| Topic | Record examples of underground nuclear explosions |
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## 1 Introduction

Nuclear explosions and in particular underground nuclear explosions had a dramatic influence on the development of modern seismology. All nuclear explosions are sources of elastic waves travelling over long distances in the Earth's atmosphere, in the Earth's oceans, and through the solid Earth, depending on the medium in which the explosion was conducted. These side effects of such explosions are well known and were used since the beginning of the nuclear age as tools to monitor the nuclear testing activity of foreign states (for details about today's monitoring activities see Chapter 17).

The development of seismic arrays (see Chapter 9), the homogenization of seismic instrumentation and the installation of global networks since the 1960s were triggered and financially supported by the wish to globally monitor test activities of nuclear underground explosions. Theoretical seismology has strongly benefited by the demand for more knowledge about the propagation and the attenuation of seismic waves in order to understand the differences between natural and artificial seismic sources.

Data from nuclear tests have been an important data source for numerous studies to investigate the 1D and 3D structure of the Earth's interior. Since, in contrast to earthquakes, the exact location and shot time of these explosions are often precisely known, they are very useful tools to investigate the structure of the Earth with elastic waves (see Ground Truth events in IS 8.6). Already the first test of a nuclear device had been used to investigate the crustal structure (Gutenberg, 1946) and since then the number of published studies using nuclear test observations to study in particular the P-wave velocity structure within the Earth is enormous.

Underground nuclear explosions (UNEs) are usually tests of nuclear weapon devices and performed at (known) test sites. However, some explosions were made outside of these recognized test sites for making cavities, moving large ground masses to redirect rivers or for conducting long-range seismic profiles. These underground explosions are per definition called Peaceful Nuclear Explosions (PNEs). Source information and waveform data from UNEs and PNEs can be retrieved from the open DTRA (http://www.rdss.info/ and there go to Research Databases / Nuclear Explosions).

Thankfully, underground nuclear explosion activity has decreased in the last decades, but we think it is important to document some typical features of nuclear underground explosions as recorded at seismic stations.

## 2 Record examples of underground nuclear explosions between 1978 and 1993 within the teleseismic distance range

Below, seismic records of underground nuclear explosions (UNEs) at 5 weapon test sites and from a peaceful nuclear explosion (PNE) are shown. All records were made in the teleseismic distance range D > 30° by vertical-component seismographs at station GRA1 of the Gräfenberg broadband array in Germany. The original BB records were filtered in the short-period range (WWSSN-SP simulation filter). The time scale is given below the records. The amplitudes have been normalized and the records are presented in Figure 1 in the following order:

| No. | Date | Time | Latitude [deg] | Longitude [deg] | Depth [km] | $m_b$ | Location (Code Name) | D [deg] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1988-12-17 | 04:18:09.2 | 49.879 | 78.924 | 0 | 5.9 | Semipalatinsk | 42.34 | UK AWE (1990) |
| 2 | 1993-10-05 | 01:59:56.68 | 41.6322 | 88.6886 | 0 | 5.9 | Lop Nor | 52.49 | ISC (2001) |
| 3 | 1988-12-04 | 05:19:53.3 | 73.3660 | 55.0010 | 0 | 5.9 | Novaya Zemlya | 30.32 | Richards (2000) |
| 4 | 1988-10-13 | 14:00:00.08 | 37.0890 | -116.0493 | 0 | 5.9 | Nevada Test Site (Dalhart) | 81.83 | ISC (2001) |
| 5 | 1987-11-19 | 16:31:00.2 | -21.845 | -138.941 | 0 | 5.7 | Mururoa | 143.58 | UK AWE (1993) |
| 6 | 1978-10-08 | 00:00:00.0 | 61.55 | 112.85 | 1.545 | 5.2 | PNE, USSR / Siberia (Vyatka) | 52.78 | Sultanov et al. (1999) |

D is the distance to the reference site of the Gräfenberg Array GRA1.The estimated yields for these explosions range between approximately 20 and 150 kt TNT for the weapon tests and is about 15 kt TNT for the PNE (No. 6).

