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Investigations of the Seismic Discrimination of Rockbursts

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13. ABSTRACT *(Maximum 200 words)*
Our principal objective in this research has been to identify and test regional discrimination measures which can help facilitate the identification of the numerous rockbursts which are likely to be encountered in CTBT monitoring. We have reviewed characteristics of rockburst mechanisms and their seismic signals for a variety of different mining, tectonic, and propagation environments; and we have discovered several problem areas for rockburst discrimination. Our recent investigations have been directed primarily at three source areas where rockbursts occur frequently: (1) the South African gold-mining region, (2) coal-mining and copper-mining regions in Poland, and (3) coal mines in eastern Kentucky and western Virginia. For each of these areas, we have collected and analyzed waveform data from a significant sample of rockburst events recorded at high quality digital seismic stations which would be critical to regional monitoring under a CTBT. The analyses have focused on assessing the value of L_g/P ratios as a function of frequency for distinguishing rockbursts from underground nuclear explosion tests. The L_g/P ratios for the rockbursts in each source area tend to be larger over a broad range of frequencies, and this appears to provide one of the most promising discriminants.

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1. Introduction

1.1 Objective

A Comprehensive Test Ban Treaty (CTBT) prohibiting nuclear weapons testing is expected to broaden the range of seismic events of interest in treaty monitoring to include both smaller events and events in geographic regions which were not previously considered important. Rockbursts present some interesting challenges for seismic discrimination in this new CTBT monitoring environment. Rockbursts and related mining-induced seismic events are frequent in mining regions throughout the world at magnitude levels which need to be addressed under a CTBT. Unlike earthquakes, which often occur at focal depths well below those normally associated with underground nuclear explosion tests, rockbursts are located in approximately the same depth range as nuclear tests; and, therefore, standard discriminants based on focal depth are not useful. Observations from several rockbursts suggest relatively weak long-period surface waves which could significantly reduce the effectiveness of the M_S-vs-m_b discriminant which is often used to distinguish between earthquakes and explosions. Since many rockbursts are small, the best opportunities for seismic identification are probably those which utilize regional seismic measurements; but reliable regional discrimination techniques have not been established or tested on various event types, including rockbursts, in many regions of interest.

Our principal objective in this research program has been to identify and test regional discriminants which can help facilitate the identification of the numerous rockburst events which are likely to be encountered in CTBT monitoring. For this purpose we have been pursuing analyses of empirical data from rockbursts in a variety of different mining, tectonic, and propagation environments. We have also been investigating theoretical techniques for modeling several of the varied rockburst mechanisms and their associated regional seismic signals in an effort to better characterize those types of rockbursts which are likely to be problematic for seismic discrimination. Finally, there is evidence in several case histories that activation of rockbursts might be deliberately triggered, thereby providing an opportunity to conceal a clandestine nuclear test if the timing and size can be adequately predicted. We have been continuing to seek historical evidence supporting this predictive capability, and we hope in the future to use theoretical model studies to further assess mining conditions which might be required to effect such evasion scenarios.

1.2 Overview

After reviewing published reports on rockbursts, it is clear that such events occur in most mining regions (cf. Figure 1). In the course of our investigations, we have reviewed the behavior of seismic signals from rockbursts in several different source regions including (1) South Africa, (2) Central Europe, (3) eastern U.S., (4) western U.S., and (5) Russia. In some of these areas rockbursts occur frequently, and they are regarded as routine; while in other mining regions rockbursts are irregular and the unexpected occurrence of such events can be surprising and catastrophic. In some of our prior reports (cf. Bennett et al., 1994, 1995), we have described several instances of catastrophic mine collapses, including an event in eastern Germany in 1989, an event in Wyoming in 1995, and an event in the Ural mountains of Russia in 1995. We analyzed discrimination characteristics of the regional and teleseismic signals from these events and reviewed the seismic source mechanisms for these and other rockburst sources.

Our recent investigations have focused primarily on rockbursts from areas where their occurrence is considered routine. In particular, we have been analyzing the characteristics of the regional signals from rockbursts in three repetitive source areas (cf. Figure 2): (1) the South African gold-mining region, (2) coal-mining and copper-mining regions in Poland, and (3) coal mines in eastern Kentucky and western Virginia. We had previously looked at the regional signals recorded at older, traditional seismic stations from the South African mine tremors and Polish rockbursts and found evidence in both areas that time-domain measurements of L_g/P ratios tended to be large, like those seen for earthquakes. This behavior contrasts with that seen for many nuclear explosions and seems to offer considerable promise for regional discrimination. In the latest phase of this research program, we have attempted to conduct more thorough and systematic analyses of the L_g and P signals recorded at selected more modern regional stations for events in each of the repetitive source zones noted above. For each source zone we selected a high-quality digital station in the regional distance range which reports to the International Data Center (IDC) and which would be critical to regional seismic monitoring there under a CTBT. Because the rockbursts in each of these source zones

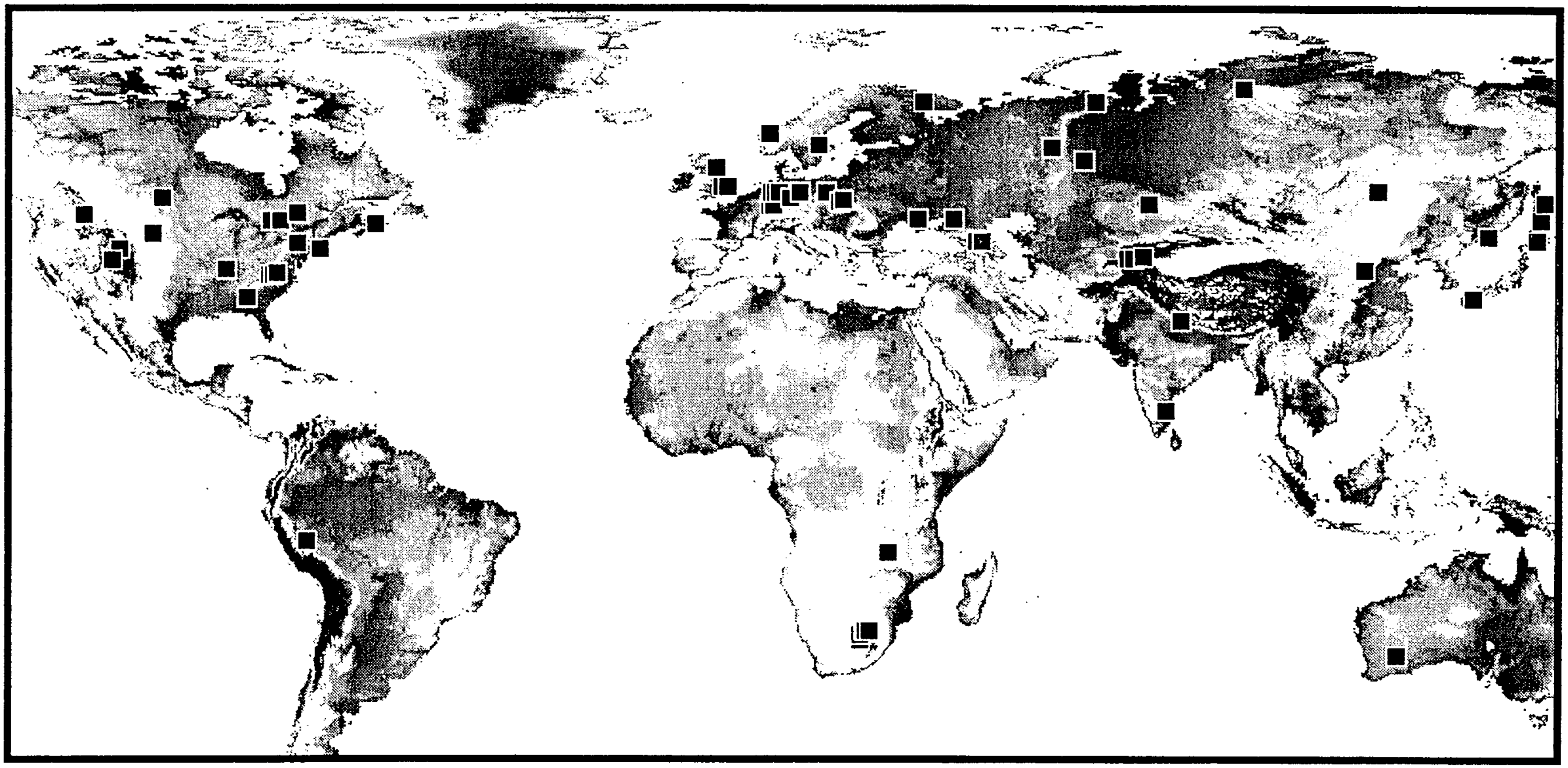

Figure 1. Locations of mining areas worldwide with reported rockbursts or mining-induced tremors.

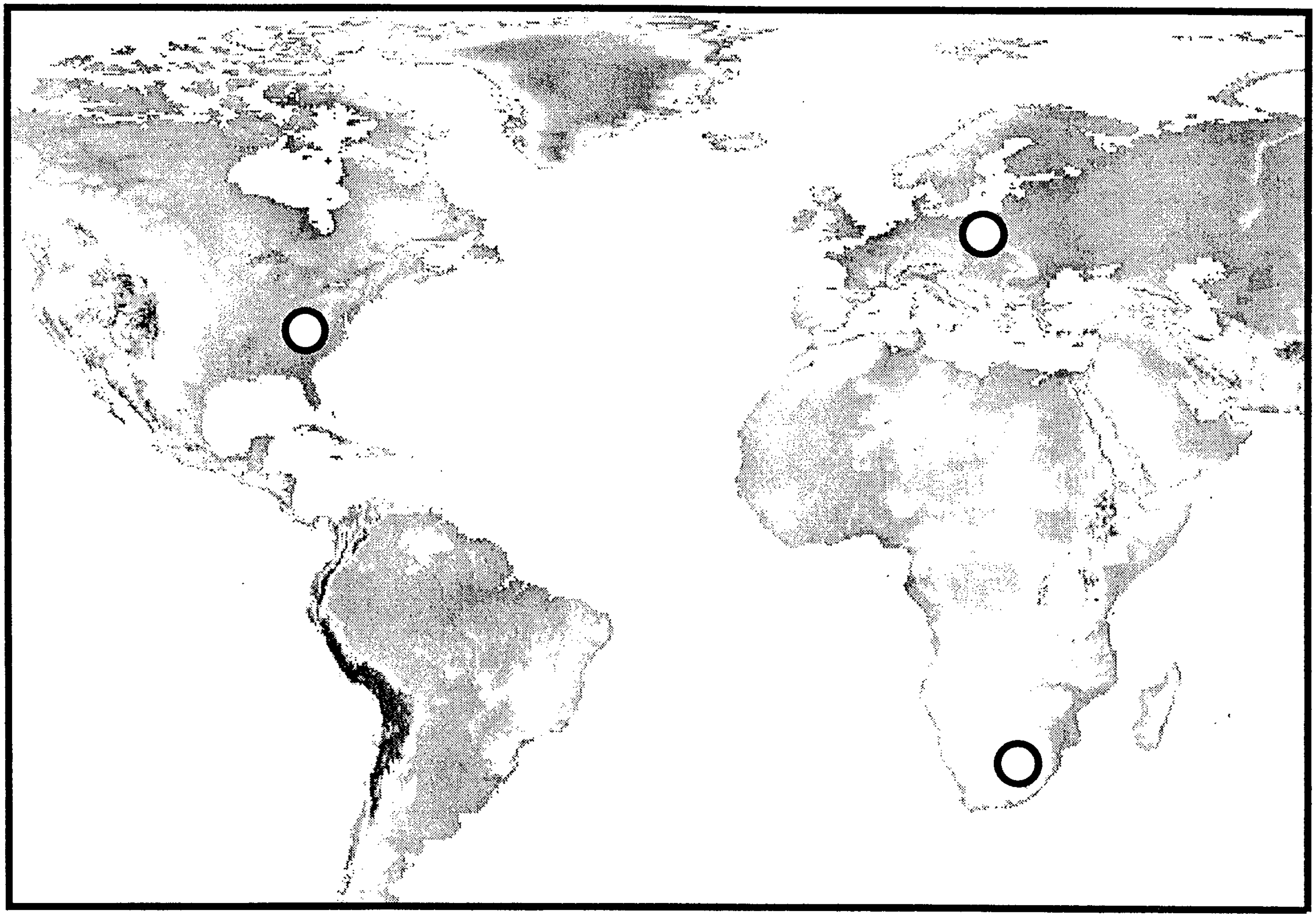

Figure 2. Locations of the three regions with recurring rockburst activity which have been the focus of recent discrimination studies.

occur with such frequency, we were able to collect from a two-year monitoring interval a fairly large waveform database of events from each area. In place of simple time-domain measurements of the maximum P and L_g amplitudes, we obtained more rigorous spectral estimates of the L_g and regional P signals derived from bandpass filter analyses. These spectral estimates were used to form L_g/P ratios as a function of frequency. In some source areas multiple rockbursts were associated with individual mines, so we were also able to analyze to some extent sensitivities in the measurements to different mine locations or possible variations in mining practice.

Because there were no nuclear explosion tests in the same source regions as the rockbursts, we were forced to extrapolate experience from other areas to analyze discrimination characteristics. In particular, we used regional recordings of selected nuclear explosion tests from the Nevada Test Site (NTS) and from the former Soviet test site in East Kazakhstan at Shagan River. The epicentral distances to the regional recording stations for the NTS explosions were about the same as those for most of our rockburst observations, while the observation distance for the Shagan River explosions was farther away. We have made our discrimination comparisons without regard to possible propagation effects. Accounting for such propagation effects on regional phase signals is the subject of on-going research in regional discriminant transportability and is beyond the scope of the research reported here.

1.3 Report Organization

This report is divided into six sections including these introductory remarks. In Section 2 we show examples of the bandpass filter analysis procedure applied to regional waveforms for rockbursts and nuclear explosions, and we describe our discrimination analyses of the L_g/P ratios as a function of frequency for the South African mine tremors. Section 3 provides similar regional discrimination analyses for Polish rockbursts. In Section 4 we describe the results of the same kind of L_g/P ratio measurements and discrimination analyses for eastern U.S. events including mine bumps in eastern Kentucky and western Virginia and also mine blasts and earthquakes from this source region. Section 5 discusses some general issues with regard to rockburst discrimination and their mechanisms. Finally, in Section 6 we summarize our observations and conclusions and discuss some ideas for future investigations on rockburst discrimination.

2. South African Mine Tremors

2.1 Background on South African Events

Rockbursts, or mine tremors as they are called in South Africa, occur in association with deep (2 - 4 km) gold mines in an arcuate zone extending 250 km from east of Johannesburg to the west and southwest into the Orange Free State. In prior reports (cf. Bennett et al., 1993, 1994, 1995) we have described the characteristics of the induced seismicity in this zone and the source mechanisms of mine tremors. To summarize, seismicity associated with mine tremors in this area is frequent (on the order of 100 events per year with magnitudes greater than 3 M_L) and events are often large (events with magnitudes of 5 M_L or greater occur on average more than once a year). Rockburst activity associated with the deep South African gold mines is considered routine, and local seismic monitoring and mining engineering analyses have been used for many decades to investigate the occurrence of the mine tremors and their relation to mining practice. Rock failure in the mines normally occurs in regions of maximum stress concentrations near the edges of the excavation and produces nearly continuous seismic activity on fracture planes within several tens of meters of the advancing mine working. The in situ stress conditions for the mining areas (cf. Gay, 1975, 1977) most often show a nearly vertical pressure axis and horizontal tension axis which is conducive to normal dip-slip fault movement. Observations from many large South African mine tremors support the conclusions that they are associated with shear failure on fracture planes near the excavation (cf. McGarr, 1971; McGarr et al., 1979) and that residual strain energy related to regional tectonics may contribute to the total energy released during the events. Such events have a double-couple mechanism and produce a quadrantal pattern of first motions similar to earthquakes, and they should be essentially indistinguishable from earthquakes. However, some of the mine tremor mechanisms may be more complex; and, as pointed out in our previous reports (cf. Bennett et al., 1995), these South African events often generate weak M_S relative to m_b, which is distinct from typical earthquakes and tends to be similar to explosions.

In an earlier phase of this research program (cf. Bennett et al., 1994), we assembled a database including 61 events thought to be mine tremors, because of their locations within the seismic zone associated with the South African gold mines, and 18 events thought to be earthquakes, which were located in southern Africa outside the mining zone. The events had magnitudes from 2.3 M_L to 5.5 M_L and occurred during the time period from 1980 to 1991. For the larger events we looked at the teleseismic measurements, but the smaller events were not well recorded beyond regional distances. In our regional discrimination analyses of these events, we used regional signals recorded at the DWWSSN station Silverton (SLR) which was located at distances between 60 km and 305 km from the mine tremor sources. Figure 3 shows a comparison of the maximum L_g amplitudes versus maximum regional P amplitudes for 31 mine tremors and 10 earthquakes measured from the vertical-component (sz) records at SLR. On average the maximum L_g amplitudes for the mine tremors are a factor of five larger than the maximum P amplitudes, and similar measurements for the earthquakes fall in the same range. Since the earthquakes and mine tremors were at somewhat different distances from SLR, we applied distance corrections using attenuation relations appropriate to South Africa and replotted the amplitude comparisons in Figure 4. L_g/P ratios still show an average of about five for both mine tremors and earthquakes. For comparison, Blandford (1981) showed similar time-domain maximum L_g and P amplitudes (normalized to the same distance range) for NTS nuclear tests with the corresponding L_g/P ratios averaging only about 0.7, much smaller than those for the South African mine tremors and earthquakes. Therefore, regional measurements of relative amplitudes of L_g and P signals appear to offer some promise for distinguishing mine tremors or rockbursts from underground nuclear explosion tests; and we have investigated this prospect further as the project has continued.

2.2 Supplemental Data for South African Events

Additional high-quality digital data for South African mine tremors at regional distances have become available in the last couple of years from the station at Boshof, South Africa (BOSA), which is an IDC alpha 3-component station. During this time we have attempted to collect waveforms recorded at BOSA from a representative sample of South African mine tremors. There has been no attempt on our part to obtain a complete sample; we have instead relied on IDC and NEIS event catalogs to identify events. Because of the procedures used in forming these catalogs, it seems likely that many smaller mine tremors from this region are not included.

