EXCITATION OF REGIONAL WAVES AND MAGNITUDE DEPENDENCE OF PHASE SPECTRAL RATIOS IN CENTRAL ASIA

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ABSTRACT

Multiple station recordings of Pn and Lg spectra from a large (m_b = 6.6) nuclear explosion, and several recent chemical explosions ($m_b \leq 3.7$) in central Asia are used to invert for source spectral parameters and path variable Q models. It is confirmed that a simplified, modified Mueller-Murphy source model fits the source spectra of nuclear explosions well. For chemical explosions, the model fits source spectra reasonably well, although the observed Pn source spectra tend to be complicated by event-variable, random fluctuations. The estimated source seismic moments (M_0) and corner frequencies (f_c) are used together with a previous data set to derive source spectral scalings for underground explosions. The new scalings essentially extend the validity of the previous scalings to a wider m_b range of between about 3.7 and 6.6. specifically, the new scalings have the previously reported features of (1) linear correlation between log M_0 and m_b, (2) larger Pn M_0 than Lg M_0 for the same explosions, (3) quarter-root scaling between f_c and M_0, and (4) higher Pn f_c than Lg f_c by factors of 4-5.

A necessary consequence of the scaling relationships is that the Pn/Lg spectral ratio from an explosion should grow rapidly in an intermediate frequency range roughly between the f_c of Pn and Lg. Owing to the scaling of f_c with event size, this frequency range shifts higher for smaller events. This magnitude dependence of the Pn/Lg spectral ratio is directly confirmed by the observation of the above explosions. Further, multiple-event stacking of the Pn/Lg ratios observed at a single station (WMQ), from many Soviet explosions with similar m_b values of about 6.0 are compared with the respective ratio from events with m_b of about 5.0. This comparison verifies the magnitude dependence, which is of great theoretical and practical significance. A simple and efficient procedure is proposed to account for the effect of the magnitude dependence of Pn/Lg ratios in the identification of explosions.

Work is being conducted to invert for source moment, corner frequency and path-variable Q values using Pg from central Asia. Currently I am calculating reasonable geometrical spreading terms of Pg, using synthetics in various velocity models developed for central Asia. I will present resulting source spectra and path Q of Pg.

KEY WORDS: seismic sources, central Eurasia, explosion discrimination, P/Lg ratios, regional wave spectra

OBJECTIVE

The primary objective of this research is to quantify the difference in the excitations of various regional waves, so that we may achieve better, quantitative understanding and criterion of the P/Lg spectral ratio discriminant of explosions. There proposed research is composed of several tasks. The first is to further improve the inverse method for simultaneous determination of source seismic moment (M_0), corner frequency (f_c) and path-variable Q_0 and η (Q at 1 hz and its power-law frequency dependence, respectively) using regional wave spectra. The second task is to apply the improved inverse method to Lg, Pn, Pg and Sg spectra from many earthquakes and explosions in Eurasia to estimate source M_0, f_c and path Q_0, η. The third task is to analyze source spectral scaling and other source spectral characteristics of seismic events, such as the amount of spectral overshoot of explosions, to explore when, how and why the P/Lg spectral ratios can be used to discriminate explosions from earthquakes.

This research provides important input to the world-wide monitoring of nuclear explosions. The source spectral behavior inferred from this study will help to understand if, when and how the P/Lg amplitude ratio can be used to discriminate explosions from earthquakes.

RESEARCH ACCOMPLISHED

Data

The data used in this study include vertical component Pn and Lg records from many explosions in central Asia. These include (a) a large, m_b = 6.6 underground nuclear explosion on May 21, 1992 in the Lop Nor Test Site (LTS), recorded by IRIS stations AAK, ARU, GAR and OBN, and by the 11 portable Passcal stations deployed during the 1991-1992, passive Tibetan plateau experiment; (b) five chemical explosions detonated in the Kazakhstan Test Site (KTS) between 1997 and 1999, with known yields of 25 or 100 ton (Myers et al., 1999). These explosions are recorded at the Kazakhstan Network (KZNET) stations; (c) fifteen Soviet underground nuclear explosions between 1987 and 1989, recorded at the Chinese Digital Seismic Network (CDSN) station WMQ. Pn and Lg spectra are obtained using the Fast Fourier Transform (FFT) of the time series.

