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A digital seismogram archive of nuclear explosion signals, recorded at the Borovoye Geophysical Observatory, Kazakhstan, from 1966 to 1996

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ABSTRACT

Seismologists from Kazakhstan, Russia, and the United States have rescued the Soviet-era archive of nuclear explosion seismograms recorded at Borovoye in northern Kazakhstan during the period 1966–1996. The signals had been stored on about 8000 magnetic tapes, which were held at the recording observatory. After hundreds of man-years of work, these digital waveforms together with significant metadata are now available via the project URL, namely http://www.ldeo.columbia.edu/res/pi/Monitoring/Data/ as a modern open database, of use to diverse communities.

Three different sets of recording systems were operated at Borovoye, each using several different seismometers and different gain levels. For some explosions, more than twenty different channels of data are available. A first data release, in 2001, contained numerous glitches and lacked many instrument responses, but could still be used for measuring accurate arrival times and for comparison of the strengths of different types of seismic waves. The project URL also links to our second major data release, for nuclear explosions in Eurasia recorded in Borovoye, in which the data have been deglitched, all instrument responses have been included, and recording systems are described in detail.

This second dataset consists of more than 3700 waveforms (digital seismograms) from almost 500 nuclear explosions in Eurasia, many of them recorded at regional distances. It is important as a training set for the development and evaluation of seismological methods of discriminating between earthquakes and underground explosions, and can be used for assessment of three-dimensional models of the Earth's interior structure.

1. Introduction

Seismic monitoring was developed in Kazakhstan by the USSR from the mid-1960s to the end of the Soviet era in 1991 with central planning from Moscow, in the specialized context of military programs to monitor nuclear weapons testing at sites around the world. Under these programs, high quality work was performed in seismometer design and construction, in field surveys to discover suitable sites for instrument deployment, and in the development of methods of data analysis and interpretation.

Kazakhstan turned out to provide superb sites for seismometer operation, because:

(a) the whole country is deep within the interior of the Eurasian continent, a long way from the usual ocean-wave sources of seismic noise, so that sites could readily be found that were very quiet; and (b) the geological structures, particularly of Northern Kazakhstan, allow seismic waves to propagate very efficiently, with minimal attenuation and minimal scattering. As a result, seismographic stations in Kazakhstan began as early as the 1960s to acquire high-quality data from nuclear explosions, which occurred somewhere around the world at a rate of approximately once a week for the 30-year period from 1961 to 1990. The seismic data (secret at that time in the Soviet Union) were used by the USSR to monitor nuclear explosions carried out by the USA, France, the UK, and China, using signals that propagated in the Earth for thousands of kilometers from nuclear test sites used by these countries, to the seismometer sites in Kazakhstan. Such signals are called

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List of symbols, abbreviations, and acronyms

AFRL	Air Force Research Laboratory
BRV	Borovoye (a small village in Northern Kazakhstan)
CTBT	Comprehensive Nuclear-Test-Ban Treaty
DARPA	Defense Advanced Research Projects Agency
KOD	The Russian abbreviation for the first seismographic system used at Borovoye
LANL	Los Alamos National Laboratory
LDEO	Lamont-Doherty Earth Observatory of Columbia University
MAD	Median Absolute Deviation
NZ	Novaya Zemlya
NZTS	Novaya Zemlya Test Site
PNEs	Peaceful Nuclear Explosions (meaning a nuclear explosion in the USSR conducted at a location other than a recognized nuclear weapons test site)
SS	An abbreviation for STsR-SS (see below), in turn the Russian abbreviation for the second seismographic system used at Borovoye
STS	Semipalatinsk Test Site
STsR-SS	A Russian abbreviation for the second seismographic system used at Borovoye
STsR-TSG	A Russian abbreviation for the third seismographic system used at Borovoye
TSG	An abbreviation for STsR-TSG (see above), in turn the Russian abbreviation for the third seismographic system used at Borovoye
UK	United Kingdom
UNE	Underground Nuclear Explosion
UNT	Underground Nuclear Test
US or USA	United States of America
USSR	Union of Soviet Socialist Republics

teleseismic, and it is a testament to the detection capability of stations in Kazakhstan that they could reliably record teleseismic signals from distant explosions with yield down to about one kiloton (about magnitude 4, using a scale based on teleseismic *P*-waves). The monitoring facilities also recorded nuclear explosions carried out by the USSR itself, many of them within Kazakhstan (for example at the Semipalatinsk Test Site, the location of about 350 underground nuclear explosions), using seismic signals that propagated in many instances less than a thousand kilometers to the in-country recording sites. Such signals are called regional, and they can be detected routinely even from explosions as small as about ten tons (about magnitude 2.5, using a scale based on regional signals that enables the assignment of magnitude for events too small the characterize teleseismically). Borovoye data are important today, primarily because they provide so many examples of the types of regional signal needed to monitor for nuclear explosions down to very low yield.

At several sites in Kazakhstan, operated by the Soviet Union in the 1970s and 1980s, the seismic data were obtained with digital recording systems. Seismic data can be recorded in analog form, for example by pen on paper, or photographically. But digital recording is much preferred over analog since digital data can more readily be analyzed for their frequency content, and for signals of interest in the presence of other signals and noise. Digital recording of seismic signals did not become widespread in western countries until the 1970s, and there are no western archives of digital data that document earthquakes and explosions prior to 1975 except for a limited number of seismic events in regions of special study.

Nuclear weapons testing has occurred only at greatly reduced levels since the mid-1990s. Moratoria on testing have been instituted by the USA, the Russian Federation, the UK, France, and China, in the context of these nuclear weapon states all having signed (and in some cases ratified) the Comprehensive Nuclear-Test-Ban Treaty (CTBT) of 1996. Such moratoria will become an actual ban on nuclear testing when the CTBT enters into force. Kazakhstan still has an important role to play in seismic monitoring for nuclear explosions, but the context is now arms control, and monitoring to demonstrate the absence of nuclear explosions. There is also the continuing need to monitor countries that are not CTBT signatories and which may carry on with active programs of nuclear testing. India and Pakistan carried out tests in May 1998; the only country testing in the present century, to date, is North Korea, which at this time of writing is known to have conducted underground nuclear tests in 2006, 2009, and 2013.

Kazakhstan is superbly located for purposes of acquiring teleseismic and regional seismic signals to monitor the territories of China, Russia, and countries of South Asia (India and Pakistan) plus Central Asia and the Middle East. The specific purpose of explosion monitoring includes verifying compliance with the Non-Proliferation Treaty (NPT), as well as the CTBT. The extensive growth in worldwide deployment of high-quality broadband seismographic stations (there are now several thousand of them) took place too late for the great majority of these stations to record nuclear explosions. The Borovoye archive is thus important today as a training set, especially useful for understanding the types of regional seismic signals which travel in the Earth's crust and uppermost mantle, and that are needed to monitor for low yield nuclear explosions.

In the USSR, one of the primary nuclear testing sites was in eastern Kazakhstan near the town of Semipalatinsk. At that time seismology throughout much of Central Asia was heavily controlled by scientists from the Ministry of Defense and Academy of Sciences of the USSR. While there were well-established earthquake studies programs in the most seismically active areas along the southern border in Tajikistan, Kyrgyzstan and the Tien Shan mountains of southern Kazakhstan, most of the seismological observations in central and northern Kazakhstan were focused on classified monitoring of the Soviet and foreign nuclear test sites.

In the mid 1980s, the Soviet government agreed to allow US university groups to make seismological observations at temporary locations surrounding the Semipalatinsk nuclear test site in Kazakhstan. This work was part of a program sponsored by the US-based Natural Resources Defense Council and the Soviet Academy of Sciences. An outgrowth of that program was an agreement between the Soviet Academy of Sciences and the Incorporated Research Institutions in Seismology (a consortium of US universities with graduate programs in seismology, often called IRIS) to establish permanent seismographic observatories throughout the USSR as part of the Global Seismographic Network being developed by IRIS and the US Geological Survey. Stations were established in Tajikistan and Kyrgyzstan, but Kazakhstan remained closed for permanent observatories.

With the gradual opening of the USSR in the early 1990s, details on extensive Soviet seismological facilities in Kazakhstan began to emerge. In June 1991, Paul Richards of Columbia University and Göran Ekström, then of Harvard University, visited the Borovoye Geophysical Observatory, previously a secret operation, and were introduced to the monitoring facilities and data archive there. In 1993, the National Nuclear Center of Kazakhstan was created and

Table 1
Borovoye Digital Archive for World-wide Underground Nuclear Tests, 1966–1996.

Country	Test site	Time period	BRV data
USSR	Semipalatinsk Test Site	1966 Dec 18–1989 Oct 19	228
	Novaya Zemlya	1967 Oct 21–1990 Oct 24	31
	Peaceful Nuclear Explosions	1967 Oct 06–1988 Sep 06	80
China	Lop Nor Test Site	1970 Sep 22–1995 May 15	11
France	Tuamotu Archipelago	1977 Mar 19–1996 Jan 27	68
United Kingdom	Nevada Test Site	1978 Apr 11–1989 Dec 08	15
United States	Nevada Test Site	1967 May 23–1992 Mar 26	278
	Total number of UNEs in the BRV archive		711

given authority for many facilities, including that at Borovoye (BRV), built in the Soviet era. For more than twenty years since Borovoye facilities became open in 1991, a series of efforts were made to rescue the signals contained in the digital archive at this Observatory. The archive in the early 1990s consisted of thousands of deteriorating digital magnetic tapes that could be read only on a limited number of recording systems. With funding from a variety of sources, the archive has been openly released in a modern format in two stages, and is now finding a variety of users.

Sections below give more details on: the Borovoye station and associated interactions between scientists from Kazakhstan, Russia, and the USA; the first major release of digital recordings of nuclear explosions from Borovoye, in April 2001; and the second major data release, which incorporated a substantial effort to deglitch the signals from nuclear explosions conducted in Eurasia. This last release also provided detail on the responses of the various seismometers and recording systems used at Borovoye.

We give examples of the signals recorded at Borovoye, and comment on their utility.

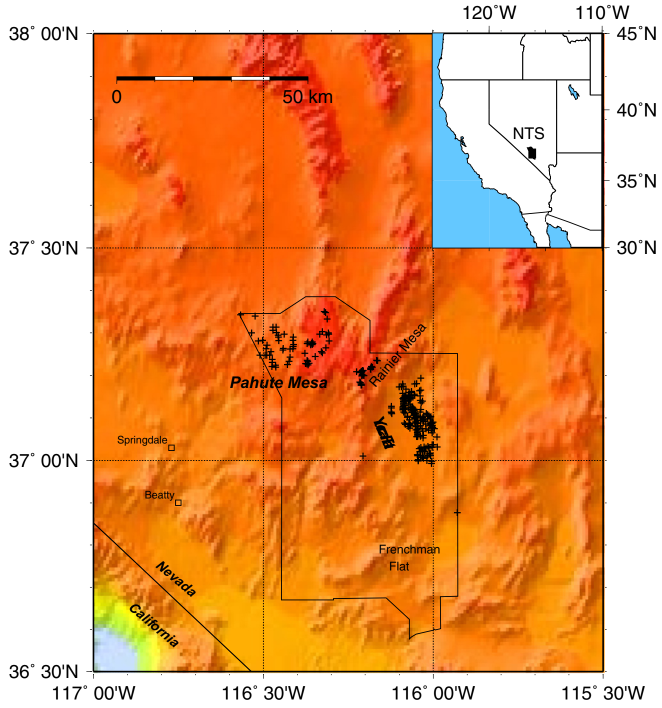

Fig. 2. Locations of underground nuclear tests carried out by the United States and jointly with United Kingdom at the Nevada Test Site (*crosses*). Most of these tests were clustered at Pahute Mesa, Yucca Flat, and Rainier Mesa.

2. The Borovoye seismographic station

Seismic recording in digital form began at Borovoye in 1966 as described by An et al. [4] under the auspices of a field program of the USSR Academy of Sciences. High-quality seismic observations continued to about 2008 when the Observatory grounds were taken over by organizations planning hotels and a casino at this site, which with its lake, rock formations, and local mountains and forests, is scenically attractive.

Prior to 1991, Russian books and journals of geophysics published detailed descriptions of seismometers and digital recording systems operated at a site characterized as "experimental" and "in Northern Kazakhstan" or "in Eastern Kazakhstan." Several articles also appeared in western journals, authored by senior Russian seismologists, describing data and sophisticated methods of data

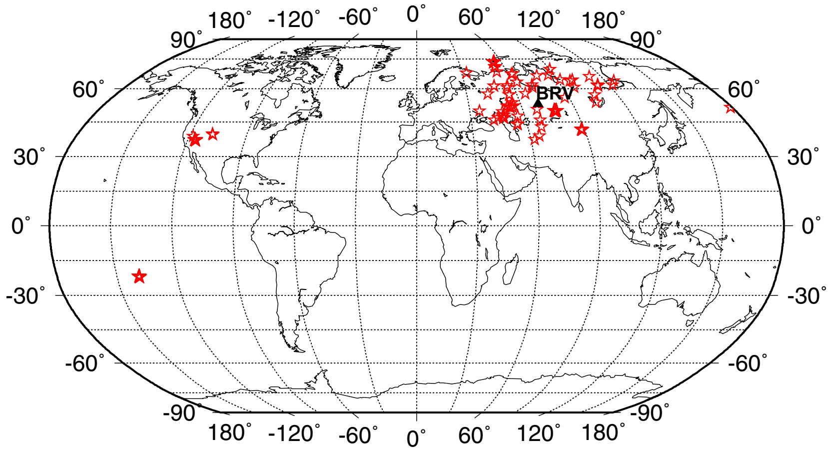

Fig. 1. Global map showing the location of underground nuclear tests for which digital signals from the Borovoye seismogram archive, from 1966 to 1996, were made available in April 2001.

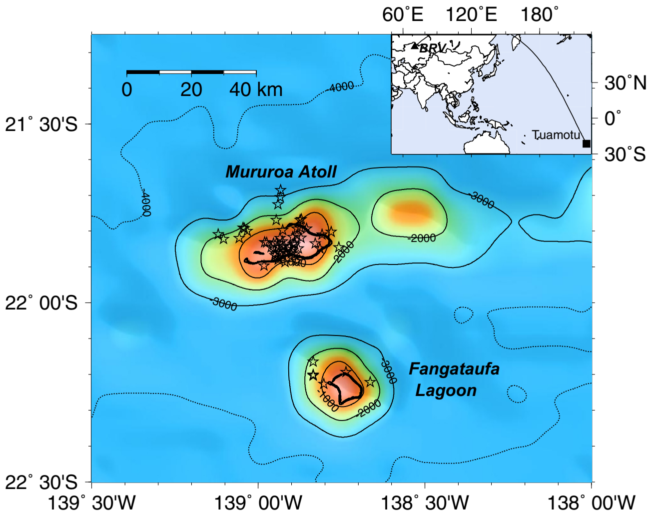

Fig. 3. Locations of underground nuclear tests carried out by France at the Tuamotu Archipelago, French Polynesia. These tests are clustered into two areas: Mururoa Atoll and Fangataufa Lagoon.

Table 2

Numbers of deglitched waveforms by region, as recorded by each of the three systems (KOD, SS, TSG) at the Borovoye Geophysical Observatory from 1966 to 1995. Note that some underground nuclear explosions are listed here as events that may have been recorded by more than one instrument system. Table 3 through Table 8 list each event in Eurasian test sites for which there is Borovoye data, and the systems that recorded them.

