SCREENING OF SEISMIC EVENTS IN ROCKBURST AREAS

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

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ABSTRACT

Rockbursts present several unique challenges for seismic discrimination and event screening in the Comprehensive Nuclear-Test-Ban Treaty (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 research is directed at identifying rockburst regions with respect to their significance to CTBT monitoring at the International Data Centre (IDC) and at investigating the performance of some promising discriminant measures for use in IDC event screening in those regions.

Based on past experience, we identified 62 areas worldwide in which there have been historical reports of rockbursts associated with mining activity. In our initial efforts under this contract, we have searched the 1995-1999 database at the prototype IDC and found more than 900 events within 50 km of 34 of these mining areas. The majority of these events had magnitudes greater than 3. The most active of these areas were (1) three areas in Poland, (2) an area on the Kola Peninsula in northern Russia, and (3) five areas in South Africa.

We have been systematically reviewing preliminary event screening results from the pIDC and waveforms for events in all the rockburst areas and comparing those to pIDC observations for events outside of rockburst areas. The large majority of events from the historical rockburst areas are not screened out, as earthquakes, by the default screening procedures currently being tested at the pIDC; however, some are. For the three most active rockburst areas noted above, only four events were "screened out"; and those were on the basis of M_s-vs-m_b. The majority of the more than 900 events, from all areas, had "insufficient data" for screening, even though most had $m_b > 3$ and many had $m_b > 4$. In general, the pIDC data are inadequate for screening events from the rockburst areas using the current default screening procedures, which are based on (1) M_s-vs-m_b, (2) source depth, and (3) offshore-vs-onshore.

In an effort to identify more effective screening procedures for use with events from rockburst areas, we have been analyzing waveform data for events in each of the areas. We have retrieved waveform data recorded by the International Monitoring System network stations for the largest events in each of 32 different historical rockburst areas. For even these relatively large events, the teleseismic signals from the events in the rockburst areas are usually weak and are not likely to provide definitive screening. On the other hand, seismic signals from events in these rockburst areas are frequently strong at stations out to about 10º from the source. Measurements based on analyses of regional signals appear, then, to offer the most promise for screening events from rockburst areas.

We have been investigating several specific regional signal measurements to determine their screening potential for events in these areas. We have utilized the frequency-band spectral measurements of P_n, and L_g phases, as currently determined at the pIDC, to get some initial impression of the behavior of regional phase spectral discriminants in screening. There appears to be a preliminary indication from these measurements that events within the rockburst areas (presumed to be predominantly rockbursts) have L_g/P_n ratios in several frequency bands which are systematically larger than events outside the rockburst areas (presumed to be predominantly earthquakes). There also seems to be an indication that the L_g signals from events within rockburst areas have a tendency to be somewhat richer in some higher frequency passbands than the L_g signals from events outside the rockburst areas.

Key Words: seismic, screening, discrimination, regional, pIDC

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 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 events 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 discriminant behavior for significant rockburst areas worldwide.

RESEARCH ACCOMPLISHED

Our initial efforts in this research program have focused on the acquisition of data from the prototype International Data Centre (pIDC). In particular, from prior experience based on review of available technical literature, we have identified 62 areas worldwide in which there have been historical reports of rockbursts associated with mining operations. We searched the Reviewed Event Bulletin (REB) database at the pIDC during the time period from the beginning of 1995 to April of 1999 for events within 50 km of each of the mining areas, which have had historical rockbursts. This search found more than 1000 events in 34 different areas (cf. Figure 1); the REB database contained no events from the remaining 28 areas. Based on the REB data, the most active of the areas, which have had historical rockbursts, were (1) three areas in Poland, (2) an area on the Kola Peninsula in northern Russia, and (3) five areas in South Africa. Although the majority of the 1000 REB events from these areas had magnitudes greater than 3 (cf. Figure 2), the detection thresholds may differ significantly between the different rockburst areas. Some of the reported Polish and Kola events had magnitudes as low as 2, while South African events are seldom smaller than 3.5. In most of the areas which have reported events in the REB, the magnitude thresholds appear to be near 3.5. It seems likely that smaller events associated with mining in some of the other areas, where no REB events were reported, may have been missed because of the pIDC reporting criteria, which require signal detection at multiple International Monitoring System (IMS) stations. We are looking at alternative event lists for selected areas to assess what events from the rockburst areas might have been overlooked by pIDC processing.