Source spectral parameters of large and small explosions

I inverted for Pn and Lg source spectral parameters of the explosions for which multiple-station recordings are available, using the inverse method of Xie (1998) and Xie and Patton (1999; hereafter referred to as XP99). These explosions include the large ("megaton") LTS and small chemical explosions (event groups (a) and (b) mentioned in the above paragraph). The resulting M_0 and f_c values are listed in Table 1.

Source spectral scalings

XP99 derived scaling relationships among m_b, M_0 and f_c values for Pn and Lg source spectra from underground nuclear explosions at the LTS and KTS, with m_b values between about 5 and 6. Here I extend the scalings with the new results reported in Table 1. Figure 1 shows m_b versus log(M_0) estimates from Pn and Lg spectra for explosions, obtained in this and previous studies. With m_b treated as the independent variable, linear regression analysis gave the following relations:
$\log M_0 = 9.83(\pm 0.20) + 1.10(\pm 0.03)\ m_b$ for Pn, $\log M_0 = 9.27(\pm 0.28) + 1.12(\pm 0.04)\ m_b$ for Lg;
Figure 2 shows the f_c versus M_0 values obtained in this and previous studies. Linear regressions over the logarithm of these values yield the following relations:
$\log M_0 = 18.02(\pm 0.29) - 4.05(\pm 0.21) \log f_c$ for Pn,
$\log M_0 = 15.19(\pm 0.21) - 3.77(\pm 0.12) \log f_c$ for Lg. For both the Lg and Pn source parameters, the new scalings in the above equations essentially confirm the respective previous scalings in XP99, with a wider range of validity in terms of m_b (the new m_b range is from about 3.7 to 6.6, expanding the previous range by 1.5). Specifically, the new scalings confirm that at the same M_0 level, Pn f_c is higher by a factor of 4 to 5 than the Lg f_c.

Observed magnitude dependence of Pn/Lg spectral ratios

As suggested by XP99, a necessary consequence of the source spectral scalings is that the frequency range, over which the observed Pn/Lg spectral ratios grow rapidly, must be dependent on the sizes of the explosions in the study area. This was directly confirmed by XP99 using observed Pn/Lg ratios from nuclear explosions in the m_b range between about 5 and 6. Here I reconfirm this dependence again with the new data that extends the m_b range to between about 3.7 and 6.6. Figure 3 redisplays the observed, station-averaged Pn/Lg spectral ratios for all of the explosions and earthquakes that were shown in Figure 12 of XP99. Also replotted are the generic Pn/Lg ratios for hypothetical explosions and earthquakes of various m_b values, calculated using (a) the source scaling relationships, (b) the modified Mueller-Murphy (MMM) source model, and (c) an average path effect, constructed using the averaged epicentral distance, $\bar{\Delta}$, $\overline{Q_0}$ and $\bar{\eta}$ in XP99. The average path in XP99 is constructed over 13 paths from the LTS to stations of the Kyrghistan and Kazakhstan networks. To compare the previous generic and observed ratios with the new observations, I corrected for the new, different path effects involved for events 052192 and 082298, and plotted the resulting Pn/Lg ratios in Figure 3.

Shapes of the new observed ratios for the large (m_b = 6.6), 052192 and small (m_b = 3.8), 082298 explosions are shifted with respect to the earlier ratios. The frequency range, over which the ratio shows a rapid increase until it reaches the Pn f_c, is shifted lower for the large explosion, and shifted higher for the small explosion. These shifts are exactly as predicted by the scaling relationships. Interestingly, the shift of the ratio from event 082298 is so significant that it falls into the earthquake population in the frequency range of 1-10 Hz. This overlap also exists for the raw ratio from 082298, with no path correction applied (not shown).

