A SCALING ANALYSIS OF FREQUENCY DEPENDENT ENERGY PARTITION FOR LOCAL AND REGIONAL SEISMIC PHASES FROM EXPLOSIONS

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ABSTRACT

It has long been recognized that seismic identification of underground nuclear tests with $m_b < 4$ will have to be based largely on discriminants which are effective in the regional distance range. Research conducted over the past 20 years has demonstrated that the most reliable of the regional discriminants considered to date are those based on high-frequency spectral ratios of the amplitudes of the seismic shear phases Sn and Lg to those of the corresponding direct P phases Pn and Pg. While much observational evidence supporting the general applicability of these regional discriminants has now been accumulated, a problem remains in that there is currently no deterministic model of shear wave generation by explosions which has been shown to be quantitatively consistent with the wide range of Sn and Lg observations from explosion sources. Consequently, extrapolation of these discrimination criteria to previously untested locations and source conditions is still subject to considerable uncertainty. The technical objectives of this research program are to determine frequency dependent source scaling relations for the regional phases Pn, Pg, Sn and Lg through statistical analyses of data recorded from underground explosions at the Semipalatinsk, Novaya Zemlya, Lop Nor and Nevada Test Site (NTS) nuclear test sites, and to apply these derived scaling relations to a quantitative evaluation of the plausibility of various proposed physical source mechanisms for the regional shear phases Sn and Lg observed from underground explosion sources.

During the first year of this program, the study effort has been focusing on analyses of regional seismic data recorded from explosions at the Degelen Mountain and Balapan testing areas of the Semipalatinsk test site. For this purpose, digital data recorded at the Borovoye Geophysical Observatory in North Kazakhstan from selected Semipalatinsk explosions is being supplemented by parametric data collected from over 20 stations of the former Soviet Union's permanent seismic network to better constrain the relative source excitation levels of the various regional seismic phases. Data from an initial sample of 23 Degelen explosions of known yield and depth of burial have now been compiled and analyzed. The yield range of these explosions extends from about 1 to 100 kt, and thus provides a good basis for quantitatively evaluating the frequency-dependent source scaling of the regional P and S wave data recorded from these explosions. Digital data recorded from these explosions at the Borovoye station have been carefully previewed by an experienced analyst and systematically edited to remove the numerous spikes and data dropouts which could contaminate any quantitative spectral analyses. These broadband Borovoye data, recorded at a range of about 650 km, show strong short-period Sn and Lg arrivals relative to the corresponding initial P phases. Spectral analyses of these data indicate large Lg/Pn ratios out to about 3 Hz, above which the Lg spectral amplitude level decreases quite rapidly to the P coda level at about 5 Hz. The observed Sn spectral amplitude levels are also greater than those of P out to about 3 Hz but decrease less rapidly than those of Lg at higher frequencies, showing spectral amplitude levels above the P coda level out to 10 Hz. The Sn/Pn and Lg/Pn spectral ratios corresponding to this sample of Degelen explosions have been statistically analyzed to derive yield scaling exponents as a function of frequency. Both of these regional phase spectral ratios show some modest yield dependence in the 1-3 Hz band but no statistically significant yield dependence at the higher frequencies used for discrimination. These observations place strong constraints on the possible S wave source generation mechanisms for these explosions. Regional phase peak amplitude data measured from recordings at some 22 Soviet network stations from Degelen explosions have also been statistically analyzed to test for any significant azimuthal dependence of the corresponding Sn/Pn and Lg/Pn peak amplitude ratios. No statistically significant azimuthal dependence has been found for either of these regional phase amplitude ratios, which provides another important constraint on the range of plausible mechanisms of S wave generation from these explosions. These source scaling analyses are currently being extended to encompass data from a representative sample of Balapan explosions in an attempt to better constrain the regional S-wave generation mechanisms for Semipalatinsk explosions.

OBJECTIVES

The technical objectives of this research program are to determine frequency dependent source scaling relations for the regional phases Pn, Pg, Sn, and Lg through statistical analyses of data recorded from underground explosions at the Semipalatinsk, Novaya Zemlya, Lop Nor, and Nevada Test Site (NTS) nuclear test sites, and to apply these derived scaling relations to a quantitative evaluation of the plausibility of various proposed physical source mechanisms for the regional shear phases Sn and Lg observed from underground explosion sources. The ultimate objective is to improve U.S. operational monitoring capability by providing a quantitative framework which can be used for confidently evaluating expected regional event discrimination performance as a function of the ranges of explosion source size and emplacement conditions which must be considered in global nuclear monitoring.

