Proceedings of the 21st Seismic Research Symposium: Technologies for Monitoring The Comprehensive Nuclear-Test-Ban Treaty

21-24 September 1999

Las Vegas, Nevada

Volume I

Seismic Regional Characterization and Wave Propagation
Seismic Event Detection, Location, and Identification Methods
Seismic Source Characterization

Approved for Public Release; further dissemination unlimited

LA-UR-99-4700

A STUDY OF SMALL-MAGNITUDE SEISMIC EVENTS DURING 1961 - 1989 ON AND NEAR THE SEMIPALATINSK TEST SITE, KAZAKSTAN

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Sponsored by U. S. Department of Defense
Defense Threat Reduction Agency
Contract No. DSWA01-97-C-0156

ABSTRACT

Official Russian sources in 1996 and 1997 have stated that 340 underground nuclear tests (UNTs) were conducted during 1961-1989 at the Semipalatinsk Test Site (STS) in Eastern Kazakstan. However, only 279 of these nuclear tests appear to have been described with well-determined coordinates, in the openly available technical literature; and only 271 have both good locations and magnitudes. Thus, good documentation has been lacking for 69 UNTs at STS.

We have used regional data from 52 stations to detect, locate, and assign magnitudes for as many of these 69 UNTs as possible. Thus, for 8 previously located events with unknown magnitudes, we have assigned magnitudes. We identify 12 pairs of concurrent UNTs where one of the paired events had not been separately detected. We give another pair of almost simultaneous UNTs where both events had been undetected, and we have been able to detect one of the UNTs but not the other. For the total of 13 event pairs where one event has now been detected but not the other, we presume detection would have been possible if the undetected event had occurred alone. We find seismic detections and locations for an additional 30 nuclear tests at STS. Their magnitude ranges from 2.7 up to 5.1 (an event in 1965 that was often obscured at teleseismic stations by signals from earthquakes in the Aleutians).

Most of the 31 newly detected and located events were sub-kiloton. We note that for the remaining undetected 17 UNTs that did not occur at the time of another UNT, the announced yield is less than one ton and thus seismic detections would not be expected. Only two UNTs remain, for which the announced yield exceeds one ton and we have been unable to find any signals.

For 17 small UNTs at STS during 1964-1988, we compare the locations (with their uncertainty) that we had earlier determined in 1994 from analysis of regional seismic waves, with ground truth information obtained in 1998 on tunnel locations at the Degelen sub-area of STS. The average error of the seismically determined locations is only about 4 km, and the ground truth location is almost always within the predicted small uncertainty of the seismically determined location.

We also report the origin time, location, and seismic magnitude of 29 chemical explosions and 3 earthquakes on or near STS during the years 1961 - 1989.

Our new documentation of STS explosions is important for purposes of evaluating the detection, location, and identification capabilities of teleseismic and regional arrays and stations.

Key Words: nuclear explosions, ground truth data, chemical explosions, seismic discrimination, Semipalatinsk Test Site

OBJECTIVE

The overall goal of this project is to improve our understanding of the capability of modern and future monitoring networks. We do this, by learning from past experiences with monitoring a test site at which hundreds of underground nuclear explosions actually occurred; and by building up the archive of information on nuclear tests.

RESEARCH ACCOMPLISHMENTS

It has been reported in recent official Russian publications (Mikhailov et al., 1996; USSR Nuclear Tests, 1997) that a total of 340 underground nuclear tests (UNTs) were carried out on the Semipalatinsk Test Site (STS) from 1961 to 1989. Only 279 of them had been included in previously published lists of Soviet underground nuclear explosions that included purportedly accurate origin times and locations (specifically, the lists contained in Bocharov et al., 1989, Ringdal et al., 1992; and Lilwall and Farthing, 1990). For eight of these 279 explosions, the magnitudes have not been available. So accurate epicenter parameters of 61 UNEs and the magnitudes of 69 UNEs appear not to been given previously for this test site (STS).

