

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

$M_s:m_b$ DISCRIMINATION STUDY OF MINING EXPLOSIONS IN WYOMING, USA AND QIANAN, CHINA

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Sponsored by Air Force Research Laboratory

Contract No. DTRA01-02-C-0003

ABSTRACT

Regional networks often record many mining explosions. The relative excitation of regional body and surface waves is useful in identifying these mining events. We investigate the use of intermediate period surface wave magnitude, M_s , and high frequency body wave magnitude, m_b , from regional mining explosions for event discrimination using techniques originally intended for teleseismic observations. Data for this study are taken from a portable broadband deployment in Wyoming recording mining explosions in the Powder River Basin and a broadband network currently deployed in northeast China. The magnitudes, M_s and m_b , were estimated for five, kiloton-size mining explosions, four in Wyoming and one in QianAn, China.

These kiloton-size mining explosions, used to remove overburden or to fragment rocks, are conducted with delays between an array of individual charges resulting in source durations up to several seconds. The total size of the explosion, its time duration and spatial characteristics generate short- to intermediate-period (1 ~ 20 s) surface waves. These surface waves provide an opportunity to constrain upper crustal shear structure and attenuation. The fundamental mode Rayleigh wave dispersion curves were estimated using multiple filter analysis and refined by phase matched filtering. The associated dispersion curves were used to make path corrections to the observed surface wave amplitudes so that intermediate period surface wave magnitude, M_s , estimates could be made for each mining explosion. Multiple surface wave observations along different paths for each event provided a measure of the importance of the path corrections. In Wyoming, the path corrections vary significantly from station to station reflecting the heterogeneous structure in the area. In China, all but one of the corrections are similar reflecting common paths across the Yanshan Uplift. Despite differences in the path corrections, the final M_s estimates in China and Wyoming produce similar values for common events as illustrated by the small standard deviation values. Regional body wave magnitudes, m_b , were estimated for these events as well. The body wave magnitudes are similar (m_b 2.9 to 3.4) sized for all the explosions except one of the Wyoming mining explosions.

The resulting network $M_s:m_b$ data were compared to data from a previous study that included earthquakes and contained, single-fired explosions (Stevens and Day, 1985). Although the previous study examined mostly larger events than those in this study, the Wyoming and China mining events plot in or near the earthquake population. Data from one Wyoming event, an anomalous blast in which a failure of the timing system caused a large portion of the blast pattern to simultaneously detonate, plots within the explosion population with m_b 4.39. The simultaneous detonation increased the body wave magnitude but had little effect on surface wave amplitudes. This study illustrates a possible approach to the inclusion of intermediate period surface waves for discrimination. The range in amplitudes associated with the raw intermediate period surface waves illustrates that path corrections are critical. The application of path corrections based upon dispersion analysis was found to significantly reduce the scatter. The actual values of M_s and m_b suggest that the surface waves generated by long duration mining explosions can make them appear earthquake like. The data from a single anomalous shot indicates that if a significant part of the total explosives is simultaneously detonated the event will fall into the explosion population.

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OBJECTIVES

Large-scale chemical blasts are routinely conducted by the mining and quarrying industries to remove overburden or to fragment rocks. Large mining explosions are conducted with delays between individual charges in an array, resulting in source durations as great as several seconds. The total size of the explosion, its time duration, and spatial characteristics can generate short- to intermediate-period (1-20 s) surface waves (Hedlin *et al.*, 2002; Zhou *et al.*, 2003; Zhou and Stump, 2004). Analysis of surface wave dispersion provides a method for determining the shear-wave velocity distribution in the Earth.

Characterization of propagation path effects provides for further study of source induced differences in the regional waveforms. Data from Wyoming and Northeast China blasts are used to study the generation of regional seismic signals from mining explosions. We focus on both the body waves and intermediate period surface waves from these sources. A physical understanding of mining explosions as sources of regional seismic waves would provide a basis for the development of seismic discriminants for the different source types. The existence of regional body waves and intermediate period surface waves from these sources suggests that a modification of the successful $M_s:m_b$ teleseismic discriminant (Stevens and Day, 1985) might be worth examination.

