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ANALYSIS OF DIGITAL SEISMOGRAMS FROM NUCLEAR EXPLOSIONS ACROSS FORTY YEARS

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It is remarkable that the most recent nuclear test explosion, by North Korea (2006 October 9), although quite small, was well-detected teleseismically. We describe how this event was promptly identified as an explosion and not an earthquake, on the basis of regionally recorded signals, in a region that apparently would have permitted such identification even if the test had been much smaller. The work of identifying underground nuclear explosions in a particular region on the basis of their seismic signals is greatly assisted by the availability of high-quality signals from both explosion (chemical or nuclear) examples, and earthquake examples, previously recorded in that same region. The Borovoye Geophysical Observatory is very important for its digital seismogram archive of nuclear explosions going back to 1966, recorded from underground nuclear tests at teleseismic and regional distances, from test sites operated by the recognized nuclear weapons states. We briefly describe a current effort to improve the quality and usability of this archive.

INTRODUCTION

Our title for this paper is chosen to include two subjects. First, we describe seismic signals from the underground nuclear test explosion of 2006 October 9, conducted by North Korea, as recorded by a high-quality station at a distance of about 370 km, and the way in which it was possible promptly to identify these signals as coming from an explosion and not an earthquake. Second, we briefly describe the archive of seismic signals from nuclear test explosions recorded digitally at Borovoye beginning in 1966, and the way in which this archive is still being improved today, by removing glitches and adding information on instrument responses, to help build confidence in global efforts to monitor compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

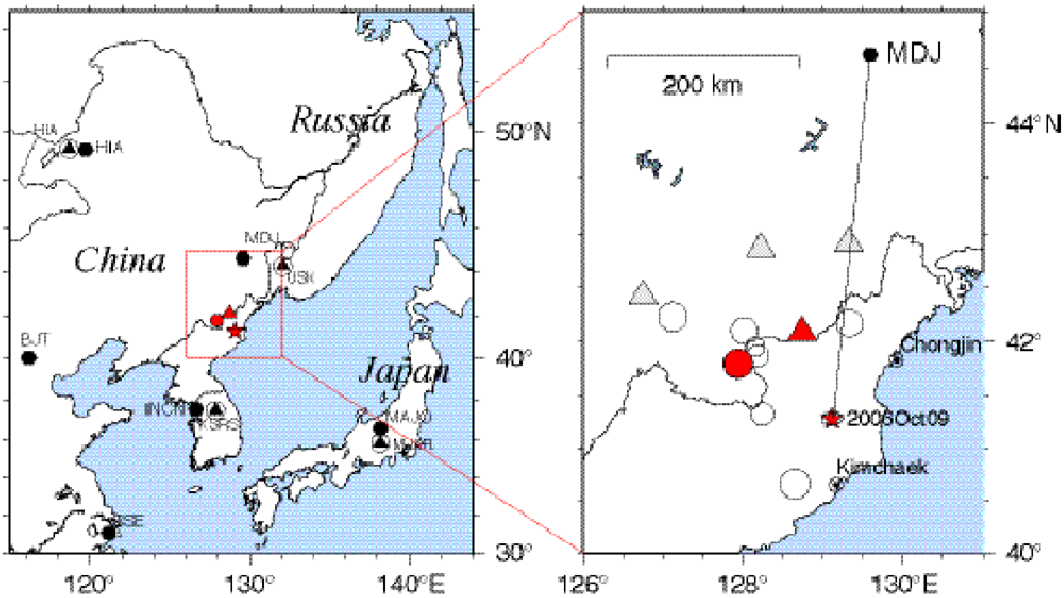
NORTH KOREA NUCLEAR TEST: SEISMIC DISCRIMINATION AT LOW YIELD

Numerous stations at teleseismic distances detected signals from the North Korean nuclear test of 2006. Within a few hours of its occurrence, the U.S. Geological Survey (USGS) reported on the web a location estimate based on data from 20 stations, and a magnitude. The USGS location estimate was revised slightly after a few days. Its so-called PDE location (a “preliminary determination of epicenter” based on seismic signals reported from 31 stations around the world) and its seismic magnitude (from ten stations) are given as 41.294 deg N, 129.093 deg E, and $mb(P) = 4.3$. Further information on the USGS effort is given by Koper *et al.* [3].