The main goal of this paper is to estimate the origin time and location, and to assign the magnitude, for as many of the 69 hitherto undocumented UNTs at STS as possible. Our analysis is based principally upon seismic observations using regional stations located in Kazakstan and elsewhere in Central Asia. We also evaluate the accuracy of locations for small UNTs at STS, as determined from regional seismic signals.

Besides underground nuclear explosions, we have obtained information about chemical explosions and earthquakes which have been detected on and near the area of STS. Their parameters also were obtained from data of regional stations, and in some cases teleseismically. It is of interest, that some of these earthquakes and chemical explosions were included in some lists of Soviet underground nuclear explosions published in the West in the mid 1980s before Russian announcements about Soviet nuclear explosions were made beginning in 1992.

It is important to develop thorough documentation of all nuclear explosions, and especially for small explosions, as an aid in evaluating the detection and identification capability of monitoring stations. Of course, explosion monitoring in the present and the future will typically be done using stations that differ from those we have used to document small explosions at STS. Nevertheless our database of small explosions (chemical and nuclear), and nearby earthquakes, can provide guidance in estimating the capability of current networks, which can be expected to be better than the capability that was available for much of the period of active nuclear testing.

In the following sections, first we summarize the information from Russia officially available on STS UNTs. Second we identify those explosions that had not been assigned accurate epicenter and magnitude parameters. Third we describe our regional seismic detections of small events on and near STS. Fourth and fifth we give the newly-determined epicenter and magnitude parameters for 31 small UNTs at STS, and discuss the accuracy of their seismically-determined locations by making comparisons with ground truth information given by Leith (1998).

1. Summary of available official information about UNTs from STS

The 340 UNTs at STS listed by Mikhailov et al. (1996) and USSR Nuclear Tests (1997) were each associated with one of three sub-areas of the test site. Thus, 209 UNTs were in the Degelen sub-area, 106 at Balapan (sometimes referred to as Shagan), and 25 at Murzhik (sometimes referred to as Konystan). These explosions covered a wide range in yield, from less than 1 ton up to 165 kilotons (kt). Among 96 UNTs with magnitude mb less than 5.0, 84 were at Degelen, only 7 at Balapan, and 5 at Murzhik, so about 88% of the smaller yield events were in tunnels at Degelen.

The origin time and coordinates (latitude, longitude and depth) of STS UNTs have so far been announced by Soviet/Russian sources only for a group of 96 events that were conducted during a period from October 1961 to December 1972 (Bocharov et al., 1989; see also Vergino, 1989). Among these 96 UNTs, 6 were small and were not mentioned by Lilwall and Farthing (1990), or by Ringdal et al. (1992). With the official Russian announcements of 1996 – 1997 it became clear that 20 small magnitude tests at STS during this 1961 – 1972 time period had not been included in the list of Bocharov et al. (1989).

In 1992, the Russian Federation declassified information about the dates on which Soviet UNTs had occurred, the number of tests and number of nuclear explosions carried out within one nuclear test, the yield range, the sub-area, and the purpose of these UNEs. But the origin time, coordinates, and yield of most Soviet UNEs are still unavailable; and their magnitudes as determined from Soviet or Russian studies have not been announced, either from the network operated by scientists, known as ESSN, or from the military network, known as SSK.

Apart from the explosion locations given by Bocharov et al. (1989), Soviet and Russian publications have not listed UNT coordinates. But within the framework of Kazakstan – US cooperation, coordinates of tunnel portals at Degelen have become available (Leith, 1998). Separately, the coordinates of Balapan shafts have been obtained through fieldwork conducted by the National Nuclear Centre of the Republic of Kazakstan, and these locations are also now available (NNCRK, 1999). We use ground truth information in Tables below whenever these locations are available for specific explosions. When ground truth is absent (for example for chemical explosions) we give coordinates determined by seismological methods — whose accuracy is demonstrated in a later section of this paper.

2. Small UNTs at STS previously undocumented by Western seismologists

In this section we identify 61 UNTs at STS, out of the 340 now officially announced, for which accurate location information has not been given in openly available publications so far as we are aware; and we identify 69 for which accurate magnitude information has not been given. We assign each of these 69 UNTs to a category that indicates why their documentation has been poor (for example, low yield, or occurrence at the same time as another UNT). The following sections then report our own efforts to acquire and generate additional information, including locations and magnitudes, for as many of these 69 UNTs as possible.

