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SEISMIC MONITORING OF NUCLEAR EXPLOSIONS

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Introduction

The original development of nuclear weapons, and their first use in 1945, was followed by several decades of further weapons development in which more than 2,000 nuclear test explosions were conducted. About 500 of these were carried out in the atmosphere, mostly in the 1950s and 1960s. They generated radioactive fallout that was detected worldwide with some regional concentrations, and aroused widespread public opposition to nuclear testing. A few nuclear tests were carried out underwater and in space. The great majority, about 1,500, were conducted underground in ways that greatly reduced fallout – the first of them in 1957, in Nevada, USA – generating signals that have been intensively studied by seismologists. Hundreds of these individual nuclear tests consisted of multiple nuclear devices and exploded almost simultaneously.

A ban on nuclear testing in the atmosphere, underwater, or in space, was negotiated and went into effect in 1963 between the USA, the USSR, and the UK. Known as the Limited Test Ban Treaty (LTBT), it has since been ratified or acceded to by more than a hundred countries. Though France and China did not sign, and China carried on with nuclear testing in the atmosphere up to 1980, eventually both these countries came to abide by its terms.

The concept of a Comprehensive Test Ban Treaty (CTBT) emerged in the 1950s, intended as a restraint upon nuclear weapons development. It was debated in many forums for more than 40 years, and finalized in terms of specific treaty text in September 1996. But this treaty is not in effect (as of 2010), due to continuing debate in specific countries that have not ratified this treaty, and whose ratification is needed as a condition for the CTBT to enter into force. They include India, North Korea, and Pakistan (not signed or ratified); and China, Israel, and the United States (signed but not ratified). Those countries that have signed the treaty are effectively adhering to a moratorium on nuclear testing. They include the five countries recognized as nuclear weapons states by the Non-Proliferation Treaty of 1968. Listing them in the order in which they acquired nuclear weapons capability, these are the USA, the USSR (whose CTBT obligations have been assumed by Russia), the UK, France, and China. The two countries that by far have conducted the most nuclear test explosions – the USA with 51% of the world total, and the USSR/Russia with 35% – ended nuclear testing in the early 1990s. See Yang et al. (2003) for lists of nuclear explosions conducted in the twentieth century, and Bennett et al. (2010) for a relevant database and seismic waveforms. Since 1996, the only nuclear explosions (as of 2010) have been those conducted by India and Pakistan (in May 1998), and by North Korea (in October 2006, and May 2009).

Seismic monitoring of nuclear explosions has been an important activity ever since the first nuclear test in July 1945 in New Mexico. Such monitoring is driven by two different objectives that have engaged a range of different institutions and organizations. The first objective, which dominated for the early decades of nuclear testing up to the early 1990s when nuclear explosions were being conducted on average about once a week, was to acquire basic information about military weapons being tested, especially if (from the point of view of the monitoring organization) the tests were being carried out by a potential adversary. Relevant questions were: what countries had nuclear weapons programs, developed to the level of carrying out nuclear explosive tests? And

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how big were these explosions? The second objective, which has become important in recent decades, has been in the context of a major initiative in nuclear arms control, namely, to achieve confidence in the capability to monitor compliance with a CTBT, recognizing that many countries considering whether or not to support such a treaty and to be bound by its terms, would need to have confidence in the monitoring system to some adequate degree. Given that monitoring cannot be done all the way down to zero yield, evaluation of progress toward this second objective entails questions such as: down to what small size can nuclear explosions be detected, and identified, and attributed with high confidence? And what are the specific capabilities of different types of monitoring program, applied to different parts of the world, to catch evidence of a nuclear test, should one occur?

Seismology is the most effective technology for monitoring nuclear tests carried out underground, which is the one environment that was not covered by the LTBT, and which is also the hardest of the environments to monitor. The importance of achieving the two objectives stated above has shaped modern seismology itself, in that much of the funding that has led to the facilities and bodies of knowledge now used widely in seismological research (including studies of seismic hazard), were stimulated by government programs intended to improve capabilities for seismic monitoring of nuclear explosions. These facilities and methods include high-quality Seismic Instrumentation, global networks that monitor for earthquakes as well as explosions, quantitative methods of characterizing seismic sources (various magnitude scales, the moment tensor), theoretical understanding of seismic wave propagation in Earth models of increasing and more realistic complexity, our knowledge of the Earth's internal structure, and methods of seismic signal detection and interpretation.

The technical capability to monitor explosions, or a perceived lack of such capability, has played a role in the development of policy options on weapons testing and/or arms control and the content of international treaties. A key technical question arising in debates has been: down to what value of yield can monitoring be accomplished – and with what level of confidence? Seismologists claim now that there is no fundamental technical problem with monitoring explosions down to 1 kt, even if determined efforts at evasion must be considered. But there have been assertions that it is possible to muffle and thus hide (or confuse the procedures for identifying) the seismic signal, even from a substantial underground explosion at the level of ten kilotons or more. These latter assertions do not appear plausible after review of the technical difficulties; but, as assertions, one finds that they continue to survive.

Seismic monitoring for underground nuclear explosions must be done with recognition of the great variety and number of earthquakes, chemical explosions, and other nonnuclear phenomena that generate seismic signals every day. Efforts to sort out and identify signals from underground nuclear explosions in the midst of signals from these other phenomena have made great progress since they commenced in the 1950s, and improvements in monitoring capability will surely continue to be made.

Sections below describe basic properties of earthquake and explosion signals, and different steps in seismic monitoring for nuclear explosions. A review is given of methods used for decades in the era when thousands of kilometers separated nuclear weapons testing activity and monitoring stations, when nuclear weapons testing was commonplace and there was little incentive to hide testing activity. Descriptions are then given of modern methods that monitor for very small explosions and the possibility of tests conducted in ways intended to evade discovery. A description is given of so-called "problem events" that were important is developing effective and in some cases new discriminants; and finally a brief summary is given of monitoring capabilities, as of 2010, emphasizing the utility of data and data products from the International Monitoring System and its associated International Data Centre that are operated today by the CTBT Organization, headquartered in Vienna, Austria.

Basic properties of earthquake and explosion signals

Seismic monitoring for underground nuclear explosions has to face the reality of hundreds of earthquakes, chemical explosions, and other nonnuclear phenomena, generating seismic signals daily that will be recorded at multiple stations by any effective monitoring network. But after decades of effort, an extensive infrastructure of national and international agencies now sorts out and identifies the signals from earthquakes, chemical explosions, and the occasional underground nuclear explosion. Modern methods of nuclear explosion monitoring are vastly more capable than they were when this work began in the late 1950s. The improvements have mostly been steady as data quality and quantity from monitoring networks increased, but with occasional jumps in capability as new types of analyses were validated.