To further explore the generality of the observed magnitude dependence of the Pn/Lg ratios from explosions in central Asia, I did an independent, direct calculation of Pn/Lg spectral ratios for fifteen Soviet underground nuclear explosions detonated at the KTS between 1987 and 1989 as recorded at the CDSN station WMQ. I stacked the Pn/Lg spectral ratios for the 10 events with $m_b \geq 6.0$ and for the 5 events with $m_b \leq 5.0$, respectively, resulting in two stacked spectral ratios with mean m_b values of 6.2 and 4.8, respectively. These are plotted in Figure 4, together with the two generic source ratios plotted in Figure 3. The path Pn and Lg Q models from the KTS to WMQ were expected to be similar to those for the average central Asia path used for generating the generic curves. The observed stacked Pn/Lg ratios in Figure 4 are very close to the respective generic ratios, directly confirming the magnitude dependence of the ratios in the study area.

A procedure to account for the magnitude dependence

Had we not known that event 082298 was an explosion and had we not been aware of the magnitude dependence of the Pn/Lg ratios in the study area, we would have mis-identified that event as an earthquake based on the ratio in Figure 3. An important outcome of this study is that, based on the scaling relationships developed in this and previous studies, we can predict how f_c values vary with m_b or M_0 values. For example, according to source scalings for explosions (equations (1) through (4)), we can estimate the factors by which the f_c values for an m_b = 3.8 event increase from those of an m_b = 5.5 event: the factor should be 2.9 for Pn f_c, and 3.2 Lg f_c. If we are in a situation of knowing the magnitude of event 082298, but not its event type, we can plot its Pn/Lg ratio with the frequency axis reduced by a factor of about 3.0 (roughly the median of the Pn and Lg factors), and compare the resulting ratio with the previously observed ratios for larger explosions, as shown in Figure 5. In that figure the new Pn/Lg ratio for 082298, plotted with the frequency normalization, is in the explosion population, and lies between the generic curves for m_b =5.0 and 6.0.

The above normalization procedure is based on scalings for explosions. Alternatively we can choose to use scalings for earthquakes (equations (18), (19), (22) and (23) of XP99). In that case the respective median of predicted frequency shift for Pn and Lg is a factor of 3.7, rather than 3.0. When a frequency-normalization by factor of 3.7 is conducted, the shift of the Pn/Lg ratio of the 082298 explosion is very similar to that shown in Figure 5 (not plotted). Therefore so long as we take into account the magnitude dependence of the Pn/Lg ratios, the event of m_b 3.8 is identified as an explosion regardless of which set of scalings are used.

CONCLUSIONS AND RECOMMENDATIONS

I would like to clarify two points of this and previous works: first, we think highly of the observations done at the Nevada Test Site (NTS); we have never suggested that the source spectral scalings developed for test sites in central Asia are valid for a test site characterized by a very different geology, such as the NTS. Second, part of our results have been direct observations. For example, the directly observed Pn/Lg ratios plotted in Figure 12 of XP99 and Figure 4 of this paper clearly show statistical trends for the ratios to vary with event magnitude in the two test sites (LTS and KTS). One might argue that our inversions of source spectral parameters are subject to some uncertainties owing to the difficult nature of spectral inversions, but the direct observations are not subject to such uncertainties.

Since it is difficult to find explosions that both span a wide magnitude range, and are well recorded at regional distances over the same (or similar) paths, the number of events that we analyzed so far was relatively small. In particular, there were no explosions in the kiloton range. There was also a lack of data from earthquakes beyond the m_b range between about 4.0 and 5.5, used by XP99. Future research should be directed to remove these limitations. Other worthwhile future research topics, judging from the results obtained so far, include the understanding of (a) whether the scalings are valid for other high-frequency regional waves, such as Pg and Sn, (b) whether the magnitude dependence of the Pn/Lg ratios extend to other types of cross-phase spe ctral ratios, such as Pn/Sn and Pg/Lg ratios in the study region, and (c) how the behavior of regional wave spectra and cross-phase ratios differ from those in central Asia in a drastically different geological environment, such as that in and around the NTS of the western U.S.

