IMPROVEMENTS TO A MAJOR DIGITAL ARCHIVE OF SEISMIC WAVEFORMS FROM NUCLEAR EXPLOSIONS: THE BOROVOYE SEISMOGRAM ARCHIVE

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ABSTRACT

We are in the final year of a three-year project to generate in modern form an easily usable archive of digital seismograms derived from regional waveforms recorded at the Borovoye Observatory (BRV), northern Kazakhstan, over a thirty-year period going back to 1966 and forward to the time when state-of-the-art sensors and dataloggers were introduced at this site by several different western groups. The BRV seismograms, which include multi-channel regional signals from 350 underground nuclear test explosions carried out in Eurasia, were made generally available to western scientists in 2001, but only as copies of the bits in the original digital waveforms. Those copies contain large numbers of glitches and did not include instrument responses for approximately two-thirds of the events. Our project is a joint effort by scientists at Lamont-Doherty Earth Observatory of Columbia University (LDEO) and at Los Alamos National Laboratory (LANL). The work of deglitching all the Borovoye digital seismograms has now been completed (at LANL). The initial work of determining instrument responses for the many different channels of the three different digital systems used at Borovoye over the thirty-year period has also been completed (at LDEO).

Three different sets of Soviet-style instruments and recording systems were used at BRV from 1966 to 1996. LANL scientists had processed the BRV regional signals for 210 nuclear tests (1355 traces) before the present project started, mainly those for which instrument responses were available (the TSG system). In this project LANL processed the waveforms of the so-called SS system for 148 nuclear tests (1679 traces), some of which were also recorded on the TSG system, and these have now been processed too (281 traces). The remaining main block of events was recorded on the oldest, so-called KOD, system, which was used in operations beginning in 1966 and which operated continuously from 1967 to 1973. The KOD system, based on three component short-period seismometers, is important as one of the few digital systems anywhere in the world in the late 1960s and early 1970s. In this final batch of deglitched (KOD) waveforms from 101 nuclear explosions, there were 835 traces.

We present examples of the resulting de-glitched waveform data, in order to indicate to potential users the quality of these recordings, and their suitability for phase picking, and for studies of amplitude, coda, and spectra.

We note that waveform data from the Borovoye archive are being used to develop new source models for Balapan nuclear tests. In the 1970s and 1980s, long-period surface waves from these tests were noted for their anomalous behavior, including large Love-wave excitation, and Rayleigh waves with polarity reversals and significant time delays. Repeated attempts in previous studies to model such observations only by tectonic release were unsuccessful. New models that also include the effects of tensile failure represented by a compensated linear vector dipole, have yet to be tested. TSG DS recordings bridge the frequency gap between the long-period observations and higher mode surface waves making up the low frequency Lg spectrum. This additional bandwidth is needed for resolving source parameters to test new models. We have made two sets of measurements on DS recordings: 20-s Ms and a slope measurement on the Lg spectrum between 0.1 and 0.8 Hz. Lg displacement spectra are not flat as expected for frequencies below the corner frequency. Rather, the spectral amplitudes roll off toward low frequency by an amount that is correlated with mb-Ms differences. These observations suggest a link between higher-mode and long-period surface wave excitations, a feature that will be exploited for investigating new source models.

OBJECTIVES

Our goal is to generate in modern form an easily usable archive of digital seismograms derived from regional waveforms recorded at the Borovoye Observatory (BRV), northern Kazakstan, over a thirty-year period going back to 1966 and spanning the time when state-of-the-art sensors and dataloggers were introduced at this site in the summer of 1994. Specifically, we expect to process 1200 to 1400 digital waveforms from the Borovoye archive, for more than 200 underground nuclear explosions in Eurasia for which digital records are available but not yet in useful form due to problems with glitches and instrument calibration that have not yet been taken into account.

RESEARCH ACCOMPLISHED

The BRV digital archive of nuclear explosion waveforms from 711 underground nuclear explosions became generally available in April 2001 as an outcome of an International Science and Technology Center (ISTC) project conducted jointly from 1997 to 2000 by the Kazakhstan National Nuclear Centre, the Russian Academy of Sciences Institute of Dynamics of the Geosphere in Moscow, and the Lamont-Doherty Earth Observatory of Columbia University. That project was initiated by Lamont, and provided 180 man-years of funding to scientists and technicians in Kazakhstan and Russia for several different projects, of which the most time-consuming was saving the Borovoye waveform archive.