RESEARCH ACCOMPLISHED

A number of focused research studies have been conducted in recent years in attempts to better define the source of the S-waves observed from underground nuclear explosions, particularly as they relate to the generation of the Lg regional phase which has come to play a central role in the identification and yield estimation of small explosions. In early studies of the seismic waves generated by underground nuclear explosions, it was generally assumed that the observed S-waves were produced by linear conversion of the primary explosion P-waves by the layered geology in the source region and along the propagation path between the source and the receiver. However, it was soon recognized that relatively strong S arrivals were also observed on the transverse components of motion at regional distances and this necessitated the addition of a nonisotropic scattering mechanism to the simple linear conversion model. Subsequent deterministic simulations of the Lg phases produced by point source explosions in planar multilayered approximations of the crustal waveguide raised further questions regarding the plausibility of the linear P to S conversion mechanism in that isotropic explosions in high velocity source media such as granite were predicted to generate very little Lg energy (Jih and McLaughlin, 1988).

These inconsistencies prompted intensive searches for alternate sources of Lg which generally focused on either scattering of the Rg phase induced by the isotropic explosion into Lg (e.g., Gupta et al., 1991, 1997) or on direct generation of S and Rg waves by the non-isotropic components of the explosion source associated with spall and other nonlinear interactions of the primary explosion source with the overlying geology and free surface (e.g., Stevens et al., 1991, 2003). Although significant theoretical and observational evidence has been marshalled to support the plausibility of both of these hypothetical sources of Lg, problems remain in that neither seems completely consistent with the wide range of Lg observational data which is currently available (Stevens et al., 2003). For example, it has been observed that Lg amplitude level correlates remarkably well with the known yields of underground explosions over broad source regions, and this fact seems difficult to reconcile with the Rg-scattering hypothesis. Moreover, both of these proposed sources would predict a pronounced dependence of Lg excitation on source depth, and this seems inconsistent with the results of Nuttli (1986) and others who have obtained reliable Lg-based yield estimates for very deep explosions, including the U.S. Peaceful Nuclear Explosion (PNE) RULISON which was detonated at a scaled depth more than six times larger than the nominal NTS containment depth. It follows that additional research is needed to identify potential sources of explosion S and Lg phases which satisfy all available constraints.

One potentially powerful constraint on the source of S-waves from explosions is provided by their frequency-dependent scaling as a function of explosion yield, depth of burial and source medium, relative to the well-documented scaling of the associated direct P-wave phases. That is, since it is well established that the scaling of the direct P-waves observed from explosions can be explained to first order by a simple isotropic source model (Mueller and Murphy, 1971), the degree to which the scaling of secondary regional phases such as Sn and Lg is similar to that of the corresponding Pn phases provides direct evidence of any significant departures from the isotropic source model. Thus, while a scaling analysis in itself will not specifically identify a physical mechanism for Lg generation, it will nonetheless provide powerful quantitative constraints which would have to be met by any proposed source mechanism.

One example of this approach was provided by Murphy et al. (2001), who analyzed the source scaling characteristics of regional phase data recorded at the Borovoye Geophysical Observatory in North Kazakhstan from a sample of 21 Soviet PNE events of known yield and depth of burial. On the basis of prior experience (e.g., Mueller and Murphy, 1971), it was assumed that the explosion seismic source, $S(\omega)$, could be approximated as a product of the form

$$S(\omega) \sim W^{n(\omega)} h^{m(\omega)} \quad 1$$

where W and h are the explosion yield and depth of burial, respectively, and $n(\omega)$, $m(\omega)$ are the associated frequency-dependent scaling exponents. The source scaling exponents estimated from a covariance statistical analysis of the observed Borovoye PNE regional phase spectral amplitude data are displayed as a function of frequency in Figure 1 for Pn and the four secondary regional phases P_{coda}, Pg, Sn and Lg. It can be seen from this figure that the source scaling exponents for all these regional phases are fairly similar over the frequency band from 0.5 to 5.0 Hz, particularly for the yield-scaling exponents. The depth scaling exponents do however show some consistent differences between phases (e.g., Lg versus Pn) over significant portions of this frequency range which could be indicative of differences in source mechanism. Unfortunately, Murphy et al. (2001) concluded that the formal uncertainty in these derived scaling exponents is too large to be able to conclude with high confidence whether these inferred depth scaling differences are statistically significant. This lack of resolving power is at least partially due to the fact that these PNE events were widely dispersed throughout the territories of the former Soviet Union and, consequently, propagation path variability made it difficult to estimate the source scaling exponents with high accuracy. In the present program we are minimizing such propagation path variability by analyzing data recorded at specific stations from multiple explosions at fixed nuclear weapons test sites. This should allow us to more precisely define any consistent differences in the source scaling of the various regional phases, which, in turn, will provide much improved quantitative constraints on proposed source mechanisms for the secondary regional shear phases Sn and Lg.