Seismic signals are traditionally grouped into teleseismic waves and regional waves, depending on the distance at which they are observed. Teleseismic waves propagate either as Body Waves through the Earth's deep interior, emerging with periods typically in the range 0.3–5 s at distances greater than about 1,500 km, or as Surface Waves, analogous to the ripples on the surface of a pond, with periods of about 15–100 s.

Teleseismic waves were the basis of most US monitoring of foreign nuclear tests prior to 1987. Teleseismic body waves are further subdivided into *P*-waves and *S*-waves. *P*-waves, which are the fastest-traveling seismic waves and are therefore the first to arrive, are excited efficiently by explosions: earthquakes tend to excite *S*-waves and surface waves more efficiently.

For subkiloton explosions, teleseismic signals can be too weak for detection at distant stations and monitoring then requires regional signals. Regional waves are of several types, including *P*-waves and *S*-waves, all propagating only at shallow depths (less than 100 km below the Earth's surface) with periods as short as 0.05 s (frequencies as high as 20 Hz, i.e., cycles per second). Regional waves reach distances up to 1,000 km and sometimes beyond, depending on source size and whether the propagation path is an attenuating one, or not. They are regional also in the sense that they have speeds and attenuation properties that vary according to details of local structures in the Earth's crust and uppermost mantle, so they can vary from place to place within continents and oceans.

Figure 1 shows a regional seismogram of a Soviet underground nuclear explosion in Kazakhstan recorded in July 1989 at a distance of slightly less than 1,000 km by a high-quality station in northwestern China. The original recording is shown in red. Different signals derived from it are shown in blue, each of them filtered to pass information in a particular band of frequencies.

Seismologists characterize the size of seismic signals by means of logarithmic magnitude scales (see *Earthquake magnitude*), with each scale based on a different type of seismic wave. A magnitude scale using teleseismic surface waves was first described in the 1930s based on the logarithm (to the base 10) of amplitude of maximum ground displacement due to surface waves with periods about 20 s. It is known as the M_s scale. Another widely used magnitude scale is that based on the amplitude of teleseismic *P*-waves. Known as m_b, it entails measurement of ground motion at about 1 s period. As part of the assignation of M_s and m_b values, for a particular seismic event as recorded at a particular station, a standard correction is applied to account for the distance between the source and the receiver at which the data was obtained. Magnitudes range from about -3 for the smallest observable microearthquakes, up to above 8 for the largest earthquake. A 1 kt underground explosion has an m_b roughly about 4, and each year there are about 7,500 shallow earthquakes worldwide with $m_b \geq 4$ (Ringdal, 1985). Although use of seismic moment has superseded use of m_b and M_s in much of modern seismology and magnitude is only an empirical estimator of seismic event size, magnitude scales are still often used in discussion of seismic monitoring because this a practical way to relate that discussion directly to properties of signal strength. For example, monitoring capability is often characterized in terms of contour maps or shaded maps indicating the magnitude levels down to which detection or identification is deemed possible with given resources, such as a particular network. We conclude this article with such a map (see Figure 8). Explosion energy is measured in kilotons. A kiloton is formally defined as a trillion calories, and is roughly the energy released by exploding a thousand tons of TNT.

The different steps in explosion monitoring

Nuclear explosion monitoring entails a series of steps, beginning with *detection* of signals (did a particular station detect anything?) and *association* (can we gather all the different signals, recorded by different stations, that originate from the same "event"?). The next steps involve making a *location* estimate and an *identification* (did it have the characteristics of an earthquake, a mining blast, a nuclear weapon test?). Then follow the steps of *yield estimation* (how big was it?) and *attribution* (if it was a nuclear test, what country carried it out?).

Detection

Concerning detection, nuclear explosion monitoring is often done with arrays of sensors, deployed as a group spread out over an area about 10 km across (or less), that facilitate methods to enhance signal-to-noise ratios. This is done typically by stacking signals from independent sensors, often with appropriate delays to increase signal strength and reduce noise. Array data can also give estimates of the direction from which signals are arriving.

In the *evaluation* of detection capability, one of the key concepts widely used in seismology is the *magnitude of completeness*, which means that *all* events above this magnitude can be recorded by the monitoring system. Transferring from magnitude to yield, one infers the capability for detecting nuclear tests (NAS, 2002). Practically, however, one of the often-cited expressions of monitoring capability is the *magnitude threshold*, above which 90% of the seismic events can be detected at more than three stations, the least number of stations for routine location.

Association

Association is the effort to identify those sets of signals, from different stations, which all originate from the same seismic event. It is one of the hardest steps in practice, particularly when multiple seismic sources around the world are active at the same time, resulting in signals from different events that are interlaced in the waveforms recorded by each station. In such cases, array data can be helpful in resolving which signals correspond to which event.

Location

To obtain a location estimate, typically the arrival times of various seismic waves are measured from the recorded waveforms such as shown in Figure 1. They are used to find four parameters: latitude, longitude, depth, and origin time. In this work, it is necessary to know the travel time from any hypothesized source location to any particular seismographic station for any type of seismic wave that the station might observe. In practice, locating seismic events accurately on a global basis (say, to within 10 km of their true location) using sparse networks (stations several hundred kilometers apart) requires extensive efforts in station calibration. Thus, it is important to include path-specific travel-time corrections to standard travel-time models to account for lateral variations of Earth structure (Murphy et al., 2005; Myers et al., 2010). Many authors have shown that greatly improved precision of location estimates can be achieved for a given region if seismic events are located in large numbers – preferably thousands of them or more, all at the same time – rather than one at a time (Richards et al., 2006; Waldhauser and Schaff, 2008).

Methods of identification

Identification of the nature of a seismic source on the basis of its seismic signals – that is, making a determination from seismograms as to whether it could be a nuclear explosion, or a natural earthquake, or a mine blast, or something more exotic such as a bolide impacting our planet and exploding in the atmosphere – is a large subject in view of the many possibilities. See for example, Richards (1988), OTA (1988), Dahlman et al. (2009), and Bowers and Selby (2009). Seismic events generate many different types of seismic wave, in various different frequency bands as shown in Figure 1, and different types of seismic source generate a different mix of seismic waves. We can make an analogy here with sound waves, and the capability of the human ear and brain to analyze them. A deep bass voice, a gunshot, a whistle, and rolling thunder, constitute a set of sound sources that are easily distinguished from each other on the basis of their different frequencies, their emergent or impulsive nature, and their duration. It is the mix of information in both the time domain and the frequency domain that is effective.

