Seismic Characteristics and Mechanisms of Rockbursts

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Contract No. F 19628-94-C-0083
Sponsored by AFOSR

Abstract

Rockbursts and related mining-induced seismicity present several interesting problems for seismic monitoring of potential underground nuclear explosion tests. Such events occur in mining areas throughout the world and may be quite frequent at levels currently of interest for CTBT. The shallow focal depths of rockbursts prevent their discrimination from nuclear tests on the basis of depth identification. Many rockbursts also appear to be inefficient in excitation of long-period surface waves which negates the effectiveness of the traditional M_S-vs-m_b discriminant. This research project is aimed at finding alternative ways to identify rockbursts or related mine tremors. One additional aspect of interest is that mine tremors may be deliberately triggered, which could provide an evasion opportunity if timing of such events can be accurately predicted. Our investigations have focussed primarily on regional seismic signal characteristics and source mechanisms which may distinguish mine tremors from other source types.

Over the past year or two, there have been several rockbursts in widely different tectonic environments. We have taken a close look at some of these events, including the February 3, 1995 (M = 5.2) mine collapse in southwestern Wyoming, the January 5, 1995 (M = 4.4) rockburst in the central Ural mountains, the October 30, 1994 (M = 5.6) mine tremor in South Africa, the March 11, 1995 (M = 4.0) mine bump in eastern Kentucky, and the March 12, 1994 (M = 3.6) mine collapse in northern New York. A consistent feature of the regional signals from all of these events appears to be relatively large S/P or L_g/P ratios. This behavior is similar to that seen in many earthquakes. The regional signals for rockbursts also often appear more complex than those from other source types. For the Wyoming event ground truth from the mine indicates collapse over a large area. Such collapses often have a strong implosional component distinct from the double-couple mechanisms seen in earthquakes.

Key Words: Seismic, Discrimination, Mechanism, Rockbursts, Earthquakes, Explosions, Regional, South Africa, Europe, North America, Evasion.

Objective

Rockbursts and related mine tremors present an unique challenge for seismic discrimination. 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 often used to distinguish between earthquakes and explosions. Therefore, the frequent occurrence of rockbursts and related events in mining regions throughout the world poses a potential problem for seismic monitoring at the levels currently considered of interest for the CTBT. Our principal objective is to identify and test regional discriminants which can help facilitate the identification of these numerous rockbursts. For this purpose we are pursuing analyses of empirical data from rockbursts in a variety of different mining, tectonic, and propagation environments. We are also 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 mining 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 are continuing to seek historical evidence supporting this predictive capability, and we also plan to use the results of theoretical model studies to further assess mining conditions which might be required to effect such evasion scenarios.

Research Accomplished

Interest in rockbursts or related mine tremors has been increasing over the past few years. This is only partially due to the recognition of the potential problem which they pose for seismic discrimination. The increased prominence for such events is due mainly to the occurrence within the past year or two of several large, destructive mine tremors which have drawn public attention because of the damage and, in some cases, fatalities which were caused by these events. The focus of our initial empirical investigations under this research program has been the characteristics of the seismic signals generated by several of these recent rockbursts. Some of these events occurred in tectonic regions different from those for which we had previously investigated the characteristics of regional seismic signals from rockbursts. Among the mining-induced events investigated for this study are the February 3, 1995 (M = 5.2) mine collapse in southwestern Wyoming, the January 5, 1995 (M = 4.4) rockburst in the central Ural mountains, the October 30, 1994 (M = 5.6) mine tremor in South Africa, the March 11, 1995 (M = 4.0) mine bump in eastern Kentucky, and the March 12, 1994 (M = 3.6) mine collapse in northern New York. For each of these events we have been attempting to compile a database of regional seismograms and performing a variety of time-domain amplitude comparisons and spectral measures of the regional phase signals. Where the data permit we have compared and contrasted the characteristics of the regional signals from these mine tremors with those from similar and alternate source types including events from the same and different tectonic regions.

