The Borovoye Geophysical Observatory, Kazakhstan

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This is a story of surprises — of a geophysical observatory and a community of scientists that until about a year ago were unknown to scientists in the West, who now have new opportunities for collaboration with expert seismologists in Russia and Kazakhstan.

The story began for us in the Spring of 1990, at the annual workshop of the Incorporated Research Institutions for Seismology (IRIS). Seismologists from the U.S.S.R. attended, and told us that permission had been given to describe a geophysical observatory at Borovoye, near Kokchetav in Northern Kazakhstan, which had operated digital seismometers since 1966. They said there was a large tape archive. Much of the data was of excellent quality and would probably be made available on request, even the data for nuclear explosions.

From a western view of modern seismology, this was a surprise for several reasons. Until recently, seismic data from the former U.S.S.R. have been hard if not impossible to acquire (Given, 1991), and have been analog rather than digital (and thus not amenable to many modern methods of quantitative analysis). For decades, since underground nuclear weapons testing began in the late 1950s and it was recognized that such activity could best be monitored seismicly, the U.S.S.R. did not participate in most global seismology programs. In the nuclear age up to the late 1980s, it was a crime in the U.S.S.R. to allow seismograms of Soviet nuclear explosions to leave the country.

However, perhaps the news of a vigorous data-based program in seismology should not have been a surprise. The Soviet Union had a long and strong tradition of seismometer development, and presumably a need to monitor underground nuclear explosions by the best available methods. We subsequently learned that Borovoye had been established as an Observatory in 1965, partly to monitor U.S. underground nuclear explosions at the Nevada Test Site, at a distance of about 10,000 km. The station had been operated from Moscow by the Academy of Sciences through the Institute for Geosphere Dynamics, headed by Prof. Vitaly Adushkin, an expert on the physics of all types of explosions.

In late 1990 we made a request for digital data from Borovoye, and received a nine-track tape in March 1991 with 43 examples of three-component signals. Two of us visited Borovoye in the summer of 1991, and here we describe the main characteristics of digital seismic systems operated at the station and give some examples of the data from nuclear explosions and earthquakes in Kazakhstan. We also comment on possibilities for future work, both with the data archive, and with the experts on earthquakes and explosion monitoring whom we met in Russia and Kazakhstan.

Station Characteristics

The Borovoye seismic station BRV, with coordinates 53°03' 29" North, 70°16' 58" East (see Figure 1), is located on a pluton about 200 km across with an ill-defined but deep Moho and monolithic granites. Seismic recordings were first made in the area in 1951 by I.P. Pasechnik. While deploying portable seismic equipment in the 1950s and 1960s for analog recording of nuclear explosions at the U.S.S.R.'s test site in eastern Kazakhstan (about 700 km away), it was found fortuitously that U.S. nuclear testing in Nevada had

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also been recorded, with signals two or three times greater at BRV than would be expected on the basis of globally averaged magnitudes for Nevada explosions. The status of "Observatory", with continuous analog recording, was accorded in 1965. The early deployment of seismic instruments was in a tunnel driven horizontally into granites rising to the south of a lake about four km across (Lake Borovoye), but now all seismometers are in a 15 m deep vault with three chambers.