The archive of nuclear explosion signals was issued as a series of modern databases, described by Kim et al. (2001). The archive was derived from original Soviet-era magnetic tapes that in many cases were in very bad condition, and for which only a limited number of tape readers existed. The tapes were written in complicated formats that had not been used even in the USSR for decades. For example, many tapes were 35 mm wide, and had 24 channels of information written across 17 separate tracks. The first steps in salvaging the archive were reading all the bits one last time from the original tapes using one of the few available tape readers, and then writing them to a mid-1990s mass store hard drive. Later steps entailed extraction of timing information, de-multiplexing, and re-formatting.

Three different sets of Soviet-style instruments and recording systems were deployed at BRV from 1966 to 1996. They are known as the KOD, STsR-SS, and STsR-TSG systems (sometimes abbreviated to KO or KOD, SS, and TS or TSG). The first BRV digital seismic system, KOD, began recording in 1966 and operated continuously from 1967 to 1973. It is based on three-component, short-period seismometers, and is important as one of the few digital seismic systems anywhere in the world in the late 1960s and early 1970s. The other Soviet-era BRV digital systems began operation in February 1973. STsR-SS is intended mainly for low-gain recording. STsR-TSG includes six long-period and seven short-period Kirnos seismometers, most recorded at two gain levels, for a total (SS + TS) of 20 data channels. The highest sensitivity is 100,000 counts/micron based on a short-period Kirnos with a special magnet and a low-noise amplifier. This instrument was important at BRV for teleseismic monitoring of numerous French and U.S. UNEs, but for purposes of this proposal it is not so important today as the lower-gain channels, on which regional signals have been recorded from UNEs in and near Central Asia. Kim and Ekström (1996) have published details of the STsR-TSG instrument responses (many channels, extending across almost 3 decades in frequency). All of these main systems are approximately flat to ground displacement over a range of frequencies. With the different instruments and gain levels, the station as a whole had a dynamic range well over 120 dB during the Soviet era.

When the BRV archive was made generally available from Lamont in 2001, the decision was made that it be essentially in its original unprocessed form (though with the addition of basic header information), but converted to a modern and widely use format for digital seismic data (CSS3.0). The original Soviet-era recordings had some severe problems, most notoriously that the digitizer typically did not write a count value on seismic waveform channels at the time when the time channel was writing the marker for an integer second. The waveform data therefore ended up with numerous glitches. Also, the original recording system addressed the practical problem of input signal with wide dynamic range, by having several different channels set at different gain levels, each recording with a limited number of bits (often, only 11 bits), so that although each UNE was usually recorded on several channels, in practice these channels were often either clipped or had inadequate resolution.

The work of deglitching thousands of digital waveforms in this project has now been completed at LANL, with the delivery in early 2009 to LDEO of 835 deglitched traces derived from 101 underground nuclear explosions in Eurasia. These events were recorded on the KOD system—the oldest and most-difficult to work with, because of the low dynamic range, the condition of the recording tapes, and the unusual instrument response (which has a notch intended to suppress microseisms). Earlier in this project, LANL had completed deglitching SS system records (1689 traces) and TSG system records (282 traces), to add to 1,335 TSG traces deglitched several years ago.

The work of deglitching has thus been completed, after nearly eighteen years since the existence of these data was first made known to western scientists (in 1991, when Richards and Göran Ekström made a two-week visit to Borovoye). Figure 1 shows examples drawn from the three systems used at the Borovoye Observatory.