Seismic methods for discriminating between earthquakes and explosions are based on interpretation of the event location (including its depth); on the relative excitation of a variety of body waves and surface waves; and on properties of the signal spectrum associated with each of these two different types of source. Within these three broad categories, many different methods have been tried, with various degrees of success. As the capabilities of each method are probed, the question of interest is often: “Down to what size of seismic event, does this method of discrimination work?” In some cases, discrimination is unambiguous even at very small event size. (For example, however small an event, it may be presumed to be an earthquake if it is located at a depth greater than 15 km below the Earth’s surface. Even a small event will attract attention if it occurs in an area that is geologically stable that for decades has had no seismic activity.)

The most useful methods for discrimination can be listed as follows:

- Interpretation of the location: Is the event in a seismic or an aseismic area? Below the floor of an ocean? At depth below a continent? There is an important role here for common sense: seismic events in Canada tend to attract less attention from western monitoring agencies than such events in North Korea (though a seismic event in the middle of the Canadian Shield would still attract attention and intensive study).
- Relative amplitude of body waves and surface waves. This can be studied by plotting the event of interest on an M_s: m_b diagram, as shown in Figure 2. The surface-wave amplitude is read typically from signals with period about 20 s, and the body-wave amplitude at about 1 s period. (Though effective for large enough events, an explosion with m_b much below 4.5 may not have large enough surface wave signals at teleseismic distances to apply this method dependably.)
- Use of the observed “first motion” of the ground. Is the initial *P*-wave motion of the ground indicative of compression radiated to all directions from the source, leading to upward motions, as would be the case for a simple explosion? Or, are dilatations recorded at some azimuths, leading to downward motions, as would sometimes be expected from earthquakes but not from explosions?

The methods described so far in this section have concerned the use of teleseismic signals, which can be used to monitor effectively for high magnitudes, and on down to somewhere in the magnitude range from 4.0 to 4.5. Since the early 1990s, there has been growing recognition of the merits of regional waves, to monitor down to far lower magnitudes, often well below magnitude 3. The method is based upon the general observation that explosion signals, when compared to earthquakes, have much stronger *P*-waves at high frequency, whereas those from earthquakes have weaker *S*-waves (and surface waves).

This modern method is being studied with frequencies in the range 0.5–20 Hz. and sometimes even higher. An example is shown in Figure 3 comparing regional signals of a very small earthquake and a small explosion. The method has been demonstrated even down to around m_b 2.

As an important example of this development, Figure 4 shows the results of an analysis of the *P*-wave and *S*-wave spectra, pertinent to identifying the very small underground nuclear explosion conducted by North Korea on October 9, 2006, and the larger test nearly 3 years later on May 25, 2009. The smaller explosion took place at 0135 h (GMT) and by 0706 h the US Geological Survey (USGS) had issued a report based on seismic signals from 20 stations around the world including sites in China, South Korea, Russia, Japan, Kazakhstan, Kyrgyzstan, Alaska, and Nevada. Its magnitude, about 4, indicated a sub-kiloton yield (see Koper et al., 2008, who discuss the uncertainty of estimating yield in view of the variability of seismic signal excitation for shots of different depth). But from such teleseismic signals, the nature of the event was difficult to distinguish from an earthquake. Fortunately, discrimination for events such as this is often very clear, provided high-quality regional data is available.

In this analysis, the original seismograms from station MDJ, located in China, are filtered in eight narrow frequency bands as illustrated in blue in Figure 1, but this time with bands centered on each of the frequencies from 1, 3, 5, 7, 9, 11, 13, to 15 Hz as indicated for the horizontal axis in Figure 4. The amplitudes of the *Pg* and *Lg* waves are measured in each narrow band, the amplitude ratio is formed (the “spectral ratio”), and the quantitative comparison can begin. Figure 4 shows how this ratio varies with frequency for the set of eight earthquakes, and for the set of four small chemical explosions. The ratio differs for these two populations as frequency rises, and the separation between them is very clear at high frequencies (from 9 to 15 Hz in this case). It is also clear that the spectral ratios of the signal recorded for the events of 2006 and 2009 are like those of the known chemical explosions.

This successful seismic discriminant based upon regional waves is important in enabling monitoring capability to be extended down to lower magnitudes. In practice, there is often very little difference between the magnitude thresholds for detection (at enough stations to enable a useful location estimate), and identification, since so many regions of the Earth are now monitored to low magnitude for earthquakes as part of investigations into seismic hazard. It may take only one regional seismogram to enable discrimination to be carried out with high confidence (provided the recording is of adequate quality, and is for a station that has an archive of signals from previous known earthquakes and explosions).

Along with the use of regional seismic waves and their spectral ratios at 5 Hz and higher, another discriminant turning out to be successful at distinguishing between earthquakes and explosions is the use of observed seismic waveforms to make estimates of the set of forces that appear to be acting at the seismic source. The set of forces here is quantified by what seismologists call the *moment tensor*. As shown by Ford et al. (2009) from study of numerous earthquakes and underground explosions, seismic events separate into specific populations as determined by the way their moment tensors behave – whether they are more representative of the all-around (isotropic) features of an explosion, or of the type of shearing motions more typical of an earthquake.

In general for underground tests, seismic data alone cannot distinguish between nuclear explosions, and chemical explosions in which all the material making up the explosive was fired within less than about a tenth of a second. But such chemical explosions, if large, are very rare. In the case of the two North Korea tests, both of which were announced as nuclear, objective evidence for the nuclear nature of the 2006 explosion came from several different detections of radionuclides that are diagnostic of a nuclear explosion. Such radionuclides were not detected from the 2009 explosion, which, however, was so large as to be implausible as a chemical explosion, since it would have to have consisted of literally thousands of tons of explosives.

Yield estimation

Yield estimation was of particular importance in the years following 1974 when a bilateral treaty between the USA and the USSR was negotiated, intended to go into effect in 1976. This was the Threshold Test Ban Treaty (TTBT), limiting the size of underground nuclear explosions conducted by these two countries to a yield of not more that 150 kt. The TTBT proved contentious, with each side sending the other several inquiries asserting that the agreed-upon limits had possibly been exceeded (Timerbaev, undated). But this treaty was finally ratified in 1990, and has become less important since the CTBT was finalized and a nuclear testing moratorium by the signatory countries began in 1996. Yield estimation is however still important as an exercise in the interpretation of signals from the few underground explosions since that date, specifically those of India and Pakistan in 1998, and of North Korea in 2006 and 2009.

For a few tens of underground nuclear explosions, most of them at the Nevada Test Site, the yield has been announced by the agency conducting the test. It has therefore been possible to calibrate observed seismic magnitudes for these tests against the announced yields, and an example is given in Figure 3 using m_b values and yields reported for Nevada explosions in tuff and rhyolite.