Region	System	Events	Traces	Dates (yymmdd)
Balapan (Kazakhstan, Semipalatinsk Test Site)	KOD	7	51	680619–730723
	SS	78	664	751029–891019
	TSG	73	575	741227–891019
Subtotal		158	1290	
Degelen (Kazakhstan, Semipalatinsk Test Site)	KOD	45	290	670226–731026
	SS	59	469	751213–891004
	TSG	59	382	741216–891004
Subtotal		163	1141	
Murzhik (Kazakhstan, Semipalatinsk Test Site)	KOD	14	102	661218–730419
	SS	4	34	760804–800404
	TSG	4	24	780319–800404
Subtotal		22	160	
Novaya Zemlya (Russian Federation)	KOD	9	68	671021–731027
	SS	17	114	730927–901024
	TSG	19	279	750823–901024
Subtotal		45	461	
PNEs (Former Soviet Union)	KOD	27	152	671006–731026
	SS	38	259	730815–880906
	TSG	28	157	760329–880906
Subtotal		93	568	
Lop Nor (China)	KOD	1	4	690922
	SS	7	58	761017–900816
	TSG	8	58	781014–950515
		16	120	
Total		497	3740	

analysis (e.g., [9]), that were using signals from this same station, later identified (e.g., [1]) as the Borovoye Geophysical Observatory. Adushkin and An [2] state that the "…Borovoye station has been used to test the majority of new Soviet instrumentation, including various digital systems."

The digital data at Borovoye were mostly written on 35 mm wide tapes and were stored at the Observatory. This original seismogram archive holds data from one of the few digital seismographic stations operated anywhere in the world during the late 1960s and early 1970s, and provides unique data for the Central Asia region for the whole 30-year period from commencement of recording, up to the end of regular nuclear weapons testing by the recognized nuclear weapons states in 1996. The archive is invaluable for global seismological studies, due to its longevity of homogeneous observation over more than 25 years, and the low-noise conditions in northern Kazakhstan. Due to the cost of recording tape, the archive is segmented rather than continuous, typically having a few hundred files per day from the various different channels as described further below.

There are about 8000 digital seismogram archive tapes. Each magnetic tape has about 10 megabytes of digital seismogram data. Digital data were recorded by three different Russian systems, called KOD, STsR-SS, and STsR-TSG. Signals come from about 100,000 seismic events, which include earthquakes, industrial and nuclear explosions, and industrial accidents. The archive also contains some recordings from a former Soviet Army base near Borovoye and digital data from seismographic stations in Central

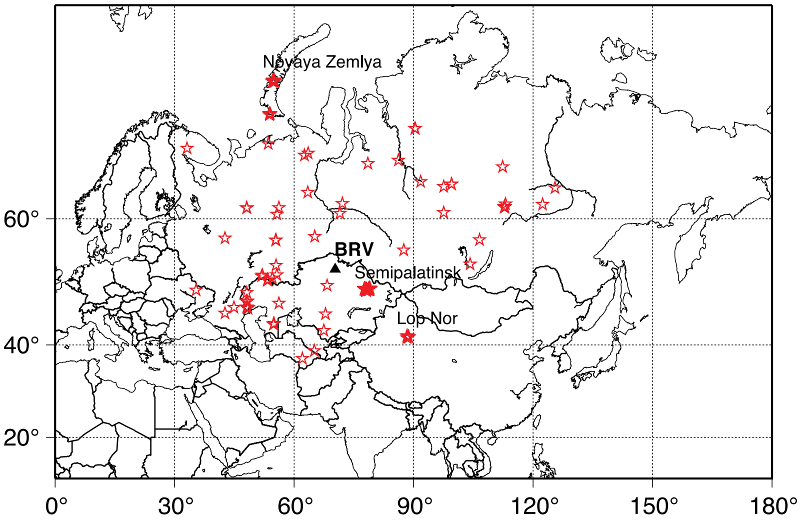

Fig. 4. Locations (red stars) of underground nuclear explosions (UNEs) recorded digitally by seismic monitoring systems at the Borovoye Geophysical Observatory (BRV) in Northern Kazakhstan. More detailed maps are given as Figs. 5–8. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Asia—including Talgar (TLG), Bishkek (formerly Frunze, FRU) and Naryn (NRN). Since underground nuclear explosions were carried out in a wide variety of geological conditions as part of the Soviet Peaceful Nuclear Explosion program, as well as at the USSR's nuclear weapons test sites, the BRVK archive of nuclear explosion data is invaluable for purposes of research on CTBT monitoring. Only with good data on explosions carried out in a variety of environments, is it possible to accomplish a rational design for an explosion monitoring network, and systematic methods of signal analysis.

The original wide tapes used as the archive medium have been deteriorating for many years and it was realized that the signals should be copied to more stable media, otherwise these valuable seismic observations would be lost forever. In order to save the digital seismogram archive at Borovoye and to make this valuable data available to interested scientists worldwide, personnel at the Lamont-Doherty Earth Observatory, Columbia University, worked with scientists at the National Nuclear Centre (NNC), Republic of Kazakhstan, and at the Institute of Dynamics of the Geosphere (IDG), Russian Academy of Sciences, beginning in the 1990s. It was recognized that NNC, IDG and LDEO had to work closely together, since the Borovoye Observatory had become a facility of the NNC in Kazakhstan, but personnel of IDG were most familiar with the content of the archive, and LDEO with IDG have designed the necessary hardware and software systems for modernization. Support for this work was provided in the early 1990s by the Joint Seismic Program of the IRIS Consortium; in the period from 1997 to 2000 by the International Science and Technology Centre, based in Moscow; and in the present century by the US Air Force Research Laboratory.

A description of operations at Borovoye during its years as a monitoring station has been reported as a feature article in EOS (Transactions of the American Geophysical Union) by Richards et al. [25] following a visit there by Richards and Ekström in 1991. Their article concluded that there was…

> "an interesting future for uses of data from Borovoye Geophysical Observatory, but there are large problems. First, there is the state of the archive, consisting of thousands of wide tapes in deteriorating condition. They are written in a 17-track format that is a barrier to modern systems. Only if the archive is copied to a more stable recording medium, and is then re-formatted incorporating reliable information on instrument responses, can its potential be realized… The archive is an irreplaceable database on the seismicity of Central Asia, and any serious attempt to work on the seismic hazard of Kazakhstan and neighboring states must recognize the importance of preserving … the archive.
>
> "At the international level, the United States has a common interest with Russia and Kazakhstan in preserving and strengthening the Non-Proliferation Treaty. The technical challenge in monitoring treaty compliance into the future includes the need to monitor for nuclear explosions in all possible types of geological environment. The country with the greatest experience in executing nuclear explosions under different shot-point conditions is the former USSR, with its several

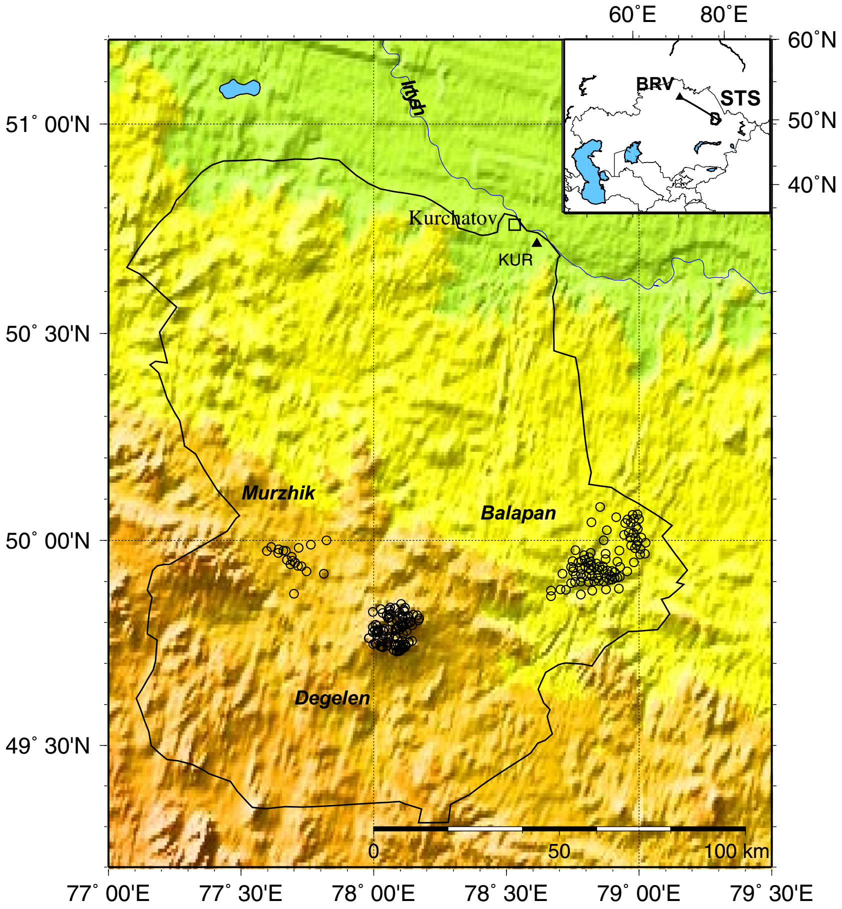

Fig. 5. UNTs at Semipalatinsk Test Site (*circles*) recorded at Borovoye (BRV) during 1966–1989. The Balapan, Degelen, and Murzhik regions are indicated.

> nuclear weapons test sites and a program of "peaceful nuclear explosions" carried out for various purposes at about one hundred different locations across a wide range of geological conditions…"

This rationale for rescuing the Borovoye archive, with its information on the signals from nuclear explosions carried out under a variety of different conditions, has turned out to be sufficiently persuasive that the work was eventually done, as reported in this paper, though it took more than 20 years to execute.

3. The first release of borovoye data

The BRV digital archive of nuclear explosion waveforms from 711 underground nuclear explosions (UNEs) was originally made available in April 2001 (for example, via http://www.ldeo.columbia.edu/res/pi/Monitoring/Arch/BRV_arch_exp.html), as an outcome of the International Science and Technology Center project mentioned above, which 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. Table 1 gives basic information on these 711 UNEs. Fig. 1 shows the location (BRV) of the Borovoye Observatory, and the main nuclear test sites at which UNEs were conducted and for which signals exist in the BRV archive.

The archive of nuclear explosion signals was issued as a series of modern databases, described by Kim et al. [11], in a 41-page report available today via http://www.ldeo.columbia.edu/Monitoring/Data/Brv_arch_ex/brv_text_table.pdf. 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 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.

Here, we may note that 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

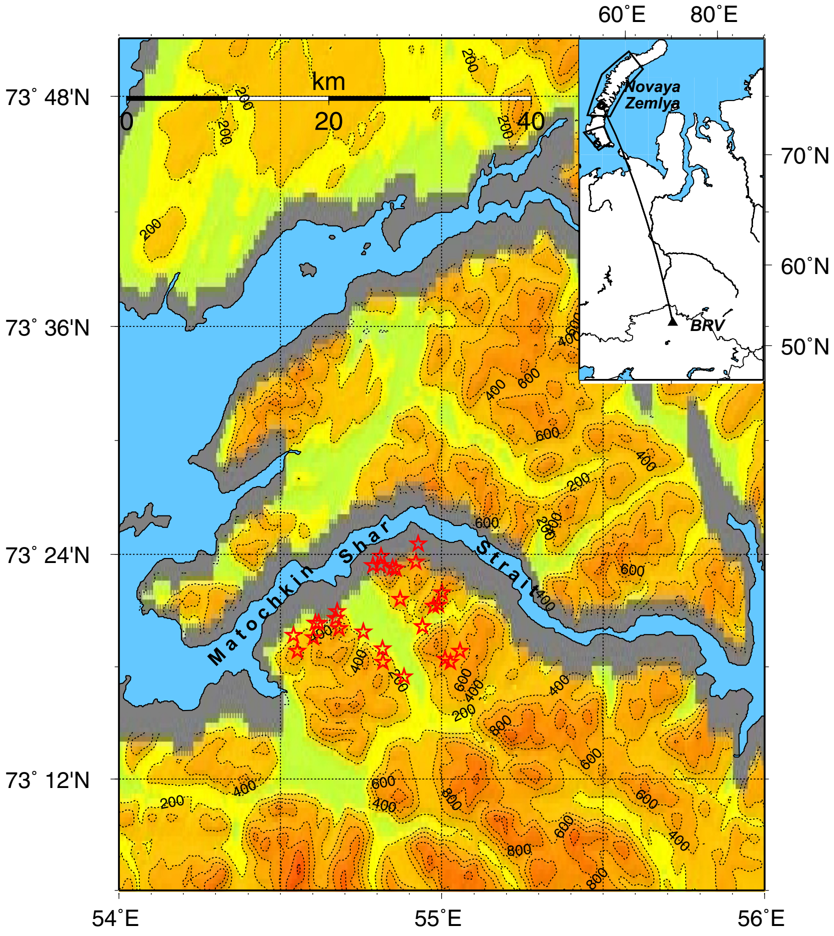

Fig. 6. Locations of UNEs (*red stars*) at the Northern Novaya Zemlya Test Site recorded at Borovoye during 1967–1990 are shown on a topographic relief map. Southern and Northern Test Sites on Novaya Zemlya, and a great circle path between BRV and the NZ test sites, are also indicated (*inset*).

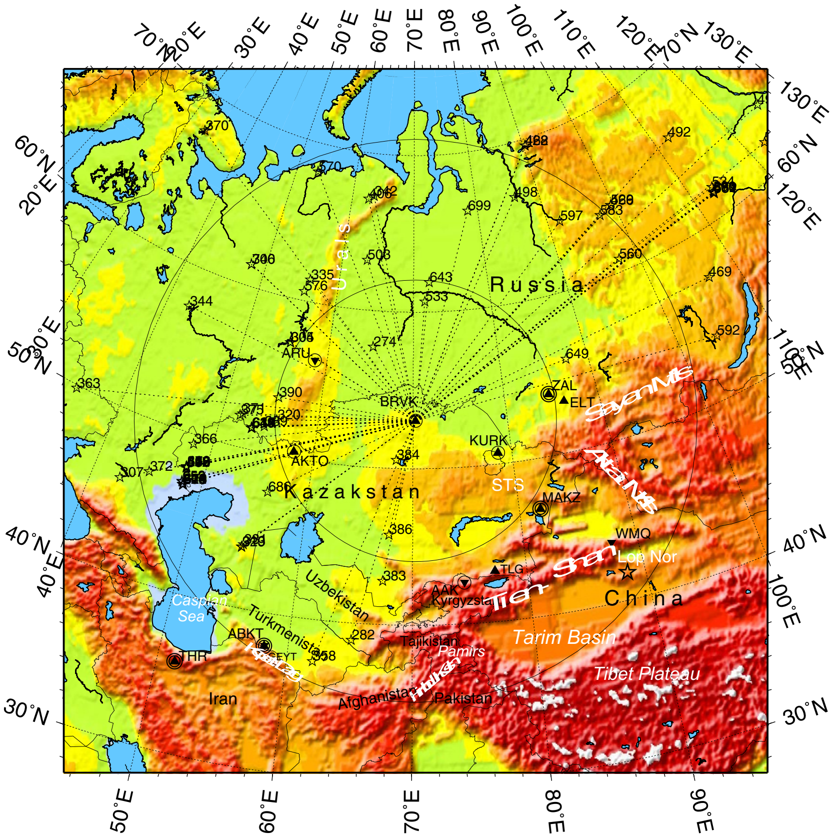

Fig. 7. Soviet PNEs (*stars*) recorded at Borovoye during 1967–1988. Event id in Table 7 is indicated for each PNE. IMS primary (*double circle*), auxiliary (*single circle*), IRIS/GSN (*inverted triangle*) and Kazakhstan Broadband Seismographic Network stations are indicated (*solid triangle*). Large circles around BRV indicate 1000 and 2000 km distance ranges from the station.

