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

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ABSTRACT

We have just started 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 30-year period going back to 1966 and spanning 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 more than 300 underground nuclear 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. These copies contain large numbers of glitches and did not include instrument responses for approximately two-thirds of the events.

Since 2001, scientists at Los Alamos National laboratory (LANL) have processed the BRV regional signals for approximately one third of the events, mainly those for which instrument responses were available. Because many different and important uses of the Borovoye archive have been made in recent years, we are completing the work of improving the archive to modern standards, as well as this may be achieved. Our project is a joint effort by scientists at Lamont-Doherty Earth Observatory of Columbia University (LDEO) and LANL.

The LANL team has deglitched waveform data recorded by the STsR-TSG system, because it was the best system, and a preliminary instrument response for this system has been available. There appear to be at least two sources of glitches, the most easily explained and corrected for being time marks. More difficult and time consuming are glitches representing bit failures either in the original data stream or in the long term deterioration of the archive. A script-driven SAC macro featuring semi-automatic glitch removal coupled with visualization for quality control was developed at LANL by Dr. W. Scott Phillips. The automatic glitch recognition and removal utilizes seismogram differentiation and localized polynomial fitting with L1 linear programming to remove the glitch and interpolate through it with high fidelity on either side of the glitch. This phase of the processing is activated on successive passes with the user specifying an amplitude threshold for the glitch recognition software on each pass. This allows each successive pass to uncover glitches with smaller and smaller amplitudes. This de-glitcher is robust and has been successfully run on even heavily contaminated signals.

The instrument response of the 24-channel STsR-TSG system may further be calibrated by using waveform data from both the STsR-TSG system and modern broadband seismographs deployed during 1994–1996. The BRV archive contains waveform data from the STsR-TSG system up to 1996, which include four French underground nuclear explosions (UNE) from Mururoa and Fangataufa conducted in 1995–1996, and two UNEs from the Lop Nor Chinese test site (10/07/1994 and 05/15/1995. In July 1994, Won-Young Kim (LDEO) deployed a modern broadband seismometer (STS-2 with T_0 = 120 sec) and a 24-bit A/D datalogger at the same seismic pier with the STsR-TSG system, for the purpose of calibrating waveform data from those systems at a later date.

The earlier STsR-SS system consists of a 3-component short-period seismometer SKM (T_0 = 2 s) and 3-component long-period seismometer SKD (T_0 = 25 s). The STsR-SS system formally operated during 02/14/1973 - 03/29/1991 and produced on-scale seismic records from many strong earthquakes and large UNEs from the Semipalatinsk test site, because the STsR-SS system long- and short-period channels are recorded with very low gain (0.5 - 5 counts/µm for SKD; 200 to 2000 counts/µm for SKM)). We have begun to determine accurate STsR-SS system responses and we are calibrating the instrument gains for each event, because many events during 1973–1991 have waveform data recorded both on STsR-TSG and STsR-SS systems.

OBJECTIVES

We propose to generate in modern form an easily usable archive of digital seismograms derived from regional waveforms recorded at the BRV, northern Kazakstan, over a 30-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 propose 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

Preliminary Work at LANL on Deglitching the Borovoye Archive

The extensive glitching of waveforms in the Borovoye Archive makes it impossible to fully utilize this data resource. Time-domain filtering, three-component processing, spectral analysis, etc., are all seriously impacted by the presence of glitches occurring throughout the time series. Researchers at LANL recognized the limitations these glitches posed for most data analysis a few years ago, and began a project to deglitch a portion of the Archive that was deemed of highest immediate value to the research programs at LANL: the data recorded on the STsR-TSG system for which instrument responses had been determined (Kim and Ekström, 1996).

Raw waveforms of the Borovoye Archive are contaminated with glitches on all seismometer channels and their different gain levels, for the entire time period that data are available. Figure 1 shows examples from the KSVM, low-gain system in the 1984–1985 time frame. The extent of visible glitching can be seen to vary greatly in these examples. Many glitches are not visible to the naked eye on the vertical scale of these plots, so the problem is more extensive than it may appear from just plotting the seismogram trace.