The source region consists of Precambrian gneiss and schist with Cretaceous granitic intrusions, and for such hard rock the reported magnitude corresponds to a yield on the order of one kiloton. Although small compared to most nuclear tests, an explosion of this size could still have enormous effects and consequences if actually used as a weapon. This test was announced by North Korea, and there was intense interest internationally in the event. Many newspapers and TV stations wanted basic information on the test itself, including examples of the seismic signals, and an interpretation of what the expert community was learning from them. Conflicting reports were being given, of the likely yield of this test. In this circumstance, seismologists at Lamont-Doherty Earth Observatory, located not far from the headquarters of major news-media headquarters in New York City, gave many interviews, and provided relevant seismograms and interpretations of their main features that were promptly published (for example, by the *New York Times* on October 10, 2006).

We analyzed seismic records from this nuclear test and compared them with similar records from eight earthquakes in the vicinity as well as from four known chemical explosions in the region. In particular we studied 3-component *P*/*S* spectral ratios, and concluded that the event was explosive based upon a comparison of its seismic records from two GSN (Global Seismographic Network) stations – MDJ and INCN — with seismic records at the same stations from known explosions and earthquakes in the region. Our results show that identification of explosions in this region can be done even down to a very small fraction of a kiloton, provided seismic data of the type available in October 2006 continue to be available.

Figure 1 (on the left) shows the location of the 2006 October 9 North Korean test together with locations of eight small earthquakes and four small chemical single-fired explosions.



Symbols: red star – location of the North Korea nuclear test; red circle – a nearby earthquake; red triangle – a nearby chemical explosion; hexagons – seismographic stations whose data are openly available (most notably station MDJ) ; encircled black triangle – IMS stations.

Figure.1.The locations of North Korea nuclear test, nearby stations, earthquakes and explosions in the North Korea-China region: on the left – general map; on the right –detailed map

Figure 1 (on the right) shows further detail on the location of eight small earthquakes and four small chemical explosions in the vicinity of the North Korea nuclear test. An error ellipse around the estimated location of the nuclear test indicates the 90% confidence region for the location uncertainty. In the Table below is the list of events which are shown in figure 1 and for which seismic records are included in this article below.

Table. Events for which seismograms are shown in this paper

Date (yr/mo/dy)	Origin time (hh:mm:s)	Lat. (°N)	Long. (°E)	*H* (km)	Mag. (M_L)	Region	Dist. (km)	Baz (°)
Nuclear Test								
2006/10/09	01:35:28.0	41.294	129.094	0	4.3	NORTH KOREA	371.3	187
Earthquakes								
1994/01/25	08:51:38.2	42.23	127.12	04	4.0	NE CHINA	332.0	218
1997/10/08	18:54:09.1	42.17	129.33	05	3.6	NORTH KOREA	272.9	185
2002/12/24	15:57:56.6	41.95	128.15	14	2.5	NORTH KOREA	318.6	202
2004/09/08	14:24:21.1	42.10	128.02	23	3.6	NE CHINA	307.3	205
2004/12/16	18:59:14.5	41.79	127.94	10	4.0	NORTH KOREA	341.6	204
Chemical Explosions								
1998/08/12	15:00:08.1	42.87	128.22	0	1.0	NE CHINA	223.6	210
1998/08/18	14:00:06.7	42.91	129.32	0	2.0	NE CHINA	190.6	187
1998/08/19	15:00:07.8	42.09	128.74	0	1.9	NE CHINA	289.2	194
1998/08/25	15:00:07.5	42.43	126.75	0	1.0	NE CHINA	334.4	224

h = focal depth in kilometers; Mag. = Local magnitude for chemical explosions and earthquakes and $m_b(P)$ for the nuclear test; Dist. = distance in kilometers from the station MDJ to the event; Baz = Azimuth of event from the station MDJ in degrees measured from North.