The February 3, 1995 mine collapse in southwestern Wyoming is particularly interesting because it is one of the largest rockbursts historically to have occurred in

North America. The event produced extensive damage, numerous injuries, and resulted in a fatality. The epicenter of the event was located by the PDE at 41.5 N 109.8 W; and, assuming the source to be at the approximate depth of the mine, the focal depth is at about 0.5 km. The Wyoming mine collapse shows many similarities to the 1989 Völkerhausen, Germany rockburst which we analyzed in detail in a previously published report (Bennett et al., 1994) and which we have described at prior PL review meetings. In particular, both events produced dilatational P-wave first motions at nearly all regional and far-regional stations at all azimuths, which is indicative of a strong implosional component. Slumping above the Wyoming mine associated with the collapse reached a maximum of 0.9 m and averaged 0.6 m over a rectangular area of 1 km by 2 km. This is quite similar to the slumping seen above the German mine which averaged 0.9 - 1 m over an area extending 2 - 3 km laterally over the mine. The cause and mechanism for this event are currently being carefully scrutinized by the U.S. Bureau of Mines, and Pechmann et al. (1995) have already produced a scientific report describing background information on seismological parameters and seismic mechanism for the event. It appears from these initial studies that this event is likely to become one of the most carefully investigated mining-induced tremors and should ultimately have a very precisely defined source mechanism for use in improving understanding of the coupling of source energy into the radiated seismic field. The radiated seismic field in this case includes observations of signals at numerous regional and far-regional stations throughout North America. We have collected seismic waveform data for most of these stations from the Wyoming mine collapse. Our analysis here focusses on the signals recorded at the array station at Lajitas, Texas ($R \approx 1470$ km; cf. Figure 1). For comparison purposes we have selected several additional events of different source types which are located at comparable epicentral distances from the Lajitas station. These include an earthquake with magnitude 4.1 m_b in western Colorado ($R \approx 1300$ km), the NTS nuclear test JUNCTION ($R \approx 1470$ km) with magnitude 5.5 m_b, and the Little Skull Mountain earthquake of 06/29/92 in the southwestern part of NTS ($R \approx 1435$ km) with magnitude 5.6 m_b. The regional waveforms from each of these latter events were provided by SMU. In addition, we have analyzed the regional signals recorded by the Pinedale, Wyoming array station from the earthquake of 04/14/95 in southwest Texas ($R \approx 1500$ km) which provides a nearly reciprocal propagation path to the Wyoming mine collapse recorded at Lajitas.

We performed narrow bandpass filter analyses on the vertical component waveforms for each of the events. Figure 2 shows the results of the filter analysis for the Wyoming mine collapse. In all filter passbands the far-regional P phase appears very emergent. Ignoring apparent noise contamination at later times in the high-frequency bands (3-6 Hz and above) and in the vicinity of the P_g window in the 2-4 Hz band, L_g/P ratios appear to be generally well above one in all frequency bands for the mine collapse. There is also an indication of a long-period Rayleigh wave on the low-frequency (0.05-0.1 Hz passband) trace, but the amplitude is very low and near the level of the low-frequency background noise. The amplitude of the Rayleigh wave in this low-frequency band is only about one-twentieth that of the P wave in the 0.1-3 Hz passbands. In comparison, similar bandpass filter analyses for the northern Colorado earthquake and the reciprocal Texas earthquake showed slightly more impulsive regional P. The L_g/P ratios for the Texas earthquake were well above one in all frequency bands, while L_g/P ratios for the northern Colorado earthquake were well above one at lower frequencies and near one in higher frequency bands. Long-period

