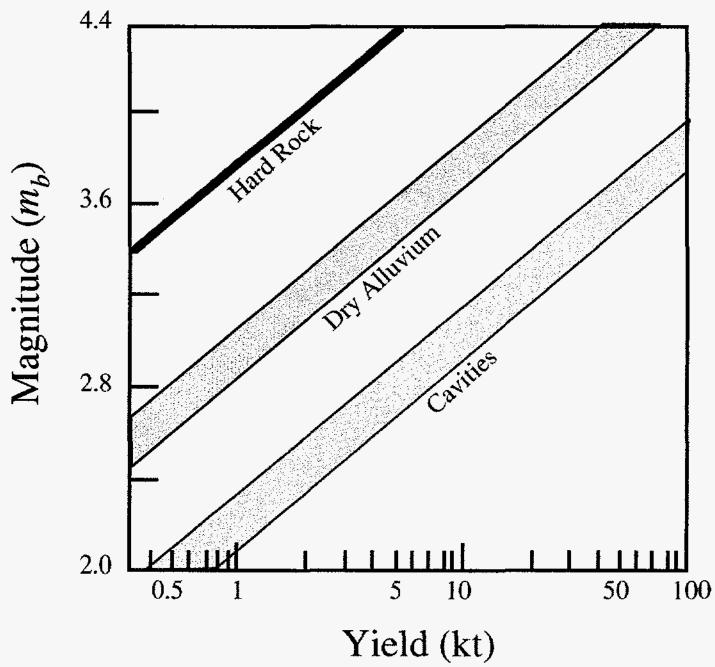

Figure 5: Estimate of expected teleseismic magnitude for a contained nuclear explosion as a function of yield. The effect of material on signal strength as well as decoupling is illustrated. After Hannon, 1985.

The largest of the GSETT-3 events have both teleseismic and regional observations. Comparison of the regional and teleseismic magnitude estimates for these few events suggests that the regional magnitudes may be biased high relative to teleseismic measurements.

The cooperative mining explosion study with The Black Thunder Coal Mine (Martin *et al.,* 1996) was designed to provide source specific information to better interpret the role that blasting practices play in the resulting regional seismograms including the magnitude or peak amplitudes in these regional seismograms. As described in this companion paper, careful documentation of the blasting practices for a number of explosions at Black Thunder was undertaken. During the course of this study three distinct types of explosions were documented; (1) Large scale cast blasts designed to remove overburden; (2) Coal shots designed to fracture the exposed coal with no cast (lower powder factors); and (3) A contained, single fired explosion. These well documented explosions provide the opportunity to explore the relationship between blasting practices and peak regional amplitudes used in making magnitude estimates. In order to minimize variations in regional observations introduced by different propagation path effects, peak regional amplitudes were measured at a single regional seismic station near Pinedale, Wyoming (PDAR). The peak amplitudes of compressional waves and a shear phase known as L_g were both measured as each is used in different types of regional magnitude determinations. This work was done

Table 1: Powder River Basin mining explosions detected and during GSETT-3

Date	Time	Latitude	Longitude	# of Phases	M_L	m_b	Teleseismic Obs (> 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		

in cooperation with Vindell Hsu at the Air Force Technical Applications Center. Figure 6 plots the peak compressional (P) and shear (L_g) amplitudes plotted as a function of total explosive weight.