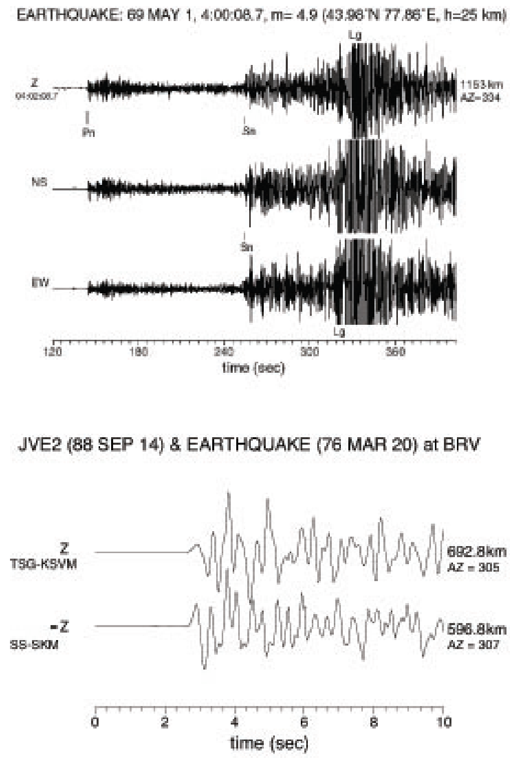

Figure 1. Shows examples from all three of the digitizing systems in use at the Borovoye Observatory (BRV), Kazakhstan, in the Soviet era. At the top, recorded on the KOD system (the oldest), is a three-component recording of the Kazakhstan earthquake of May 1, 1969. Though slightly clipped, this data is of remarkable quality and can be used for phase picking and quantitative studies of coda (albeit not for study of spectra of the strongest ground motion). At the bottom, is a comparison of the first arrivals at BRV of an explosion signal from a Shagan River explosion (JVE2, September 14, 1988, on the TSG system which was the third recording system in operation at BRV); and an earthquake signal on March 20, 1976 (recorded on a channel of the SS system, the second system in operation at BRV). Note the polarity reversal of the earthquake arrival compared to that of the explosion.

There are many possible uses of the dataset being generated in this project, as listed for example below, in the Conclusions and Recommendations section. In this paper, we next give a brief preliminary report on some of the surface-wave signals recorded at BRV, showing how they document effects of tectonics release, and perhaps spall and/or tensile failure, as well as the usual isotropic radiation expected from an explosion.

Analysis of Surface Waves Recorded at Borovoye, for their Indications of Non-Isotropic Source Effects

In the 1970s and 1980s, long-period excitation of surface waves in the Balapan sub-region of the Soviet Semipalatinsk test site in central Asia were noted for anomalous behavior, including the generation of large Love waves and Rayleigh waves with polarity reversals and significant time delays (Rygg, 1979; Cleary, 1981; Helle and Rygg, 1984; Herrin and Goforth, 1986). Repeated attempts to model the observations with tectonic release were not completely successful (Given and Mellman, 1986; Ekström and Richards, 1994), although tectonic release models of reverse faulting explained observations best (Patton, 1980; Harkrider, 1981; Day and Stevens, 1986; Day et al., 1987). New explosion source models for tensile failure represented by a compensated linear vector dipole (CLVD) (Patton and Taylor, 2008) have yet to be tested to see if they can explain the full suit of observations, including m_b–M_s scaling with respect to predictions of the Mueller-Murphy model (Mueller and Murphy, 1971; hereafter referred to as MM71). Due to broader frequency content and a fairly complete recording history of Semipalatinsk Test Site (STS) explosions, waveform data from the Borovoye archive offer the opportunity to re-evaluate old models and test new models of the explosion source.

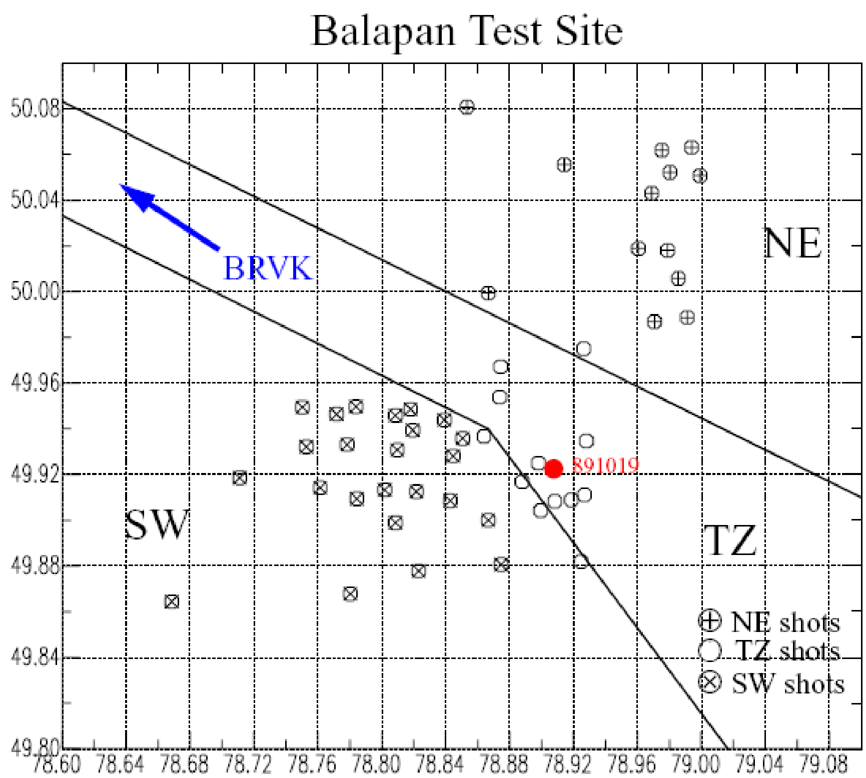

Figure 2. Map of the Balapan sub-region of the Semipalatinsk Test Site showing locations of 50 tests currently understudy and the boundaries of NE, TZ, and SW test areas introduced by Ringdal et al. (1992). The explosion on 891019 is used as the master for subsequent cross-correlation analysis.