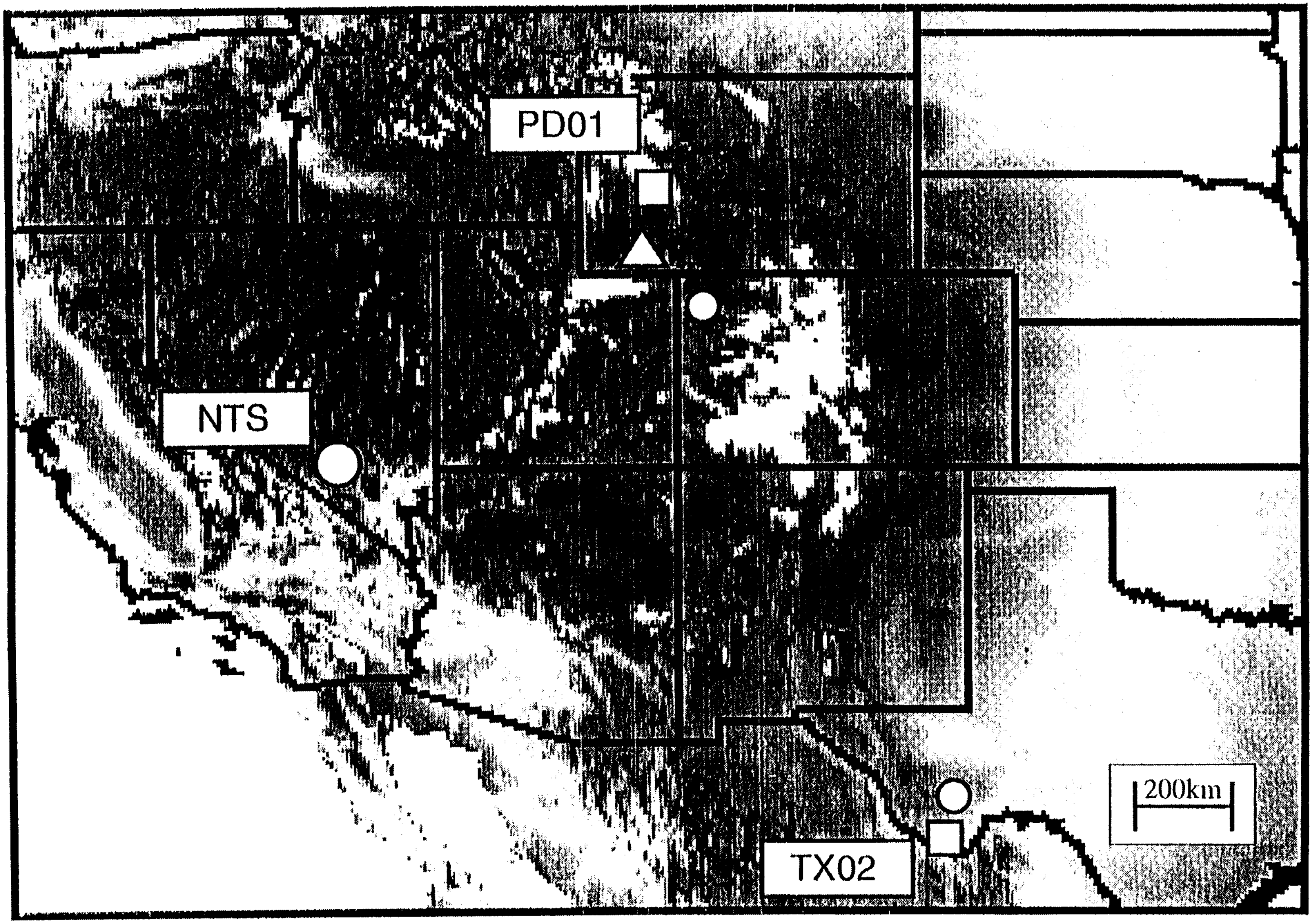

Figure 1. Locations of southwestern Wyoming rockburst of February 3, 1995 (△), earthquakes used in comparisons (○) and regional seismic stations (□).