There appear to be at least two sources of glitches. The most easily corrected and explained are time marks characterized by a distinct period and the largest amplitude glitches. There are some waveforms for which the time-mark glitch is the primary problem.

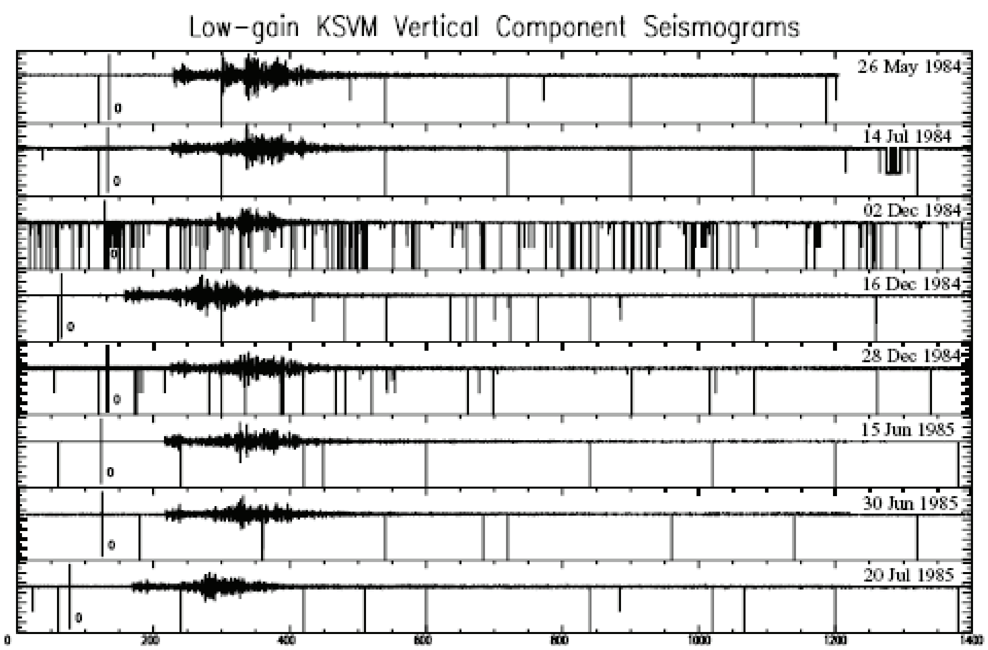

Figure 1. Example BRV archive seismograms (KSVM channel – low-gain) with various levels of glitches.

The more difficult and time consuming glitches appear in some cases to be bit errors. During interactive passes over problematic waveforms, we have found many glitches where the difference between the glitch and the apparent waveform is either a power of 2 (e.g., 16, 32, 64, 128 ...) or a sum of powers of 2 (e.g., 48 = 16 + 32, 96 = 32 + 64, 80 = 16 + 64, ...) which represent bit failures either in the original data stream or in the long-term deterioration of the archive. Many of these small bit errors are readily found by the deglitcher that will be discussed below. While the repair process is at best semi-automatic, the opportunity for restoring this unique historical digital waveform archive of Soviet-era and Chinese tests is now at hand with the availability of reliable deglitching software, albeit the labor to do so is tedious and time consuming.

The deglitching project at LANL led to the development of a processing code by Dr. W. Scott Phillips for removing glitches on successive passes over the seismogram. This code is a script-driven seismic analysis code (SAC) macro featuring semi-automatic glitch removal capabilities coupled with visualization of the deglitching for quality control purposes. This macro and attending Fortran codes are far more sophisticated than the glitch-removal command in SAC. The automatic glitch recognition and removal phase utilizes a process of seismogram differentiation and localized polynomial fitting with L1 linear programming software to remove the glitch, interpolate through it, and return the seismogram with high fidelity on either side of the glitch. This phase of the processing is activated on successive passes with the user specifying an amplitude threshold for the glitch recognition software on each pass. This allows each successive pass to uncover glitches with smaller and smaller amplitudes. An example where this deglitching software was applied to the most seriously contaminated seismogram in Figure 1 is shown in Figure 2.