Figure 2 shows locations from the report of Kim et al. (2001) for 50 Balapan explosions currently under study. Also shown are test areas called Northeast (NE), Transition Zone (TZ), and Southwest (SW) from the study of Ringdal et al. (1992). Filtered vertical-component displacement traces of the TSG DS instrument system for these 50 explosions are given in Figure 3 along with epicentral distances to Borovoye (BRV), teleseismic m_b calculated by Blacknest seismologists (Ringdal et al. 1992), and a reference to the study of Ekström and Richards (E&R94) for those events whose surface waves were analyzed for moment tensor descriptions. In Fig. 3 the traces are arranged in order of increasing distance from 679.7 to 696.1 km, a span of only 16.4 km. Red and blue boxes demarcate the arrivals of fundamental- and higher-mode Rayleigh waves.

A cross-correlation analysis was carried out on the fundamental-mode Rayleigh waves in order to detect polarity reversals and time delays. This analysis was applied to two filter bands, one between 0.04 and 0.1 Hz and the other at lower frequencies between 0.03 and 0.07 Hz. Before cross-correlation, the seismograms were distance-equalized by accounting for the slight differences in distance of the different explosions, using a phase velocity dispersion based upon an average Balapan velocity model (Bonner et al., 2001).

The explosion on 891019 was chosen as the master for cross-correlation (CC) analysis because of its excellent signal quality, low level of tectonic release (E&R94), and location on a back-azimuth near the population centroid. The polarity of 891019's signal was assumed to be normal. The CC analysis yields polarity and apparent time delay relative to 891019. A measure of confidence in the CC results based on the ratio of the 2nd maximum absolute value to the maximum absolute value of the c-c function is also computed and called R. There are more reversed polarities for the lower frequency pass-band than for the higher. Theory predicts that reversals occur first at low frequencies and progress to higher frequencies as the strength of the CLVD source increases. A threshold of 0.9 was arbitrarily selected to indicate results of lower confidence.

A summary plot of polarity reversals and time delays determined from cross-correlation analysis is shown in Figure 4. By definition, the delay for the master event, plotted as a blue dot, is 0.0. Different symbols are used to identify events according to polarity and confidence level (e.g., $R \geq 0.9$, shown with a × symbol). A solid dot indicates the polarity identified by E&R94. For 770629 and 831120, no dot is given because their surface waves were not analyzed by E&R94.

To tie results in Figure 4 with those determined from teleseismic studies, there must be events in common since the CC method used here and by Helle and Rygg, as well as the phase-matched filter method of Herrin and Goforth, is inherently relative to the chosen master event. The shot 791202 is in common with Helle and Rygg's data set. A small time advance of 0.4 s was found for Borovoye while Helle and Rygg measured a delay of 0.8 s. This suggests a correction of 1.2 s added to all measurements in Fig. 4 in order to compare with their results. After making this correction, the time delays for reversed NW shots range between 3 and 6 s in agreement with the delays determined by Helle and Rygg.

Low-frequency observations of Lg spectra and correlations with M_s.

Fisk (2006) presents *Pn/Lg* spectral ratio observations for STS explosions. For large explosions, SNR appears to be adequate for *Pn* and *Lg* waves recorded at WMQ and MAK for frequencies as low as ~0.2 Hz (see his Fig. 11). As such, the behavior of *Pn/Lg* spectral ratios is considered reliable at low frequencies for large explosion groupings in his Figs. 14 - 17. The observed up-turn in spectral ratios at low frequencies is qualitatively consistent with a roll-off in the spectra of *Lg* waves if the low-frequency spectrum of *Pn* waves is flat as predicted by the MM71 model.

Path-corrected *Lg* displacement spectra were obtained by Fourier transforming BRV signals recorded on the DS instrument system for a time window corresponding to average apparent velocities of 3.77 and 3.21 km/s. For an average distance of 688 km, the corresponding window length is 32 s. A multi-taper algorithm was applied involving 512-point transforms and 7 tapers. Amplitude corrections for instrumental response were performed in the frequency domain, and signal-to-noise checks were made to ensure at least a factor of two threshold for the frequency band of interest. Noise spectra were taken in a window just proceeding the signal window (e.g., ending with an apparent velocity of ~3.8 km/s). A correction for attenuation was made using a power-law Q model, $746*f^{0.2}$ (W. S. Phillips and J. Xie, pers. comm.).

