Science & Global Security, 1993, Volume 3, pp.289–309
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Printed in the United States of America

Teleseismic Monitoring of Underground Nuclear Explosions at the Nevada Test Site from Borovoye, Kazakhstan

Vitaly V. Adushkin[a] and Vadim A. An[a]

This paper outlines the results of three decades of teleseismic observations of US underground nuclear explosions from the Borovoye calibrated seismic station in Kazakhstan in the Commonwealth of Independent States. The Borovoye site is an extraordinary "sweet spot" to monitor tests. As a result, it has been possible to verify underground nuclear explosions at the Nevada Test Site in the United States through teleseismic data, starting even at the lowest yield of 2–5 kilotons. In addition, if sufficient information from other seismic stations can be obtained to identify the geological medium of the explosion, measurements from Borovoye can be used to estimate the yield of US explosions to about 20 percent uncertainty—a remarkable precision.

INTRODUCTION

Underground nuclear explosions are primarily monitored through data from a network of seismic stations, which means that the performance of each individual station in the system is considerably important. This paper examines the capabilities of the Borovoye seismic station to monitor underground nuclear explosions at the Nevada Test Site (NTS). The primary data are based on observations of explosions at three sub-areas of the Nevada test site: Pahute Mesa, Rainier Mesa and Yucca Flat. The overwhelming majority of US underground nuclear explosions were carried out at these locations. The paper also examines the results of recordings of explosions at other NTS ranges, and at US test sites outside the NTS.

The Borovoye seismic station is located near Kokchetav in northern Kazakhstan. Situated at 53°03'29" N and 70°16'58" E,[1] the seismic station sits

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[a] Institute of the Dynamics of Geospheres of the Russian Academy of Sciences, Leninsky Prospect 38, Korpus 6, 117334, Moscow, Russia

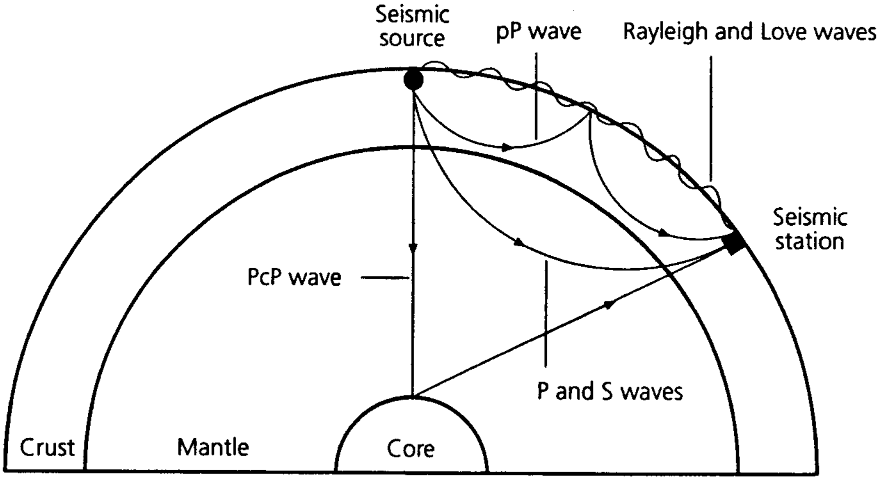

Figure 1: Various types of seismic waves generated by either an earthquake or explosion.

within a 15 meter deep vault in a mass of ancient, fractured granite, which outcrops at the surface. Dense, slightly fractured granites starting at a depth of 5–10 meters are characterized seismologically by a P-wave velocity of C_p= 5.7–6.2 km sec^{-1}. P or primary waves are the fastest of seismic energy waves that travel through the body of the Earth, as opposed to along the surface. They are compressional waves, which alternately compress and expand the material they pass through. The Moho, or boundary between the Earth's crust and underlying mantle layer, is found beneath Borovoye at a depth of 52–55 kilometers, with a velocity for P waves of C_p = 8.25–8.40 km sec^{-1}. At this boundary, the seismic velocity increases abruptly. Figure 1 illustrates the various seismic waves propagating through the Earth.

In the late 1950s, during seismic research near the Soviet Union's Semipalatinsk nuclear test site, we learned that P waves produced by underground nuclear explosions at the NTS could be recorded with great efficiency in the Borovoye region. Subsequently, observations from stations as far as 100 kilometers from Borovoye established that this efficiency is characteristic of the entire Kokchetav geologic area. It became clear that the seismic station was one of the most sensitive in the Soviet Union for monitoring the NTS, despite the fact that Borovoye is 10,000 kilometers away from Nevada.

Non-stop seismic observations of the NTS began at the Borovoye station in 1960. Recording using digital seismic instruments first developed in the Soviet Union at the Earth Physics Institute of the Academy of Sciences has been constant since 1965.[2] Subsequently, Borovoye station has been used to

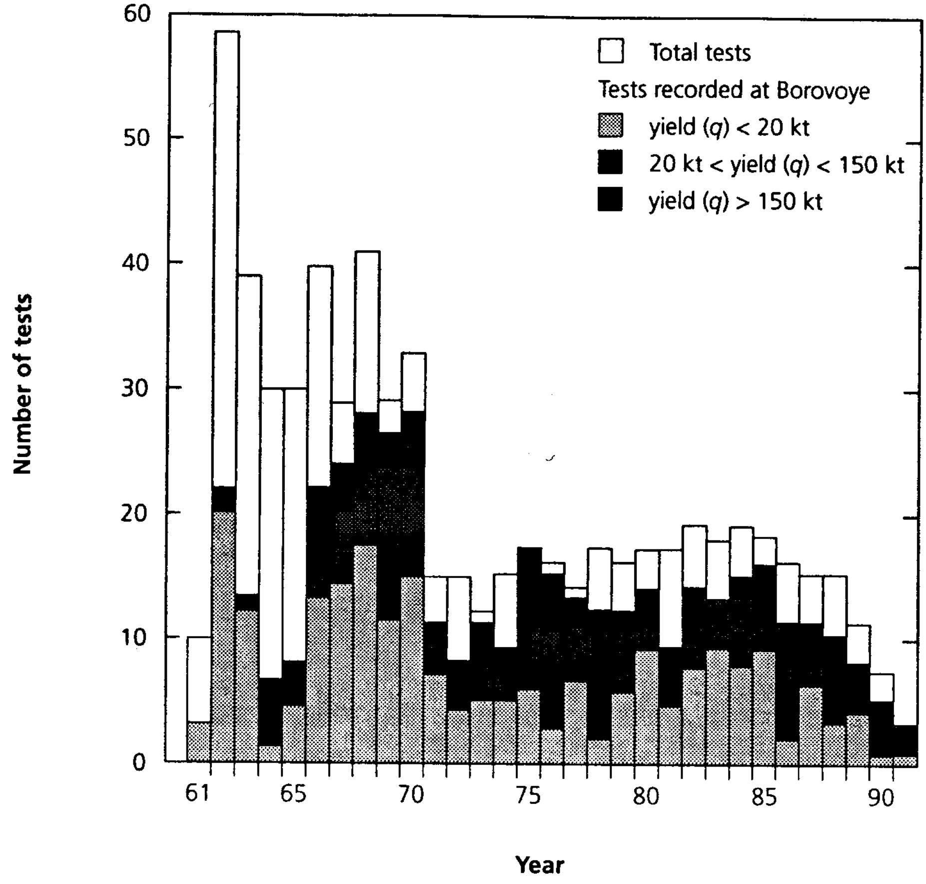

Figure 2: Underground nuclear tests in the US, from 15 September 1961 through 16 April 1991, by year. Shaded bars represent tests recorded at Borovoye.

test the majority of new Soviet seismic instruments, including various digital systems.