Thus, the International Seismological Centre (ISC) has reported the seismically-determined location and magnitudes of 271 UNTs at STS. The ISC relies upon volunteered reports of seismic wave arrival times and amplitudes from thousands of stations around the world, and publishes its estimated locations and magnitudes together with the reported data used to derive them. Many researchers have carried out additional levels of analysis based upon ISC data for subsets of the STS events listed by the ISC. One of the largest such efforts, by the British Atomic Weapons Establishment (AWE), has applied the Joint Epicenter Determination method described by Douglas (1967) to ISC data, using several UNTs at STS as master events for which ground truth information was given by Bocharov et al. (1989). The AWE location estimates are given by Lilwall and Farthing (1990). AWE has also obtained maximum likelihood *mb*'s for 239 STS UNTs and has made them widely available on an informal basis. AWE *mb*'s for 100 UNTs and one chemical explosion in the Balapan sub-area were published by Ringdal et al. (1992). An additional 8 UNTs, not mentioned by Lilwall and Farthing (1990) or Ringdal et al. (1992), are given with locations but not magnitudes by Bocharov et al. (1989) and Vergino (1989).

Table 1. The list of weak UNTs at STS with Y < 1 ton, which could not be detected even at typical regional distances

N	#	Date	N	#	Date
1	283	1968 May 23	9	517	1979 Apr 10
2	317	1970 Feb 18	10	520	1979 Jun 12
3	359	1972 Apr 20	11	543	1980 Mar 14
4	387	1973 Sep 20	12	567	1981 Mar 25
5	397	1974 Feb 28	13	572	1981 Jun 04
6	484	1978 May 24	14	581	1981 Oct 16
7	486	1978 Jun 02	15	607	1983 Mar 11
8	516	1979 Mar 23			

Using information from the official Russian publications, we can tentatively give three reasons why many UNTs were not included in lists of events accurately located by seismic methods. First, some UNTs have now been announced as having had yield less than 1 ton; such tests would generally be too small for either regional or teleseismic detection. Second, some UNTs were carried out at essentially the same time as another UNT and only one test was reported. Third, some UNTs have now been announced as having had yield greater than 1 ton, but they may still have been too weak for teleseismic detection with high confidence, given the networks in operation at the time. For these events, we can inquire as to the possibility of regional detection as discussed in the following sections. Let us now list events in these three categories.

2.1. Weak UNTs with yield Y announced as less than 1 ton

This category consists of the 15 UNTs listed in Table 1. They would not be detected by standard instruments at distances more than 100 – 150 km. One of these small UNTs, with yield *Y* less than 1 ton, was carried out at Balapan (#387); the other 14 were carried out in the Degelen sub area. The number preceding the date corresponds to the numeration of UNTs in official Russian lists. We use the same numbering system throughout this paper.

2.2. Pairs of UNTs exploded simultaneously

This category is concerned with pairs of tests carried out within a short time interval, or even simultaneously, but with a spatial and/or temporal interval that requires them to be listed as different tests. As origin times and locations have not been officially announced, our discussion of which tests occurred in pairs, such that one test obscures another, has to be tentative. [Note: each UNT can include multiple explosions provided they are close enough in space and time — as specified in the 1990 revised protocol to the Threshold Test Ban Treaty.]