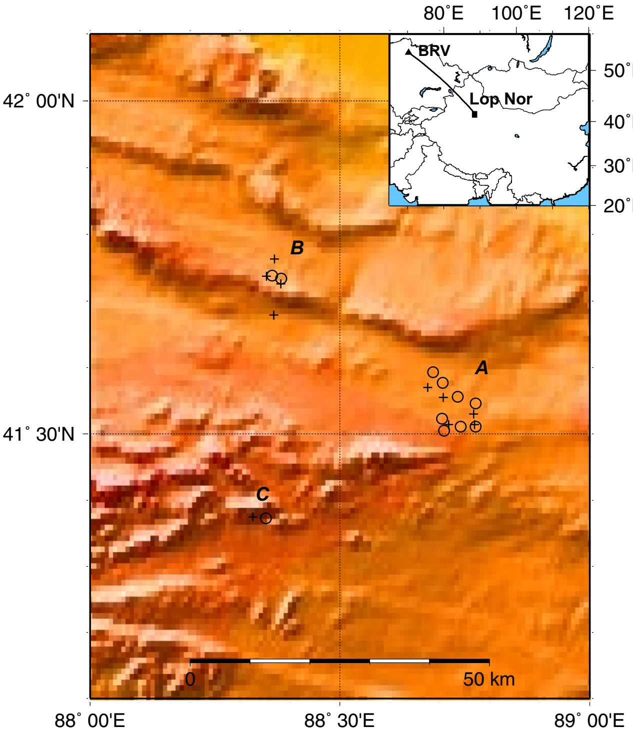

Fig. 8. Locations of UNEs at the Lop Nor Chinese Test Site. Notice that UNEs are clustered into three groups: A, B and C. UNEs not contained in the BRV archive are plotted with crosses.

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 US UNEs.

All of these main systems are approximately flat to ground displacement over a range of frequencies. Kim and Ekström [10] have published details of the STsR-TSG instrumental system, which has many channels, extending across almost 3 decades in frequency. Information on the other two systems has not previously been given in western scientific papers, and is given below.

We note that numerous modern broadband sensors began to be deployed at Borovoye once it opened to western scientists, the first of which was installed by Won-Young Kim in July 1994. These modern sensors recorded the final underground nuclear explosions conducted by China, the May 1998 tests of India and Pakistan, and the tests in this century by North Korea. They have also recorded numerous earthquakes at regional distances. The station code BRVK is used to represent Borovoye today.

During the cold war, when so many underground nuclear tests were conducted (more than 1500), the signals recorded at Borovoye were in the teleseismic range for explosions at the main test sites used by the USA, the UK, and France. Fig. 2 shows the location of USA and UK nuclear tests at the Nevada Test Site (today, called the Nevada National Security Site), for which there are teleseismic signals in the Borovoye archive. Fig. 3 shows the location of French nuclear tests in the South Pacific, whose teleseismic signals were recorded at BRV (via paths in this case that traversed the Earth's core).

Table 3
Deglitched Borovoye data for UNEs in the Balapan subarea of STS, 1968–1988.

Test No.	Date Year-Mo-Da	Time (hr:mn:sec)	Latitude (°N)	Longitude (°E)	*m*b (*P*)	Instrument type	Comments
285	1968–06-19	05:05:59.8	49.98025	78.98550	5.28	KODB/M	Bocharov
312	1969–11-30	03:32:59.7	49.92428	78.95575	6.02	KODB/M	Bocharov
341	1971–06-30	03:56:59.8	49.94600	78.98047	4.94	KODB/M	Bocharov
355	1972–02-10	05:03:00.0	50.02428	78.87808	5.27	KODB/M	Bocharov
373	1972–11-02	01:27:00.2	49.92697	78.81725	6.16	KODB	Bocharov
377	1972–12-10	04:27:10.0	50.02700	78.99556	5.96	KODB/M	Bocharov/Double
382	1973–07-23	01:23:00.11	49.96889	78.81750	6.17	KODB/M	AWE/NNC
416	1974–12-27	05:46:59.35	49.96583	79.00333	5.50	TSG	AWE/NNC
433	1975–10-29	04:46:59.82	49.95389	78.87389	5.61	SS/TSG	AWE/NNC
435	1975–12-25	05:16:59.65	50.04389	78.82000	5.69	TSG	AWE/NNC
440	1976–04-21	05:02:59.70	49.90056	78.83083	5.12	SS/TSG	AWE/NNC
443	1976–06-09	03:02:59.75	49.99361	79.02444	5.07	TSG	AWE/NNC
444	1976–07-04	02:56:59.94	49.90417	78.89944	5.85	SS/TSG	AWE/NNC
448	1976–08-28	02:56:59.99	49.97500	78.92639	5.74	SS/TSG	AWE/NNC
453	1976–11-23	05:02:59.75	50.01306	78.94333	5.79	SS	AWE/NNC
454	1976–12-07	04:56:59.85	49.94389	78.83917	5.80	SS/TSG	AWE/NNC
460	1977–05-29	02:57:00.01	49.94639	78.77167	5.75	SS/TSG	AWE/NNC
461	1977–06-29	03:07:00.35	49.99944	78.86667	5.20	SS/TSG	AWE/NNC
468	1977–09-05	03:02:59.86	50.05556	78.91417	5.73	SS/TSG	AWE/NNC
474	1977–10-29	03:07:04.92	50.05222	78.98028	5.56	SS/TSG	AWE/NNC/Double
478	1977–11-30	04:06:59.85	49.96722	78.87444	5.89	SS/TSG	AWE/NNC
487	1978–06-11	02:57:00.08	49.91333	78.80194	5.83	SS/TSG	AWE/NNC
488	1978–07-05	02:46:59.97	49.90000	78.86667	5.77	SS/TSG	AWE/NNC
496	1978–09-15	02:36:59.90	49.92833	78.86167	5.89	SS/TSG	AWE/NNC
505	1978–11-04	05:05:59.81	50.04167	78.94722	5.56	SS/TSG	AWE/NNC
506	1978–11-29	04:33:04.99	49.95333	78.79528	5.96	SS/TSG	AWE/NNC/Double
514	1979–02-01	04:13:00.17	50.08083	78.85333	5.29	SS/TSG	AWE/NNC
521	1979–06-23	02:57:00.02	49.91472	78.84583	6.16	TSG	AWE/NNC
522	1979–07-07	03:46:59.81	50.03306	78.98917	5.84	SS	AWE/NNC
526	1979–08-04	03:56:59.97	49.90306	78.88778	6.13	SS/TSG	AWE/NNC
528	1979–08-18	02:51:59.61	49.94806	78.91889	6.13	SS/TSG	AWE/NNC
538	1979–10-28	03:16:59.45	49.99667	78.99500	5.98	SS/TSG	AWE/NNC
540	1979–12-02	04:36:59.95	49.90944	78.78444	5.99	SS/TSG	AWE/NNC
542	1979–12-23	04:56:59.93	49.93222	78.75278	6.13	SS/TSG	AWE/NNC
546	1980–04-25	03:57:00.03	49.97639	78.75944	5.45	SS	AWE/NNC
548	1980–06-12	03:27:00.11	49.98872	78.99108	5.52	SS/TSG	AWE/NNC
552	1980–06-29	02:33:00.19	49.94861	78.81806	5.69	SS/TSG	AWE/NNC
554	1980–09-14	02:42:41.63	49.93667	78.79750	6.21	SS	AWE/NNC
558	1980–10-12	03:34:16.58	49.96750	79.02250	5.88	SS/TSG	AWE/NNC
564	1980–12-14	03:47:08.91	49.90889	78.91861	5.93	SS/TSG	AWE/NNC
566	1980–12-27	04:09:10.56	50.06194	78.97528	5.87	SS/TSG	AWE/NNC
568	1981–03-29	04:03:52.51	50.01806	78.97881	5.49	SS/TSG	AWE/NNC
569	1981–04-22	01:17:13.82	49.89889	78.80861	5.94	SS/TSG	AWE/NNC
571	1981–05-27	03:58:14.82	49.98694	78.97056	5.30	SS/TSG	AWE/NNC
577	1981–09-13	02:17:20.76	49.91333	78.89444	6.06	SS/TSG	AWE/NNC
582	1981–10-18	03:57:05.14	49.92806	78.84472	6.00	SS/TSG	AWE/NNC
585	1981–11-29	03:35:11.11	49.90194	78.84889	5.62	SS/TSG	AWE/NNC
587	1981–12-27	03:43:16.62	49.93306	78.77833	6.16	SS/TSG	AWE/NNC
589	1982–04-25	03:23:07.88	49.91694	78.88778	6.03	SS/TSG	AWE/NNC
591	1982–07-04	01:17:16.65	49.95861	78.81167	6.08	SS/TSG	AWE/NNC
594	1982–08-31	01:31:03.17	49.91417	78.76139	5.20	SS/TSG	AWE/NNC
604	1982–12-05	03:37:15.04	49.93083	78.80972	6.08	SS/TSG	AWE/NNC
606	1982–12-26	03:35:16.68	50.06306	78.99389	5.58	SS/TSG	AWE/NNC
611	1983–06-12	02:36:46.01	49.92500	78.89806	6.02	SS/TSG	AWE/NNC
625	1983–10-06	01:47:09.08	49.92458	78.75069	5.95	SS	AWE/NNC
626	1983–10-26	01:55:07.33	49.91250	78.82167	6.04	SS/TSG	AWE/NNC
628	1983–11-20	03:27:06.86	50.05083	78.99917	5.33	SS/TSG	AWE/NNC
632	1984–02-19	03:57:05.85	49.89611	78.74306	5.77	SS	AWE/NNC
633	1984–03-07	02:39:08.80	50.05000	78.95611	5.56	SS	AWE/NNC
634	1984–03-29	05:19:10.66	49.91111	78.92694	5.86	SS/TSG	AWE/NNC
636	1984–04-25	01:09:05.99	49.93583	78.85056	5.90	SS/TSG	AWE/NNC
637	1984–05-26	03:13:14.85	49.97889	79.00556	6.01	SS/TSG	AWE/NNC
638	1984–07-14	01:09:12.99	49.90944	78.87722	6.10	SS/TSG	AWE/NNC
654	1984–10-27	01:50:12.93	49.93472	78.92806	6.19	SS/TSG	AWE/NNC
656	1984–12-02	03:19:08.85	50.00611	79.00889	5.77	SS/TSG	AWE/NNC
657	1984–12-16	03:55:05.07	49.94583	78.80861	6.12	SS/TSG	AWE/NNC
658	1984–12-28	03:50:13.09	49.88028	78.70389	6.00	SS/TSG	AWE/NNC
659	1985–02-10	03:27:09.98	49.89917	78.78056	5.83	SS	AWE/NNC
660	1985–04-25	00:57:08.97	49.92667	78.88083	5.84	SS	AWE/NNC
661	1985–06-15	00:57:03.25	49.90861	78.84278	6.05	SS/TSG	IDG/NNC
663	1985–06-30	02:39:05.26	49.86444	78.66861	5.92	SS/TSG	IDG/NNC
667	1985–07-20	00:53:16.91	49.94972	78.78389	5.89	SS/TSG	AWE/NNC
670	1987–03-12	01:57:19.57	49.93528	78.82889	5.31	SS/TSG	AWE/NNC
671	1987–04-03	01:17:10.28	49.91806	78.78028	6.12	SS/TSG	AWE/NNC

Table 3 (*continued*)

Test No.	Date Year-Mo-Da	Time (hr:mn:sec)	Latitude (°N)	Longitude (°E)	*m*b (*P*)	Instrument type	Comments
673	1987–04-17	01:03:07.09	49.87778	78.66889	5.92	SS/TSG	AWE/NNC
678	1987–06-20	00:53:07.09	49.93528	78.74417	6.03	SS/TSG	AWE/NNC
683	1987–08-02	00:58:09.27	49.88056	78.87472	5.83	SS/TSG	IDG/NNC
688	1987–11-15	03:31:09.08	49.89861	78.75806	5.98	SS	AWE/NNC
689	1987–12-13	03:21:07.31	49.96306	78.79306	6.06	SS	IDG/NNC
691	1987–12-27	03:05:07.00	49.87944	78.72500	6.00	SS	IDG/NNC
693	1988–02-13	03:05:08.327	49.93667	78.86389	5.97	SS/TSG	IDG/NNC
694	1988–04-03	01:33:08.294	49.90833	78.90833	5.99	SS/TSG	IDG/NNC
696	1988–05-04	00:57:09.261	49.94944	78.75028	6.09	SS/TSG	IDG/NNC
698	1988–06-14	02:27:08.98	50.01889	78.96056	4.80	SS/TSG	AWE/NNC
701	1988–09-14	03:59:59.69	49.87778	78.82306	6.03	SS/TSG	AWE/NNC
703	1988–11-12	03:30:06.26	50.04306	78.96889	5.24	SS/TSG	AWE/NNC
706	1988–12-17	04:18:09.291	49.88194	78.92472	5.83	SS/TSG	IDG/NNC
708	1989–01-22	03:57:09.02	49.93944	78.81944	6.10	SS/TSG	AWE/NNC
709	1989–02-12	04:15:09.342	49.91861	78.71111	5.86	SS/TSG	IDG/NNC
711	1989–07-08	03:47:00.03	49.86778	78.78028	5.55	SS/TSG	AWE/NNC
712	1989–09-02	04:16:59.85	50.00583	78.98556	4.94	SS/TSG	AWE/NNC
714	1989–10-19	09:49:59.81	49.92222	78.90833	5.86	SS/TSG	AWE/NNC

Notes on Table 3.
Test No. = unique test number given in Mikhailov et al. [20] for 715 nuclear tests in USSR.
*m*b(*P*) = teleseismic body-wave magnitude from Marshall et al. [18].
Bocharov = ground truth data from Bocharov et al. [6].
NNC = ground truth location reported by the National Nuclear Center [21].
AWE = origin time from Lilwall and Farthing [17].
Doubl = double test (preceded or followed by another test at Degelen within a few seconds).

Of particular interest in the Borovoye archive, are the signals of UNEs recorded at regional distances. Such signals are typically more complicated that those recorded teleseismically, but they are important to understand in view of the fact that they can enable monitoring to be carried out for UNEs of lower magnitude. Therefore, special efforts have been made, as we next describe, to improve the usability of Borovoye recordings made from nuclear tests conducted in Eurasia, many of which were at regional distances from the Observatory.

4. The second release of Borovoye data

The Borovoye archive made available to researchers in 2001 had two substantial defects, both of which have been corrected in the second major data release, which focuses on the signals from underground nuclear explosions in Eurasia. First, the digital data for some signals suffered from a significant number of glitches, and it was left to the user to decide how to manage them. Second, information on the instrument responses of the numerous different recording channels was incomplete, thus preventing much of the archive from being used for spectral analysis or for applications requiring knowledge of absolute ground motion derived from the recordings.

Issuance of the archive in 2001 promoted efforts at the Los Alamos National Laboratory (LANL) to remove the glitches, and scientific results based upon the deglitched records, for those recordings for which the instrument responses were known, found many uses. Consequently a new project was initiated, with the intent to complete work on deglitching and instrument responses. This work has now been concluded, and the deglitched waveforms are available at http://www.ldeo.columbia.edu/res/pi/Monitoring/Arch/BRV_arch_deglitched.html.