The line $m_b = 4.05 + 0.75 \log (\text{Yield})$ fits the data well (yield in kilotons). Such a calibration curve can be applied to obtain a seismic yield estimate for Nevada explosions with unannounced yield. But it requires correction, prior to its use in obtaining a seismic yield estimate for an explosion at a different site. This must be done, to allow for physical and geological differences between the sites. For example, in different rock types there can be different efficiencies in the coupling of nuclear yield into seismic energy; and differences in the propagation efficiencies as seismic waves travel out from the source of interest, as compared to seismic signals from a Nevada explosion. In this connection, it is of interest to note m_b and yield for the US nuclear explosion LONGSHOT (conducted in 1965 in the volcanic breccias of an Aleutian island). The m_b value is 5.9, corresponding to a yield of about 300 kt. if the Nevada curve of Figure 5 is applied directly. But the announced yield for LONGSHOT is 80 kt. One way to obtain a calibration curve for the Aleutians is therefore to add a correction of about 0.4 m_b units to the Nevada values of m_b at a given yield, before the curve of Figure 5 is used to supply a seismic yield estimate in this new location. This m_b correction, for a site differing from that where a calibration curve is directly available, is called the *bias*. If the bias correction is not applied, then a Nevada magnitude–yield curve can give too high a seismic yield estimate for a non-Nevada explosion.

Note that the Nevada Test Site is in a region of active tectonics, with significant episodes of volcanism in the last few million years, resulting in high temperatures within the upper mantle, and thus anomalous attenuation of seismic waves propagating through the hot and partially molten upper layers of the Earth, 100 or 200 km in thickness beneath the Nevada Test Site. Such propagation through an attenuating medium is presumed to be a contributing cause of bias.

The existence of m_b bias has long been known in seismology in connection with what is called "station bias." By this term is meant the systematic difference between mean m_b values (obtained for a particular seismic event by averaging reported m_b from seismometers all over the globe), and m_b reported by just one station. For example, the station BMO in Oregon (another region of active tectonism) has reported m_b values that for a given earthquake are typically about 0.3 units below the global average; and station KJN in Finland (in a stable shield region) reports values about 0.15 m_b units higher than the average. Their station bias values are thus −0.3 and +0.15, respectively. Station bias values commonly range over ±0.4 m_b units, so it may be expected that source region bias (which is what must be applied when a standard m_b – yield curve is used for different source regions) will also range over about 0.8 m_b units.

The nuclear weapons test site of the USSR that conducted the most underground nuclear explosions was near the city of Semipalatinsk, in northeastern Kazakhstan. Several multi-megaton underground explosions were conducted on Russia's Novaya Zemlya island test site, far to the north of continental Eurasia (see Khalturin et al., 2005). But these were all prior to the intended date of entry-into-force of the TTBT (March 1976). After that date, the magnitude of the largest underground tests at Semipalatinsk rose higher and higher over several years, with some magnitudes exceeding 6.1. Such magnitudes, according to the Nevada Test Site formula discussed above, $m_b = 4.05 + 0.75 \log(\text{Yield})$, implied yields great than 500 kt, far in excess of the TTBT limit (150 kt). Intensive discussion in political and technical areas ensued with stronger and stronger evidence accumulating to indicate a substantial test site bias between the Nevada and Semipalatinsk test Sites. For example, it was of great interest that teleseismic signals from the largest underground explosions from these two tests, if recorded at the same station in a shield region, looked significantly different. The teleseismic *P*-wave from a large underground explosion at the site in Kazakhstan would routinely have frequency content at the 5 Hz level and sometimes higher (Der et al., 1985). The signal from Nevada would not contain such high frequencies. It was as if the signal from Nevada had passed through some type of filter, which of course would reduce its amplitude. Correcting for that effect would mean that the appropriate relation between magnitude and yield for an underground nuclear explosion at Semipalatinsk had the form

$$m_b = 4.05 + \text{bias} + 0.75 \log(\text{Yield}),$$

and Ringdal et al. (1992) and Murphy (1996) among many others concluded that the appropriate formula relating teleseismic *P*-wave magnitude and yield at Semipalatinsk should be this equation with a bias of 0.4. Support for this conclusion came from many arguments (see Richards, 1988 for a review). But in the political realm, the most persuasive was the very practical one associated with a Joint Verification Experiment of September 14, 1988, in which a team from the USA at the Semipalatinsk Test Site was allowed to make close-in measurements (within a few tens of meters) of a large Soviet underground nuclear explosion, in particular of the speed and extent of the shock wave it sent out into rock near the source at that test site. From such shock measurements, a reliable non-seismic method provided an accurate yield estimate (it was in the range 100–150 kt). Stations around the world provided measurements teleseismically, giving a seismic magnitude around 6.1 – comparable with the largest magnitudes of Semipalatinsk explosions since 1976, indicating that they too had been conducted in a way that respected the 150 kt limit of the TTBT. A reciprocal Joint Verification Experiment had been conducted at the Nevada Test Site, on August 17, 1988 with a Russian team making its own close-in measurements of the shock wave from a large US underground nuclear test intended to be in the range 100–150 kt. According to many news reports, the yield of this explosion slightly exceeded 150 kt. Timerbaev (undated) and news reports give it as 180 kt.

Problem events

The work of monitoring – for both earthquakes and explosions – is done in practice by hundreds of professionals who process the vast majority of seismic events routinely, and who also look out for the occasional events that, in the context of monitoring for the possibility of underground nuclear explosions, exhibit interesting characteristics, and which may then become the subject of special study.

These special events have stimulated the development of effective new discrimination techniques and a better appreciation of overall monitoring capability. Examples include a mine collapse in 1989 in Germany and two such collapses in 1995, in the Urals (Russia) and in Wyoming (USA); a small earthquake of magnitude 3.5 and its smaller aftershock in 1997 beneath the Kara Sea near Russia's former nuclear test site on Novaya Zemlya; and two underwater explosions in 2000 associated with the loss of a Russian submarine in the Barents Sea; the series of nuclear explosions carried out by India and Pakistan in 1998; and the nuclear tests conducted by North Korea in 2006 and 2009.

The mining collapses were seismically detected all over the world. For example, stations that detected the Wyoming event of 1995 are indicated in Figure 6. Mining collapses such as these have caused concern because their mix of surface waves and body waves as recorded teleseismically can appear explosion like using the classical M_s: m_b discriminant, as shown in Figure 2 (see above). But a careful analysis of regional and teleseismic waves from these events has showed that although the surface waves were quite weak, and in this respect seemed explosion like, they had the wrong sign. Therefore the motion at the source was *implosive* (the ground had moved inward toward the source) rather than *explosive*. Indeed, mining collapses are an implosion phenomenon, and it was important to learn that their implosive nature could be reliably determined from seismic recordings. Teleseismic waveforms from the Wyoming mine collapse are shown in Figure 7. This is an example of the use of what seismologists call the "first motion" of the *P*-wave, which is clearly downward in these data.