From 15 September 1961 through 16 April 1991, the US conducted 652 underground nuclear explosions,[3–7] 414 of which were recorded at Borovoye.* Figure 2 shows a breakdown of the tests by year and yield range. Some tests were not recorded because of low yield—their seismic signal was not large

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* Borovoye seismic station is equipped with short-period and long-period equipment in the 0.5–5.0 hertz and 0.04–0.1 hertz frequency bands, with maximum responses of 10^5 and 10^3 counts per micron, respectively. The range of recordable amplitudes is 10^2 to 2×10^4 nanometers in the short-period range and 1 to 2×10^6 nanometers in the long-period range.

enough to be read at Borovoye. Others were missed because of technical problems such as breakdown or changes in equipment.

MORPHOLOGY OF SEISMIC WAVES AND MICROSEISMS

Borovoye seismic station is located in a nearly aseismic region, with a low level of natural and anthropogenic microseisms. The nearest earthquakes take place 900–1,000 kilometers away from Borovoye. This natural seismic quiet is extremely important for monitoring, which involves a constant struggle to detect the desired seismic signal distinct from the "background noise."

Specifically, the level of microseisms at Borovoye is estimated at amplitudes of 1–10 nanometers in the recordable short-period range, with periods of 2–3 seconds. In the long-period range of 6–8 seconds, the level is 100–200 nanometers. Figure 3 shows the spectral density of the microseisms.

From underground nuclear explosions at the NTS, Borovoye seismic station first records the fastest seismic waves—P-wave groups with a travel time of 13 minutes. It then records a pP wave—a P wave that has been reflected once from the Earth's surface—3.5 minutes later; an S wave—a shear wave with side-to-side motion, which travels more slowly through the Earth, after 7 more minutes; and finally the waves that have traveled along the Earth's surface, beginning 27 minutes later. An S wave is observed only after very large explosions in which m_b (denoting the magnitude of seismic waves) > 6.3–6.4; that is, if $m_b < 6.3$ for P waves, S waves could not be observed. This is because explosions do not propagate much shear wave energy, and those S waves that are generated do not travel long distances efficiently, so are too attenuated by the time they arrive at Borovoye to be distinguished from the background seismicity.

A P wave is recorded at Borovoye as a brief oscillation train of pulse form with maximum amplitudes (A_{max}) in the vertical channel that fade to a level of 0.3 A_{max} within 15–20 seconds. Figure 4 gives the characteristic form for a recorded P-wave group. As the yield of an explosion decreases the amplitude of the first peak ("1" in figure 4) decreases to 0. The second oscillation ("4" in figure 4) has been interpreted as the arrival of a PcP wave (a P wave reflected off the Earth's core) or of a pP wave.

If this is indeed a PcP wave, as some researchers believe,[8] then a thin layer of material characterized by decreased seismic velocity might exist at the core-mantle boundary. This has yet to be confirmed, however, since the onset of this wave has not been isolated in its pure form.

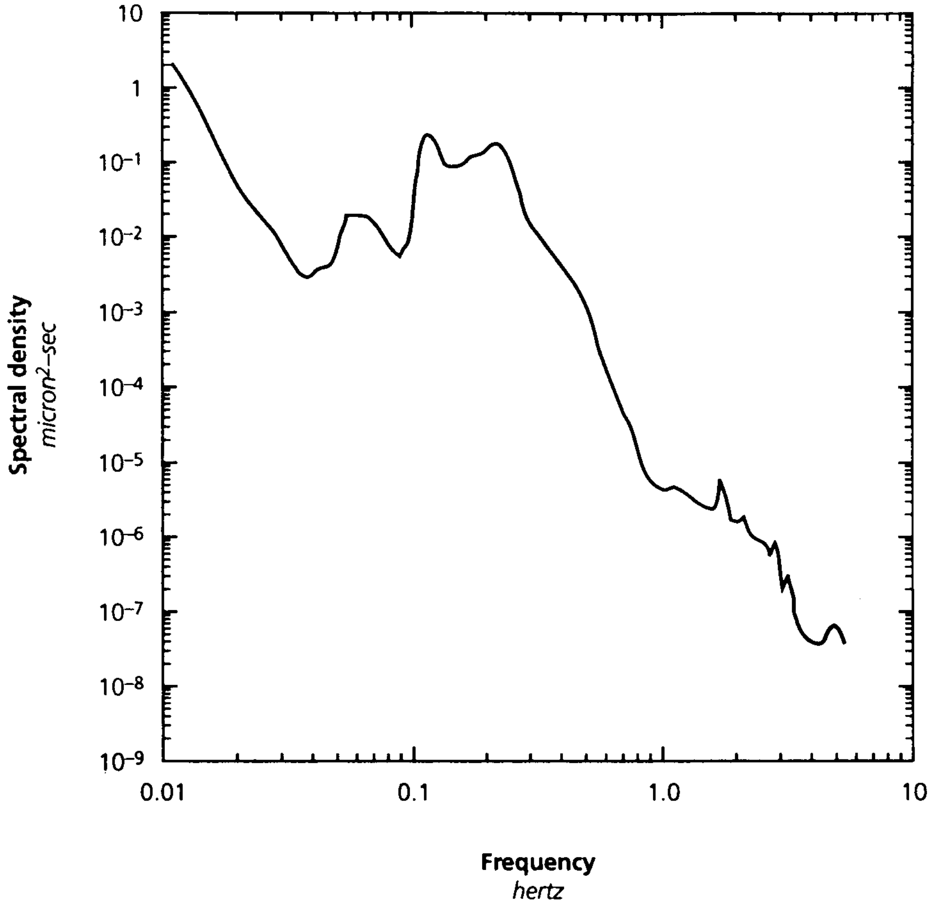

Figure 3: Microseismic background at the Borovoye seismic station.

In any case, a P-wave group registers clearly, starting from the lower threshold of m_b = 4.0–4.1. The oscillation period, T, which corresponds to the maximum amplitude in the P-wave group, falls in the range of T = 0.7–1.4 seconds. It is negligibly dependent on the value m_b and increases in the interval m_b = 4.0–6.4 per 0.09 seconds per unit of magnitude. The pP wave becomes visible after explosions with magnitudes m_b > 4.5–4.7.