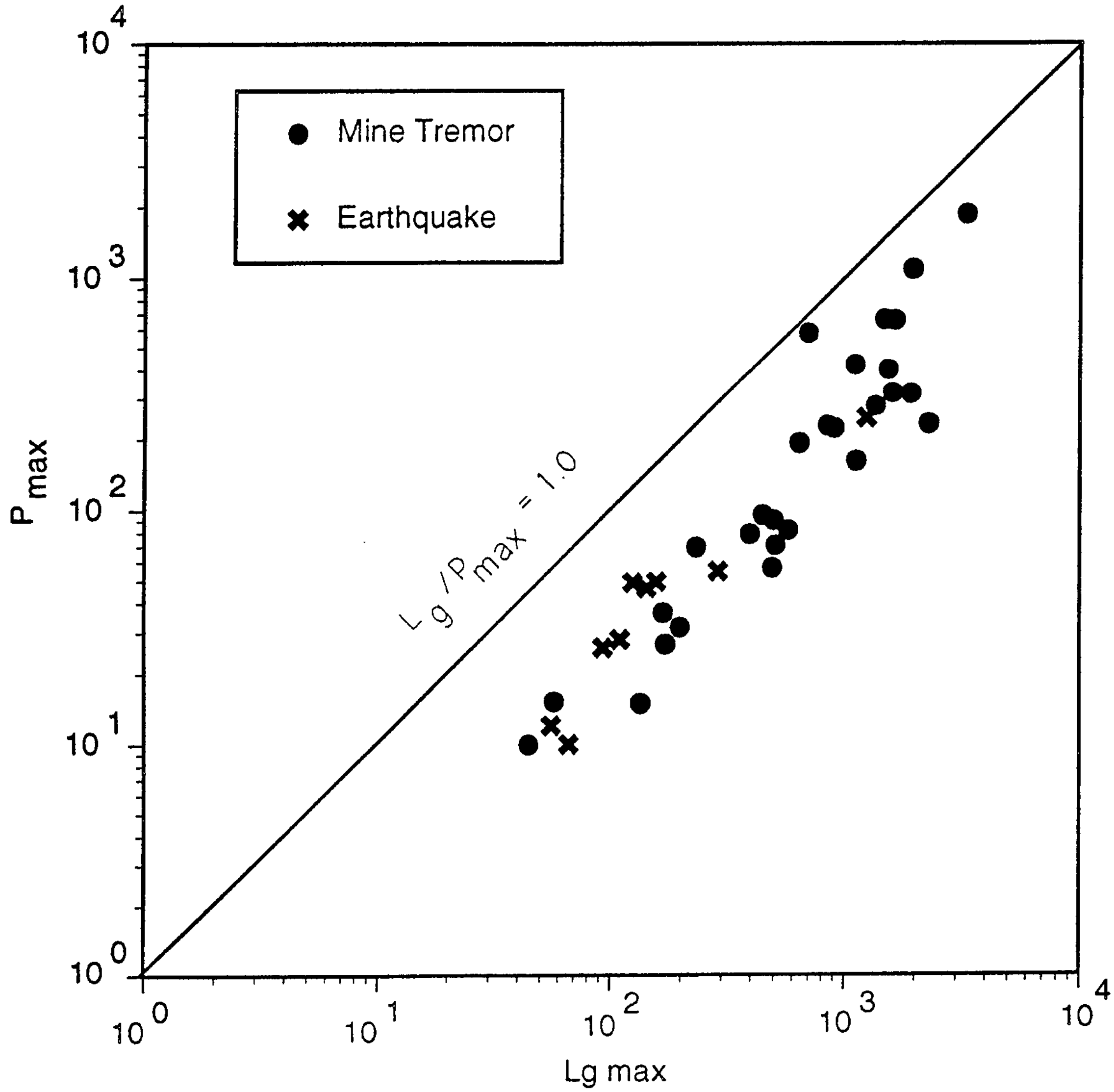

Figure 3. Comparisons of the maximum P versus Lg amplitudes measured from time-domain records at DWWSSN station SLR from 31 South African mine tremors and 10 southern Africa earthquakes.

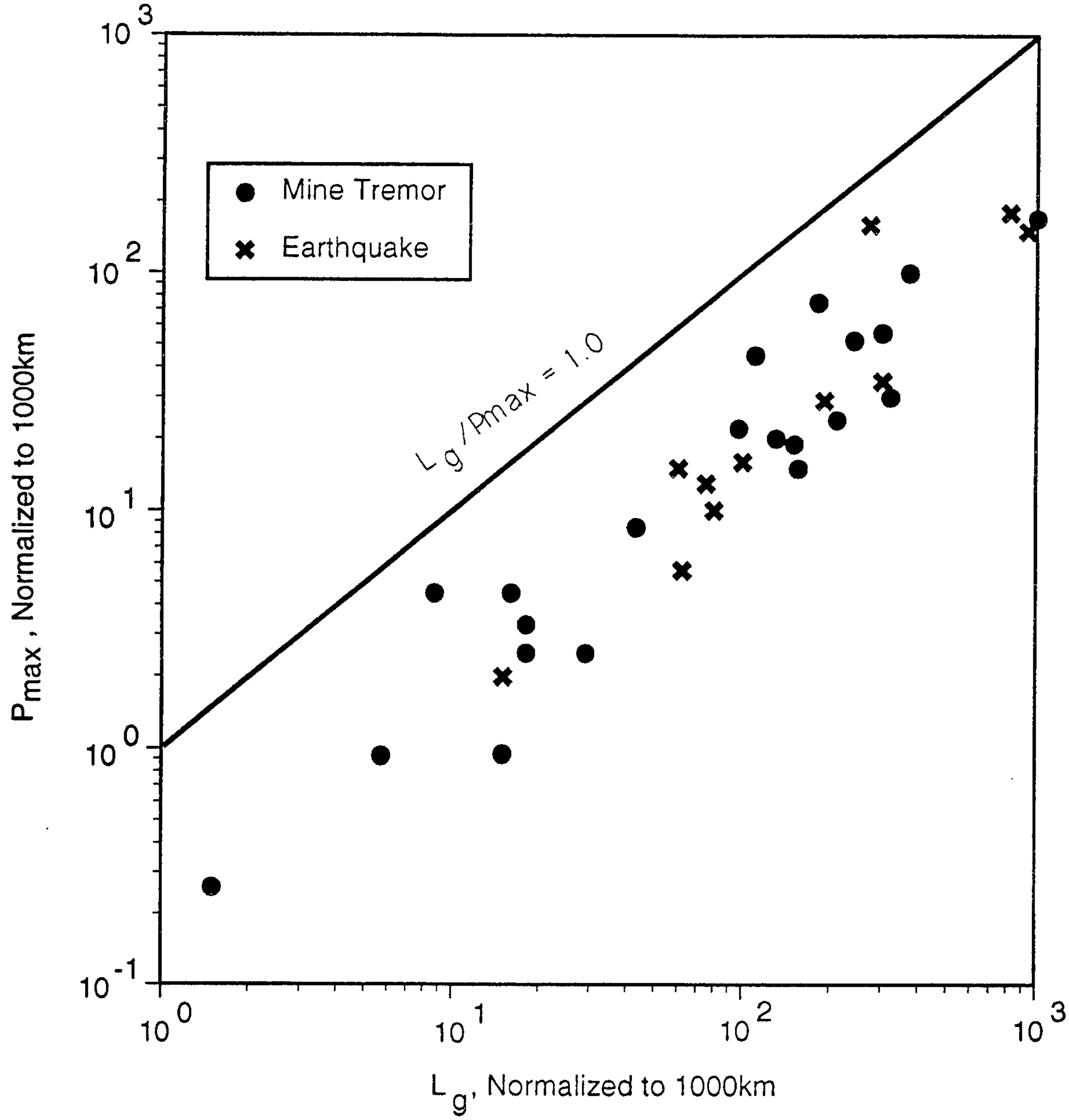

Figure 4. Distance-normalized P versus Lg amplitudes for South African events observed at station SLR.

Table 1 shows a list of 21 events from the South African gold mining region; based on their locations we assume these events are mine tremors. The majority of events shown come from information supplied by the IDC except for the two earliest events. The magnitudes in all cases are body-wave magnitudes and cover a range from 3.65 m_b to 5.60 m_b. Because the mine tremors come from several different mines, the epicentral distances to station BOSA range from 160 km to 388 km.

Figure 5 shows the locations of the events in the database relative to station BOSA. The event locations tend to show clustering in the vicinity of several mines. The southernmost cluster, closest to BOSA, corresponds to the Orange Free State mines near Welkom and includes six of the events in Table 1. The cluster just to the north includes five events and corresponds to the Klerksdorp mining area. Still farther north the event locations are more spread out along an east-west trend which follows the structure and a high concentration of gold mines from Far West Rand to Central Rand. Historically mine tremors have also been associated with gold mining somewhat farther east (East Rand) nearer Johannesburg, but none of those were reported by the IDC during this time period. The three events at the westernmost end of the trend have locations which are somewhat west of most of the historical mine tremor seismicity. This is particularly true for the event of September 2, 1995 which has a reported location almost 150 km west of the Far West Rand mining area. Although there are gold mines in this area, they have not historically shown much evidence of induced seismicity. There are three possible explanations for these events: (1) they are mine tremors from Far West Rand which have been mislocated, (2) they are mine tremors from a relatively new area, or (3) they are not mine tremors but some other type of seismic source. Based on similarities between the waveforms at BOSA for these and other mine tremors from the Far West Rand mining area, we believe that explanation (1) is the most likely. The events of September 2, 1995, June 30, 1995 and August 8, 1995 are probably mine tremors from Far West Rand.

2.3 Analyses of Regional Signals from the Mine Tremors

We have analyzed the behavior of regional signals at station BOSA from these South African mine tremors using similar bandpass filter analyses to those described in several of our prior reports (cf. Bennett et al., 1994, 1995). In particular, a suite of narrow bandpass filters with progressively higher corner

Table 1. South African Mine Tremors in Supplemental Database.

Date	Origin Time	Lat (S)	Lon (E)	Mag	R (km) BOSA
10/30/94	06:06:27	28.03	26.74	5.60	160
01/02/95	15:16:02	26.36	27.22	4.30	325
06/30/95	16:58:34	26.11	26.36	3.88	300
07/04/95	06:38:14	27.80	26.68	4.47	165
08/08/95	17:41:55	26.15	26.57	3.76	300
08/11/95	11:53:01	26.40	27.23	4.04	315
09/02/95	18:40:40	26.08	25.46	3.65	280
09/03/95	08:12:23	26.90	26.64	4.33	235
09/05/95	00:03:30	25.97	27.60	3.95	375
09/12/95	13:11:45	27.78	26.64	4.23	165
12/17/95	22:31:31	27.82	26.69	4.55	166
01/16/96	22:45:43	27.83	26.62	4.27	160
02/25/96	06:18:17	26.93	26.70	4.32	235
03/01/96	05:34;28	26.16	28.06	4.32	388
03/12/96	18:49:01	26.83	26.56	4.54	236
03/27/96	22:28:38	26.27	26.94	3.77	308
04/25/96	16:50:56	26.93	26.59	3.99	228
04/26/96	17:12:55	26.30	27.10	3.90	315
04/29/96	18:53:00	27.74	26.59	3.75	163
04/29/96	21:07:18	26.37	27.33	4.02	322
05/06/96	17:17:33	26.94	26.90	4.26	246

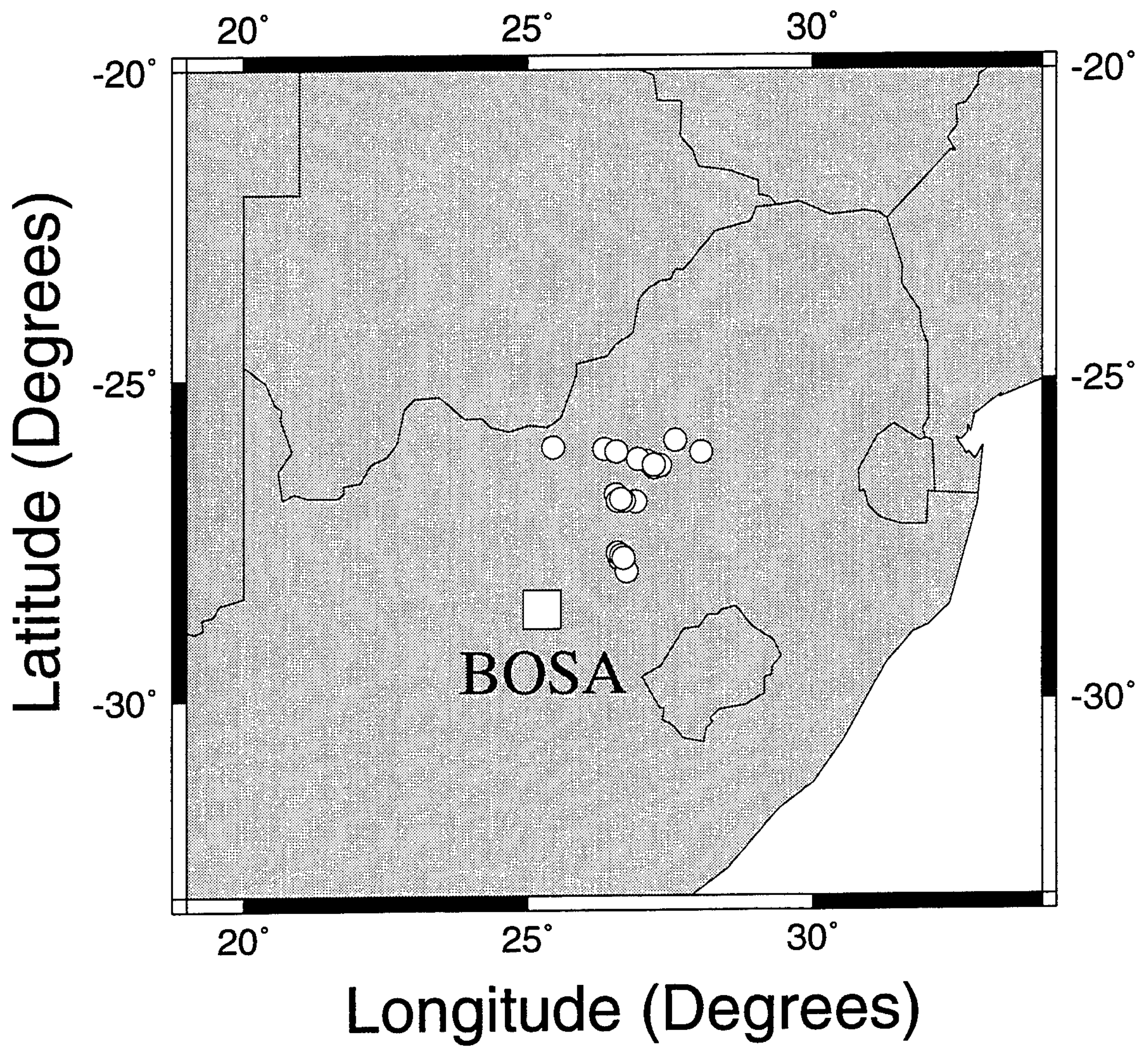

Figure 5. Map showing the locations of 21 South African events from mine tremor zones associated with deep gold mining relative to station BOSA.

frequencies was applied to each of the vertical-component records. The sequence of eight filters covered overlapping passbands of 0.01 - 0.1 Hz, 0.1 - 1.0 Hz, 0.5 - 2.0 Hz, 1.0 - 3.0 Hz, 2.0 - 4.0 Hz, 3.0 - 6.0 Hz, 4.0 - 8.0 Hz, and 6.0 - 12.0 Hz. Figure 6 shows the results of the bandpass filter analysis applied to the vertical-component record at BOSA from the Orange Free State mine tremor of October 30, 1994; the filter output traces have been individually normalized in this representation. The plot shows a strong regional P phase which appears relatively simple at low frequencies but becomes more complex and shows greater duration at high frequencies. The next prominent arrival on the filtered traces is the L_g phase which is the largest signal at all frequencies above about 2 Hz. This signal is followed by a strong R_g phase which shows clear dispersion for frequencies between about 0.5 Hz and 3 Hz. Finally, in the lowest frequency band (0.05 - 0.1 Hz), there is evidence of a fundamental-mode Rayleigh wave.

We used the bandpass filter analysis to compute L_g/P ratios as a function of frequency for the South African mine tremors recorded at BOSA. For each event we measured the peak-to-peak maximum amplitudes in the L_g and regional P group velocity windows from the filter output trace for each frequency band. We calculated the L_g/P ratios and plotted the result as a function of the center frequency corresponding to the filter passband. Figure 7 shows the L_g/P ratios as a function of frequency for 14 South African mine tremors from Table 1 above. The ratios show considerable scatter between events but generally lie between values of one and ten over the range of frequencies with the scatter appearing somewhat reduced at higher frequencies. The L_g/P ratios for the mine tremors also seem to show a general trend to decline somewhat with increasing frequency. Some of the scatter between events may be related to propagation differences from different mines. This is illustrated in Figure 7 by the behavior of the ratios for the events in the first column (generally solid symbols), which correspond to five events from the Orange Free State mine area, and for the events in the second column (generally hollow symbols), which correspond to five events from the Klerksdorp mine area. The solid symbols seem to be fairly constant or increase slightly with increasing frequency, while the hollow symbols seem to show more of a decline. Figure 8 illustrates the average trends for the South African mine tremors from the combined areas compared to L_g/P averages for just the Orange Free State and Klerksdorp events. The average L_g/P ratio for all areas is largest at about 1.25

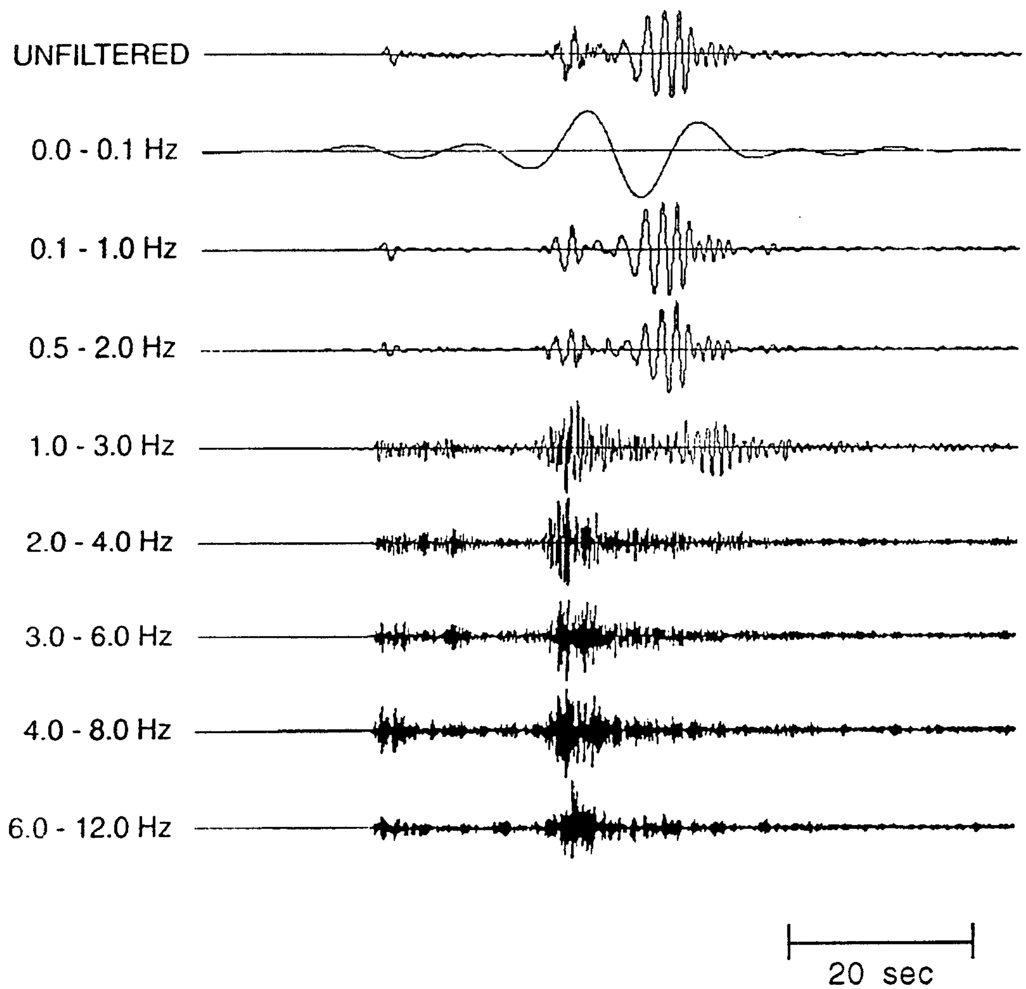

Figure 6. Example of bandpass filter analysis applied to BOSA record for for South African mine tremor of October 30, 1994.