Marshall and Basham (1972) have suggested that M_s estimation can be extended to smaller events and shorter periods. It is recognized that regional observations hold the key to better monitoring at low magnitudes. There is therefore high interest in extending $M_s:m_b$ applicability to regional data (Patton, 2001; Bonner, *et al.*, 2003). Characterization of short-period propagation path effects on regional surface waves will be critical to such applications. To understand the applicability of this discriminant the relative surface wave excitation difference between contained possibly nuclear single-fired explosions and delay-fired mining explosions must also be assessed (Myers *et al.*, 1999). The data and propagation models from Wyoming and northeast China provide the basis for the study of some of these effects. Path specific models for both northeast China and Wyoming will be used to investigate a possible broadband regional discriminant, $M_s:m_b$.

RESEARCH ACCOMPLISHED

Study Areas and Data

Data for this study are taken from a portable broadband deployment in Wyoming recording mining explosions in the Powder River Basin (Figure 1a and 1b) and a broadband network currently deployed in northeast China (Figure 1c).

The Wyoming events (Figure 1b) are four kiloton size (2.07, 1.12, 1.26 and 2.70 kiloton for event 96201, 96214, 96215 and 97226, respectively) cast blasts from the Black Thunder Mine, the largest producer of coal in North America. Four temporary broadband seismic stations were deployed in a ring at 200 km range from the mine. To examine the range dependence of the waveforms station KRET was deployed about 100 km north of the mine along the azimuth to CUST. The Powder River Basin is outlined in white in Figure 1a. The total explosive of the QianAn event is 1.3 kiloton from an iron mine in China, the largest open-pit iron mine in Asia. Stations AYPY, BAKOU, MJPU and YFANG are four broadband seismic stations operated by Southern Methodist University (SMU) and Institute of Geophysics, China Seismological Bureau (IGCSB) (Figure 1c). Station BJT is a China Digital Seismic Network (CDSN) station. The raw observed vertical component seismic data from these five events are presented in Figure 2.

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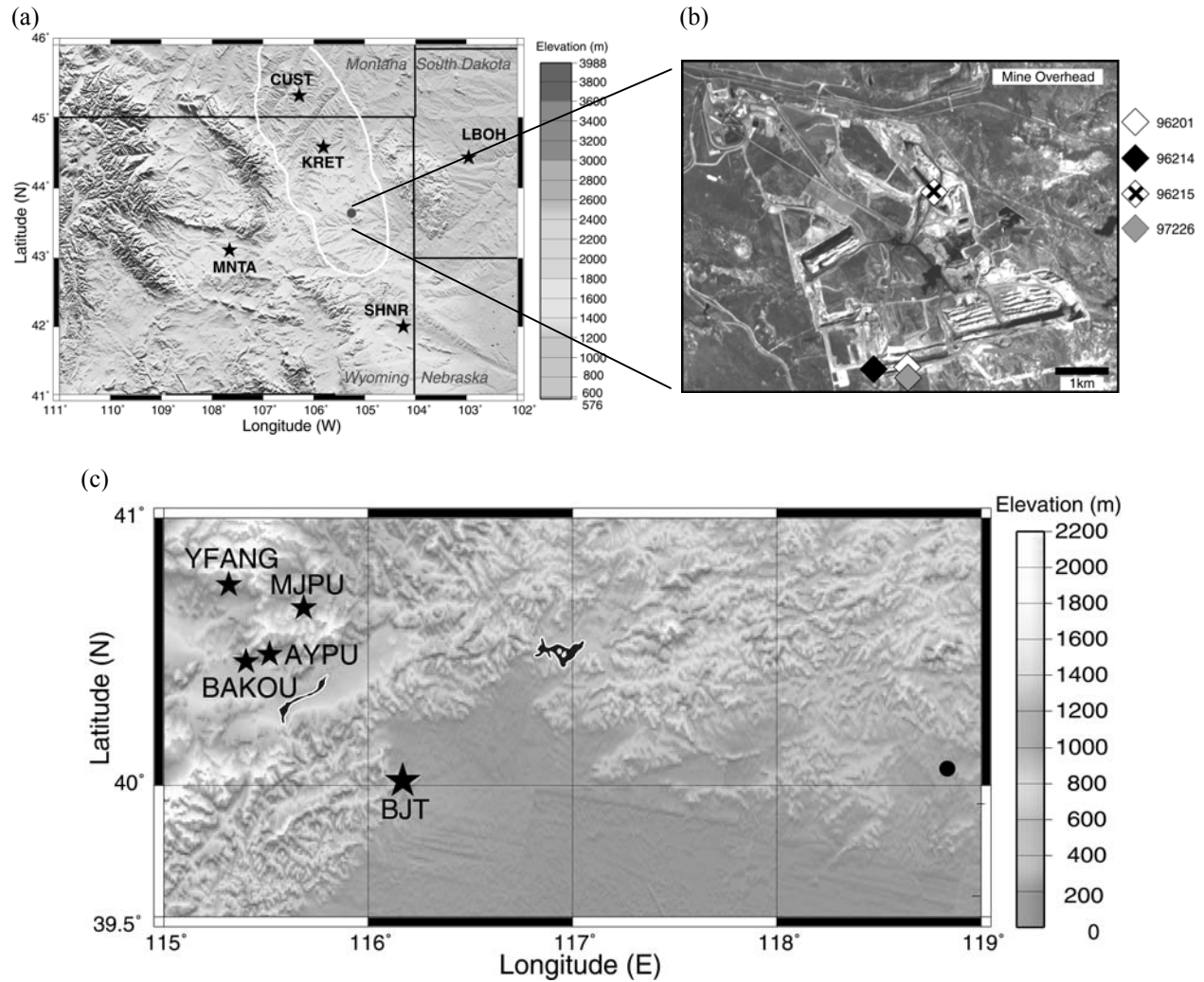