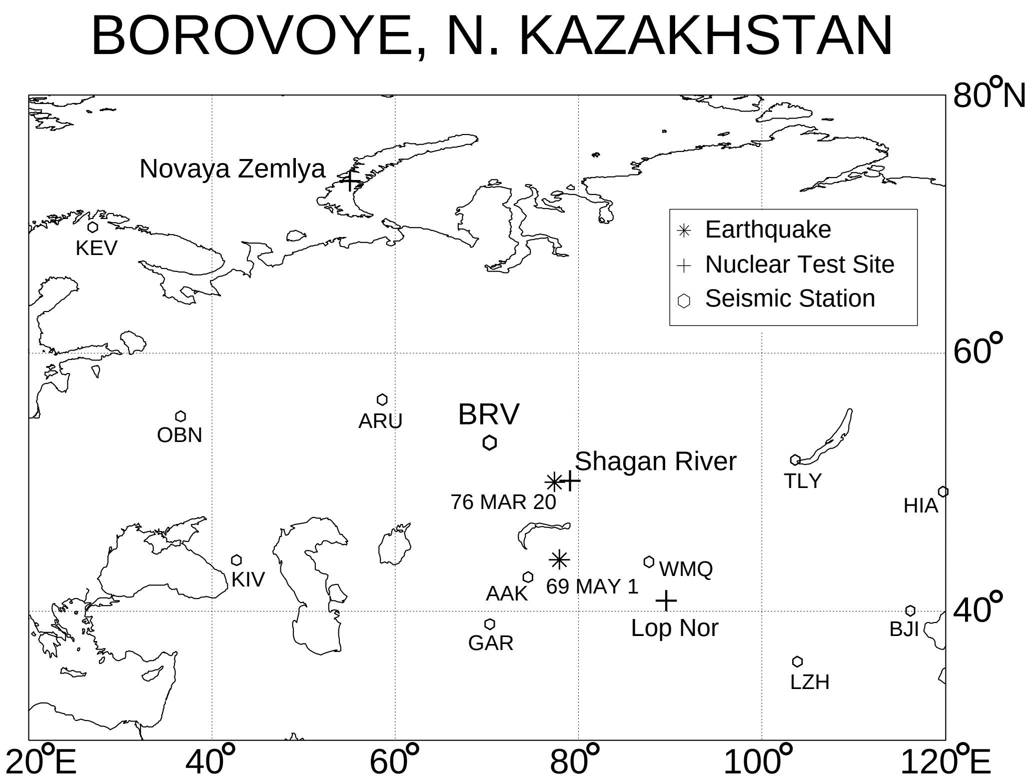


Fig. 1. Location map showing the Borovoye Geophysical Observatory (BRV), operated since 1965, epicenters of two Kazakhstan earthquakes, sites of nuclear testing, and digital seismic stations of the IRIS/USGS and Chinese networks installed in recent years. An IRIS global network station is now planned for BRV, plus installation of a small aperture array by U.S. seismologists.

The first BRV digital seismic system, known as KOD, began recording in 1966 with continuous operation from 1967 to 1973. It is based on three component short-period seismometers, and is important as one of the few digital systems in the late 1960s – early 1970s. The second BRV digital system, known as STR, has operated from February, 1973 to the present. It consists of two separate parts: STR-SS (intended mainly for low-gain recording); and STR-TSG, which includes six long-period and seven short-period Kirnos seismometers, most recorded at two gain levels for a total of twenty data channels. The highest sensitivity is 100,000 counts/micron (based on a short-period Kirnos with a special magnet, and a low-noise amplifier). We were told that BRV has a detection capability with this instrument down to magnitude 4.2 for all parts of the world. At some distances (e.g. in the core shadow) the detection is based on a phase other than *P*. The third BRV digital system, known as ASST, installed in April 1990, uses broadband force-balance seismometers and is still under test.

All of these main systems are approximately flat to ground displacement over a range of frequencies. With the different instruments and gain levels, about 50 digital channels are available, with a dynamic range around 135 dB for the station as a whole. Figure 2 shows several examples of instrument responses, for channels from which we now have data examples.