We have also been systematically reviewing screening results and waveforms for events in all the rockburst areas. Screening results have been retrieved and compared for all events from the historical rockburst areas for which screening was attempted at the pIDC. Although the majority of events from these areas are not screened out as earthquakes, some are. Of the events in the principal rockburst areas, only four are “Screened Out” by the current pIDC default screening procedures based on (1) M_S-vs-m_b, (2) source depth, and (3) offshore-vs-onshore (cf. Table 1). Approximately 44 events from these areas are categorized as “Not-Screened.” A closer look at the screening measurements (cf. Table 2) indicates that the four “Screened-Out” events (three in South Africa and one in Poland) are screened on the basis of M_S-vs-m_b. Figure 3 shows a plot of M_S versus m_b for several historical events including numerous rockbursts, which has been adapted from a prior plot by Bennett and McLaughlin (1997). Where they were available, we have used pIDC magnitude measurements; National Earthquake Information Center magnitudes are used for some of the older events. These events include several of the largest rockbursts (e.g. the 1989 Völkershausen, Germany mine collapse; the 1994 Orange Free State, South Africa mine tremor; the 1995 southwestern Wyoming mine collapse; and the 1995 Urals rockburst in Russia). For reference we also show several decision lines which provide a potential basis for event screening. The four rockburst events, as described above, which are screened out by the preliminary pIDC screening procedures have been circled on this plot. It should be noted that the actual pIDC screening procedure incorporates an estimate of the M_S-m_b uncertainty associated with each event; so that the 3.1 M_S South African mine tremor is barely screened out at the nominal 97.5% confidence level. Furthermore, based on this screening procedure, many of the other events shown here would not be screened out, except for those that lie well above the line. Several of the "Not-Screened" events in South Africa have low M_S magnitudes and/or large M_S-m_b uncertainties which do not allow them to be screened out. The large magnitude uncertainties can be directly attributed to the small number of IMS stations reporting magnitudes. The relatively low M_S values from rockburst events is probably caused by their mechanisms, as suggested by Bennett and McLaughlin (1997) and by Pechmann et al. (1995). If the source mechanisms of mine collapses and some other types of rockbursts may be represented as closing of a shallow, horizontal tension crack, we would expect the kind of reduced long-period surface wave excitation and low M_S relative to m_b which is observed from many of these events.

We also looked more closely at the "Not-Screened" events and found that events which are "Not-Screened" in Poland often show what appear to be erroneous indications of depth. While the depths determined from the unconstrained pIDC location procedures for these Polish events are often greater than 10 km, the associated uncertainties are large; so that these events are not screened out based on their depths. Because these events are induced by the mining activity and are clearly shallow, any depths greater than a few kilometers determined from the location scheme are suspect, and probably erroneous. Therefore, event focal depths cannot provide reliable screening out of events from rockburst areas, except for a few areas where some natural earthquake activity may also be present and occurring at greater depths in the crust.

The remainder of the more than 900 events have "Insufficient Data," even though most have $m_b > 3$ and many have $m_b > 4$. As can be seen in Table 2 and as we would expect from their locations, none of the events from the three principal rockburst areas are categorized as "Offshore." It is, in fact, remarkable that some of these events are categorized as "Mixed." This is probably indicative of a large location uncertainty, which overlaps offshore areas, for some of these events. Although some of the historical rockburst areas are located along coasts or on islands (as can be seen in Figure 1 above), it is unlikely that any rockbursts can be categorized as "Offshore."

We are continuing to look at the other historical rockburst areas; but, in general, the pIDC data are inadequate for screening events from the principal rockburst areas based on the current default screening procedures. In particular, observations from predominantly teleseismic stations and the related discriminant measures, which rely on those observations, do not appear to be useful for screening most events from rockburst areas. We have, therefore, begun looking into alternative screening procedures for characterizing events from the historical rockburst areas, with particular emphasis on screening based on regional signal observations. These investigations have focused on (1) retrieval and analyses of waveform data from REB events in each of the areas; (2) analyses and comparisons of routine parametric measurements, which are currently being made at the pIDC, for use in screening of events within historical rockburst areas and outside those areas; and (3) investigation of selected regional phase signal characteristics for events from the rockburst areas. We have retrieved waveform data from each station which reported seismic signals from the largest of the REB events in each of the 34 areas. In addition, we have retrieved waveform data from additional REB events for several of the rockburst areas. This should enable analyses of the variability of the regional signals from within these rockburst areas. Past studies (cf. Bennett et al., 1994, 1995) have suggested remarkable consistency in the regional phase signals between events from individual rockburst areas. However, we also know that variations in mining practice can produce some differences in focal mechanisms (cf. Hasegawa et al., 1989; Gibowicz and Kijko, 1994; Bennett and McLaughlin, 1997) which can cause regional signal changes. It is anticipated that these observations of the variability for regional phases within selected rockburst areas will lead to better understanding of the uncertainty associated with potential discriminant measures based on the regional signal characteristics. The recorded signals will be used to determine discriminant measures, as described above, and to determine their reliability for future event screening in these areas.

