REGIONAL SIGNAL CHARACTERISTICS FOR USE IN SCREENING SEISMIC EVENTS IN ROCKBURST AREAS

Theron J. Bennett, Margaret E. Marshall, and Ronald W. Cook
Maxwell Technologies, Inc.

Sponsored by The Defense Threat Reduction Agency
Arms Control Technology Division
Nuclear Treaties Branch

Contract No. DSWA01-98-C-0153

ABSTRACT

Because of their shallow focal depths, small magnitudes, and often anomalous focal mechanisms, rockbursts may sometimes be difficult to discriminate from other seismic source types. The goals of this research project are to improve CTBT monitoring capability in the vicinity of rockburst areas by carefully analyzing the characteristics of rockburst sources and signals and to develop better regional discrimination techniques for these events using International Monitoring System (IMS) station observations. To accomplish this objective we have collected PIDC data from more than 1000 events in the vicinity (within 50 km) of 35 known historical rockburst sites worldwide for the five year time period starting at the beginning of 1995; 27 other sites of historical rockburst produced no events in the REB during this time period. Based on these REB data, the most active rockburst areas were found to be in Poland, the Kola Peninsula in northern Russia, and South Africa; but rockburst areas in North America, Germany, Tajikistan, and Japan have also been investigated. Although the majority of these events had REB magnitudes in the range $3 \le m_b \le 4$, very few (n = 5) were "screened" by the nominal screening procedures at the PIDC. A somewhat larger number (n = 49) were "not-screened," but most were "not considered" or had "insufficient data" for screening. We have analyzed the PIDC screening results for these rockburst events in detail, and they indicate that teleseismic discrimination procedures are not likely to be effective for screening these rockburst sources. However, there does appear to be some evidence that regional signals recorded by IMS stations from events in these rockburst areas may have differences related to source type. We are, therefore, focusing on several regional phase signal measurements; and we have been developing parametric measures, which have been indicated in some prior regional discrimination studies, to evaluate their potential value for screening and event identification in rockurst areas. For use in these studies, waveform data have been retrieved from regional (Δ less than about 20°) IMS stations for event samples from each of the 35 historical rockburst areas described above. For several more active areas (like Poland and South Africa) larger data samples have been retrieved to analyze variability in the regional signals between events. The regional discriminant measures being investigated include L_g/P ratios, L_g spectral ratios, regional LP signals, and regional phase complexity. We have also been seeking to establish better ground truth for events in some of the rockburst areas. In particular, several events in the western U.S. are known, from local seismic network operations, to be associated with mine collapses, mine explosions, and earthquake activity in Utah and Wyoming. We have retrieved IMS station records from several of these events and are comparing signal characteristics between these different source types and also with older recordings of NTS explosions recorded for similar paths, and at some common stations, to help define source-related differences. We hope to establish similar ground truth for some of the other more-active historical rockburst source areas.

OBJECTIVE

Rockbursts present several unique challenges for seismic discrimination and event screening in the CTBT monitoring environment. Rockbursts are located in approximately the same depth range as nuclear tests, so depth discriminants are likely to be ineffective. Some rockburst mechanisms produce relatively weak long-period surface waves which could negate screening based on M_S-vs-m_b. Since many rockbursts are small, their screening is likely to depend heavily on observations from a few regional stations. The current studies will identify rockburst regions with respect to their significance to CTBT monitoring and focus on the performance of three promising discriminant measures for use in IDC event screening in those regions. The research program includes the following elements: (1) systematic collection of IDC data for events in known rockburst areas worldwide, (2) determination of S/P or L_g/P ratios for events from rockburst areas, (3) measurement and analyses of complexity of regional signals from evens in rockburst areas, (4) determination of LP surface-wave excitation for events in rockburst areas, (5) relation of the range of behavior of observed signal characteristics to those expected from reported rockburst and other source mechanisms, and (6) prediction of seismic signal and discrimination behavior for significant rockburst areas worldwide.