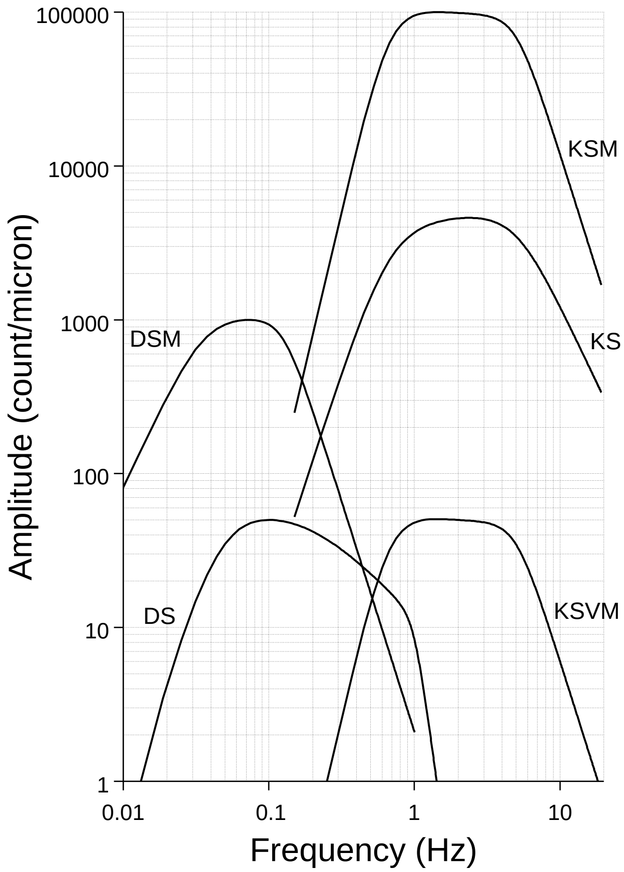


Fig. 2. Instrument responses for the STR-TSG digital system at BRV. Each curve is marked to show the type of Kimos seismometer use.

Station Operation

BRV combines the work of research seismologists with the very different responsibility of rigorous reporting every day on all observed earthquakes and explosions. Soon after the station became openly known in about 1989, it became by far the most active node (in terms of data reporting) of the U.S.S.R. Unified Seismic Observing Network (headquarters in Obninsk, about 100 km southwest of Moscow).

There are three types of routine reporting of seismic signals at BRV: urgent, daily, and weekly. Thus, a computer estimate of hypocentral coordinates (seismic source location) is available two minutes after a *P*-wave arrival with good signal-to-noise ratio, and urgent reporting to Obninsk is done within one hour for large events. A daily message is sent to Obninsk listing arrival times, amplitudes, and dominant periods of seismic signals.

BRV detects about 1000 seismic events per month, of which about 100 are routinely processed (including a magnitude, and an estimate of source location) using only the data from BRV itself. This information is summarized in a weekly bulletin, published at Borovoye only a few days in arrears. Thus, on July 30, 1991, we were given a copy of the bulletin for July 18-24 describing several hundred detections, and location estimates and magnitudes for 17 events. Subsequently, we found that eleven of these events were included in the "Quick Determination of Epicenters" (QED) bulletin put out by the U.S. Geological Survey.

The staff at BRV includes about 80 people (25 of them scientists and senior technicians based in Moscow). More and more of the routine analysis is being transferred to computers, using algorithms described by Kedrov and Ovtchinnikov (1990). Their paper describes the automatic signal processing at "an experimental station in Eastern Kazakhstan … near Kokchetav" — it is obviously Borovoye, though this is not stated. Adushkin and An (1990) is another recently-available source of information in English on Borovoye.

A limiting factor in station operation since the 1960s has been the cost and quality of magnetic recording tape. There is therefore no continuous archive, but rather an archive built from about 100 files of signals per day. For most of the more than 25 years of station operation, the archive has been written on a wide (35 mm) tape. Up to 24 channels of digital data are written with many different sample rates and time stamps, using a special 17-track format. We understand the archive consists principally of about 7000 17-track wide tapes, each tape containing about 10 megabytes of data. Most of the signals are from earthquakes, but also in the archive are seismic data for virtually all nuclear explosions carried out since the mid-1960s by the Soviet Union, the United States, France, China, and the United Kingdom, on average about one nuclear explosion per week for thirty years.