With regard to the waveform data, we note that even the largest events from the rockburst areas are usually not very well recorded by the existing IMS network. The recorded signals are often weak and near the background noise level, particularly for stations beyond about 10°, for most of the events. This is illustrated in Figure 4 for a pIDC event of magnitude 4 M_L from a known rockburst area in southern Utah. The top part of Figure 4 shows, for the passband 2-4 Hz, the strong regional signals at the pIDC stations from 1.9º to 6.9º. However, beyond 11.4º the signal character for this event severely deteriorates, as can be seen in the bottom part of Figure 4. Even though the pIDC has managed to pick some phases at the more distant stations, the signal-to-noise level is often not very good. This behavior is fairly typical of the pIDC station waveforms for magnitude 3-4 events from the various rockburst areas. Figures 5 and 6 show the regional signals at pIDC stations, out to 10º, for events in two other rockburst areas. For the magnitude 3.8 M_L Polish rockburst in Figure 5, there are clear and strong P_n, P_g, and L_g phases at stations in northern Europe over a distance range from 2.2º to 9.8º. The magnitude 3.9 M_L South African rockburst, in Figure 6, shows good P_n, P_g, S_n, and L_g phases at the available pIDC regional stations between 2.7º and 8.9º. Although some IMS teleseismic stations may occasionally contribute to observations for use in event location, screening procedures for events in rockburst areas are likely to require higher quality signals and will probably depend on good regional signals observed over a sparse station network.

We are currently in the process of performing systematic analyses on the waveforms recorded at the regional stations for the largest events from each of the 34 rockburst areas for which we have retrieved pIDC data. We are determining L_g/P ratios as a function of frequency for these events and comparing with our past experience from other source types and with events from other rockburst areas. We have defined a regional signal complexity measure and have begun making a series of measurements on the regional P phases for the pIDC events, which we will compare to similar measurements for explosions and earthquakes. We are also attempting to look more closely at the character of regional long-period surface waves from these rockburst area events, by filtering the broadband records to enhance the low-frequency signals.

We have also reviewed results from some of the routine parametric measurements currently made at the pIDC to obtain some initial assessment of their potential use in event screening. In particular, we have been looking at measurements from events within historical rockburst areas compared to events outside the known rockburst areas. There appears to be a preliminary indication from these measurements that the observed seismic signals for events within the rockburst areas (presumed to be predominantly rockbursts) may be systematically different than those for events outside the rockburst areas (presumed to be predominantly earthquakes). Figure 7 shows that, for the distribution of L_g/P_n ratios in the frequency band 2-4 Hz, the ratios appear to be somewhat larger for events within rockburst areas than outside rockburst areas. We see similar systematic differences in each of the frequency bands for which the parametric measurements are available (viz. 4-6 Hz, 6-8 Hz, and 8-10 Hz). These observations suggest that the rockbursts are more efficient in generation of high-frequency shear waves (or less efficient in generating regional P) than earthquakes. We have also found differences in the L_g/P_g, S/P_n, L_g spectral ratios, and SP/LP ratios between pIDC events inside and outside rockburst areas. These results look rather interesting and need to be investigated more closely to understand their implications for event screening at the IDC.

CONCLUSIONS AND RECOMMENDATIONS

Over the past four years the pIDC has reported about 1000 REB events from more than half of the 64 known historical rockburst areas worldwide. Approximately 85% of these events had magnitudes greater than 3. Less than 1% of these events are screened out by the default screening procedures which are currently in use at the pIDC. In general, screening procedures based on focal depth, M_S-vs-m_b, and offshore-vs-onshore location are not likely to be effective for event screening in rockburst areas; in most cases IMS data from teleseismic stations are insufficient to obtain the measurements required to perform the screening. Screening of events in rockburst areas is likely to require the use of discriminant measures based on signal observations at regional stations. We have been looking at L_g/P, S/P, L_g spectral ratios, regional P complexity, and at regional long-period surface waves from events in rockburst areas. We have found that there appear to be some systematic differences in the regional signals between events inside and outside rockburst areas. Preliminary results suggest that rockbursts may be more efficient in generation of high-frequency regional shear waves than earthquakes.