RESEARCH ACCOMPLISHED

In prior reports on rockbursts, we have noted that mining-induced seismic activity occurs in mining regions all over the world. In assessing what impact these events have on CTBT monitoring at the IDC/PIDC, we have first identified where historical rockbursts (including all types of mining-induced events) have occurred and then looked more closely at the events reported in the PIDC REB bulletins in the vicinity of those locations for the time period 1995 – Present. Figure 1 shows 104 locations worldwide where we have found reports of apparent mining-induced seismic activity. This is an increase of about 40 locations from the map which we previously published (cf. Bennett et al., 1999), and will no doubt continue to grow. The majority of the new locations, which we have identified, are in the U.S. or Canada; this is at least partly because information on mining activity in these areas is more readily available. In many cases, the new locations represent refinements of old locations where we have now identified separate mines with associated induced activity (e.g. in Ontario Province, Canada). However, in some cases the mine locations may be significantly separated; so it is probably better to keep a more complete list. The mapped locations also include a few new areas where mining-induced activity has been reported (e.g. Alaska, western Washington, and Vancouver Island). 1122 events are included in the PIDC REB bulletins within 50 km of 43 historical rockburst locations; these locations are shown as closed circles on the map. It should be noted that, while no REB events have occurred in the vicinity of the remaining 61 historical rockburst locations, there are small seismic events (below the REB threshold) occurring in many of these areas. There is also a potential for somewhat larger mining-induced events in most areas. Most of the 1122 REB events near the historical rockburst sites occur in just a few areas: (1) three areas in Poland, (2) a mining area on the Kola peninsula in Russia, and (3) five areas in the gold mining region of South Africa. However, a few other broader scale mining areas have been the locations of several REB events; these include several mining areas in North America, Germany, Tajikistan, and Japan. The majority of the REB events from the rockburst areas have magnitudes in the range 3 – 4.

Nominal PIDC screening procedures fail to provide event discrimination for almost all events in rockburst areas. Less than 0.5 % of the more than 1000 events from the seven mining areas denoted above are "screened out" by the nominal procedures based on event focal depth and M_S-versus-m_b; that is, these events cannot be reliably designated as earthquake-like by the nominal criteria. This is probably to be expected, since most events in these rockburst areas occur at shallow depths and many seem to be inefficient in generating LP surface waves (cf. Bennett and McLaughlin, 1997). At last year's meeting, we presented detailed analyses of the actual discriminant measures for 5 events, which were "screened out," and 49 events, which were "not screened," from these seven areas. However, it is probably more significant that the large majority of the REB events from these mining areas are categorized as having "insufficient data" or "not considered." Although 90% of the REB events in these areas had magnitudes greater than 3.0, some have M_L but no m_b; and about half would fall below the somewhat arbitrary cutoff of $m_b \geq 3.5$ to be considered for PIDC screening. For most events in these areas, there is no indication of focal depth; and LP surface wave magnitudes have not been measured. So, in general the data available at IMS stations for applying the nominal teleseismic screening procedures are not adequate for characterization of events from most rockburst areas.

Because many rockbursts are small, the strongest seismic signals are often those recorded at regional stations. By comparing IMS station observations for events from the vicinity of historical rockbursts with similar observations from outside those areas, we have found some systematic differences in several regional signal parametric measurements, which are routinely determined at the PIDC/IDC. For example, observations of short-period/long-period (SP/LP) energy ratios seem to indicate that events from rockburst areas have more high-frequency energy relative to low-frequency energy than events from outside those areas. Assuming that events from the rockburst areas are more likely to be rockbursts and those from outside the areas are more likely to be earthquakes, this result may have implications for source characterization of regional events. We also found that on average L_g/P_n and S_n/P_n ratios in several different frequency bands appeared to be systematically larger for events from within rockburst areas compared to events outside. There were also indication in the L_g spectral ratios that events from rockburst areas tended to generate relatively more high-frequency L_g than sources outside the areas. We have also been looking into two other measurements which may be useful for characterizing rockburst events at regional distances:

