Source scaling of Pn, Lg spectra and their ratios from explosions in central Asia: Implications for the identification of small seismic events at regional distances

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Abstract

Multiple station recordings of Pn and Lg spectra from an mb=6.6 nuclear explosion and several mb ≤ 3.7 chemical explosions in central Asia are used to invert for source seismic moments (M₀), corner frequencies (fₖ), and path-variable Q models. A modified Mueller-Murphy source model fits the nuclear explosion well, and fits the chemical explosions reasonably well, although Pn from chemical explosions are complicated by event-variable spectral fluctuations. New source spectral scalings are derived for underground explosions in a wide mb range between ~ 3.7 and 6.6; they preserve features of the previous scalings, such as (1) larger Pn M₀ than Lg M₀, (2) quarter-root scaling between fₖ and M₀, and (3) higher Pn fₖ than Lg fₖ by factors of ~4. A necessary and important consequence of the scalings is that the Pn/Lg spectral ratio grows rapidly in an intermediate frequency range between the fₖ of Pn and Lg. Since fₖ scales with event size, this frequency range shifts higher for smaller events. This magnitude dependence is directly confirmed using observed Pn/Lg ratios from the above explosions. It is also confirmed using Pn/Lg ratios observed at station WMQ using many mb~ 6 and mb~ 5 Soviet explosions. A procedure is proposed to account for the magnitude dependence of Pn/Lg ratios in the explosion identification.

Introduction

Of the high-frequency regional seismic phases, Pn and Lg are usually the easiest to identify. Pn is the first-arriving phase between about 2° and 12.5° and constitutes multiple P waves refracted at the Moho [e.g., Cerveny & Ravindra, 1971]. Lg is the last arriving, and typically the most prominent high-frequency phase beyond about 100-200 km in continental areas. Lg can be
treated either as a sum of higher mode surface waves [e.g., Knopoff et al., 1973], or multiple supercritically reflected S waves in the continental crust [Bouchon, 1982]. Both Pn and Lg phases have been extensively used to study seismic sources and lithospheric structure. In nuclear explosion seismology, Pn/Lg spectral ratios have been used to discriminate explosions from earthquakes [e.g., Blandford, 1981; Nuttli, 1981]. A fundamental problem in using Pn and Lg waves to study seismic sources and identify explosions has been the lack of detailed knowledge on the excitation of these phases. This is particularly true for the Lg wave. For earthquake sources there has been a long-standing debate on whether or not the transfer function between local S waves and Lg is flat [e.g., Harr et al., 1986]. For explosion sources, excitation of Lg is further complicated by the fact that, in a 1D isotropic medium, there should be no direct source radiation into regional S waves, such as Lg or Sn [e.g., Dahlman and Israelson, 1977]. To explain the observed large amplitude of Lg from explosions, various mechanisms have been proposed, including those involving 3D near source scattering or cracking, cavity rebound, spall, and interactions of non-spherical wave fields [e.g., Gupta et al., 1992; Xie and Lay, 1994; Vogfjord, 1997; Johnson and Sammis, 2001]. If these mechanisms are responsible for the excitation of Lg, they may also affect other regional phases. Evaluation of the contribution of each mechanism requires a separation of source spectra from the recorded regional waves, which are also affected by complex path effects. Uncertainties in source and path effects in regional wave signals have been a fundamental problem in seismology, and have led some seismologists to question whether and how the spectral ratios between regional P and S waves can be used to identify explosions [Ringdal et al., 1998].

Based on earlier stochastic modeling of regional waves, Xie [1993, 1998] developed and modified a non-linear inverse method that permits a simultaneous determination of source spectral parameters and path-variable Q using regional wave spectra. The method has been used recently by Xie et al. [1996], Cong et al. [1996] and Xie and Patton [1999] to study spectral characteristics of excitation and attenuation of Pn and Lg from many underground nuclear explosions.
and earthquakes in central Asia. In these studies, earthquake and explosion sources are modeled by the Brune, and modified Mueller-Murphy (MMM) source model [Sereno et al., 1988], respectively. Optimal seismic moments (M₀) and corner frequencies (fₖ) associated with these source models were obtained using both Pn and Lg phases for each event population (explosions and earthquakes). Scaling relationships among body-wave magnitudes (mₐ), M₀ and fₖ were then developed. As summarized in Xie and Patton [1999] (hereafter referred to as XP99), interesting features of these scalings include: (1) M₀ from both phases (Pn and Lg) and source types (explosions and earthquakes) correlates with mₐ linearly with slopes slightly higher than 1.0; (2) for explosions, M₀ estimated using Pn are systematically larger than those estimated using Lg; (3) for both explosions and earthquakes Pn fₖ are systematically higher, by a factor of ∼4 than the Lg fₖ at the same mₐ level. The last feature is surprising since it has not been predicted by any existing theoretical models (although some models can easily explain this feature, see Discussion). It also leads to an inference that the Pn/Lg spectral ratio should vary with frequency (Figure 1). Roughly speaking, at frequencies below Lg fₖ, the ratio is relatively constant. Above the Lg fₖ the ratio increases drastically with increasing frequency. This drastic increase stops beyond the Pn fₖ, which is significantly higher than the Lg fₖ. The difference in source models for explosions and earthquakes makes the frequency variation more drastic for explosions than for earthquakes. Also, since the fₖ values increase with decreasing source size (mₐ or M₀), the frequency range of the rapid increase of Pn/Lg ratio is inferred to be dependent on the event magnitude.