The initial focus of this study has been on the analysis of broadband digital data recorded at the Borovoye station from underground nuclear explosions of know yield and depth of burial which were conducted at the Degelen Mountain area of the former Soviet Semipalatinsk test site. The vertical component data recorded at this station from 20 such Degelen explosions are plotted as a function of apparent group velocity, in order of increasing yield, in

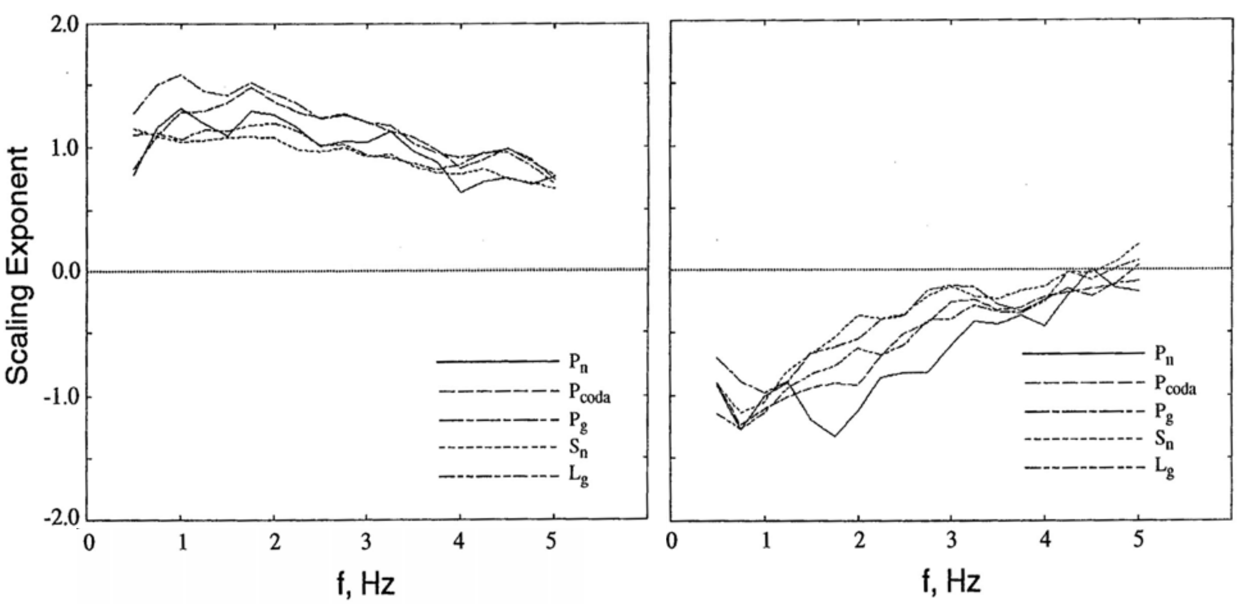

Figure 1. Comparison of yield (left) and depth (right) frequency-dependent scaling exponents determined for the different regional phases recorded at Borovoye from the selected Soviet PNE events.

Figure 2. It can be seen that this sample of explosions encompasses a range of yields extending from 1.1 to 78 kt. Moreover, these data, recorded at a distance of about 650 km, show evidence of strong short-period Sn and Lg relative to the corresponding Pn phases. These digital data have been carefully previewed by an experienced analyst and systematically edited to remove the numerous spikes and data dropouts which could contaminate any subsequent quantitative spectral analyses.