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Table 1. Explosions used in the multiple-station spectral inversions

Event ID	Origin Time (H:M:S)	m_b	Yield (ton)	Pn M_0† (Nm)	Pn f_c† (hz)	Lg M_0† (Nm)	Lg f_c† (hz)
052192	04:59:57.5	6.6	-	1.5(±0.3)×10^{17}	1.7(± 0.1)	4.3(±0.6)×10^{16}	0.4(±0.1)
080397	08:07:20.0	-	25	7.3(±0.7)×10^{13}	10.0(±0.4)	1.1(±0.3)×10^{13}	3.4(±0.1)
083197	07:08:39.2	-	25	3.5(±0.9) ×10^{13}	13.0(±0.8)	2.9(±1.1)×10^{12}	5.3(±0.2)
092897	07:30:15.1	-	25	1.1(±0.2)×10^{13}	19.8(±1.5)	1.2(±0.1)×10^{12}	6.6(±0.2)
082298	05:00:19.0	3.8	100	1.1(±0.2)×10^{14}	9.3(±0.4)	2.7(±0.5)×10^{13}	2.9(±0.2)
092599	05:00:05.7	3.7	100	9.7(±2.5)×10^{13}	8.7(±0.7)	3.3(±0.5)×10^{13}	3.2(±0.1)

Event ID is composed of the month, date and year of the explosion. Event time, location and m_b values are from the U.S. Geological Survey preliminary determination of epicenters (PDE) bulletin, or the International Monitoring System (IDC) bulletin. Event 052192 is a nuclear explosion in the Lop Nor Test Site. All other events are chemical explosions in the Kazakhstan Test Site.

†M_0, f_c values are from spectral inversions of this study.