Fig. 4 shows the location of Borovoye, and of the hundreds of nuclear explosions in Eurasia recorded by the Observatory. In many cases these recordings were made at regional distances, and thus include seismic signals known as *Pn*, *Pg*, *Sn*, and *Lg*, which have traveled mainly in the Earth's crust and uppermost mantle rather than at greater depths in the Earth's interior. Table 2 summarizes the numbers of recorded explosions in Eurasia and the numbers of recordings (traces) associated with six different groups of explosions, namely the Balapan, Degelen, and Murzhik sub-regions of the Semipalatinsk Test Site in Kazakhstan; the Novaya Zemlya Test Site in Russia; the wide-ranging locations of the Peaceful Nuclear Explosions (PNEs) conducted by the Soviet Union; and the Lop Nor Test Site in China.

Fig. 5 through Fig. 8 show the locations of underground nuclear explosions, for which deglitched data are now available, in four different groupings, namely: the Semipalatinsk Test Site (Fig. 5); the Novaya Zemlya Test Site (Fig. 6); the Soviet Peaceful Nuclear Explosions (Fig. 7); and the Lop Nor Test Site in China (Fig. 8).

Tables 3–5, list information for these explosions at the sub-regions Balapan, Degelen, and Murzhik (respectively) for the Semipalatinsk Test Site. Tables 6–8, give explosion details for Novaya Zemlya, Soviet Peaceful Nuclear Explosions, and Lop Nor (China). In these Tables, the precision of the seismically determined origin times are indicated by their decimal points. The column headed "Instrument type" specifies the instrument used, and KODB = KOD high-gain system; KODM = KOD low-gain system; SS = STsR-SS system; TSG = STsR-TSG system (see Kim and Ekström, 1996);

5. Deglitching and deriving instrument responses

Following the first release of Borovoye data in April 2001, personnel at Los Alamos National Laboratory (LANL) became familiar with the BRV archive. They processed approximately one third of it to remove glitches, using the results of Kim and Ekström [10] to correct for instrument response for the TSG recording system in use at BRV, and used the resulting corrected waveforms in a variety of practical studies to improve nuclear explosion monitoring in Central Asia and the surrounding regions.

These corrected waveforms were used for regional seismic discrimination studies, coda wave magnitude studies, and regional M_s studies, primarily using the STsR-TSG or TS instrumentation. LANL personnel also used a limited subset of the earlier KOD and STsR-SS

Table 4
Deglitched Borovoye data for UNEs in the Degelen subarea of STS, 1967–1989.

Test No.	Date Year-Mo-Da	Time (hr:mn:sec)	Latitude (°N)	Longitude (°E)	*m*b (*P*)	Instrument type	Comments
264	1967–02-26	03:57:59.8	49.74569	78.08231	6.03	KODB	Bocharov
266	1967–04-20	04:08:01.0	49.74161	78.10542	5.56	KODB	Bocharov
267	1967–05-28	04:07:59.6	49.75642	78.01689	5.46	KODB	Bocharov
268	1967–06-29	02:56:59.9	49.81669	78.04903	5.34	KODB/M	Bocharov
269	1967–07-15	03:26:59.9	49.83592	78.11817	5.39	KODB	Bocharov
270	1967–08-04	06:58:00.3	49.76028	78.05550	5.32	KODB/M	Bocharov
271	1967–09-02	04:04:00.0	49.74194	78.02556	4.10	KODB	Khalturin
275	1967–10-17	05:04:00.2	49.78089	78.00383	5.63	KODB/M	Bocharov
277	1967–10-30	06:04:00.0	49.79436	78.00786	5.41	KODB/M	Bocharov
279	1967–12-08	06:03:59.8	49.81714	78.16378	5.31	KODB	Bocharov
280	1968–01-07	03:46:59.9	49.75442	78.03094	4.98	KODB	Bocharov
281	1968–04-24	10:35:59.7	49.84519	78.10322	4.91	KODB	Bocharov
284	1968–06-11	03:05:59.7	49.79300	78.14508	5.24	KODB/M	Bocharov
294	1968–11-09	02:54:00.1	49.80053	78.13911	4.75	KODB	Bocharov
296	1968–12-18	05:01:59.7	49.74594	78.09203	5.04	KODB/M	Bocharov
297	1969–03-07	08:26:59.8	49.82147	78.06267	5.66	KODB/M	Bocharov
300	1969–05-16	04:02:59.7	49.75942	78.07578	5.26	KODB/M	Bocharov
302	1969–07-04	02:46:59.6	49.74603	78.11133	5.24	KODB/M	Bocharov
303	1969–07-23	02:47:00.2	49.81564	78.12961	5.50	KODB/M	Bocharov
306	1969–09-11	04:02:00.0	49.77631	77.99669	4.91	KODB/M	Bocharov
308	1969–10-01	04:02:59.9	49.78250	78.09831	5.26	KODB/M	Bocharov
315	1969–12-29	04:02:00.0	49.73367	78.10225	4.22	KODB	Bocharov
316	1970–01-29	07:03:00.0	49.79558	78.12389	5.60	KODB/M	Bocharov
318	1970–03-27	05:02:59.6	49.74781	77.99897	4.93	KODB/M	Bocharov
319	1970–05-27	04:03:00.0	49.73131	78.09861	4.20	KODB	Bocharov
321	1970–06-28	01:58:00.0	49.80150	78.10681	5.87	KODB/M	Bocharov
324	1970–07-24	03:57:00.0	49.80972	78.12839	5.34	KODB/M	Bocharov
326	1970–09-06	04:02:59.9	49.78889	77.99750	5.53	KODB/M	Bocharov
330	1970–12-17	07:01:00.0	49.74564	78.09917	5.43	KODB/M	Bocharov
332	1971–01-29	05:03:00.0	49.80528	78.16861	4.47	KODB	Khalturin
333	1971–03-22	04:33:00.3	49.79847	78.10897	5.77	KODB/M	Bocharov
337	1971–04-25	03:32:59.9	49.76853	78.03392	6.08	KODB/M	Bocharov
338	1971–05-25	04:03:00.4	49.80164	78.13883	5.05	KODB/M	Bocharov
350	1971–11-29	06:02:59.9	49.74342	78.07850	5.46	KODB/M	Bocharov
351	1971–12-15	07:52:59.8	49.82639	77.99731	4.90	KODB	Bocharov
353	1971–12-30	06:21:00.2	49.74917	78.00611	5.84	KODB/M	Bocharov
356	1972–03-10	04:56:59.8	49.74531	78.11969	5.45	KODM	Bocharov
357	1972–03-28	04:22:00.1	49.73306	78.07569	5.18	KODB/M	Bocharov
360	1972–06-07	01:28:00.0	49.82675	78.11547	5.42	KODB/M	Bocharov
365	1972–08-16	03:16:59.8	49.76547	78.05883	5.11	KODB/M	Bocharov
376	1972–12-10	04:27:00.0	49.81939	78.05822	5.72	KODB/M	Bocharov/Double
378	1972–12-28	04:27:00.0	49.73919	78.10625	4.60	KODB	Bocharov
379	1973–02-16	05:03:00.0	49.81583	78.10667	5.48	KODB/M	AWE/Leith
381	1973–07-10	01:27:00.15	49.79111	78.01278	5.34	KODB	AWE/Leith
391	1973–10-26	04:27:00.14	49.75222	78.13250	5.23	KODB/M	AWE/Leith
414	1974–12-16	06:23:00.14	49.76778	78.08167	4.94	TSG	AWE/Leith
415	1974–12-16	06:41:00.34	49.83306	78.02667	4.89	TSG	AWE/Leith
434	1975–12-13	04:56:59.99	49.81333	78.10861	5.00	SS/TSG	AWE/Leith
436	1976–01-15	04:46:59.97	49.81000	78.17139	5.18	SS/TSG	AWE/Leith
441	1976–04-21	04:58:00.16	49.75472	78.10750	4.94	SS/TSG	AWE/Leith
442	1976–05-19	02:57:00.2	49.77750	78.01556	4.72	SS	AWE/Leith
445	1976–07-23	02:33:00.19	49.74333	78.05167	4.96	SS	AWE/Leith
451	1976–10-30	04:57:00.21	49.83139	78.05722	4.62	SS/TSG	AWE/Leith
456	1976–12-30	03:57:00.31	49.78028	78.03667	5.09	TSG	AWE/Leith
457	1977–03-29	03:56:59.95	49.77639	78.01750	5.41	SS/TSG	AWE/Leith
459	1977–04-25	04:07:00.16	49.81333	78.10861	5.07	SS/TSG	AWE/Leith
463	1977–07-30	01:57:00.11	49.75056	78.04917	5.13	SS/TSG	AWE/Leith
465	1977–08-17	04:26:59.97	49.83083	78.11389	5.01	SS/TSG	AWE/Leith
479	1977–12-26	04:03:00.24	49.81083	78.05417	4.91	SS/TSG	AWE/Leith
482	1978–03-26	03:56:59.96	49.76194	77.98250	5.69	SS/TSG	AWE/Leith
483	1978–04-22	03:07:00.01	49.75167	78.13167	5.35	TSG	AWE/Leith
485	1978–05-29	04:56:59.85	49.79139	78.09444	4.68	SS/TSG	AWE/Leith
489	1978–07-28	02:46:59.89	49.75500	78.14500	5.75	TSG	AWE/Leith
493	1978–08-29	02:36:59.95	49.81333	78.10861	5.20	SS	AWE/Leith/Double
501	1978–10-15	05:37:00.14	49.73667	78.11111	5.15	SS/TSG	AWE/Leith
504	1978–10-31	04:17:00.19	49.78861	78.10750	5.25	SS/TSG	AWE/Leith
509	1978–12-14	04:43:00.03	49.81583	78.10667	4.74	SS/TSG	AWE/Leith
511	1978–12-20	04:33:00.04	49.81083	78.05417	4.71	SS/TSG	AWE/Leith
518	1979–05-06	03:17:00.07	49.76194	77.98250	5.22	SS/TSG	AWE/Leith
519	1979–05-31	05:55:00.05	49.81278	78.05944	5.27	SS/TSG	AWE/Leith
532	1979–09-27	04:13:00.00	49.75056	78.04917	4.42	SS/TSG	AWE/Leith
535	1979–10-18	04:17:00.11	49.82417	78.09750	5.23	SS/TSG	AWE/Leith
539	1979–11-30	04:53:00.58	49.78306	78.08667	4.42	SS/TSG	AWE/Leith
541	1979–12-21	04:42:00.09	49.79222	78.11300	4.71	SS/TSG	AWE/Leith

Table 4 (*continued*)

Test No.	Date Year-Mo-Da	Time (hr:mn:sec)	Latitude (°N)	Longitude (°E)	*mb* (*P*)	Instrument type	Comments
545	1980–04-10	04:07:00.19	49.78250	78.05722	4.98	SS/TSG	AWE/Leith
547	1980–05-22	03:57:00.14	49.77972	78.03639	5.53	SS/TSG	AWE/Leith
553	1980–07-31	03:33:00.07	49.79056	78.09083	5.33	SS/TSG	AWE/Leith
555	1980–09-25	06:21:13.06	49.78333	78.08056	4.83	SS/TSG	AWE/Leith
573	1981–06-30	01:57:15.34	49.76750	78.08083	5.16	SS/TSG	AWE/Leith
574	1981–07-17	02:37:18.12	49.80139	78.13139	5.07	TSG	AWE/Leith
575	1981–08-14	02:27:15.24	49.75222	78.05306	4.88	SS/TSG	AWE/Leith
584	1981–11-20	04:57:05.07	49.73667	78.10417	5.00	SS	AWE/Leith
586	1981–12-22	04:31:05.27	49.83417	78.08028	4.96	SS/TSG	AWE/Leith
588	1982–02-19	03:56:13.42	49.82333	78.03333	5.40	SS/TSG	AWE/Leith
590	1982–06-25	02:03:07.16	49.77139	78.11083	4.57	SS/TSG	AWE/Leith
593	1982–08-23	02:43:06.70	49.74028	78.03083	4.44	SS	AWE/Leith
596	1982–09-21	02:57:03.17	49.77917	78.12472	5.15	SS/TSG	AWE/Leith
605	1982–12-25	04:23:08.38	49.78111	78.03500	4.47	SS/TSG	AWE/Leith
608	1983–03-30	04:17:10.22	49.78500	78.04056	4.61	SS/TSG	AWE/Leith
609	1983–04-12	03:41:08.26	49.78556	78.08472	4.65	SS/TSG	AWE/Leith
610	1983–05-30	03:33:47.04	49.74111	78.12028	5.43	SS	AWE/Leith
612	1983–06-24	02:56:13.85	49.73972	78.03583	4.46	SS/TSG	AWE/Leith
617	1983–09-11	06:33:13.10	49.78472	78.08417	4.48	SS/TSG	AWE/Leith
629	1983–11-29	02:19:08.80	49.73028	78.09583	5.31	SS	AWE/Leith
631	1983–12-26	04:29:09.25	49.79000	78.10917	5.48	SS/TSG	AWE/Leith
635	1984–04-15	03:17:11.46	49.76056	78.08917	5.72	SS/TSG	AWE/Leith
648	1984–09-09	02:59:08.85	49.80444	78.08750	4.89	SS/TSG	AWE/Leith
650	1984–10-18	04:57:08.32	49.72944	78.08639	4.25	SS/TSG	AWE/Leith
655	1984–11-23	03:55:07.48	49.81250	78.05944	4.38	SS/TSG	AWE/Leith
668	1985–07-25	03:11:09.23	49.81917	78.14944	4.82	SS/TSG	AWE/Leith
669	1987–02-26	04:58:24.32	49.83417	78.08111	5.40	SS/TSG	AWE/Leith
676	1987–05-06	04:02:08.11	49.77583	78.01222	5.60	SS/TSG	AWE/Leith
677	1987–06-06	02:37:09.25	49.83667	78.06167	5.40	SS/TSG	AWE/Leith
680	1987–07-17	01:17:09.18	49.77583	78.01972	5.80	SS	AWE/Leith
685	1987–09-18	02:32:10.01	49.80444	78.08750	4.30	SS	AWE/Leith
687	1987–10-16	06:06:06.99	49.72972	78.08667	4.60	SS/TSG	AWE/Leith
690	1987–12-20	02:55:09.14	49.77583	78.01222	4.80	SS/TSG	AWE/Leith
692	1988–02-06	04:19:09.13	49.77583	78.01972	4.70	SS/TSG	AWE/Leith
695	1988–04-22	09:30:09.44	49.79028	78.10694	4.90	SS/TSG	AWE/Leith
702	1988–10-18	03:40:09.16	49.78000	78.01722	4.90	SS/TSG	AWE/Leith
704	1988–11-23	03:57:08.99	49.77944	78.03722	5.40	SS/TSG	AWE/Leith
707	1988–12-28	05:28:10	49.80111	78.06861	3.74	SS/TSG	Khalturin/Leith
710	1989–02-17	04:01:09.22	49.82778	78.05972	5.00	SS/TSG	AWE/Leith
713	1989–10-04	11:30:00.16	49.74833	78.00944	4.60	SS/TSG	AWE/Leith

Notes on Table 4.
Test no. = unique test number given in Mikhailov et al. (1996) for 715 nuclear tests in USSR.
mb(*P*) = teleseismic body-wave magnitude from Marshall et al. [18] and Ringdal et al. [26].
Bocharov = ground truth data from Bocharov et al. [6].
Leith = ground truth location from Leith [16] for entrance to the tunnels.
AWE = origin time from Lilwall and Farthing [17].
Khalturin = location and origin time from Khalturin et al. [15].
Doubl = double test (preceded or followed by another test at Balapan within a few seconds.

data for discrimination studies of selected events, but were unable to use discriminants based on ratios of different frequency bands as the archive did not then contain response information for those earlier systems (KOD, SS).