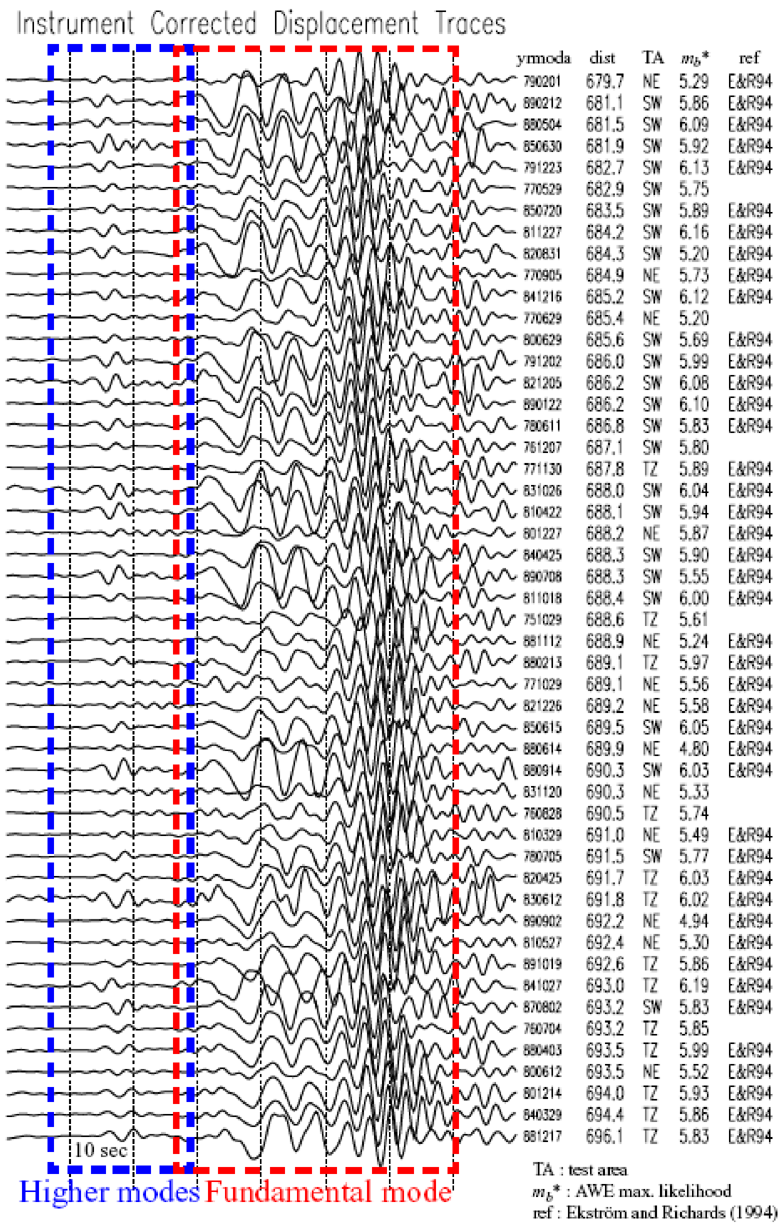

Figure 3. Profile of instrument-corrected, vertical-component displacement traces for the TSG DS system, ordered by increasing distance from the Borovoye station. Passband is 0.03 – 0.5 hz. Blue box demarcates higher-mode arrivals making up Lg waves at low frequencies. Red box demarcates arrivals of the fundamental-mode Rayleigh wave.