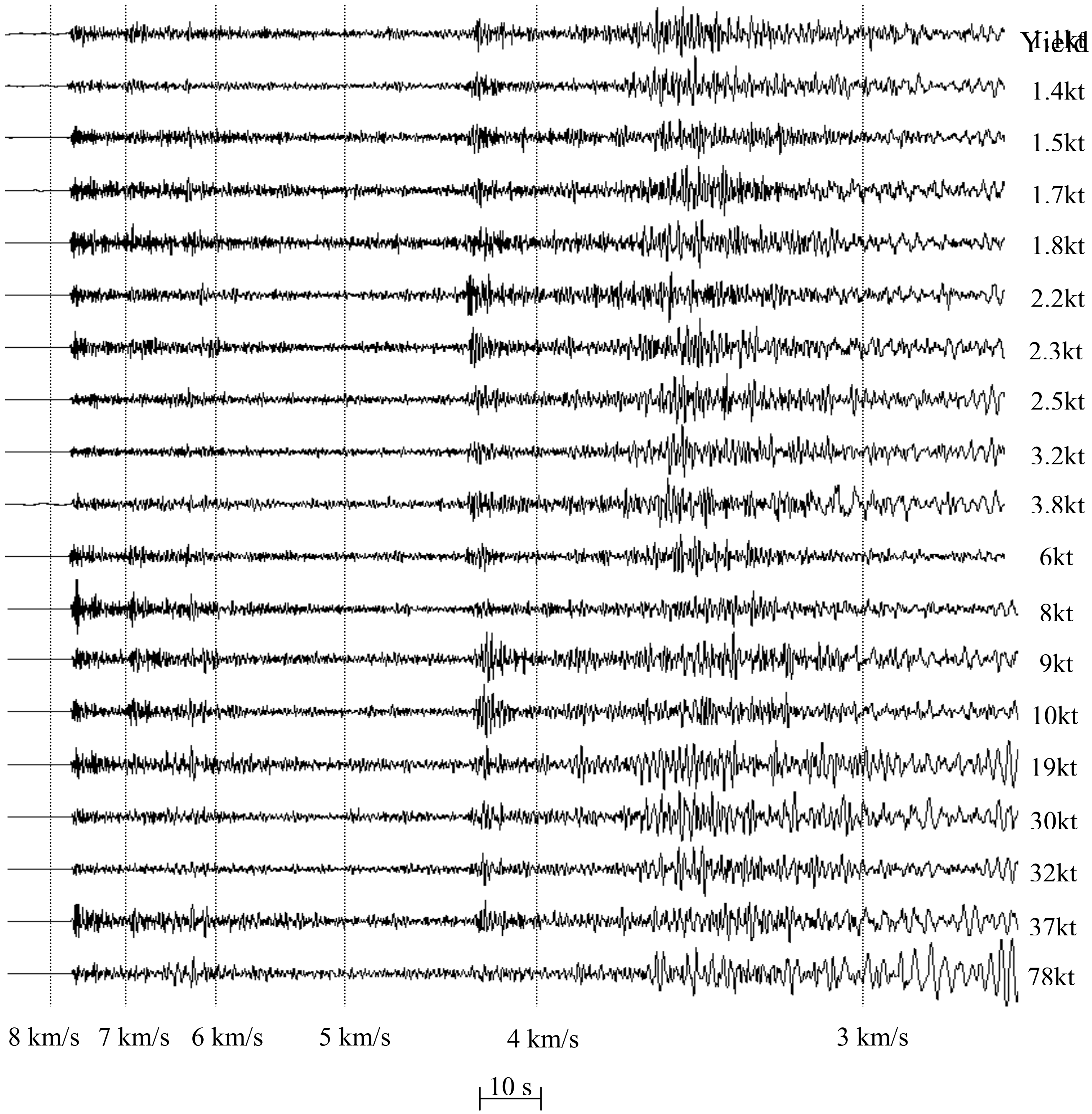

Figure 2. Vertical component digital data recorded at the Borovoye Station (Δ ≈ 650 km) from a sample of Degelen Mountain nuclear explosions of known yield and depth of burial. The data are plotted as a function of apparent group velocity and in order of increasing yield.

The Borovoye data of Figure 2 have been processed to obtain estimates of the different regional phase spectra for each event. In the first step of this processing, the data for each explosion were bandpass filtered using a Gaussian comb of filters spaced at intervals of 0.25 Hz between 0.5 and 10 Hz, where each filter is characterized by a Q value of $6f_c$, with f_c the filter center frequency. Filters of this type have been used by us (Murphy et al., 2001) and a number of other investigators in previous studies and have been found to provide spectral estimates which are useful for purposes of seismic analyses. Figure 3 shows an example of filter outputs encompassing this frequency range for the 1.8 kt Degelen Mountain explosion of October 4, 1989, where the selected time windows for the Pn, Sn and Lg regional phases are indicated. It can be seen that these data indicate large Lg/Pn ratios out to about 2 Hz, above which the Lg spectral amplitude level decreases quite rapidly to the P coda level at about 5 Hz. The observed Sn spectral amplitude levels are also greater than those of Pn out to about 3 Hz but decrease less rapidly than those of Lg at higher frequencies, showing spectral amplitude levels above the P coda levels out to 10 Hz. For purposes of the source scaling analysis, the spectral amplitude levels at each filter center frequency were estimated by computing RMS values from the instrument corrected filter outputs in each of the designated regional phase time windows.