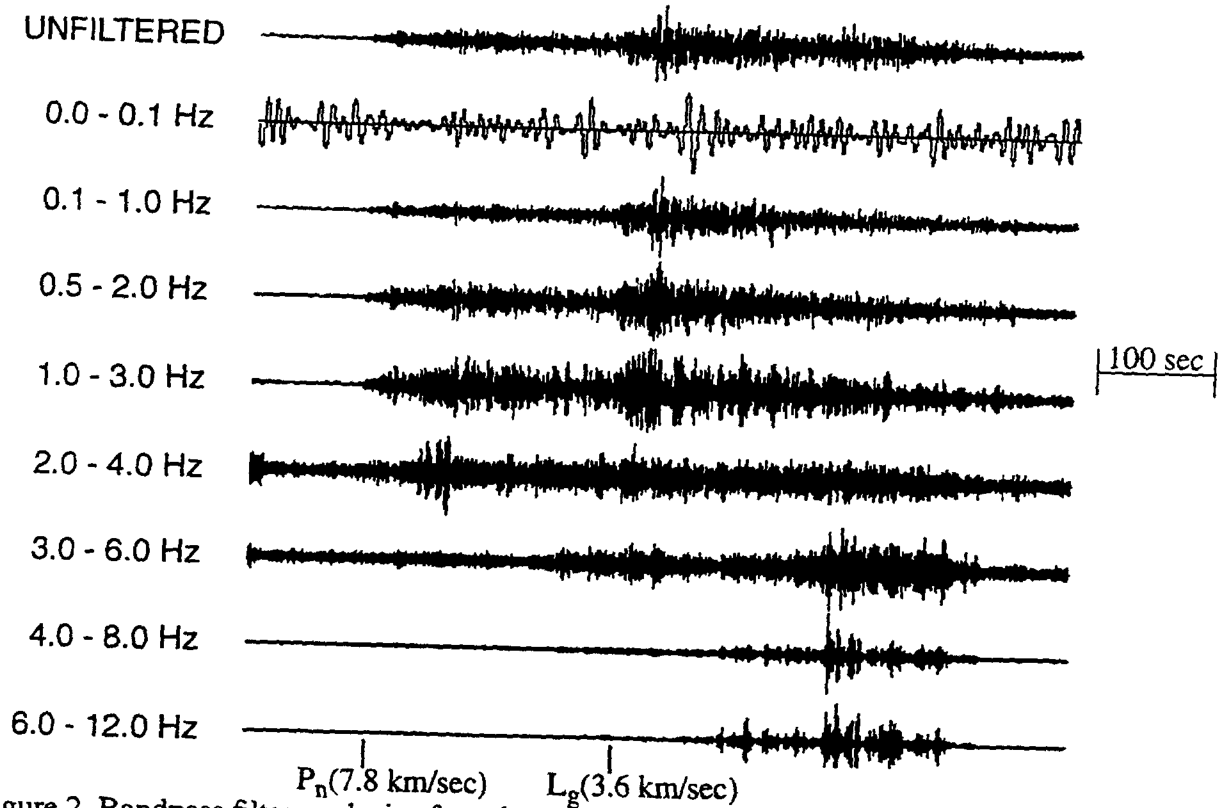

Figure 2. Bandpass filter analysis of southwestern Wyoming rockburst of February 3, 1995 recorded at Texas array (R = 1470 km). Note emergent P and large L_g/P ratio.