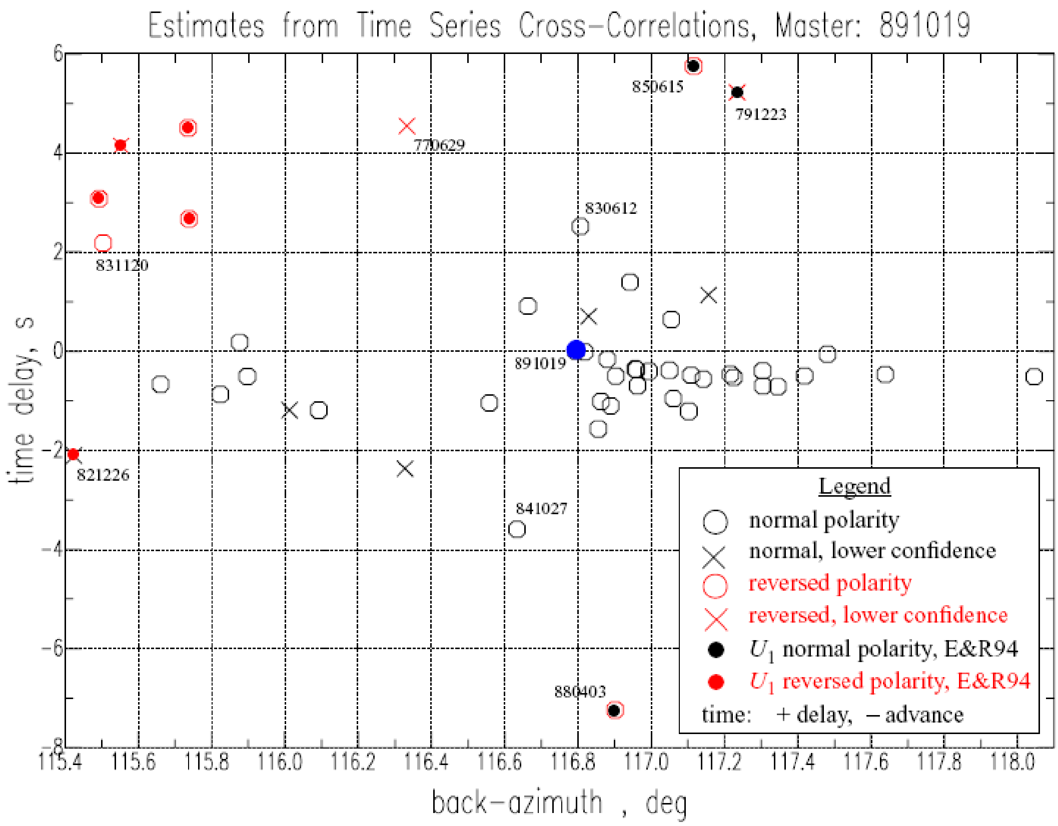

Figure 4. Summary of time delays as a function of back-azimuth across the array of explosion sources, showing events with reversed waveforms and significant time delays compared to normal waveforms.

Lg displacement spectra are not flat for frequencies below the corner frequency as expected based on the model of MM71. Rather, the spectral amplitudes are found to roll-off toward low frequency, consistent with the *Pn*/*Lg* observations of Fisk. Furthermore, the shots with the highest slopes also show reversed Rayleigh waves at BRV and in the E&R94 study. These observation suggest that the low-frequency slope of *Lg* spectra may be correlated with effects on Rayleigh waves as predicted by the monopole + CLVD source model and *Rg*-to-*S* scattering. This possibility is explored in Figure 5 where slope estimates are plotted against m_b–M_s differences.

Figure 5a shows a plot of slope for the *Lg* spectrum in the range 0.1 to 0.8 hz, against m_b–M_s where m_b is the Blacknest maximum-likelihood estimate reported in Ringdal et al and M_s is determined from DS recordings using the Marshall and Basham method (Marshall and Basham, 1972). All M_s determinations but one (831120) are based on Rayleigh wave amplitudes in the 17–23-s period pass-band. Figure 5b shows the same slope measurements but m_b–M_s has been adjusted for test site m_b bias as determined Ringdal et al. While the cause of systematic variations of m_b-m_{bLg} across Balapan is not well understood, conventional wisdom holds that the effect is in the m_b, not the m_{bLg}. As such, m_b has been adjusted on an event-by-event basis for those explosions with both m_b and NORSAR m_{bLg} measurements. When m_{bLg} is not available, the average bias for the test area given in equation (18) of Ringdal et al. is used.

Three explosions (881112, 880614, 810319 - ordered by decreasing slope estimate) show obvious reduced correlation since the slopes are among the highest values, yet their m_b–M_s estimates are near the mean of the population. 880614 does not have a NORSAR m_{bLg} measurement and is the smallest event in the dataset (4.8 m_b).