With the exception of the Mururoa test all other records show a clear positive (compressional) first arrival. This is what one expects from an explosion source at all distances and azimuths if sufficient recording bandwidth and signal-to-noise ratio (SNR) is provided (see Chapter 4, Figs. 4.9 ??? and 4.10 ??? and Figures 2 and 3 below). For the Mururoa test the waveforms are influenced by the PKP caustic (Hilbert Transformation of the signal!) in the distance range around D = 145° (see Chapter 2, section 2.5.4.3 ??, Figs. 2.34 and 2.35 ??) and therefore the onset polarity cannot be read reliably. Note the remarkable differences in P waveforms, which are rather short and simple for events No. 1, 2, 5 and 6 but much more complex and longer for events No. 3 and 4. This is mainly due to the specific geology and/or complex topography at the test sites in Nevada and on Novaya Zemlya. Additionally, for event No. 3, we observe also later P energy, about 5 s after the first onset, at an epicentral distance of about 30º due to the seismic energy refracted, reflected and scattered in the upper mantle (see Figure 4 and Chapter 2, Fig. 2.29 ??) and for event No. 5 the distinguished onsets, about 5 and 10 s after the first onset are later PKP-type onsets (see Schlittenhardt, 1996).

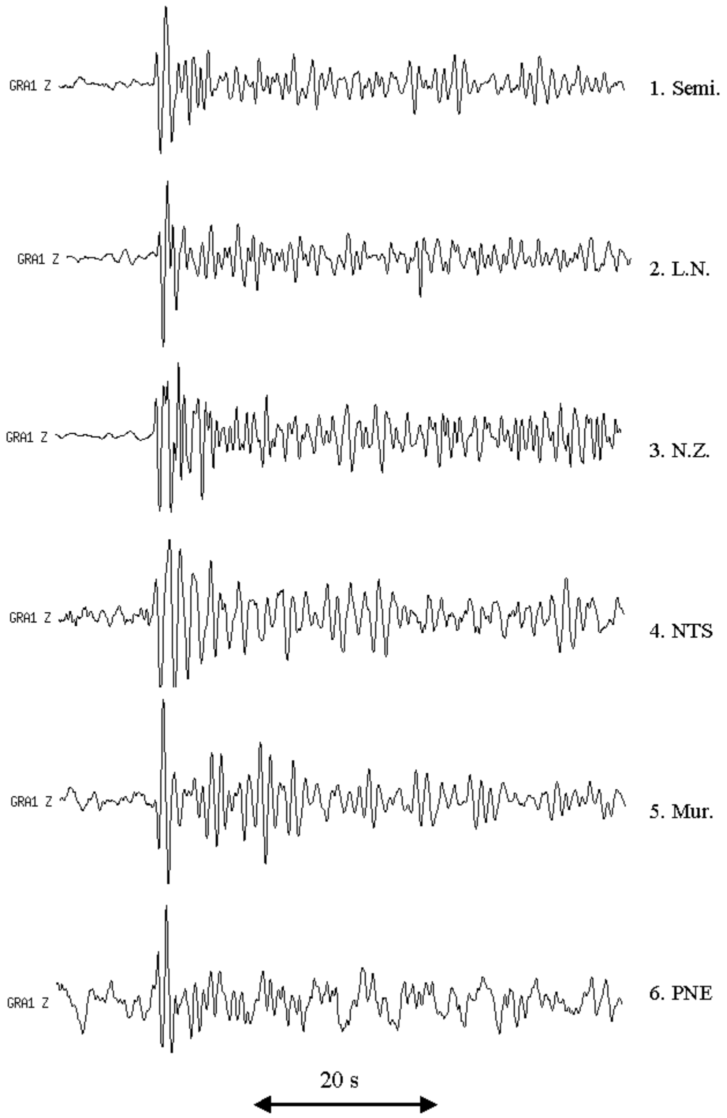


**Figure 1** Short-period filtered seismograms (WWSSN-SP simulation filter) recorded at station GRA1 of the Gräfenberg broadband array in Germany from underground nuclear explosions in six different areas. For source parameters and distances to GRA1 see the list above.