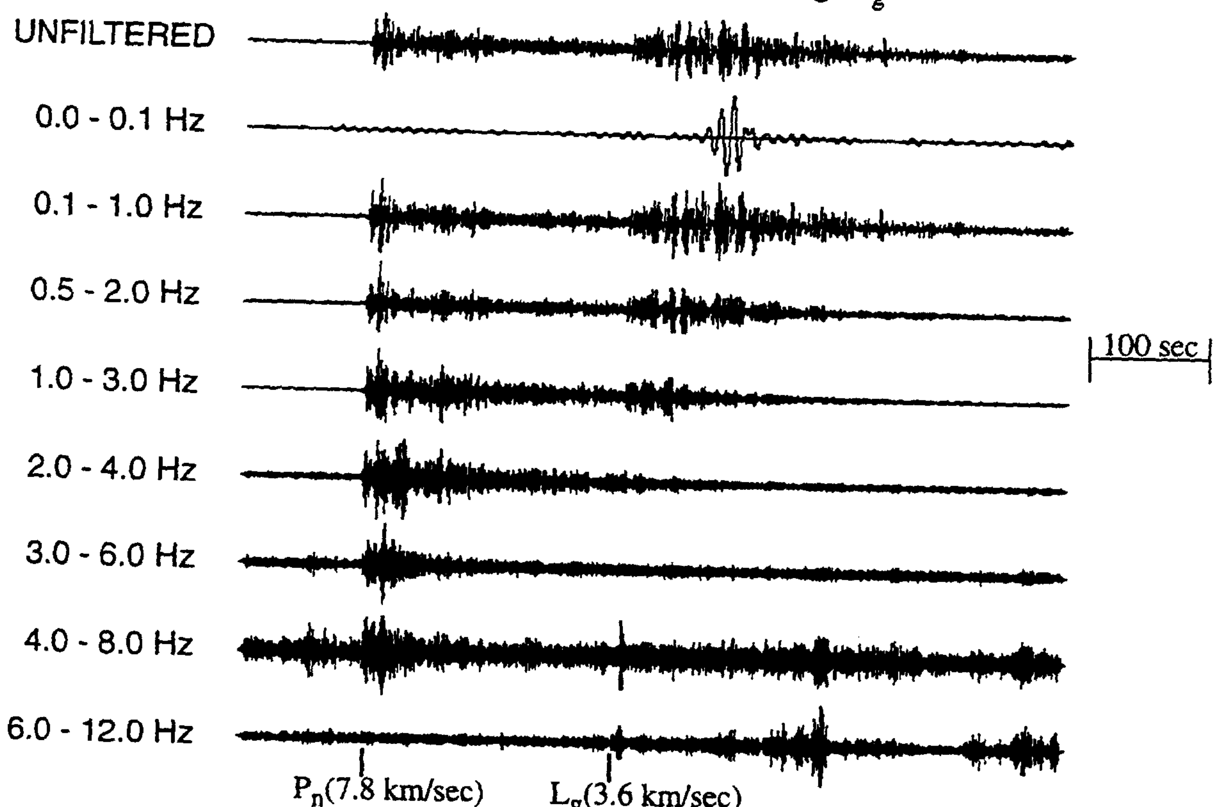

Figure 3. Bandpass filter analysis of the JUNCTION nuclear test recorded at the Texas array (R = 1470 km). Note sharp onset of P.

Rayleigh wave signals in the low-frequency passband were relatively large for the southern Texas earthquake but at or below the noise level for the Colorado earthquake. Perhaps the most interesting comparison from the standpoint of regional discrimination is to the band-pass filter results from the JUNCTION nuclear test. Figure 3 shows that analysis. The regional P phase is most prominent and has a clear onset at nearly all the high-frequency passbands from 0.1 to 6 Hz. The L_g/P ratio is near one at low frequencies (0.1-1.0 Hz) but falls off to well below one at high frequencies. It is also interesting that the passband 0.05-0.1 Hz shows a fairly strong long-period Rayleigh wave for the nuclear explosion about one-fortieth the size of the P in the 0.1-3 Hz passbands. The filter analysis of the Little Skull Mountain earthquake in southern Nevada revealed an even more prominent long-period Rayleigh signal with an amplitude in the 0.05-0.1 Hz band about two-thirds that of the regional P in the 0.1-3 Hz bands. These observations appear to be consistent with the report by Pechmann et al. (1995) that the surface-wave magnitude and moment magnitude for the Wyoming mine collapse were at least half a magnitude unit lower than m_b and M_L, which make these differences more like those typically seen for nuclear explosions than for earthquakes. The relatively large L_g/P ratios over a range in frequencies is also consistent with the behavior which we have seen for rockbursts in several other tectonic regions (cf. Bennett et al., 1994).