The Kara Sea earthquake was too small to apply the M_s: m_b discriminant (the surface waves were too small to measure reliably). This event showed the importance of accurate locations, and of using spectral ratios of regionally recorded *P*-waves and *S*-waves to discriminate small events (Richards and Kim, 1997).

As we have discussed earlier, the North Korea nuclear test of 2006 was of interest as an example of a nuclear explosion that was promptly detected globally, though its yield has been estimated at less than 1 kt. This event required regional seismic data in order to determine that indeed an explosion had been carried out and that the signals were not from an earthquake. Subsequently, xenon radionuclides were detected that decisively identified the explosion as nuclear.

Evasion

Several methods have been proposed, by which underground explosions might be concealed. One method is simply to make them small enough; but then there would be relatively little to learn, from the point of view of a weapons designer. The more important methods are those which combine as many features as possible, designed to reduce seismic signal-to-noise ratios at all relevant monitoring stations. Proposed methods include: emplacement of the nuclear device in material such as dry alluvium, to reduce the coupling of explosion energy into seismic signal (but that method is likely to result in leakage of detectable radioactivity); waiting until a sufficiently large natural earthquake occurs fairly near a test site (which presents the formidable challenge of identifying the event within a few minutes of its occurrence as large enough, and then within a couple of minutes executing the weapons test so that its seismic signals would hopefully be swamped by the large and prolonged signals from the earthquake); and setting off a sequence of several explosions that are designed to simulate a natural earthquake signal.

Careful study of each of these methods indicates that they are relatively ineffective in comparison with the methods known as cavity decoupling and mine masking, which we next discuss, and which are widely regarded as setting the practical levels down to which seismic monitoring of nuclear explosions is possible.

When an underground explosive device is tightly packed into its hole ("tamped" or "fully coupled"), and is detonated at sufficient depth to contain all radioactive products, a shock wave travels some distance from the shot-point out into the surrounding rock at speeds that exceed the normal *P*-wave speed. This nonlinear phenomenon reduces at sufficient distance from the shot-point, and thereafter the wave propagation can be regarded as elastic. The so-called "elastic radius" for a tamped explosion, i.e., the radius beyond which wave propagation is linear, is roughly 100 meters times the cube root of the yield (in kilotons).

If the explosion is set off inside a large underground cavity instead of being tamped, then the shock wave set up in the rock can be weakened or even eliminated, in which case only elastic waves are radiated. The explosion is said to be fully decoupled if only elastic waves result, and theoretical work begun in 1958 has addressed the question of how much weaker the seismic signal might be made. Theoretical work has indicated that signals could thereby be reduced by factors in the range 50–100, compared to a tamped explosion. The cavity radius itself is the "elastic radius" for a fully decoupled shot. For salt, the cavity radius required for full decoupling has been estimated at about 25 m times the cube root of the yield (in kilotons). For hard rock, the cavity size for full decoupling is comparable; for weak salt it is somewhat greater. See Sykes (1996) for further discussion, and Denny and Goodman (1990) for estimates of the decoupling factor derived from the practical experience in 1966 of carrying out a small nuclear explosion (about 0.38 kt) in the cavity produced by a tamped shot of 5.3 kt conducted 2 years earlier in a Mississippi salt dome. They conclude that the amplitude reduction is about 70, at low frequencies, for salt. At frequencies that have conventionally been used for seismic monitoring, the seismic signal strength is proportional (very roughly) to the volume within the elastic radius. This volume is substantially reduced by fully decoupling, which is the reason why cavity decoupling has been proposed as offering the technical possibility of a clandestine program of nuclear testing. However, the signal strength is not nearly so strongly reduced, by decoupling, at frequencies above that associated with resonances of the internal surface at the elastic radius. In practice, the frequency above which decoupling is likely to be substantially less effective is around 10–20 Hz, divided by the cube root of the yield (in kilotons). The overall effect on the seismic signals from a fully decoupled shot of yield *Y*, given the results of Denny and Goodman, is to make these signals look like those from a tamped shot of yield *Y*/70.

A thorough discussion of decoupling as an evasion scenario would have to include several non-seismological considerations. These include: the military significance of being able to carry out nuclear tests up to various different yield levels (e.g., 0.1, 1, or 10 kt.); and the political consequences if a clandestine test program were uncovered. Technical considerations include methods of (clandestine) cavity construction, and the capabilities of non-seismological surveillance techniques. Leakage of radioactivity from an underground cavity would be a challenge, given that much of the energy of a decoupled explosion goes into pumping up the pressure in the cavity. While some assert that clandestine use of cavity decoupling would be so difficult to execute that it belongs to the realm of fantasy, others have been persuaded that the risk might indeed be manageable, and that estimates of concealable yields, under this evasion scenario, must be made. The NAS (2002) report describes ten "layers of difficulty" with successfully hiding an underground nuclear explosion via cavity decoupling, concluding that even a nation committing significant resources to this work could not have confidence in being able to get away with tests above 1 or 2 kt.

The evasion scenario known as mine masking hypothesizes the execution of an underground nuclear weapon test explosion in a mining region, concurrently with a large mine blast. Such blasts in a big commercial operation consist of hundreds of separate charges, fired in sequence to break and/or move as much rock as possible, in a procedure known as ripple-firing (Khalturin et al., 1998). Regardless of the logistical difficulties of such a scenario, estimates of the possibilities of concealment via this approach can come from taking examples of signals from large mine blasts, and signals from small underground nuclear explosions, then adding them together before subjecting them to the methods used to discriminate between various types of seismic events. What is typically found, is that the maximum size of the identifiable waves (e.g., the *P*-waves) from the mine blast is about that expected from individual sub-blasts (commonly called "delays"), and these amplitudes are spread out over a longer time in seismograms.

A study of mine masking possibilities by Smith (1993) used several different examples of mine-blast seismograms together with single-fired explosion records, and found a number of features that could be used to identify a simultaneous shot within a ripple-fired blast. He concluded that to conceal a single-fired deep detonation (depth is required for containment of radionuclides), the single explosive shot should not exceed 10% of the total explosive.

The conclusion here is that mine blasts are not effective for concealing large releases of energy at the level associated with kiloton-scale nuclear weapons tests, unless the nuclear explosion were subject to efforts at decoupling. Again non-seismic considerations arise, including an assessment of the plausibility of carrying out a complicated decoupled and masked nuclear explosion at the same time and location as a large mine blast that would itself attract some level of monitoring attention – particularly if the seismic signals seemed unusual in comparison with those from prior blasting in the region.