Figure 2 shows three-component seismograms at station MDJ, in northeast China — from the three events shown in red in Figure 1. These three are: the nuclear explosion; one of the eight small earthquakes; and one of the small chemical explosions. Figure 3 shows seismograms from four of the earthquakes noted in Figure 1 and from all four of the small chemical explosions, as recorded at station MDJ. Traces are referred to the origin time for each event. The event date, origin time and local magnitude are indicated. Seismograms are ordered in increasing distance for each type of seismic source. These signals were recorded on an instrument with a response proportional to ground velocity over a broad frequency band, and are shown here after being passed in the band from 1 to 15 Hz

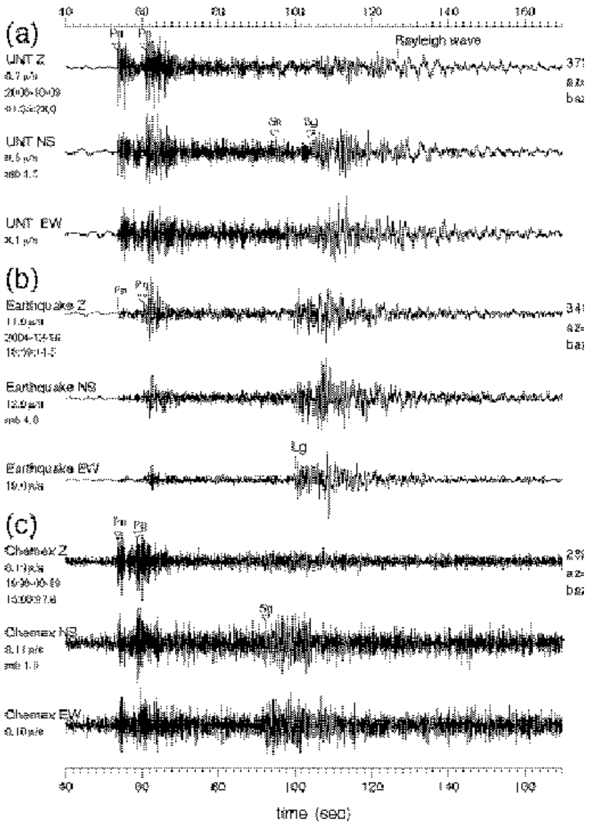


Figure 2. Three-component seismic records (Z, vertical; NS, north-south; EW, east-west) at station MDJ: a - the nuclear test of 2006 October 9, with strong P-waves, a short-period Rayleigh wave (Rg, indicating a shallow source), and weak shear waves (Lg). b - a small earthquake (located at the red circle shown in Figure 1) on 2004 December 16. It lacks Rg and has relatively strong shear waves, c - a single-fired chemical explosion (located at the red triangle in Figure 1) on 1998 August 19. Traces are aligned on P-arrivals