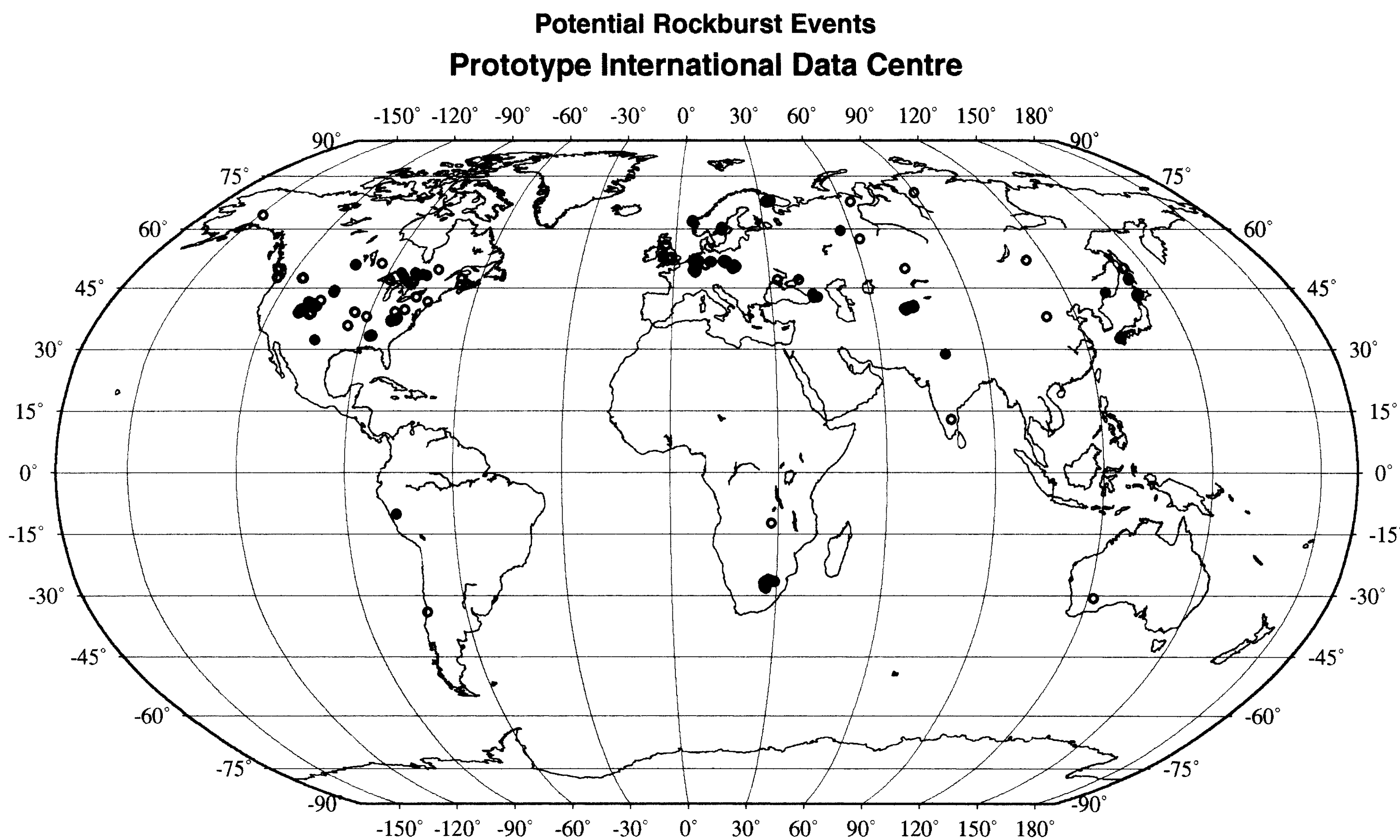

Figure 1. Locations of 104 historical rockburst areas worldwide. 1122 PIDC REB events have occurred within 50 km of 43 sites (closed circles) but no REB events at other sites (open circles).

regional P-wave complexity and regional LP signals. We have made some systematic measurements on the regional P signals recorded at IMS and other stations for selected events in some more-active rockburst areas and compared signal duration and envelope characteristics with similar measurements for other source types in the same region at comparable distances. We are currently analyzing these results to identify any differences. To analyze regional LP signals, we have attempted to isolate low-frequency surface-wave signals on the broadband IMS station recordings for several events from selected rockburst areas using low-frequency band-pass filters. Although we have recovered some reasonable LP signals for some small rockburst events, the signal-to-noise levels are often small; and comparisons between events may not be reliable. More robust signal processing schemes may be required to determine reliable LP surface-wave signals from these small regional events.

To better understand the variability between rockburst sources and to evaluate potential regional discriminant measures more completely, we have been attempting to develop improved ground truth for events in several areas. One of the most active rockburst areas in North America is the Wasatch Plateau-Book Cliffs coal mining area in southern Utah (cf. Arabasz and Wyss, 1999). Events as large as 4 M_L occur in association with longwall mining in this area; and several events from this area are included in the PIDC REB (cf. Figure 2). This area of the western U.S. is particularly interesting for seismic event discrimination because it includes a variety of seismic source types (viz. rockbursts, mineblasts, nuclear tests, and earthquakes) recorded at similar distances and in similar propagation environments. In addition to the Utah rockbursts, a trona mining area just north of the Utah border in southwestern Wyoming has been the site of several mine collapses, including one of the largest induced mining events ever in North America (a 5.2 m_b event on 1995/02/03). In addition to the mining-induced activity, there is significant commercial blasting activity associated with mines in northwestern Colorado, southwestern and eastern Wyoming, and southern Montana. Many of these have been large enough to be included in the REB. Natural earthquake activity extending along the Wasatch front and other areas of the southern Basin and Range provide alternative source types for comparison. Finally, nuclear tests at NTS, recorded in some cases at seismic stations common to the PIDC and at similar distances, provide a unique database for careful comparison of regional seismic signal characteristics from the different source types important to CTBT monitoring. It is also noteworthy that we have excellent ground truth information for many of these events from the local seismic network operated by the University of Utah, as well as from reports on blasting activity at U.S. mines now being reported by the USGS. As a result, we are able to associate individual mine tremor events in Utah with specific mines. The event locations we show in Figure 2 are, except for nuclear tests, the PIDC REB locations. For most events we have alternative ground truth locations based on the local network information which in some cases show large differences compared to the REB. For example, there is a 1999 mineblast plotted in the south-central Utah rockburst area in Figure 2, which based on USGS ground truth information actually occurred more than 300 km to the south in northern Arizona. For each of the ground truth events in Figure 2, we are collecting the available IMS station waveform data, as well as other regional waveforms for some of the older nuclear tests; and these will be used to test and analyze the potential regional discriminant measures described above.