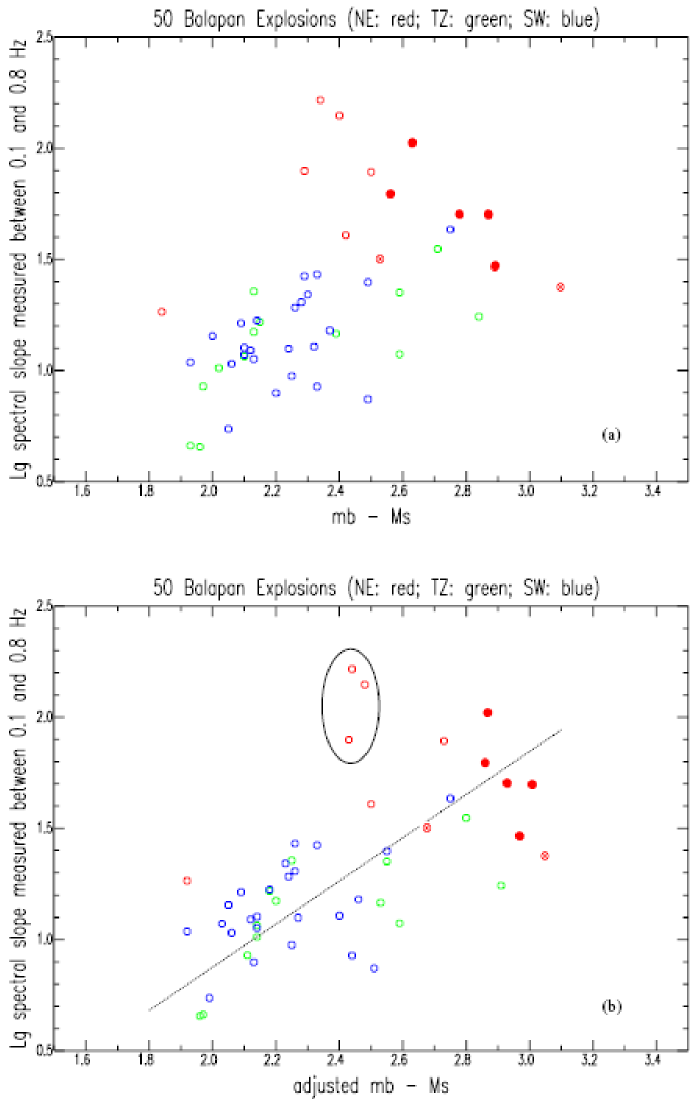

Figure 5. Plots of Lg spectral slope measured between 0.1 and 0.8 hz against m_b–M_s for all 50 Balapan explosions analyzed so far in this study. (a) shows the correlation for raw m_b–M_s values, while (b) shows the correlatian for adjusted m_b–M_s values where m_b has been corrected on an event-by-event basis for m_b–m_{bLg} residuals showing systematic variation around the test site. Solid red dots are those NE explosions with negative polarity from E&R94. Waveforms for two NE explosions are plotted with a red circle-and-cross symbol because waveform cross-correlation suggests they are reversed polarity with sizable time delays (770629, 831120). Three obvious data points with poor correlation are enclosed by an ellipse. The line plotted in Figure 5b has a slope that is identical Rg synthetics plotted in Figures 6a and 6c of Patton (2009, these Proceedings).

Summarizing these observations, a correlation does appear to exist between low-frequency *Lg* spectral slope and M_s corrected for source size using m_b. This finding is very interesting in the context of spectral ratio observations of Fisk (2006) where regional spectral ratios are seen to turn upward at low frequencies in contradiction to the Mueller-Murphy model. The correlations shown here suggest that the upturn is real, and is related to roll-off in *Lg* spectra at low frequencies. A correlation is predicted on the basis of fundamental- mode Rayleigh wave excitation due to a compound monopole + CLVD source.

CONCLUSIONS AND RECOMMENDATIONS

We have been able successfully to deglitch a major archive of digitally-recorded nuclear explosions conducted in Eurasia, all recordings coming from the same Observatory namely that at Borovoye, Kazakhstan, the oldest explosion having occurred in 1966. We plan to release this dataset at the conclusion of the present project. The dataset consists of multi-channel recordings of hundreds of underground nuclear explosions in Eurasia, most of them recorded on the three Soviet-era systems in use at Borovoye from 1966 to the early 1990s, and brought up-to-date with recordings of a few explosions after the installation of western sensors and data-loggers beginning in 1994.

Ongoing studies likely to benefit from an improved Borovoye digital waveform archive (and that can also help assure we have the correct gains and responses), include new source models as discussed above, and also:

- Yield estimation, using RMS Lg, Rg, and coda.
- Effects of source depth and shot-point geology, for example using PNEs from different regions.
- Discrimination using spectral ratios of seismic signals from earthquakes and UNEs, for example at the Semipalatinsk and Lop Nor test sites (in shafts and tunnels — which may impose their own slight differences on observed spectra).
- Discrimination between regional seismic signals of nuclear explosions and mining blasts of various types. (Note that mining blast signals are being routinely acquired today by the well-instrumented modem BRVK station.)