Event detection capability of the international monitoring system

In 1976, a group of international scientists was established at the Conference on Disarmament in Geneva, for the study of monitoring technologies and data analysis methods in the context of supporting a future test ban treaty. This group of scientific experts (GSE) played an essential role in laying the scientific groundwork for the final stage of CTBT negotiations conducted from 1994 to 1996. Prior to the negotiation, GSE organized a series of technical tests – GSETT-1 in 1984, GSETT-2 in 1991, and GSETT-3 in 1995. These tests contributed significantly to the development of the international system being built today to support treaty verification.

The finalized sections of the CTBT include an extensive description of networks to monitor treaty compliance using hydroacoustic, infrasound, and radionuclide technologies as well as seismological methods. The CTBT Organization (CTBTO) operates an International Monitoring System specified in treaty text, as well as an International Data Centre to analyze signals sent via satellite to headquarters in Vienna. Extensive descriptive material on these networks is available online (see http://www.ctbto.org).

To implement the CTBT seismic monitoring system, a sequential four-step process is needed to build each station (CTBTO PrepComm, 2009): (1) Site survey, (2) Installation, (3) Certification, and (4) Operation. It must be demonstrated for IMS stations that data received at the International Data Centre (IDC) are *authentic*. This is achieved through a special digital "signature" embedded in the data flow from each station. The IMS station must be certified to ensure that all of its equipment, infrastructure, and settings meet the technical specifications set by the CTBTO, and to also ensure that all data are transmitted to the IDC through the Global Communication Infrastructure (GCI) in a timely manner.

Here, we note that the primary seismographic network is to consist of 50 stations, many of them arrays; and that location estimates are based upon detection of signal at 3 stations or more. An auxiliary network of 120 continuously operating stations is available to provide seismic waveform data, again via satellite, in order to help characterize the events detected by the primary network. Although these two networks are not completely built, there are enough stations operating to provide good indications of what the detection capability will be when all stations are installed and providing data.

Figure 8 shows maps of the detection capability of the primary seismic network of the IMS. The upper figure shows the actual capability of 38 operating stations based upon experience in the year 2007. The lower figure shows how much this capability is expected to improve when 11 additional stations are operational, most of them in Eurasia. Capability is expressed in terms of magnitude thresholds, above which 90% of the seismic events are expected to be detected at enough stations to provide a location estimate. The work of identifying events is left to member states. This work is not just a technical matter since it is a political act for one country to make an allegation that another country has committed a treaty violation. The evidence in support of such an allegation can come from the IMS and IDC, as well as from the National Technical Means of member states, and/or from a subset of the thousands of seismographic stations operated around the world for purposes not directly related to monitoring for nuclear explosions.

Summary

We have described the basic steps in monitoring nuclear explosions, and have emphasized the seismic monitoring system specified by the Comprehensive Nuclear Test Ban Treaty of 1996.

When the treaty was being negotiated, the goal for the International Monitoring System was that it be capable of detecting and identifying treaty violations – nuclear explosive tests – at the 1 kt level and higher, if they were not evasively tested. Recognizing that a 1 kt underground nuclear explosion has a magnitude in the range about 4–4.5, if it is conducted in the way that almost all the more than 1,500 prior underground nuclear explosions were carried out (i.e., well tamped and not with intent to reduce the signals picked up by monitoring networks), the evidence from Figure 8 is that this design capability has been significantly exceeded. For almost the entire northern hemisphere, including Eurasia and North America, capability is good down to about magnitude 3.3. This corresponds to a yield of less than 100 t (0.1 kt) for a well-tamped explosion in hard rock. Only time will tell whether this capability, combined with other monitoring assets, is deemed adequate to support entry into force of the CTBT.

Acronyms

CTBT–Comprehensive Test Ban Treaty or Comprehensive Nuclear-Test-Ban Treaty (its formal name)
CTBTO–CTBT Organization
IDC–International Data Centre (of the CTBTO)
IMS–International Monitoring System (of the CTBTO)
LTBT–Limited Test Ban Treaty
TTBT–Threshold Test Ban Treaty

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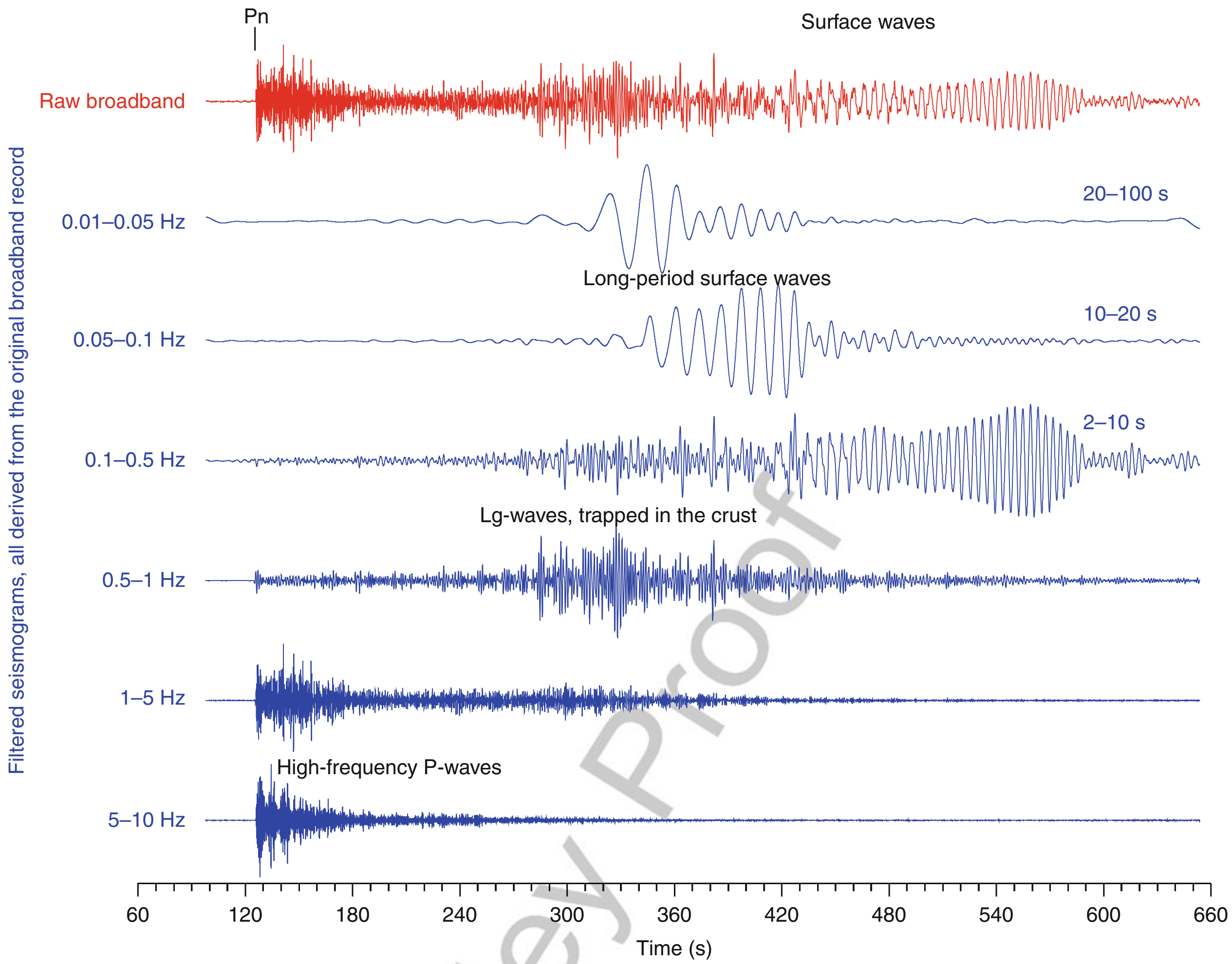
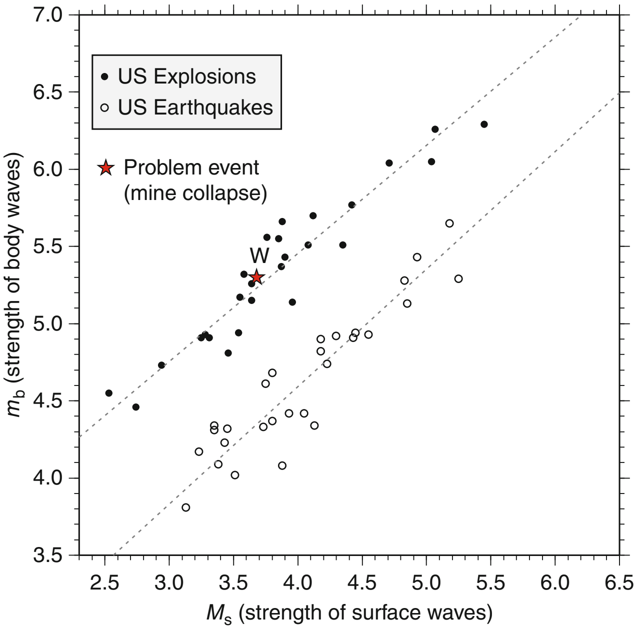
Cross-references