Table 2. 17 pairs of UNTs at STS which were exploded simultaneously or with a short time interval

Date	Subarea	Test numbers	Detected test: test no.	mb	Undetected test: test no.
1970 Jun 28	Both Degelen	321 & 322	321	5.7	322
1970 Sep 06	Both Degelen	325 & 326	?	5.4	325 or 326
1971 Mar 22	Both Degelen	333 & 334	333	5.7	334
1971 Dec 30	Both Degelen	353 & 354	354	5.7	353
1972 Jun 07	Both Degelen	360 & 361	?	5.4	360 or 361
1972 Dec 10	Degelen	376	376	5.6	-
	Balapan	377	377	6.0	-
Both tests were detected, with a 10 sec interval					
1975 Feb 20	Both Degelen	417 & 418	?	5.7	417 or 418
1976 Dec 07	Both Balapan	454 & 455	454	5.9	455
1977 Mar 29	Degelen	457	457	5.4	-
	Murzhik	458	not detected	-	458
1977 Oct 29	Degelen	473	473	5.6	-
	Balapan	474	474	5.6	-
Both tests were detected, with a 4.9 sec interval					
1977 Dec 26	Both Degelen	479 & 480	?	4.9	479 or 480
1978 Aug 29	Degelen	493	493	5.2	-
	Balapan	494	494	5.9	-
Both tests were detected, with a 8.8 sec interval					
1978 Nov 29	Degelen	507	507	5.3	-
	Balapan	506	506	5.9	-
Both tests were detected, with a 4.8 sec interval					
1979 Jul 18	Murzhik	524	524	5.2	-
	Degelen	525	not detected	-	525
1980 Dec 05	Both Degelen	561 & 562	-	-	561 and 562
Both tests were undetected					
1983 Nov 29	Both Degelen	629 & 630	?	5.4	629 or 630
1987 Apr 03	Balapan	671	671	6.1	-
	Degelen	672	not detected	-	672

In the last columns of Table 2 are shown the numbers of the 14 UNTs unreported by the ISC. These are events ## 322, 325 (or 326), 334, 353, 360 (or 361), 417 (or 418), 455, 458, 479 (or 480), 525, 561 and 562, 629 (or 630) and 672. These double tests can be the object of special investigation. Only one pair of UNTs from this table — 561 and 562 — was unreported by the ISC, so one event from this pair potentially can be detected.

Thus, we note that in the official lists there are 19 pairs exploded on the same day. Two of them were on the same day but are known to be separated by a long time interval: ## 414 and 415 (December 16, 1974, Degelen) with more then three hours time interval; and ## 440 and 441 (April 21, 1976, at Degelen and Balapan and hence with a significant spatial separation) with a four minutes interval.

The last 17 pairs of UNTs at STS (Table 2) were carried out on the same day with a small time interval, presumably not more then several seconds. Only for four pairs were both tests detected and reported as separate explosions in the standard western publications. The time intervals between the two tests in each of these four pairs varied from 4.8 to 10 s. For 12 other pairs only one test (for each pair) was reported by the ISC. For one pair — ##561 & 562 — neither test was reported.

2.3. Small UNTs with yield more than 1 ton, not reported by the ISC

These events, listed in Table 3, are most interesting for us because potentially they can be detected at regional distances. They are the main object of our investigation.

Table 3. List of 33 separate UNTs (Y > 1 ton) which were not reported in standard western publications, but which potentially can be detected at regional distances

N	##	Date	Sub area	N	##	Date	Sub area
1	#224	1964 Jun 06	Deg	18	#404	1974 Jul 29	Bal
2	#226	1964 Aug 18	Deg	19	#412	1974 Nov 28	Mur
3	#228	1964 Sep 30	Deg	20	#424	1975 Jul 15	Deg
4	#232	1965 Feb 04	Deg	21	#429	1975 Oct 05	Deg
5	#234	1966 Mar 27	Deg	22	#437	1976 Mar 17	Deg
6	#259	1966 Oct 29	Deg	23	#439	1976 Apr 10	Deg
7	#260	1966 Nov 19	Deg	24	#447	1976 Aug 04	Mur
8	#271	1967 Sep 02	Deg	25	#476	1977 Nov 12	Bal
9	#292	1968 Oct 29	Deg	26	#477	1977 Nov 27	Deg
10	#298	1969 Apr 04	Deg	27	#551	1980 Jun 25	Deg
11	#299	1969 Apr 13	Deg	28	#559	1980 Oct 23	Deg
12	#310	1969 Oct 30	Deg	29	#561	1980 Dec 05	Deg
13	#311	1969 Nov 27	Deg	30	#627	1983 Nov 02	Deg
14	#332	1971 Jan 29	Deg	31	#664	1985 Jul 11	Deg
15	#336	1971 Apr 09	Deg	32	#665	1985 Jul 19	Deg
16	#393	1973 Nov 04	Bal	33	#707	1988 Dec 28	Deg
17	#395	1973 Dec 31	Deg				