Another example of improved ground truth information for events in one of the more active rockburst areas is shown in Figure 3. Europe has several notable historical rockburst areas, including some that produce large and numerous seismic events. As noted previously, there are two very active mining areas in Poland: (1) in the vicinity of copper mines near Lubin (at about 51.5° N 16.0° E) and (2) at coal mines in Upper Silesia (centered near 50.5° N 19.0° E). These sources produce the largest number of REB events in the vicinity of known rockburst areas and have included large events with magnitudes as great as 5 m_b, although the largest since the start of the PIDC REB bulletins has only been 4.2 m_b. Another site of a large mining-induced event is in eastern Germany near Völkershausen, where a 5.4 m_b event occurred at a potash mine in 1989; however, this site has been relatively quiet since and has contributed little to the REB events list. In fact, in the REB there are several much more active rockburst areas in the Ruhr valley mines of western Germany (near 51.5° N 7.0° E), where events have reached 3.5 m_b, and in southwestern Germany near the French border (at about 49.0° N 6.5° E), where event magnitudes have reached 4.2 M_L. For each of these areas, there is fairly good coverage by local seismic networks; and we have been using information compiled by the Federal Institute for Geosciences and Natural Resources in Hanover, Germany (BGR) and by the Institute of Geophysics of the Polish Academy of Sciences to establish better ground truth for many of the PIDC REB events. As can be seen on the map in Figure 3, in addition to the rockbursts there are numerous chemical explosions (e.g. near the Germany/Poland border and within Poland) and earthquake sources for which we are developing better ground truth information. For each of these events, we are also retrieving the available regional IMS station data for comparing and testing the potential regional discriminant measures for use in event screening at the PIDC/IDC.