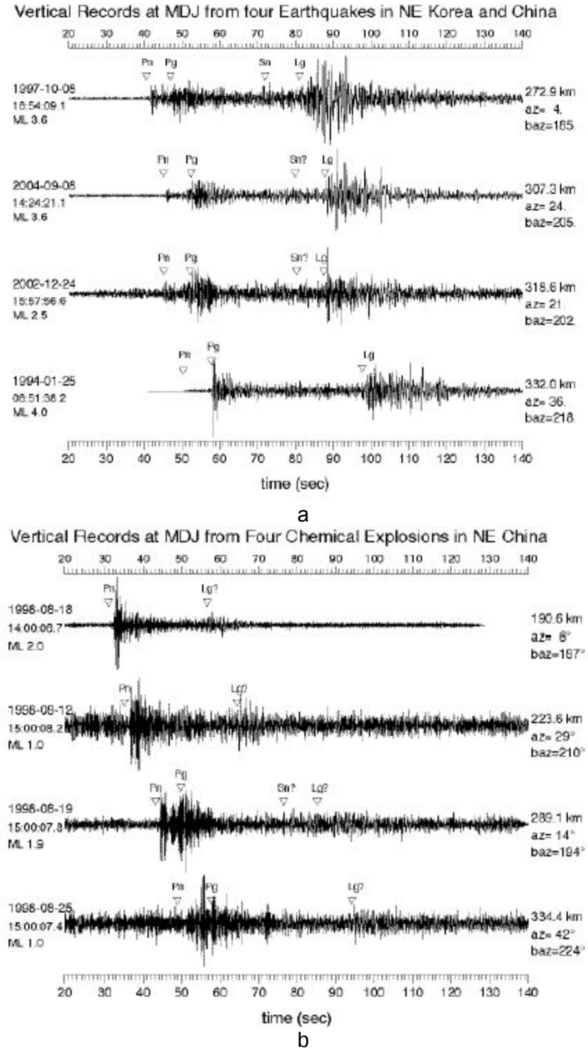


Figure 3. Vertical-component seismic signals at station MDJ. Seismograms: a - from four earthquakes that occurred in North Korea and Northeastern China within 200 km of each other; b - Seismograms from four chemical explosions carried out in August 1998 in Northeastern China

And Figure 4 shows a comparison of spectral ratios for the Pg and the Lg phases for all eight earthquakes, for four chemical explosions, and for the event of main interest — the North Korean nuclear test. A mean value at each discrete frequency is plotted for earthquakes (solid circles) and explosions (solid triangles), with a colored bar used to indicate the scatter (± one standard deviation). The earthquake results are offset slightly to the left of each frequency grid point, and the chemical explosion results are offset to the right, to avoid superposition that would obscure the results. The chemical explosions clearly have higher P/S spectral ratios than the earthquakes at almost all frequencies. Separation of the two populations is better at high frequencies. The event of 2006 October 9 clearly falls in with the explosion population. Since the chemical explosions had very low yields (one or two tons), we may conclude that discrimination of explosions can be done in this region even at the level of a few per cent of one kiloton, provided data of the quality of the MDJ station are available

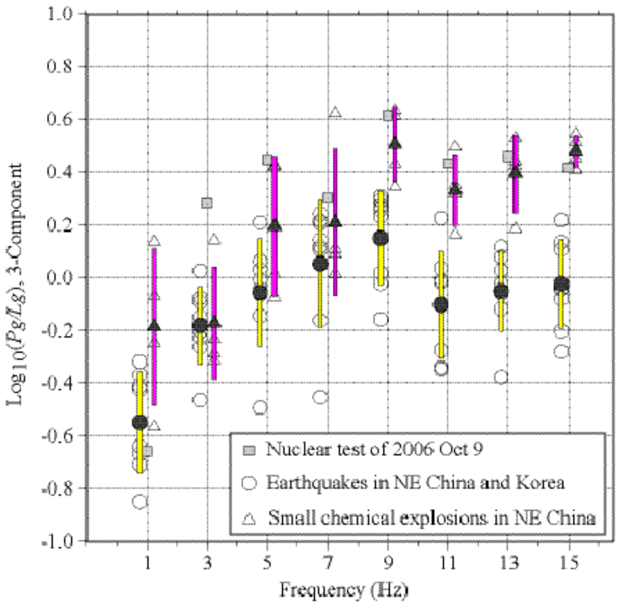


Figure 4. Three-component Pg/Lg spectral ratios at eight discrete frequencies are plotted for earthquakes, chemical explosions, and the nuclear test

It is very clear from Figure 4 that the nuclear explosion falls into the explosion category and is not a natural earthquake. We note that successful discrimination for this event using seismological methods has been reported by several authors, including Che *et al.* [1], Kværna *et al.* [4] and Koper *et al.* [3]. The last of these papers presents a discussion of the way in which estimates of the yield are dependent upon depth of burial.