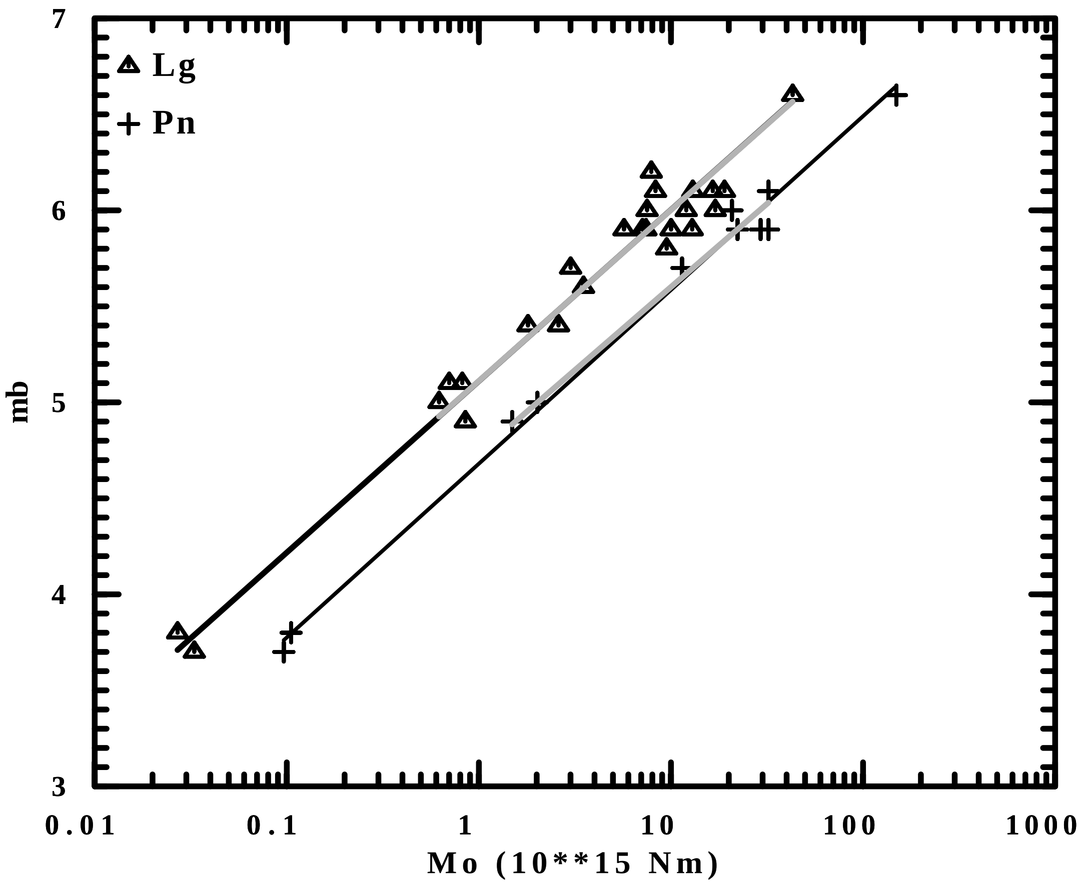

Figure 1. m_b versus logarithm of M_0 for underground explosions in the KTS and LTS. Data points included are those in Figure 7 of Xie and Patton (1999), plus those of the large nuclear underground explosion and two 100-ton chemical explosions obtained in this study. The three 25 ton explosions have no reliable m_b estimates and are not included. New and previous linear regression results are shown by black and gray lines.