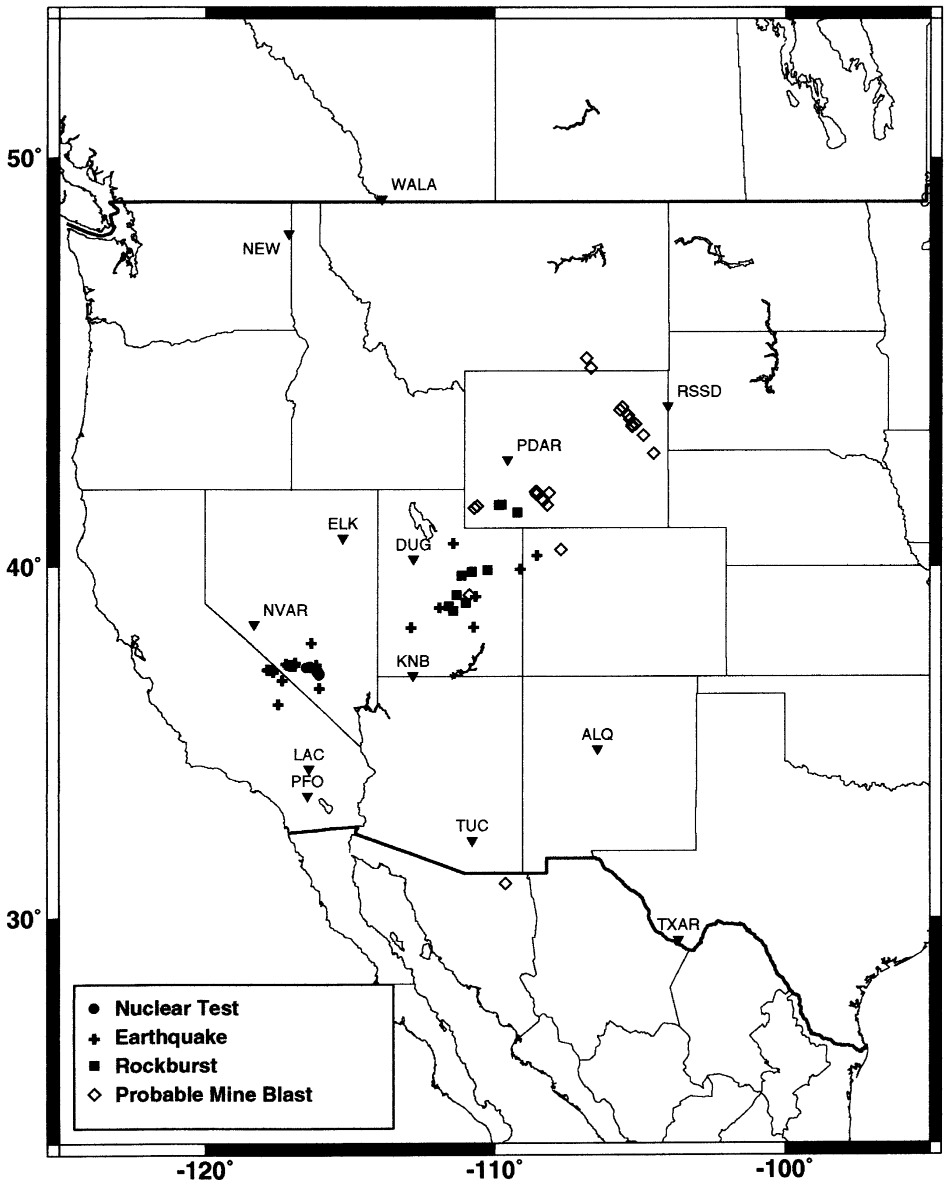

Figure 2. Locations of selected rockbursts, explosions and earthquakes recorded at the PIDC and other regional stations in the western U.S.

We have begun testing of the variability of regional discriminant measures for some of the events in the western U.S. shown in Figure 2 above. One of the most promising regional discriminant measures for use in event screening has been P/S or P/L_g amplitude ratios based on observations at regional stations (cf. Taylor et al., 1988; Bennett et al., 1992; Fisk et al., 1999). Bennett et al. (1996) suggested that there might also be systematic differences in the L_g/P ratios between rockbursts or mine tremors and underground nuclear tests. This is illustrated in Figure 4 where we compare the ratios for rockbursts in three different source areas with nuclear tests in two source areas. Although the results appear mixed at low frequencies, at higher frequencies the L_g/P ratios are on average larger for the rockburst events than for the nuclear tests.

To evaluate the reliability of this discriminant for event screening, it is necessary to have some idea of its variability between events. We have been looking at the regional phase signals at IMS stations for several of the Utah rockbursts and comparing them to similar measurements for other source types recorded at similar distances. Figure 5 shows the L_g/P amplitude ratios in different frequency bands for mine tremors at three coal mines compared to a Wyoming mine blast, a Utah earthquake, and the GORBEA nuclear test. It can first be noted that there is significant variability (about a factor of 4) in the ratios for several frequency bands