We note that a total of 61 previously undocumented UNTs are given in Tables 1, 2, and 3, namely, 15 UNTs with yield less than 1 ton; 13 UNTs that occurred at essentially the same time as another UNT, including one of the pair ##561 and 562; and 33 UNTs which potentially can be detected at regional distances, including the other of the pair ## 561 and 562. In the next section we report our locations and magnitudes, based on regional detections, for most of these 33 UNTs.

3. Detection of small events from STS from regional recordings in Central Asia

Our work on this subject was carried out in two stages. The first, in late 1993, resulted in a technical report (Khalturin et al., 1994), produced prior to the publication of the first Russian preliminary list of Soviet UNTs (Gorin et al., 1994). Information about the dates on which UNTs occurred, and ground truth locations, were not then available for us. We used regional data, and tried to detect and locate all seismic events at STS which could be UNTs, chemical explosions or earthquakes. The second stage was carried out in 1997 – 99, in light of official information on UNT dates and acquisition of ground truth locations.

Our results are based mainly on seismic data acquired by the Complex Seismological Expedition (CSE) of the Institute of the Physics of the Earth, Russian Academy of Sciences. Also we used bulletins of other regional stations of Central Asia including the Altai region. In total we used the records or bulletins of more than 50 seismographic stations. Most useful for detecting and locating small magnitude UNTs, were seismograms of narrow-band short period instruments installed in several stations by CSE in North Kazakstan at distances of 500 km to 1200 km from STS. Long-term CSE observations in this region show that high-frequency regional phases propagate very efficiently.

The seismographic network operated by CSE was used to acquire observations in the Kazakstan region throughout the period of UNT activity at STS — from 1961 to 1989. During the long-term monitoring effort, besides the well-known intermediate and large magnitude UNTs from STS, several tens of small magnitude events were detected that were not mentioned by Lilwall and Farthing (1990), or Ringdal et al. (1992). These events can be UNTs, or they could be chemical explosions used for military experiments and for construction. Few of these signals can be from earthquakes, which are very rare in the Semipalatinsk region since it is located on the far western flank of the Altai seismic zone.

Our first stage of study (Khalturin et al., 1994) examined data for 57 of these events that were on or near STS; estimated their coordinates, origin time, and magnitude; and made a preliminary identification as to the nature of each event (nuclear or chemical explosion, or earthquake). We now know that these 57 events consisted of 19 UNTs, 27 chemical explosions, 8 small magnitude UNTs known from Bocharov et al. (1989), and three earthquakes. Our first stage identified all of the UNTs and earthquakes correctly, but wrongly listed two of the chemical explosions as UNTs, and two other chemical explosions as "either UNE or chemical explosion".

Our second stage of study, in this paper, done following the release of UNT date information, has examined data for 71 events on or near STS, and has resulted in estimates of the origin time and magnitude of an additional 12 small UNTs which were missed in the first stage. So, from the 33 previously undocumented UNTs of Table 3, our first stage of study uncovered 19 UNTs and the present paper documents another 12.

Magnitude estimation of small known UNTs

Among the analysed signals were 8 small UNEs known from Bocharov et al. (1989) but listed there without magnitudes. Four of these events had been reported using teleseismic signals by Sykes and Ruggi (1986, 1989), who also listed a magnitude for three of the events.

For these 8 events the energy class K is known from regional records at several stations, allowing us to give the value of $mb(K)$ as in Table 4, using the relation $mb(K) = 0.46\,K - 0.64$ (Khalturin et al., 1998).