As a rule, a Rayleigh wave (a type of wave traveling along the Earth's surface) is observed very faintly at Borovoye, and only after the most powerful explosions (see figure 5). Such a wave registers from m_b = 5.3–5.5 in the form of two groups of waves with periods of 19–21 seconds and 16–17 seconds, which follow one another approximately every two minutes. After explosions

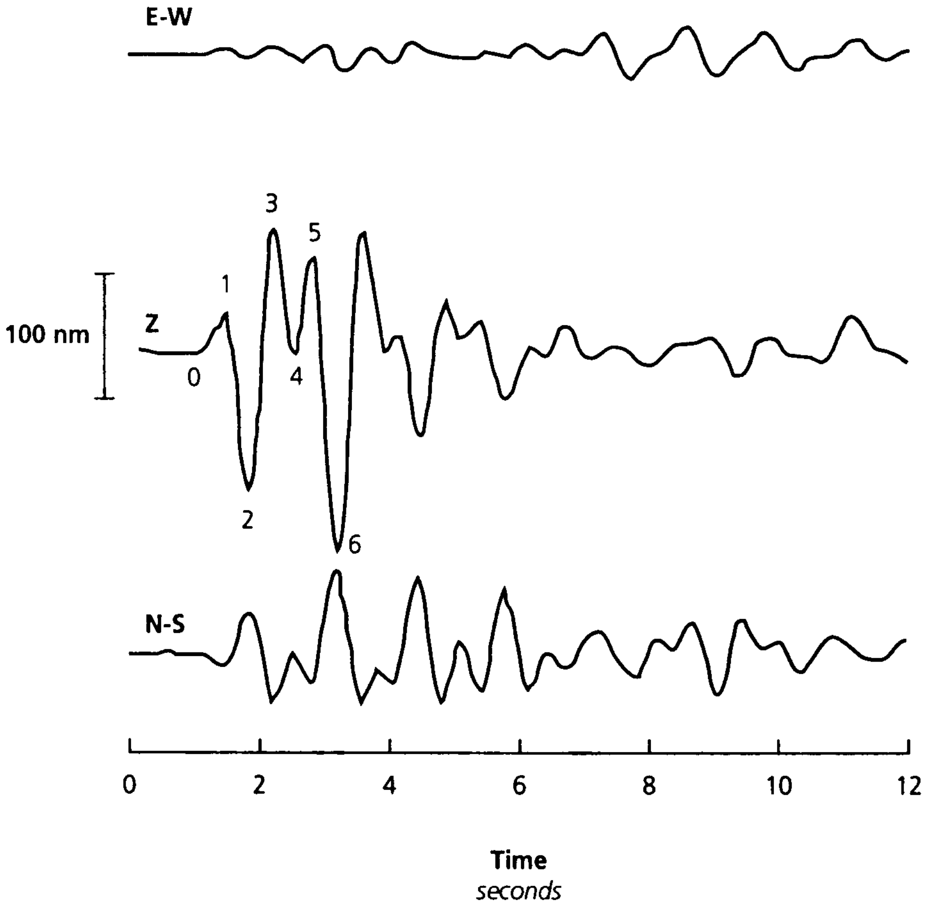

Figure 4: Seismogram of a P-wave group from an underground nuclear explosion at the NTS, that was registered at Borovoye station: Rousanne, 12 November 1981, $t_0 = 15^h00^m00^s.1$, Yucca Flat, $m_b = 5.4$.

with a yield of over 600–700 kilotons ($m_b > 6.0$–6.1), the number of observable Rayleigh wave groups increases to between 7–9. The first wave is tracked with a period of 30–32 seconds at 8 or 9 minutes before the onset of a group with a period of 20 seconds. The greatest value of the ratio of the amplitude of a Rayleigh wave to its period is generally observed in a group with a period of 16–17 seconds. In essence, detection of a Love wave at Borovoye indicates a very powerful explosion at the NTS.

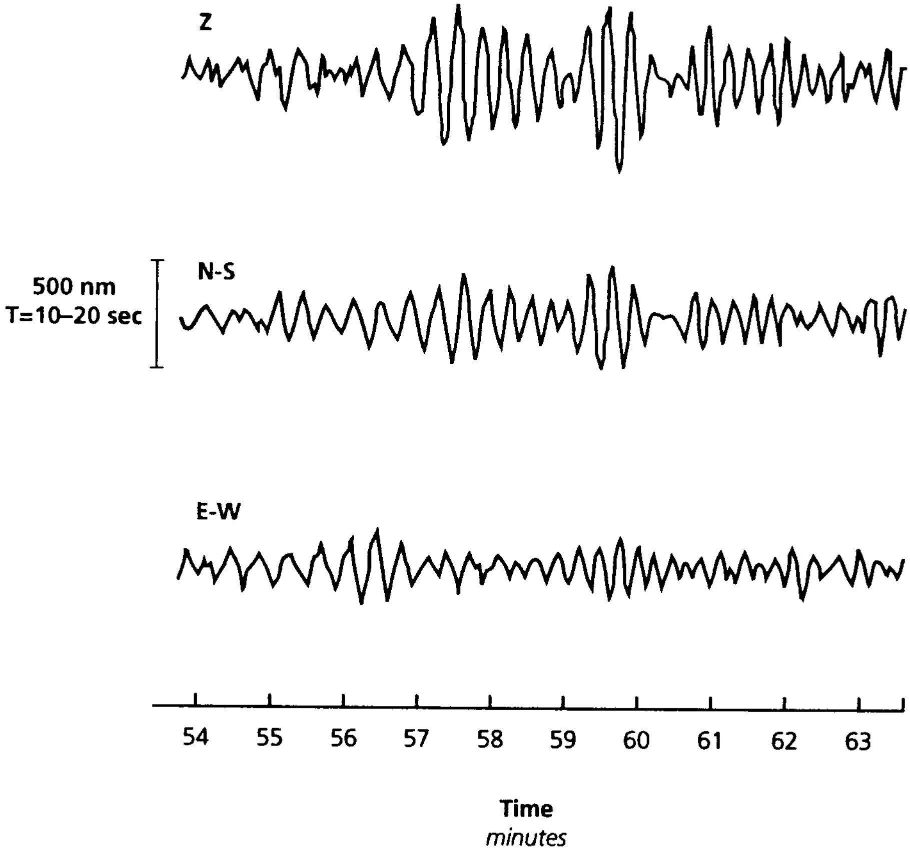

Figure 5: Seismogram of a Rayleigh ground wave at Borovoye seismic station, from an underground nuclear explosion at NTS: Alamo, 7 July 1988, $t_0 = 15^h05^m00^s.072$, Pahute Mesa, M_s = 4.3, m_b = 5.7. (Time in minutes after explosion occurred.).