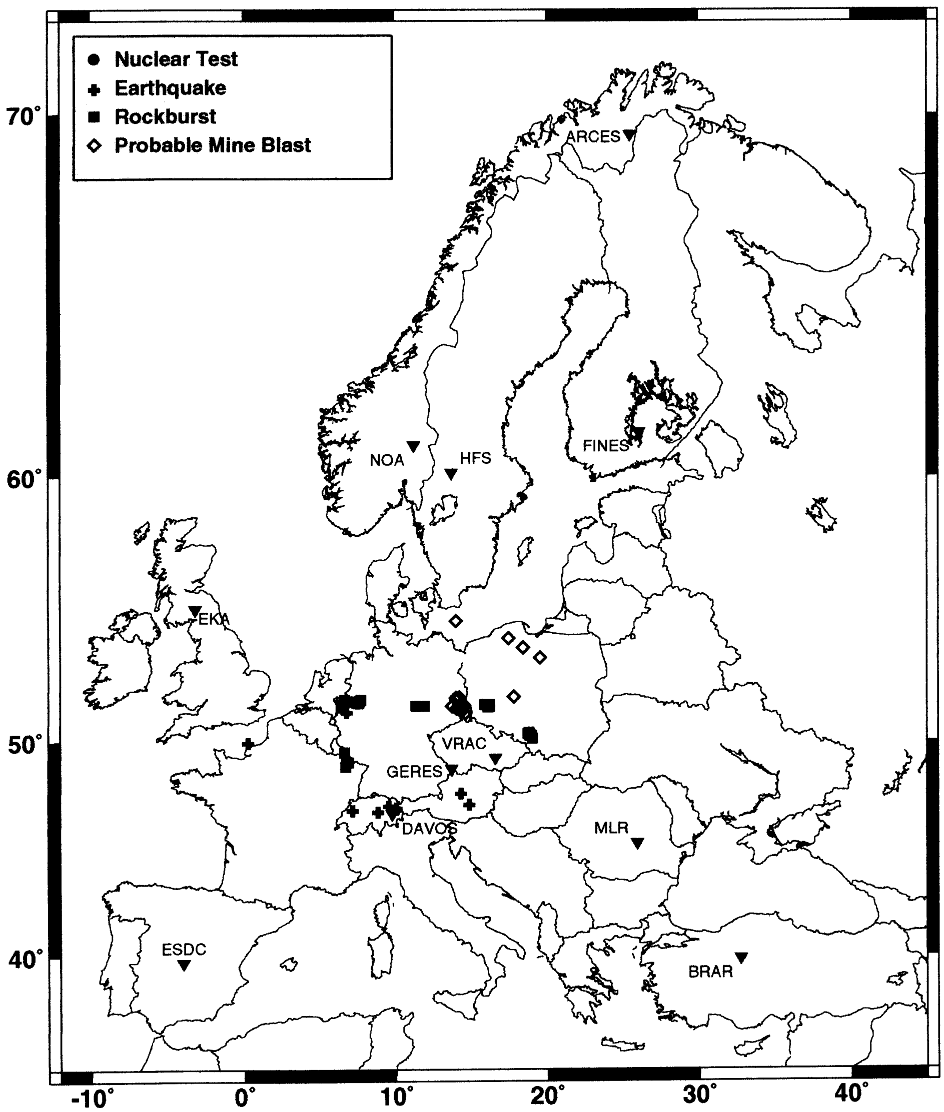

Figure 3. Locations of selected rockbursts, explosions and earthquakes recorded at the PIDC regional stations in Europe.

between the mining-induced events at different mines. Although further study is needed, this would appear to be a source effect and not a propagation effect, since the paths don't vary much between these events. It is also rather remarkable that the L_g/P_g ratios (shown in the top plot) are actually quite large for the nuclear test; in fact, the ratios for the nuclear test at high frequencies are almost as large as for the earthquake and larger than those for the mine tremors and mineblast. The L_g/P_n ratios (shown in the bottom plot) tend to be lower for the nuclear test; at high frequencies the ratios for the nuclear test and the mineblast tend to be similar and about a factor of two lower than the Utah earthquake and the Willow Creek mining-induced event. However, there is no discernible difference at high frequencies between the L_g/P_n ratios for the

Skyline mining-induced event and the nuclear test and mineblast. The behavior of the L_g/P ratios for GORBEA seems to be anomalous compared to the average behavior for NTS events, which we showed in Figure 4; this needs to be looked at more closely. We expect to see some differences in the L_g/P ratios between mining-induced events because of the effects of differences in mining practice on source mechanism (cf. Bennett and McLaughlin, 1997); we intend to investigate these differences with more observations from these mines and in other mining areas where we have good ground truth information. Alternative regional signal measurements need to be studied more thoroughly for application to cases where the L_g/P discriminant and associated screening procedures do not work.