Body Waves
Earthquake Magnitude
Monitoring of CTBT
Seismic Instrumentation
Seismological Networks
Surface Waves



Seismic Monitoring of Nuclear Explosions, Figure 1 The seismogram recorded at station WMQ in northwestern China, for an underground nuclear explosion on July 8, 1989 in Kazakhstan at a distance of almost 1,000 km, is shown in red (*top*). Filtered versions of the original trace in different frequency bands are shown in *blue*. Time in seconds at *bottom* is with respect to the time the explosion occurred. Different types of seismic wave propagate at different frequencies, and hence their ground motions show up in different bands. *P*-waves, in this case the regional wave called *Pn* that travels in the uppermost mantle, arrive about 120 s after the explosion at this distance, involving short-period (high frequency) motions. Long-period surface waves can be seen in the top two *blue* traces. Some surface waves arrive up to 600 s after the explosion at this distance and, thus, travel as much as five times slower than *P*-waves. *S*-waves (weak in this example) are shear waves, traveling slower than *P* waves. A high-frequency wave marked as *Lg*, which is often the largest wave at regional distances from an earthquake but is only weakly excited by explosions, is dominated by shearing motions and is largely trapped in the Earth's crust. The amplitude of ground motion in the longest period band is less than 2% the amplitude in the short period band from 1 to 5 Hz. (Adapted from work of W.-Y. Kim.)



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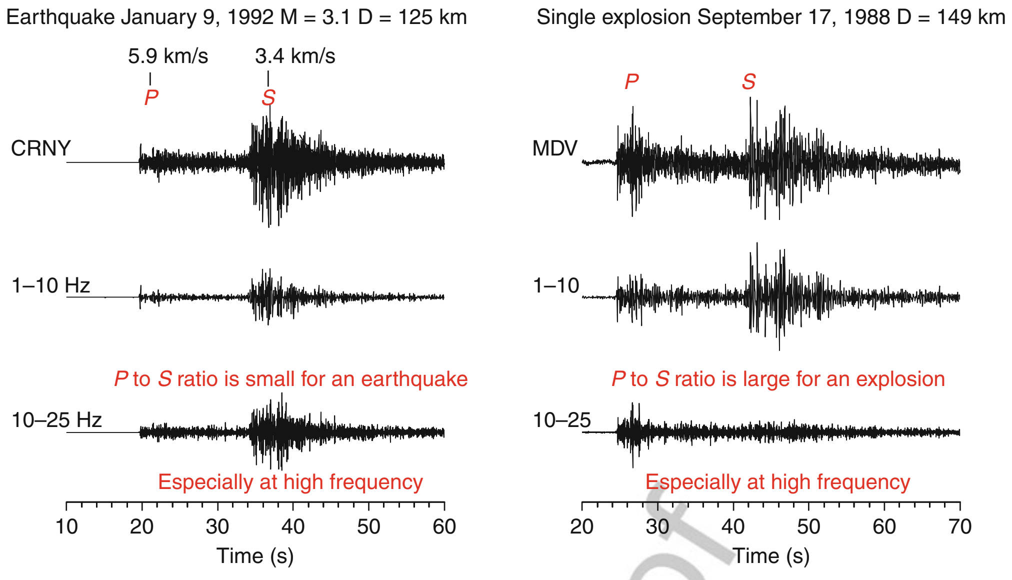
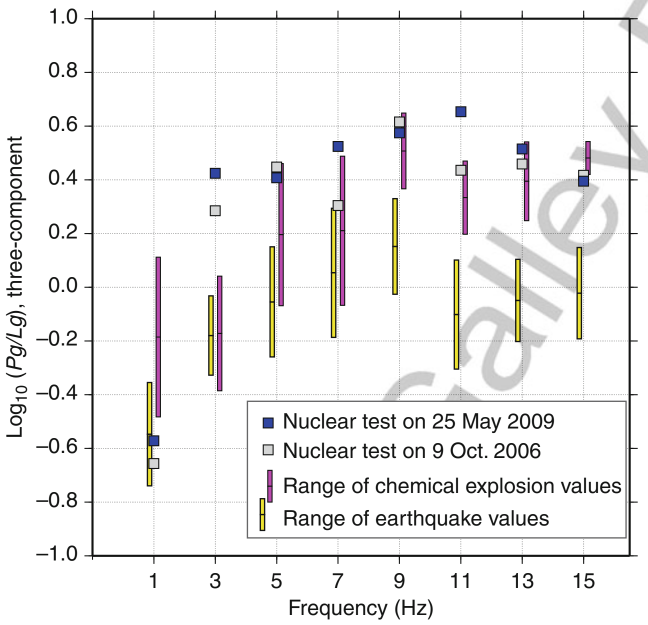
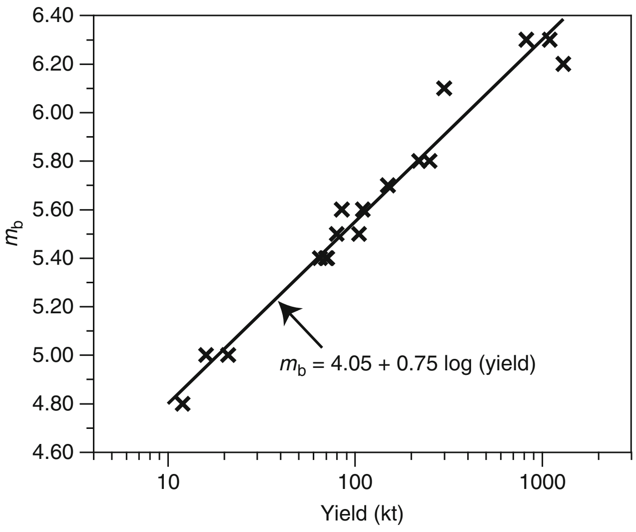
Seismic Monitoring of Nuclear Explosions, Figure 2 An M_s: m_b diagram from Bowers and Walter (2002). It can be seen here that for seismic events of the same M_s value, earthquakes have a significantly smaller m_b value than do the explosions. The offset is about 0.8 m_b units, at $M_s = 5$. Because magnitudes are based on logarithmic scales, and $10^{0.8} \sim 6$, it follows that at frequencies near those at which body wave magnitude is measured (about 1 Hz), the *P*-waves from an underground nuclear explosion are about 6 times larger than such waves from an earthquake having the same strength of surface waves. Also, indicated by the red star are the body-wave and surface-wave magnitudes of an interesting but fortunately rare event, a large mine collapse with *P*-wave magnitude greater than 5. This event, which plots with the explosion population, is discussed further below – see Figures 6 and 7.