A coordinated effort was therefore begun in 2007, by personnel at Lamont-Doherty Earth Observatory and LANL, to remove glitches and to incorporate instrument response information for the KOD and SS systems as well as for TSG, and thus to access information from all channels of Borovoye data, for underground nuclear explosions conducted in Eurasia.

5.1. Technical approach to deglitching

When the BRV archive was made generally available 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 (namely, 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 glitches, which could be numerous in some recordings of ground motion. The original recording system addressed the practical problem of input signals having 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.

Despite these defects, ways to extract the underlying information have been found. For example, empirical travel-time information, needed to generate Source Specific Station Corrections for the BRV station (which today is part of the International Monitoring System headquartered in Vienna) can be obtained by picking first and secondary arrivals from a high-gain channel. But the spectrum of the strongest ground motion is often best obtained from one of the lower-gain channels. Coda can be measured from both high-gain and low-gain channels.

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. Many glitches are

Table 5
Deglitched Borovoye data for UNEs in the Murzhik subarea of STS, 1967–1980.

Test No.	Date Year-Mo-Da	Time (hr:mn:sec)	Latitude (°N)	Longitude (°E)	*mb* (*P*)	Instrument type	Comments
262	1966–12-18	04:58:00.0	49.92458	77.74722	5.92	KODB	Bocharov
272	1967–09-16	04:04:00.3	49.93719	77.72811	5.25	KODB/M	Bocharov
273	1967–09-22	05:04:00.0	49.95964	77.69106	5.16	KODB	Bocharov
278	1967–11-22	04:03:59.9	49.94194	77.68683	4.41	KODB	Bocharov
301	1969–05-31	05:01:59.4	49.95031	77.69422	5.29	KODB/M	Bocharov
314	1969–12-28	03:47:00.2	49.93733	77.71422	5.79	KODB/M	Bocharov
323	1970–07-21	03:02:59.7	49.95242	77.67289	5.38	KODB/M	Bocharov
328	1970–11-04	06:02:59.8	49.98922	77.76244	5.44	KODB/M	Bocharov
339	1971–06-06	04:02:59.7	49.97542	77.66028	5.53	KODB/M	Bocharov
340	1971–06-19	04:04:00.1	49.96903	77.64081	5.54	KODB/M	Bocharov
347	1971–10-09	06:02:59.7	49.97789	77.64144	5.37	KODB/M	Bocharov
348	1971–10-21	06:02:59.7	49.97381	77.59733	5.58	KODB/M	Bocharov
367	1972–08-26	03:46:59.7	49.98197	77.71661	5.36	KODB/M	Bocharov
380	1973–04-19	04:32:59.92	49.984	77.614	5.36	KODB/M	AWE
447	1976–08-04	02:57:00	49.87	77.70	4.20	SS	Khalturin
481	1978–03-19	03:46:59.82	49.945	77.704	5.19	SS/TSG	AWE
515	1979–02-16	04:04:00.50	49.974	77.668	5.39	SS/TSG	AWE
524	1979–07-18	03:17:04.92	49.919	77.812	5.16	SS/TSG	AWE
544	1980–04-04	05:32:59.83	50.000	77.823	4.90	SS/TSG	AWE

Notes on Table 5.
Test no. = unique test number given in Mikhailov et al. (1996) for 715 nuclear tests in USSR.
mb(*P*) = teleseismic body-wave magnitude from Marshall et al. [18] and Ringdal et al. [26].
Bocharov = ground truth data from Bocharov et al. [6].
AWE = origin time from Lilwall and Farthing [17].
Khalturin = location and origin time from Khalturin et al. [15].

Table 6
Deglitched Borovoye data for UNEs at the Novaya Zemlya Test Site, 1967–1990.

Test no.	Date Year-Mo-Da	Time (hr:mn:sec)	Lat. (°N)	Long. (°E)	*mb* (*P*)	Inst. type	Comments
276	1967–10-21	04:59:58.49	73.390	54.810	5.98	KODB/M	Salvo exp. in two tunnels
293	1968–11-07	10:02:05.49	73.387	54.858	6.13	KODB/M	Salvo exp. in single tunnel
309	1969–10-14	07:00:06.61	73.390	54.787	6.18	KODB/M	3 Explosions
327	1970–10-14	05:59:57.57	73.304	55.027	6.79	KODB/M	3 Explosions 150–1500 kt
345	1971–09-27	05:59:55.75	73.393	54.920	6.67	KODB/M	4 Explosions 150–1500 kt
368	1972–08-28	05:59:56.87	73.388	54.847	6.49	KODB/M	4 Explosions
385	1973–09-12	06:59:54.81	73.314	55.056	6.97	KODB/M	Highest yield Soviet UNT
388	1973–09-27	07:00:01.12	70.731	53.827	5.89	KODB/SS	Southern Test Site
392	1973–10-27	07:00:00.61	70.780	54.026	6.98	KODB/M/SS	Southern Test Site
427	1975–08-23	08:59:58.25	73.334	54.682	6.55	TSG	Salvo exp. with 8 explosions
430	1975–10-18	08:59:59.40	70.816	53.744	6.75	TSG	2 expls. shaft Yu-6 N
431	1975–10-18	Single explosion in shaft Yu-7 simultaneously with test #430 both Southern Test Site					
432	1975–10-21	11:59:58.03	73.307	55.010	6.60	SS/TSG	5 Explosions
449	1976–09-29	02:59:57.70	73.360	54.871	5.83	SS/TSG	2 expls. reference for JED
450	1976–10-20	07:59:58.07	73.398	54.812	4.98	SS/TSG	4 Explosions
467	1977–09-01	02:59:57.97	73.339	54.619	5.66	TSG	4 Explosions
471	1977–10-09	10:59:58.12	73.409	54.927	4.36	SS/TSG	Single explosion 0.001–20 kt
491	1978–08-10	07:59:57.93	73.291	54.883	6.00	SS/TSG	6 Explosions
499	1978–09-27	02:04:58.60	73.349	54.676	5.63	SS/TSG	7 Explosions
531	1979–09-24	03:29:59.75	73.343	54.672	5.77	TSG	3 Explosions
536	1979–10-18	07:09:58.75	73.316	54.816	5.79	SS/TSG	4 Explosions
557	1980–10-11	07:09:57.47	73.336	54.940	5.76	SS	7 Explosions
580	1981–10-01	12:14:57.23	73.304	54.818	5.97	TSG	4 Explosions
599	1982–10-11	07:14:58.63	73.339	54.608	5.58	TSG	4 Explosions
616	1983–08-18	16:09:58.90	73.354	54.974	5.91	SS	5 Explosions
624	1983–09-25	13:09:58.22	73.328	54.541	5.77	SS/TSG	4 Explosions
651	1984–10-25	06:29:58.12	73.355	54.990	5.82	SS/TSG	4 Explosions
682	1987–08-02	02:00:00.20	73.326	54.602	5.82	SS/TSG	5 Explosions
697	1988–05-07	22:49:58.34	73.314	54.553	5.58	SS/TSG	3 Explosions
705	1988–12-04	05:19:53.30	73.366	55.001	5.89	SS/TSG	5 Explosions
715	1990–10-24	14:57:58.45	73.331	54.757	5.70	SS/TSG	8 expls. last Soviet test

Notes on Table 6.
Test no. = unique test id number given in Mikhailov et al. (1996) for nuclear tests in USSR; *mb*(*P*), from Marshall et al. [19]; location and origin time from Marshall et al. [19] and Richards [22].
salvo exp. (salvo explosion) means two or more separate explosions where a period of time between successive individual explosions does not exceed 5 s and where the burial points of all explosive devices can be connected by segments of straight lines, each of them connecting two burial points and does not exceed 40 km in length.

Table 7
Deglitched Borovoye data for Peaceful Nuclear Explosions in the Former Soviet Union, 1967–1988.

Test No.	Date Year-Mo-Da	Time (hr:mn:sec)	Lat. (°N)	Long. (°E)	Depth (m)	*m*b (*P*)	Distance (°)	Az (°)	Instrument type
274	1967–10-06	06:59:57.5	57.70	65.20	172	4.7	5.46	330.2	KODB
282	1968–05-21	03:59:11.98	38.918	65.032	2440	5.4	14.59	196.4	KODB
304	1969–09-02	04:59:58.61	57.220	55.393	1212	4.8	9.45	302.1	KODB
305	1969–09-08	04:59:58.70	57.220	55.417	1208	4.8	9.44	302.1	KOD
307	1969–09-26	06:59:58.14	45.848	42.600	712	5.6	19.23	259.2	KOD
313	1969–12-06	07:02:59.85	43.867	54.800	407	5.8	13.73	234.2	KOD
320	1970–06-25	04:59:55.5	52.20	55.70	702	4.9	8.88	270.3	KODB
329	1970–12-12	07:00:59.83	43.85	54.80	497	6.0	13.74	234.2	KOD
331	1970–12-23	07:00:59.76	44.025	54.933	470	6.0	13.55	234.3	KOD
335	1971–03-23	06:59:58.38	61.40	56.20	127	5.5	11.25	323.4	KOD
342	1971–07-02	17:00:01.13	67.283	63.467	542	4.7	14.60	349.5	KODB
344	1971–09-19	11:00:01.08	57.508	42.643	610	4.5	16.23	296.9	KODB
346	1971–10-04	10:00:00.14	61.358	48.092	595	4.6	14.49	313.6	KODB
352	1971–12-22	06:59:59.0	47.897	48.133	986	6.0	14.94	258.7	KOD
358	1972–04-11	06:00:01.92	37.35	62.05	1720	4.9	16.72	203.3	KODB
363	1972–07-09	07:00:01.25	49.80	35.40	2483	4.8	21.77	275.6	KODB
366	1972–08-20	03:00:00.01	49.400	48.142	489	5.7	14.28	264.1	KOD
370	1972–09-04	07:00:00	67.75	33.10	131	4.6	22.92	324.0	KODB
371	1972–09-21	09:00:00.31	52.118	52.068	485	5.0	11.08	272.4	KODB
372	1972–10-03	09:00:00.18	46.853	44.938	485	5.6	17.34	259.3	KODB
375	1972–11-24	09:00:00.04	51.990	51.867	675	4.5	11.22	271.9	KODB
383	1973–08-15	02:00:00.02	42.775	67.408	600	5.3	10.46	191.7	KOD/SS
384	1973–08-28	03:00:00.04	50.527	68.323	395	5.2	2.81	206.4	KOD/SS
386	1973–09-19	03:00:00.18	45.758	67.825	615	5.1	7.47	193.3	KOD/SS
389	1973–09-30	05:00:00.35	51.65	54.55	1145	5.2	9.69	268.0	KODB
390	1973–10-26	05:59:59.5	53.65	55.40	2026	4.8	8.89	279.8	KODB
406	1974–08-29	15:00:00.39	67.085	62.625	583	5.0	14.51	348.1	SS
428	1975–09-29	11:00:00.43	69.578	90.337	834	4.8	18.91	21.7	SS
438	1976–03-29	07:00:00.23	47.897	48.133	986	4.3	14.94	258.7	SS/TSG
446	1976–07-29	05:00:00.5	47.870	48.150	1000	5.9	14.94	258.6	SS/TSG
452	1976–11-05	03:59:59.98	61.458	112.860	1522	5.3	24.00	52.6	SS
462	1977–07-26	17:00:00.22	69.575	90.375	850	5.0	18.92	21.7	SS/TSG
466	1977–08-20	22:00:00.78	64.108	99.558	600	5.0	18.57	42.1	TSG
469	1977–09-10	16:00:00.18	57.251	106.551	550	4.8	20.88	63.9	SS/TSG
470	1977–09-30	06:59:58.43	47.897	48.161	1500	5.0	14.92	258.7	SS
490	1978–08-09	18:00:00.79	63.678	125.522	567	5.6	29.74	47.3	SS
492	1978–08-24	18:00:00.35	65.925	112.338	577	5.1	24.25	41.7	SS/TSG
498	1978–09-21	15:00:00.19	66.598	86.210	886	5.2	15.62	23.9	SS/TSG
500	1978–10-08	00:00:00.0	61.55	112.85	1545	5.2	23.99	52.4	SS
502	1978–10-17	04:59:59.06	47.850	48.120	1040	5.8	14.97	258.6	SS
503	1978–10-17	14:00:00.16	63.185	63.432	593	5.5	10.74	343.2	SS
510	1978–12-18	07:59:58.5	47.860	48.160	630	5.9	14.94	258.6	SS/TSG
513	1979–01-17	07:59:58.5	47.920	48.120	995	6.0	14.93	258.8	SS/TSG
523	1979–07-14	04:59:58.0	47.880	48.120	849	5.6	14.95	258.7	SS/TSG
527	1979–08-12	18:00:00.21	61.803	122.430	982	4.9	28.52	51.4	SS/TSG
529	1979–09-06	18:00:00.31	64.110	99.562	599	4.9	18.57	42.1	SS/TSG
533	1979–10-04	16:00:00.03	60.675	71.455	837	5.4	7.64	4.3	SS/TSG
534	1979–10-07	21:00:00.22	61.85	113.10	1545	5.0	24.12	51.7	SS/TSG
537	1979–10-24	05:59:59.0	47.850	48.140	915	5.8	14.96	258.6	SS/TSG
556	1980–10-08	06:00:00.29	46.757	48.275	1050	5.2	15.43	254.8	SS
560	1980–11-01	13:00:00.42	60.80	97.55	720	5.2	16.60	51.5	TSG
570	1981–05-25	05:00:00.32	68.20	53.50	1511	5.5	17.10	338.6	SS
576	1981–09-02	03:59:59.99	60.60	55.70	2088	4.4	10.94	319.3	TSG
578	1981–09-26	05:00:00.28	46.790	48.313	1050	5.2	15.39	254.8	TSG
579	1981–09-26	05:03:59.94	46.771	48.304	1050	5.3	15.41	254.8	TSG
583	1981–10-22	14:00:00.36	63.80	97.55	581	5.1	17.64	41.9	TSG
592	1982–07-30	21:00:00.00	53.80	104.15	554	5.0	20.00	74.2	TSG
597	1982–09-25	18:00:00.18	64.35	91.80	554	5.2	15.74	35.8	TSG
613	1983–07-10	04:00:00.00	51.363	53.306	907	5.3	10.51	267.5	SS
614	1983–07-10	04:04:59.94	51.367	53.327	917	5.3	10.50	267.5	SS
615	1983–07-10	04:09:59.85	51.380	53.340	841	5.3	10.49	267.6	SS
618	1983–09-24	05:00:00.03	46.783	48.315	1050	5.2	15.39	254.8	SS
619	1983–09-24	05:05:00.03	46.788	48.297	1050	5.1	15.40	254.8	SS
620	1983–09-24	05:10:00.08	46.767	48.310	920	5.0	15.40	254.8	SS
621	1983–09-24	05:15:00.14	46.749	48.303	1100	5.2	15.42	254.7	SS
622	1983–09-24	05:19:59.93	46.754	48.288	950	5.4	15.42	254.8	SS
623	1983–09-24	05:25:00.00	46.766	48.274	1100	5.3	15.43	254.8	SS
639	1984–07-21	02:59:59.81	51.358	53.319	846	5.4	10.51	267.5	SS
640	1984–07-21	03:04:59.71	51.371	53.337	955	5.3	10.49	267.6	SS
641	1984–07-21	03:09:59.85	51.391	53.351	844	5.4	10.48	267.6	SS
643	1984–08-25	19:00:00.33	61.90	72.10	726	5.3	8.89	5.5	SS
649	1984–09-17	21:00:00.03	55.834	87.526	557	5.0	10.37	67.6	TSG
652	1984–10-27	06:00:00.10	46.90	48.15	1000	5.0	15.43	255.4	SS/TSG
653	1984–10-27	06:05:00.00	46.95	48.10	1000	5.0	15.43	255.6	SS/TSG

(*continued on next page*)

Table 7 (*continued*)

Test No.	Date Year-Mo-Da	Time (hr:mn:sec)	Lat. (°N)	Long. (°E)	Depth (m)	*m*b (*P*)	Distance (°)	Az (°)	Instrument type
681	1987–07-24	02:00:00.0	61.45	112.80	1515	5.1	23.97	52.7	SS
684	1987–08-12	01:30:00.5	61.45	112.80	815	5.0	23.97	52.7	SS
686	1987–10-03	15:15:00.03	47.60	56.20	1002	5.3	10.49	244.3	SS/TSG
699	1988–08-22	16:20:00.07	66.280	78.491	829	5.3	13.83	13.9	SS/TSG
700	1988–09-06	16:19:59.94	61.361	48.092	820	4.8	14.49	313.7	SS/TSG

Notes on Table 7:
Test no. = nuclear test number given in Mikhailov et al. (1996).
Date and Time = origin time of the tests given in Sultanov et al. [30].
Latitude and Longitude = location of tests as given in Sultanov et al. [30].
*m*b(*P*) = body-wave magnitude of the tests given in Sultanov et al. [30].
Distance = epicentral distance in degrees from the PNE to Borovoye.
Az = azimuth in degrees from the station to PNE.
Precision of the origin time was indicated in Sultanov et al. by the decimal point. Further discussion of PNE ground truth information is given by Fujita et al. [8].