The magnitude dependence of Pn/Lg ratios, inferred from the source scaling relationships, was confirmed with direct observations [Figure 12 of XP99]. Nevertheless, it has been viewed as being controversial by some colleagues [Xie et al., 2001]. Several concerns regarding this dependence have been raised, including (a) that the observation of XP99 only utilized data over a limited magnitude range (roughly between mₐ of 5 and 6 for explosions), (b) the Mueller-Murphy source model was developed at close-in distances and is not confirmed to be adequate for regional
wave excitations, and (c) some observations of Pn/Lg ratios made using different methods and/or data from different regions have not suggested such a dependence. This paper is devoted to addressing these concerns and to a further understanding of the excitations of Pn and Lg. I will report a new and substantial analyses of Pn and Lg from many more explosions in central Asia, with a much wider mb range (from below 3.7 to 6.6) than in XP99. For those explosions that are recorded by multiple stations, I will present the optimal source spectral parameters obtained using the inverse method of Xie [1993, 1998] under the MMM source model. The adequacy of this source model will be examined for large nuclear explosions and small chemical explosions. I will then use the previous and new source spectral parameters to develop new source spectral scalings for Pn and Lg from explosions, and compare the new scalings to those reported previously. Using direct observations of Pn/Lg spectral ratios from many nuclear and chemical explosions in the Lop Nor Test Site (LTS) and Kazakhstan Test Site (KTS; also known as the Semipalatinsk Test Site), I will confirm that the ratios are indeed dependent on the source magnitudes. Based on the source scaling relationships, I will propose a correction for the magnitude dependence of the Pn/Lg ratio when it is used for explosion discrimination. I will also discuss the physical meaning of my observations. Finally, I will clarify the range of validity of my observations, and discuss their implications, as well as the origin of the controversy concerning spectral characteristics of the Pn, Lg spectra and their ratios.

**Stochastic modeling and method of inversion**

Stochastic models relating observed regional wave spectra to model parameters describing source and path effects were first introduced by Street et al. [1975], and have been given in detail in studies cited in the previous section. For convenience, here I briefly re-write a simplified version of the stochastic model given by equations (1) through (6) of XP99. For a single event, \( A_i(f) \), the observed regional wave spectra at the ith station and frequency f, is expressed as
\[ A_i(f) = S(f)G(\Delta_i)\exp\left(-\frac{\pi f \Delta_i}{V_g Q_i(f)}\right)r_i(f), \]

where \(\Delta_i\), \(V_g\) and \(Q_i(f)\) are the distance, group velocity and apparent quality factor, respectively. \(r_i(f)\) describes the combined random amplitude effects from source, path and site. \(S(f)\) is the source spectrum, which for \(Pn\) from explosions is given by the MMM model:

\[ S(f) = \frac{M_0}{4\pi \rho \alpha^3} \frac{1}{\left[1 + (1 - 2\beta)f^2/f_c^2 + \beta^2 f^4/f_c^4\right]^{1/2}} \]

where \(\beta\) is the overshoot parameter, \(\rho\) and \(\alpha\) are density and \(P\) wave velocity in the source zone, respectively. \(S(f)\) for \(Lg\) from explosions is given in the same form as equation (2), except quantities \(\rho\) and \(\alpha\) represent the crustal averages of density and \(S\) wave velocity, respectively [Street et al., 1975; Sereno et al., 1988]. The geometrical spreading term, \(G(\Delta_i)\), is assumed to take the form of \(\Delta_0^{-1}(\Delta_0/\Delta_i)^m\), with \(\Delta_0\) and \(m\) being a reference distance and decay rate at large distances, respectively (for \(Lg\) \(\Delta_0\) and \(m\) are chosen to be 100 km and 0.5 whereas for \(Pn\) they are chosen to be 1 km and 1.3; see Street et al. [1975] and XP99). \(Q_i(f)\) takes form,

\[ Q_i(f) = Q_{0i} f^{\eta_i} \]

where \(Q_{0i}\) and \(\eta_i\) are apparent \(Q\) at 1 Hz and its power-law frequency dependence, respectively. The term "apparent" comes from the fact that \(Q_i(f)\) absorbs any error caused by the unaccounted radiation pattern and site response factors in the simplified modeling. Once \(\beta\) is chosen (1.0 for \(Pn\) and 0.75 for \(Lg\), respectively; for details see Xie et al. [1996] and XP99), the source and path effects are completely described by a model parameter vector,

\[ m^T = \left(M_0, f_c, Q_{01}, \eta_1, \ldots, Q_{0N}, \eta_N\right)^T \]

where \(N\) is the number of stations recording the event, and the size of \(m\) is \(2N + 2\). The optimal \(m\) is defined as one that maximizes the posterior probability density function,
\[ \sigma_M(m) = \text{const} \times \rho_m(m) \times \exp \left\{ - \sum_{i=1}^{N} \sum_{j=1}^{J_i} \ln^2 \left[ r_i(f_j) \right] \right\}, \quad (5) \]

where \( J_i \) is the total number of discrete frequencies, \( f_j \), available at the \( i \)th station. \( \rho_m(m) \) is the marginal density function of a priori knowledge on the model. A simple form of \( \rho_m(m) \) is a "box car" (hard bound). For example, if one knows a priori that for station 1, the possible range of \( Q_{01} \) and \( \eta_1 \) are \( (Q_{01}', Q_{01}'') \) and \( (\eta_1', \eta_1'') \), then \( \rho_m(m) \) is

\[ \rho_m(m) = \frac{H(Q_{01} - Q_{01}') - H(Q_{01} - Q_{01}'')} {Q_{01,1} - Q_{01,2}} \times \frac{H(\eta_1 - \eta_1') - H(\eta_1 - \eta_1'')} {\eta_1' - \eta_1''}, \quad (6) \]

where \( H \) denotes a step function. The search for optimal \( m \) is conducted in a loop over all possible combinations of \( (M_0, f_c) \) values, and the uncertainty in the resulting \( m \) is estimated with a linear approximation [Xie, 1993, 1998].