Figure 1. Study areas (a: Wyoming, USA; c: QianAn, China) with the locations of stations (stars) and events (dots). b is the locations of four events at Wyoming superposed on a satellite photo of the Black Thunder coal mine at Powder River Basin outlined by white line in (a), Wyoming.

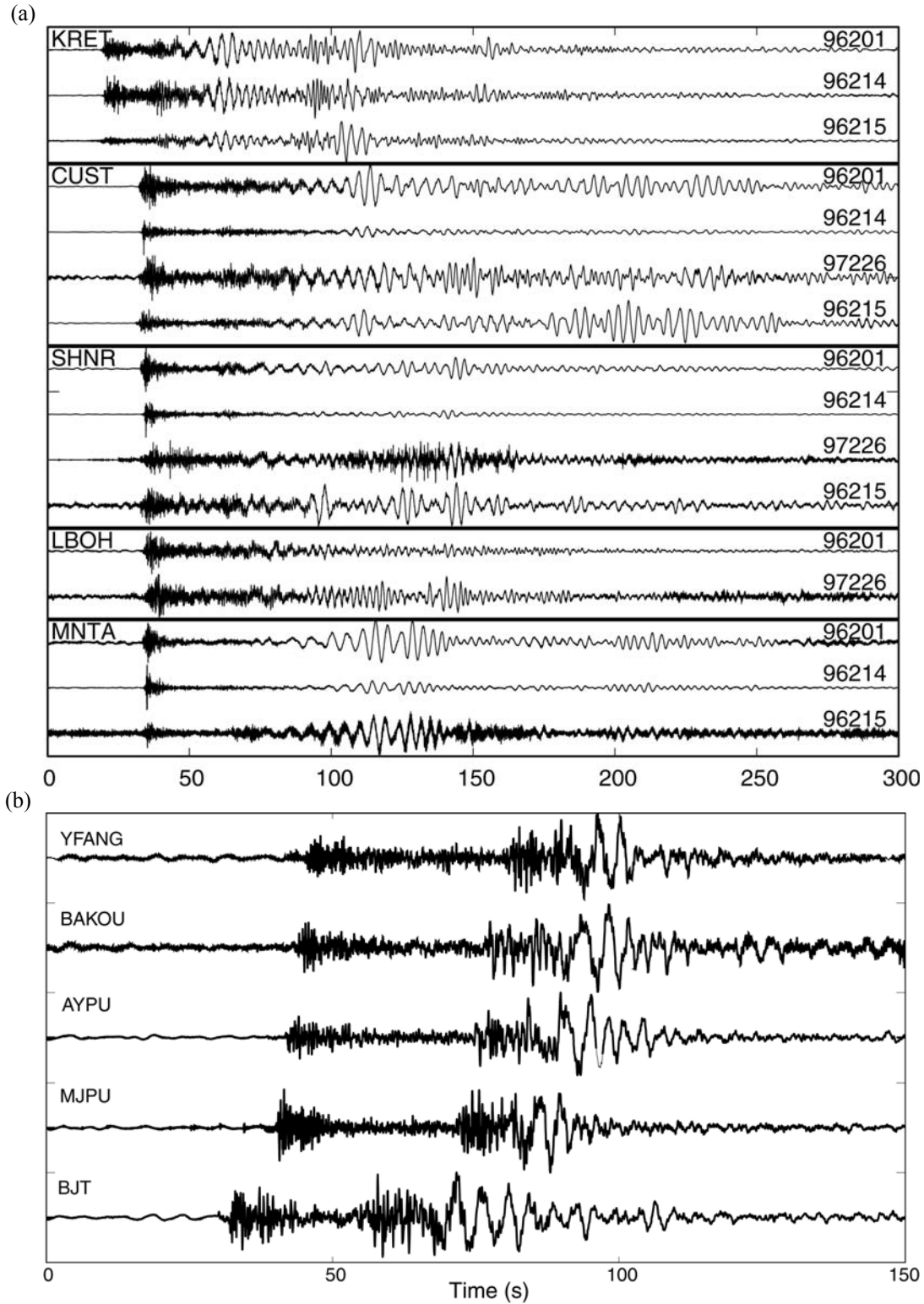


Figure 2. Vertical-component seismograms at all stations for the four events at Wyoming (a) and the event in QianAn, China (b).

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M_s Estimation

Quantification of dispersion curves and the inferred velocity model for intermediate period surface waves opens the opportunity to estimate surface wave magnitudes at intermediate periods. Application of such estimates to the explosion waveforms and determination of body wave magnitudes provides for the investigation of such measures as discriminants between earthquakes and explosions.

Comparing M_s and m_b values for earthquakes and nuclear explosions has proven to be a successful teleseismic discriminant (Stevens and Day, 1985) since for a common body wave magnitude, earthquakes are more efficient in generating surface waves than are explosions. The theoretical understanding of this relationship is related to the source function of the two event types, the materials surrounding the source, and the source depth.