Table 8
Deglitched Borovoye data for Chinese Underground Nuclear Tests at Lop Nor, 1969–1995.

N	Date Year-Mo-Da	Time (hr:mn:sec)	Latitude (°N)	Longitude (°E)	*m*b (*P*)	Event id	Instrument type	Comments
01	1969–09-22	16:15:01.57	41.373	88.352	5.2	CH01	KODB	C, tunnel
02	1976–10-17	05:00:01.37	41.734	88.383	4.9	CH04	SS	B, tunnel
03	1978–10-14	01:00:00.25	41.511	88.772	4.9	CH05	SS/TSG	A, shaft
04	1983–10-06	10:00:00.52	41.523	88.705	5.5	CH07	SS/TSG	A, shaft
05	1984–10-03	06:00:00.58	41.577	88.706	5.4	CH08	SS	A, shaft
06	1984–12-19	06:00:00.86	41.738	88.365	4.7	CH09	SS/TSG	B, tunnel
07	1987–06-05	05:00:00.73	41.505	88.709	6.2	CH10	SS/TSG	A, shaft
08	1990–08-16	05:00:00.16	41.511	88.742	6.2	CH13	SS/TSG	A, shaft
09	1993–10-05	01:59:58.99	41.593	88.687	5.9	CH16	TSG	A, shaft
10	1994–10-07	03:26:00.37	41.556	88.736	5.9	CH18	TSG	A, shaft
11	1995–05-15	04:06:00.31	41.546	88.772	6.1	CH19	TSG	A, shaft

Notes on Table 7.
Location and origin time from Engdahl [7]; teleseismic body-wave magnitude from the US Geological Survey's Preliminary Determination of Epicenters. Precision locations for Lop Nor nuclear explosions are given by Waldhauser et al. [31].

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 at time marks (see above) characterized by a distinct period. These are typically the glitches having the largest amplitude. There are some waveforms for which the time-mark glitch is the only problem. The type of glitch found to be more difficult and time-consuming to correct, concerned instances that typically involved bit errors. Thus, during interactive passes over problematic waveforms, we found many glitches where the difference between the glitch and the apparent waveform was 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. The labor to do this work was time-consuming and required technical judgments.

The most common defects in the salvaged Borovoye waveform archive resulting from the ISTC project were single point glitches and multiple point glitches of short duration. We did not investigate the sources of the glitches in detail, but simply resolved to repair them via interpolation to allow subsequent analysis of the digital data. We discovered a range of glitch amplitudes in these data, many smaller than waveform amplitudes, which compelled us to design an automated, interactive script to perform the repair work.

The repair procedure developed and applied at Los Alamos National Laboratory relies upon a high passed, differentiated trace to identify glitches, and a fourth-order polynomial fit to find the glitch edge points and perform the repair. Prior to analysis, we marked poor data, such as saturated intervals, that the automated procedure should ignore. We also removed the median and applied ten-point tapers to the beginning and end of the entire waveform. To identify glitches, we differentiated the trace, then applied a two-pole, causal, high pass Butterworth filter with a corner set to two-thirds the Nyquist frequency, removed the median, and took absolute values. This procedure brought out small glitches that would otherwise be buried in the waveform. The user sets a threshold and a time window, and the procedure cycles through that subset of glitches. Additional passes with lower thresholds or different time windows may be run until the user decides that repair is complete.

For each glitch that is identified using the high-pass, differentiated trace, we set an initial analysis window of length ten times the sample interval. A fourth-order polynomial is fit to the waveform data in this window, using L1 minimization to avoid effects of the glitch. Glitches are defined using a three-sigma threshold based on a robust residual spread estimate (median absolute deviation, MAD; e.g., [27]), and are replaced using the polynomial coefficients. The L1 fit procedure matches five waveform points exactly, and those points may or may not include the nearest edge points on either side of the glitch. As a fine adjustment, we add a linear function to the polynomial to ensure that those edge points are matched exactly. The original glitch and repaired waveform are then displayed, whereupon the user may:

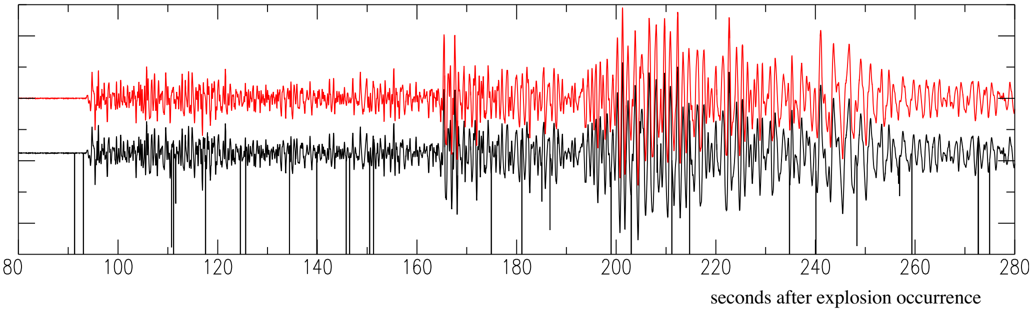

Fig. 9. An example of a glitched recording (shown in black) and the result of deglitching (shown in red). This Borovoye record is for an underground nuclear test conducted at the Semipalatinsk Test Site on 1984 December 02. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

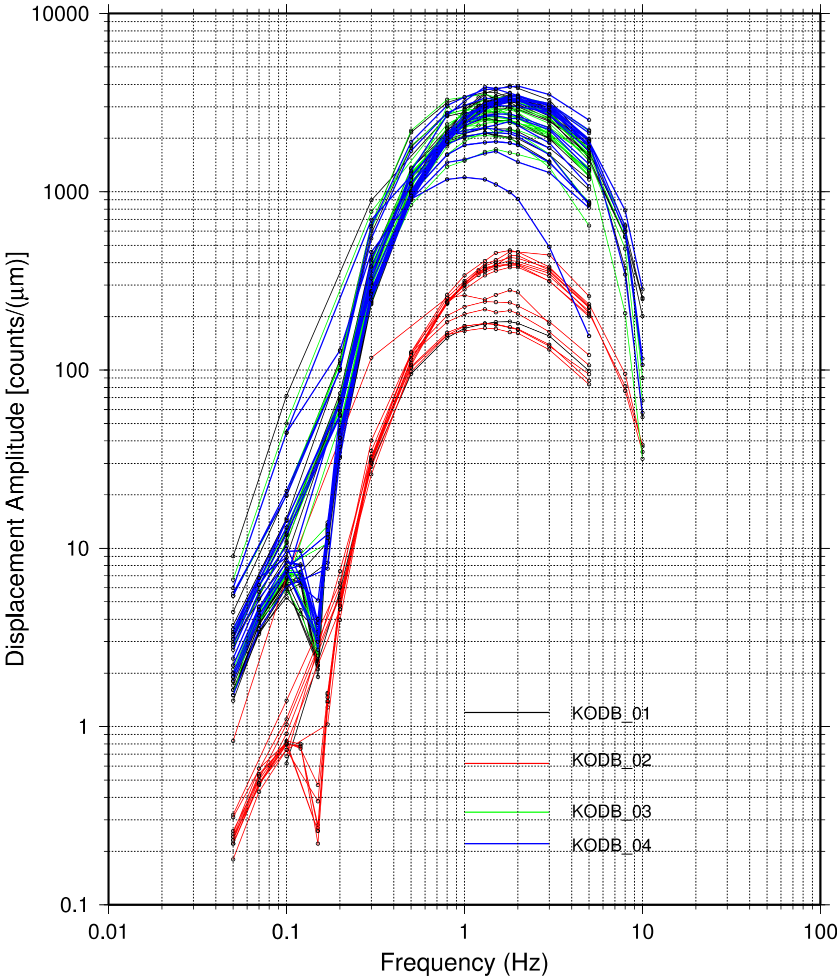

Fig. 10. 78 frequency-amplitude response curves of the KODB system, 1967–1973. To be correct, all responses need to have a minimum at a frequency of 0.15 Hz (intended to suppress microseisms). Linear interpolation between frequencies of 0.1 and 0.2 Hz is not appropriate.

(1) accept the repair; (2) pick one or more of the glitch edge points and window endpoints, and refit the waveform; (3) expand the window, pick as above, and refit the waveform; or (4) skip the repair of that segment.

Fig. 9 shows two versions of a recording, lasting about 200 s, of a Borovoye digital seismogram of an underground nuclear test. The deglitched version is shown in red, in comparison with the glitched record shown in black. The quality of the deglitched data is high enough to enable detailed spectral analysis, and evaluation of methods of discrimination between earthquakes and explosions [24].

The next two sub-sections describe the two earliest seismographic systems used at Borovoye.

5.2. The KOD digital seismograph system

The KOD system was intended for multichannel digital recordings of ground motion via magnetic tape for three components

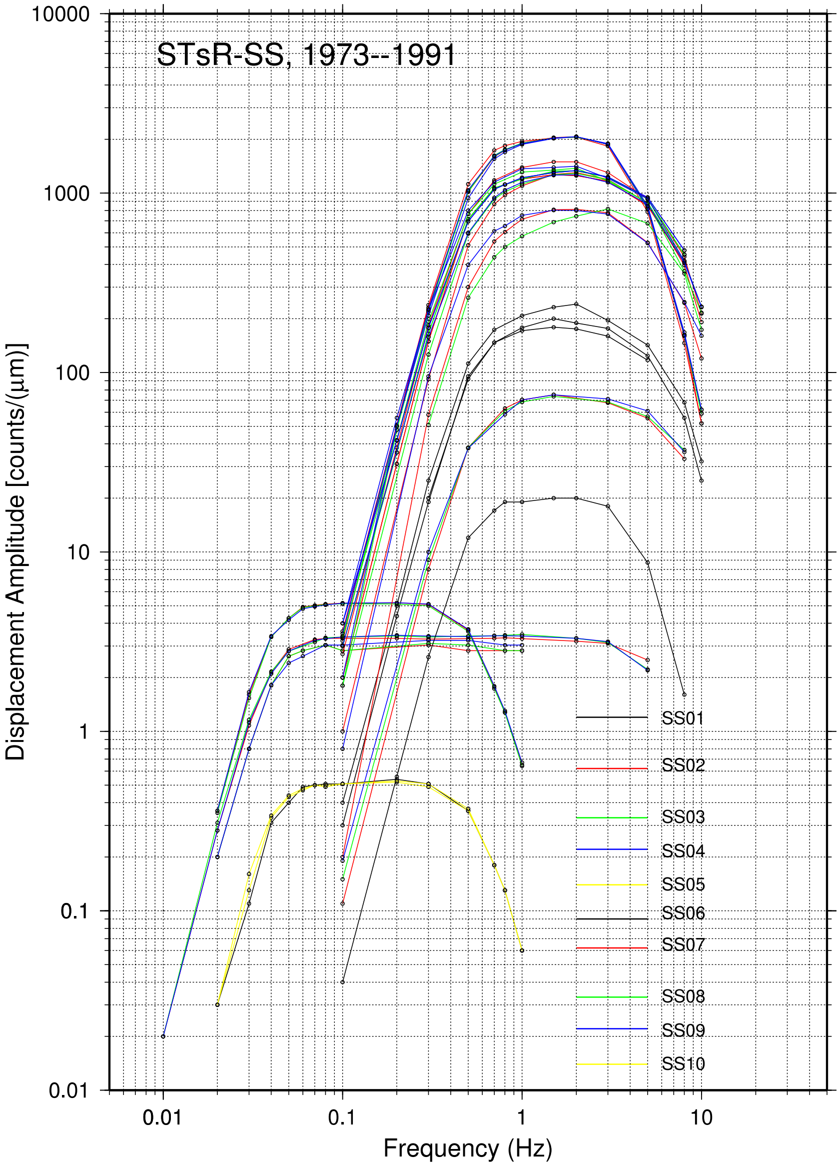

Fig. 11. Frequency-amplitude calibration curves of 10-channel STsR-SS system are plotted.

(Z, N–S, E–W) in the frequency band 0.03–5 Hz. This band of recording was provided by two separate seismometers: the relatively long-period SKD seismometer; and the short-period SKM-3 seismometer, combined as described by Osadchiy and Daragan [23].

However at Borovoye the KOD system was used somewhat differently. It was modified to be based upon the SKM-3 seismometer, using a pre-amplifier with low self-noise, a post-amplifier, and A/D converter, and a switch with ten channels. Five even channels (called KODB, with higher gain) were written to magnetic tape using one tape recorder (LMR), and five uneven channels (called KODM, with lower gain) were written to magnetic tape by using another tape recorder. The full dynamic range on the two levels was about 80 dB, providing for registration of ground displacement from 3 nm to 12,000 nm in the band from 0.4 Hz to 5 Hz. Fig. 10 shows several amplitude responses of the KODB system.

Time corrections to the internal clock of the KOD system were noted each 12 h with an accuracy of about 0.01 s, and time corrections were noted in a log book. For example, the time correction to the arrival time of the *Pn*-wave from the PNE of September 8, 1969, is −0.55 s.

5.3. The STsR-SS digital seismograph system

Commonly abbreviated as the SS system, this consists of a 3-component, short-period seismometer, namely SKM-3 (Kirnos high-gain) and a 3-component, extended-period seismometer called SKD (Kirnos-Arkhangel'skiy broadband) [28,29].

The STsR-SS system recorded a total of 10 channels on 17-track tape with 11-bit analog-to-digital conversion. Usually, the data streams consisted of signals from 3-component short-period, 3-component extended-period, and a low-gain short-period vertical component.

Shishkevish [28] called the SKD seismometer with the natural period, $T_0 = 25$ s, an *extended-period* seismometer, a term that we also adopted. The SKM-3 seismometer is the later model of SKM and has an adjustable natural period, T_0, between 1.5 to 3.5 s [28]. Hence, it is also called a short-to-intermediate-period

Table 9
Characteristics of the three seismograph systems used to provide digitized ground motions at Borovoye (BRV).