**Data**

The data used in this study are vertical component Pn and Lg records from many explosions in central Asia. These include (a) a large, \( m_b = 6.6 \) underground nuclear explosion, detonated on May 21, 1992 in the LTS, recorded by Incorporated Research Institution for Seismology (IRIS) stations AAK, ARU, GAR and OBN, and by the 11 portable Passcal stations deployed during the passive Tibetan experiment [McNamara et al., 1996]; (b) five chemical explosions detonated in the KTS between 1997 and 1999, with known yields of 25 or 100 ton. These explosions are recorded at the Kazakhstan Network (KZNET) stations [e.g., Kim et al., 1996]; (c) fifteen Soviet underground nuclear explosions between 1987 and 1989, recorded at Chinese Digital Seismic Network (CDSN) station WMQ. Pn and Lg spectra are obtained using the Fast Fourier Transform (FFT) of time series collected from broadband (BHZ) or short period (SHZ) channels. The signal processing procedure is the same as that described by Xie [1993] and Xie and Patton [1999]. In particular, for Lg the FFT was done with a 20% taper window with the two corners set at group velocities of about 3.0 and 3.5 km/s (slightly adjustable depending on the waveforms).
For Pn the average amplitude spectra from multiple windows are used. These windows are of a constant length of 4.5 s, with the centroid times increasing at a step of 2.25 s to successively cover the entire Pn and Pn coda with group velocities greater than 6.6 km/s. Signal/noise (S/N) ratios, defined as the ratios of power-spectral densities of Pn or Lg with respect to pre-P noise, were computed and only the spectral estimates with S/N ratios greater than 2 are used. The highest frequency available in the resulting spectral estimates are limited by either the S/N ratio, and/or the instrument cut-off frequency, and vary between about 7.5 Hz (BHZ channels of IRIS and CDSN stations) to above 30 Hz (SHZ channels of the KZNET stations).

**Inversion for Source Spectral Parameters**

I inverted for source spectral parameters of the explosions for which multiple-station recordings are available, using the inverse method described earlier. The results are presented in the following sections.

**The Lop Nor explosion of May 21, 1992**

This event is the largest underground explosion ever detonated at the LTS, with an $m_b$ of 6.6. Pn records are available from IRIS station AAK and seven of the Passcal portable stations in eastern Tibet (Figure 2; for an example of the waveforms, cf. McNamara et al., 1996, Figure 10). A priori knowledge of Pn Q to station AAK was available from XP99, and takes the form of $Q_0 = 385(\pm 36)$ and $\eta = 0.41 (\pm 0.02)$. Using these in the spectral inversion (equation (6)), I obtain Pn $M_0$, $f_c$ values that are listed in Table 1, and path averaged $Q_0$ of 420 and $\eta$ of 0.5, respectively. Lg spectra from this event were available at IRIS stations AAK, GAR, KIV and OBN, and Passcal stations BUDO, MAQI and TUNL. For paths to Passcal stations further south, Lg was blocked. Lg $M_0$ and $f_c$ values of this explosion were already estimated in Xie et al. [1996] using spectra from the four IRIS stations. I re-inverted these values by adding Lg spectra from the 3 Passcal stations, using no a priori knowledge since the Lg spectral inversion is generally much more robust than the Pn inversion [XP99]. The resulting optimal Lg $M_0$ and $f_c$ values from the
re-inversion were unchanged from those estimated by Xie et al. [1996]. The average Lg Q₀ and η values to the three Passcal stations are estimated to be 491 and 0.6, respectively.

The estimated path Q₀i and ηi values can be used to correct for the path effect in the observed spectra, yielding the "observed" source spectra. Hereafter I will drop the quotation marks, and it is understood that the quantity approximates the true source spectra, subject to the precision of the path correction. The observed source spectra can be compared with the synthetic source spectra constructed using the optimal M₀ and f_c values and the MMM source model. The degree of the fit indicates the adequacy of the stochastic model. Figure 3 (top left panel) shows that, the fits using both Pn and Lg are good for the 052192 explosion. Similar good fits have been shown for underground nuclear explosions in Xie et al. [1996] and XP99, indicating that the MMM source model is grossly adequate for these explosions.