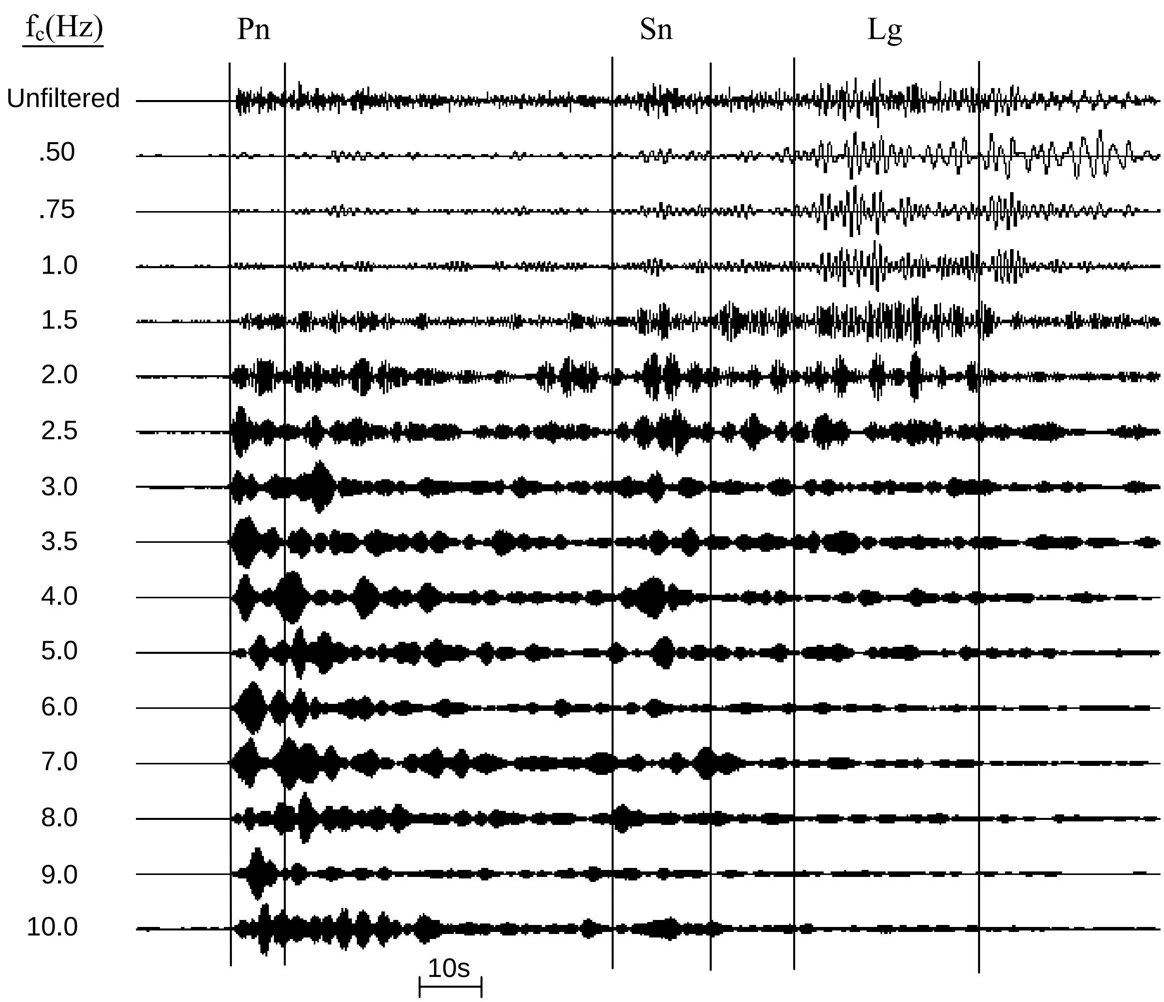

Figure 3. Bandpass filter processing results for the Borovoye recording of the 1.8 kt Degelen Mountain nuclear explosion of October 4, 1989.

An initial yield-scaling analysis has been conducted using the regional phase spectral ratios Sn/Pn and Lg/Pn. That is, the observed Degelen spectral amplitude data were statistically analyzed using an assumed yield-scaling relation of the form

$$\frac{\text{Sn}(\omega)}{\text{Pn}(\omega)} \sim W^{n(\omega)} \qquad 2$$

and a corresponding relation for the Lg/Pn spectral ratio. The resulting yield-scaling exponents are displayed as functions of frequency in Figure 4. Now if the frequency-dependent yield-scaling for the secondary phases Sn and Lg are the same as that for Pn, then the scaling exponents for these ratios would not be significantly different from zero. In fact, the inferred yield-scaling exponents are quite small ranging only from about –0.25 to +0.10, which indicates that the ratios vary by less than a factor of 3 over the nearly two orders of magnitude range in yield encompassed by this sample of Degelen Mountain explosions. More specifically, the scaling exponents differ significantly from zero at the 95% confidence level only in the narrow frequency range from about 1 to 3 Hz. Note that the estimated scaling exponents for the Lg/Pn ratio are effectively zero above 5 Hz, consistent with our previous observation from Figure 3 that the Lg spectral amplitude appears to drop to the P coda level at about this frequency. It follows that, in the higher frequency ranges used for regional discrimination purposes, these source scaling results are not inconsistent with an Sn, Lg generation mechanism with a linear, frequency independent conversion of direct P-wave energy.

A corresponding analysis of the dependence of these Degelen regional phase spectral ratios on source depth is complicated by the fact that our sample of known yield explosions encompasses only a limited depth range from 83 to 332 m, corresponding to a scaled depth range which extends only from 62 to 101 m/kt$^{1/3}$. Consequently, it is not possible to estimate statistically robust source depth scaling relations at this time. However, qualitative comparisons of the observed ratios indicate that any systematic differences in the source depth dependencies between Sn, Lg, and Pn must be quite small, at least over this limited range in depth. This fact is illustrated for Sn in Figure 5 which shows comparisons of observed Sn/Pn ratios which sample the available ranges of depth and scaled depth. It can be seen that these observed ratios are essentially identical over the sampled ranges of depth and scaled depth, consistent with a source depth scaling for Sn which must be very similar to that for Pn. Similar conclusions apply to the corresponding observed Lg/Pn spectral ratios.