In practice it is not possible to distinguish seismically between a small underground nuclear explosion and a large single-fired chemical explosion. The fact that radionuclides were reported from this test by several different groups, is important as an indication of how greatly the capability for radionuclide monitoring has improved since this technology began to be used by the International Monitoring System.

THE BOROVOYE SEISMOGRAM ARCHIVE

There have been very few nuclear test explosions since the Comprehensive Nuclear-Test-Ban Treaty was opened for signature in 1996. This is fortunate from the point of view of establishing an international norm of behavior, but for purposes of building experience today, in seismic discrimination between earthquakes and explosions, it is then necessary to search archives acquired many years ago during the period when nuclear tests were being conducted much more frequently, in order to find examples of the type of explosion signals that modern monitoring networks must be designed to detect and identify. The archive of the Borovoye Geophysical Observatory (BRV) plays a very important role here, because of its extensive archive of digital seismic recordings, beginning in 1966, from 711 underground nuclear tests conducted by the USSR (339 events recorded by BRV), China (11 events), France (68), the United Kingdom (15), and the United States (278).

During the years from 1997 to 2000, with funding from the International Science and Technology Centre, scientists at Lamont-Doherty Earth Observatory, the National Nuclear Centre of the Republic of Kazakhstan, and the Russian Academy of Sciences' Institute of Dynamics of the Geosphere, worked to transfer this archive from thousands of Soviet-era magnetic tapes to a modern database that is easily transferable today between different types of modern recording media. The BRV digital archive of nuclear explosion waveforms from 711 underground nuclear explosions worldwide became generally available in April 2001 (for example, via http://www.ldeo.columbia.edu/res/pi/Monitoring/Arch/BRV_arch_exp.html). The archive of nuclear explosion signals was issued as a series of modern databases, described by Kim and others in a report available today as a 41-page PDF file via http://www.ldeo.columbia.edu/Monitoring/Data/Brv_arch_ex/brv_text_table.pdf . Of particular interest here, because they were recorded at regional distances, are the digital seismic signals obtained at BRV from 228 underground nuclear tests recorded at approximately 700 km from Soviet nuclear testing at the Semipalatinsk Test Site; and from 11 underground nuclear tests recorded at approximately 1800 km from nuclear testing by China at the Lop Nor Test Site.

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 basic header information), but converted to a modern and widely use format for digital seismic data (CSS3.0). The original Soviet-era recordings had some severe problems, most notoriously that the digitizer typically did not write a count value on seismic waveform channels at the time when the time channel was writing the marker for an integer second. Also, the original recording system addressed the practical problem of input signal with wide dynamic range by having several different channels set at different gain levels, each recording with a limited number of bits (often, only 11 bits), so that although each underground nuclear explosion was usually recorded on several channels, in practice these channels were often either clipped or had inadequate resolution. In either case, it has proven difficult to obtain good spectral measurements from the Borovoye archive without addressing the difficulties described above. But despite these difficulties, ways to extract the underlying information have been found. For example, empirical travel-time information, needed to generate Source Specific Station Corrections for the modern BRVK station (which today is part of the International Monitoring System), can be obtained by picking first and secondary arrivals from a high-gain channel. The spectrum of the strongest ground motion is often best obtained from one of the lower-gain channels. Fortunately, even for a channel that is clipped on the largest amplitudes, coda studies can be conducted using the later part of the recorded signal.