Recent chemical explosions in Kazakhstan

I retrieved and analyzed Pn and Lg signals from five chemical explosions between 1997 and 1999, detonated at the KTS. Event parameters of these explosions, including the yields, available mb values and numbers of recording stations, are listed in Table 1. The 082298, 100-ton explosion is best recorded, with seven regional KZNET stations providing useful Pn and Lg waveforms (Figure 4). For the three 25 ton explosions, levels of lower-frequency seismic signals drastically decrease with the increasing depths of burial [Myers et al., 1999]. The 092897 explosion was the deepest and seismically the weakest, generating useful Pn and Lg signals at only two to three stations. There is no available a priori knowledge on Pn Q from the KTS explosions to any stations. However, the paths to station MAK approximately overlap with the two-station path between stations KUR and MAK (Figure 2), over which inter-station Q₀ and η values have been estimated to be Q₀ = 277(±68) and η = 0.61 (±0.05) for Pn, and Q₀ = 591(±87) and η = 0.38 (±0.04) for Lg [Xie et al., 1996; XP99]. I therefore used these estimates as a priori knowledge for path Q from the explosions to station MAK, and inverted the Pn and Lg spectra from all five
explosions. The resulting optimal $M_0$, $f_c$ values (Table 1) are used to construct synthetic source spectra. Figure 3 (panels other than the top left) shows these spectra versus the observed source spectra.

In Figure 3, all observed Pn source spectra from the KTS explosions rapidly fluctuate about the smooth synthetic spectra. The observed Lg source spectra fluctuate less for all events except for 082298. For the latter event, the observed Pn and Lg source spectra fluctuate similarly at lower frequencies, both showing a local peak between 2-3 Hz, and a trough around 4 Hz. Owing to these fluctuations, the fit of observed to synthetic source spectra for the chemical explosions is not as good as the fit for the nuclear explosions shown in the top left panel of Figure 3 and in previous studies [e.g., Xie et al., 1996, Figure 3; XP99, Figure 6]. Details of the spectral fluctuations in Figure 3 differ for different chemical explosions, suggesting that the fluctuations are primarily caused by source complexity. Apparently, the MMM source model does not represent the observed spectra for these chemical explosions as well as for nuclear explosions. Nevertheless, for these chemical explosions the deviations of the observed spectra from the stochastic model are localized at frequencies, and are not systematic among events. Overall, the optimal $M_0$ values for these chemical explosions obtained under the MMM model are subject to greater uncertainties, but still grossly approximate the average level of source spectra at low frequencies. Likewise the optimal $f_c$ value still approximately locates a frequency, beyond which source spectra decay monotonically about a trend of $f^{-2}$. The relatively poorer fit of the MMM model to the chemical explosions used in this study may be partly caused by the abnormal depths and emplacement conditions of some of these explosions [Myer et al., 1999]. If so, chemical explosions with more normal depths and emplacement conditions may be better fit by the MMM source model.

**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 the last section. Figure 5 shows $m_b$ versus $\log(M_0)$ estimates from Pn and Lg spectra for explosions, obtained in this and previous studies. For both Pn and Lg, $\log(M_0)$ linearly correlates with $m_b$ in the entire available range of $m_b$ (between 3.7 and 6.6; note there are no reliable $m_b$ estimates for the three 25-ton explosions). With $m_b$ treated as the independent variable, linear regression analysis gave the following relations:

$$\log M_0 = 9.83 (\pm 0.20) + 1.10 (\pm 0.03) m_b \quad \text{for Pn},$$  

$$\log M_0 = 9.27 (\pm 0.28) + 1.12 (\pm 0.04) m_b \quad \text{for Lg}.$$  

Figure 6 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:

$$\log M_0 = 18.02 (\pm 0.29) - 4.05 (\pm 0.21) \log f_c \quad \text{for Pn},$$  

$$\log M_0 = 15.19 (\pm 0.21) - 3.77 (\pm 0.12) \log f_c \quad \text{for Lg}.$$  

For the Lg source parameters, the new scalings in equations (8) and (10) are virtually unchanged from the respective previous scalings (equations (17) and (21) of XP99), except the standard errors are somewhat smaller. For the Pn source parameters, the changes are somewhat greater in that (a) the intercept in equation (7) above is larger than that in equation (16) of XP99 by 0.3; and (b) the slope in equation (9) above is closer to -4.0 than the value of -4.73 in equation (20) of XP99. The physical meanings of the changes are that according to the new scalings, (a) Pn $M_0$ tends to be more separated from Lg $M_0$ for explosions with the same magnitude, and (b) for Pn, the rate of decrease of $f_c$ with increasing $M_0$ is more similar to that for Lg, both following quarter-root scalings. These changes in Pn spectral scalings are not surprising since in XP99, Pn spectral parameters were available only for a small number of eight events, within a limited $m_b$ range (4.9 to 6.0). In fact, in the latter $m_b$ range, the changes brought by the new scalings are trivial (see gray and solid straight lines in Figures 5 and 6). I note that in that $m_b$ range both the
previous and new $m_b$-$M_\text{0}$ scalings are also consistent with the scaling developed using teleseismic P waves from Shagan River explosions (Ringdal et al., 1992, equation (13); note that a conversion of $\psi$ in to $M_\text{0}$ changes -2.57 to 9.42). The slopes of the $Pn M_\text{0}$-$f_c$ scalings are also consistent with that of Denney and Johnson (1991) if quarter-root containment is assumed [H.J. Patton, written communication, 2001]. In brief, my new analysis confirms, in a wider $m_b$ range, the scaling relationships in XP99 for explosions.

**Magnitude dependence of $Pn/Lg$ spectral ratios**

As mentioned earlier, 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. This was confirmed by XP99 using observations for LTS explosions in the $m_b$ range between about 5 and 6. Here I confirm this dependence again with the new data that extends the $m_b$ range to between about 3.7 and 6.6.