Table 4. 8 known UNTs for which we can now assign magnitudes

Date	Time (to nearest s)	K	mb (K)	mb**	Comment
1961 Oct 11	07:40:00	11.8	4.78	-	A
1962 Feb 02	08:00:00	13.6	5.63	-	B-1
1965 Jul 29	06:00:00	10.7	4.28	4.5	B-2
1965 Oct 14	04:00:00	10.7	4.28	-	A
1968 Oct 21	03:52:00	10.2	4.05	-	A
1968 Nov 12	07:30:00	10.6	4.24	-	A
1970 May 27	04:03:00	10.3	4.20	3.8	B-3
1972 Dec 28	04:27:00	11.4	4.60	4.9	B-4

**mb from Sykes and Ruggi (1989).

4. Detection of small underground nuclear explosions from STS

All but two of the small UNTs shown in Table 3 were detected regionally at temporary and permanent stations of CSE. Their parameters are listed in Table 5. Origin times were estimated for all 31 of them.

For the 19 largest of these small events, we give location estimates, K values, and mb(K). For the 12 smallest events we give estimated mb(Lg) values, which range from 2.2 to 3.7.

One relatively large UNT, with *mb*(*K*) 5.1 (February 4, 1965), was not reported by standard western publications as it was obscured teleseismically by a swarm of Aleutian earthquakes. We can be sure this was a coincidence rather than an effort to obscure the event, because the origin time (06:00:00) was typical for UNTs of the mid-1960s. But even if we exclude this large event, the *mb* value (calculated from *K*) for missed events ranges up to 4.55, and during 1964 – 1989, about 10 Soviet UNTs at STS, with magnitude 4.0 or more, had teleseismic signals that were too weak or too noisy to lead to publication of good location estimates. Some of these events were detected teleseismically at particular arrays (Ringdal, 1990).

Table 5. Small announced UNTs studied in this paper

No.	Date	Time	Subarea	(Lat.,	Long.)	K	mb(K)	mb(Lg)	m(NOR)	Note
224	1964 Jun 06	00:00:00	Deg	49.7747	77.9881	11.0	4.42	-	-	
226	1964 Aug 18	06:00:00	Deg	49.0206	78.0819	8.5	3.27	-	-	
228	1964 Sep 30	Not detected								
232	1965 Feb 04	06:00:00	Deg	49.7731	77.9914	12.5	5.10	-	-	A
234	1965 Mar 27	06:30:00	Deg	49.7747	77.9881	8.4	3.22	-	-	
259	1966 Oct 29	03:58:00	Deg	49.7847	77.9994	9.0	3.50	-	-	
260	1966 Nov 19	03:58:00	Deg	49.8297	78.0575	8.7	3.36	-	-	
271	1967 Sep 02	04:04:00	Deg	49.7419	78.0256	10.3	4.10	-	-	
292	1968 Oct 29	03:54:00	Deg	49.8333	78.0928	10.8	4.33	-	-	
298	1969 Apr 04	04:57:00	Deg	49.7533	78.0536	9.2	3.60	-	-	
299	1969 Apr 13	04:04:00	Deg	49.7356	78.1047	11.3	4.55	-	-	
310	1969 Oct 30	Not detected								
311	1969 Nov 27	05:02:00	Deg	49.8367	78.0597	10.3	4.10	-	-	
332	1971 Jan 29	05:03:00	Deg	49.8053	78.1686	11.1	4.47	-	-	
336	1971 Apr 09	02:33:00	Deg	49.8322	77.9994	9.6	3.78	-	-	B
393	1973 Nov 04	03:57:00	Bal	50.0716	78.9362	-	-	2.6	-	
395	1973 Dec 31	04:03:00	Deg	49.7394	78.0863	10.6	4.24	-	4.0	
404	1974 Jul 29	03:28:00	Bal	n/a		-	-	3.3	-	
412	1974 Nov 28	05:57:00	Mur	n/a		-	-	2.8	-	
424	1975 Jul 15	02:57:00	Deg	49.7914	78.0944	-	-	3.3	-	
429	1975 Oct 05	04:27:00	Deg	49.7831	78.0867	10.7	4.28	-	4.0	SR1
437	1976 Mar 17	02:57:00	Deg	49.7556	78.0992	-	-	2.2	-	
439	1976 Apr 10	05:03:00	Deg	49.7550	78.0475	-	-	3.0	-	
447	1976 Aug 04	02:57:00	Mur	49.87	77.7	10.5	4.20	-	3.8	SR2
476	1977 Nov 12	05:11:00	Bal	n/a		-	-	2.8	-	
477	1977 Nov 27	03:57:00	Deg	49.7544	78.0503	9.9	3.92	-	3.4	
551	1980 Jun 25	02:27:00	Deg	49.8258	78.0994	-	-	3.7	-	
559	1980 Oct 23	03:57:11	Deg	49.7517	78.1317	-	-	2.5	-	
561	1980 Dec 05	04:17:16	Deg	49.7517	78.1317	-	-	3.6	-	
627	1983 Nov 02	04:18:54	Deg	49.7792	78.1247	-	-	3.0	-	
664	1985 Jul 11	02:57:02	Deg	49.7506	78.0492	10.2	4.05	-	3.5	SR3
665	1985 Jul 19	04:00:08	Deg	49.8011	78.0686	-	-	2.5	-	
707	1988 Dec 28	05:28:10	Deg	49.8011	78.0686	9.5	3.74	-	3.63	C