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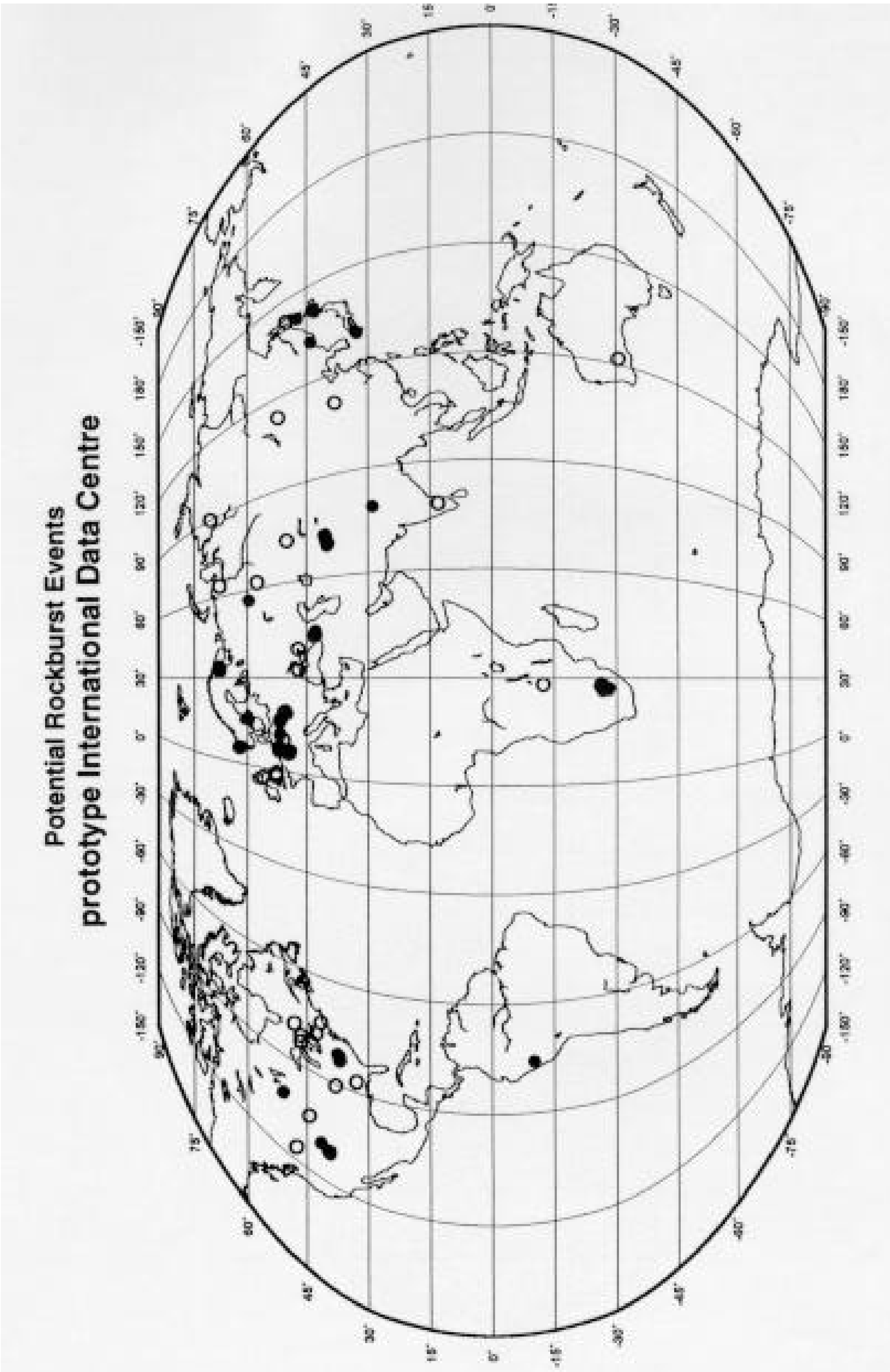

Figure 1. Locations of 990 events in 1995-1999 pIDC REB database that are within 50km of historical rockburst sites. Closed circles indicate sites with at least one REB event, and open circles show sites with none.