LANL's emphasis has been to deglitch the STsR–TSG data with available response information. Far less deglitching of the older KOD and STsR-SS data has been carried out due to its limited utility without sensor response information to correct the data to reflect accurate ground motion. Scott Phillips developed the deglitching process and codes for his work on regional coda wave magnitudes. George Randall has applied the deglitcher to data for a regional discrimination study and Howard Patton to data for a regional *Ms* study. Multiple gain channels were processed in many cases to extend the dynamic range of the recovered data. High-gain channels are frequently

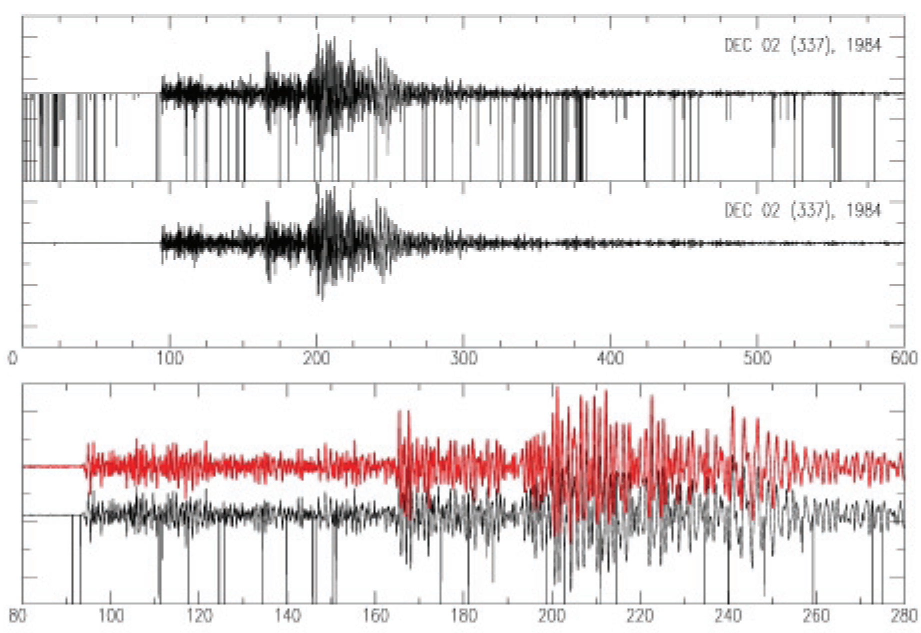

Figure 2. Plots show the raw time series, and after deglitching, for 10 minutes of data, including a long segment of coda waves. The lower plot is an enlargement of 200 s of data, centered on the main signal. The deglitched waveform is plotted in red.

clipped, but provide useful coda information and can be picked for the first arriving *P* phase. Low-gain channels frequently provide useful data when high-gain channels are clipped but are composed of largely quantization noise in lower amplitude segments of the seismograms. The deglitched waveforms have been entered into the LANL Research database, and delivered to the NNSA Knowledge Base along with the research results for discrimination, regional *Ms*, and regional coda wave magnitude studies.