The standard way to work from the archive is to mount a wide tape on a unique Russian-made reader, and to select from the 24 available channels just three which are then written to standard 9-track tape in what is known as ADM format. We have read BRV data on three Kazakhstan earthquakes, plus explosion data for twelve events at Shagan River, two at Degelen Mountain, five at Novaya Zemlya, and six at the Lop Nor test site of the Peoples Republic of China. All the useful data we have so far received are in ADM format, and we have made it available in a modern format (AH) both through the DARPA-funded Center for Seismic Studies (in Arlington, Virginia), and the NSF-funded IRIS Data Management Center (at the University of Washington, Seattle). Note that in the last two years, the Center for Seismic Studies has also received several hundred seismograms from Soviet analog stations, for nuclear explosions at Soviet test sites.

In addition to its main work with digital seismic data, Borovoye Geophysical Observatory has long been the site of measurements of the Earth's gravity and geomagnetic fields (absolute and relative), and there is an active research group probing the ionosphere with long wavelength electromagnetic signals.

Examples of Borovoye Seismic Data

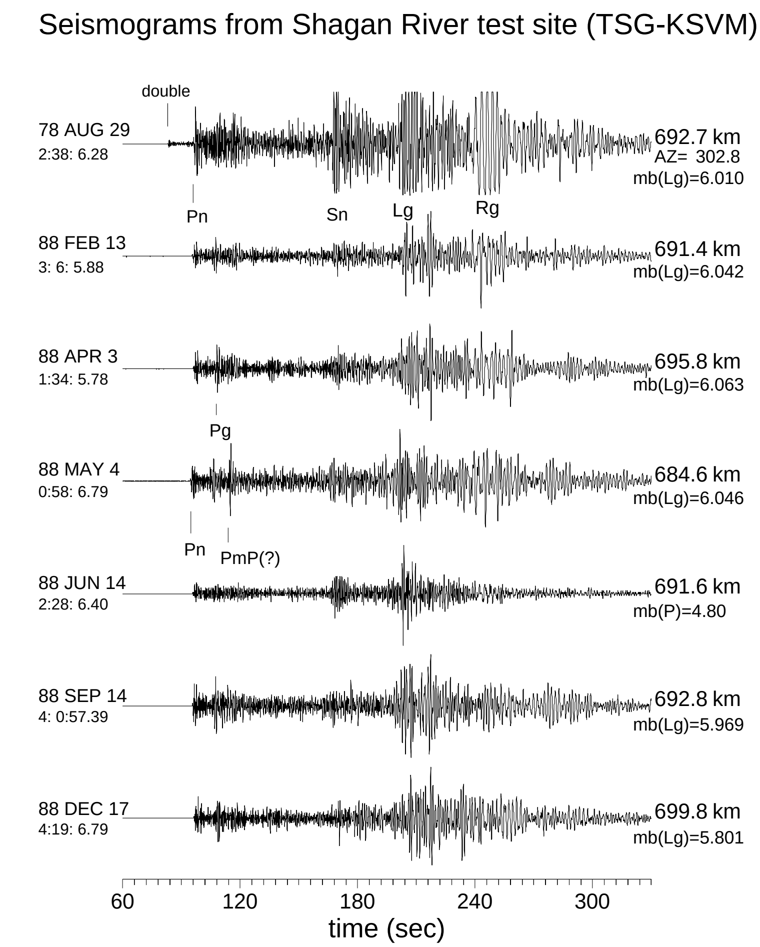
Figure 3a shows seven seismograms at BRV for nuclear explosions at the Shagan River test site in Eastern Kazakhstan, a distance of about 700 km. The regional waves *Pn*, *Lg*, and *Rg* are clearly seen. Even though these explosions are less than 20 km apart there is noticeable variability in the waveforms, especially for phases marked as *Pg* and *PmP*. Note the appearance of the first trace in Figure 3a, which has a precursor that turns out to have been another nuclear explosion, conducted at the Degelen Mountain test site about ten seconds prior to the Shagan River shot.

Figure 3b shows two BRV seismograms for nuclear explosions at Novaya Zemlya: the *Lg* signal is quite weak for this 2380 km path.