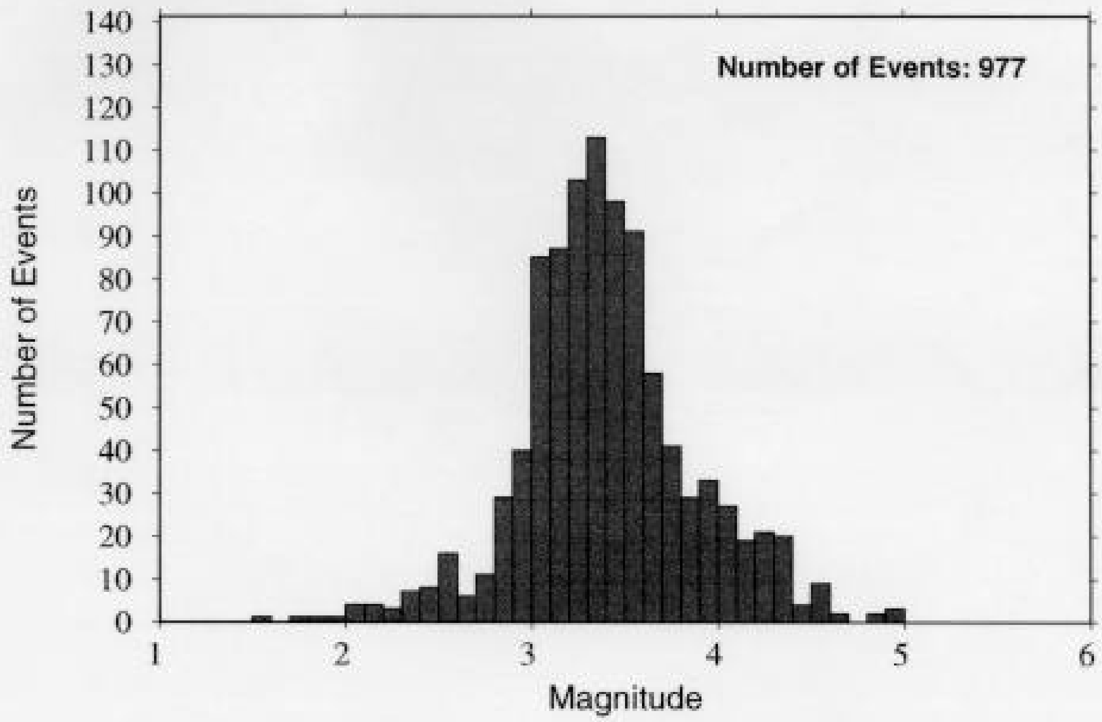

Figure 2. Distribution of potential rockburst events with respect to REB magnitude (m_b or M_L).

Table 1. PIDC preliminary screening results for the three principal rockburst areas.

Rockburst Region	Screened	Not-Screened	Insufficient Data
Poland	1	33	618
Kola Peninsula	0	5	161
South Africa	3	6	104

Table 2. Basis for pIDC preliminary screening results for the three principal rockburst areas.

Rockburst Region	m_b, M_s Measured	$1.25m_s - M_s + 2\sigma_M < 2.2$	Depth > 0	$D - 2\sigma_D > 10$	Offshore
Poland	1	1	33	0	0
Kola Peninsula	0	0	5	0	0
South Africa	8	3	1	0	0