IDENTIFICATION OF EXPLOSIONS AND EARTHQUAKES

Explosions and earthquakes are distinguished from each other through a set of several criteria whose efficacy varies. An earthquake can often be differentiated from an explosion by identifying the polarity, or direction, of the first compressional wave to be received at the seismic station. If the first "motion" of the wave is rising, then either an earthquake or explosion may have generated it, but a descending first motion pinpoints an earthquake source. However, it is difficult to identify the polarity of the first compression halfwave after an explosion of less than 10 or 20 kilotons. Another complication is that the NTS is not located in an aseismic area.

A correlation of the magnitudes identified for body waves (those that travel through the Earth) and surface waves is a more reliable way to differentiate explosions from earthquakes. Using the $m_b : M_s$ criterion, Borovoye station is capable of identifying 80–90 percent of all earthquakes, without missing any explosions. However, this criterion works only down to $M_s = 4.2$–4.3, which corresponds to an explosive yield on the order of 80–100 kilotons. The use of frequency and phase-locked filtrations (based on the well-known dispersion of a Rayleigh wave) may lower the amplitude threshold of detection by 6–12 decibels. In essence, filtration of the data can extend the detection level even lower. Research continues in this area.

Identification criterion to distinguish underground nuclear explosions from the earthquakes based on time-spectrum analysis of the short period P-wave code was worked out. It was also used to identify explosion and earthquake P waves by its frequency and the form of the record. This analysis is the line filtration of the income signal by the shortband and frequency filters and by representation of the filtered signals amplitude as time and frequency ratio filter. A seismogram of the 10 kiloton explosion at NTS recorded at Borovoye station and a diagram of the time-spectrum analysis of this explosion are in figure 6. This diagram is created on eight successive five-second intervals on each of the five filters. Changing of the spectrum frequency structure in time on the seismogram of the explosion is essentially different from the same spectrum on the seismogram of the same intensity earthquake. Use of the different spectrums allowed a clear discrimination between 38 explosions done at the NTS and 19 earthquakes at different parts of the Earth. The efficiency of this method for identifying earthquakes at the regions directly adjacent to the NTS should be studied. It is necessary to study the efficacy of the method for identifying earthquakes in the regions directly adjacent to the NTS.

ESTIMATING EXPLOSION YIELDS

An initial means to estimate the yield of an explosion is with the magnitude of the P wave. It has been noted[1] that the difference in magnitude $\delta m_b^{BRV} - m_b$ (BRV for Borovoye) is 0.70 ± 0.18, and is practically independent of the NTS range, the enclosing rocks (tuff or alluvium) and the value m_b. That is, the Borovoye observation unit is consistently 0.70 units higher than the standard values published by the International Seismic Center, representing a global-average value. However, δm_b^{BRV} deviates from the mean value by as much as ± 0.5 units of magnitude, which cannot be explained by metering errors at Borovoye station. It is most likely that such large deviations in δm_b^{BRV} are

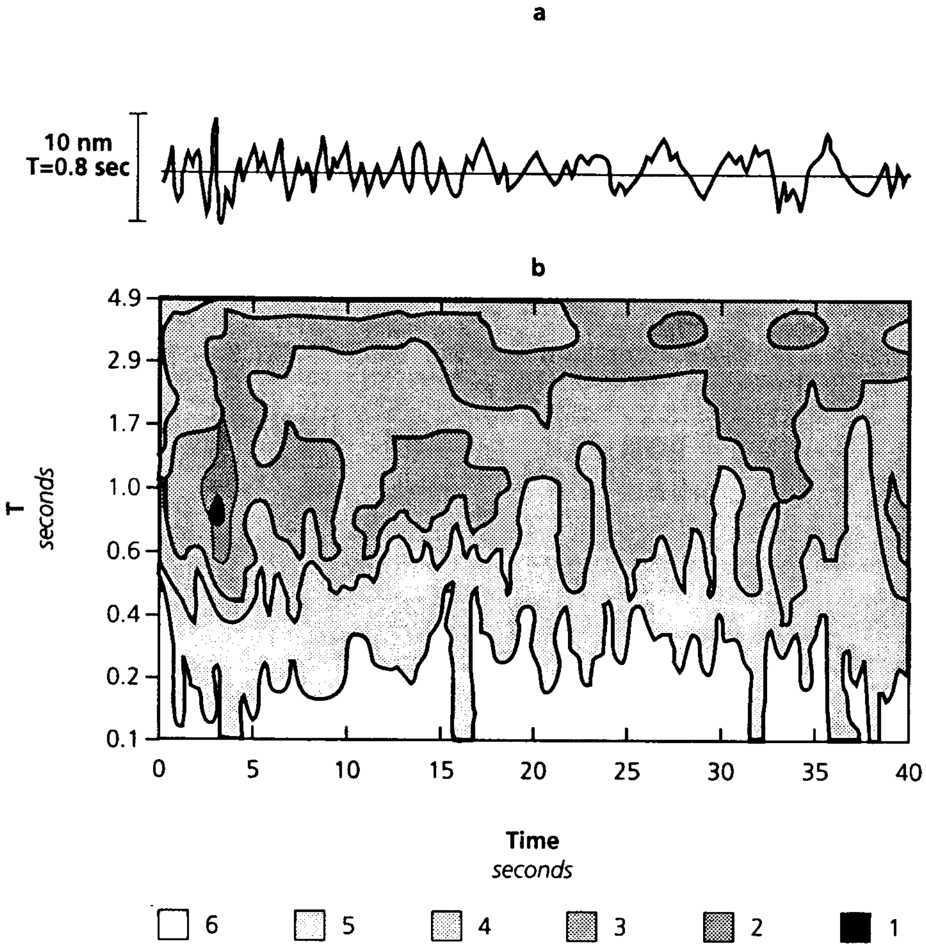

Figure 6: Example of a spectral-time analysis for a recording of a P wave at Borovoye station, from an underground nuclear explosion at the NTS: Packard, 15 January 1969, t_0 = 19.00.00.070, m_b^{BRV} = 5.1, Yucca Flat. (a) Seismogram of the vertical channel, (b) diagram of a spectral-time analysis, with contours of diverse shading in the diagram corresponding to normalized amplitudes in the frequency-time plane: 1–1; 2–0.6; 3–0.3; 4–0.1; 5 –0.03; 6 < 0.03.

related to the number and types of seismic stations which, in each individual case, report their results to the International Seismic Center and hence determine the mean value of the magnitude of m_b. Other causes may also be responsible.