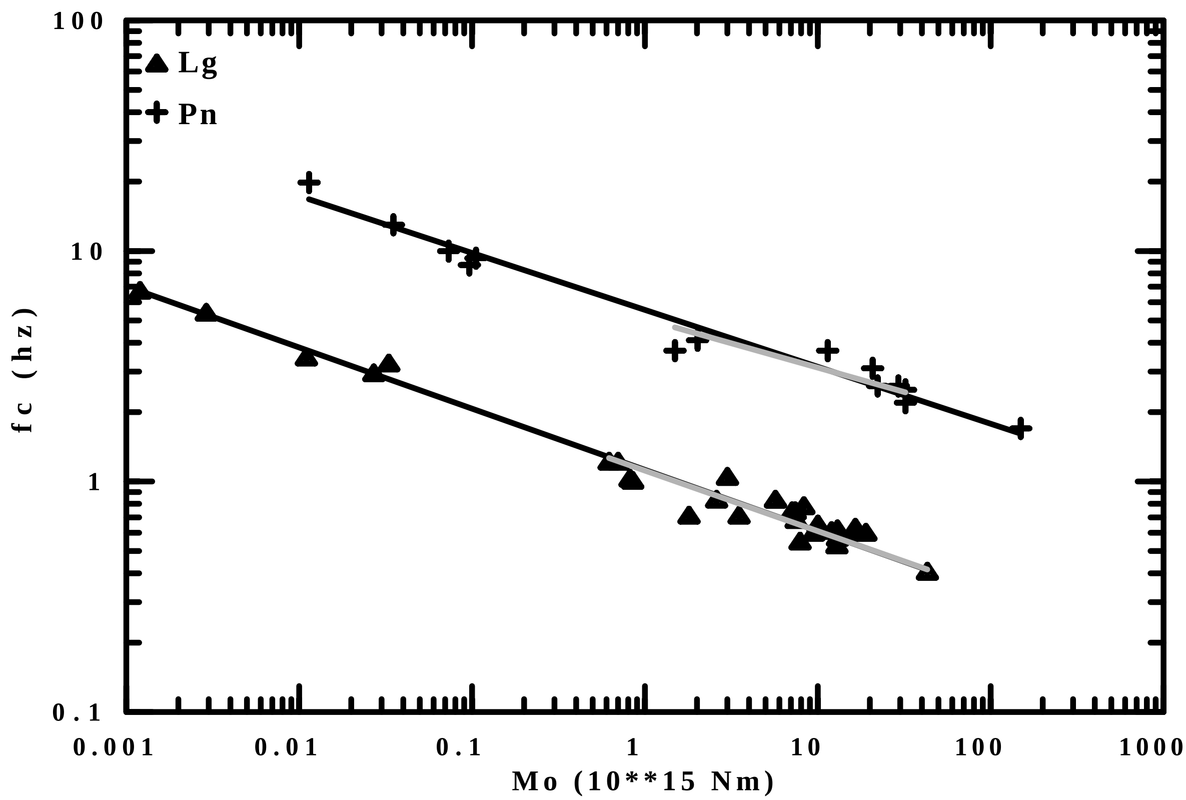

Figure 2. Logarithm of M_0 versus logarithm of f_c values for the explosions. Data points are from this study, and Figure 9 of Xie and Patton, 1999. New and previous linear regression results are shown by black and gray lines.