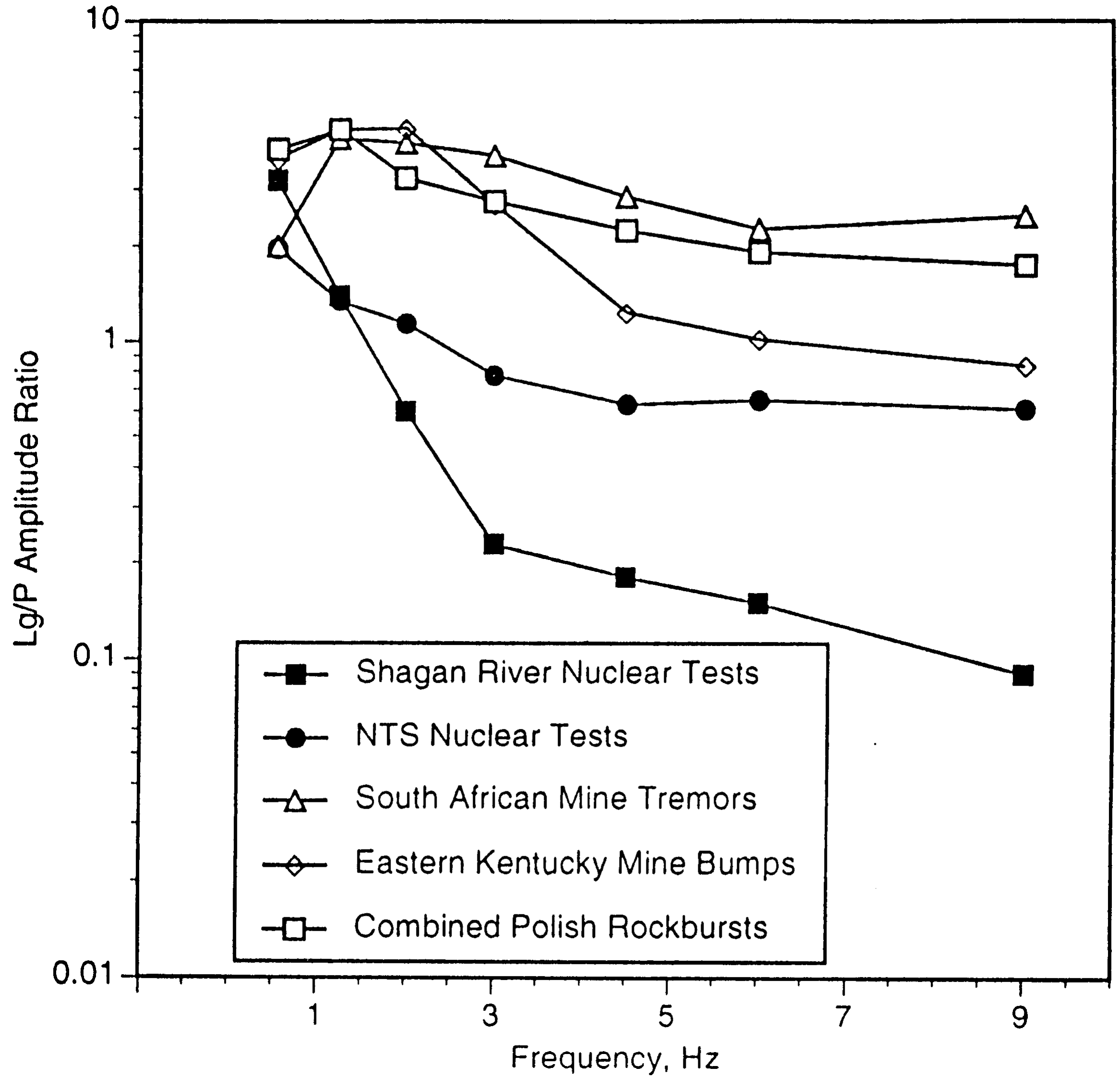

Figure 4. Comparison of Lg/P ratios in different frequency bands for rockbursts from three different source areas with average Lg/P ratios for nuclear explosion tests at NTS and Shagan River (cf. Bennett et al., 1996).

