

Seismic signature

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Following the nuclear test carried out by North Korea on 9 October 2006, seismic data provided a detailed picture of the event — negating arguments against the Comprehensive Nuclear Test Ban Treaty based on allegations of inadequate monitoring capability.

The Comprehensive Nuclear Test Ban Treaty (CTBT) bans all nuclear explosions, whether made for military or civilian purposes. It opened for signature in 1996, but has yet to come into force as it has to be ratified by 44 states that are specified in an annex of the treaty. The United States Senate denied consent to ratification in October 1999, slowing international momentum towards enacting the treaty. In the debate leading up to the Senate's

denial, a number of objections were raised, including remarkable statements to the effect that underground nuclear explosions as large as 70 kilotons could be concealed (that is, not even detected). Those statements are contradicted by extensive experience — the explosion in North Korea on 9 October 2006 is the most recent example, and in several respects, is an important one.

The Korean detonation was the first nuclear test since the CTBT

Organization — headquartered in Vienna (Austria) — began, in February 2000, to process signals from a global monitoring network that uses seismic, radionuclide, infrasound and hydroacoustic technologies. As well as the records from the CTBTO network (which are not public), more broadly available data relevant to explosion monitoring are generated by the loosely organized efforts of numerous institutions that acquire and process data for purposes other than treaty monitoring — for example, from regional and national networks of seismic sensors. Such additional stations provided excellent seismic data following the test in October 2006.

The nuclear explosion in North Korea was large enough to be detected globally. Signals from the test were promptly detected at seismographic stations in Australia, Europe, North America and Asia, and were used, for example, by the United States Geological Survey (USGS) to provide a good estimate of the location of the North Korean test about five hours after it occurred. But identifying the event as an explosion, not an earthquake — and as a nuclear explosion — was more difficult. Most of the signals gathered around the globe provided very little information on the nature of the event, because it was too small to generate waves observable at distant stations across a broad band of frequencies. To tell whether it was an earthquake or an explosion, broadband data were needed from stations operated at distances preferably less than 1,000 kilometres — data that for an event of this size (determined from distant stations to be about magnitude 4) would include regional seismic waves propagating within the Earth's crust or within the upper layers of the mantle. Monitoring capability has greatly improved over the past twenty years,

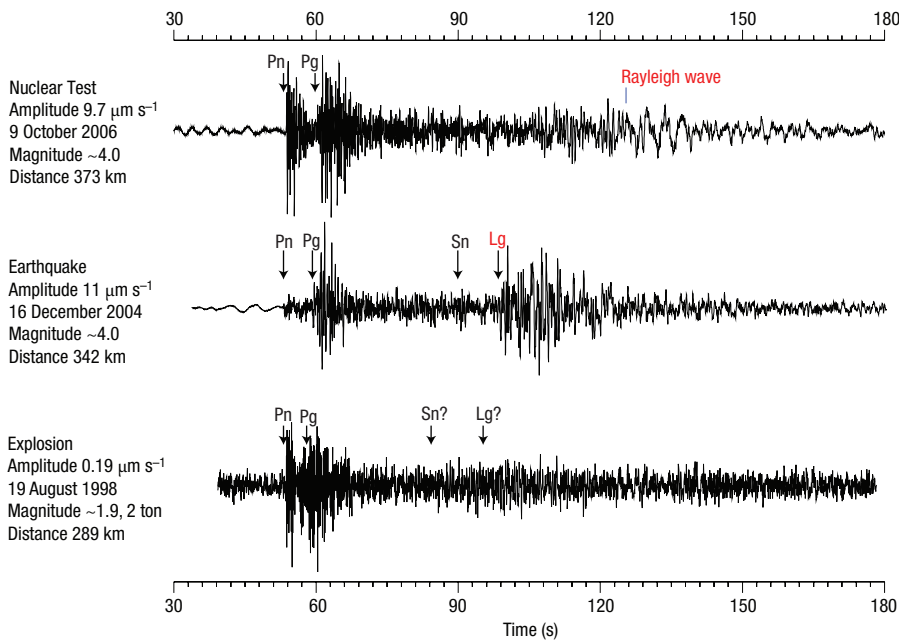


Figure 1 Seismograms, including that of the North Korea nuclear test on 9 October 2006. Vertical ground velocity is plotted, measured in micrometres per second, as recorded at station MDJ. For comparison with the test (upper trace), data from an earthquake of comparable magnitude (middle trace) and for a small chemical explosion of two tons of TNT equivalent (lower trace) are shown. The explosions cause a sudden onset of P-waves that travel by two different paths (Pn via the crust and mantle; Pg via the crust alone) and weak shear waves (Lg). For the earthquake, P-waves emerge more slowly, and shear-waves are strong.