Figure 3c shows BRV data (KOD system) for a Kazakhstan earthquake of 1969 May 1 that was cited by Landers (1972) as an event that appeared in some respects to have the seismological characteristics of an explosion (e.g. a high body-wave to surface-wave magnitude ratio). Other teleseismic studies, however, indicated a source depth greater than 20 km, and hence that this is indeed the record of an earthquake. There is a concurrent much larger earthquake in Tonga, making the Kazakhstan surface waves very hard to measure outside the U.S.S.R.

Another interesting Kazakhstan earthquake occurred on 1976 March 20 near the Shagan River test site, and in Figure 3d is shown BRV data for this event and for the large nuclear explosion carried out on 1988 September 14 as part of the U.S./U.S.S.R. project known as the Joint Verification Experiment. Both signals are from short-period vertical instruments, and we show the earthquake signal with reversed polarity to facilitate the comparison in the Figure. It is clear that the earthquake *P*-wave arrival was a dilatation at BRV. Since this earthquake had the radiation pattern of a thrust fault, all teleseismic signals showed compression. Only with data such as that from BRV, could the event be discriminated as an earthquake on the basis of its pattern of seismic "first motions."

a



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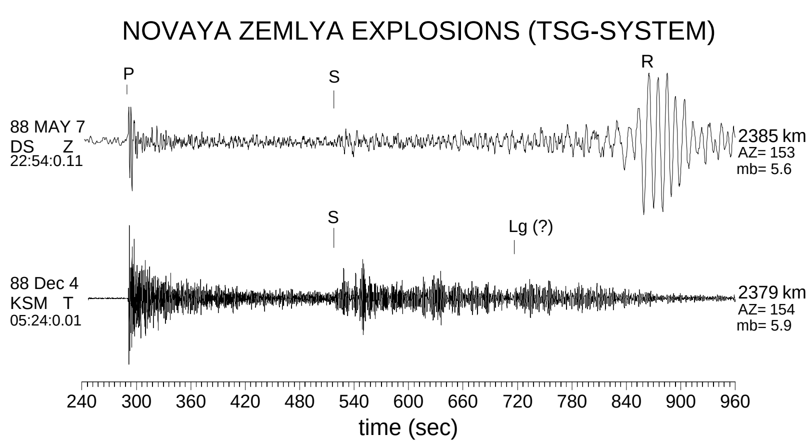

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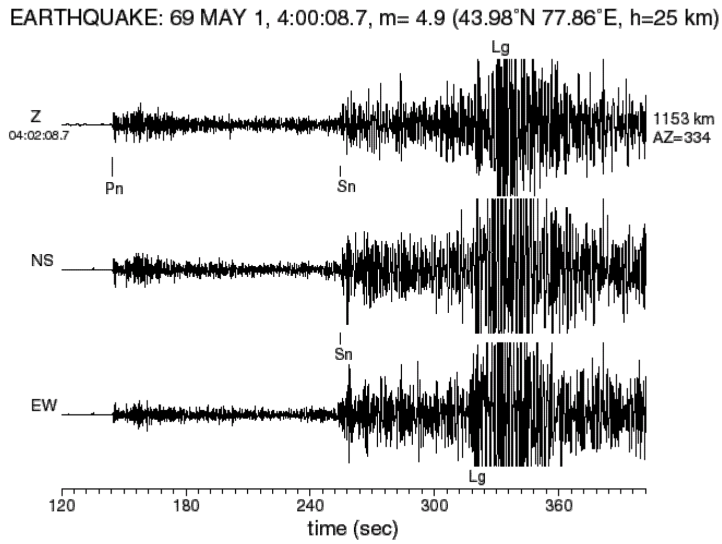