Simulation of Broadband Spectra

LANL researchers have also experimented with constructing broadband Rayleigh wave amplitude spectra using waveforms off the low-gain KSVM channel and the longer period DS channel. An example of the corrected records is shown in Figure 3. Low-frequency (~0.3 Hz) *Rg* waves are commonly recorded on the vertical component KSVM channel for many Balapan explosions, and this Figure shows an example for the last nuclear test conducted at the Semipalatinsk test site on 19 October 1989. Surface waves are well recorded on the DS channel for this event. The lower plot shows spectra obtained for the time windows indicated on the seismograms, where the amplitudes have been corrected in the frequency domain for the instrument responses of the KSVM and DS systems. The shapes of these responses are plotted with the data, a step made possible because the instrument responses for the TSG system have been worked out and these responses are included with the current CSS3.0 formatted data. The instrument-corrected KSVM spectrum for Rayleigh waves (red) shows good agreement with the corrected DS spectrum (black) out to almost 0.2 Hz. The DS spectrum is suspect for frequencies above 0.5 Hz due to unusual response behavior. In any case, the broadband spectrum (green) was constructed by suturing the two channels in the 0.4-0.6 Hz range. This procedure has been carried out on most Balapan explosions occurring in the 1987–89 time frame, and all show extremely rapid amplitude fall-off for frequencies above 0.5 Hz. A goal of this proposed work is to construct broadband waveforms using better instrument response information to combine data channels.

Table 1. Characteristics of STsR-SS System in Borovoye Waveform Archive

System name	Seismometer	Channel type	Ts(1) (sec)	Ds(2)	Sm(3) (ct/µm)	fn(4) (Hz)	dt(5) (msec)	Channel number
STsR-SS 02/14/73-03/29/91(7)	SKM-3 (76-80)	HG(6)	2	0.5	2000	1.8	24	7,8, 9
					1000	1.8	32	7,8,9
		LG(Z)			200	1.8	32	1
	SKD	HG	25	0.71	5	0.14	192	2,3,4
		LG			0.5	0.14	192	1,5,10

(1) Ts = Seismometer natural period in seconds. (2) Ds = Seismometer damping constant, critical damping= 0.71. (3) Sm = Nominal sensitivity (gain) in counts/micron [ct/µm] for ground displacement. (4) fn = Normalization frequency where nominal sensitivity is measured. (5) dt = Sampling interval in milliseconds. (6) HG is actually the base channel and not necessarily a high-gain; LG =low-gain channels and (Z) indicates that it is only vertical component. (7) These date are the formal period of operation of the systems by Russian Institute for the Dynamics of the Geospheres, Moscow, Russia. However, notice that the BRV waveform archive contains waveform data from TSG system up to 1996.