M_s in these teleseismic studies was defined for Rayleigh waves by Gutenberg (1945) with periods near 20 s for events recorded at epicentral distances greater than 20°. Marshall and Basham (1972) have suggested that M_s determination can be extended to smaller events and shorter periods. Regional observations hold the key to better monitoring at low magnitudes and it is therefore of interest to extend $M_s:m_b$ applicability to regional data (Patton, 2001; Bonner, *et al.*, 2003). The mining explosion data from China (Zhou *et al.*, 2003) and similar data from mining explosions in Wyoming (Zhou and Stump, 2004) provide regional data for exploring this set of discriminants.

Following the suggestion of Marshall and Basham (1972) the regional M_s is defined as:

$$M_s = \log_{10}(A) + B'(\Delta) + P(T) \quad (1)$$

Where A is the Rayleigh wave amplitude (zero-to-peak in nanometers), $B'(\Delta)$ is an attenuation correction as a function of distance (Δ) in degrees, and $P(T)$ is a path correction as a function of period T. The distance correction, $B'(\Delta)$, is particularly important at regional distances. Basham (1971) suggested $0.8 \cdot \log_{10}(\Delta)$ as an appropriate distance correction for both earthquakes and explosions in the period range 8-14 s. If one knows the group velocity dispersion curve then the path correction $P(T)$ can be estimated as (Marshall and Basham, 1972; Denny *et al.*, 1987; Bonner *et al.*, 2003):

$$P(T) = \frac{U}{T^{3/2} \sqrt{\frac{dU}{dT}}} \quad (2)$$

The $P(T)$ corrections are normalized to 20 s period in order to compare the short-period results with conventional M_s measurements.