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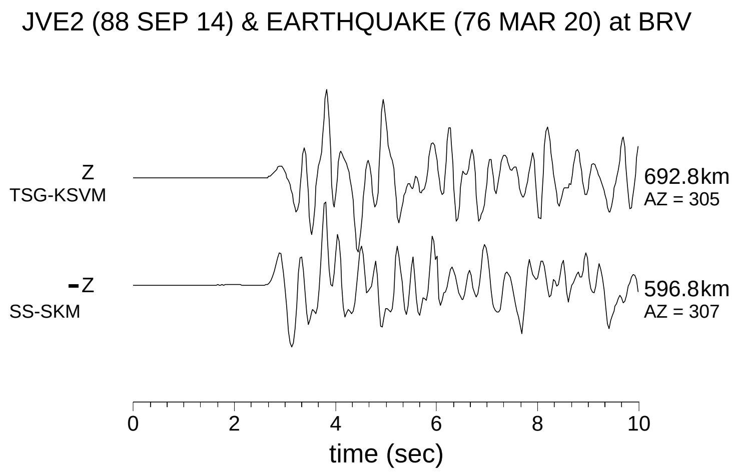

Fig. 3 (a) Seven examples of short-period vertical digital recordings at BRV, of nuclear explosions at the Shagan River test site (TSG-KSVM). Regional phases are indicated, as are Lg-wave magnitudes determined by NORSAR. (b) Examples of BRV data for two nuclear explosions at Novaya Zemlya (TSG-System). Upper: long-period vertical. Lower: short-period horizontal, rotated to show the transverse component. (c) Three-component BRV data (KOD system) for the Kazakhstan earthquake of May 1, 1969, at 4:00:08.7, m = 4.9, 43.98°N, 77.86°E, h = 25km. Though slightly clipped, this data is of remarkable quality. (d) A comparison of the first arrivals at BRV of an explosion signal from a Shagan River explosion (JVE2, September 14, 1988), and an earthquake signal on March 20, 1976 (polarity reversed).

Possibilities for Future Joint Research

Problems of data availability and quality have almost always been the factors limiting progress in seismology. Thus the "discovery" (in the sense of Christopher Columbus) of a major new database is an important event for western seismologists. Also important, is the opportunity to work with expert seismologists from Russia and Kazakhstan who are knowledgeable in monitoring of nuclear explosions carried out in various types of hard rock quite unlike the Nevada Test Site environment. In future joint projects based on BRV data, we and other seismologists from the West hope to study:

- regional structure and tectonics associated with earthquakes in Kazakhstan (a vast country with areas of high seismic hazard to the south and east);
- tectonic release associated with large nuclear explosions at Shagan River (in particular a reconciliation of BRV data with teleseismic surface waves, for those explosions having an additional "earthquake-like" moment tensor);
- nuclear explosions conducted in salt domes in the Azgir region of Western Kazakhstan (important in evaluating the decoupling scenario, in which seismic monitoring capability is reduced for nuclear explosions set off within a cavity);
- the seismic signals from large chemical explosions in Kazakhstan and nearby states (to develop methods of identifying such sources, thus discriminating them from small nuclear explosions); and
- the improvement in monitoring seismic activity worldwide, by addition of BRV data and data from the new digital seismic stations installed since 1988 by IRIS and the USGS within Eurasia. Borovoye data may be of particular interest in monitoring South Asia.

Comments and Conclusions

We have sketched 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. Second, there are problems of re-organizing the Observatory to operate in a wholly changed political environment. Under the Soviet system, Borovoye was a major project of the All-Union Academy of Sciences, doing work of interest (for example) to the Soviet Ministry of Atomic Energy and Power. But in 1992 there is no central system of Soviet support, and instead a relationship between Kazakhstan and Russia that is not always hospitable to a field station formerly operated from Moscow.

Yet there are important roles for Borovoye still to play. The archive is an irreplaceable database on the seismicity of Central Asia, and any serious attempt to work on seismic hazard of Kazakhstan and neighboring states must recognize the importance of preserving both the archive and the community that can use it at Borovoye.

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 U.S.S.R., with its several 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 *[Scheimer and Borg, 1984; Sykes and Ruggi, 1989]*. Here too, Borovoye represents an important database and expertise that could assist in international plans for continuing the non-proliferation regime.

Acknowledgements

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