but it crucially depends on ease of access to near-real-time data, and to archives of relevant signals from known sources against which new signals can be compared. Fortunately, good data taken sufficiently close to the North Korea test site were at hand. We estimate that the region can be monitored for explosions down to a few tons of TNT equivalent.

Figure 1 shows traces registered by a station at Mudanjiang (known as MDJ), about 370 km to the north of the test site. MDJ is a joint station of the New China Digital Seismographic Network (operated by the China Earthquake Administration), and the Global Seismographic Network (operated by the USGS and the Incorporated Research Institutions for Seismology Consortium, IRIS, a trans-university research organisation). Data are archived continuously by the IRIS data management centre, and are openly available. MDJ is the station nearest the North Korea test site used by the USGS, but there are several other sets of seismographic stations currently operated by research groups within 500 km of this site, additional to stations used by treaty-monitoring agencies and by China's national earthquake monitoring network.

On 9 October 2006, MDJ registered a high-quality seismogram (the uppermost trace of Fig. 1). Demonstrating that the source of the signals was indeed explosive is best done by comparison against signals of earthquakes and other explosions from the same general region, preferably recorded at the same station. It is not always possible to find such other signals, but in the present case we soon found 'good' earthquakes for comparison. An example of an earthquake seismogram, from an event 342 km from MDJ, is shown in the middle trace of Fig. 1. We also found, for further comparison, good records from four small underground chemical explosions, conducted in 1998 as part of a geophysical refraction survey in China just north of the border with North Korea (data shown in the lowest trace of Fig. 1).

The seismogram of 9 October has three important features. First, it shows an impulsive onset of compressional waves (denoted Pn and Pg), characteristic of an explosion. Second, peaks indicative of shear waves in the crust, which would be typical of an earthquake, are very weak — unlike the middle trace acquired at the same station during an earthquake, in which shear waves, labelled Lg, are clearly seen. And third, short-period 'Rayleigh waves' are apparent. They have a period about 3 s and are known to be excited only by sources at a depth not more than about 3 or 4 km, which is much shallower than typical earthquakes.