The relationships between m_b^{BRV} and the yield of an explosion[3,4] are presented in figure 7. It is apparent that explosions in such rocks as alluvium, tuff and rhyolite at Pahute Mesa, Rainier Mesa and Yucca Flat are practically indistinguishable through the values for m_b^{BRV}. The magnitudes of m_b^{BRV} for

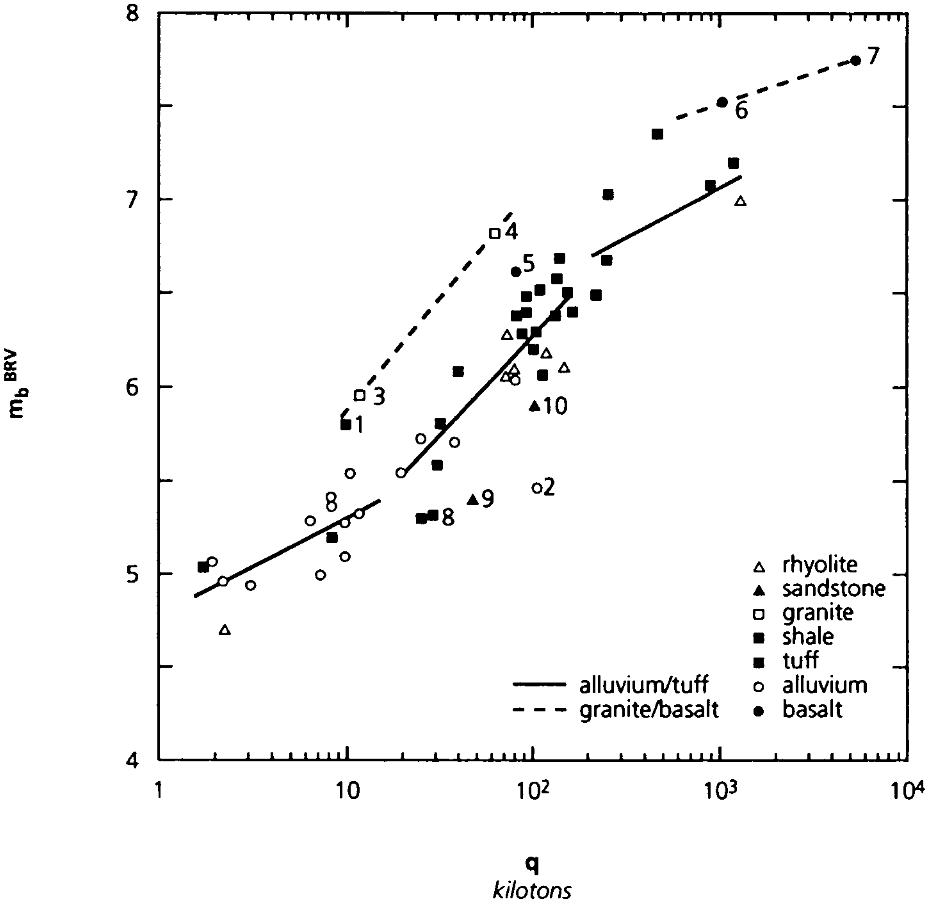

Figure 7: m_b^{BRV} as a function of an announced yield q (kilotons). The numbers indicate explosions: 1-Baneberry (NTS), 2-Sedan (NTS), 3-Shoal (Central Nevada), 4-Pile Driver (NTS, Climax Stock), 5, 6, 7-Amchitka, Aleutian Islands, 8-Gas Buggy (New Mexico), 9, 10-Rulison, Rio Blanco (Colorado).

NTS explosions in Nevada granite (nos. 3 and 4 in figure 7) and in lavas and basalt on Amchitka Island (nos. 5, 6 and 7 in figure 7) are systematically higher by 0.4–0.8 units than the global average.

A significant feature of the graph in figure 7 is the absence of a linear relationship between m_b^{BRV} and log q within the investigated range of 1–10^3 kilotons (where q is the explosion yield in kilotons). Based on the data presented and using piecewise approximation, the following relationships were constructed for three ranges of explosive yield at NTS:

$$
\begin{aligned}
m_b^{BRV} &= 0.52 \cdot \log q + 4.78, \text{ for } q < 20 \text{ kilotons} \\
m_b^{BRV} &= 1.07 \cdot \log q + 4.13, \text{ for } 20 \leq q \leq 150 \text{ kilotons} \qquad (1) \\
m_b^{BRV} &= 0.53 \cdot \log q + 5.48, \text{ for } q > 150 \text{ kilotons}
\end{aligned}
$$

These numbers were calibrated from announced US test yields.

Apparently, the nature of the relationship between m_b^{BRV} and yield is tied to the considerable effect by the depth of a charge on seismic efficiency. This is because higher yield explosions are carried out at greater depths. The relationship is also linked to any change, based on depth, in the physical, mechanical and gas-forming properties of the enclosing rocks, which determine the action of an explosion on the surrounding environment. It is obvious that the depth of an explosion influences not only the lithostatic pressure, but also the stability, density, porosity and wave velocity of elastic waves and the moisture content of rocks. All of these properties have an integral effect on the transfer of the energy from an explosion to the creation of seismic waves. It follows from the relationship in equation 1 that two conventional boundaries have been singled out at the NTS by all of the properties that influence the action of an explosion on the surrounding environment and, accordingly, the seismic efficiency. One boundary is at a depth of 200–250 meters. Nuclear weapons with yields of between 20 and 150 kilotons are generally detonated at depths of 200–450 meters. Those with yields greater than 150 kilotons are detonated at 450–550 meters.

A yield estimate based only on the use of P waves has an error of approximately 200 percent. However, estimates of US yields can be improved by an order of magnitude through the use of additional seismic instruments. A yield estimate can also be made significantly more accurate by using records of seismic oscillations recorded at other locations, such as on US territory.

In the graph in figure 7, the magnitudes of several explosions at the NTS differ considerably from equation 1. For example, the unusually low m_b^{BRV} value for the Sedan explosion may be explained by the fact that the explosion formed a crater, and was a shallow blast carried out to test the use of an explosion for excavation. A considerable portion of the explosion's energy was expended in moving 12 million tons of rock and forming an airborne shock wave. However, there is no explanation for the unusually high m_b^{BRV} value after the Baneberry explosion (no. 1 in figure 7). The yield of this explosion may have exceeded the published yield, or the nuclear charge may have been placed in rock with a high moisture content. This latter possibility is indicated by the unusual shape of the seismic signal received at Borovoye—an evenly attenuating sinusoidal oscillation with a period of 0.7 seconds (figure