Figures 7(a) and (b) redisplay the previously observed, station-averaged $Pn/Lg$ spectral ratios for all explosions and selected earthquakes shown in Figure 12 of XP99. Also redisplayed are the "generic" $Pn/Lg$ ratios in XP99, for hypothetical explosions and earthquakes of various $m_b$ values, calculated using (a) the source scaling relationships, (b) the MMM or Brune source model, and (c) an average path effect constructed using the averaged epicentral distance ($\bar{\Delta}$), $Q_0$ and $\bar{\eta}$ in XP99. To compare these with the $Pn/Lg$ ratios from explosions 052192 and 082298 in this study, I corrected the path effects in the latter ratios into that of the average path in XP99. These new, path-corrected $Pn/Lg$ ratios are plotted in Figure 7.

Shapes of the new observed ratios for the large ($m_b = 6.6$) and small ($m_b = 3.8$) 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 relationship, as mentioned earlier. Interestingly, the shift of the ratio from event 082298 is so significant that it falls
into the earthquake population in the frequency range of about 1-6 Hz. This overlap exists for the raw ratio from 082298, with no path correction applied (not shown). I varied the average $\bar{Q}_0$ and $\bar{\eta}$ values in the calculation to explore the possibility that the frequency-shift of the new ratios are caused by using imprecise path corrections. By varying average $\bar{Q}_0$ by up to 15% and $\bar{\eta}$ by up to 0.15, I found that variations of $\bar{\eta}$ for event 082298 has the most significant effect on the path-corrected Pn/Lg ratio, since this ratio is observed at quite high frequencies (above 20 Hz) where attenuation effects are sensitive to the value of $\bar{\eta}$. However, even for that case, the ratio mainly changes its level in the relative flat portion between about 15 to 25 Hz, and the overall shape is still similar to that shown in Figure 7. It should also be noted that the path $Q_0i$ and $\eta_i$ values in this study are obtained with a priori knowledge from XP99, ensuring that these values are inherently consistent with the previous values. I therefore conclude that cause of the frequency shifts in Figure 7 is variations in source spectral ratios, rather than artifact of imprecise path correction, which can only have a secondary effect.

To further explore the generality of the observed magnitude dependence of the Pn/Lg ratios from explosions in central Asia, I calculated Pn/Lg spectral ratios for fifteen Soviet underground nuclear explosions detonated at the KTS between 1987 and 1989 (Table 2) as recorded at the CDSN station WMQ. No attempt was made to invert for source spectral parameters or path Q using these single-station recordings. Rather, 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 8, together with the two "generic" source ratios predicted by XP99 (Figure 12 of XP99; Figure 7 of this paper). 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 [Xie et al., 1996; XP99]. Indeed, the observed stacked Pn/Lg ratios in Figure 8 are very close to the respective generic ratios, confirming the similarity in Q models, as well as the magnitude dependence of the
A procedure to account for the magnitude dependence of Pn/Lg ratios

Previously, the observed magnitude dependence of S/P ratios has led to disagreements on whether and how these ratios can be used to identify explosions. A good example of such disagreements was presented by Ringdal et al. [1998], who questioned whether the August 16, 1997 seismic event in Novaya Zemlya studied by Richards and Kim [1997] can be identified as an explosion based on comparison of P/Sn ratios crossing a large magnitude range (between about 3.5 and 5.7). Interestingly, Ringdal et al. based their argument on an observed magnitude dependence of explosion-generated P/Sn ratios similar to those reported in this study, over paths from Novaya Zemlya to Scandinavia. In this study, we have demonstrated that, 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, we could well have mis-identified that event as an earthquake based on the ratio in Figure 7. 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 (7) through (10)), we can estimate the factors by which the $f_c$ values for an $m_b = 3.8$ event increase from those of an $m_b = 5.0$ event: the factor should be 2.1 for Pn $f_c$, and 2.3 for 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 2.2 (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 9. In that figure the new Pn/Lg ratio for 082298, plotted with the frequency normalization, is in the explosion population.

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 2.5, rather than 2.2. A frequency normalization using the factor of 2.5 will shift the Pn/Lg ratio slightly more than shown in Figure 9, causing the ratio to separate slightly further from the earthquake population. Therefore so long as we take into account the magnitude dependence of the Pn/Lg ratios, the event of mb 3.8 is identified as an explosion regardless of which set of scalings are used.

Discussion

The source spectral scalings of Pn and Lg spectra, and the magnitude dependence of their ratios in this and proceeding papers, such as XP99, are observed under the following conditions: (1) All epicentral distances involved are greater than 200 km, with most distances greater than about 400 to 500 km. The distances involved for Pn observations are also smaller than the 1,400 km cross-over of Pn and deep-turning mantle P waves. (2) All explosions and stations are in a narrow zone of approximately 15° by 10° in central Asia (Figure 2), with grossly similar geologic environment. (3) All events whose source spectra were inverted were recorded by multiple stations. In the distance range used, Pn and Lg are well separated from Pg, Sn and other phases so that chances of mixing different phases are minimized.

Previous observations of P/Lg ratios for the Nevada Test Site (NTS) explosions [e.g., Taylor, 1996] showed little if any dependence of the ratios on frequency or event magnitude. This is in sharp contrast to the observations reported for central Asia in this study and XP99. A probable cause for this difference is that the modes of excitations of Lg and/or Pn waves from explosions in the NTS are different from those in central Asia owing to the different geological environments. The different modes of excitations may also explain why Bennett et al. [1996, 1997] found P/Lg ratios to be frequency-dependent for explosions in central Asia, but frequency-independent for the NTS explosions.