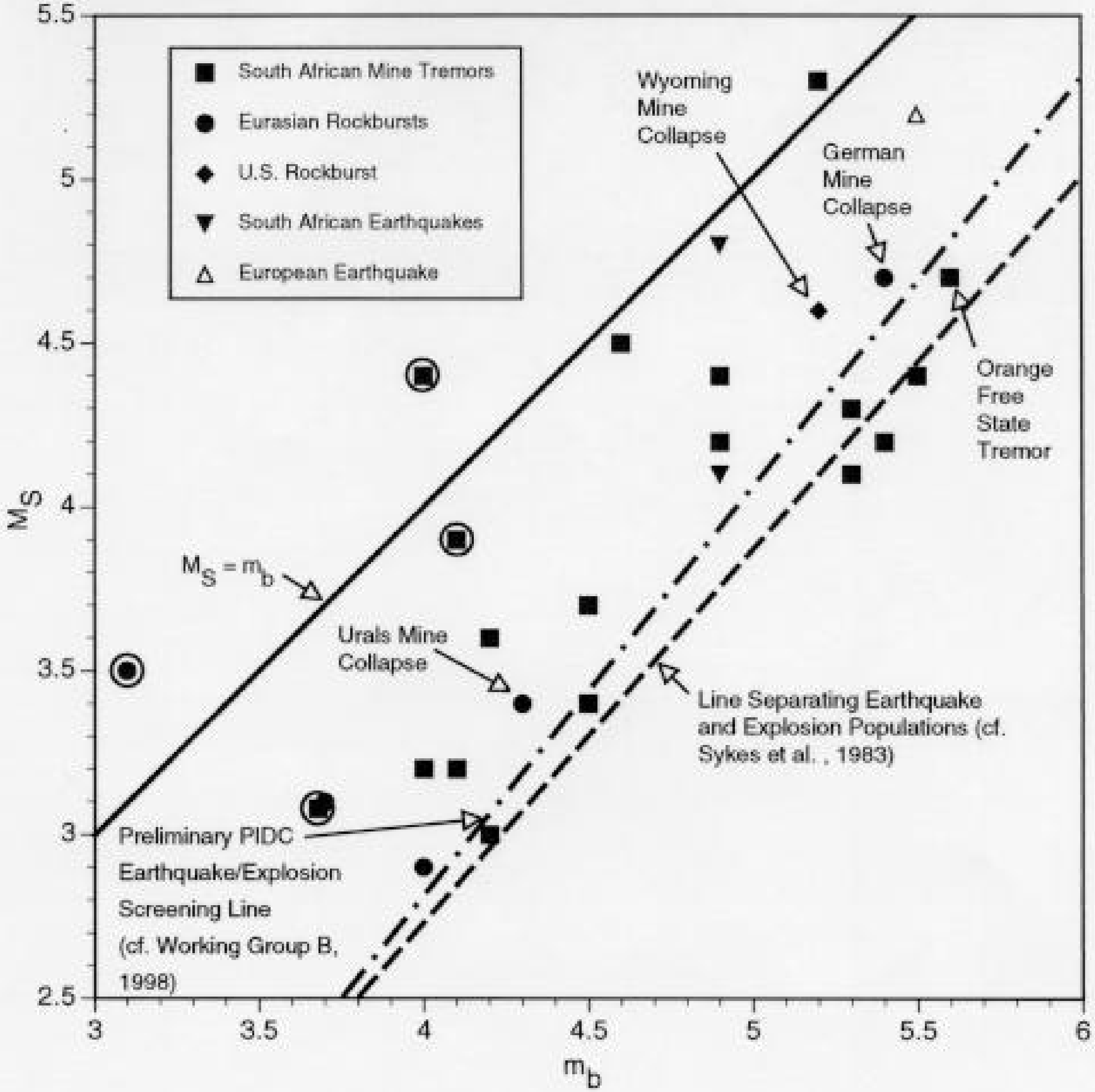

Figure 3. Ms-versus-mb observations for rockbursts and selected other events with earthquake/explosion screening lines shown for reference. Circled symbols show the four events from the principal rockburst areas which are screened out on the basis of the preliminary screening procedures at the pIDC.