## 3 Records of the nuclear-weapon tests of India and Pakistan

Figures 2 and 3 show vertical component records of broadband stations of the German Regional Seismography Network (GRSN) from the underground nuclear weapons tests of India and Pakistan in 1998. All records were filtered narrowband in the short-period range around 1 Hz and sorted according to the epicentral distance. The source parameters are:

India: 1998-11-05, 10:13:44.2, 27.0780°N, 71.7190°E, depth 0 km, mb 5.2 (Barker et al., 1999) with epicentral distance and backazimuth from GRFO: D = 50.99° and BAZ = 92.94°.

Pakistan: 1998-05-30, 06:54:54.87, 28.4434°N, 63.7375°E, depth 0 km; mb 4.7 (ISC, 2001) with epicentral distance and backazimuth from GRFO: D = 44.91° and BAZ = 98.12°.

The P-wave onsets are generally simple. However, they are masked by noise at the more noisy stations. Surface-wave amplitudes were very weak and could not be analyzed at this large distance.

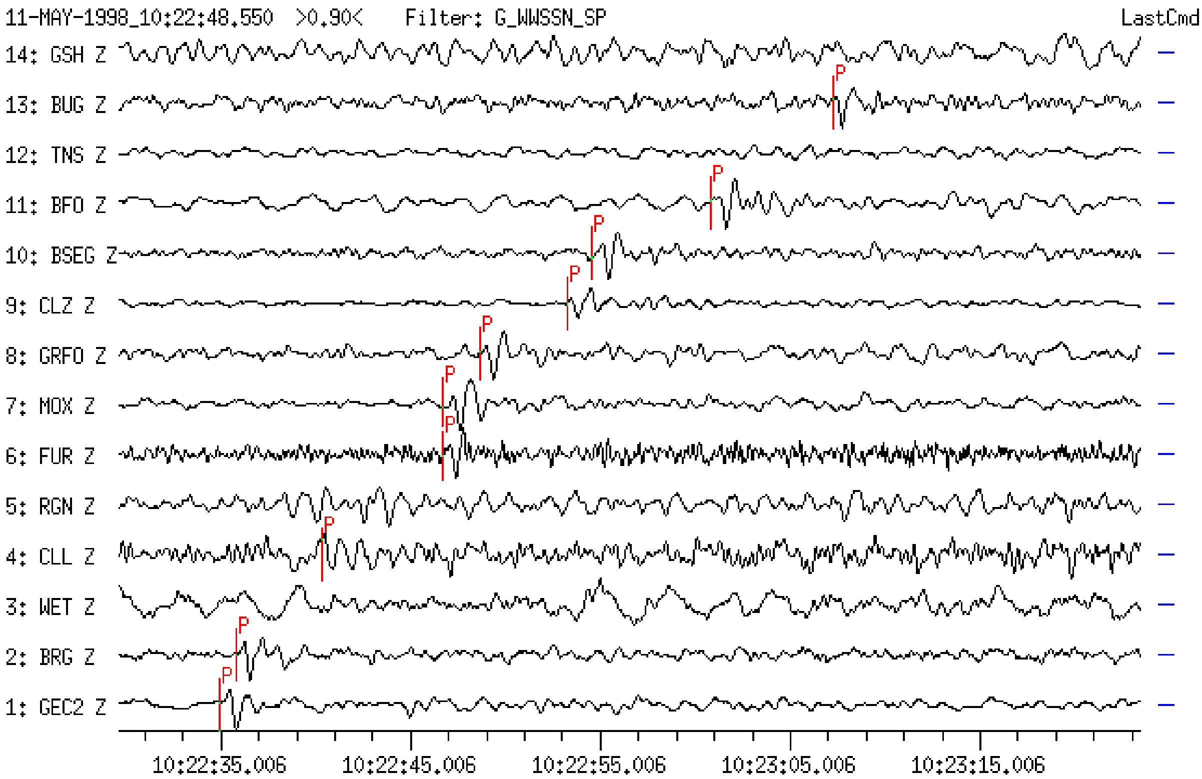


**Figure 2** Records of the Indian underground nuclear test on 11 May 1998. For source parameters see above. The broadband records were filtered with the WWSSN-SP response. Typical for explosions are the compressional first onset polarities at stations with high SNR.