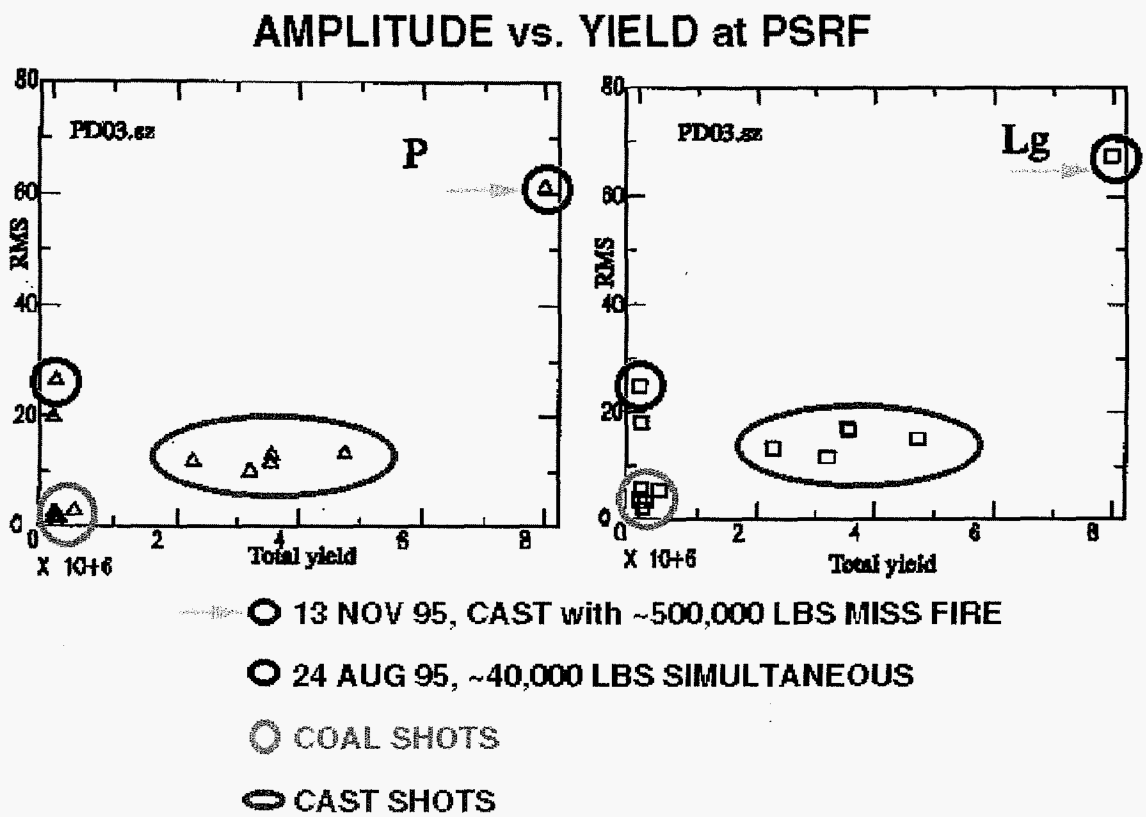

Figure 6: Peak P and L_g amplitudes at the regional station PDAR for a number of mining explosion shot types from a single surface coal mine.

The coal shots produce the smallest amplitude signals which are nearly an order of magnitude smaller amplitude than those from the cast shots (about 1 magnitude unit difference since it is a logarithmic scale). The cast shots, although producing larger absolute amplitude regional signals, show little increase in amplitude with explosive yield between 2 and 5 million lb. of total explosive per cast shot (with the exception of one which will be discussed later). For comparison, the single fired contained explosion with a total explosive weight of about 40,000 lb. has slightly larger peak amplitudes than the cast shots. The reduced size of the regional signals generated by the cast shots and their insensitivity to total explosive yield is a reflection of the effect of delay firing the explosions. Delay firing is intended to control ground motions near the shot and apparently has the same effect at regional distances.

The one anomalous cast shot has peak amplitudes that are nearly a factor of 5 larger than any of the other cast shots and larger than the single fired explosion. As will be demonstrated in the next section of this paper, this explosion included the unexpected, simultaneous detonation of a large number of explosive boreholes at the end of the delay-fired sequence.

4. Comparison of In-Mine and Regional Observations from Mining Explosions - Minimizing Signal Size and Reducing Signal Ambiguity The peak regional amplitudes plotted in Figure 6 suggest that blasting practices in the mine have a strong signature on the regional waveforms. This suggestion is further explored in this last section of the paper as a variety of in-mine measurements (seismic, acoustic and video) are compared to the accompanying regional seismic signals.

The top left hand side of Figure 7 displays in-mine waveforms (~10 km) for comparison to regional waveforms from the same explosions shown on the bottom left hand side. The 16 June cast was chosen because it is one of the cast shots that showed little increase in regional amplitude with explosive size in Figure 6. Both the near-source and regional