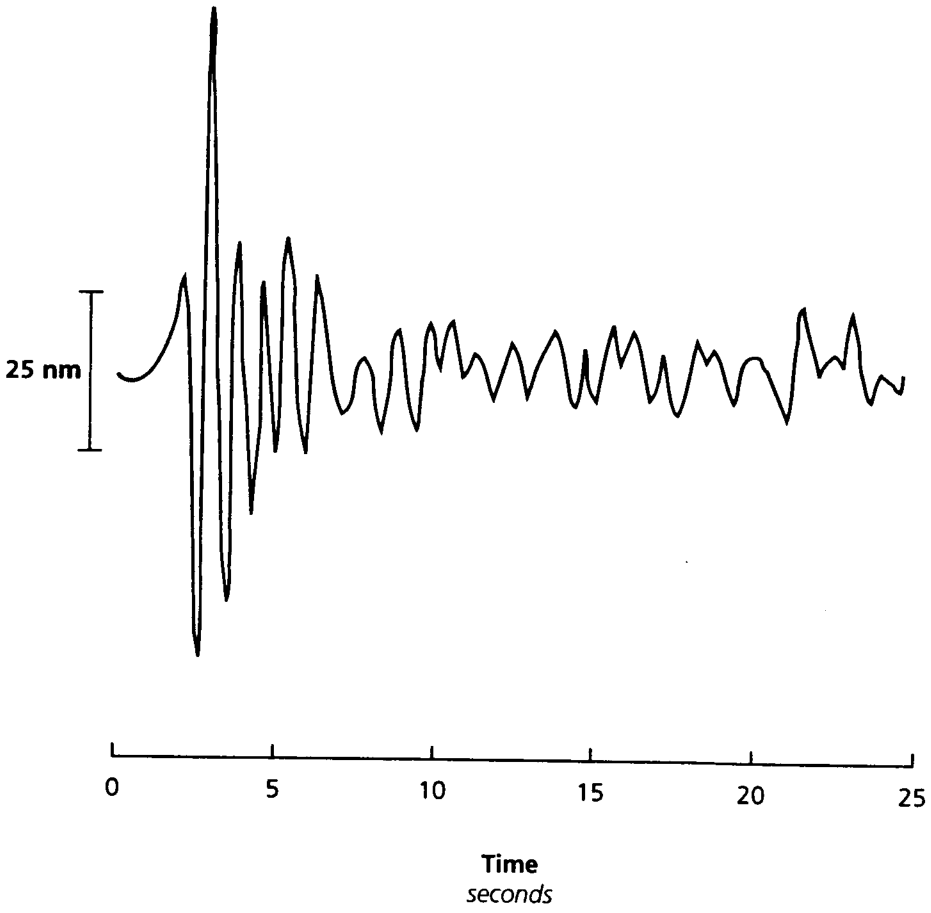

Figure 8: Recording of a P wave from the Baneberry, US explosion, 18 December 1970, using the vertical short-period channel of Borovoye station.

8). It resembles the recording of a high-Q electrical circuit excited by short impulses.

The magnitude (M_s^{BRV}) found at Borovoye for a Rayleigh surface wave may have a scatter, relative to M_s, of as much as ±0.5 units. Nevertheless, as figure 9 shows, M_s^{BRV} tends to increase, relative to M_s, the global average published by the International Seismic Center, by roughly 0.2 units. Figure 10 demonstrates the relationship between M_s^{BRV} and the yield of an explosion at NTS. It may be expressed by the equation

$$M_s^{BRV} = 1.22 \cdot \log q + 1.95 \qquad (2)$$

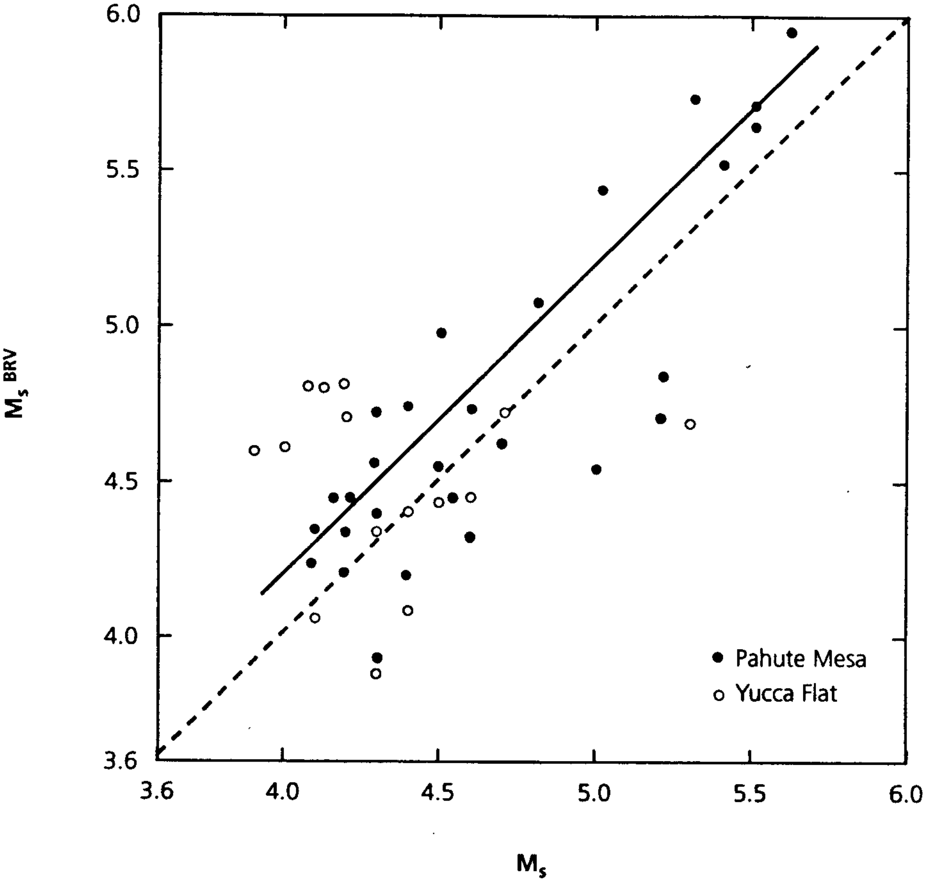

Figure 9: M_s^{BRV} as a function of M_s. The magnitude of the surface wave at Borovoye is 0.2 units greater than the global average.

It is apparent in figures 7 and 9 that an estimate of explosive yield based solely on data from m_b^{BRV} and M_s^{BRV} will harbor considerable error. Therefore, the form of the oscillations in the P-wave group is normally used to increase the accuracy of determining an explosion's yield. The form contains information about conditions at the origin that affect the explosion's seismic efficiency. This technique has already been utilized extensively.[9, 10, 11, 12]