System	Seismometer	T_0 (s)	D_s	Chan name	Gain (C/μm)	freqn (Hz)	Δt (ms)	Chan no.	Time period
KODB (high-gain)	SKM-3	3.5	0.7	SHZ	3386	1.8	30	1	67-02-26
				SHN	2940	1.8	30	3	–73-10-26
				SHE	3354	1.8	30	4	
				SLZb	423	1.8	30	2	
KODM (low-gain)				SLZ	421	1.8	30	1	67-06-29
				SLN	321	1.8	30	3	–73-10-26
				SLE	371	1.8	30	4	
				SHZm	3386	1.8	30	2	
SS	SKM-3	2	0.5	s07Z	1249	2	32	7	73-06-06
				s08N	1330	2	32	8	–82-07-04
				s09E	1336	2	32	9	
								1	
	LG(Z)			s07Z	2059	2	24	7	82-08-21
				s08N	2054	2	24	8	–91-07-15
				s09E	2057	2	24	9	
				s06Z	20	2	96	6	
									81-08-14–
	SKD	25	0.5	l02Z	3.31	0.1	192	2	73-06-06
				l03N	3.36	0.1	192	3	–82-07-04
				l04E	3.36	0.1	192	4	
				l02Z	5.19	0.1	192	2	82-08-23
				l03N	5.14	0.1	192	3	–91-07-15
				l04E	5.17	0.1	192	4	
	LG			l01Z	0.51	0.1	192	1	82-08-23
				l05N	0.51	0.1	192	5	–91-07-15
				l10E	0.51	0.1	192	10	
TSG	KSVM	1.5	0.5	sZ01	50	1	26	1	80-07-20–96-01-27
				sZ02	4600	1	26	2	83-12-16–96-01-27
	KSM	1.5	0.5	sZ03	1000	1	26	3	85-03-23
				sN04	1000	1	26	4	–96-01-27
				sE05	1000	1	26	5	
	KS	1.5	0.71	sZ06	1000	1.5	26	6	85-03-23–96-01-27
				sZ07	2000	1.5	26	7	74-12-16
				sN08	2000	1.5	26	8	–82-01-30
				sE09	2000	1.5	26	9	
				sZ07	4500	1.5	26	7	82-03-24
				sN08	4500	1.5	26	8	–91-01-27
				sE09	4500	1.5	26	9	
	KSM	1.5	0.5	sZ10	100,000	1	26	10	85-01-22
				sN11	100,000	1	26	11	–88-10-31
				sE12	100,000	1	26	12	
	DS	20	0.71	lZ19	50	0.1	312	19	74-07-12
				lN20	50	0.1	312	20	–88-06-28
				lE21	50	0.1	312	21	
	DSM	28	0.71	lZ22	1000	0.07	312	22	75-11-19
				lN23	1000	0.07	312	23	–88-12-02
				lE24	1000	0.07	312	24	
				lZ15	10	0.07	312	15	85-01-26
				lN16	10	0.07	312	16	–88-12-02
				lN17	10	0.07	312	17	
	DS	20	0.71	lZ13	50	0.1	312	13	83-11-03–84-01-18
				lN14	50	0.1	312	14	83-11-03–85-02-13

Notes on Table 9.
KOD (KODB and KODM) systems were operated from 1966–Nov 1973 and had polarity reversal on all channels; STsR-SS (SS) and STsR-TSG (TSG) systems were operated from Feb. 1973 to 1995.
T_0 = seismometer natural period in seconds.
D_s = seismometer damping constant, critical damping = 0.71.
Gain = sensitivity in counts/μm for ground displacement.
freqn = normalization frequency, where the gain is measured.
Δt = sampling interval in milliseconds.
LG = low-gain channels and (Z) indicates that it is only vertical-component.

high-gain seismometer. We called it a high-gain *short-period* seismometer in our data rescue project.

From 1973 June 06 to 1981 June 30, 3-component short-period signals from the SKM-3 seismometer were recorded on channels 7, 8 and 9 for vertical-, NS-, and EW-components, respectively.

These three-component data are assigned component names s07Z, s08 N and s09E; low-gain vertical-component SKM-3 data were recorded on channel 1 (s01Z); 3-component extended-period signals from the SKD seismometer are recorded on channels 2, 3, and 4 (102Z, 103 N and 104E); and channels 5, 6 and 10 were unused.

From 1981 August 14 to 1982 July 04, 3-component short-period signals from the SKM-3 seismometer were recorded on channels 7, 8 and 9 for vertical-, NS-, and EW-components, respectively. The sampling interval for these channels was changed from 0.032 s to 0.024 s. The low-gain vertical-component SKM-3 data were recorded on channel 6 (s06Z) with a sampling interval of 0.096 s.

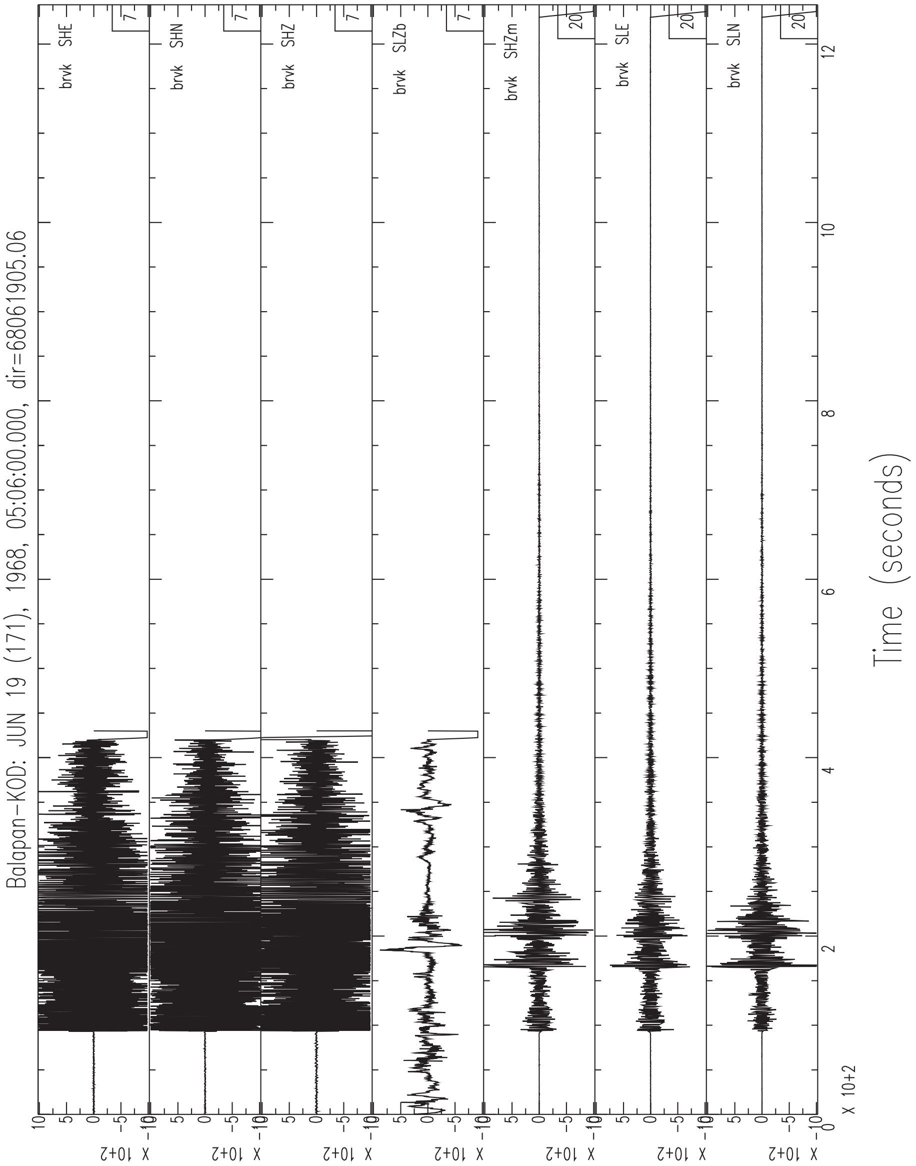

Fig. 12. First of seven sets of BRV seismograms on the KOD system for a UNE at the Balapan area of the Semipalatinsk Test Site, Kazakhstan; test of 1968 June 19.

3-component extended-period signals from the SKD seismometer were recorded on channels 2, 3, and 4 (l02Z, l03 N and l04E); and channels 1, 5 and 10 were unused. Although the sampling intervals have changed for short-period channels (6, 7, 8, and 9), the shapes of the amplitude responses for these channels followed the previous period.

From 1982 August 23 to 1991 July 15, 3-component short-period signals from the SKM-3 seismometer were recorded on channels 7, 8 and 9 (component name: s07Z, s08 N and s09E); low-gain vertical-component signals from the SKM-3 seismometer were recorded on channel 6 (s06Z); 3-component extended-period signals from SKD seismometer were recorded on channels 2, 3, and 4 (102Z, l03 N and 104E); and low-gain 3-component extended-period SKD data were recorded on channels 1, 5 and 10 (101Z, 105 N and 110E); hence all of the 10 channels of the STsR-SS system were utilized during this period, but we note that the shapes of the amplitude responses for all channels were changed from those of the previous periods.

Fig. 11 shows 40 available frequency-amplitude calibration curves for the STsR-SS system, for the period 1973 to 1991 given in the Borovoye waveform data archive.

5.4. Summary of instrument responses at BRV

In Table 9, we summarize responses for all three systems at Borovoye: KOD, SS, and TSG. Extensive additional details on all three systems, and how they changed with time, are to be found in a technical report by Kim et al. [14], available on-line as http://www.ldeo.columbia.edu/res/pi/Monitoring/Doc/AFRL-RV-HA-TR-2010-1024_07C0004_Final.pdf.

6. Examples of regional signals

More than 3700 deglitched and calibrated seismograms from nuclear explosions in Eurasia, many of them recorded at regional distances, are for many users the main result of this project. Prior

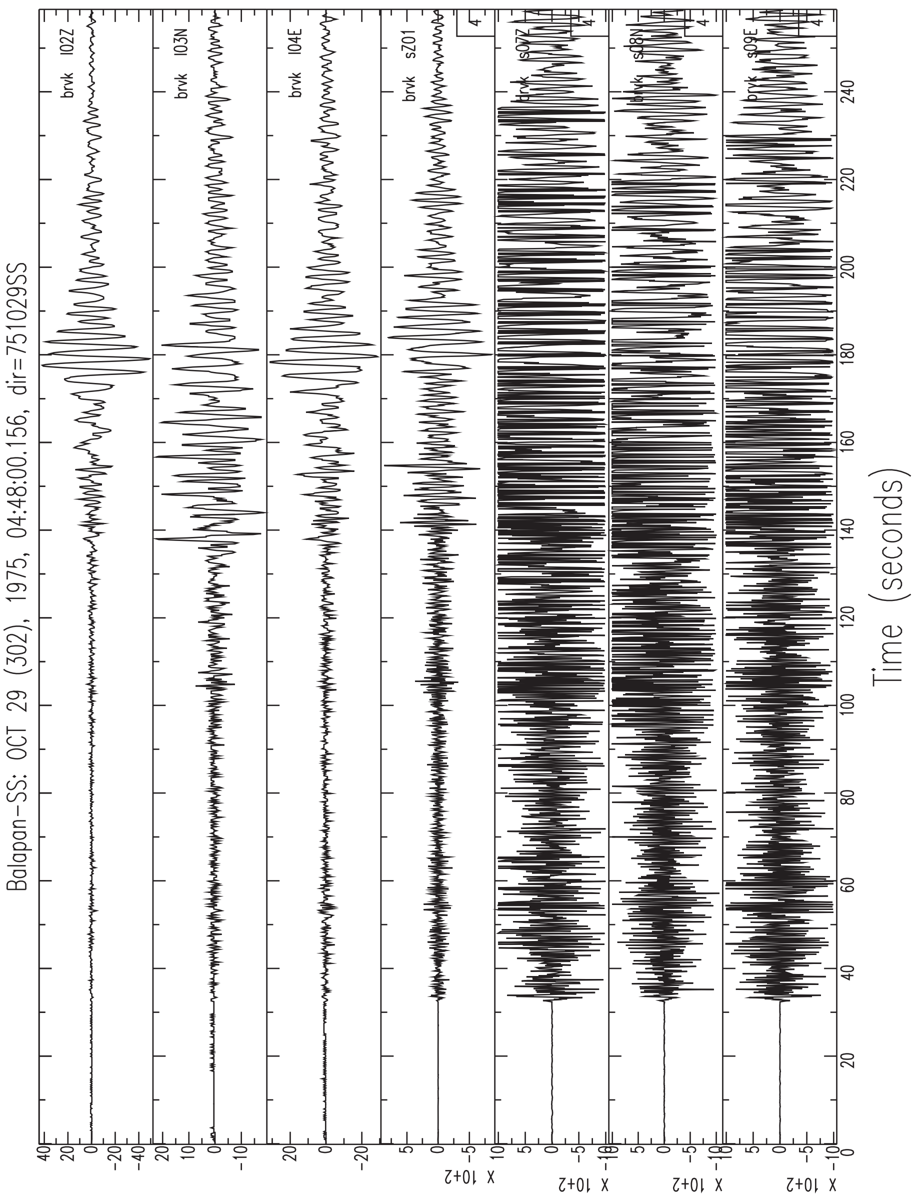

Fig. 13. First of 78 sets of BRV seismograms on the SS system for a UNE at the Balapan area of the Semipalatinsk Test Site, Kazakhstan; test of 1975 October 29.

to the deglitching effort, personnel at Los Alamos National Laboratory had become familiar with some of these data, in particular with waveforms recorded on the TSG system. With our second data release we have approximately trebled the number of waveforms analyzed, by successfully processing the data recorded by earlier systems. Here we give examples of the waveforms from all three systems.

From Table 2 we see that these thousands of waveforms can be organized into 497 sets, each set corresponding to one particular underground nuclear explosion (UNE), as recorded on one of the three different systems at Borovoye. These waveforms, now deglitched and documented with instrument responses, are the main result of this project, together with preliminary analyses of these data as presented in the US at Monitoring Research Reviews in 2007, 2008, and 2009 [12,13,5]. Details of the sampling rate and instrument response of the three systems emerged throughout the years in which we did our work. Difficulties of the KOD system included Soviet publications describing the impulse response that did not match our own information from stations operators in Kazakhstan. Difficulties of the SS system included changes in sampling rate and an appreciation that the data are aliased to some degree—details that were not thoroughly understood until late in the project.

We have prepared all 497 of these waveform sets as a series of PDF documents to enable potential users to get a sense of which seismograms are likely to be useful for reading arrival times (a high-gain channel may be best), or for computing spectra (a low-gain channel may be best for this purpose), or for coda studies (both low-gain and high-gain channels are relevant). These files are available to interested users online via http://www.ldeo.columbia.edu/res/pi/Monitoring/Arch/BRV_arch_deglitched.html but there are far too many to include in this paper. Instead, to present our results in an orderly way in this section, we give 5 sets of examples, in Fig. 12 through Fig. 16, each set representing the seismograms from one particular underground nuclear test as recorded on a particular digital seismographic system—either KOD, or SS, or TSG.