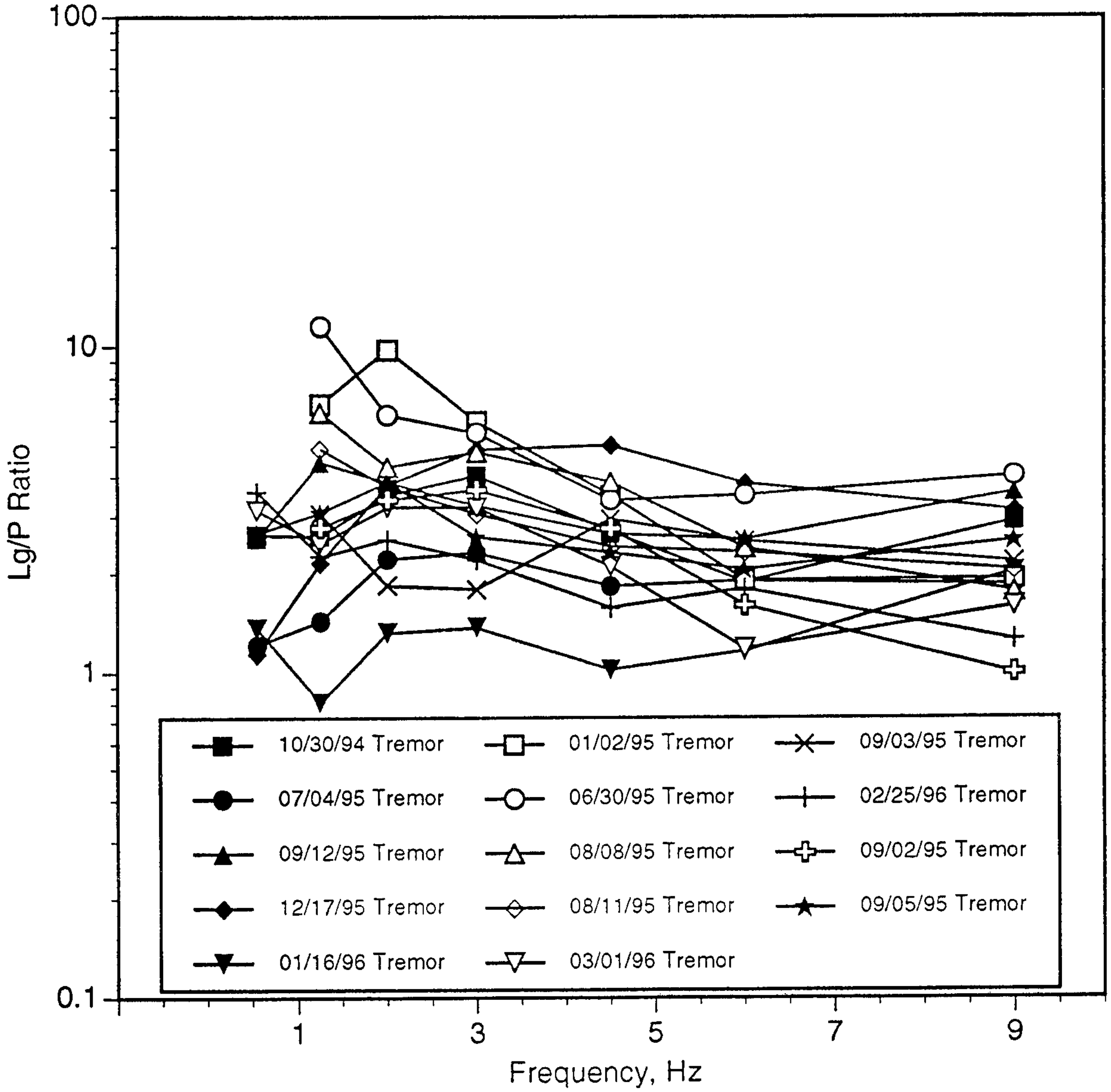

Figure 7. Lg/P ratios as a function of frequency determined at station BOSA from bandpass filter analyses for 14 South African mine tremors.

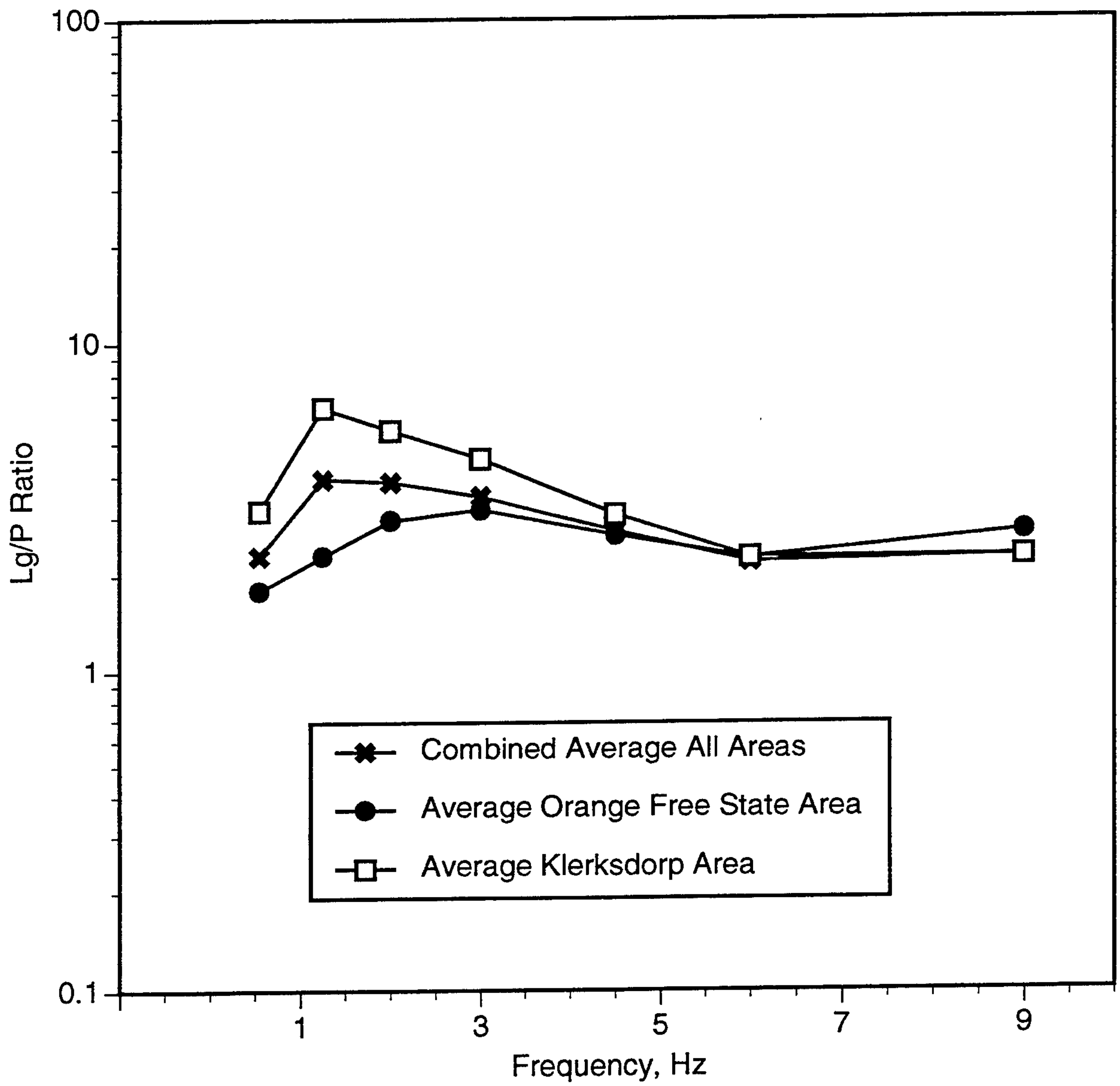

Figure 8. Comparison of average Lg/P ratios as a function of frequency measured at station BOSA for the total event sample, five events in Orange Free State mine area, and five events in Klerksdorp mine area.

Hz where the ratio is near four and shows a slow decline to values near two for higher frequencies. The average L_g/P ratio for the Orange Free State tremors has a maximum value of three near 3.0 Hz, while the average ratio for the Klerksdorp tremors has a maximum value between six and seven at 1.25 Hz. The biggest differences in L_g/P ratios between the two different source areas appear to be at lower frequencies while the average ratios nearly coincide at higher frequencies.

We do not have nuclear explosion tests in South Africa to permit a direct empirical comparison of regional signal measurements between South African mine tremors and nuclear explosions. However, we do have observations at regional distances from NTS nuclear explosions in the western U.S. and Shagan River nuclear explosions in Eurasia. The NTS nuclear explosion records we used in this study were from the four Lawrence Livermore National Laboratory (LLNL) stations at ranges between 230 km and 410 km, similar to the distance range of the South African mine tremor observations. The nearest regional station with a significant sample of regional recordings from Shagan River nuclear tests is the Chinese Digital Seismic Station Network (CDSSN) station WMQ at a range of about 950 km, a considerably greater distance than that of the mine tremors at BOSA. We have performed similar bandpass filter analyses on samples of the regional recordings from nuclear explosion tests at NTS recorded by the LLNL stations and at Shagan River recorded by WMQ. Figure 9 shows the results of the bandpass filter analysis applied to the vertical-component record obtained at LLNL station KNB (R = 295 km) from the NTS underground nuclear explosion GORBEA. The initial arrival is a relatively weak P_n phase followed by the more prominent P_g signals. The regional P signals appear relatively complex, particularly in higher frequency passbands. The L_g is the most prominent signal for passbands from about 0.5 Hz to 3.0 Hz but tends to fall off and become indistinct at high frequencies. The lowest frequency passband (0.01 - 0.1 Hz) again shows a clear fundamental-mode Rayleigh wave.

We applied the same bandpass filter analysis to a sample of ten NTS nuclear explosion tests recorded by the four LLNL array stations. We computed the L_g/P ratios as a function of frequency for the NTS nuclear tests using the bandpass filter analysis results in the same manner as described above. We next averaged the ratios over all the explosions and all stations. The average L_g/P ratios are plotted in Figure 10. The average L_g/P ratios for the NTS

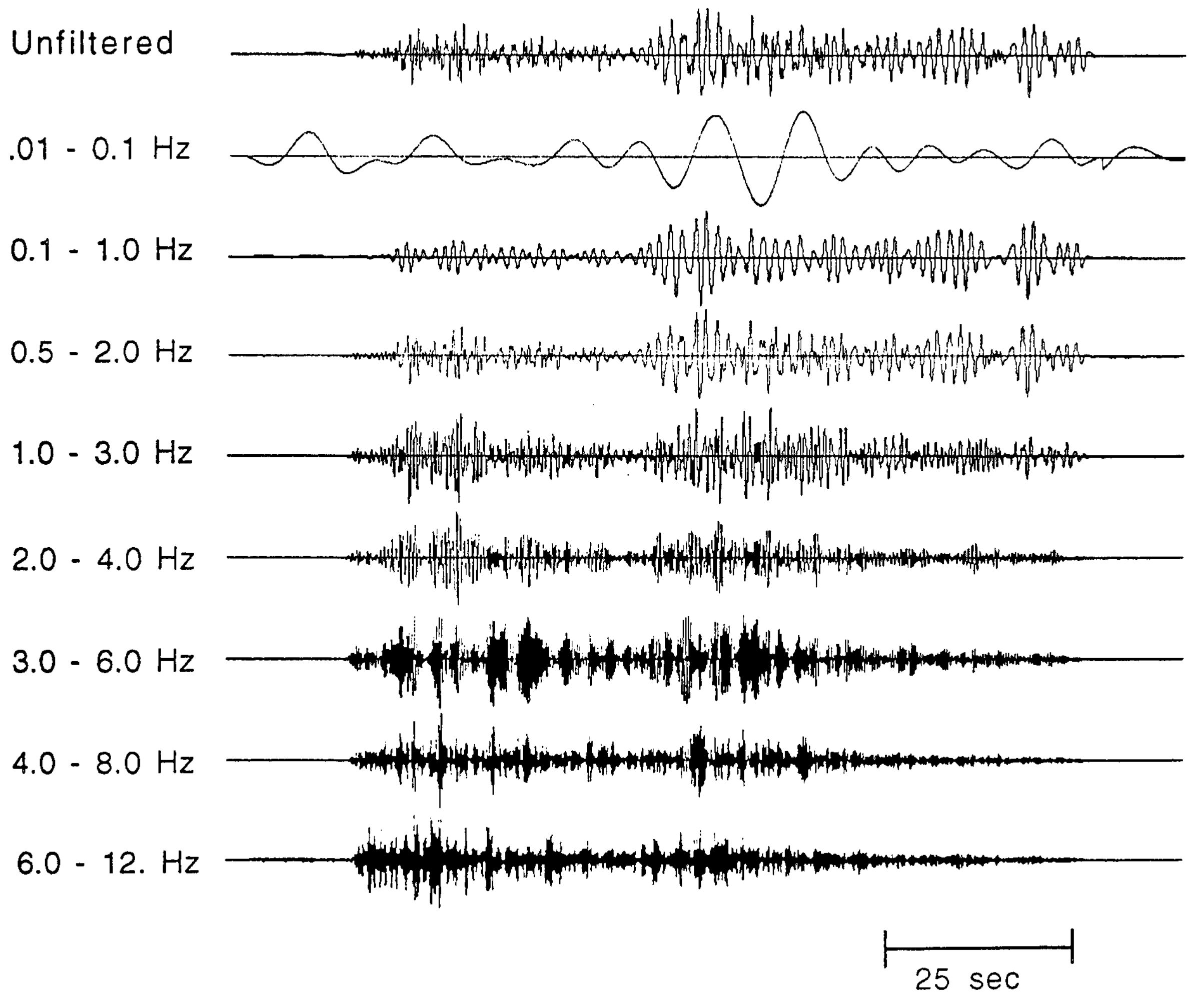

Figure 9. Example of bandpass filter analysis applied to KNB record for the NTS nuclear explosion GORBEA.

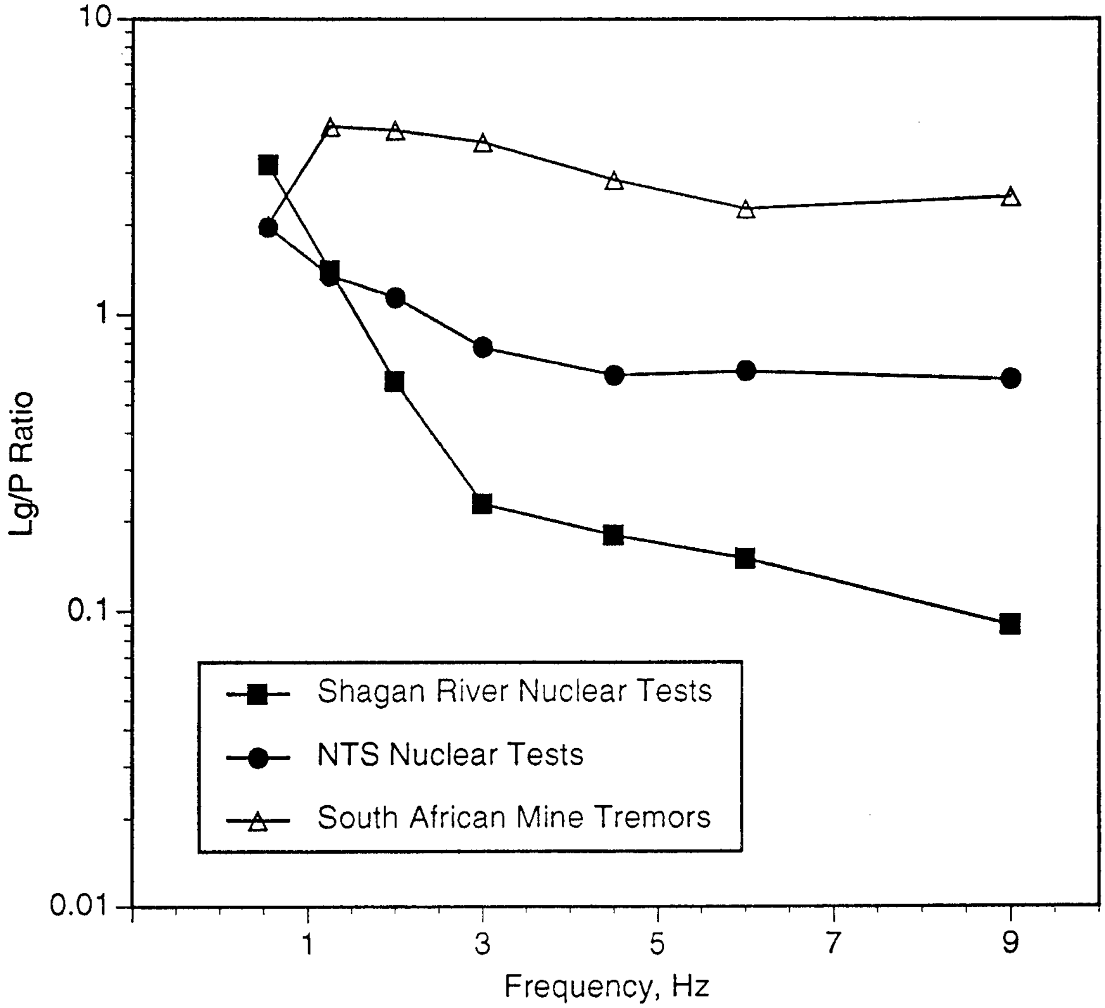

Figure 10. Comparison of average Lg/P ratios as a function of frequency for 10 South African mine tremors and 10 NTS and 10 Shagan River nuclear explosion tests.

nuclear explosions have values somewhat greater than one at frequencies from 0.5 Hz to 2 Hz but fall off to below one at frequencies above 3 Hz. At the lowest frequencies there is no difference in the average L_g/P ratios between the South African tremors and the NTS nuclear tests, but above 1 Hz there is clear separation between the average values. The L_g/P ratios for the NTS nuclear explosions are fairly consistent between events, and as a result the scatter and corresponding sigma values are fairly low over most of the frequency band. The scatter about the mean L_g/P ratios is considerably larger for the South African mine tremors at all frequencies (cf. Figure 7 above), and this is reflected in larger sigma values. Nevertheless, at frequencies of 2 Hz and above the two populations are completely separate at the one-sigma level. Comparing Figures 7 and 10 we see that the L_g/P ratios for all the South African mine tremors lie above the mean NTS explosion L_g/P ratios for frequencies of 2 Hz and above. As a second comparison, we also show in Figure 10 the average L_g/P ratios determined from the same bandpass filter analysis applied to 10 nuclear explosions at the former Soviet test site at Shagan River observed at station WMQ. The average L_g/P ratios from the Shagan River explosions fall well below the mine tremors except at the lowest frequency. The L_g/P ratios for the explosions in this case drop off much more rapidly with increasing frequency, probably due to propagation differences for the L_g and P signals at the larger range of the Shagan River observations. Research is continuing on how to take into account such propagation differences in assessing observed differences in regional signal spectra to provide an adjustment to the regional discriminant measures.