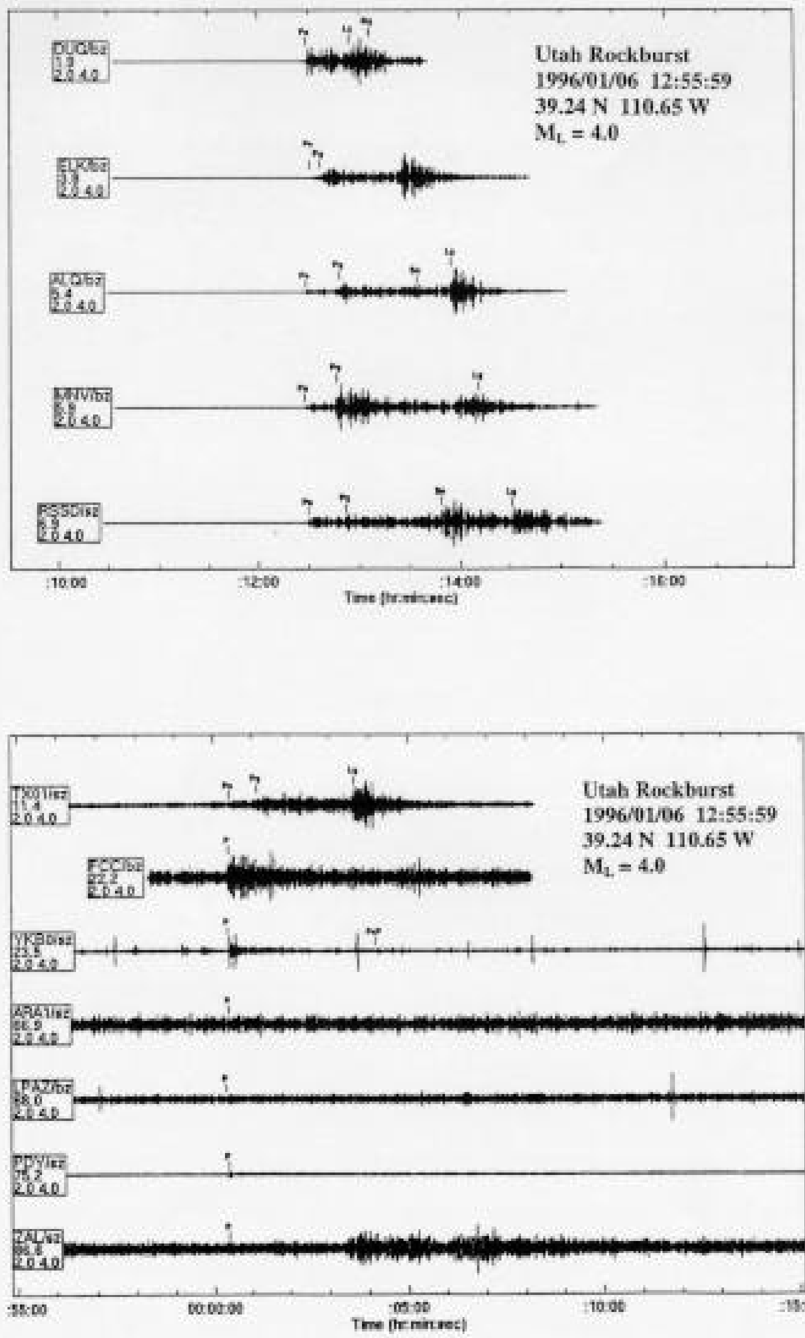

Figure 4. Seismic signals at pIDC stations from event in southwestern Utah rockburst area. Top – 5 stations at distances within 10°; Bottom – 7 stations at distances beyond 10°.

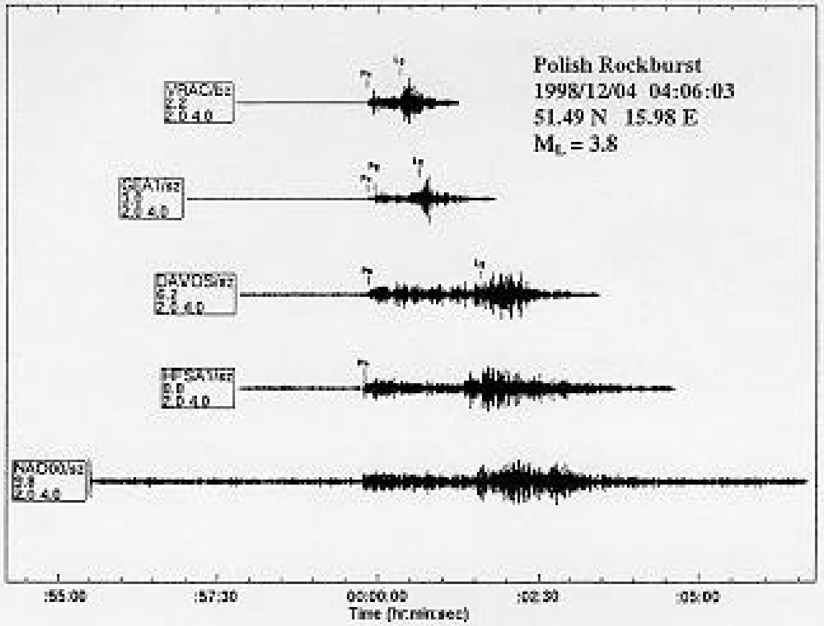

Figure 5. Seismic signals at 5 pIDC stations within 10° of event in Polish rockburst area.

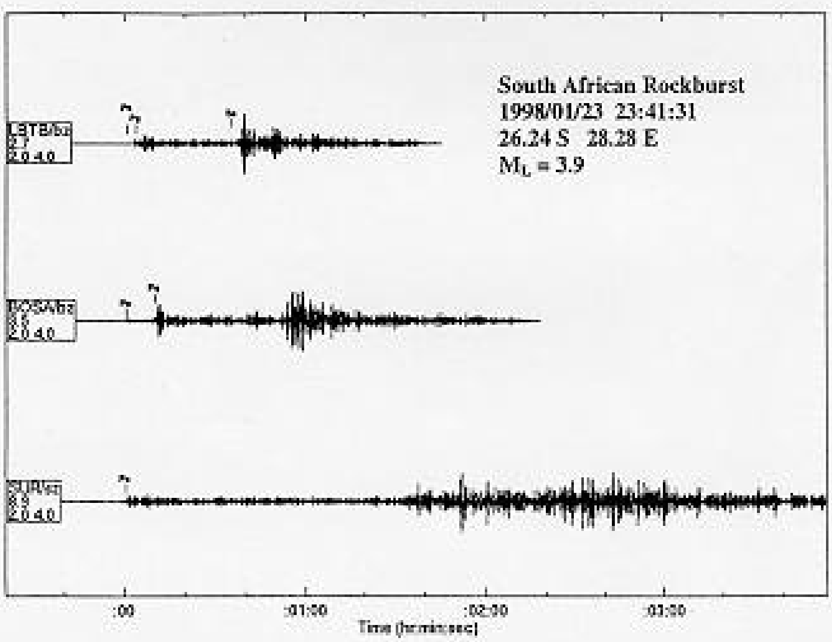

Figure 6. Seismic signals at 3 pIDC stations within 10° of event in South African rockburst area.