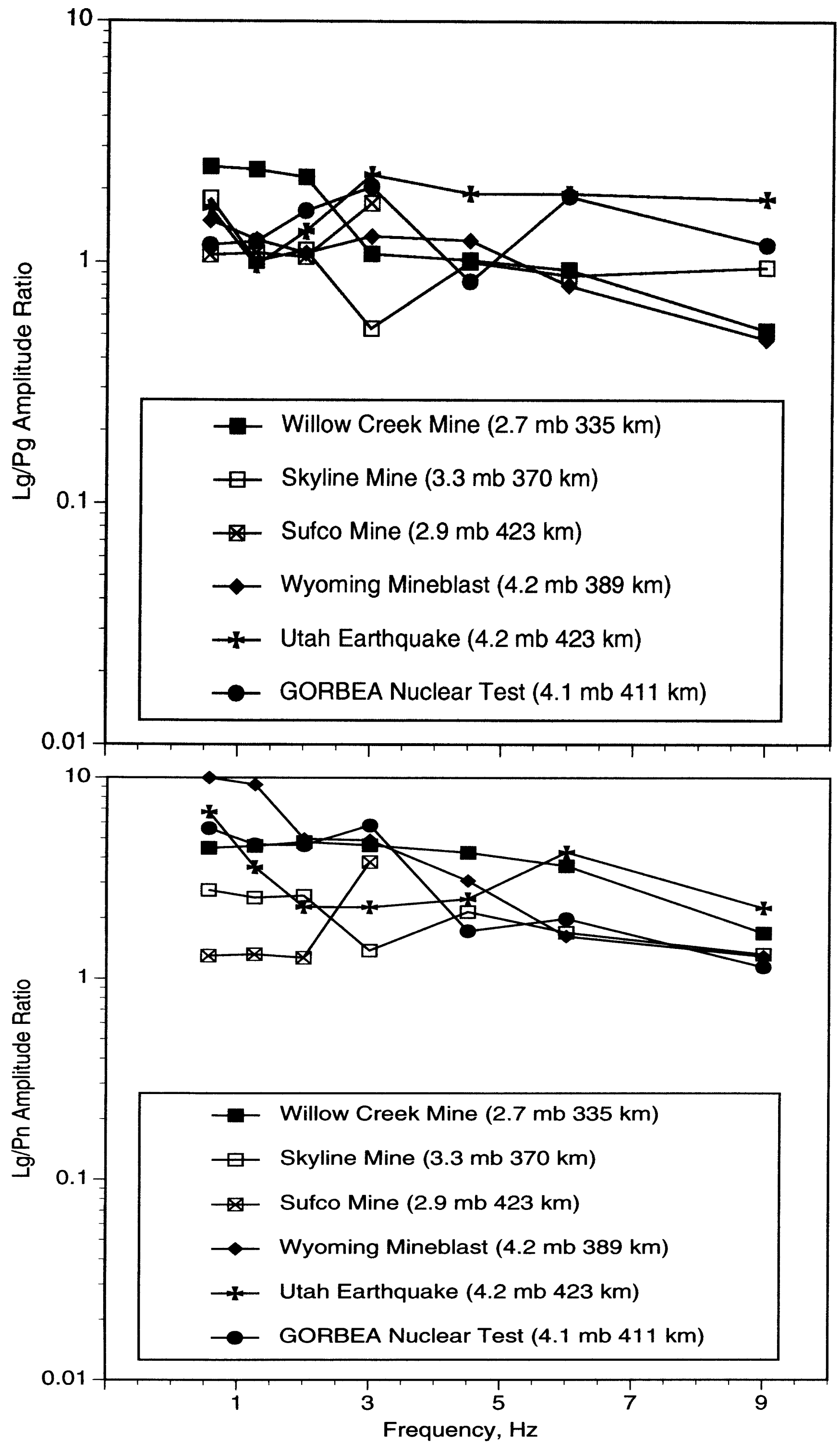

Figure 5. Comparison of Lg/Pg (top) and Lg/Pn (bottom) ratios in different frequency bands for several Utah mine tremors, a Wyoming mineblast, a Utah earthquake, and an NTS nuclear test recorded at similar regional distances.

CONCLUSIONS AND RECOMMENDATIONS

Rockbursts occur in mining areas throughout the world; and, although they are often small, there is a potential for larger events in most rockburst areas. Nominal PIDC/IDC screening procedures almost always fail in rockburst regions; the reason for failure is usually that the IMS station data at teleseismic distances are insufficient. Regional stations usually provide the strongest seismic signals from small rockburst events, and there appear to be some systematic differences in a variety of regional signal parametric measurements at IMS stations between rockburst and non-rockburst regions worldwide. We are continuing to investigate these and some other regional signal characteristics observed at IMS stations for selected events in a variety of rockburst areas where we have good ground truth. For one such area in the western U.S., where there is good ground truth for rockbursts, mineblasts, earthquakes, and nuclear explosions recorded at similar distances and similar stations, some preliminary results for screening with regional L_g/P ratios appear less promising than originally hoped. Further analyses and improved understanding of the variability in regional signal characteristics between events and between source regions are needed.

Key Words: seismic, screening, discrimination, regional, CTBT, PIDC, IDC, IMS

REFERENCES

Arabasz, W. J., and M. Wyss (1999), "Spatially-Varying b-Values in Coal-Mining Seismicity in Utah: Inferred Influence of Heterogeneity and Stress Differences on Local Mean Magnitude," Paper Presented at the 1999 Fall Annual Meeting of the American Geophysical Union.

Bennett, T. J., A. K. Campanella, J. F. Scheimer, and J. R. Murphy (1992), "Demonstration of Regional Discrimination of Eurasian Seismic Evnets Using Observations at Soviet IRIS and CDSN Stations," PL-TR-92-2090, ADA253275.

Bennett, T. J., M. E. Marshall, B. W. Barker, K. L. McLaughlin (1996), "Investigations of the Seismic Discrimination of Rockbursts," PL-TR-96-2184.

Bennett, T. J., and K. L. McLaughlin (1997), "Seismic Characteristics and Mechanisms of Rockbursts for Use in Seismic Discrimination," in Rockbursts and Seismicity in Mines, edited by S. J. Gibowicz and S. Lasocki, 61-66.

Bennett, T. J., M. E. Marshall, and R. W. Cook (1999), "Screening of Seismic Events in Rockburst Areas," Proceedings of the 21st Seismic Research Symposium, Las Vegas, 363- 373.

Fisk, M., S. Bottone, H. Gray, and G. McCartor (1999), "Event Characterization Using Regional Seismic Data," Proceedings of the 21st Seismic Research Symposium, Las Vegas, 427-437.

Taylor, S. R., N. W. Sherman, and M. D. Denny (1988), "Spectral Discrimination Between NTS Explosions and Western United States Earthquakes at Regional Distances," Bull. Seism. Soc. Am., 78, 1563-1579.