The South African mine tremor of 10/30/94 occurred in the Orange Free State mining district and was well recorded by the broad-band digital station at Boshof, South Africa ($R \approx 155$ km). In spite of the large magnitude of the event (viz. 5.6 m_b) and the proximity of the station, the regional signals are well recorded and on scale. The recorded waveforms provide an excellent opportunity to study the close-range behavior of the regional phase signals from South African tremors. We have also retrieved data for several mine tremors from other South African mining districts in the vicinity of Johannesburg at somewhat larger regional distances from the Boshof station which could be useful for investigating source variability and propagation effects. Figure 4 shows a bandpass filter analysis of the vertical-component record for the 10/30/94 mine tremor. The records show a strong R_g phase which is most prominent in the 0.5-2.0 Hz passband and clearly indicates the shallow focus of the source. S/P ratios are greater than one in each of the passbands. Finally, there is an indication on the trace corresponding to the 0.05-0.1 Hz passband of a fairly strong long-period surface wave. The amplitude of this surface wave is only about one-tenth the amplitude of the regional P signal in the 0.1-3 Hz passbands; however, it is difficult to draw implications from this observation since we have not compensated for the instrument response and we do not have available direct comparisons with other source types. Nevertheless, it should be noted that we have previously observed that South African mine tremors often produce M_S magnitudes at teleseismic stations which are up to one magnitude unit lower than the corresponding m_b (cf. Bennett et al., 1994). Similar long-period surface wave measurements at Boshof and other near-regional stations could provide a valuable link to understanding this surface-wave anomaly for rockburst sources.

With regard to the seismic source mechanism of rockbursts, six distinct models for mining-induced events were described by Hasegawa et al. (1989). These models are schematically illustrated in Figure 5. The various source models produce different seismic radiation, and we would expect this to be represented in differences in the regional signals which may be observed. Some rockburst mechanisms may simply correspond to the individual models shown in Figure 5, but others may be more