Here, we may note that three different sets of Soviet-style instruments and recording systems were deployed at BRV from 1966 to 1996. We know them 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 two 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, in most cases recorded at two gain levels, for a total (SS + TS) of 20 data channels. The highest sensitivity is 100,000 counts/micron based on a short-period Kirnos with a special magnet and a low-noise amplifier. This instrument was important at BRV for teleseismic monitoring of numerous French and U.S. underground nuclear explosions (with capability for detection down to one kiloton at the Nevada Test Site of the United States). But for purposes of developing good discriminants from regional signals the high gain channel is not so important today as the lower-gain channels, on which regional signals have been recorded from underground nuclear explosions in and near Central Asia. Kim and Ekström [2] have published details of the STsR-TSG instrument responses (many channels, extending across almost three decades in frequency). All of these main systems are approximately flat to ground displacement over a range of frequencies. With the different instruments and gain levels, the BRV station as a whole had a dynamic range around 135 dB during the Soviet era.

In view of the importance of the Borovoye digital seismogram archive of underground nuclear explosions, we have been working on a project to remove the glitches in the archived recordings, and to combine the corrected recordings with detailed instrument responses in order to reproduce, as far as may be possible, modern broadband recordings of numerous events from underground nuclear explosions conducted several decades ago. This work is enabled, in part, by the fact that as different instrumental systems were introduced at Borovoye, they overlapped with previous systems. Thus in July 1994, when Won-Young Kim deployed a modern broadband seismometer (STS-2 with T0 = 120 sec) and a 24-bit A/D datalogger on the same seismic pier with the Borovoye archive seismic systems under the auspices of the IRIS Joint Seismic Program (JSP), he arranged with operators at the Borovoye Geophysical Observatory to continue running the then-existing STsR-SS and STsR-TSG systems for the purpose of calibrating waveform data from those systems at a later date. Hence, there are waveform data from both the TSG system and modern BRVK broadband systems during 1994–1996, which, together with information obtained from log books, have assisted in providing complete calibration of the TSG system. In particular, the four underground nuclear explosions from French test sites at Mururoa and Fangataufa conducted in 1995–1996, and two from the Lop Nor Chinese test site, 1994 October 7, and 1995 May 15, were recorded by the TSG system and by a modern STS-2 system.

In this paper we give two examples of what can be done with the Borovoye waveforms. Figure 5 shows the successful removal of numerous glitches, and Figure 6 shows how it is even possible to synthesize a broadband signal from combining the deglitched waveforms from separate channels. The records from the 14 September 1988 UNE , conducted as part of the Joint Verification Experiment, at the Balapan region of the Semipalatinsk test site (recorded by the TSG system at BRV) are used as an example in figure 6.

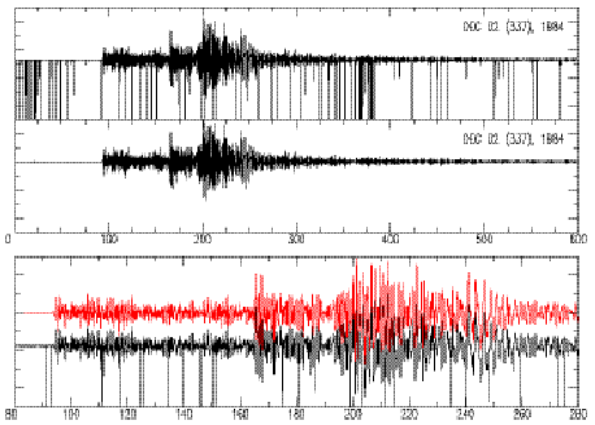


Figure 5. An example of data deglitching: the first top plot shows the raw time series; the second top plot - time series after deglitching, for 10 minutes of data, including a long segment of coda waves; the lower plot (black) is an enlargement of 200 s of data, centered on the main signal. The deglitched waveform is plotted in red