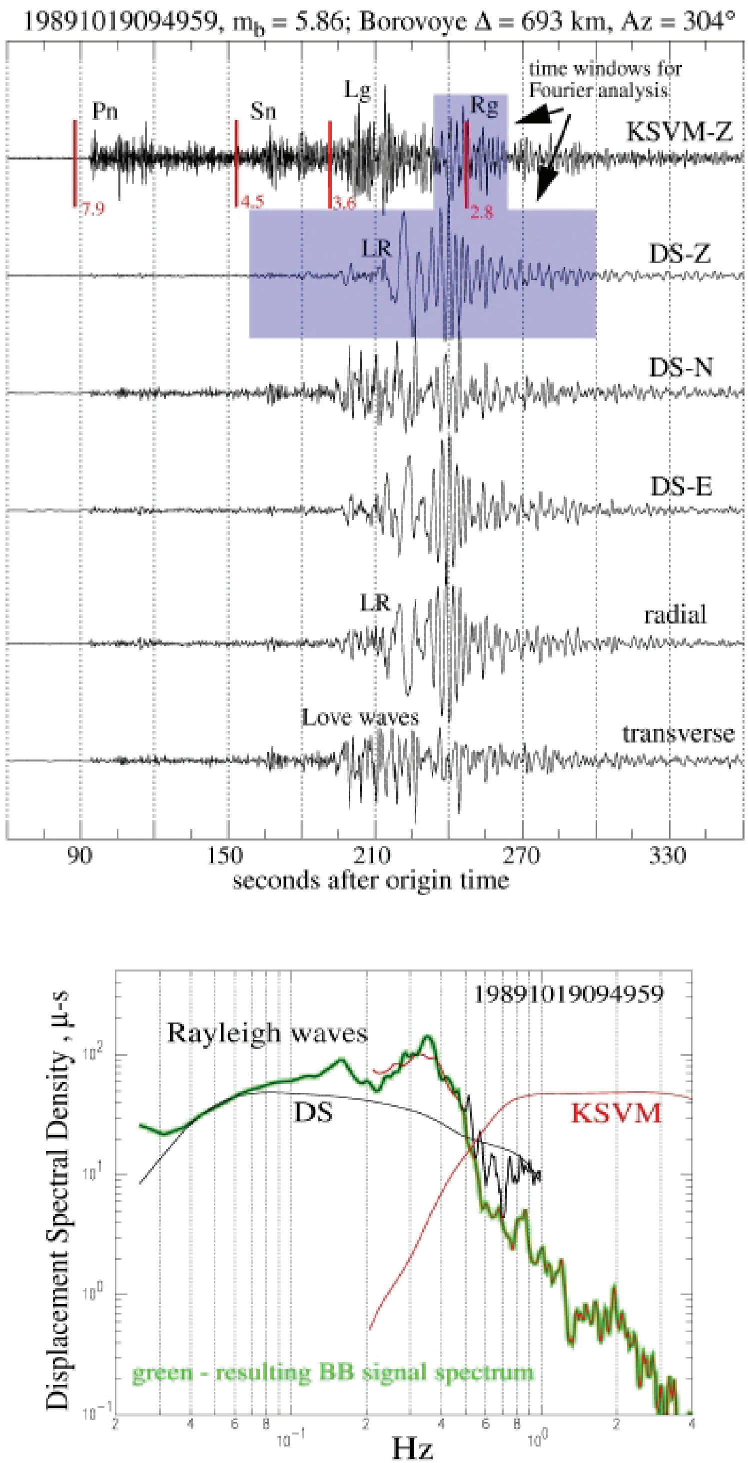

Figure 3. Top: BRV seismograms, after processing. Bottom: corresponding spectra.

Preliminary Determination of STsR–SS System Response

The STsR-SS system consists of 3-component short-period seismometer SKM (T_0=2 s) and 3-component long-period seismometer SKD (T_0 = 25 s)(see Figure 4). The SS system formally operated during the period 14 February 1973 to 29 March 1991, and UNE data in the BRV explosion archive covers the period from 6 June 1973 (an NTS explosion) to 16 August 1990 (Lop Nor test site). The SS system produced 10 channel digital seismogram data with 3-component short- and long-period waveform data, and a low-gain short-period vertical-component, plus an additional combination of long- and short-period channels to fill the sequential digitization process. Hence, the sampling intervals are designed as integer multiples of each channel. Short-period channels are sampled at 32 milliseconds (msec), and long–period channels are sampled with 192 msec intervals. Although the SS system has been operated together with STsR–TSG system, the accurate instrument response of short- and long-period seismographs of the SS system have not yet been determined, mainly due to lack of reliable calibration pulses. Hence, we will determine accurate instrument responses of the SS system by comparing the waveform data from SS system that are also recorded on TSG system. As indicated by the characteristics shown in Table 1, the SS system has produced many on–scale waveforms due to its low gain channels.