First column is the explosion identifying number used by Mikhailov et al.(1996). Time, *K* and *mb*(*Lg*) are based on regional observations of CSE. (Lat., Long.) on Degelen Mountain are from Leith (1998). Event #447 is assigned to the Balapan sub-area in USSR

Nuclear Tests (1997), whereas in our opinion it took place in Murzhik. *mb*(*K*) — calculation of *mb* from *K* using the relationship: $mb(K) = 0.46\ K - 0.64$. *m*(NOR) — from F. Ringdal (pers. comm., 1994), based on teleseismic signals at NORSAR.

Comments on Table 5:
A — This event was obscured by many Aleutian earthquakes, up to *mb* 6.4 on that day.
B — The yield of this explosion has been announced as 0.23 kt (USSR Nuclear Tests, 1997)
C — This event was mentioned by Ringdal (1990). SR# — These three events are listed by Sykes and Ruggi (1986, 1989) with the following coordinates and *mb*:
1. 55.8N and 75.1E; *mb* = 4.6. 2. 49.9N and 77.7E; *mb* = 4.1. 3. 50.0N and 78.0E; *mb* = 4.0.

5. Comparison of ground truth and seismologically-determined locations, for small UNTs

Our earlier study (Khalturin et al. 1994) determined coordinates of 18 small-magnitude UNTs (one additional UNT was detected only by one station) on the basis of arrival times of regional waves, and estimated the location uncertainty, which was typically an area of the order of 100 km^2. One of those UNT was at Balapan for which we do not yet know the ground truth coordinates. For 17 UNTs (magnitudes 3.8-4.6), which occurred at Degelen, we can now compare the seismically-located epicenters with ground truth recently obtained for that sub-area by Leith (1998).

For these small UNTs, regional signals were acquired at CSE stations located at distances in the range 500 – 1400 km from STS. We mostly used data from bulletins but did read waveforms ourselves in some cases. Thus for these 17 UNTs we had 20 records and 49 station bulletin data from stations to the south; and 37 station bulletin data from stations to the east or west. So on average for the location of one event we had about one record and about three pieces of data from station bulletins located to the south of STS, and about 2 data from stations located to the east or west. On each record, 2 or 3 regional phases were measured (typically *Pn*, *Sn*, *Lg*). To obtain a preliminary estimate of location and origin time, we usually used (if they were available) three values of time intervals such as $t(Lg) - t(Sn)$; $t(Lg) - t(Pn)$ and $t(Sn) - t(Pn)$ from each station record or bulletin. Having estimated the origin time (t_0) in this way, the next step for location was to use time intervals such as $t(Pn) - t_0$; $t(Sn) - t_0$ and $t(Lg) - t_0$.