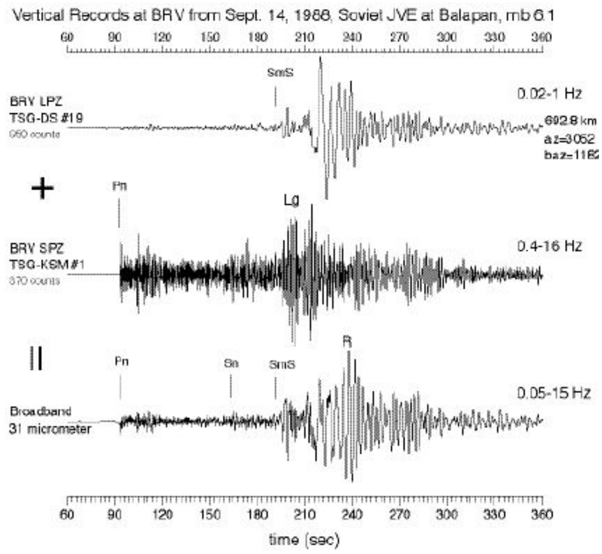


Figure 6. An example of a broadband seismic record (bottom seismogram) synthesized using long- and short-period seismograms (top two seismograms) recorded by the TSG system at BRV

Our goal in the effort to improve the quality of the Borovoye archive of explosion recordings, by removing glitches and correcting for instrument responses for signals at regional distances, is to provide an openly-available dataset that can enable a variety of research efforts to evaluate practical discriminants and thus to improve the capability to monitor compliance with the CTBT. If we are successful, then our efforts will add to the work of many scientists in Russia and Kazakhstan who originally established the quality of the Borovoye Observatory and who carefully acquired data at Borovoye over three decades.

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СОҢҒЫ 40 ЖЫЛДАҒЫ ЯДРОЛЫҚ ЖАРЫЛЫСТАРДЫҢ ЦИФРЛЫҚ СЕЙСМОГРАММАЛАРЫН ТАЛДАУ

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Жақындағы ядролық жарылыстар, мысалы Солтүстік Кореядағы (2006 ж. қазанның 9), олардың аз қуаттығына қарамай, сейсмикалық көзқарасы жағынан жақсы табылған және дереу, жерсілкіну емес, жарылыс деп танылған. Белгіленген бір аумақта ядролық жарылыстарды тануы жарылыстардың (химиялық және ядролық) сондай-ақ жерсілкінулердің бұрын тіркелген сапалы сейсмикалық жазбаларына байланысты. Осыған қатысты «Бурабай» сейсмикалық обсерваториясы, ядролық қаруы бар мемлекеттер жүргізген ядролық жарылыстар бойынша белгілі ядролық полигондардан телесейсмикалық және аумақтық қашықтарындағы, 1966 ж. басталған мұрағаттық цифрлық сейсмограммалары арқасында маңызды болып табылады. Ядролық

сынауларына бәрін сыйыдыратын тыйым салу туралы шартын (ЯСБТШ) қолдау үшін осы мұрағаттың сапасы мен пайдалылығын жақсарту бойынша күш салуы сипатталады.

АНАЛИЗ ЦИФРОВЫХ СЕЙСМОГРАММ ЯДЕРНЫХ ВЗРЫВОВ ЗА ПОСЛЕДНИЕ 40 ЛЕТ

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Недавние ядерные испытания, в частности, в Северной Корее (9 октября 2006 г.), несмотря на их маломощность, хорошо обнаружены с сейсмической точки зрения и незамедлительно распознаны как взрыв, а не как землетрясение. Распознавание подземных ядерных испытаний в определенном регионе в значительной степени зависит от ранее зарегистрированных здесь качественных сейсмических записей как взрывов (химических или ядерных), так и землетрясений. Геофизическая обсерватория «Боровое» очень важна в этом отношении благодаря архивным цифровым сейсмограммам по ядерным взрывам, зарегистрированным, начиная еще с 1966 г., на телесейсмических и региональных расстояниях от известных полигонов, использованных державами, обладавшими ядерным оружием. Характеризуются усилия по улучшению качества и полезности данного архива для поддержки Договора о всеобъемлющем запрещении ядерных испытаний (ОДВЗЯИ).