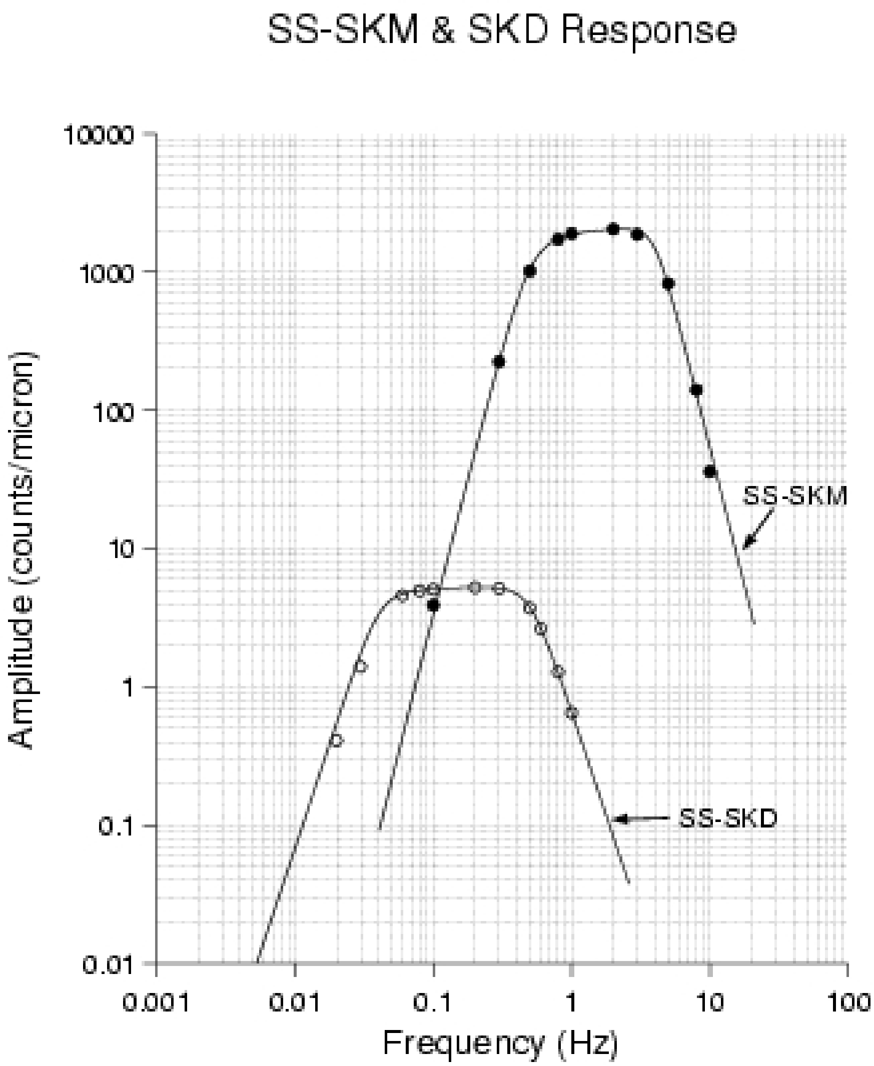

Figure 4. A preliminary, nominal displacement spectral amplitude response of the STsR–SS short–period (SKM) and long–period seismographs (SKD).

Regional Spectra and Spectral Ratios for the Lop Nor Test Site

China carried out nuclear tests at the Lop Nor test site in western China beginning in 1964. From 1969 to 1996, 22 underground nuclear tests (UNTs) are known to have been conducted at this site. The Borovoye archive has waveform data from 11 UNTs as listed in Table 2. Three additional Lop Nor UNTs were recorded by a modern broadband seismographic system deployed in Kazakstan by Won-Young Kim from Lamont in the summer of 1994. Kim encouraged the Borovoye staff to continue operating the ailing TSG system so that we would have seismic data from the TSG system that can be calibrated against the modern, high-dynamic range broadband system. Hence, we have two latest Lop Nor UNTs recorded both by the TSG and the modern (STS–2 seismometer and datalogger with a 24-bit A/D) broadband system, as well as the three UNTs with only broadband recording, providing a unique data set. UNTs at Lop Nor are clustered into two groups; according to the topography and geology, UNTs in subregion A are in vertical shafts, while UNTs in subregion B are detonated in horizontal tunnels (Waldhauser et al., 2004).

The BRV archive include the first known underground nuclear test at Lop Nor on Sept. 22, 1969. This archive provides the greatest number of seismographic records available at a single site at regional distances (see Table 2). The magnitude of these events ranges from $m_b(P)$ 4.9 to 6.2 and vertical-component records from 12 UNTs are shown in Figure 5. The epicentral distance from the Lop Nor Chinese Test Site to BRV is about 1840-1895 km and records show clear *Sn* and *Lg* waves (Fig. 5), but note that *Sn* and *Lg* waves are less well excited by the smallest event on July 29, 1996 ($m_b(P)$= 4.9). Such observation would be important to verify if the magnitude dependence of *P/S* spectral amplitude ratios reported by Ringdal (1997) applies to events at Lop Nor. We are studying this size-dependence of spectral ratios for Lop Nor explosions.