3. Polish Rockbursts

3.1 Background on Polish Events

The rockbursts in Poland occur in coal and copper mines concentrated in two broad zones, one in Lower Silesia centered near 51.1 N 15.8 E and the other in Upper Silesia centered near 51.0 N 19.0 E (cf. Gibowicz and Kijko, 1994; Bennett et al., 1993). The Lower Silesia area includes rockbursts from the copper mines near Lubin and coal mines throughout the area, and the Upper Silesia area includes induced seismic activity associated with the subsurface coal mines near Bytom as well as with a surface coal mine near Belchatow. The Lower Silesia mining has gone on for many decades, while the Upper Silesia mining began development about 20 years ago. In both of these areas, frequent induced seismicity associated with the mining has been experienced; thousands of events are recorded each year by local networks with about a dozen events exceeding magnitude 3 M_L (Gibowicz and Kijko, 1994). Rockbursts with magnitudes greater than 4 M_L have been reported historically from each of the Polish mining areas with magnitudes occasionally reaching as high as 4.6 M_L at Belchatow and 4.5 M_L at Lubin (cf. Gibowicz, 1984; Bennett et al., 1993). The depths of the rockbursts in the Polish coal mines is closely correlated with the depth of excavation (viz. 0.5 km to 1 km); while in the subsurface copper mine rockbursts occur somewhat above the excavation (Gibowicz and Kijko, 1994).

Gibowicz (1984) reported mechanisms for several of the larger rockbursts from the Polish mining regions including normal dip-slip for events near Lubin, normal dip-slip as well as oblique reverse motions in Bytom events, and reverse dip-slip motion for the Belchatow area. The dip-slip motions would be consistent with concentration of stresses on fractures or planes of weakness near the edges of the excavations. The reverse motions associated with rockbursts at the open-pit mine near Belchatow could result from a combination of unloading, due to removal of overburden, and changes in pore-pressure due to groundwater withdrawal in the vicinity of the excavation. It is believed that this mechanism may act as a trigger to release ambient tectonic stresses left over from prior orogenic episodes (cf. Gibowicz and Kijko, 1994). Although most of the rockburst events in Poland seem to have mechanisms which are adequately represented by double-couple sources similar to earthquakes, Wiejacz (1991) reported that rockbursts in the Lubin region occasionally had isotropic components representing up to 25 percent of the mechanism. Such mechanisms could be a source of some differences in discriminant measures between rockbursts and earthquakes.

In the prior stage of this research program (cf. Bennett et al., 1994), we assembled a database including 48 rockbursts in central Europe, including 45 events thought to be rockbursts because of their locations in the Lower Silesia and Upper Silesia mining zones in Poland. The Polish events in the database had magnitudes from 2.81 m_b to 4.7 m_b and occurred during the time period from 1980 to 1991. In our regional discrimination analysis of those events, we focused on the regional signals recorded at the high-quality GDSN station at Grafenburg, Germany (GRFO), which was located at distances between about 310 km and 610 km from the Polish rockbursts. Figure 11 shows a comparison of the time-domain maximum amplitude measurements for the L_g and regional P phases for 26 Polish rockbursts from three different mining areas. On average the maximum L_g amplitudes for the combined sample are about a factor of two to three larger than the maximum P amplitudes. There also seems to be some tendency for the more distant Belchatow (Upper Silesia) events to have larger L_g/P ratios. Again the L_g/P ratios obtained from these time-domain measurements for the Polish rockbursts appear to be considerably larger than those found by Blandford (1981) for nuclear explosion tests. In our recent studies we have conducted additional investigations of the regional signals from Polish rockbursts.

3.2 Supplemental Data for Polish Rockbursts

In our further analyses of the regional signals from the Polish rockbursts, we have relied primarily on the signals recorded by the GERESS array, which is designated as an IDC alpha array station. Over the last couple of years, we have attempted to collect a representative sample of the digital waveforms recorded at GERESS from the Polish rockbursts in Lower Silesia and Upper Silesia. We again relied on IDC and NEIS event catalogs to select events and made no attempt to recover a complete sample. There are without doubt smaller rockbursts from these mining areas which are not included in the event catalogs.

We show in Table 2 a list of 41 events from the Polish rockburst zones. The list includes 21 events from Lower Silesia and 20 events from Upper Silesia. The magnitudes for the rockbursts are between 2.60 M_L and 4.05 M_L.

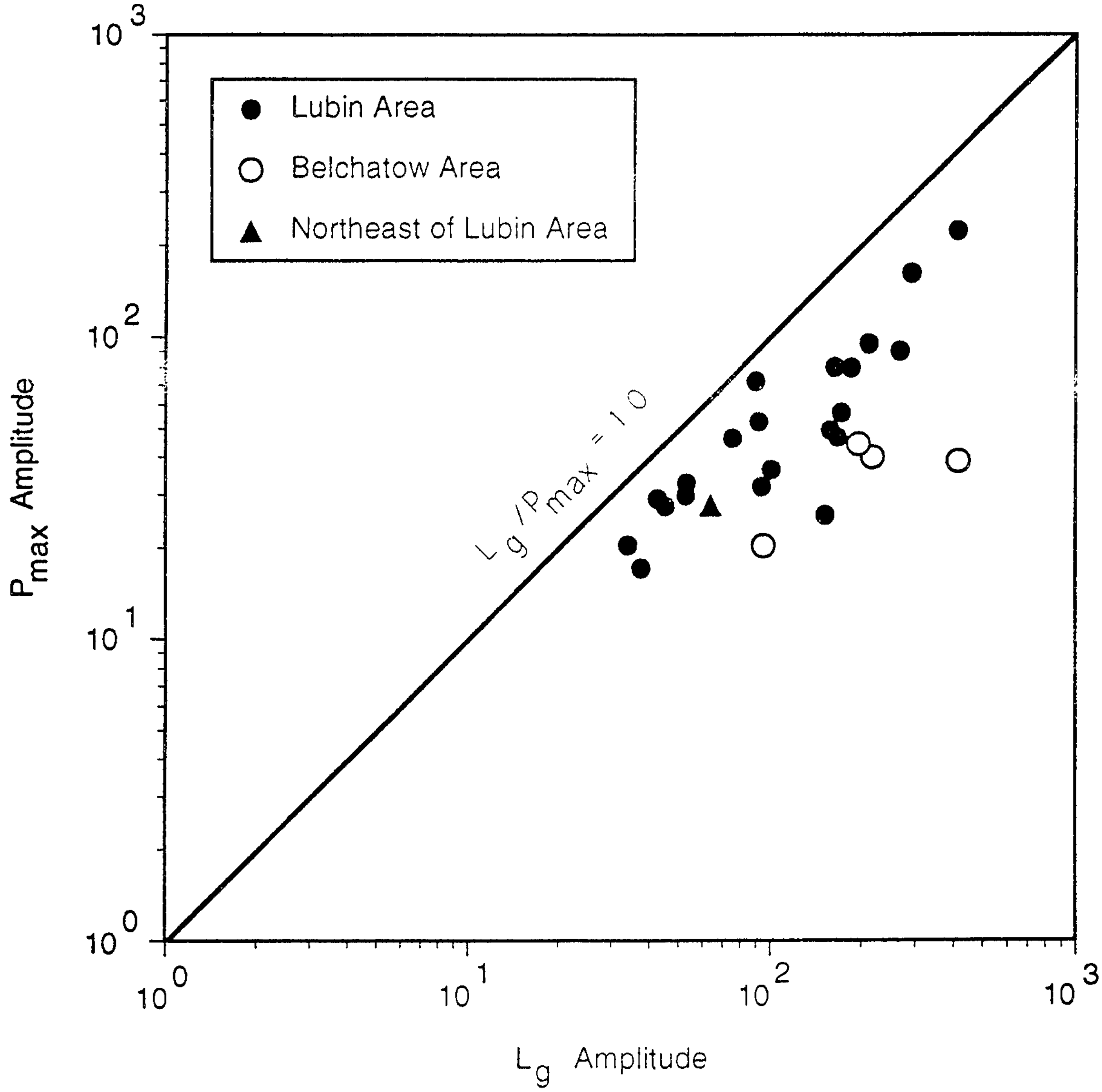

Figure 11. Comparison of the maximum P versus Lg amplitudes measured from time-domain records at German array station GRFO for 26 mining-induced rockbursts in three different source areas.

Table 2. Polish Rockbursts in Supplemental Database.

Date	Origin Time	Lat (N)	Lon (E)	Mag	R (km) GEC2
10/18/94	10:12:29	51.43	15.75	3.80	322
10/19/94	11:19:26	51.33	15.72	3.70	312
11/13/94	20:13:53	51.59	16.07	3.80	349
11/20/94	09:35:06	51.51	16.26	2.85	349
11/22/94	05:19:46	51.53	16.09	3.60	345
11/22/94	12:29:10	51.55	16.08	3.80	346
12/05/94	22:44:23	51.54	16.18	3.50	349
12/10/94	13:34:12	51.67	16.29	3.90	365
12/11/94	19:01:03	51.26	15.84	-	309
12/12/94	12:10:20	51.36	15.82	-	318
12/27/94	05:10:54	51.32	15.59	3.60	307
12/31/94	08:16:09	51.14	15.65	3.60	291
01/05/95	19:17:51	51.39	15.65	3.80	316
01/15/95	13:53:36	51.63	16.25	3.40	359
01/17/95	09:40:15	51.27	15.66	3.40	305
01/17/95	18:22:44	51.20	15.78	2.60	301
01/21/95	13:00:52	51.56	16.29	3.70	355
01/26/95	05:35:48	51.62	16.22	3.80	357
02/12/95	01:03:32	51.62	16.35	-	363
02/26/95	11:39:42	51.63	16.13	-	355
03/08/95	11:11:48	51.56	16.18	2.89	350
07/01/95	05:42:06	50.54	18.89	3.60	419
07/09/95	07:51:44	50.44	18.72	4.03	404
07/21/95	21:11:45	49.84	18.44	2.80	3.61
08/09/95	17:26:29	50.25	18.94	3.32	410
08/12/95	05:52:00	50.31	19.00	3.64	417
08/14/95	22:53:14	50.45	18.96	3.97	420
08/24/95	11:23:57	50.47	18.86	3.80	415
08/30/95	21:42:50	50.40	18.88	-	415
09/07/95	22:03:07	50.36	19.20	3.72	431
09/11/95	11:57:39	50.36	18.93	4.05	414
01/08/96	10:09:49	50.42	18.97	-	419
01/10/96	06:38:03	50.23	19.29	3.31	433
01/12/96	14:45:26	50.28	19.11	3.42	423
01/16/96	07:27:53	50.07	19.33	3.35	430
01/24/96	05:34:28	50.47	18.75	3.10	407
02/08/96	14:29:07	50.34	18.98	3.21	417
02/09/96	06:37:04	50.63	18.48	3.64	398
02/25/96	02:31:25	50.17	18.21	3.19	358
02/25/96	14:00:09	50.46	18.86	3.65	414
03/09/96	22:12:24	50.74	19.17	3.45	447

The rockburst events in Table 2 come from several different mines in Lower Silesia and Upper Silesia; and the waveforms, therefore, cover a range of distances between about 290 km and 365 km from GERESS, and those in Upper Silesia are at distances between about 360 km and 450 km. We tried in all cases to use in our analyses the waveform records obtained at the GERESS array element GEC2, which seems to be an array element with better signal-to-noise characteristics than some of the other GERESS elements.

Figure 12 shows the locations of the events in the database, as reported by the IDC, relative to the GERESS array station. The map shows the two event clusters: one in Lower Silesia to the west and the other in Upper Silesia to the east. The Lower Silesia cluster appears tighter but seems to include one event group north of Lubin, probably related to the copper mine, and another group southwest of Lubin, probably associated with the coal mines. The Upper Silesia cluster appears to be more diffuse. Most of the rockburst activity in the Upper Silesia area appears to be coming from the coal mines near Bytom. None of the events are from the vicinity of the surface mine near Belchatow, which lies about 100 km farther north. Two of the mapped events (one on July 21, 1995 and one on February 2, 1996) appear to be located close to the border with the Czech Republic. These events were rather small (magnitude of 2.80 M_L and 3.19 M_L respectively), so it is possible that the locations might be inaccurate. However, after reviewing the waveforms at GERESS for these two events, the relative timing of the regional phases seems to indicate that they were actually somewhat closer to the recording station than other events in the zone. The events are most likely rockbursts at mines somewhat south and west of Bytom.

3.3 Analyses of Regional Signals from the Rockbursts

We applied the same bandpass filter analysis, as described in Section 2.3 above, to the vertical-component records at station GEC2 for the Polish rockbursts from the two source zones. We again measured the maximum L_g and regional P peak-to-peak amplitudes from the filter outputs and calculated L_g/P ratios as a function of the center frequency of the filter passband. Figure 13 shows the L_g/P ratios as a function of frequency for 20 rockbursts, including ten from the Lower Silesia zone (left-hand column) and ten from the Upper Silesia zone (right-hand column). Overall the L_g/P ratios for the Polish rockbursts exhibit very similar behavior to that seen in Figure 7 above for the

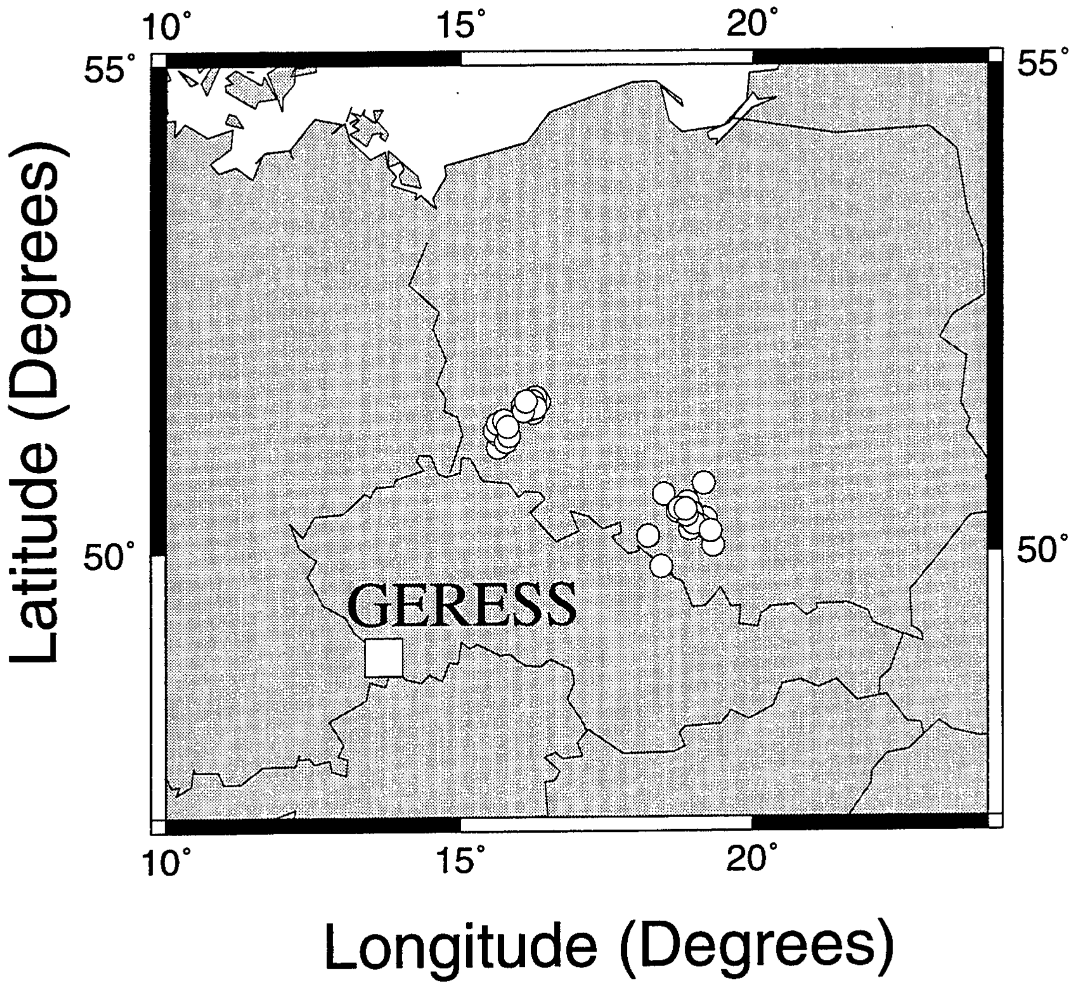

Figure 12. Map showing the locations of 41 Polish events from rockburst zones in Lower Silesia (west) and Upper Silesia (east) relative to station Geress.

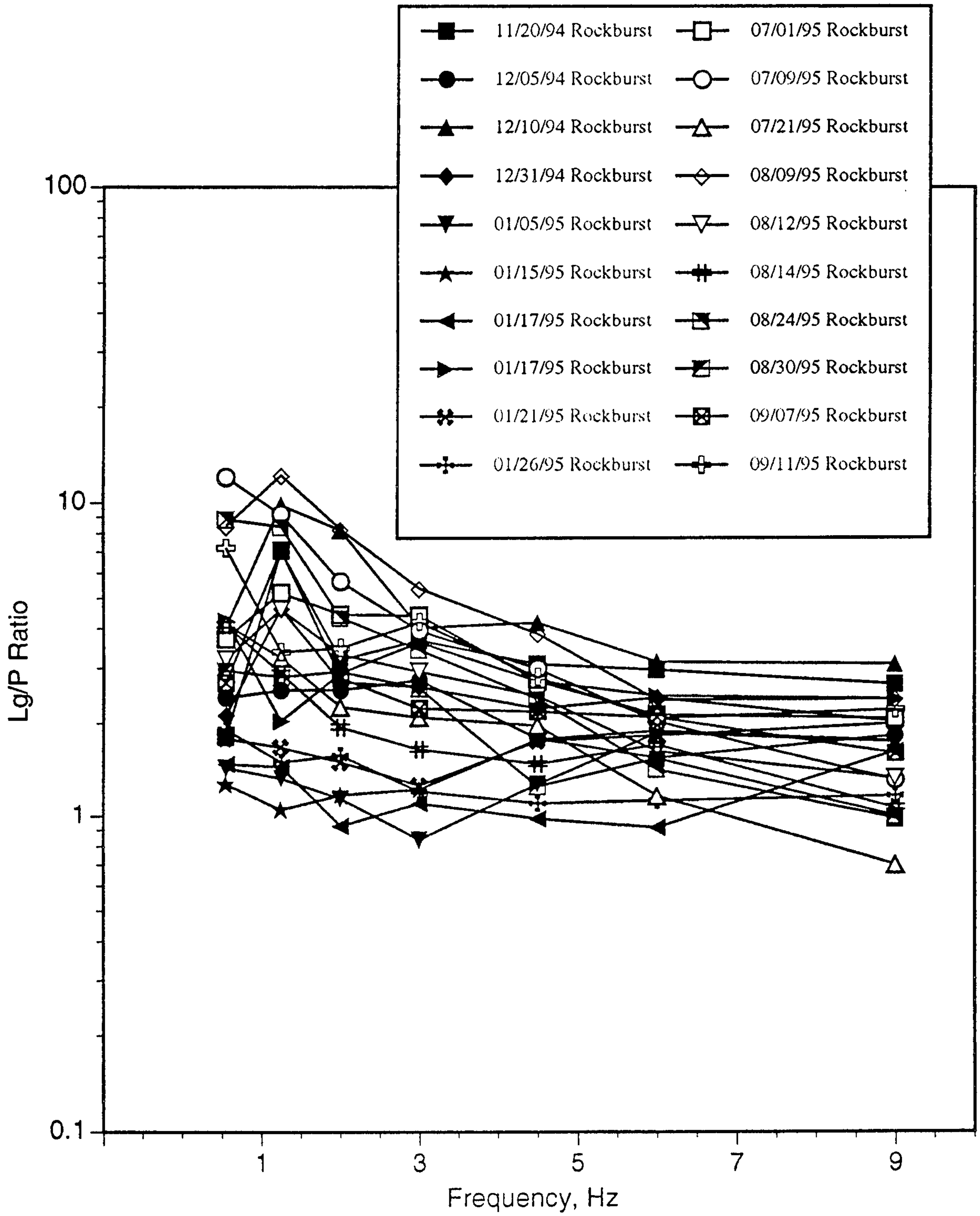

Figure 13. Lg/P ratios as a function of frequency determined at array station GERESS from bandpass filter analyses for 20 Polish rockbursts.