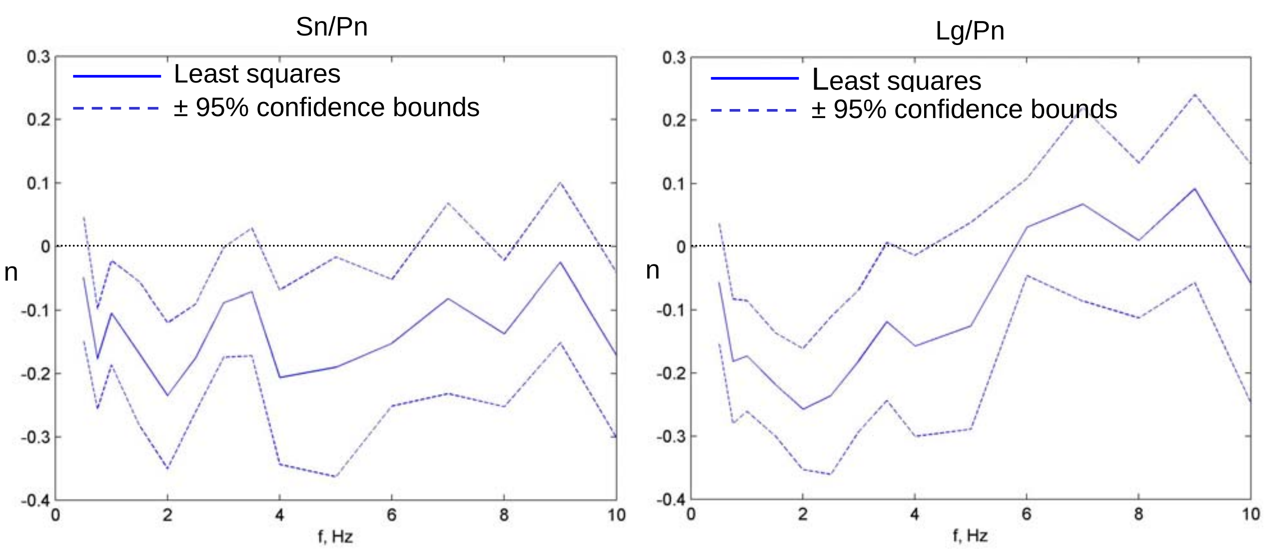

Figure 4. Estimated yield-scaling exponents as a function of frequency for the Sn/Pn (left) and Lg/Pn (right) regional phase spectral ratios for Degelen Mountain explosions.

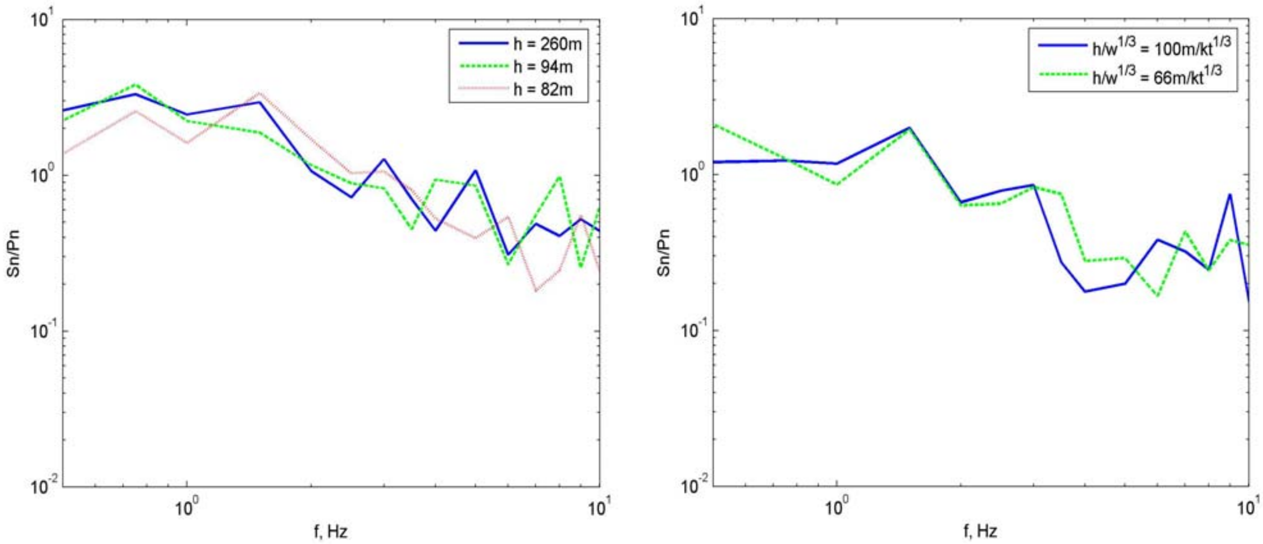

Figure 5. Comparison of observed Degelen Mountain explosion Sn/Pn spectral ratios as a function of source depth (left) and scaled depth (right).