Table 2. Borovoye data for Chinese Nuclear Tests at Lop Nor Test Site, 1969–1995[1]

N	Date Year-Mo-Da	Time (hr:mn:sec)	Lat. (°N)	Long. (°E)	$m_b(P)$	Instrument type[2]	Comments
01	1969-09-22	16:15:01.57	41.373	88.352	5.2	KODB	**tunnel**/*P* wave only
02	1976-10-17	05:00:00.82	41.7086	88.3897	4.9	SS	**tunnel**
03	1978-10-14	01:00:00.17	41.5413	88.7545	4.9	SS/TSG	shaft
04	1983-10-06	10:00:00.14	41.5409	88.7283	5.5	SS/TSG	shaft
05	1984-10-03	06:00:00.08	41.5799	88.7246	5.4	SS	shaft
06	1984-12-19	05:59:59.82	41.7081	88.3862	4.7	SS/TSG	**tunnel**
07	1987-06-05	05:00:00.48	41.5558	88.7431	6.2	SS/TSG	shaft
08	1990-08-16	05:00:00.05	41.5274	88.7358	6.2	SS/TSG	shaft
09	1993-10-05	01:59:59.69	41.5957	88.7060	5.9	TSG	shaft
10	1994-10-07	03:26:00.18	41.5735	88.7191	5.9	TSG/BB	shaft
11	1995-05-15	04:06:00.20	41.5513	88.7496	6.1	TSG/BB	shaft
12	1995-08-17	01:00:00.14	41.5412	88.7522	6.1	BB	shaft
13	1996-06-08	02:56:00.06	41.5804	88.6893	5.9	BB	shaft
14	1996-07-29	01:49:00.17	41.7163	88.3748	4.9	BB	**tunnel**

[1] location and origin time from Waldhauser et al. (2004), except the first UNT on Sept. 22, 1969; body–wave magnitude from PDE.

[2] Instrument type= instrument used, KODB= KOD low-gain system; SS=STsR–SS system; TSG=STsR–TSG system; BB = broadband sensor (STS-2 with T_0=120 s) and 24-bit A/D datalogger.