South African mine tremors. The ratios again show considerable scatter between events but generally lie between values of one and ten over the range of frequencies. The scatter here also appears to be somewhat reduced at higher frequencies, and there is an overall trend suggesting a slow decrease in the L_g/P ratios with increasing frequency. It is hard to discern in Figure 13, but there does seem to be a tendency for the L_g/P ratios to show a more rapid decline with frequency for the events from the Upper Silesia source zone than for those from the Lower Silesia zone. This is more apparent in Figure 14 where we compare average L_g/P ratios as a function of frequency for the two regions separately with the combined average ratios for both areas. The average L_g/P ratios for the combined areas is largest at a frequency of 1.25 Hz where the ratio is between four and five. This combined ratio shows a slow decline to a minimum value of about 1.8 at high frequencies. In comparison, the average L_g/P ratio for the Upper Silesia rockbursts has a maximum value near six at 1.25 Hz and decreases to a value near 1.4 at high frequencies; while the average L_g/P ratio for the Lower Silesia rockbursts has a maximum value just above three at 1.25 Hz and has minimum values near two at high frequencies. It seem likely that the differences in the dependence of the average L_g/P ratios on frequency, as seen in Figure 14, is related to propagation differences, but further study would be useful to resolve this issue. It is particularly interesting that we see a very similar dependence here, between the nearer and farther sources, to that which we saw above in Figure 8 for the South African mine tremors. This observation would seem to support the idea that a frequency-dependent adjustment should be made to L_g/P ratios at different distances to account for propagation effects.

As was the case for South Africa, we do not have nuclear explosion tests in central Europe to provide a direct empirical comparison of regional signal measurements for the Polish rockbursts. We have again fallen back on the observations from the NTS nuclear explosions at LLNL stations, which are at similar ranges (viz. between 230 km and 410 km) to the Polish rockbursts recorded at GERESS. Figure 15 shows the comparison between the average L_g/P ratios as a function of frequency for the Polish rockbursts and the average ratios for the NTS nuclear tests. The nuclear test average is the same as described above in Section 2.3 and was determined by applying the same bandpass filter analysis to obtain the L_g/P ratios and then averaging over the ten event NTS explosion sample and all four stations. Comparing the average

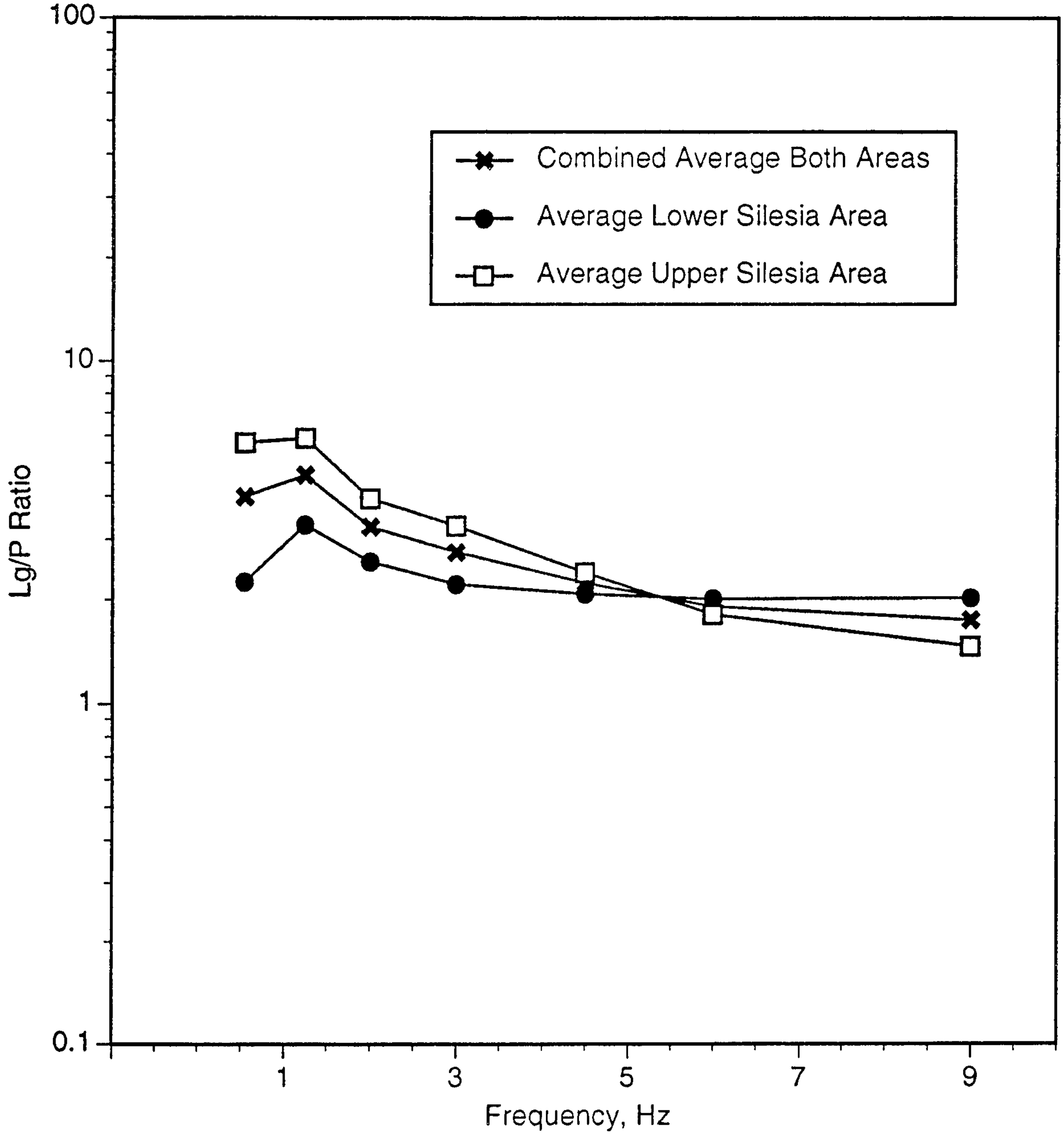

Figure 14. Comparison of average Lg/P ratios as a function of frequency measured at station GERESS for the combined event sample, 10 events in Lower Silesia area, and 10 events in Upper Silesia area.

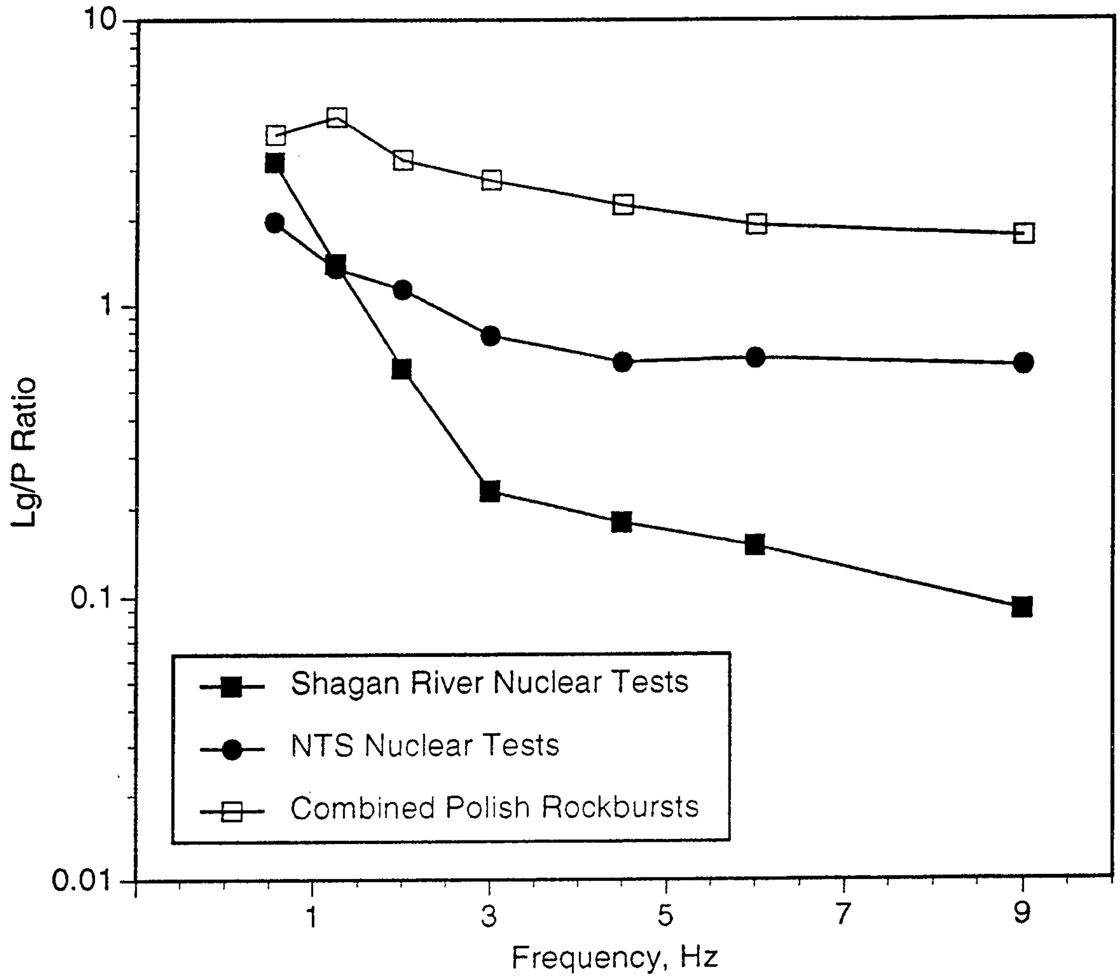

Figure 15. Comparison of average Lg/P ratios as a function of frequency for 20 Polish rockbursts and 10 NTS and 10 Shagan River nuclear explosion tests.

L_g/P ratios for the Polish rockbursts and NTS nuclear tests, the ratios are much smaller for the nuclear tests. The difference in this case appears to be fairly constant over the frequency band and averages about a factor of three to four. Although the observations overlap at the one-sigma level at lower frequencies, the sigma values are smaller above about 2 Hz; and there seems to be significant separation between the different source types. As a second comparison we show also in Figure 15 the average L_g/P ratios for ten Shagan River nuclear tests recorded at CDSN station WMQ. In this case the average ratio drops off much more rapidly and falls much further below the average L_g/P ratios for the Polish rockbursts at high frequencies. At these high frequencies the average L_g/P ratios for the Polish rockbursts are about a factor of ten to twenty larger than the average ratios computed for the Shagan River explosions at WMQ. To some extent the bigger difference here is likely to be a propagation effect caused by the larger source-to-station distances for the nuclear tests at WMQ; this effect requires further study.

4. Mine Bumps in Eastern Kentucky and Western Virginia

4.1 Background on Eastern U.S. Events

Rockbursts occur in mining regions throughout much of North America. In the underground coal mining areas of the eastern U.S., such rockbursts are referred to as mine bumps. Records of such bumps kept by the former U.S. Bureau of Mines (cf. Iannacchione and Zelanko, 1995) date back to the early part of this century, and they indicate that the heaviest concentrations of such induced seismic activity have been in the states of West Virginia, Virginia, and Kentucky. Although mine bumps are not as frequent in the eastern U.S. as are the rockbursts in Poland or the mine tremors in South Africa, they do seem to present recurring problems at specific mines. Magnitudes as high as 4.5 M_L have been reported for this region, and magnitudes greater than 3 M_L have been reported for many mines. Because of a lack of local seismic monitoring networks, many smaller bumps throughout the coal-mining region of the Southern Appalachian Basin probably go undetected. Historically most eastern U.S. mine bumps have occurred in areas where the overburden was thick (400 meters to more than 600 meters). In addition to thick overburden or mine depth, Iannacchione and Zelanko (1995) correlate eastern U.S. mine bumps with a variety of factors associated with high ambient stress conditions. These factors include proximity of geologic structures, including faults or rigid, overlying or underlying strata, and certain mining practices which may act to concentrate stresses. Lack of adequate seismic monitoring in the vicinity of eastern U.S. coal mines has prevented observations which could establish actual source mechanisms for specific mine bumps or even for series of mine bumps from specific mines. In a previous report (cf. Bennett et al., 1993) we reviewed the models which have been inferred for rockbursts in general and the associated seismic mechanisms. Maleki (1995) describes case studies for a coal mine in eastern Kentucky where the mine bumps included both pillar failure in areas of room-and-pillar mining and more extensive ceiling collapse in areas of longwall mining. Complex interaction of the induced stress fields associated with mining in different areas of the mine are thought to be responsible for high stress concentrations which have generated the larger mine bumps in this area. Improved seismic monitoring and source mechanism studies at some of the coal mines in the eastern U.S. with recurring bump activity would be extremely useful in improving understanding of these mine bump sources.

4.2 The Mine Bump Database for Eastern Kentucky and Western Virginia

Our attention to rockbursts in the eastern U.S. was initially spurred by a mine bump in March 1995 in eastern Kentucky. As we described in our preceding report (cf. Bennett et al., 1995), this event had a magnitude of 3.6 m_b and occurred as one in a series of bumps which have caused problems at the Lynch mine near Cumberland, Kentucky over several years. That event was well recorded at regional stations throughout the southeastern U.S. at ranges from 230 km to 640 km. In our earlier study we performed a bandpass filter analysis on the vertical-component record at station BLA (R = 237 km) and found that L_g/P ratios were generally high with values between five and one over the frequency range of the filters.

Over the past several months, we have been able to acquire high-quality digital data for additional eastern U.S. mine bumps recorded at station BLA, which is an IDC auxiliary station. Some of these data were obtained directly from IDC, but the majority were kindly provided by Martin Chapman of Virginia Tech University and Carol Finn of AFTAC. The database includes not only mine bumps but also additional source types including earthquakes and surface mine blasts from the surrounding region. Table 3 shows a list of 20 events which have been identified as mine bumps in the eastern Kentucky/western Virginia region over the last two years. Nineteen of these events occurred at a single mine, the Lynch mine in eastern Kentucky referred to above. One event (June 29, 1996) occurred at the Buchanan No. 1 mine near Oakwood, Virginia, which has been the source of prior large mine bumps in 1988 and 1989. The magnitudes for the mine bumps shown in the table cover a range from about 2.29 M_L to 4.22 M_L. For the more recent events, we used the magnitudes and locations reported by the IDC; but for some of the events not reported by IDC we used the known location of the Lynch mine, and we inferred the M_L magnitudes by comparing relative maximum amplitudes recorded at BLA for the events with a similar amplitude measure for the October 26, 1995 mine bump which had a magnitude of 4.06 M_L reported by IDC. The epicentral distance to BLA for the Lynch mine events is roughly the same (about 237 km) for all events, and the Buchanan mine bump is only about 140 km from BLA.

Table 3. Kentucky/Virginia Mine Bumps in Database.

Date	Origin Time	Lat (N)	Lon (W)	Mag	R (km) BLA
07/27/94	05:13:55	36.90	83.05	3.01	237
07/27/94	06:31:36	36.90	83.05	2.29	237
07/27/94	06:33:09	36.90	83.05	3.26	237
08/01/94	02:13:36	36.90	83.05	3.38	237
08/02/94	03:14:27	36.90	83.05	3.06	237
08/03/94	08:53:14	36.90	83.05	3.86	237
08/03/94	09:56:55	36.90	83.05	3.20	237
02/04/95	22:05:08	36.90	83.05	3.39	237
02/04/95	22:37:18	36.90	83.05	3.34	237
03/11/95	08:15:54	36.85	82.85	4.22	220
03/11/95	09:50:06	36.99	83.18	3.45	247
07/22/95	05:52:35	36.90	83.05	2.91	237
07/22/95	05:53:12	36.90	83.05	3.24	237
10/26/95	00:37:31	36.93	83.04	4.06	235
04/19/96	08:50:16	36.96	82.98	3.90	229
05/04/96	09:18:46	36.86	82.90	4.07	224
05/11/96	05:41:54	37.04	82.99	3.78	229
05/13/96	20:19:00	36.88	83.00	4.03	232
05/13/96	20:50:55	36.90	83.05	3.46	237
06/29/96	19:30:44	37.17	82.00	4.19	140

Table 4. Kentucky/Tennessee/Virginia Earthquakes in Database.

Date	Origin Time	Lat (N)	Lon (W)	Mag	R (km) BLA
08/17/90	21:01:18	36.79	83.34	4.00	264
09/08/90	00:03:57	38.06	83.73	3.30	277
07/05/95	14:16:45	35.37	84.21	3.70	397
07/07/95	21:01:03	36.52	81.87	3.00	151
12/15/95	10:16:40	36.07	83.64	3.00	314

Figure 16 shows the locations of the mine bumps in the database relative to station BLA. The variations in locations about the Lynch mine are mainly indicative of location uncertainty. The mine workings extend away from the mine opening over a considerable area, but it is likely that most bumps are actually occurring within 2 km of the nominal mine location (Chapman, 1995). The Buchanan mine bump in western Virginia is located at very nearly the same azimuth as the Lynch mine bumps but about 100 km closer to station BLA.