ESTIMATION METHODOLOGY

To improve estimation capability beyond that possible from the method

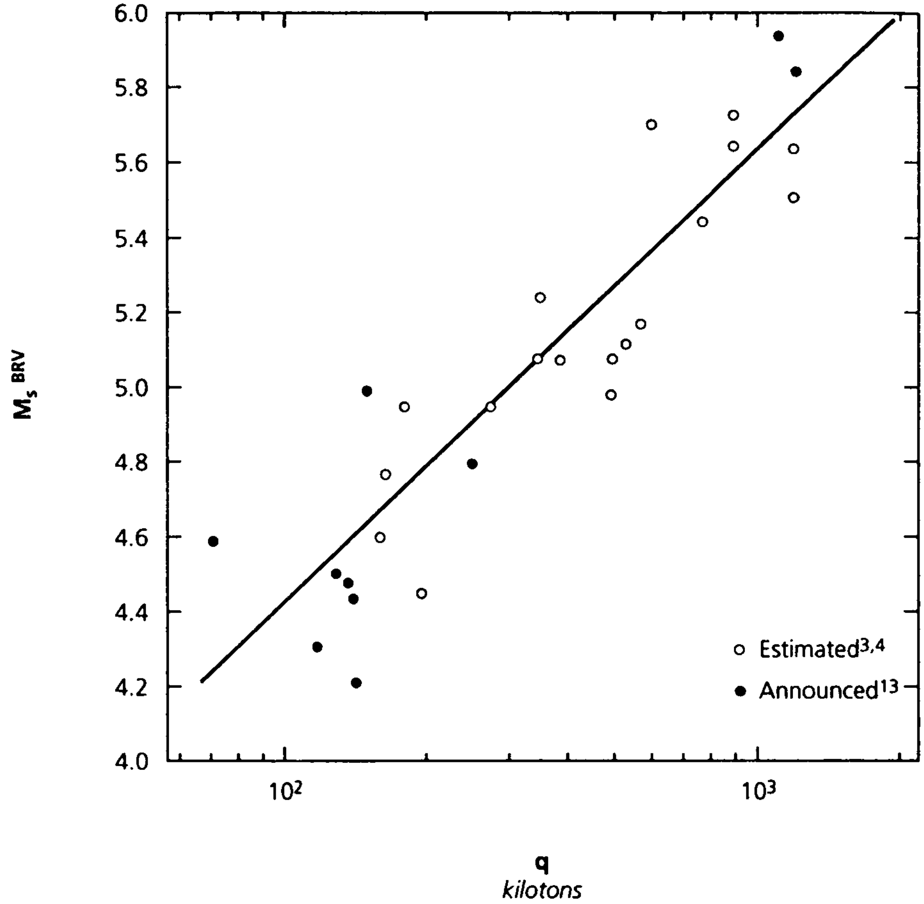

Figure 10: M_s^{BRV} as a function of yield.

already described, we use the following steps:

(i) The value of the "nominal" (as it is conventionally named) magnitude m_b^* is used, instead of the magnitude m_b^{BRV}. This value is found in the vertical short-period channel through the amplitude and period of the second oscillation half-cycle after the moment of the onset ("2" in figure 4).

Magnitude m_b^* is used by the Soviet seismic observation service because the magnitude m_b^{BRV} is conventionally found in a time interval 25 seconds after the moment of onset of a P wave. However, the interference of two waves (a P wave and a succeeding PcP or pP wave) occurs in this time interval at an epicentral distance of 90°. The maximum amplitude ("6" in figure 4) is sometimes generated in this case. It is dependent not only on an explosion's yield, but also on the value of a phase shift between interfering oscillations. In addition, a visible oscillation period with the maximum amplitude is noticeably altered. This process of interference may also be one of the causes of the scattering of m_b^{BRV} relative to m_b, when m_b^* is found before the moment of interference.

(ii) The form of a recording of a P-wave group obtained at Borovoye station from an explosion at the NTS is characterized by diverse attenuation of the P wave code. (see figures 4 and 8). The attenuation varies because different parts of the test site feature different rock types. Some researchers[14] used the time in which the amplitude decreases to $0.3 \cdot A_{max}$ as the characteristic of attenuation of P waves. The given methodology inserts the conventional factor K as the characteristic of attenuation. It is equal to the ratio of the intensity of oscillations at intervals of 0–3 seconds and 3–10 seconds after the moment of onset of a P wave.

(iii) The yield of an explosion is estimated with a correlation obtained through regression analysis of the parameters of explosions with announced yields at the NTS:

$$\log q_{BRV}\,(\text{kilotons}) = 0.747 \cdot m_b^* - 0.294 \cdot K - 2.021 \qquad (3)$$

Table 1 gives examples of an estimation that uses equation 3 to find the yields of several explosions in the range $m_b^* = 5.0–6.4$, which corresponds to $q = 20–150$ kilotons. It is apparent that the yield estimates do not exceed announced values by more than ±20 percent if observations from other seismic stations can be used to gain information on the geology and hydrology of the region of the explosion source. Therefore, this method reduces, by a factor of 10, errors in yield estimates obtained through the correlation in equation 1.

It is noteworthy that many years of observations for the NTS-Borovoye path detected cyclical changes in the travel time and amplitude of a P wave, with primary cycles of 10–11 and 6–7 years.[15,16] We assume that these changes result from periodic variations in the elastic properties of the environment along the trajectory of a seismic wave. In our data for 1967–1989, the maximum variation in the travel time was 0.2 seconds (approximately 0.02 percent), but the maximum amplitude variation reached 100 percent. It is possible that this phenomenon is responsible for some of the uncertainty in the relationship between magnitude and yield (see figure 7).

Table 1: Estimated yield of underground nuclear explosions at the NTS from P-wave formation at Borovoye.

Date	Name	Yield kt	m_b^{BRV}	m_b^*	K	q^{BRV} kt	δq %
23/05/67	Scotch	155	6.5	6.25	1.37	176	+14
26/05/67	Knickerbrocker	76	6.1	5.79	1.18	91	+20
08/12/68	Schooner	30	5.6	5.24	1.28	33	+10
05/02/70	Labis	25	5.3	5.05	1.03	28	+12
23/03/70	Shaper	-	6.4	6.01	1.61	99	-
26/05/70	Flask	105	6.3	5.98	1.77	84	-20
08/07/71	Miniata	83	6.4	5.97	1.94	74	-11
26/04/73	Starwort	90	6.4	5.92	1.58	86	-4
06/09/79	Hearts	-	6.5	6.37	2.14	128	-
28/01/82	Jornada	-	6.5	6.30	1.71	152	-
05/08/82	Atrisco	-	6.4	6.34	1.68	166	-
01/09/83	Chancellor	-	6.1	5.76	0.89	105	-
17/07/86	Cybar	-	6.2	5.88	1.06	115	-
17/08/88	Kearsarge	-	6.0	5.80	1.08	99	-

CONCLUSIONS

The ability of Borovoye seismic station to register P waves from explosions at the NTS with great accuracy is apparently due to the geological peculiarities of the structure of the Earth's crust around Borovoye. By all measures, the Borovoye site is extraordinarily sensitive. P waves are the first seismic waves to arrive, they are easy to identify, and they travel for great distances, even when generated by small explosions. Our results enabled the development of methods and algorithms for detecting, identifying and estimating the yield of an explosion. They were implemented in an automated system for registering and processing seismic phenomena.

Many years of observations at Borovoye station demonstrate that a highly sensitive, well-calibrated seismic station makes it possible, even from a distance on the order of 10,000 kilometers, to detect and identify the main parameters of an underground nuclear explosion with a yield as low as 2–5 kilotons. Taking into account additional geological information concerning the source of the explosion, derived from observations at other seismic stations, it is also possible to estimate the yields of these explosions with uncertainties of less than 20 percent.

ACKNOWLEDGEMENTS

The authors express gratitude to Gregory E. van der Vink for advice and help in preparing this article. The translation of the manuscript was provided by the Office of Congressman Edward J. Markey.