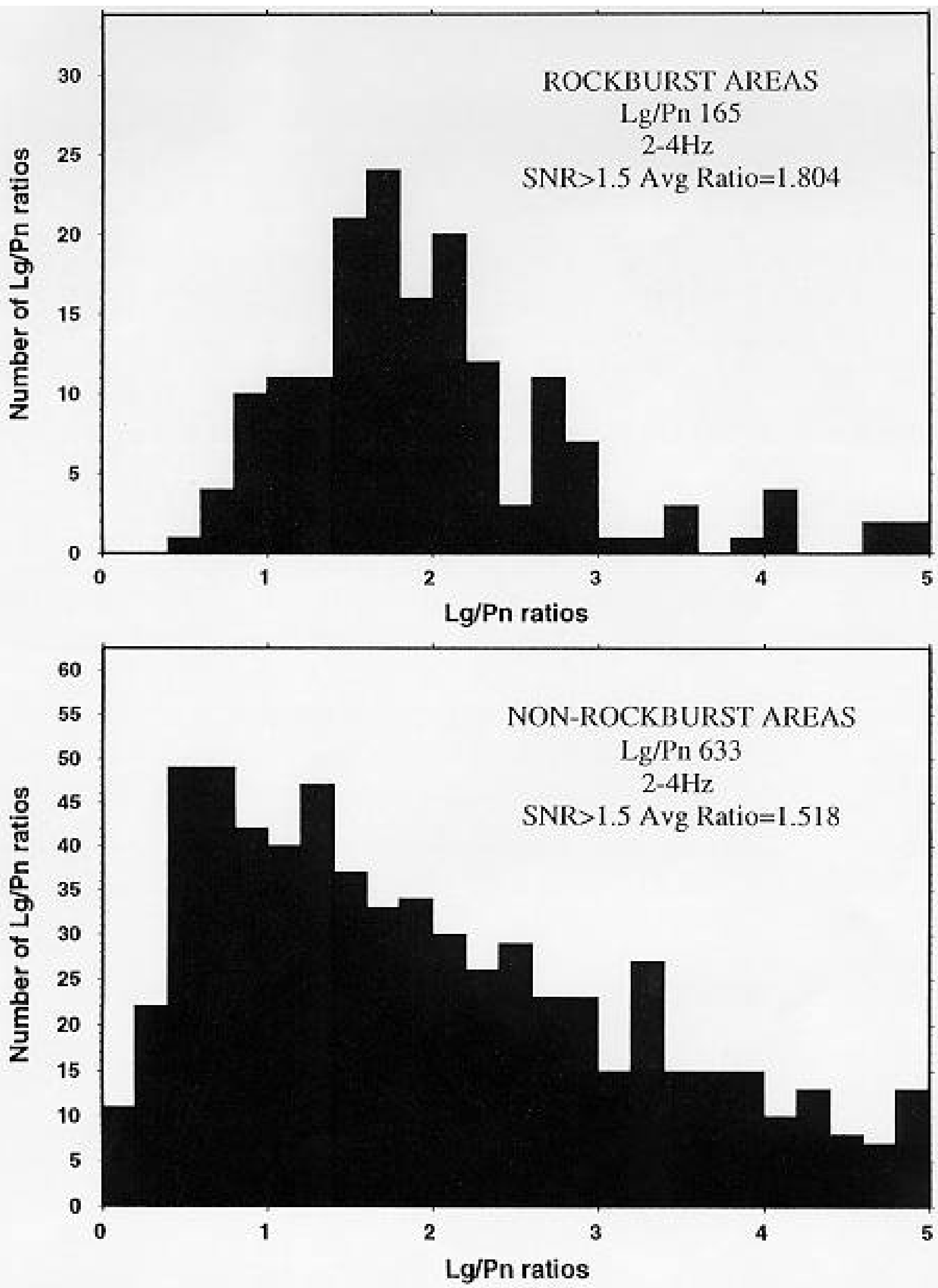

Figure 7. Distribution of Lg/Pn ratios in the 2-4Hz passband for pIDC events within the rockburst areas compared with event sample from outside rockburst areas.