For event location we used travel times of regional phases as given by Nersesov and Rautian (1964), based on a Pamirs-Baikal profile, and observations slightly adapted by Khalturin for Northeast Kazakstan. Our locations, and the comparison with ground truth information, are given in Table 6. On average, the seismically-determined location error was only about 4 km. The ground truth location was found to lie within the interval specified by Khalturin et al. (1994) as the location uncertainty in almost all cases, and only marginally outside that interval in the few cases where it was outside. The average of absolute errors for all 17 UNTs is only 3.2 km in latitude, and 4.4 km in longitude. The average of signed errors is only 0.53 km in latitude and 0.45 km in longitude (i.e., real epicenters systematically lie 0.53 km south and 0.45 km west of our estimated locations). Since the average length of the seismic paths was 750 km, the systematic error is remarkable small — about 0.07%, corresponding to an error in velocity of about 0.005 km/s.

We have thus been able to demonstrate the utility of regional seismic waves for purposes of accurate estimation of UNT locations, even when only a few records are available per event. The location uncertainty is so small in our case, because of the availability of travel-time tables appropriate to the region.

Table 6. Comparison of seismically-determined locations based on regional phases (Khalturin et al., 1994) and ground truth locations (Leith,1998), for small UNTs at the Semipalatinsk Test Site.

Date	Latitude Seism.	G.T.	Δ Lat km	Longitude Seism.	G.T.	Δ Long km
1964 Jun 06	49.79	49.774	1.8	78.00	77.988	0.9
1964 Aug 18	49.81	49.820	-1.1	78.10	78.082	1.3
1965 Feb 04	49.78	49.773	0.8	78.12	77.991	9.2
1965 Mar 27	49.82	49.775	5.0	78.00	77.988	0.9
1966 Oct 29	49.74	49.785	-5.0	78.07	78.000	5.0
1966 Nov 19	49.70	49.730	-3.3	78.20	78.058	10.2
1967 Sep 02	49.79	49.742	5.3	78.02	78.026	-0.4
1968 Oct 29	49.84	49.833	0.8	78.14	78.105	2.5
1969 Apr 13	49.70	49.736	-4.0	77.92	78.105	-13.3
1969 Nov 27	49.79	49.837	-5.2	78.20	78.060	10.0
1971 Jan 29	49.77	49.805	-3.9	78.11	78.169	-4.2
1971 Apr 09	49.88	49.832	5.3	78.02	78.039	-1.4
1973 Dec 31	49.75	49.739	1.2	78.04	78.086	-3.3
1975 Oct 05	49.81	49.783	3.0	78.10	78.087	0.9
1977 Nov 27	49.80	49.754	5.1	78.06	78.050	0.7
1985 Jul 11	49.78	49.750	3.3	77.90	78.049	-10.7
1988 Dec 28	49.80	49.801	-0.1	78.06	78.069	-0.6

6. General discussion

A longer version of this paper, with the same title and authors, has been submitted for publication in the journal Pure and Applied Geophysics (special volumes on CTBT monitoring). The longer version lists 29 chemical explosions on and near STS, as well as several earthquakes; shows the magnitude distribution of all observed UNTs (it appears more than 40 were sub-kiloton); and shows that the yield estimated for each UNT on the basis of its magnitude *mb* is in good agreement with the officially announced total yield on UNTs for each year at STS.

CONCLUSIONS AND RECOMMENDATIONS

The most important point to draw from our study is that detection capability has been very good for recent decades in Central Asia, since all but two UNTs at the Semipalatinsk Test Site with yields announced as greater than 1 ton have now been associated with regional detections. Detections have also been very good using only teleseismic data. But for accurate location and confident identification, additional data is often needed. In practice, such additional data can often be provided by regional stations. When regional travel times are well calibrated, they can be used to proved accurate locations even when few stations are available.

Now that we have documented an almost complete list of UNTs at the main test site of the former Soviet Union, we recommend that efforts be supported to build up the database of waveforms, particularly for the small events, since these are the types of signal the IMS must be designed to detect and identify. A waveform database for these events can be an important training set, as well as a basis for comparison with problem events in the future.

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