Group velocities of fundamental mode Rayleigh waves were estimated using the Multiple Filter Analysis (MFA) technique (Dziewonski *et al.*, 1969) and refined with Phase Matched Filtering (PMF) (Herrin and Goforth, 1977). A set of programs written by Herrmann (1988) has been run for MFA and PMF. A program written by David Harkrider (personal communication) at Weston Geophysical has been used to calculate $P(T)$ using equation 2 and the empirically derived group velocity curves for the regions of interest. To calculate the $P(T)$ correction, we averaged the dispersion curves for each path obtained after PMF (Figure 3). Although the period range of the surface waves from those mining explosions are from 1 to 20 s, the periods of the maximum amplitudes of Rayleigh waves recorded at these near regional distances fall at about 4~5 s for both regions (Figure 10 in Zhou and Stump, 2004 for Wyoming, and Figure 6 in Zhou *et al.*, 2003 for China). Based on these observations, we decided to make our surface wave measurements at period of 4.5 s. The $P(T)$ corrections for Wyoming and China are listed in Table 1. The amplitudes of surface waves are measured from the fundamental Rayleigh waves after PMF. The average M_s of all stations for all events with the standard deviations (σ) are listed in Table 2.

For the Wyoming data, the path corrections (Table 1) vary significantly from station to station reflecting the heterogeneous structure in the area. For the China data, all but one of the corrections are similar reflecting common paths across the Yanshan Uplift. In China, the station BJT has a quite different path correction because the path from the explosion to this station is dominated by the Hebei Plain. Despite differences in the path corrections, in both China and Wyoming the final M_s estimates produced similar values at the different stations for common events

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as illustrated by the small standard deviation values in Table 2. This result suggests that the intermediate period surface wave estimation procedure used here is a consistent measure.

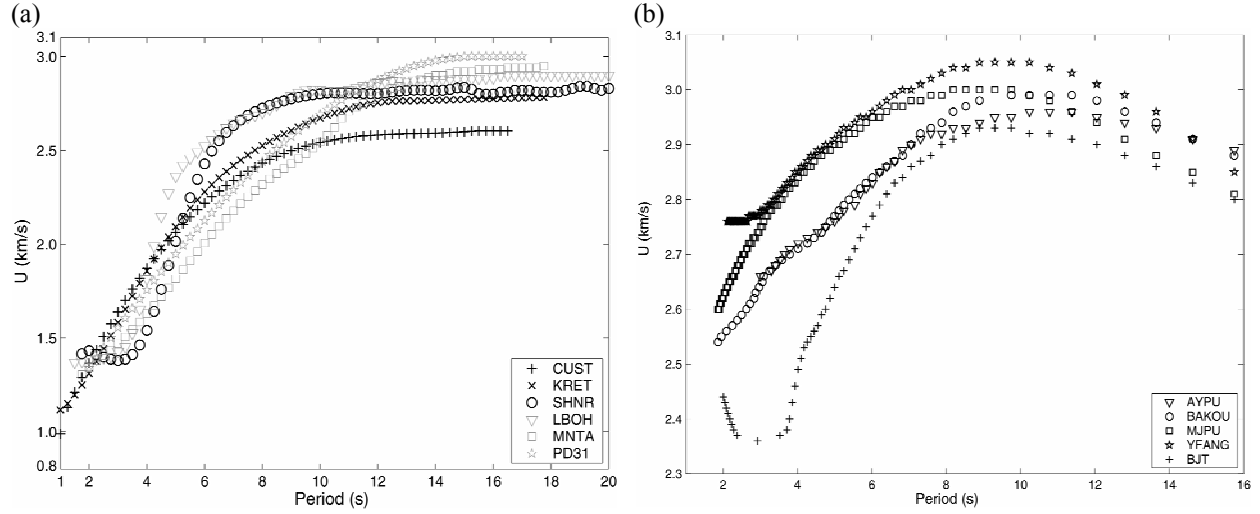


Figure 3. Averaged dispersion curves from Wyoming events (a) and QianAn event (b)

Table 1. P(T) corrections for Wyoming, USA and QianAn, China

Region	Station	P(T)
Wyoming, USA	CUST	-0.69
	KRET	-0.63
	LBOH	0.23
	MNTA	-0.35
	SHNR	-0.24
QianAn, China	AYPU	-0.63
	BAKOU	-0.54
	BJT	-0.17
	MJPU	-0.49
	YFANG	-0.54