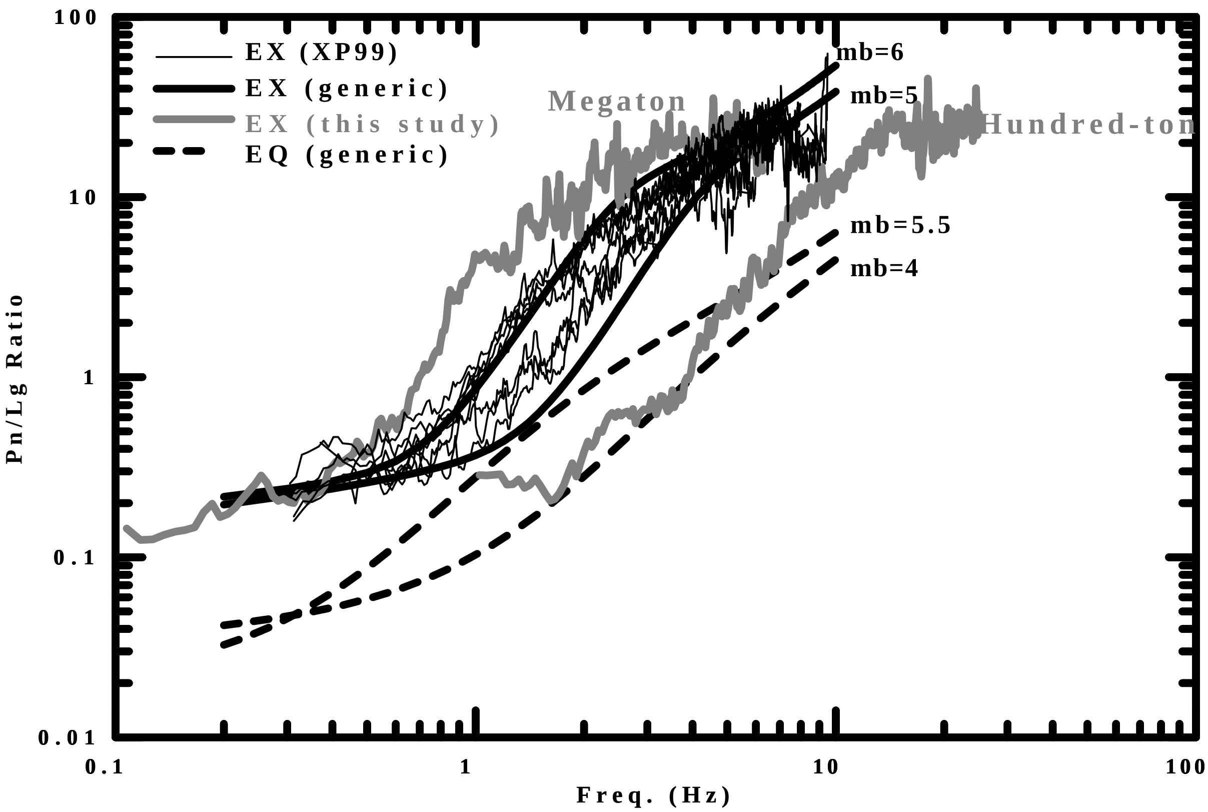

Figure 3. Pn/Lg spectral ratios of ground motion. "EX" and "EQ" denote ratios for explosions and earthquakes, respectively. Continuous smooth curves are generic ratios calculated for hypothetical explosions with m_b of 5.6 and 6.0. Dashed smooth curves are generic ratios calculated for hypothetical earthquakes with m_b of 4.0 and 5.5. All generic ratios are calculated at an average central Asian station about 1000 km away from the sources, and have been shown in Figure 12 of Xie and Patton (1999). Fluctuating, black curves denoted as "EX (XP99)" are station-averages of the observed ratios from explosions with m_b clustered near 5.0 and 6.0, by Xie and Patton (1999). Observed ratios from this study (gray curves) are station-averaged ratios from the 052192 ("megaton") and 082298 ("Hundred-ton") explosions, with path corrections. The path corrections are made by first reducing the observed Pn/Lg ratios to the source using the average Q models for paths from events 052192 and 082298. The resulting ratios are then back-propagated to the average central Asian station by using the Q models mentioned in Figure 12 of XP99. Note that the ratio from the 082298 explosion are well within the earthquake population between 1-10 Hz. This is also true when no path correction is applied (not shown).

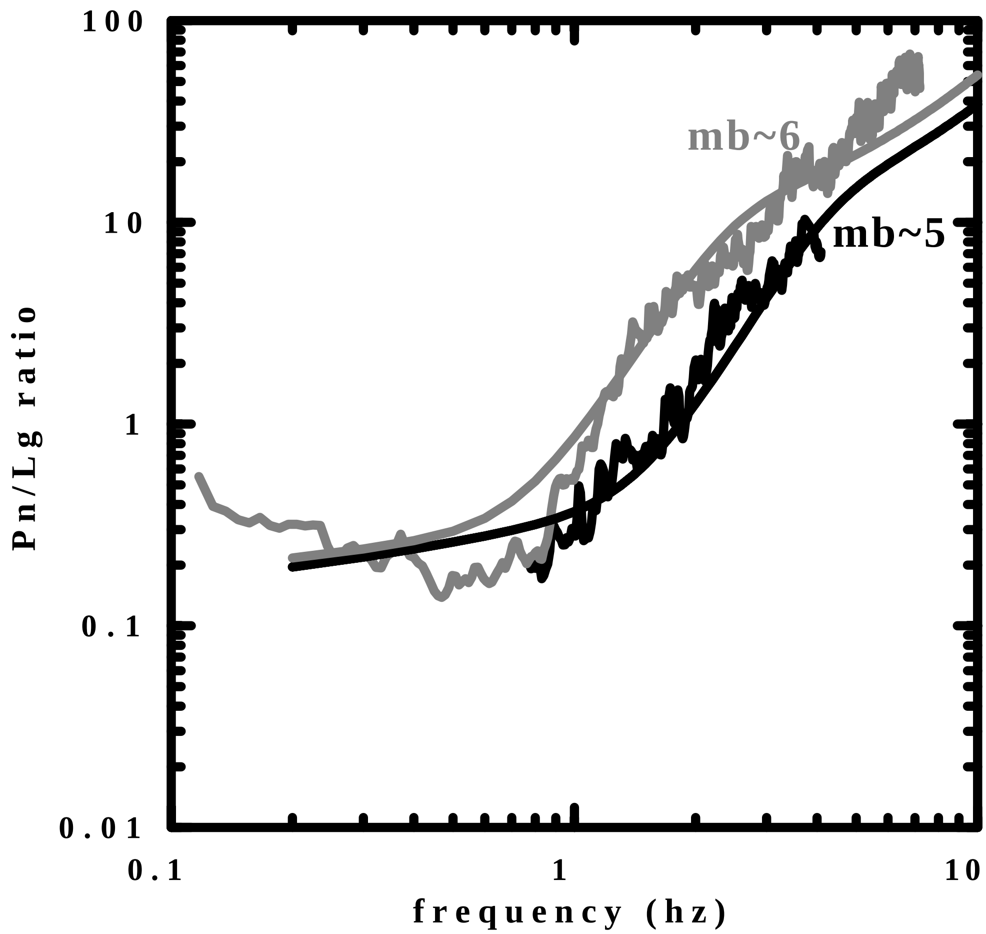

Figure 4. Event-stacked Pn/Lg spectral ratios for Soviet explosions with magnitudes around 5.0 and 6.0, respectively, observed at station WMQ. Superposed are the generic ratios for average central Asian paths (the same as those in Figure 3). The observed ratios are surprisingly close to the generic ratios.