Appendix: Signal Detection

At Borovoye, data recorded on short-period P waves are mainly used to detect and identify an explosion, as well as to estimate its yield and determine its epicenter—the point on the Earth's surface directly above the explosion.

A seismic signal is detected through the customary method, which includes preliminary frequency filtration and identification of the relations of the dispersions of recorded oscillations in small (approximately one second) and large (approximately 20 seconds) time "windows." Then a polarization analysis is conducted through the E.A. Flinn method in order to verify the preliminary solution and find the approach azimuth, the angle of incidence and the polarization parameters of the seismic wave.[17] The type of wave is identified by the angle of incidence to vertical and the degree of polarization.

An estimate of the geographic coordinates of the epicenter and the time at the origin is based on the observed approach azimuth (α_p) and the angle of incidence (i_p) of a P wave. The computation of the epicentral coordinates takes into account systematic discrepancies in the approach azimuth and the angle of incidence. The true azimuth from Borovoye to the NTS is computed through the geographic coordinates of the station and epicenters of published explosions. It may vary, depending on the sub-area of the NTS, within a range $\alpha = 5.01°–5.43°$. The observable mean value of the approach azimuth of a P wave ($\alpha_p = 353.04° \pm 0.19°$) was found through the 73 most powerful explosions. Thus, the systematic discrepancy of the approach azimuth is $\delta\alpha = -12.2°$. The observable mean value of the angle of incidence of a P wave is $i_p = 18.56° \pm 0.13°$. A value based on the A.R. Banghar tables[18] was adopted for the "true" angle of incidence $i = 14.66°$ for $\Delta = 90°$. (Δ = epicentral distance measured in degrees of arc from the earth's core; $\Delta = 90°$ is the approximate distance from Nevada to Borovoye.) The tables were calculated from a travel-time curve of an E. Herrin P wave.[19] Thus, the systematic discrepancy in the value of the angle of incidence is $\delta i = 3.90°$. It is noteworthy that the approach azimuth and angle of incidence are found at Borovoye through the direction of the major axis of quasiellipses of polarization in the first oscillation in a P-wave group.

The error in a measurement of the approach azimuth and angle of incidence by a ternary system at Borovoye station is roughly 1°. This corresponds to the maximum error in finding the epicentral coordinates: an azimuth error of 100–150 kilometers and a radial error of 300–400 kilometers. The error in finding the epicentral distance creates the maximum error in finding the time at the origin, which may be as much as 20 seconds.

Figure A-1 shows a local travel-time curve of a P wave for the main NTS test ranges, based on data from Borovoye station. It is expressed by the equation

$$t_p = 4.81 \cdot \Delta° + 348.66 \text{ (seconds)} \qquad \text{(A-1)}$$

Based on the travel-time curve (equation A-1), the travel time of a P wave with $\Delta = 90°$ differs from the H. Jeffreys–K.E. Bullen travel-time curve[20] by –1.14 seconds, from the E. Herrin curve[19] by +0.84 seconds, and from the S.D. Kogan curve[21] by +0.54 seconds. In other words, the most accurate travel-time curve of a P wave with a ground source is a travel-time curve from reference.[21] The local travel-time curve (equation A-1) is given for sea level, taking into account the high-velocity geological sections at the NTS ranges.[22] The Borovoye station's elevation above sea level (h = 340 meters) was not factored in. The local travel-time curve was plotted for 167 explosions. It turned out that the travel time deviated by more than 0.3 seconds in only seven cases. We may assume that this was due not to any physical phenomena, but simply to erroneous information about the source parameters. The travel time of a P wave from the NTS to Borovoye is independent of a value m_b in a range $m_b = 4.0–6.4$.

The algorithm described above for detecting and identifying the main parameters of the origin was implemented in the "Seismostation" automated programming system, which has functioned at Borovoye station since 1989.[23] This system processes all signals as having originated from surface sources. It has not been possible to completely automate the identification of seismic wave types with this system; a seismologist must interpret the final results.

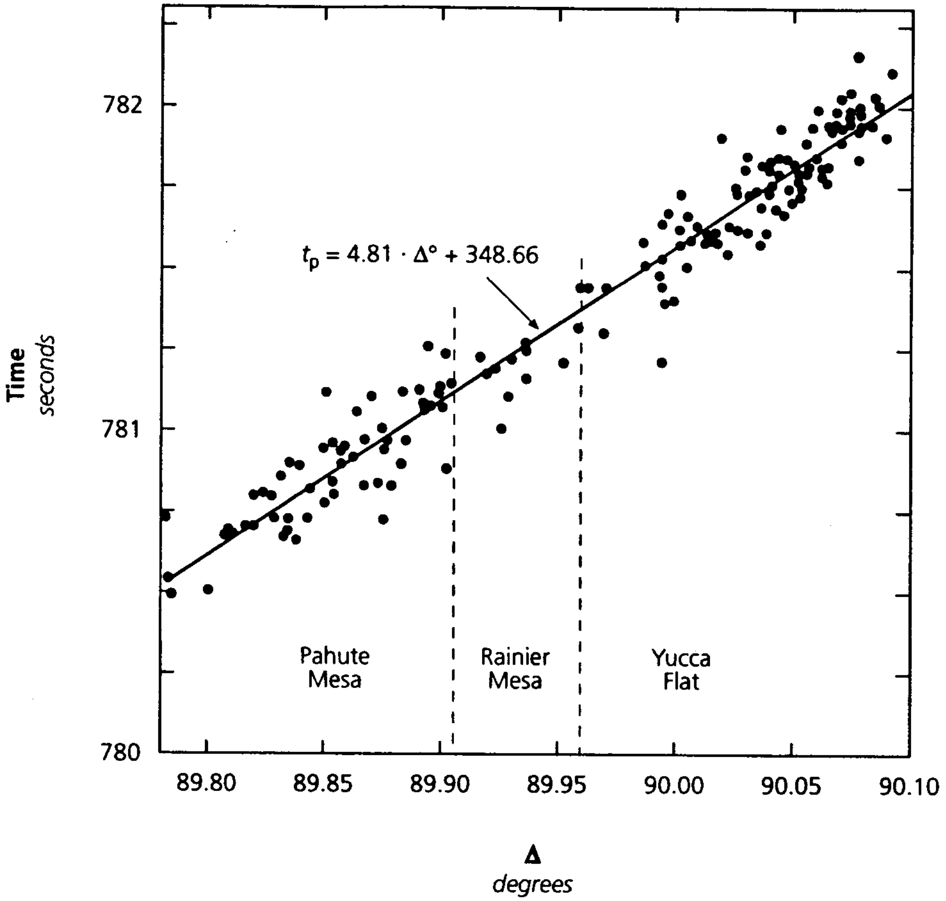

Figure A-1: Local travel-time curve of a P wave for NTS sub-areas Pahute Mesa, Rainier Mesa, and Yucca Flat, relative to Borovoye station, corrected to sea level.

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