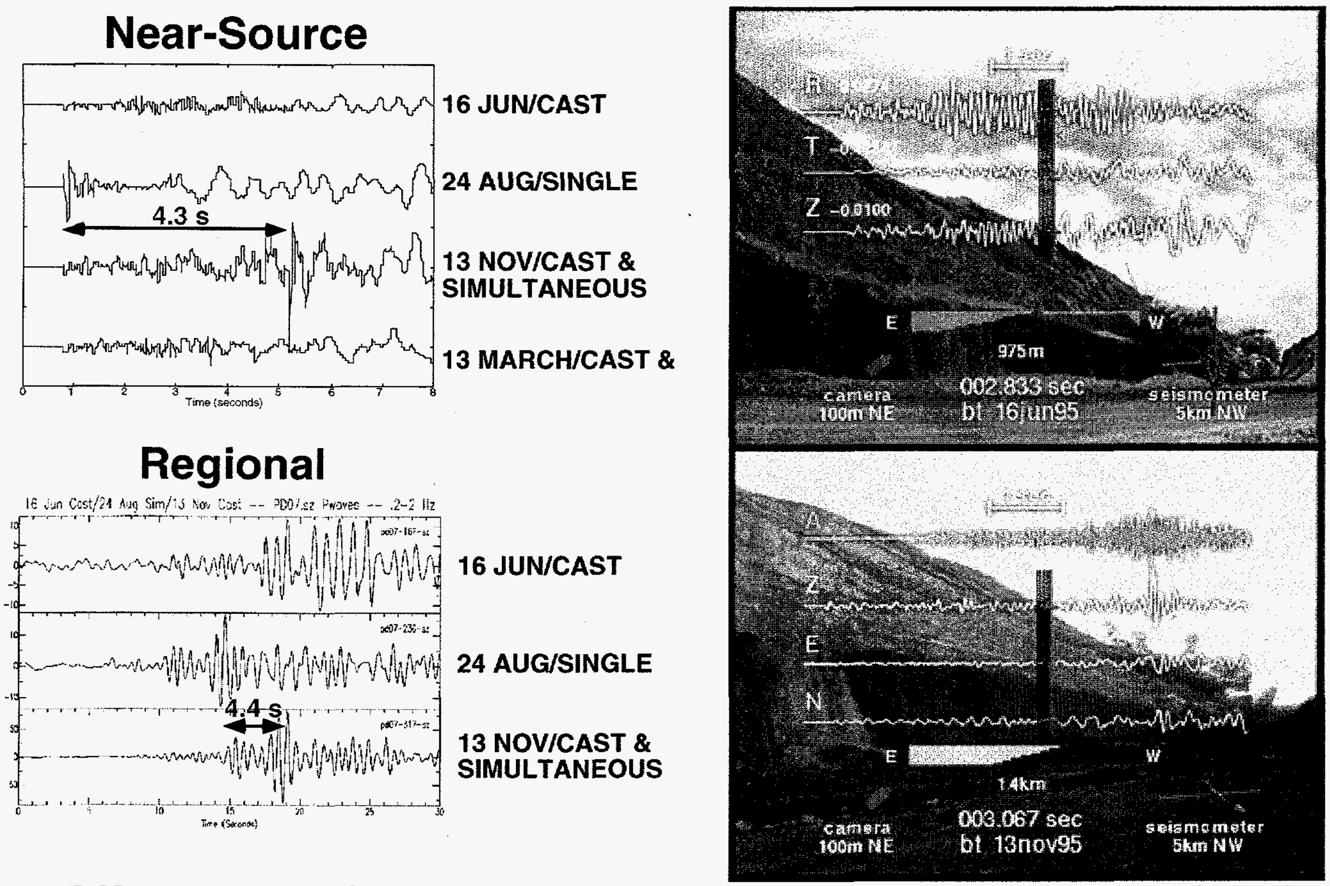

Figure 7: Near source (top left) and regional (top right) seismograms are compared from a good cast shot (16 June, upper right), a single contained shot (24 August) and two problematic cast shots (13 November, lower right, and 13 March).

waveforms illustrate the controlled effect of a smoothly proceeding delay-fired explosion. This result can be compared to the contained single fired explosion (24 Aug) which is much more impulsive in nature. Two abnormal cast blasts are also included, 13 Nov and 13 Mar. The 13 Nov explosion is the one which produced the very large regional amplitudes displayed in Figure 6. Focusing first on the 13 Nov event one can see from the in-mine data that the explosion progresses in a regular fashion initially but that at 4.3 seconds into the explosion there is an impulsive signal. Time aligning the first P waves from the simultaneous explosion (24 Aug) with this anomalous shot at regional distances suggests that there is a signal identical to the single shot 4.4 seconds into the regional waveform. A similar, but smaller amplitude, simultaneous detonation was documented for the 13 March explosion. The right hand side of

Figure 7 illustrates combined in-mine seismic, acoustic and video data from the 16 June (top) and 13 Nov (bottom) cast blasts. This data synergy also supports the interpretation that the 13 Nov cast blast included the simultaneous detonation of a number of boreholes approximately 4.3 seconds into the blast. It is this simultaneous detonation that is responsible for the large peak amplitudes, observed at regional distances.

5. Conclusions and Recommendations Large scale mining explosions, especially those associated with the detonation of a large amount of explosives simultaneously, are observed at regional (100-2000 km) and occasionally teleseismic (2000-10000 km) distances with seismic sensors. As a result of the CTBT verification system, the largest of these events will have to be associated with standard mining operations to avoid the conclusion that the signal was created by a small nuclear explosion.

Results from analysis of regional seismic data and information collected from a cooperative in-mine study of large scale blasting practices suggests that techniques designed to reduce seismic amplitudes close-in have a similar effect at regional distances. The smaller the regional seismic signal, the less problematic it becomes for CTBT monitoring. Also, characteristic signals of the large, well performing cast blasts are different from a simultaneously detonated explosion thus avoiding ambiguity in signal identification.

Anomalously performing explosions documented with close-in monitoring also produce complementary signals at regional distances thus reflecting the signature of the blast performance even at these more distant stations. Improved understanding of blasting practices and their effects on regional seismograms provides the opportunity for improved monitoring of a CTBT. Similarly, blasting practices designed to maximize explosive efficiency while minimizing ground motion within the mine are exactly those practices best for reducing both the size and ambiguity of regional seismic signals.

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