Table 2. Averaged M_s of events

Event Code	Yield (kg)	M_s	σ
96201	2065412	3.04	0.14
96214	1117171	2.94	0.10
96215	1264181	3.02	0.20
97226	2704937	2.94	0.35
02363	1301000	2.86	0.26

m_b Estimation

For the events in Wyoming, we use the Denny *et al.* (1987) body wave magnitude formula, which was specifically developed for the western United States from an extensive database of earthquakes and nuclear explosions at or near the Nevada Test Site. It is:

$$m_b = \log_{10}(A) + 2.4 \cdot \log(\Delta) - 3.95 + c_i \quad (3)$$

Where A is the peak-to-peak amplitude in nanometers of the P_n wave, Δ is the distance in km and c_i is the site correction.

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In order to measure the amplitude of P_n phases from the Wyoming events, we integrated the original velocity seismograms into displacement after removing the instrument response. The displacement seismograms with a 0.5 Hz 3rd-order Butterworth high pass filter applied are presented in Figure 4. The same procedure has been applied to the QianAn data (Figure 4). Between epicentral distance of about 2° and 12.5° , P_n is the first-arriving phase. As an emergent phase, sometimes P_n is difficult to pick. To estimate the magnitude m_b we followed Vergino and Mensing (1990) and picked the maximum peak-to-peak amplitude of the first 3-5 cycles of the seismograms.

Evernden (1967) has shown that the patterns of P_n amplitudes versus Δ in the western and eastern United States are markedly different. The differences in the two regions are related to crustal origin and age. The velocity structures of northeast China are more similar to the eastern United States than the western United States. Based on this comparison, we use Evernden's (1967) formula to estimate m_b for QianAn:

$$m_b = -3.27 + \log_{10}(A/T) + 2 \log_{10} \Delta, \quad (4)$$

where A is the zero-to-peak amplitude in nanometers (nm), T is the period in s and Δ is distance in kilometers.

Table 3 lists the average m_b values estimated for all events with accompanying standard deviations. The standard deviations of the estimates indicate the similarity of the P_n measurements among the broadband instruments in China and Wyoming. The body wave magnitudes for all but one of the mining explosions in both regions range from 2.9 to 3.38.

The one anomalous event from Wyoming, 96214, with a m_b 4.39 is almost an order of magnitude larger than the others. Near-source observations of this blast documented that the delay firing of this explosion failed resulting in the nearly simultaneous detonation of the last half of the explosion. This simultaneous detonation resulted in a very impulsive source that is reflected in the m_b values observed at regional distances.

Stevens and Day (1985) presented an analysis of m_b versus M_s for earthquakes and explosions using 1,260 earthquakes for which m_b and M_s were recorded by National Earthquake Information Service (NEIS) during 1980 and 1981 and explosion data through 1982 for which m_b and M_s were available. They found that above approximately m_b 5.5, the earthquake and explosion populations are well separated, and for smaller events there is a small amount of mixing. We reproduce their figures here as Figure 5 superposing our m_b : M_s data for the four events in Wyoming and one in China. All of our events fall at the very smallest range of Stevens and Day study. Since the events are small, all of the estimates are based upon regional observations, whereas the Stevens and Day (1985) observations are primarily teleseismic. Despite these significant differences it is interesting to compare the two results. Except for the anomalous event (96214), all our mining blasts plot in the earthquake population, a result consistent with the robust intermediate period surface waves generated from these events.

The one anomalous event (96214) had about the same surface wave magnitude of the other events but the body wave magnitude is almost one full magnitude unit higher moving it into the explosion population. The only difference between this event and the other four is the time over which the explosion was detonated with the anomaly being nearly simultaneously detonated. This comparison suggests that the time function of mining and single-fired explosion may play a critical role in the performance of this discriminant.