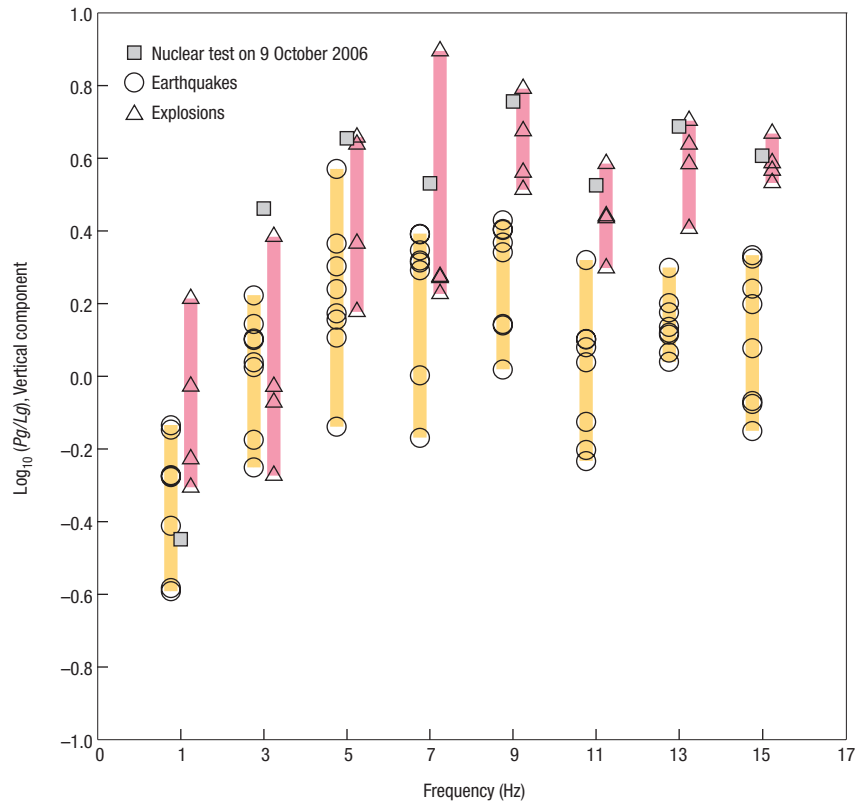


Figure 2 Measurements of the spectral amplitude ratio between P- and S-waves. Amplitudes were determined from narrow bands centred on eight frequencies using the crustal phases Pg or Lg, and vertical recordings as shown in Fig. 1 (ref. 2). The explosions (triangles, with the full range marked in pink) consistently have higher values than the earthquakes (circles, with the range in yellow). The event of 9 October 2006 (squares) clearly falls in the explosion population.

The earthquake record shows strong shear waves in the crust (S-waves) and a relatively weak onset of compressional waves (P-waves). The chemical explosion record is remarkably similar to that of the nuclear test — featuring two impulsive P-waves and weak S-waves — though its amplitude is about fifty times smaller. The ratio of P- to S-wave amplitudes is typically high for an explosion and small for an earthquake^{1,2}. We measured this ratio at a number of different frequencies for each source. Figure 2 shows this ratio for the two 'training sets' (circles and triangles), which separate better and better at higher frequencies. It is clear that the explosion of 9 October 2006 (marked by squares) falls into the explosion population.

For a few days following the test, there was speculation that the test could have been a large chemical explosion rather than a nuclear one. Indeed from seismic signals alone, at this size (that is, about magnitude 4) it is technically possible to carry out a chemical explosion that is indistinguishable from a nuclear one, provided the explosives or blasting agents

are wired up with detonators throughout the volume of the material to be exploded, and the material is all exploded almost simultaneously. The United States carried out such a 'chemical kiloton' experiment in September 1993 at the Nevada Test Site and the seismic signals — even from nearby stations — were found to be essentially the same as those from a small nuclear test. But it would be very difficult to carry out such a 'fake test' clandestinely in view of the physically large amounts (hundreds of tons) of explosives that would need to be brought in — close attention is paid to the test site by those with access to high-quality satellite imagery, both commercial and non-commercial. The high risk of eventual discovery of a fake nuclear test seemed to us to make such a large chemical explosion not credible, although this was not a universal opinion. (Non-seismic evidence that it was a nuclear explosion was obtained from radionuclides detected a few days after the test.)

Had the seismic signals been significantly smaller, and identifiable as some type of explosion, then conceptually under a CTBT

regime this could have been a situation for which an on-site inspection might be requested to obtain additional data on the explosion type. To engage in discussion of this event in the context of CTBT monitoring is, however, hypothetical as the treaty has neither been signed by North Korea, nor is it in effect. Moreover, North Korea announced this nuclear test and — according to news reports — let China know of the test just before it was to occur. But it is clear that the test would have been well-detected, and located and identified as an explosion, in the absence of any prior announcement.

While acknowledging the difficulty of getting the CTBT back on track with signatures and ratification from a number of key countries, including India, Pakistan and North Korea, it still has strong proponents, having been signed by 176 countries (including the US, in 1996, and also Russia, China and Israel). An international commission on weapons of mass destruction — led by Hans Blix, a former Director-General of the International Atomic Energy Agency — recently listed 60 steps needed to achieve progress in nuclear arms control, recognizing that

existing stockpiles include about 27,000 nuclear warheads. The highest priority identified by the commission was bringing the CTBT into force. From the experience of monitoring the North Korea test of 9 October 2006, verification capability does not seem to be a fundamental issue in doing so, provided sufficient resources are assigned to do the work.

References

1. Hartse, H. E., Taylor, S. R., Phillips, W. S. & Randall, G. E. *Bull. Seismol. Soc. Am.* **87**, 551–568 (1997).
2. Kim, W.-Y., Aharonian, V., Lerner-Lam, A. L. & Richards, P. G. *Bull. Seismol. Soc. Am.* **87**, 569–588 (1997).