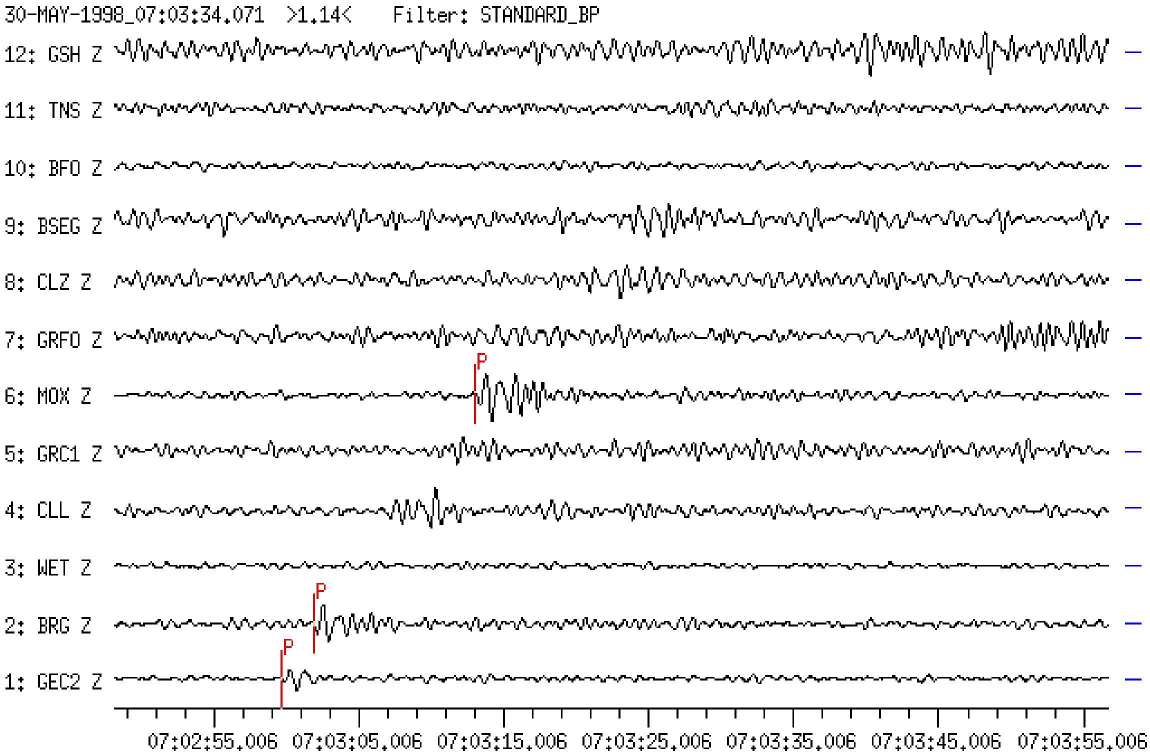


**Figure 3** Records of the Pakistani underground nuclear test of 30 May 1998. For source parameters see above. The relatively small amplitudes of this 0.5 magnitude units smaller explosion are disturbed by high noise levels at the stations and the energy of an aftershock sequence of an earthquake in the Afghanistan-Tajikistan border region (see, e.g., Kværna et al., 2002). Therefore, the broadband records were bandpass filtered between 0.8 and 1.2 Hz, which has a narrower (about 0.5 octaves) bandwidth than the standard WWSSN-SP filter (about 1 octave) used for the Indian explosion (Fig. 2). It results in a better visibility of the signal (higher SNR). However, the signal onset is so emergent that it is not possible to read reliable first motion polarities. Note the apparently negative first onsets at stations BRG and MOX! For related discussions see section 4.2 in Chapter 4 of this Manual.

# 4 Records of underground nuclear explosions at regional distances (7°< D ≤ 30°)

At shorter distances (D ≤ 30°) records from underground nuclear explosions (UNEs) still contain a rather large amount of high-frequency energy. This is mainly due to the difference in the source process as compared to an earthquakes (see Fig. 3.5 ??? in Chapter 3 and the related discussions in Section 3.1.1.3 ?? of this Manual). Two examples are shown below.