Additional causes for the lack of previously documented magnitude dependence of phase
spectral ratios may include that some observations have been conducted at short distances (e.g. at \( \Delta < 200 \) km), and/or with different data processing procedures. In this and the proceeding papers, Pn/Lg ratios are obtained by first obtaining amplitude spectra by straight-forward Fourier Transformation, then taking the ratio of Pn/Lg spectra. Stacking is then conducted over ratios either from multiple station recordings of the same event, or from single-station recordings of multiple, similar events. The stacked ratios have the same frequency resolution as carried by the original data, while also being smooth enough to show systematic variations with event size (\( m_b \)). Smoothing by stacking or other means of the Pn/Lg ratios is necessary owing to the enormous random fluctuation of spectral ratios. In Appendix A I further elaborate on these fluctuations and their reduction by using multiple short Lg windows. In other studies, often the Pn/Lg ratios are calculated using single records. Effects of random fluctuations were overcome primarily by averaging ratios in pre-selected frequency bands that have a typical width of 1 to 2 Hz. That practice significantly sacrifices the frequency resolution. Moreover, the exact numerical procedures with which the average was done, such as band-pass filtered, time-domain rms average or frequency domain log-average, are non-trivial and non-identical with one another [e.g., Rodgers et al., 1997]. In view of all these complications, I suggest that the lack of previously documented magnitude dependences of phase spectral ratios may be caused by different geological environments involved, different distance ranges used (e.g., at \( \Delta < 200 \) km), and different data processing procedures used.

The observation on source scalings of Pn, Lg spectra and the magnitude dependence of their ratios put constraints on underlying mechanisms for the excitation of Pn and Lg. First, there is a systematic discrepancy between the \( M_0 \) values estimated using Pn and those using Lg (equations (7) and (8); Figure 5). A similar discrepancy has been reported by earlier authors such as Sereno et al. [1988], who suggested that the discrepancy may be quantified a coefficient \( \kappa \), which in our notation can be defined by equalizing Lg \( M_0 \) to \( \kappa \) times Pn \( M_0 \). Using equations (7) and
(8) of this paper, I obtain a $\kappa$ of about 0.28, a value that is surprisingly close to 0.27 estimated for Scandinavia by Sereno et al. [1988], and is consistent with the expectation that explosions generate weaker Lg than Pn. It seems reasonable to require any mechanisms proposed for regional wave excitation to reproduce the observed $\kappa$ values.

In addition to the discrepancy in $M_0$ estimates, results of this and proceeding works further require that in the frequency domain, the transfer function between excitation of Pn and Lg is not flat. The non-flat transfer function has raised concerns as to whether it is physical. We do not yet quite understand the detailed physical processes responsible for regional wave excitations. Pn seems to involve a simpler process since it can be generated in a simple 1D medium for explosions, and since it tends to contain the anticipated radiation pattern for earthquake sources [Zhao and Ebel, 1991; XP99]. The mode of Lg excitation is controversial and may involve one or more possible, complex mechanisms as mentioned in the Introduction. Some mechanisms, such as near source scattering or spall, may well result in non-flat Lg to Pn transfer functions under favorable source conditions. I note that even for earthquake sources which can excite strong Lg in a simple 1D medium, it has long been proposed that the transfer function between the local S waves and Lg was not flat [Harr et al., 1986].

**Conclusions**

Seismic Pn and Lg spectra are retrieved for many underground explosions in central Asia. These include a very large, $m_b = 6.6$ nuclear explosion at the Lop Nor Test Site (LTS), five recent chemical explosions with yields of 25 and 100 ton at the Kazakhstan Test Site (KTS), and fifteen Soviet nuclear explosions in the KTS between 1987 and 1989. Pn and Lg spectra from the very large nuclear explosion and small chemical explosions are collected at multiple stations, thus permitting simultaneous inversions for source seismic moments ($M_0$), corner frequencies ($f_c$) and path-variable $Q_0$ and $\eta$. Such inversions are conducted using a stochastic forward model, a previously developed non-linear method and a priori information on path Q for Pn and Lg. The
resulting source spectral parameters are used to construct synthetic source spectra, which are compared with the observed, path-corrected source spectra to check for the adequacy of the stochastic model used. The comparisons for nuclear explosions in this and previous studies indicate that the modified Mueller-Murphy (MMM) source model fits the observed Pn and Lg source spectra very well. For chemical explosions, the MMM source model represents the observed source spectra reasonably well, although the observed Pn source spectra contain event-variable spectral fluctuations at localized frequencies, indicating some higher-order source spectral complications. The abnormal depths and emplacement conditions of some chemical explosions may have contributed to the complications.

The $M_0$ and $f_c$ values for the very large nuclear explosion and the chemical explosions are added to the previously obtained values for nuclear explosions with $m_b$ between 5 and 6 to re-derive scaling relationships among body-wave magnitude ($m_b$), $M_0$ and $f_c$ values. The new scalings are consistent with the previously developed scaling relationships for explosions with a narrower $m_b$ range. In particular, it is confirmed that (1) log $M_0$ from both Pn and Lg correlates with $m_b$ linearly with slopes slightly higher than 1.0, (2) Pn $M_0$ are systematically larger than Lg $M_0$, (3) both Pn $f_c$ and Lg $f_c$ scale as quarter root of $M_0$, and (4) Pn $f_c$ are systematically higher, by a factor of $\sim 4$, than the Lg $f_c$ at the same $m_b$ level. The $m_b$ range in which the new scalings are derived is between about 3.7 to 6.6.