Table 3. Averaged m_b of events

Event Code	Yield (kg)	m_b	σ
96201	2065412	3.38	0.09
96214	1117171	4.39	0.09
96215	1264181	3.28	0.17
97226	2704937	3.32	0.13
02363	1301000	2.90	0.09

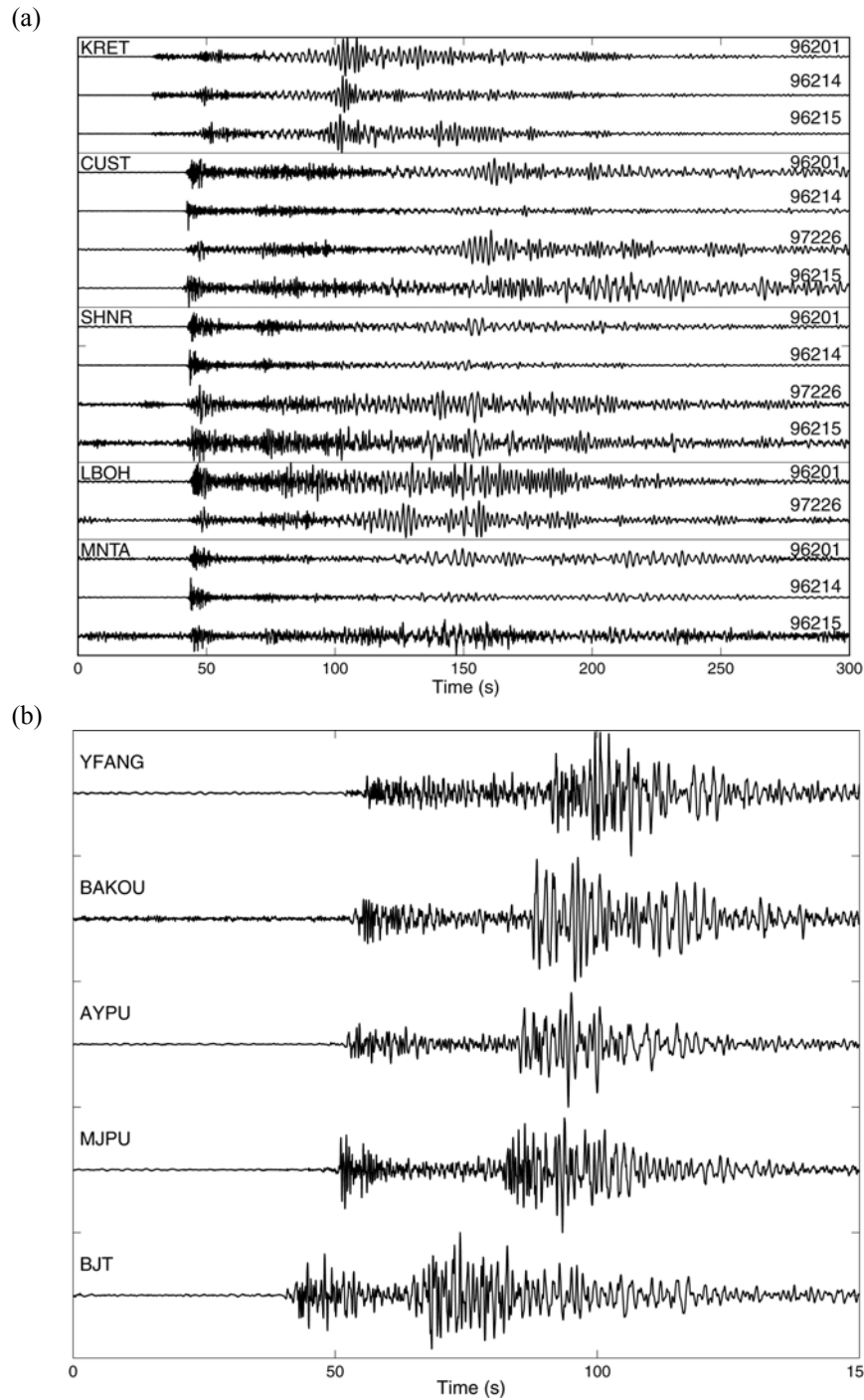


Figure 4. Displacement seismograms for all events in Wyoming (a) and QianAn (b) after removing the instrument response (STS-2) and applying a 3rd-order Butterworth high pass filter with corner frequency of 0.5 Hz.