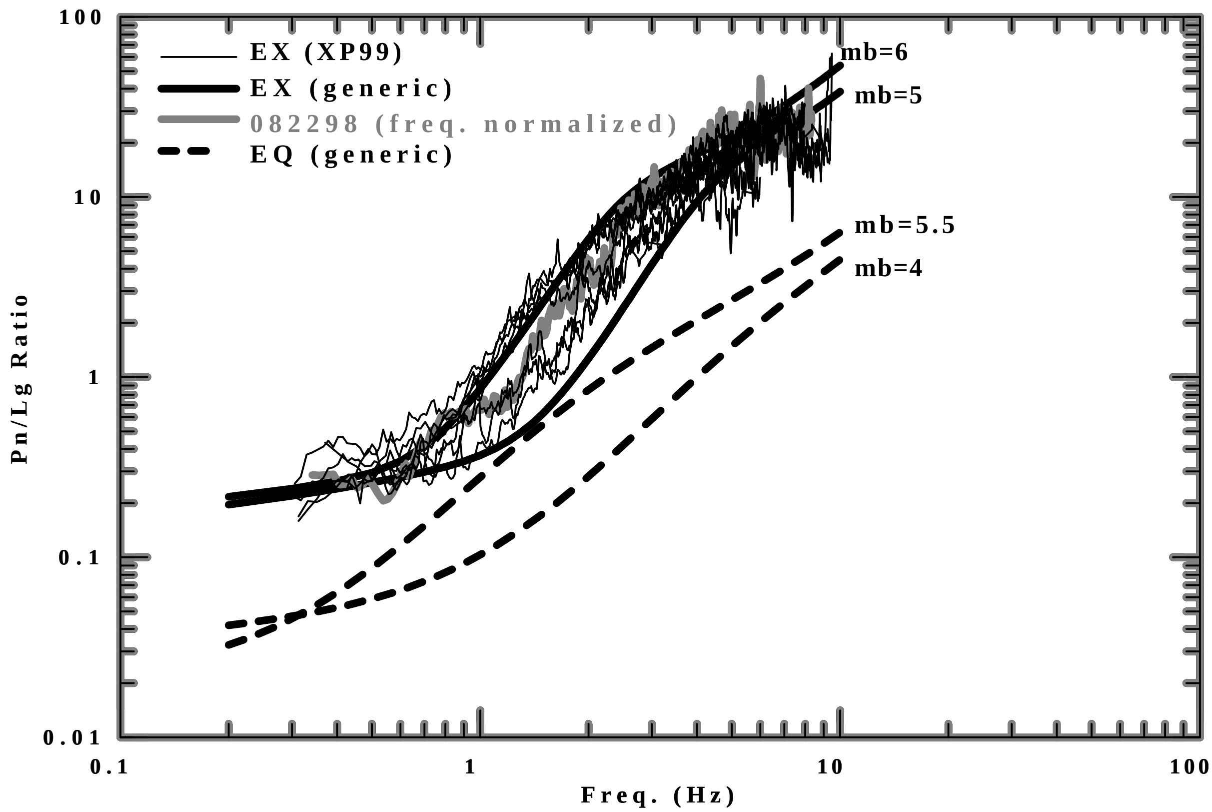

Figure 5. Same as Figure 3 except that ratio for the event of 052192 is not shown, and ratio for the event of 082298 is shown with a frequency reduction of a factor of 3.0. As predicted by the scaling relationships (equations (1) through (4)), the frequency reduction indeed shifts the ratio of 082298 into the position of an m_b = 5.5 explosion.