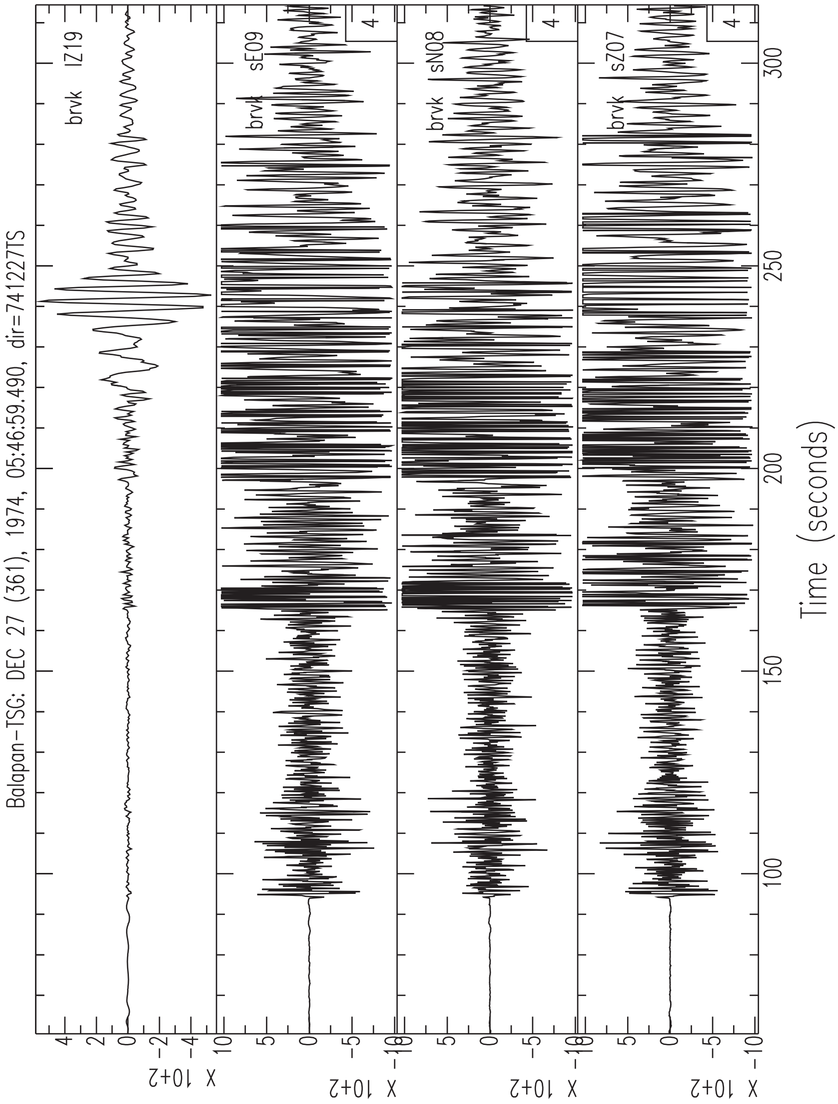

Fig. 14. First of 73 sets of BRV seismograms on the TSG system for a UNE at the Balapan area of the Semipalatinsk Test Site, Kazakhstan; test of 1974 December 27.

6.1. Specific seismograms

Our choice, in culling the 497 sets down to 5 has been, first, to show for the Balapan region of the Semipalatinsk Test Site in Kazakhstan, the first UNE as recorded on the KOD system (Fig. 12), on the SS system (Fig. 13), and on the TSG system (Fig. 14). And then we show the last PNE recorded on the SS system (Fig. 15), and finally the last UNE at the Lop Nor Test site as recorded on the TSG system (Fig. 16).

Thus, Fig. 12 shows the first of seven sets of BRV seismograms on the KOD system for a UNE at Balapan (the test of 1968 June 19 recorded at less than a thousand km). It shows high-gain and low-gain channels, and immediately it is apparent which channels are appropriate for picking arrival times (high-gain), measuring spectral levels (low-gain) and quantifying coda (both high-gain and low-gain). This is a short-period set of records, which may be compared and contrasted with the seismograms (also from Balapan explosions) shown in Fig. 13 (SS) and Fig. 14 (TSG), which contain extended band-width information, and which, for example contain *Rg* signals (a Rayleigh wave, excited only by very shallow seismic sources). The longer-period records have *Rg* as the strongest phase at this regional distance.

There is a total of 343 sets of records for UNEs in all sub-regions of the Semipalatinsk Test Site, and these regional signals with their *Pg*, *Pn*, *Sn*, *Lg*, and *Rg* phases are now available for study of different source effects as documented by a digital station, Borovoye, that long operated at the same distance from the test site. In contrast with these regional signals, the teleseismic recordings from Novaya Zemlya UNEs show impulsive teleseismic *P*-wave arrivals.

Fig. 15 shows some of the SS system seismograms for an unusual PNE conducted in the Soviet Union on 1984 July 21, consisting of three separate nuclear shots five minutes apart. *P*-arrivals are very impulsive, with weak *S*-waves arriving later. And finally Fig. 16 shows some of the TSG system seismograms for a UNE at the Lop Nor Test Site, in China, for the explosion of 1995 May 15. The regional waves are still quite strong, though teleseismic waves are arriving also. The *Rg* phase again is an indication of a very shallow seismic source.

7. Concluding summary and comments

More than 2000 nuclear test explosions were conducted during the Cold War (about three-quarters of them, underground). They

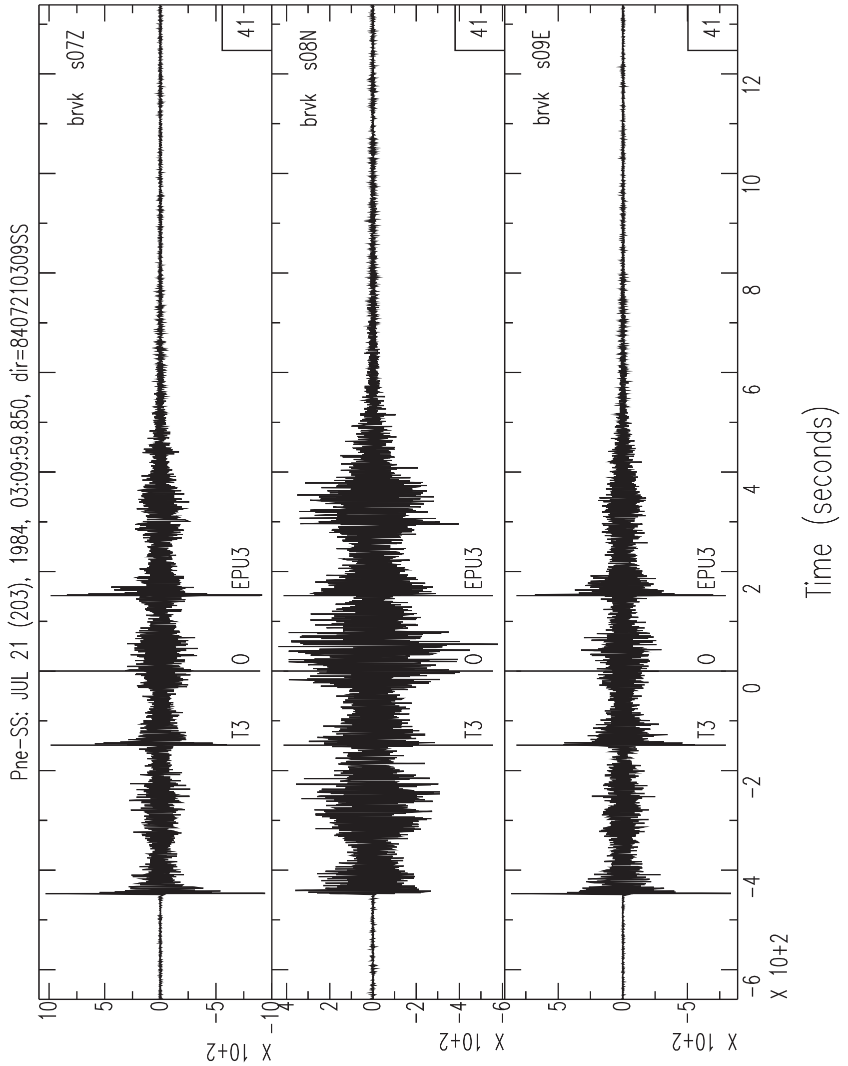

Fig. 15. Last of 38 sets of BRV seismograms on the SS system for a PNE in the Soviet Union; tests of 1984 July 21, being three separate shots five minutes apart, centered at (51.37°N, 53.34°E), depth 900, 15 kt, mb 5.

took place about once a week from the 1940s to the 1980s, initially in the atmosphere and then mostly underground after the mid-1960s. They represent an extreme activity in human history. Most of them took place in an era when there were very few seismographic stations operating with the high standards routinely achieved via broadband high-dynamic-range instrumentation available today.

This project took advantage of Soviet-era digital seismic recordings, all of them made at the Borovoye Geophysical Observatory in Kazakhstan, of ground motion from numerous underground nuclear explosions that occurred globally over a period of three decades, from 1966 to 1996. We have prepared these recordings in a modern format, to make them usable by the seismic monitoring community for numerous ongoing and future studies of Earth structure, attenuation characteristics, and explosion source physics including source representation by body force equivalents and associated source spectra. We have paid special attention to the recordings of underground nuclear explosions conducted in Eurasia, because many of them took place at regional distances (typically, less than a thousand km) from Borovoye, so that they contain the types of seismic signal most useful for detecting and characterizing small nuclear explosions.

To produce the newly-formatted signals required major efforts at Los Alamos National Laboratory to remove glitches in the original records, and at the Lamont-Doherty Earth Observatory to obtain instrument responses. Three different recording systems operated at Borovoye: the KOD system from 1967 to 1973; the SS system from 1973 to 1990; and the TSG system from 1974 to 1995. Each system included channels of low-gain and high-gain recording; and each system included vertical, north/south, and east/west channels. In the final years of this data rescue, particular attention was paid to data from the KOD and SS systems, which had not previously been deglitched and instrument-corrected. We have prepared waveforms from nuclear explosions at the following five test sites: Balapan (1269 traces), Degelen (1146 traces), and Murzhik (160 traces), all in Kazakhstan on the Semipalatinsk Test site; Novaya Zemlya (461 traces) in Russia; and Lop Nor (120 traces) in China; and also from many Peaceful Nuclear Explosions (552 traces) in Russia. Although the dynamic range of specific channels is limited by the low number of bits in the recording system, the scientific content of the signals across the many different channels approaches that for modern recording systems. The improved Borovoye archive now provides many practical examples of the types of explosion signals that modern monitoring

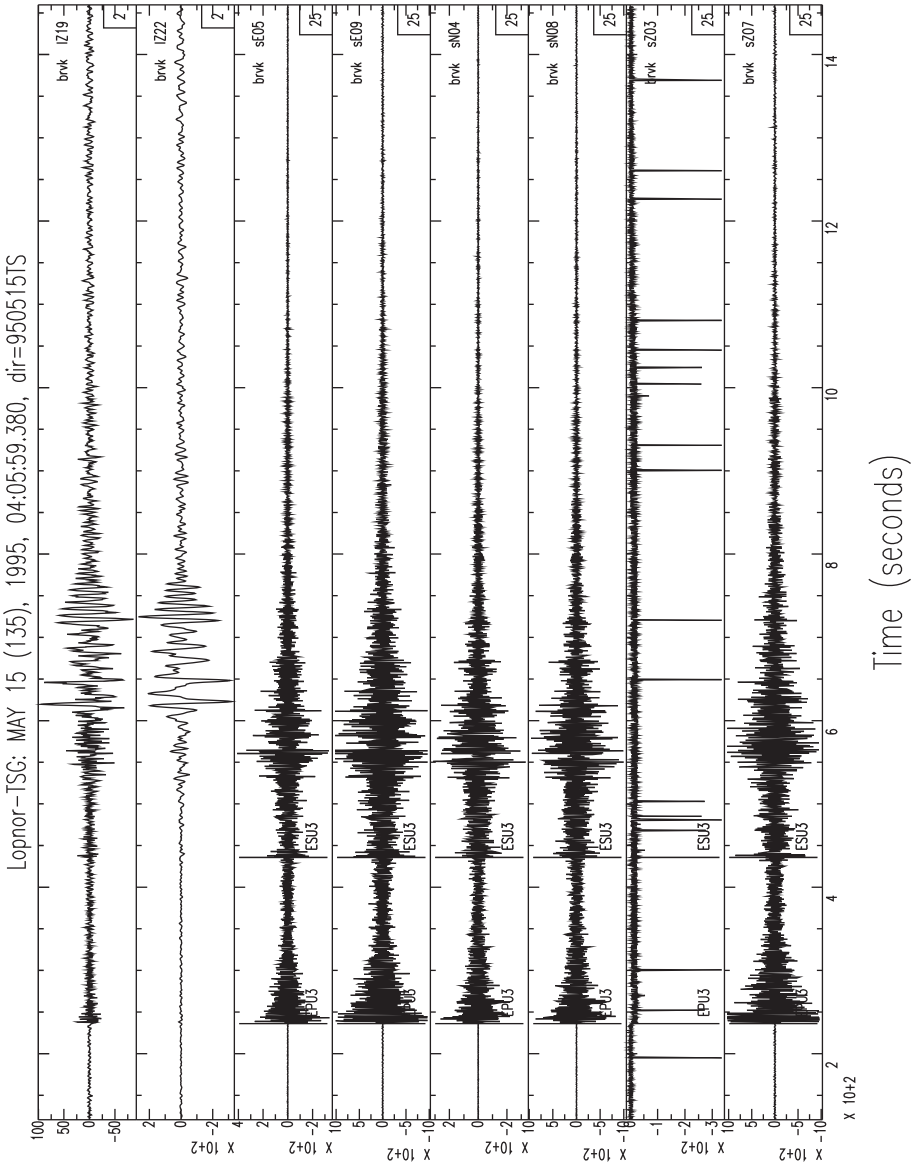

Fig. 16. Last of eight sets of BRV seismograms on the TSG system for a UNE at the Lop Nor Test Site, China; test of 1995 May 15.

networks (which do not have large archives of explosion signals) must be designed to detect and identify.

From a long-term perspective (centuries and longer), it is important to archive high-quality signals from past explosions, to make them usable for diverse research at present and in the future, because they are unique and are so much better than earthquake signals for certain types of study of the interior of planet Earth (see, e.g., [3]). In future we can expect that theory and computation will improve our capability to extract information from seismic signals. High-quality recordings will thus continue to provide a basis for increasing our knowledge of Earth structure, as geophysicists in the future develop better methods of analysis applied to the best signals recorded in the past. This is a project that must be maintained long-term, augmented to archive high quality signals from all energetic explosions especially from those at yield levels that will not be achieved again unless nuclear explosions resume on a large scale.

The example provided in this paper, of a successful data rescue applied to a Soviet archive of explosions recorded at regional distances, needs to be repeated for nuclear explosions conducted in the early decades of active weapons testing by the United States and the United Kingdom, by France, and by China.

Acknowledgments

Hundreds of people contributed to the work reported in this paper. For example, for decades the Borovoye station operated with staff from local villages, organized in three shifts of eight hours each day. When Richards and Ekström visited in 1991, they witnessed the expertise of these villagers, who would almost immediately recognize the global location of numerous earthquakes each day, just from cursory examination of their waveforms. A dedicated professional staff maintained the station for decades, keeping accurate time, and deciding which data segments to archive.

We thank the IRIS Consortium, the International Science and Technology Centre, the Defense Advanced Research Projects Agency, and the US Air Force Research Laboratory, for funding at different times over the duration of this data rescue project.

We appreciate the diligence of Anton Dainty (1942–2014) for his care and supervision of this work from about 2000 to 2010, and Alexei P. Vassiliev (1934–2014) for his enthusiasm and willingness to explain to us the history of the Borovoye Observatory. Vitaly Khalturin (1927–2007) guided our work from the 1990s onward.

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