Because modern seismographic stations, now being installed in large numbers for many different purposes, lack archives of nuclear explosion signals, it is important to build up such archives for stations in a wide variety of sites. We recommend a program of acquiring and circulating electronic versions of hard copies of nuclear explosion signals from areas of interest, often recorded photographically or as ink on paper, and therefore requiring digitizing. If this work is not done soon, it may be too late to save the original recordings.

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REFERENCES

Bonner, J. L., D. C. Pearson, W. S. Phillips, and S. R. Taylor (2001). Shallow velocity structure at the Shagan River test site in Kazakhstan, *Pure appl. Geophys*. 158: 2017–2039.

Cleary, J. R. (1981). Anomalous Rayleigh waves from presumed explosions in East Kazakh, in *Identification of Seismic Sources--Earthquake or Underground Explosion, NATO Advanced Study Institute Series,* E. S. Huseby and S. Mykkeltveit, Editors, D. Reidel Publishing Co., Dordrecht, 191–199.

Day, S. M. and J. L. Stevens (1986). An explanation for apparent time delays in phase-reversed Rayleigh waves from underground nuclear explosions, *Geophys. Res. Lett.* 13: 1423–1425.

Day, S. M., J. T. Cherry, N. Rimer, and J. L. Stevens (1987). Nonlinear model of tectonic release from underground explosions, *Bull. Seismol. Soc. Am*. 77: 996–1016.

Ekström, G. and P. G. Richards (1994). Empirical measurements of tectonic moment release in nuclear explosions from teleseismic surface waves and body waves, *Geophys. J. Int.* 117: 120–140.

Fisk, M. D. (2006). Source spectral modeling of regional *P/S* discriminants at nuclear test sites in China and the former Soviet Union, *Bull. Seismol. Soc. Am.* 96: 2348–2367.

Given, J. W. and G. R. Mellman (1986). Estimating explosion and tectonic release source parameters of underground nuclear explosions from Rayleigh and Love wave observations, Final report, Part I, AFGL-TR-86-0171(I), Air Force Geophysics Laboratory, Hanscom Air Force Base, MA, 70 pp.

Harkrider, D. G. (1981). Coupling near-source phenomena into surface wave generation, in *Identification of Seismic Sources--Earthquake or Underground Explosion, NATO Advanced Study Institute Series,* E. S. Huseby and S. Mykkeltveit, Editors, D. Reidel Publishing Co., Dordrecht, 277–326.

Helle, H. B. and E. Rygg (1986). Determination of tectonic release from surface waves generated by nuclear explosions in Eastern Kazakhstan, *Bull. Seismol. Soc. Am.* 74: 1883–1898.

Herrin, E. and T. Goforth (1986). Phase analysis of Rayleigh waves from the Shagan River test site in the USSR, *Bull. Seismol. Soc. Am.* 76: 1739–1754.

Kim, W.-Y. and G. Ekström (1996). Instrument responses of digital seismographs at Borovoye, Kazakhstan, by inversion of transient calibration pulses, *Bull. Seismol. Soc. Am.* 86: 191–203.

Kim, W.-Y., P. G. Richards, V. Adushkin, and V. Ovtchinnikov (2001). Borovoye digital archive for underground nuclear tests during 1966-1996, Data report on the web at http://www.ldeo.columbia.edu/Monitoring/Data/Brv_arch_ex/brv_text_table.pdf, Borovoye Archive for UNT.

Marshall, P. D. and P. W. Basham (1972). Discrimination between earthquakes and underground explosions employing an improved M_s scale, *Geophys. J. R. Astr. Soc.* 28: 431–458.

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

Patton, H. J. (1980). Surface-wave generation by underground nuclear explosions releasing tectonic strain, Lawrence Livermore National Laboratory, University of California, Report No. UCRL-53062, 16 pp.

Patton, H. J. and S. R. Taylor (2008). Effects of shock-induced tensile failure on m_b-M_s discrimination: Contrasts between historic nuclear explosions and the North Korean test of 9 October 2006, *Geophys. Res. Lett.* 35: L14301.

Patton, H. J. (2009). Explosion source model development in support of seismic monitoring technologies: applications of new models for shock-induced tensile failure, these Proceedings.

Ringdal, F., P. D. Marshall, and R. W. Alewine (1992). Seismic yield determination of Soviet underground nuclear explosions at the Shagan River test site, *Geophys. J. Int.* 109: 65–77.

Rygg, E. (1979). Anomalous surface waves from underground explosions, *Bull. Seismol. Soc. Am.* 69: 1995–2002.