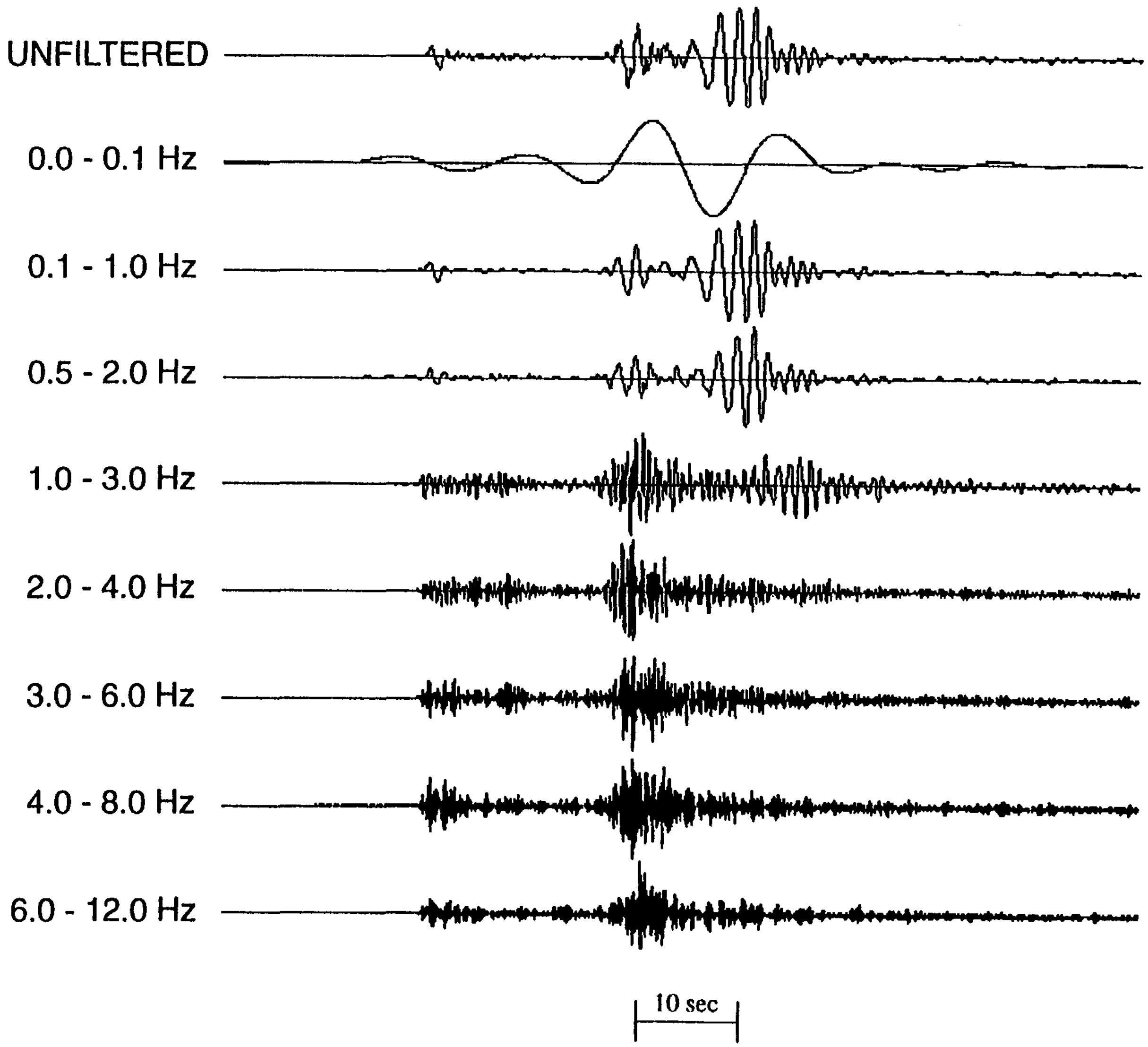

Figure 4. Bandpass filter analysis of large South African rockburst of October 30, 1994 recorded at station BOSA (R = 155 km). Note long-period surface wave, strong R_g and large L_g/P ratio.