The regional earthquakes in the database are shown in Table 4. These events surround the mine bump locations and include events in eastern Kentucky and eastern Tennessee. The epicentral distances from the earthquakes to station BLA are between about 150 km and 400 km. The earthquakes have magnitudes between 3.0 M_L and 4.0 M_L, in about the same range as the mine bumps. In addition to the earthquakes, we have BLA records for nine mine blasts. There is little available information about these blast sources except that they were apparently located in eastern Kentucky and were designated as mine blasts by analysts at Virginia Tech University (Finn, 1996a). Based on the relative timing of the L_g and regional P signals on the records at station BLA, we estimate that these blasts occurred at epicentral distances between about 200 km and 300 km from station BLA. The magnitudes of the blasts were inferred from the relative maximum amplitudes on the records at station BLA compared to amplitudes of the mine bumps with known magnitudes. From this we estimate that the blast magnitudes were in a range from about 3.05 M_L to 3.65 M_L.

4.3 Analyses of Regional Signals from the Mine Bumps

We performed the same bandpass-filter analysis, as described in Section 2.3 and Section 3.3 above, on the vertical-component records at station BLA for the mine bumps in this database for the eastern U.S. The L_g/P ratios as a function of frequency were determined from the filter outputs. Figure 17 shows the L_g/P ratios as a function of frequency for 12 mine bumps, including 11 from the Lynch and the one from the Buchanan mine. In general, the L_g/P ratios in Figure 17 show considerably less scatter than we saw for the Polish rockbursts and for the South African mine tremors. One reason for this reduced scatter could be the nearly constant propagation path for the eastern Kentucky mine bumps. However, we note that even the western Virginia mine bump (June 29, 1996) falls within the relatively small scatter seen here for the L_g/P ratios from

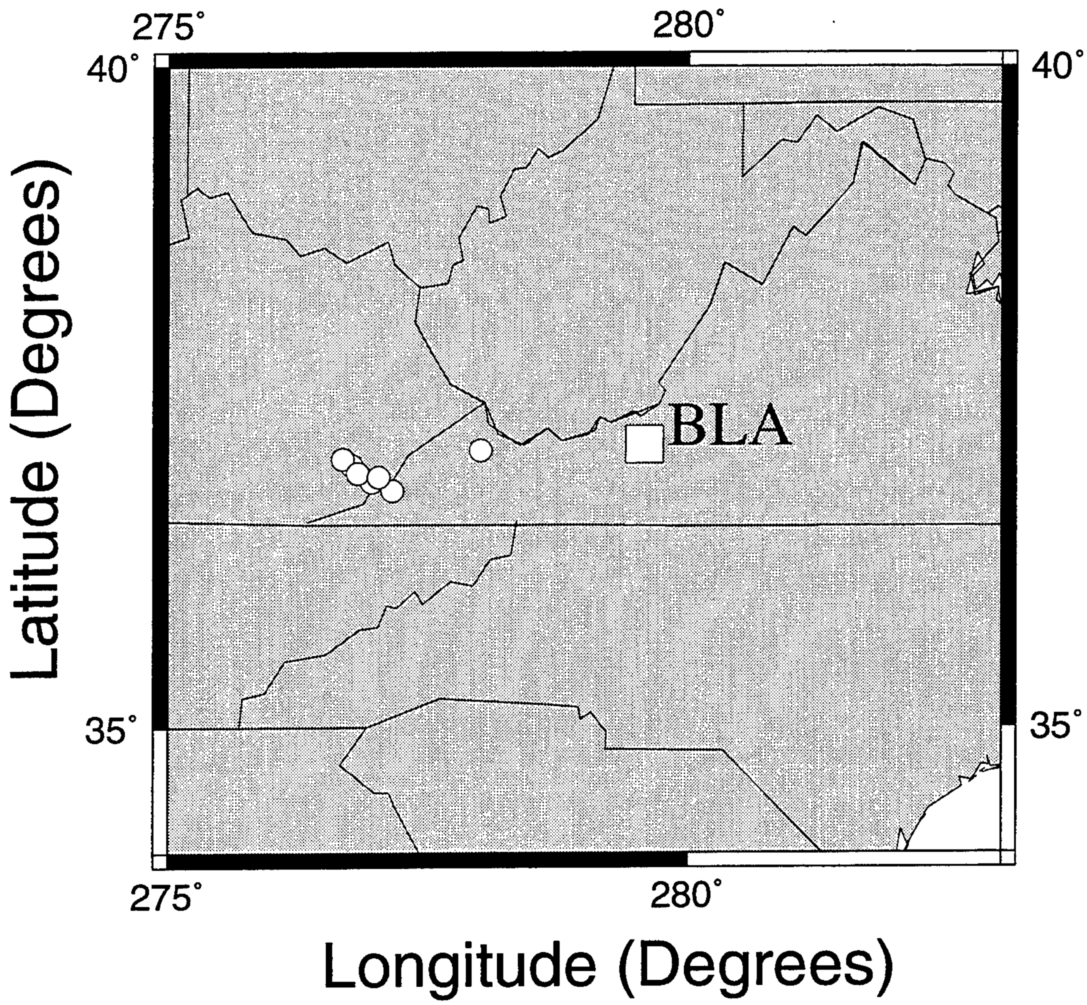

Figure 16. Map showing the locations of 20 eastern U.S. mine bumps from two coal mines in eastern Kentucky and western Virginia relative to station BLA.

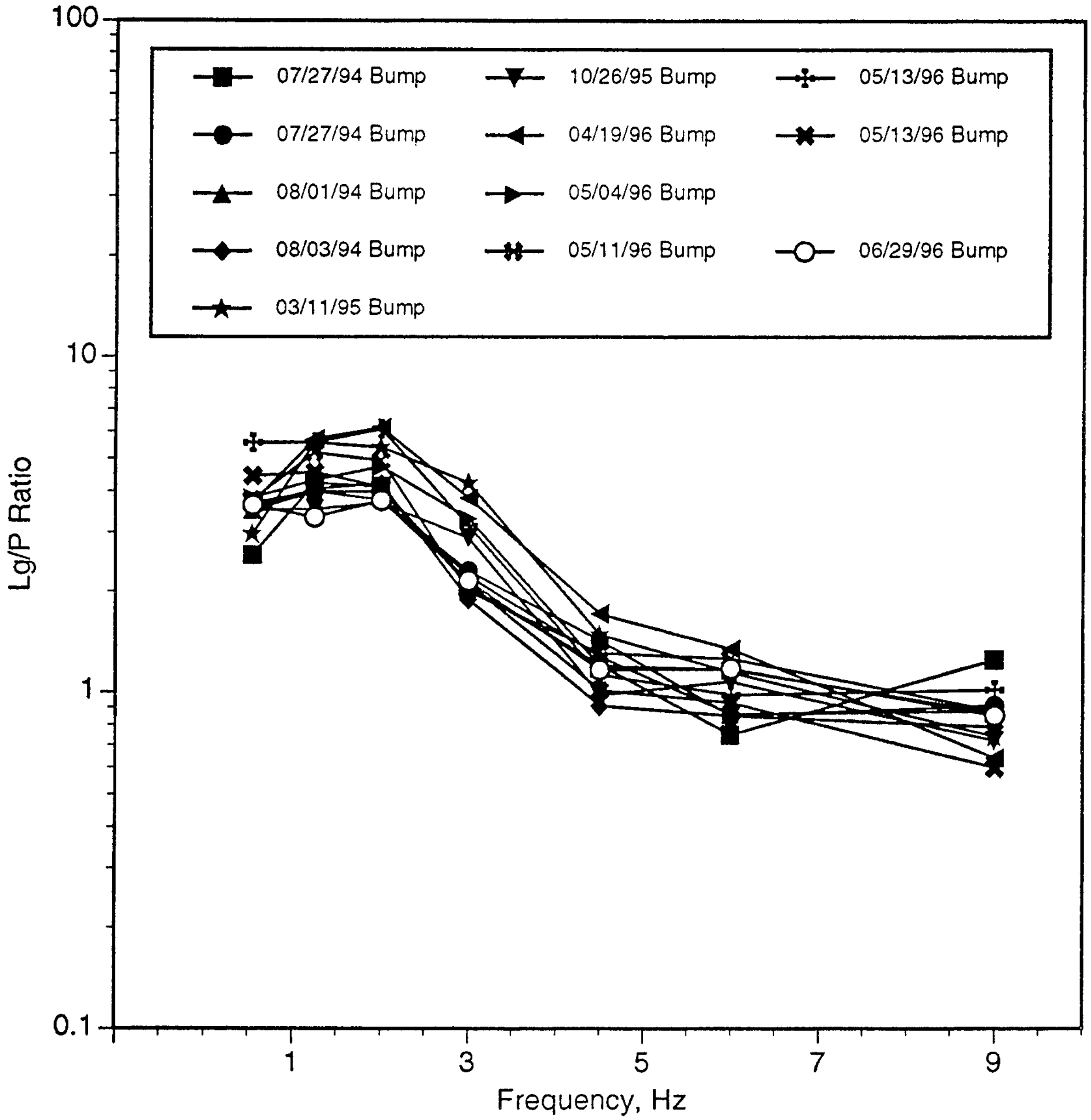

Figure 17. Lg/P ratios as a function of frequency determined at station BLA from bandpass filter analyses for 12 eastern Kentucky/western Virginia mine bumps.

the eastern Kentucky mine bumps. So, whatever the reason, the L_g/P ratios observed at BLA for the eastern Kentucky/western Virginia mine bumps show greater consistency between events. Further study would be useful to resolve whether this is a result of reduced effects from the propagation path or greater similarities between mine bump mechanisms from these mines. Somewhat unlike the rockbursts from the other areas, the L_g/P ratios for the mine bumps in eastern Kentucky/western Virginia appear to show a sharper decline with increasing frequency. This is apparent in Figure 17 where the ratios appear to have maximum values in the 1 Hz to 2 Hz range and then decline toward higher frequencies. In Figure 18 we compare the average L_g/P ratios for the eastern Kentucky mine bumps and for the western Virginia bump. The ratios are seen to be very similar, with the biggest differences at lower frequencies, near 1.25 Hz. The average L_g/P ratios have their maxima at 1.25 Hz and 2 Hz where they reach values of about four. This is followed by a rather abrupt decline over the bands from 2 Hz to 4.5 Hz before the average ratios level off at values around one at higher frequencies.

We have again used the L_g/P ratios from NTS nuclear tests recorded at the LLNL stations and from Shagan River nuclear tests recorded at station WMQ as comparisons for discrimination analyses. The epicentral distance range for the NTS nuclear tests at LLNL stations is again fairly similar to the distances for our eastern U.S. mine bump observations, even though the tectonic conditions and seismic propagation environment may be quite different. Figure 19 shows the comparison of the average L_g/P ratios as a function of frequency for the mine bumps and the NTS nuclear tests. The biggest differences between the different source types appear to occur at frequencies between about 1.25 Hz and 3 Hz. In this band the differences are about a factor of three to four. Because the eastern Kentucky/western Virginia mine bumps L_g/P ratios fall off so rapidly toward higher frequencies, the differences are much smaller there. Thus, differences at frequencies above 4.5 Hz are less than a factor of two. However, as we noted above, the scatter about the mean for the mine bump observations is much smaller than for the other source areas. Even though the average L_g/P ratios between the different source types are not so well separated in Figure 19, as a result of smaller sigma values, there is total separation in the ratios at the one-sigma level over the broad band of frequencies from 0.5 Hz to 4.5 Hz. The proximity between the L_g/P average ratios for the mine bumps and NTS explosions at the highest frequencies (viz. 6

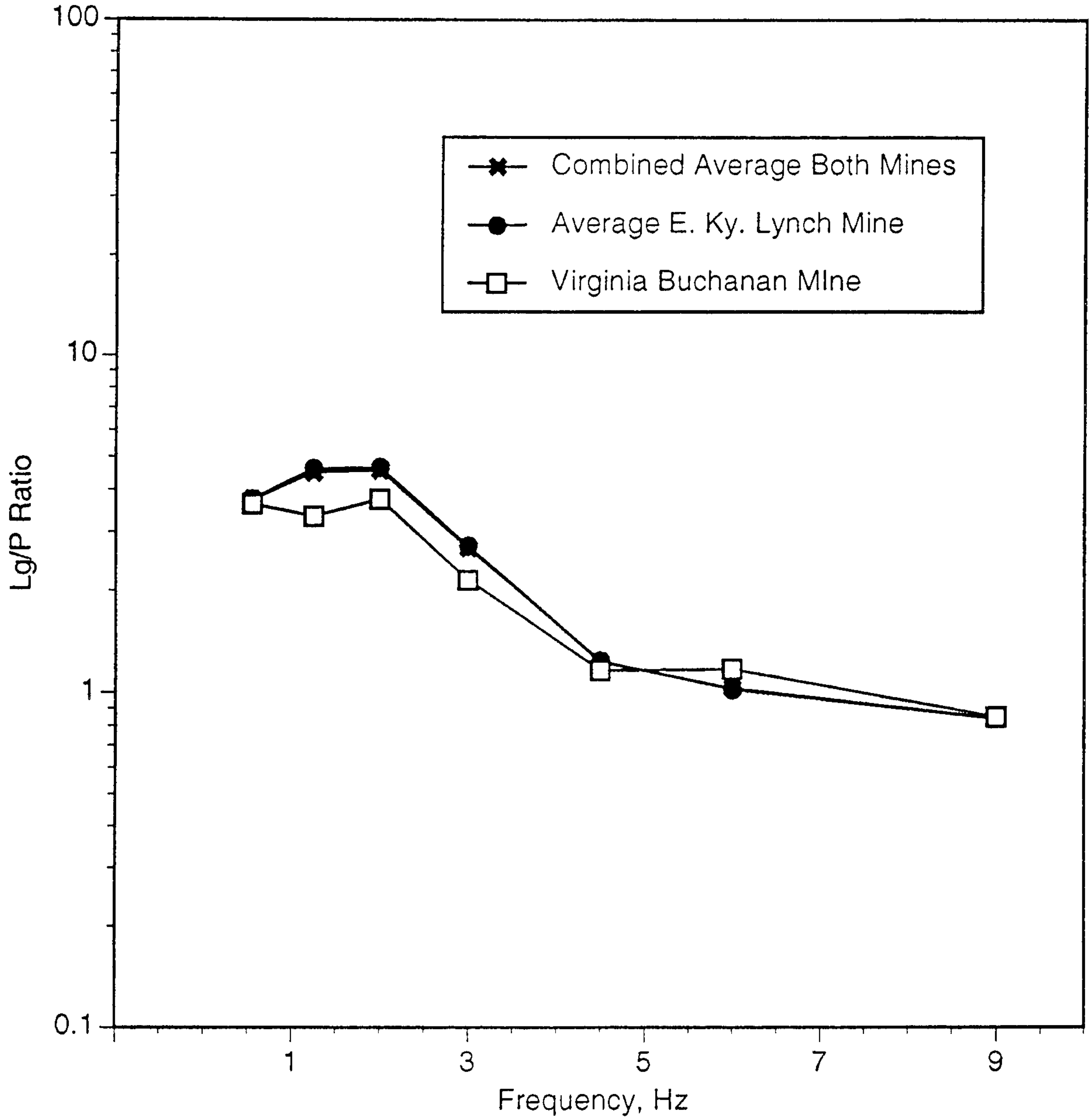

Figure 18. Comparison of average Lg/P ratios as a function of frequency measured at station BLA for the combined mine bump sample, 11 events at the Lynch mine in eastern Kentucky, and one event at the Buchanan mine in western Virginia.

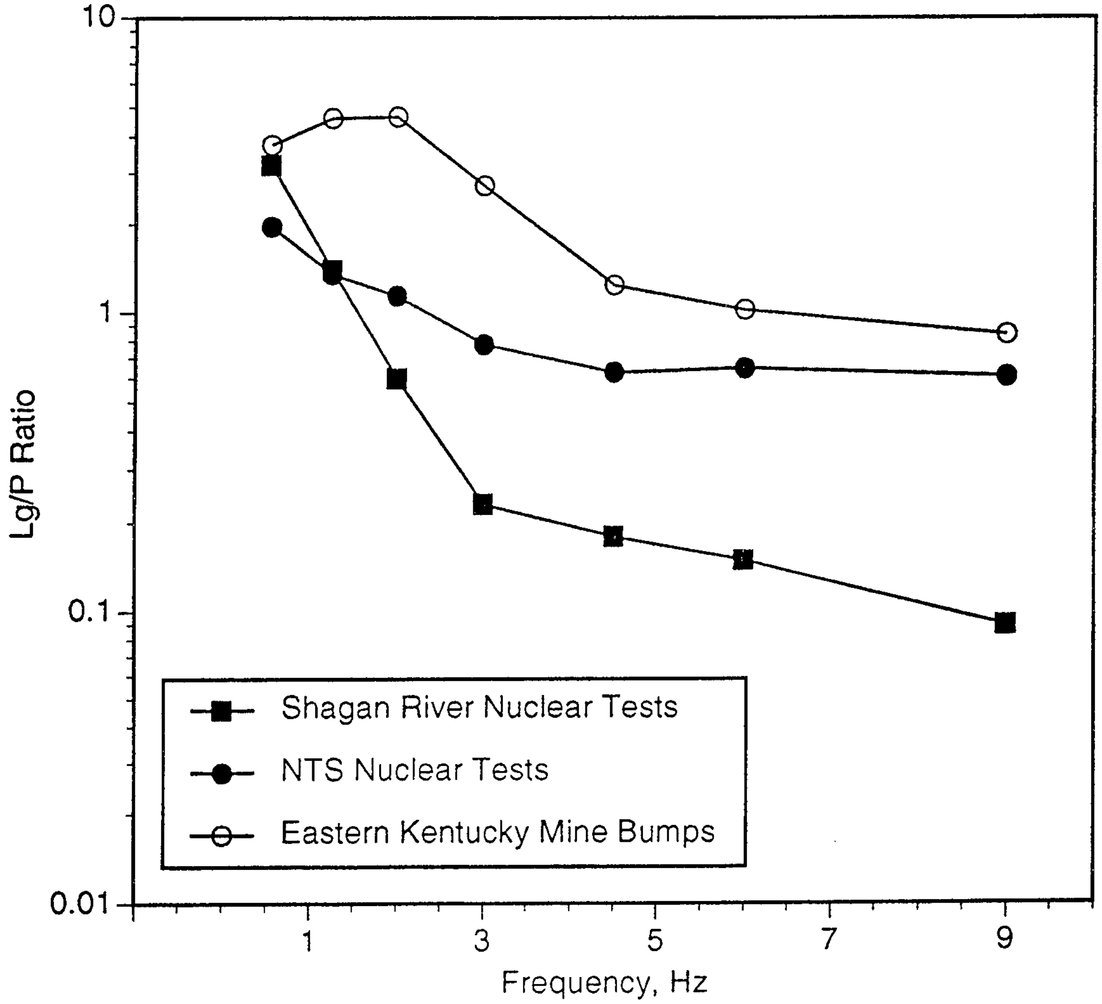

Figure 19. Comparison of average Lg/P ratios as a function of frequency for 12 eastern U.S. mine bumps and 10 NTS and 10 Shagan River nuclear explosion tests.

Hz and 9 Hz) causes the observations to overlap at the one-sigma level. In Figure 19 we also see that the differences in the average L_g/P ratios are still quite large between the mine bumps and the Shagan River nuclear tests; the differences are about a factor of ten at frequencies above 1.25 Hz. We note again that additional work is needed to assess how the larger observation distances at Shagan River and propagation path differences affect the L_g/P ratios there. For the eastern Kentucky/western Virginia region, we again see differences in the L_g/P ratios between mine bumps and underground nuclear test experience; but there is some indication that the frequency bands most useful for discrimination may be different there.