One limitation of the above analysis is that it is based on a single station at a fixed azimuth and thus provides no bounds on possible azimuthal variations in the Pn, Sn, and Lg seismic source functions. Unfortunately, the available digital regional data from Degelen explosions are not adequate to address this issue. As an alternative, regional phase peak amplitude data measured from Degelen explosion analog recordings at some 22 Soviet network stations have also been statistically analyzed. Although such data provide no diagnostic information on possible frequency-dependent effects, they do permit us to examine possible azimuthal effects in the short-period band extending from about 1 to 3 Hz. Figure 6 shows the average observed Degelen explosion Sn/Pn and Lg/Pn peak amplitude ratios at each of the 22 stations, plotted as a function of source to station azimuth. These results indicate that any azimuthal variations in the seismic source functions of these regional phases must be fairly small relative to the single station variability at a fixed azimuth, at least in the short-period band sampled by these data.

Sn/Pn and Lg/Pn peak amplitude ratios for 23 Degelen explosions recorded at Soviet network station AAB ($\Delta \approx 730$ km) are plotted as a function of event m_b value in Figure 7. It can be seen that these observed peak amplitude ratio values show no obvious systematic dependence on m_b. That is, these observations at a station at a very different azimuth (i.e., 180° versus 310°) are generally consistent with the Borovoye results which indicated a weak dependence of the regional phase spectral ratios on explosion yield.

CONCLUSIONS AND RECOMMENDATIONS

During the first year of this investigation the research has focused on seismic source scaling analyses of regional Pn, Sn, and Lg phase data recorded from underground nuclear explosions at the former Soviet Semipalatinsk test site. Digital data recorded at the Borovoye station from a sample of Degelen Mountain explosions of known yield and depth of burial have now been processed and analyzed to define regional phase spectra over the frequency range

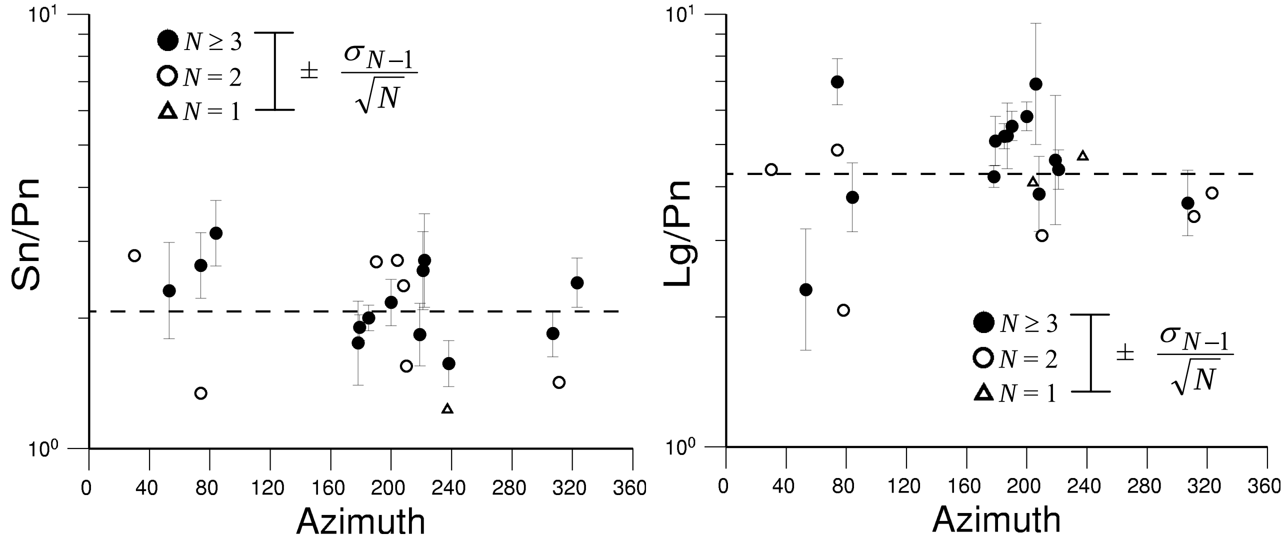

Figure 6. Average observed Degelen Mountain explosion Sn/Pn (left) and Lg/Pn (right) peak amplitude ratios as a function of source to station azimuth for Soviet permanent network stations.