## 4.1 UNE at the Northern Novaya Zemlya Test Site

Source data: 1990-10-24, 14:57:58.5, 73.3310°N, 54.7570°E, depth 0 km, mb 5.7 (Richards, 2000). The distances to the recording stations shown in Fig. 4 are: D = 9.99° (ARCES), 15.98° (FINES), 20.41° (NORES) and 30.40° (GERES).

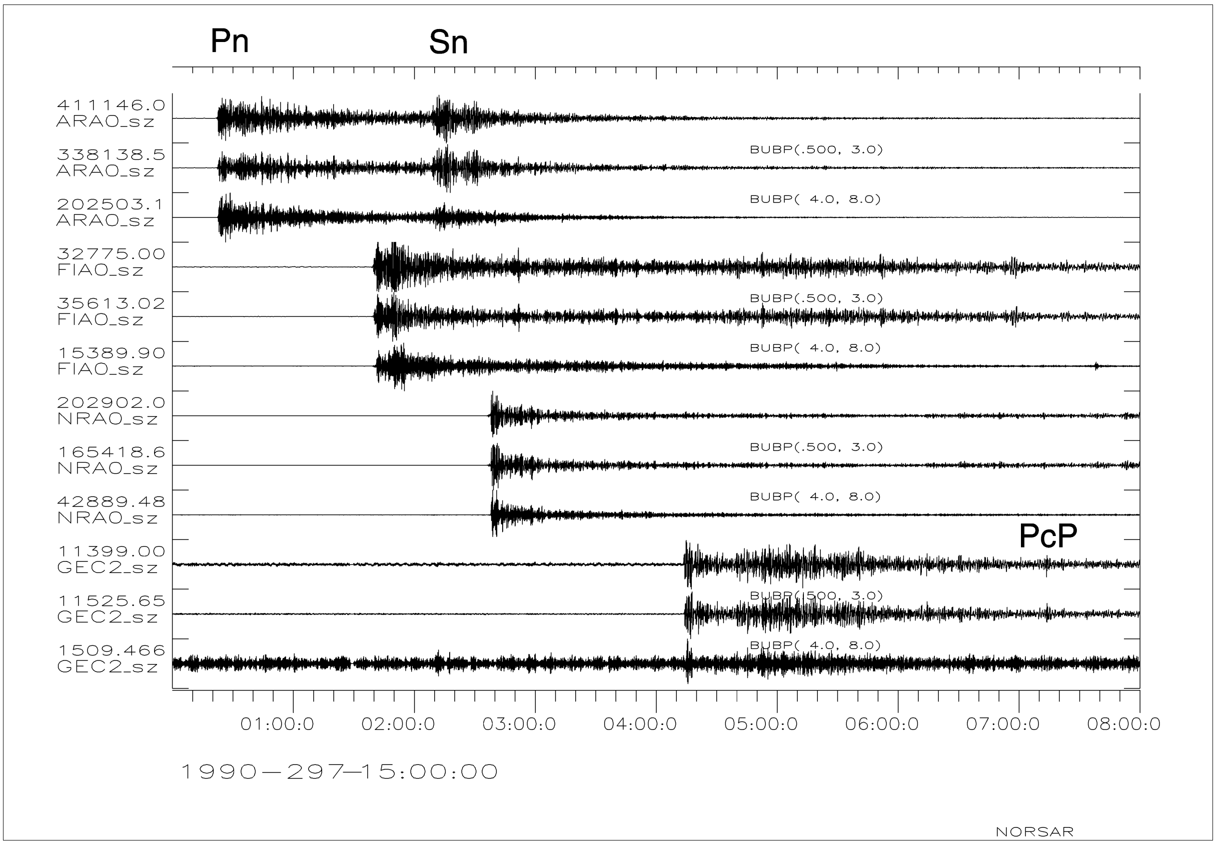


**Figure 4** Records of the key stations ARA0, FIA0, NRA0 and GEC2 of the small aperture short-period arrays ARCES, FINES, NORES and GERES from the Novaya Zemlya test of 24 October 1990. These arrays are specialized for regional signals and ARCES, FINES and GERES are part of the International Monitoring System (IMS) under the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in Vienna (see Chapter 17). Shown are the vertical component records a) unfiltered, b) band-pass filtered between 0.5 and 3 Hz, and c) band-pass filtered between 4 and 8 Hz. Note the relatively strong high-frequency energy that is well developed in the P-wave group up to a distance of ~30° but no longer visible above the level of signal coda for S waves beyond 10° distance. S waves are stronger