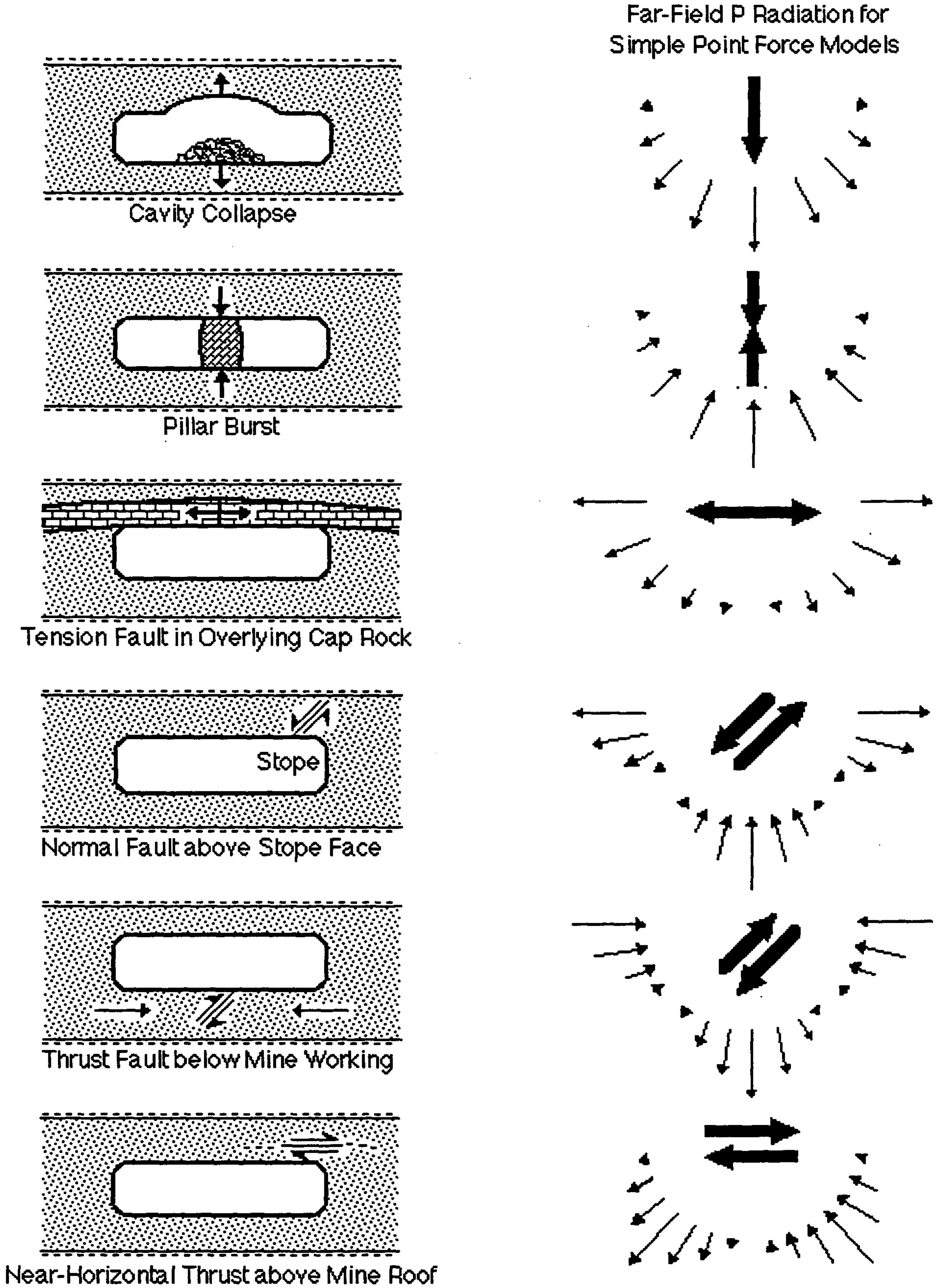

Figure 5. Simplified models of six rockburst mechanisms and corresponding P-wave radiation patterns (adapted from Hasegawa et al., 1989).

complex and represent combined effects of more than one model. In South Africa many large rockbursts are associated with shear failure on faults or zones of weakness near the excavation. These events often have double-couple mechanisms similar to those found in earthquakes and may draw some of their energy from the ambient regional tectonic stress field. Because South African rockbursts have been large, frequent, catastrophic, and studied for many years, that experience tends to dominate global understanding of rockburst behavior. However, the occurrence of some of the larger events in recent years in other tectonic regions (as described above) has suggested that some of the other models may also be significant and may sometimes produce more complex, non-earthquake mechanisms. Such anomalous mechanisms could present problems for seismic discrimination.

Some of the clearest examples of non-double-couple mechanisms appear to be mine collapse events. Simple calculations suggest that the gravitational potential energy released by dropping of the rock mass above the mine is adequate to account for the seismic energy in the 1989 Völkershausen, Germany event (cf. Bennett et al., 1994) and in the 1995 Wyoming event (cf. Pechmann, 1995). In the latter study the collapse was modeled as a horizontally oriented tension crack which closes by vertical motion. It was found that such a model generates dilatational first motions at all regional stations and fits the observed regional waveforms better than pure implosional or double-couple models. We believe that such a model can also explain the explosion-like M_S-m_b differences seen in many rockbursts of this type. Rockbursts which can be represented as closure of tension cracks would be expected to have low M_S because the Rayleigh waves for the shallow sources draw their principal energy from the M_{xx} and M_{yy} components of the moment tensor. The M_S-vs-m_b excitation will also depend to some extent on the rate of closure of the crack. If the collapse occurs more rapidly, the rockburst is more likely to appear explosion-like. However, a slower collapse or a rockburst associated with shear motion adjacent to the mine opening might be more likely to appear earthquake-like. Depending on the details of their mechanisms, rockbursts are likely to cover a broad range in M_S-vs-m_b and corner frequency dependence which overlaps explosion and earthquake behavior.

Conclusions and Recommendations

Rockbursts and related mine tremors pose some unique problems for seismic discrimination under a CTBT. They occur in mining areas throughout the world and are frequent in some areas. Because rockbursts are shallow, depth discriminants will not be effective. Observations from events in several different regions indicate a relatively low excitation of long-period Rayleigh waves in rockburst events. This behavior tends to make some rockburst events appear explosion-like with respect to the traditional M_S-vs-m_b discriminant. Regional phase signals observed from rockbursts or mine tremors in several regions show consistently large S/P or L_g/P ratios, which is analogous to the behavior seen in many earthquakes. Regional signal observations for some events also suggest greater complexity in the rockburst sources. Several of the larger recent rockbursts which have occurred in different parts of the world are known to have been associated with large-scale collapse in mine workings. Such collapses have a strong implosional component and may tend to be weak exciters of long-period Rayleigh waves. We are continuing to investigate the implications of different rockburst mechanisms for various regional discrimination methods.

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