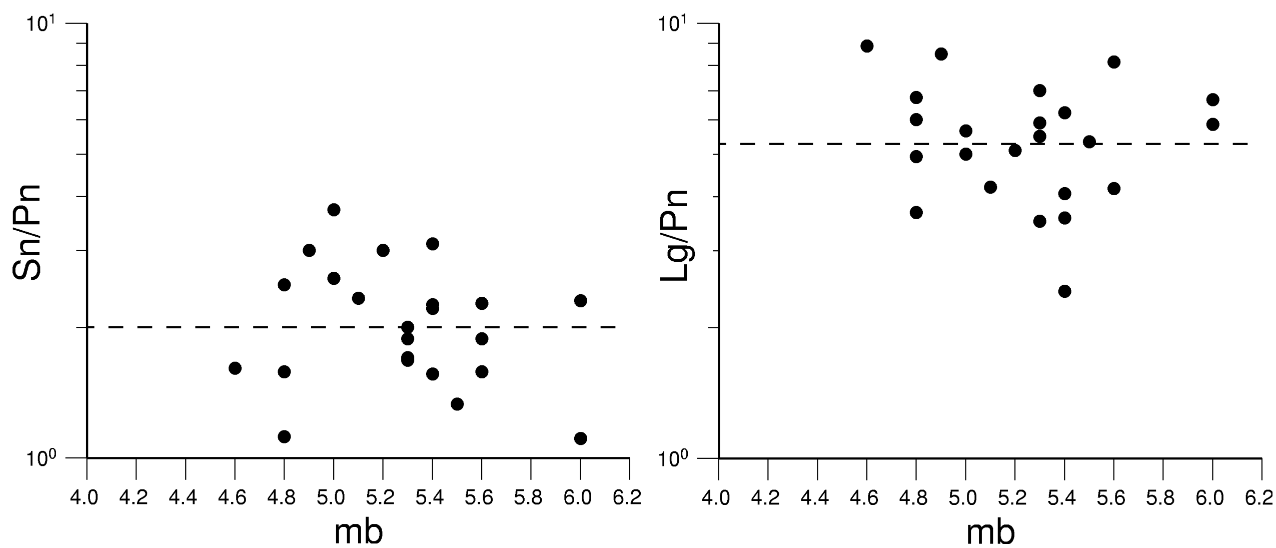

Figure 7. Degelen Mountain explosion Sn/Pn (left) and Lg/Pn (right) peak amplitude ratios as a function of mb at the Soviet permanent network station AAB.

from 0.5 to 10 Hz. Results of yield scaling analyses of the corresponding Sn/Pn and Lg/Pn spectral ratio data were found to be consistent with an Sn, Lg source generation mechanism which is compatable with a linear, frequency independent conversion of direct P wave energy from the explosion, at least in the higher frequency ranges used for regional discrimination. Moreover, it has been found that these observed regional phase spectral ratios are essentially independent of source depth over the limited range in depth sampled by these Degelen explosions, consistent with source depth scaling relations for the Sn and Lg phases which must be very similar to that for Pn. These source scaling analyses are currently being extended to encompass explosions at the Balapan area of the Semipalatinsk test site.

REFERENCES

Gupta, I. N, T. W. McElfresh, and R. A. Wagner (1991), Near-source scattering of Rayleigh to P in teleseismic arrivals from Pahute Mesa NTS shots, in *Explosion Source Phenomenology, AGU Geophysical Monograph* 65, ISBN 0-87590-031-3: 151–159.

Gupta, I. N., T. Zhang, and R. Wagner (1977), Low-frequency Lg from NTS and Kazakh nuclear explosions – observations and interpretations, *Bull. Seism. Soc. Am*., 87: 1115–1125.

Jih, R. S., and K. L. McLaughlin (1988), Investigation of explosion generated SV Lg waves in 2-D heterogeneous crustal models by finite-difference method, report No. AFGL-TR-88-0025.

Mueller, R. A. and J. R. Murphy (1971), Seismic characteristics of underground nuclear detonations, I: seismic spectrum scaling, *Bull. Seism. Soc. Am*. 61: 1675–1692.

Murphy, J. R., I. O. Kitov, B. W. Barker and D. D. Sultanov (2001), Seismic source characteristics of soviet peaceful nuclear explosions, monitoring the Comprehensive Nuclear-Test-Ban Treaty, in *Source Processes and Explosion Yield Estimation, PAGEOPH Topical Volume*, Birkhauser, 2077–2101.

Nuttli, O. W. (1986), Yield Estimates of Nevada Test Site Explosions Obtained from Seismic L_g Waves, *J. Geophys. Res*., 91: 2137–2151.

Stevens, J. L., T. G. Barker, S. M. Day, K. L. McLaughlin, N. Rimer, and B. Shkoller (1991), Simulation of teleseismic body waves, regional seismograms, and Rayleigh Wave Phase Shifts using two-dimensional nonlinear models of explosion sources, *Explosion Source Phenomenology, AGU Geophysical Monograph* 65, ISBN 0-87590-031-3: 239–252.

Stevens, J. L., G. E. Baker, H. Xu, T. J. Bennett, N. Rimer, and S. M. Day (2003), The physical basis of Lg generation by explosion sources," in *Proceedings of the 25th Seismic Research Review – Nuclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. 1, pp. 456-466.