A necessary consequence of the scaling relationships is that the frequency range of a rapid growth of the Pn/Lg spectral ratios is dependent on event magnitude. This frequency range shifts higher for smaller explosions. This magnitude dependence is of great practical significance in identifying explosions using P/S ratios. Theoretically this magnitude dependence, together with the source spectral scalings that cause it, require an underlinging physics that the excitation of Pn and Lg are connected by a non-flat transfer function in the frequency domain.
Owing to the great importance of the predicted magnitude dependence of Pn/Lg ratios, I calculated the station-averaged ratios for the very large nuclear explosion and a small chemical explosion, to see if the observed ratios support such dependence. Additionally, Pn/Lg ratios, observed at a single station (WMQ) from many Soviet explosions of mb near 6.0, are stacked to see if the resulting ratio differs from the respective stacked ratio for explosions with mb near 5.0. All of the calculations and comparisons verify the magnitude dependence of Pn/Lg ratios for the underground explosions that were studied. Moreover, it is demonstrated that, based on the scaling relationships, a simple correction may be applied to the observed Pn/Lg ratios to account for the magnitude dependence in discriminating explosions.

This study focuses on the Pn and Lg spectra from explosions. 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 analyzed so far is relatively small. Some chemical explosions have abnormal depths of burial and there are no explosions in the kiloton range. There is also a lack of data from earthquakes beyond the mb 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 spectral ratios, such as Pn/Sn and Pg/Lg ratios, and (c) whether 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 Nevada test site of the western U.S.

**Appendix A: Reduction of Variability of Pn/Lg Spectral Ratios by Choice of Lg Windows**

A question addressed by this paper is whether there is a statistical trend for explosion-excited Pn/Lg ratios to be dependent on the explosion magnitude. This question has been
answered by examinations of stacked ratios (statistical means of the ratios) for each event population with similar magnitudes, such as that presented in Figure 8. In the practice of explosion discrimination, another important question to ask is how variable the ratios are within each event population. If both Pn and Lg signals satisfy assumptions that (1) they are independent random signals obeying Gaussian distribution, and (2) their spectra are obtained using rectangular windows with no smoothing effect, then their power spectral ratios should obey an $F$ distribution of degrees of 2 by 2 (Jenkins and Watts, 1969; Aki and Richards, 1980). In that case the Pn/Lg spectral ratio would be wildly variable and can not be quantified by a closed-form theoretical variance. When taking the logarithm of the respective amplitude spectral ratios, Xie and Nuttli [1988, equations (B10)-(B12)] give a theoretical variance of $\pi^2/12$. In practice both assumptions are not strictly valid. Hence in this appendix I investigate the variance and the coefficient of variation (c.o.v., defined as sample standard deviation divided by the mean) of the Pn/Lg spectral ratios empirically. To do so I chose to calculate the variance and c.o.v. associated with Pn/Lg ratios from the $m_b \sim 6$ Soviet explosions recorded by station WMQ (Figure 8) because of the relative large number of samples ($M=10$). Figure A1(a) shows the stacked ratio (the same as in Figure 8) and the sample standard deviations (s.s.d.). I estimate that the average c.o.v. between 0.3 and 7.0 hz is 0.40. Physically, this means that the ratios are subject to a 40% uncertainty measured by one standard deviation.

The c.o.v. may be reduced by changing the time window used to retrieve Lg spectra. In this study, Pn spectral estimated are obtained by averaging spectra from moving windows with a constant length of 4.5 s. The Lg spectral estimates, on the other hand, are obtained using a single group velocity window between $v_g$ of 3.0 and 3.5 km/s (the window length, $T_w$, is about 45 s at a typical distance of 950 km from the KTS to WMQ). The frequency resolutions of the Pn and Lg spectra are about ten times different, and the higher resolution of Lg spectra (about 0.02 hz) is excessive in terms of forming Pn/Lg ratios. An alternative way to retrieve smoother Lg spectra is
to also use multiple short windows, such as those used by Atkinson and Mereu [1992, equation (3)]. As a test, I calculated new Lg spectra from the m_b ~ 6 Soviet explosions recorded at WMQ. The new calculation was done using multiple windows with a constant length of 9 s and 50% overlap to cover the entire Lg wave trains. Lg spectra thus obtained are then root-mean-square averaged, and multiplied by a factor \( \sqrt{T_w/9} \) (see Atkinson and Mereu for reason of the multiplication). The new Pn/Lg spectral ratios were then formed with their mean and s.s.d. plotted in Figure A1(b). As expected, the new stacked ratios form a smoothed version of previous ratios (Figure A1(a)), at a cost of lower frequency resolution. The average c.o.v. between 0.3 and 7.0 hz for the new ratios is 0.24, which is 40% lower than the value of 0.4 obtained for previous Pn/Lg ratios (note that the mean of the new ratio also contains less fluctuation, so the reduction of the variability is underestimated using only the c.o.v.). In the practice of explosion discrimination, the use of multiple, short Lg windows (or other means of spectral smoothing to a frequency resolution of 0.1-0.2 hz) may be more preferable since they reduce the uncertainty (spectral fluctuation) associated with the Pn/Lg ratios.