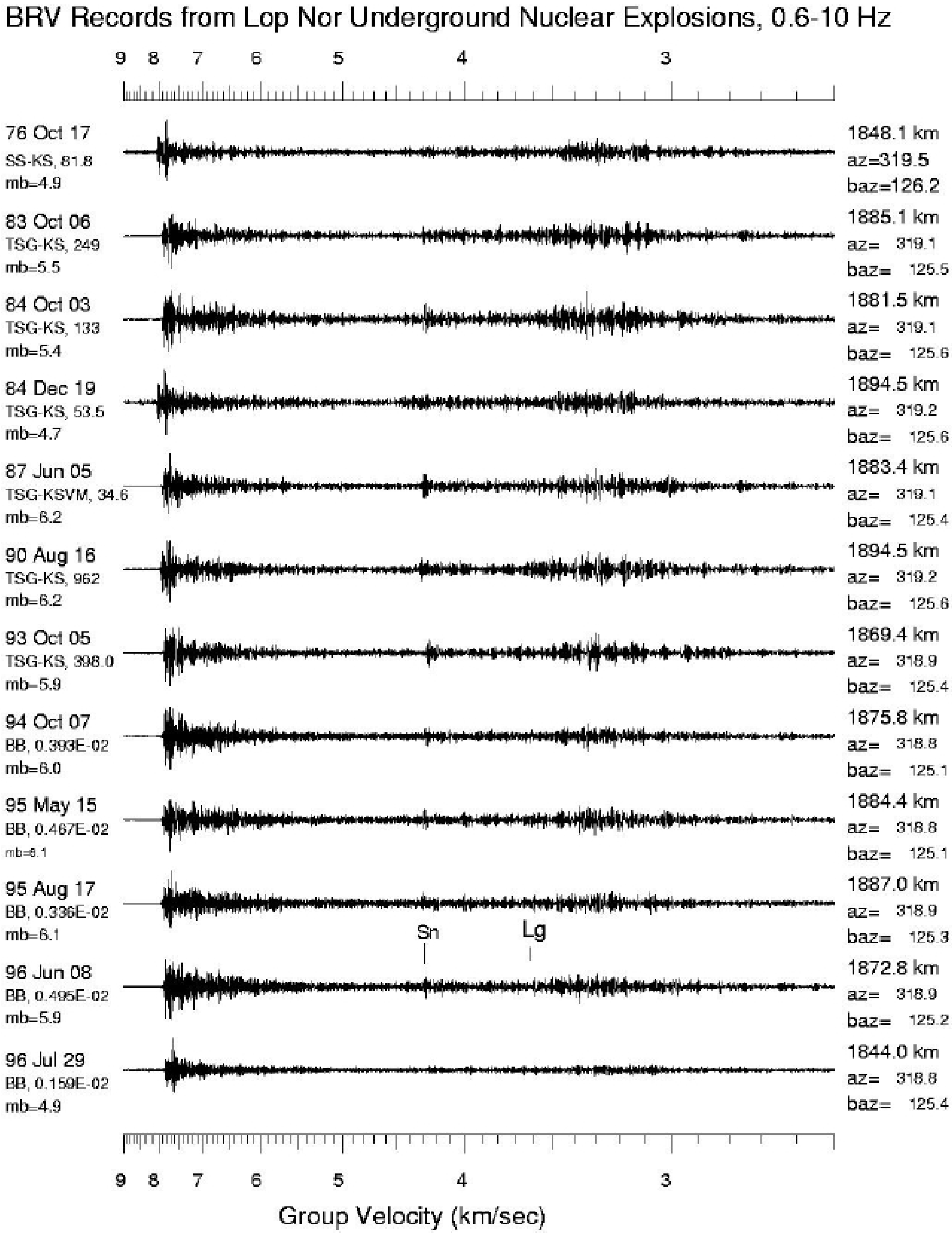

Figure 5. Vertical component records at BRV from 12 underground nuclear tests from Lop Nor. Records are plotted with group velocity in km/sec and event date, instrument used and magnitude are indicated at the beginning of each trace. SS–KS=SS system KS channel, TSG–KS=TSG system KS channel, and BB=new broadband system.

CONCLUSIONS AND RECOMMENDATIONS

Since our project has just begun, we list a number of studies, some of them ongoing within the monitoring community, which are likely to benefit from our project, i.e., an improved BRV waveform archive. The candidate studies are presented as the following questions:

- Can the traditional *mb: Ms* discriminant, long applied to teleseismic signals in which *Ms* is measured from amplitudes of surface waves with period around 20 s, be applied successfully to small seismic events recorded at regional distances, for which the *Ms* measurement is made at a period significantly shorter than 20 s? Practical answers to this question are needed for underground nuclear explosions conducted in (for example) Eurasia, in regions having characteristics very different from the western U.S. where most U.S. testing experience was acquired. Studies of this nature can benefit from the improved BRV archive because for many events it contains short-period and long-period channels.
- How consistently do the regional seismic signals of nuclear explosions exhibit features that are consistently different from the regional signals generated by shallow earthquakes (within the crust), by sub-crustal earthquakes, and by deeper earthquakes? (Note that many earthquake signals are being routinely acquired today by the well-instrumented modem BRVK station.)
- How consistently do the regional seismic signals of nuclear explosions exhibit features that are consistently different from regional signals from mining blasts of various types? (Note that mining blast signals are being routinely acquired today by the well-instrumented modem BRVK station.)

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