We also performed bandpass filter analyses on the mine blast and earthquake records at BLA for the event sample described in Section 4.2. Figure 20 shows the L_g/P ratios as a function of frequency for the nine mine blasts. The scatter in the ratios here is much larger than those which we found for the mine bumps in Figure 17, although the overall trend with frequency seems to be similar. The L_g/P ratios for the mine blasts again seem to have maxima at frequencies from 1.25 Hz to 2 Hz and then rapidly decline before leveling off at frequencies from 4.5 Hz to 9 Hz. Similar L_g/P ratios for the regional earthquakes from Table 4 are shown in Figure 21. These earthquake ratios show large scatter, but the overall trend indicates a slow decline in the earthquake L_g/P ratios with increasing frequency.

Figure 22 shows a comparison of the average L_g/P ratios as a function of frequency observed at station BLA for the different source types in the eastern Kentucky/eastern Tennessee/western Virginia region and similar L_g/P ratios for nuclear tests at NTS and Shagan River. First, looking at the different types of events from this source region, at low frequencies the average L_g/P ratios are largest for the earthquakes and mine blasts; and at high frequencies the average L_g/P ratios are largest for the earthquakes. The average L_g/P ratios for the mine bumps and mine blasts seem to exhibit a very similar behavior with frequency, showing maximum values at frequencies from 1.25 Hz to 2 Hz, rapid decline between 2 Hz and 4.5 Hz, and leveling off from 4.5 Hz to 9 Hz. These results appear to agree with the assessment of Finn and Wood (1996b) who find, for much the same event sample, that L_g/P ratio slopes and high-frequency L_g/P ratios can be used to distinguish between mine bumps and earthquakes but not between mine bumps and mine blasts. They argue that additional

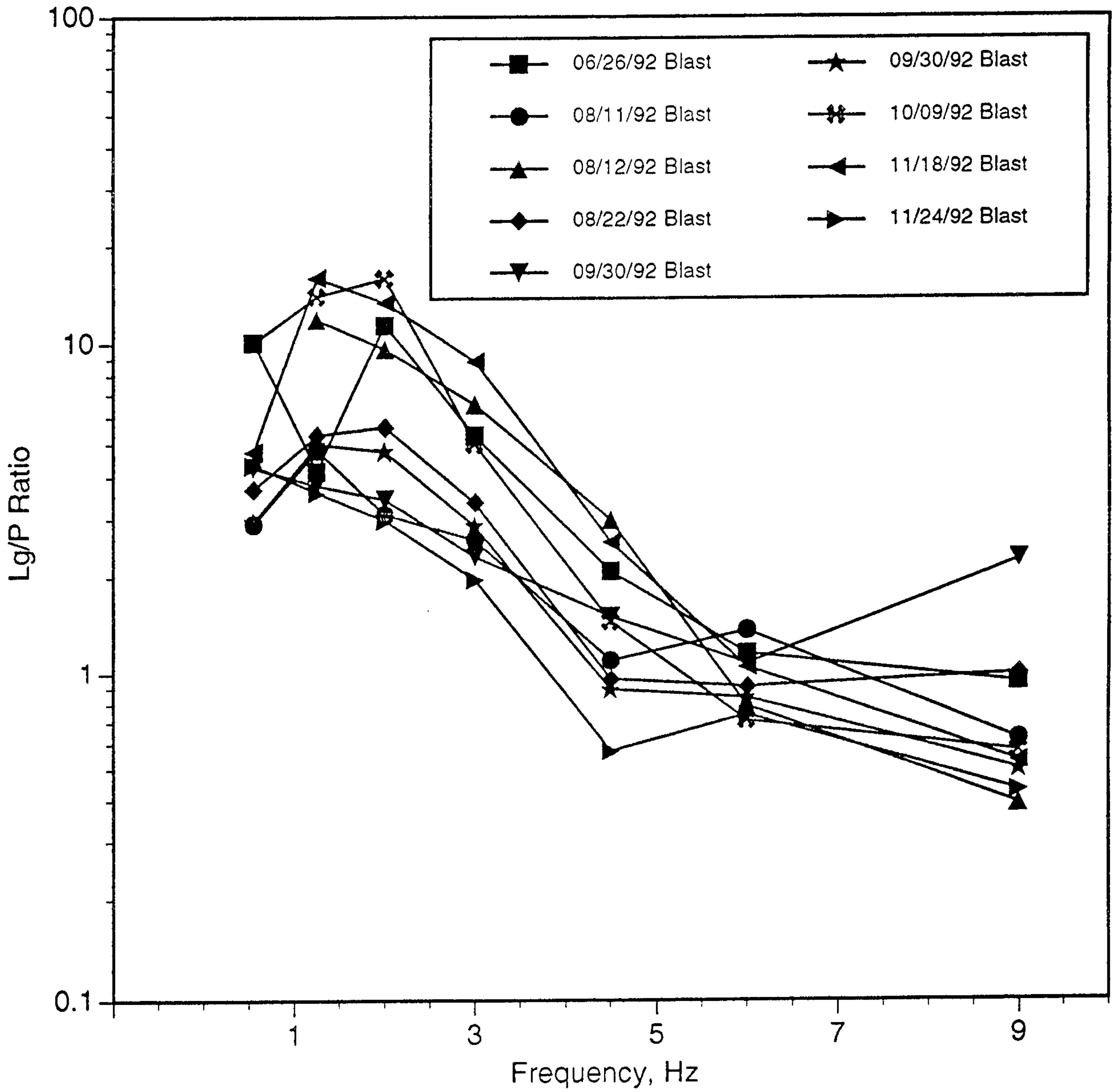

Figure 20. Lg/P ratios as a function of frequency determined at station BLA for nine mine blasts in the eastern Kentucky area.

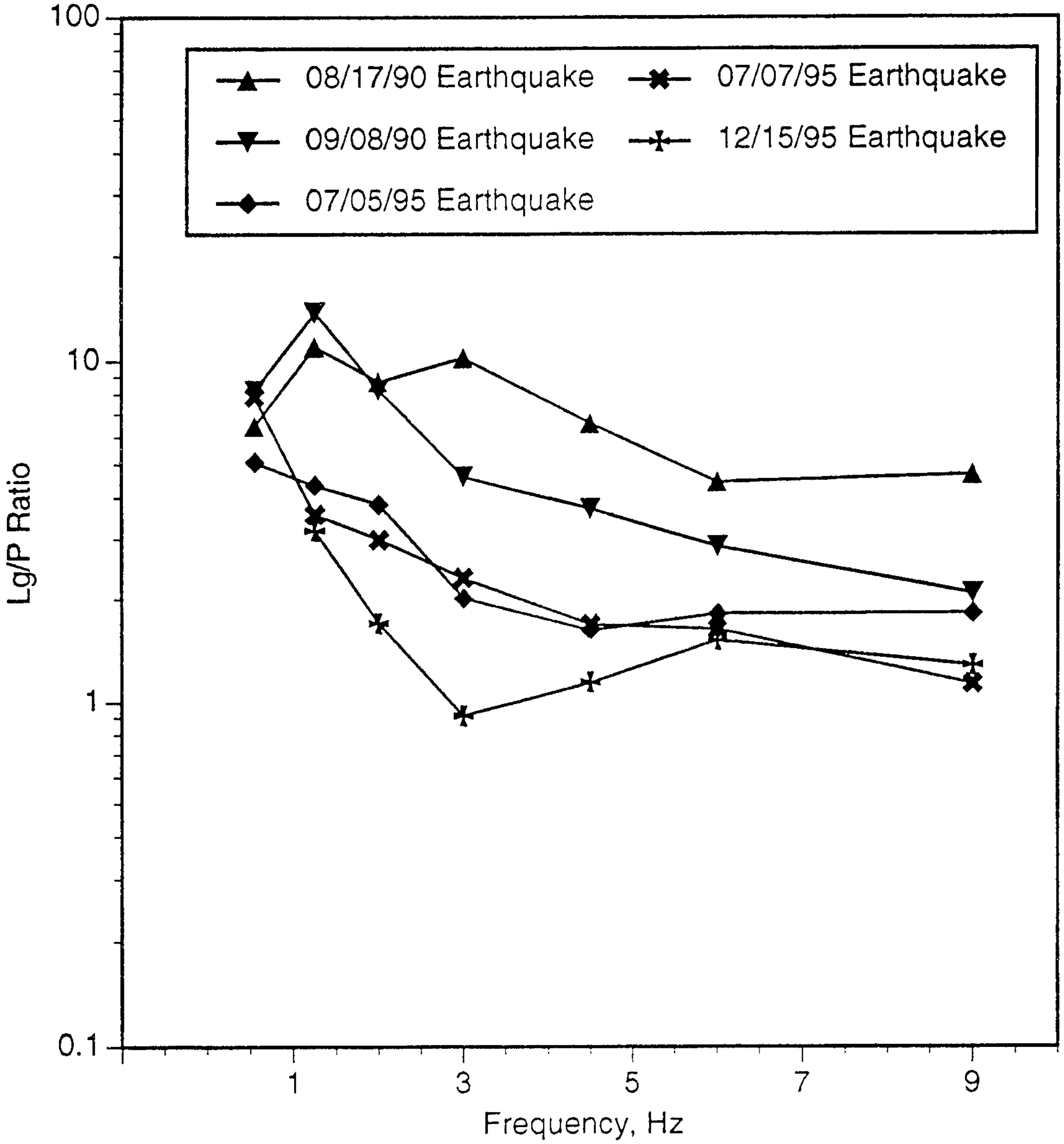

Figure 21. Lg/P ratios as a function of frequency measured at station BLA for five earthquakes in the eastern Kentucky/eastern Tennessee area.

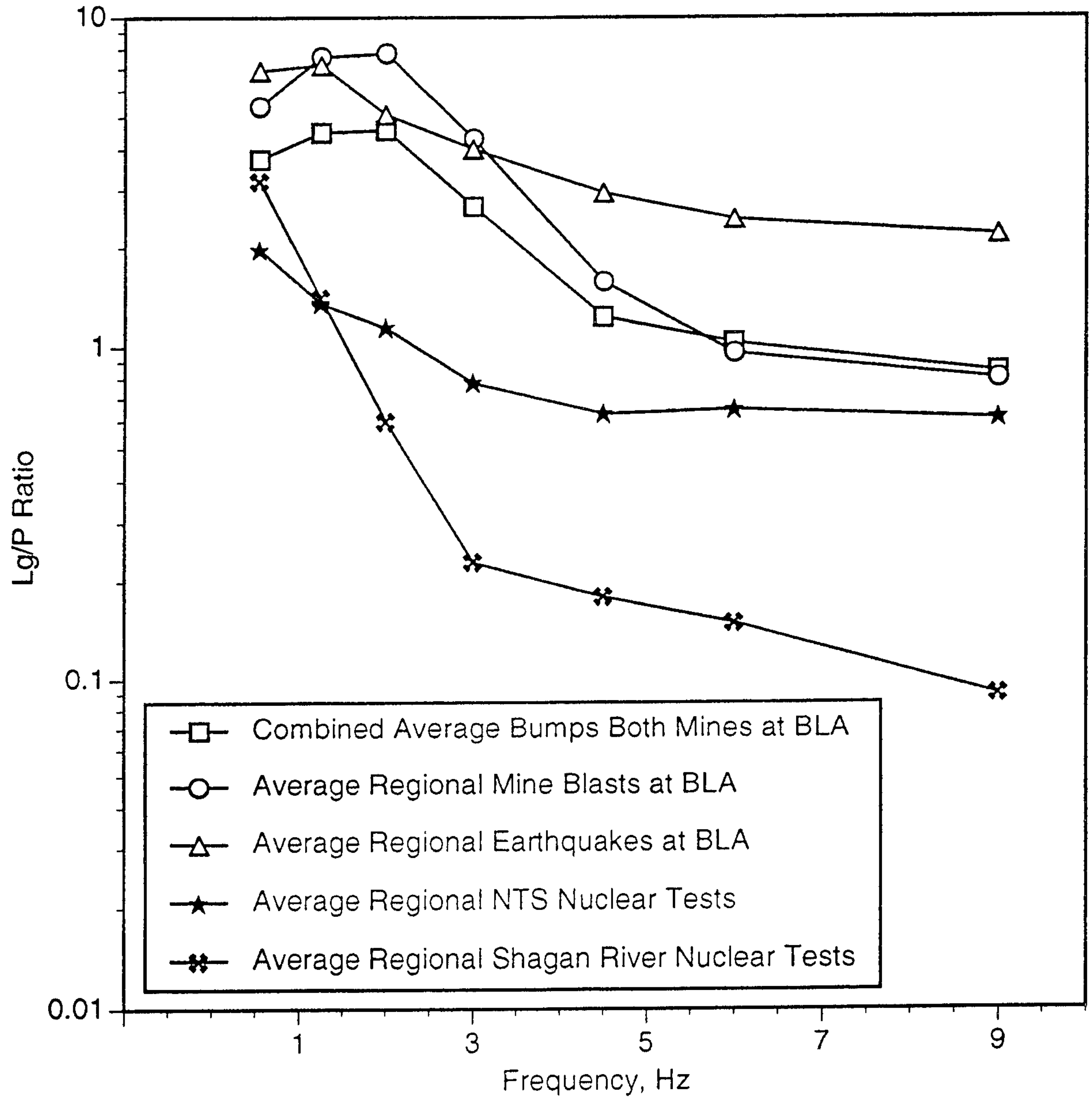

Figure 22. Comparison of average Lg/P ratios as a function of frequency measured at station BLA for regional mine bumps, mine blasts, and earthquakes with similar average ratios measured at regional stations from NTS and Shagan River nuclear explosion tests.

discriminant measures including analysis of R_g could be helpful for discriminating mine bumps and mine blasts.

The implications of Figure 22 for discrimination of mine bumps, like those in the eastern U.S., from underground nuclear explosions are not clear. The L_g/P ratios measured for the nuclear tests are significantly different from those for the mine bumps, with maximum differences over the frequency range from about 1.25 Hz to 3 Hz. However, the L_g/P ratios as a function of frequency are remarkably dissimilar for the mine blasts and the nuclear explosions. Considering such differences it's hard to argue that the mine blasts provide any kind of calibration for potential nuclear tests in the same region. On the other hand, we know there are regional phase propagation differences between the western U.S. and eastern U.S. Such differences could affect L_g and regional P propagation and hence the L_g/P ratios as a function of frequency. Additional investigations are needed to resolve the effects of propagation on regional phase spectra and L_g/P ratios; we are currently involved in separate research to determine such effects for various regions of interest.

5. Issues for Rockburst Mechanisms and Discrimination

5.1 Rockburst Mechanisms

In previous reports (cf. Bennett et al., 1993, 1995) we described the various mechanisms associated with rockbursts. The mechanisms of some rockbursts are associated with fault slip, while others seem to be more accurately represented as collapses. Figure 23 shows six distinct models of rockburst source mechanisms identified by Hasegawa et al. (1989). The six models include (1) cavity collapse, (2) pillar burst, (3) tensile failure in the cap rock, (4) normal faulting above the advancing stope, (5) thrust faulting on fractures above or below the excavation, and (6) near-horizontal thrusting between rock layers in the shallow region above the mine roof.

Several of these models are essentially the same as earthquakes (viz. models four through six), and the mechanisms should be similar to the double-couple normally seen in earthquakes. We would expect these events to produce a quadrantal pattern of first motions, as shown on the right in Figure 23, similar to those associated with earthquakes. In general, these types of rockbursts could be expected to produce discriminant measures which are indistinguishable from earthquakes. However, there could still be some areas of difference between such fault-rupture rockbursts and earthquakes. First, the source depths are generally quite different. Nearly all rockbursts occur within close proximity to the excavation level which is within a few kilometers of the earth's surface, while most earthquakes have focal depths well into the earth's crust and usually deeper than five kilometers. Such focal depth differences can strongly influence the radiated seismic signals and, in particular, the relative amplitudes of regional phase signals. Second, earthquakes and rockbursts in the same area may have different mechanisms. The earthquake mechanism represents the response of a pre-existing rupture surface to the ambient tectonic stress field; while the rupture surface associated with rockbursts have orientations tied closely to mining practice, and the stress field near the rupture is often strongly modified in both intensity and orientation by the local mine conditions. Given these kinds of differences, it would not be surprising to find systematic differences in the seismic signals between rockbursts and earthquakes.

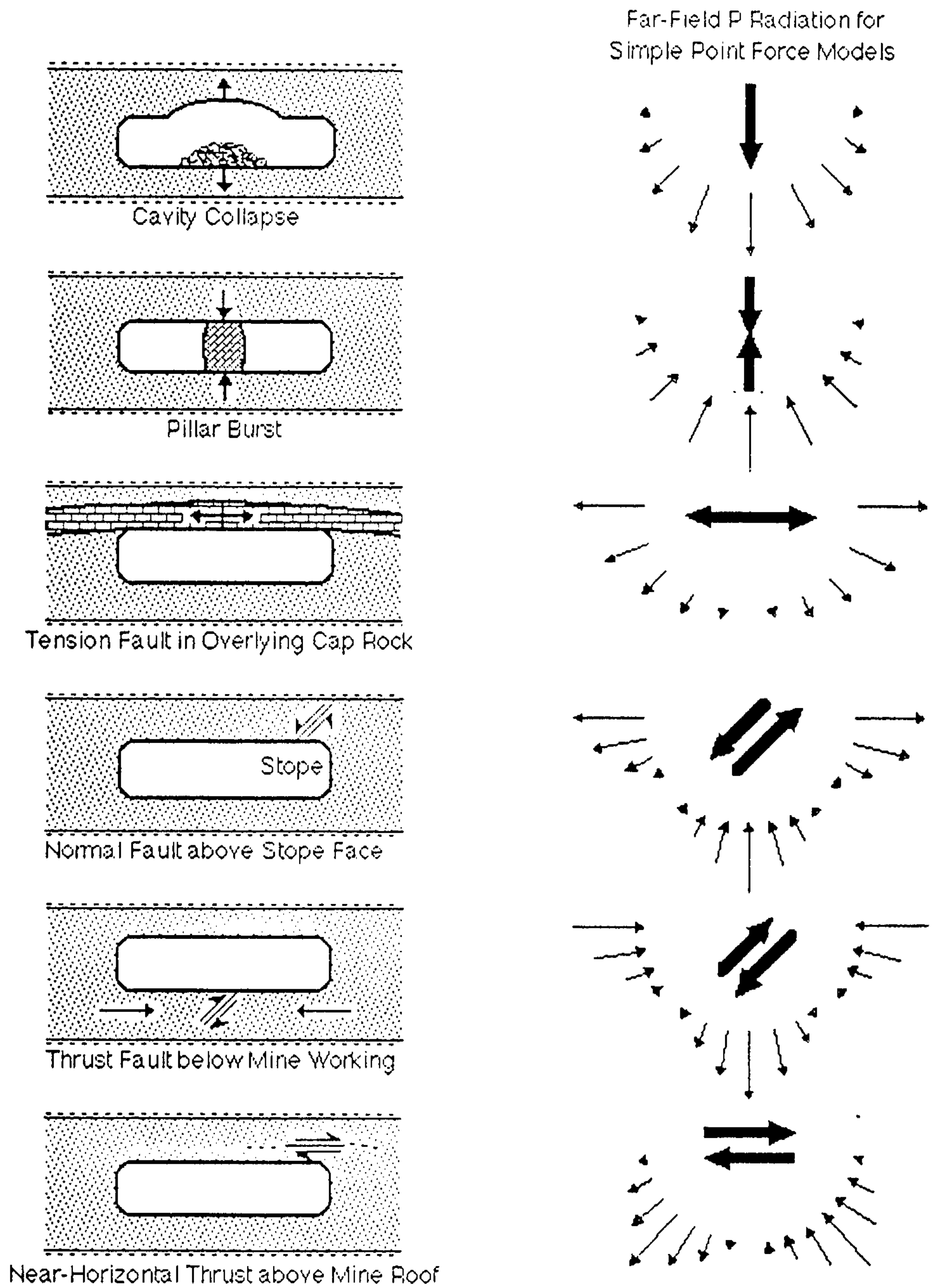

Figure 23. Simplified models of six rockburst mechanisms and corresponding radiation patterns (adapted from Hasegawa et al., 1989).