attenuated then P waves. At GEC2 the core reflection PcP is nicely visible and the P-wave coda is dominated by energy refracted, reflected and scattered in the upper mantle. Each trace is normalized by its maximum amplitude, which is given in digital counts together with the channel name. The time axis is labeled at each minute after 15:00:00 with 10 s between two ticks.

### 4.2 UNE of India in 1998

In Figure 2 we showed data of the Indian UNE of 5 May 1998 as it was observed in Europe. This event could also be observed at regional distances, e.g., at the Pakistani station NIL (Figure 5).

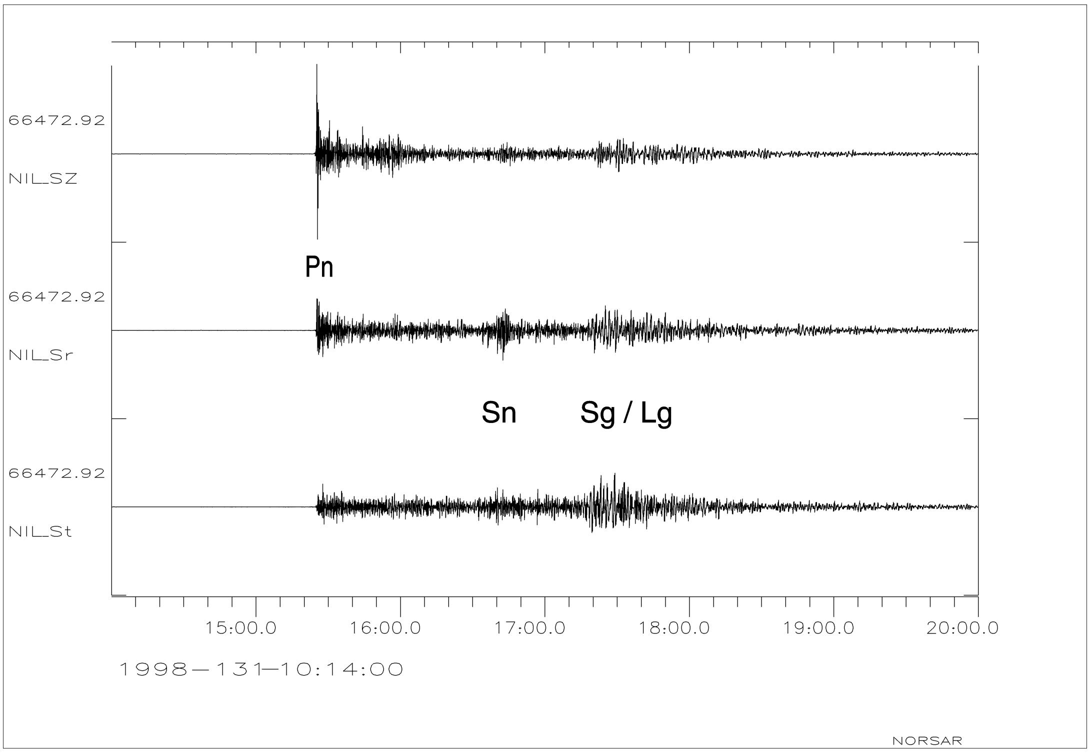


**Figure 5** Z-R-T rotated three-component record at the IRIS/IDA station NIL, Pakistan. The epicentral distance to the Indian test site is about 740 km; the amplitudes are normalized by the largest signal, which is given in counts at each channel name; shown are unfiltered data. Note the strong P- but weak S-wave arrivals. The time axis is labelled for each minute after 10:14:00 with 10 s between two ticks.

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