**Acknowledgements**

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References


Figure Captions

Figure 1. Schematic showing the effect of source size on the observed Pn/Lg ratios from underground explosions. The curve is a "generic" Pn/Lg ratio, constructed using the modified Mueller-Murphy source model, realistic fc values for Pn and Lg, and the effects of an averaged path for central Asia [see Figure 12 of Xie and Patton, 1999]. The ratio grows rapidly in the intermediate frequency range between Pn fc and Lg fc. The gray arrow shows the direction of the shift when the fc value increases with decreasing event size.

Figure 2. Map showing locations of the nuclear and chemical explosions (stars), seismographic stations (triangles), and paths used in this study. The explosion of 05/21/92 (mb = 6.6) is at the Lop Nor Test Site (LTS). Explosions to the south of station KURK are at the Kazakhstan Test Site (KTS), and are divided into two clusters in the east (Shagan River) and west (Degelen Mountain) sites. Stations inside the Tibetan Plateau are those deployed in the 1992, Passcal Tibetan experiment [McNamara et al., 1996]. Dashed lines are paths over which Pn is observed, but Lg is blocked. Paths from the LTS to stations in eastern Europe are only partly shown [cf. Figure 2 of Xie et al., 1996]. Dotted lines denote single-station paths from Soviet explosions between 1987-1989.

Figure 3. Observed and synthetic Lg and Pn source spectra for the LTS nuclear explosion and five KTS chemical explosions. Fluctuating curves are the observed source spectra, obtained by correcting the path effects using the estimated Q0i and ηi values for Pn or Lg spectra at individual stations (equation (1)), then averaging the path-corrected spectra over the available stations. Solid curves are synthetic source spectra, constructed using the MMM source model and the estimated M0 and fc values. Station-averaged values of (Q0, η) from the 082298 explosion to the seven recording stations are (425, 0.5) for Pn and (534, 0.4) for Lg.

Figure 4. Record section showing vertical component seismograms containing Pn and Lg from
the 082298 KTS chemical explosion. High-pass filtering at 1 Hz is applied. Station KUR is within the cross-over distances of Pg/Pn and Sg/Lg, hence is not used in spectral inversions. The first arrival at all other stations is Pn. Straight line marks the arrival of signal with a typical Lg group velocity (3.5 km/s).

**Figure 5.** $m_b$ 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 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 6.** 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 7.** (a) Pn/Lg spectral ratios of ground motion. All ratios are calculated using the square root of the power spectral density (p.s.d) of Pn and Lg, so that the window-length effect of the Fourier Transform is normalized. "EX" and "EQ" denote ratios for explosions and earthquakes, respectively. "Generic ratios" are from Xie and Patton [1999], calculated for hypothetical explosions and earthquakes with the $m_b$ values indicated, at an average central Asian station about 1000 km away from the sources. 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 [Xie and Patton, Figure 12, left panel]. Observed ratios from this study (gray curves) are station-averaged ratios from the 052192 ($m_b$~6.6) and 082298 ("Hundred-ton") explosions, with path corrections. The path corrections are made by first reducing the observed Pn/Lg ratios to the sources 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
Xie and Patton [1999]. (b) Same as in (a), except that the fluctuating black curves are selected ratios for earthquakes with $m_b$ between about 4 and 5.5, rather than for the explosions [Figure 12 of XP99, right panel]. Note that the ratios from the 082298 explosion are generally within the earthquake population between about 1-6 Hz. This is also true when no path correction is applied (not shown).

**Figure 8.** Event-stacked Pn/Lg spectral ratios for Soviet explosions with magnitudes around 5.0 and 6.0, respectively, at station WMQ. Superposed are the "generic ratios" for average central Asian paths (the same as those in Figure 7). The observed ratios are surprisingly close to the generic ratios.

**Figure 9.** Same as Figure 7(a) 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 2.2. As predicted by the scaling relationships (equations (7) through (10)), the frequency reduction indeed shifts the ratio of 082298 into the position of an $m_b$=5.0 explosion at most frequencies.

**Figure A1** (a) Event-stacked Pn/Lg spectral ratios for Soviet explosions with magnitudes around 6.0 (black curve; same as gray curve in Figure 8), and the associated sample standard deviations (vertical gray lines). (b) Same as in (a), except the ratios and the sample standard deviations are obtained using the new Lg spectral estimates, which are calculated with multiple overlapping windows with a constant length of 9s.
Table 1. Explosions used in the multiple-station spectral inversions

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<th>Longitude (° E)</th>
<th>mb</th>
<th># of Pn records</th>
<th># of Lg records</th>
<th>Yield (ton)</th>
<th>Pn M0† (Nm)</th>
<th>Pn f0† (hz)</th>
<th>Lg M0† (Nm)</th>
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<td>1.7(±0.1)</td>
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<td>5</td>
<td>25</td>
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<td>10.0(±0.4)</td>
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<td>78.849</td>
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Event ID is composed of the month, date and year of the explosion. Event time, location and mb 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 in the Lop Nor Test Site. All other events are chemical explosions in the Kazakhstan Test Site.

†M0, f0 values are from spectral inversions of this study.
Table 2. Explosions used in the single station Pn/Lg spectral ratio analysis

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Event ID is composed of the month, date and year of the explosion. Event time, location and m_b values are from the same sources as in Table 1. All events are recorded at CDSN station WMQ.
Xie 2001, Fig. 1.
Xie 2001, Fig. 2.
Xie 2001, Fig. 3.
Xie 2001, Fig. 4.
Xie 2001, Fig. 5.
Xie 2001, Fig. 6.
Xie 2001, Fig. 7.
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Xie 2001, Fig. a1.