The first three rockburst models described above are even more clearly different from earthquakes. The mechanisms are not double-couple; and the radiated seismic field, as shown to the right in Figure 23, would be expected to be dipolar. As we noted previously (cf. Bennett et al., 1993), only rare examples of non-double-couple rockburst sources have been identified in the literature (cf. Sileny, 1989; Wong et al., 1989; Gibowicz and Kijko, 1994). Most large rockbursts from areas which have been studied most closely (viz. South Africa and Poland) have had seismic mechanisms dominated by double-couple associated with shear failure in the vicinity of the excavation. However, some recent mining-induced events in less regular rockburst regions appear to have had strong collapse mechanisms. These would include the 1989 Volkershausen, Germany event (cf. Ahorner, 1989), the 1995 Wyoming event (cf. Pechmann et al., 1995), and the 1995 Ural mountains event (cf. Bennett et al., 1995). While it seems unlikely that the seismic mechanisms in these events are as simple as models one or two in Figure 23, representations of these sources must include a strong non-double-couple component. In our previous report we reviewed moment tensor representations of mine-collapse sources. We showed there using a non-linear discrete-element computer code that the stress field introduced by a large room collapse may be represented by a closing tension crack. Moment tensor representations of the closing tension crack model were found to be inefficient in excitation of fundamental-mode Rayleigh waves, which could explain relatively small M_S values seen for some rockbursts.

No single mechanism seems to fit all rockbursts. Our studies suggest that rockbursts can be represented by a moment tensor including a closing tension crack plus some tectonic release component. Results of rockburst studies suggest that we should expect there to be a spectrum of events ranging from little or no tectonic component to those dominated by the tectonic component. The degree to which such events look earthquake-like or explosion-like will depend upon the ratio of the tectonic release moment to the tension-crack moment and the time functions for the two mechanisms.

5.2 The M_S-versus-m_b Discriminant

M_S-versus-m_b is a traditional teleseismic discriminant which has long been recognized as one of the most reliable methods for distinguishing earthquakes from underground nuclear explosions. Since many rockbursts have fault-slip mechanisms, it might be reasonable to assume that the M_S-versus-m_b discriminant could also work to help identify them. Unfortunately, there isn't much empirical data available to test this hypothesis. Most rockbursts are not large enough to produce the observable long-period Rayleigh-wave signals at teleseismic distances which are needed to determine M_S. In an earlier phase of this research project (cf. Bennett et al., 1995), we identified several large rockbursts in South Africa, central Europe, and the western U.S. which did produce measurable surface-wave magnitudes at teleseismic stations. We found teleseismic M_S measurements for 12 rockbursts, most of which were in South Africa. Figure 24 shows the M_S-versus-m_b observations for the large rockbursts. On average the rockburst M_S values fall between 0.5 and 1.0 magnitude units below the corresponding m_b observations; all but one event falls below the equivalence line for M_S and m_b. Many of the rockburst events appear to have M_S values which are more explosion-like, as can be seen by comparing the M_S-versus-m_b values to the line separating the earthquake and explosion populations recommended by Sykes et al. (1983). Several of the mine collapse events discussed in the preceding section have M_S-versus-m_b values which fall close to this decision line. It is interesting to note that many of the South African events also seem to have low M_S values relative to m_b, and these events are thought to have mechanisms more closely tied to fault rupture with little contribution from collapse. The relatively low M_S values for South African rockbursts seem to be corroborated by far-regional measurements of long-period Rayleigh-wave signals (cf. Bennett et al., 1994, 1995) for the events occurring there. Additional theoretical studies are needed on rockburst mechanisms from this area to identify factors other than collapse which could be responsible for the anomalous surface wave generation from these types of sources.

5.3 Regional Discrimination of Rockbursts

Throughout much of this research program, we have focused on regional signal measurements from smaller rockbursts with magnitudes of about 3 m_b. The majority of rockbursts worldwide fall in this magnitude range or smaller, and it is the abundance of events near this magnitude level which is likely to cause significant problems for CTBT monitoring. As described in previous sections of this report, rockbursts from many different source regions seem to show consistently large L_g/P ratios. Figure 25 shows the average L_g/P ratios as a

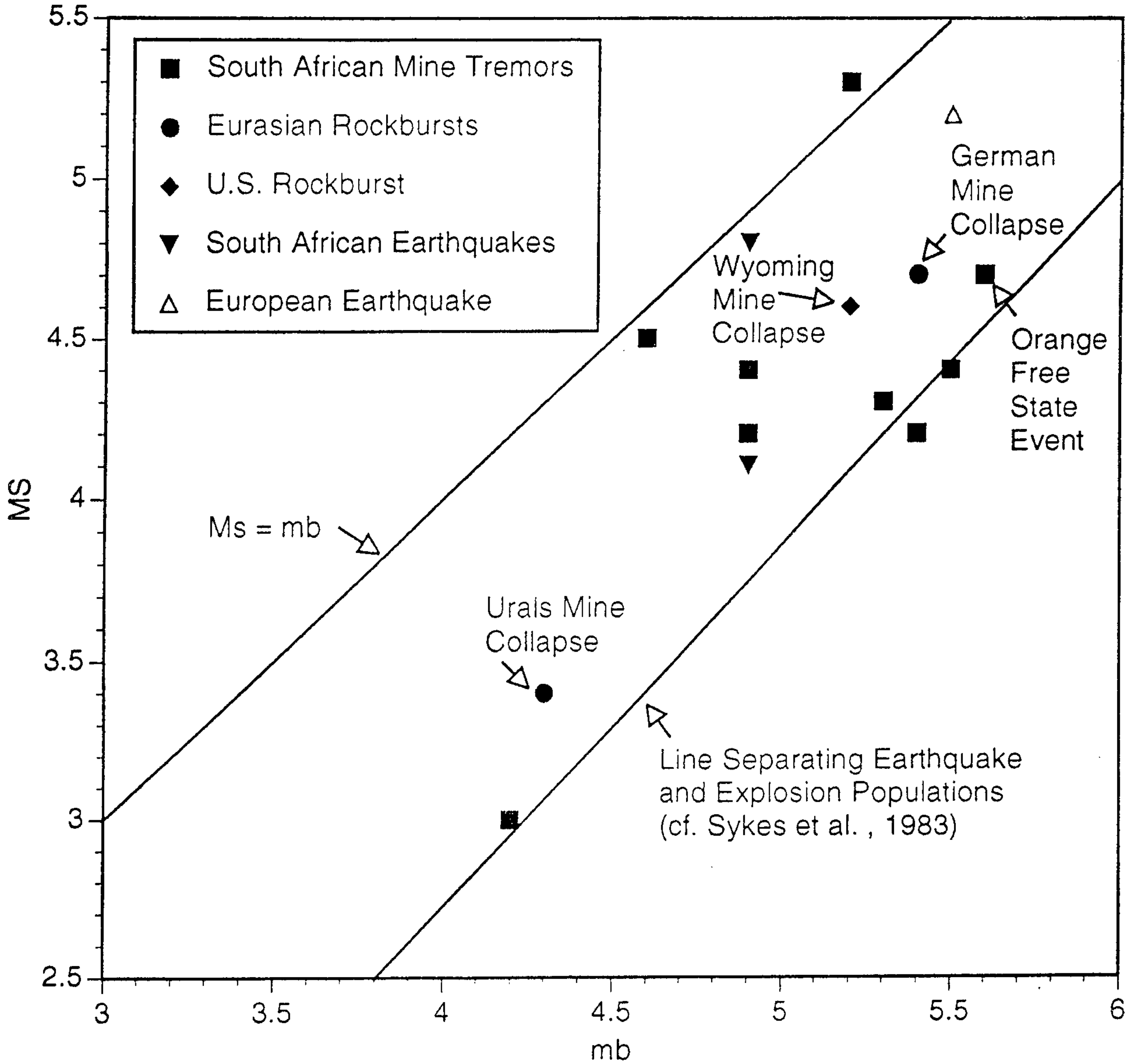

Figure 24. Comparisons of MS versus mb for large rockbursts in four source regions with similar observations for earthquakes in the same regions.

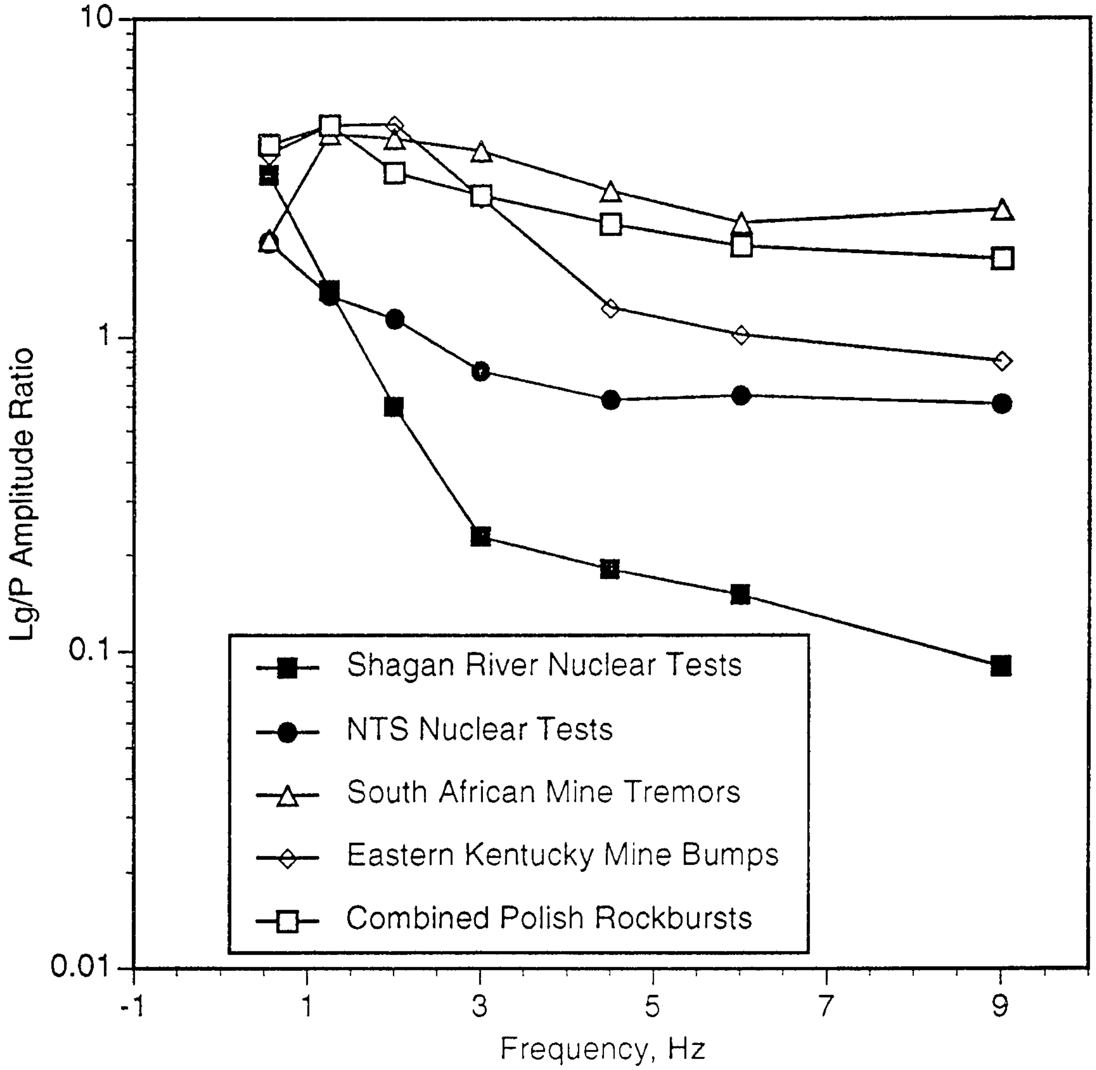

Figure 25. Comparison of average Lg/P ratios for rockbursts from three different source areas with average Lg/P ratios for nuclear explosion tests at NTS and Shagan River.

function of frequency for rockbursts in three quite different source areas. The L_g/P ratios from all three regions have values falling in the range from one to ten over a broad range of frequencies from 0.55 Hz to 9 Hz. The average ratios show similar frequency dependence for the three areas with consistent maximum values of four to five near 1.25 Hz declining to minimum values of one to three near 6 Hz and 9 Hz. We found the decline with frequency to be more rapid for eastern U.S. mine bumps than for the rockbursts in the other source areas. In comparison, average L_g/P ratios measured at regional stations for underground nuclear explosions at NTS and Shagan River have rather large values at low frequencies (maximum values of two to three at 0.55 Hz) but fall off more rapidly at higher frequencies to minimum values of about 0.7 for NTS explosions and about 0.1-0.2 for Shagan River explosions. In general the biggest overall differences in L_g/P ratios for the rockbursts and nuclear explosions seem to be at a frequency of about 3 Hz. The differences there amount to about a factor of nine on average, with somewhat lower factors for comparisons between rockbursts and NTS explosions than for comparisons between rockbursts and Shagan River explosions.

These observations of a possible discriminant based on the L_g/P ratios for rockbursts suggest that we should probably take a closer look at other regional phases for use in identification of these events. In particular, characteristics of L_g and regional P phases considered separately may offer additional insight into rockburst discrimination and transportability of discriminant measures into new areas. Our observations also indicate that R_g phases frequently represent strong regional signals from rockburst sources in many areas. Comparison of the R_g signal characteristics for these rockbursts with similar signals which are often observed for shallow explosion sources could also lead to identification of diagnostic differences.

6. Summary and Conclusions

6.1 Review of Procedures and Main Findings

Rockbursts present some unique problems for seismic discrimination which have become more important because of the necessity for seismic monitoring at the low levels of interest under a CTBT. Under this research program we have sought to identify the characteristics of seismic signals from rockbursts and the physical properties and phenomenology observed in the vicinity of the mines for such events from a variety of source areas around the world. It is believed that this information can be used to investigate and refine the mechanisms for the rockburst sources and will aid in understanding the controllability of such events by adjusting mining practice. These issues are an important key to the identification of unknown events in mining areas for reliable discrimination and for determining the feasibility of nuclear test evasion scenarios which might use the deliberate triggering of a rockburst to conceal a clandestine explosion.

In the earlier phases of this research program, we reviewed the occurrence of rockburst activity in a variety of regions worldwide and described some general features of the source mechanisms. We also collected and analyzed regional and teleseismic waveform data from selected source regions using primarily data from some of the more traditional sources. We also performed some simulations of the rockburst source using a discrete element computer code, which demonstrated that the rockburst source for several recent large events might be well represented as a closing tension crack. In the recent stages of this research, we have focused on analyses of regional signals from several of the modern digital seismic stations which are being used by the IDC. We have used these data to look at several large, catastrophic events which occurred in unusual areas and also to investigate more routine events from several mining areas.

In the most recent phase of our research, which is the main topic of this report, we have conducted more systematic discrimination analyses on events in three of the most active rockburst areas in the world: the South African gold-mining area, the Polish coal-mining and copper-mining areas, and the eastern U.S. coal mining area. For each of these source areas, we collected digital waveform data from the key regional stations used by IDC for relatively large samples of events which occurred during the last two years. We performed spectral analyses on the regional signals and attempted to identify characteristic spectral behavior in the regional signals which would distinguish the rockbursts from underground nuclear explosion tests.

Our findings show that L_g/P ratios as a function of frequency for the rockbursts in all three source areas are generally larger than similar ratios for underground nuclear explosion tests. Average L_g/P ratios for rockbursts in different source areas are consistently greater than one over a range of frequencies and show similar frequency dependence, with maximum values at low frequencies and declining toward high frequencies; but the rate of decline seems to vary somewhat between regions. The L_g/P ratios are on average a factor of three to ten lower for nuclear explosions at regional stations; but it is recognized that in these comparisons no account has been taken of possible propagation differences. L_g/P ratios show considerable scatter for rockbursts in the same general source region, but the scatter is reduced for events from a common mine. There is a tendency for L_g/P ratios from events at nearer distances to show less variation with frequency, while at larger distances the ratios seem to decline more rapidly as frequency increases. In the eastern U.S. where the database includes rockbursts, mine blasts, and earthquakes, the average L_g/P ratios as a function of frequency tend to look more alike for the rockbursts and mine blasts than for the earthquakes. The eastern U.S. earthquakes seem to maintain larger L_g/P ratios at higher frequencies than either the mine bumps or the mine blasts in that area.

6.2 Recommendations for Future Research

Although we seem to have a promising discriminant in L_g/P ratios as a function of frequency, the rockburst identification problem is not completely solved. Additional work is needed to demonstrate that the observed differences in L_g/P ratios between rockbursts and nuclear explosions are source related and can be extrapolated into uncalibrated regions. Theoretical research on the sensitivities of regional measurements of L_g/P ratios to source mechanism and attenuation as well as additional empirical observations of the behavior of L_g/P ratios in different distance ranges would be useful to further establish the reliability of this discriminant. Much of our observational evidence for the L_g/P ratio discriminant between rockbursts and nuclear tests comes from near-regional observations. Additional research is needed to identify distance ranges at which we can expect to achieve effective discrimination for different regional monitoring environments. We have found empirical evidence that the M_S-vs-m_b discriminant seems to break down for some rockbursts, and we have identified some theoretical models of the rockburst source which could be the cause of this problem. It would be useful to define more precisely the rockburst mechanisms which produce anomalous M_S, the mining conditions which lead to such mechanisms, and where such mining conditions are likely to be found in monitoring regions of interest. In this work we have focused much of our investigation on L_g/P ratios as discriminants. Discriminants based on analyses of other regional phases including R_g, regional S, or L_g and regional P considered separately may also have something to offer for regional discrimination of rockbursts. Additional survey work of mining practices could also be useful in countries where nuclear proliferation is an issue to identify whether there is a potential for rockburst events which could lead to false alarms. Finally, we have not accomplished much in this research to resolve the possible evasion scenario involving deliberate triggering of a rockburst to conceal a simultaneous, nearby nuclear explosion test. Additional field studies of rockbursts and the effect of destressing procedures to control rockbursts in specific mines could help to assess the feasibility of such evasion techniques.

Acknowledgments

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