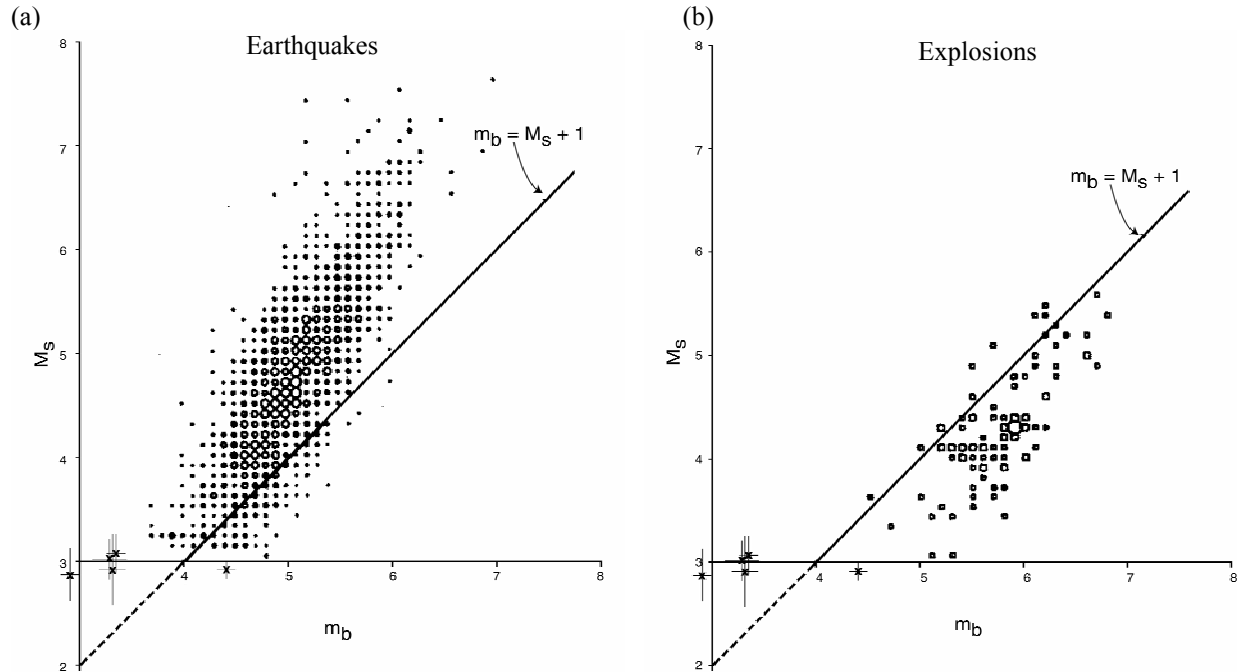


Figure 5. The m_b : M_s plots for earthquakes (a) and explosions (b). The figures were from Stevens and Day (1985) superposed with our results (x-mark) and the standard deviations.

CONCLUSIONS AND RECOMMENDATIONS

The mining explosion data in China has been used to estimate m_b and intermediate period M_s for purposes of investigating an intermediate period discriminant. We also analyzed a similar data set of large scale mining explosions from Wyoming where the surface wave dispersion is well characterized at intermediate periods. These two data sets suggest that mining explosions with long time durations produce larger intermediate period surface waves than single-fired explosions. The enhanced surface waves can make these events look earthquake-like. An anomalous mining explosion in which the delay timing failed resulted in the simultaneous detonation of a large portion of the blast and resulted in significantly enhanced P waves that put the event into the explosion population. A synthetic modeling exercise to quantify the relationship between the timing of the mining explosion, the components of the source model and the resulting body and surface waves is needed to better understand these effects.

ACKNOWLEDGEMENTS

The authors would like to thank Craig Pearson at Los Alamos National Laboratory, Michael Hedlin at the University of California San Diego, and Vindell Hsu at the Air Force Technical Applications Center for their collaboration in conducting experiments in Wyoming. David Blackwell, Robert Gregory, Eugene Herrin at Southern Methodist University, John Ferguson at the University of Texas at Dallas, and Jessie Bonner at Weston Geophysical Corporation who provided critical comments on this study. Robert Herrmann provided programs for multiple filter analysis and phase matched filter. The explosion data from QianAn mine was from the cooperative project between Southern Methodist University and the Institute of Geophysics, China Seismological Bureau. We would like to thank Yun-tai Chen and his research group and Mary Templeton at Incorporated Research Institutions for Seismology (IRIS/PASSCAL) Instrument Center for their help with network installation and data collection.

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