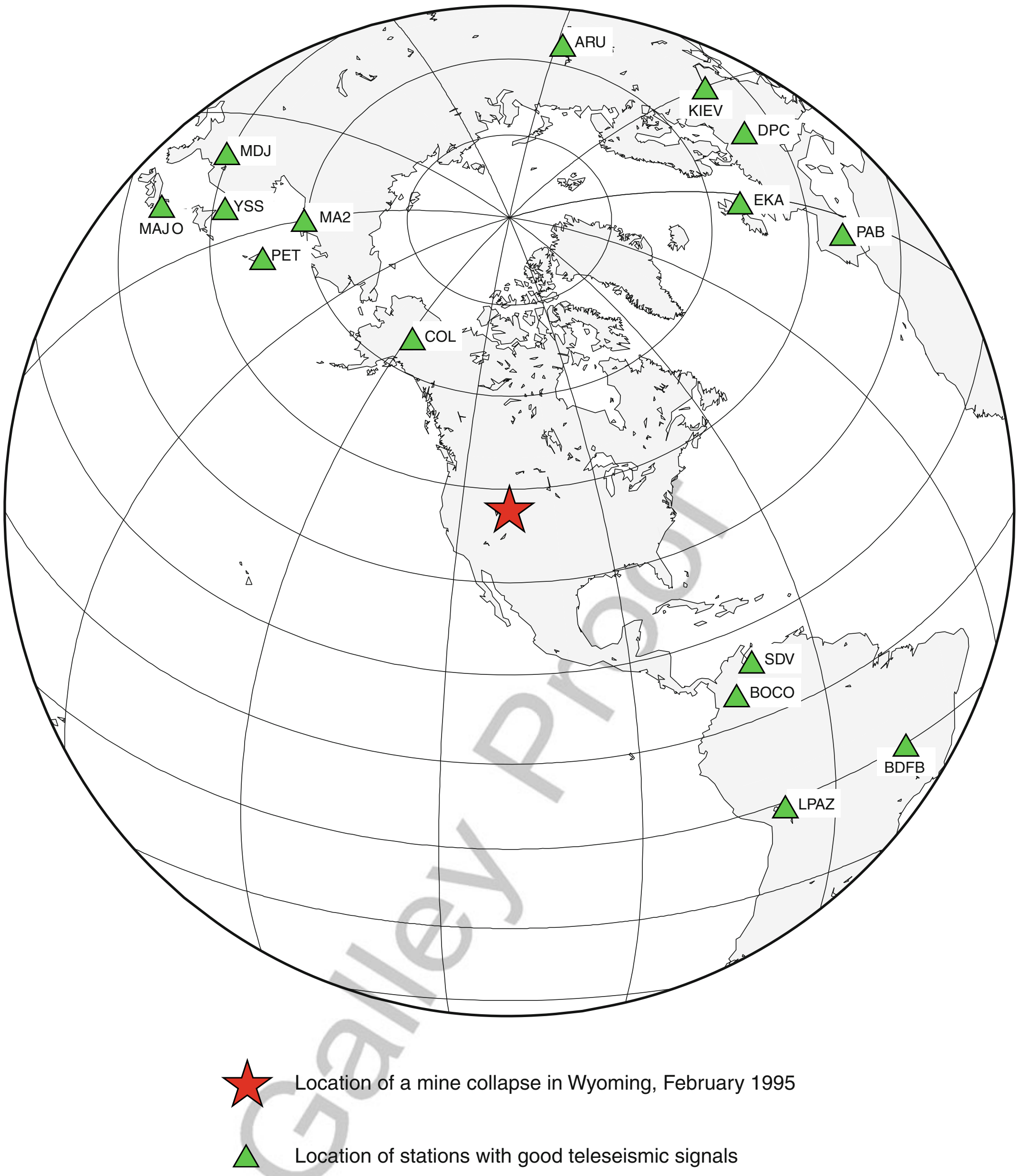
Seismic Monitoring of Nuclear Explosions, Figure 3 Typical vertical-component records from an earthquake and an explosion. Traces plotted are: unfiltered (*top*), low-frequency bandpass filtered (*middle*), and high-frequency bandpass filtered (*bottom*). Example Gaussian time windows used for *Pg* and *Lg* spectral amplitude measurements are shown on the unfiltered earthquake trace. (From Kim et al., 1993.)



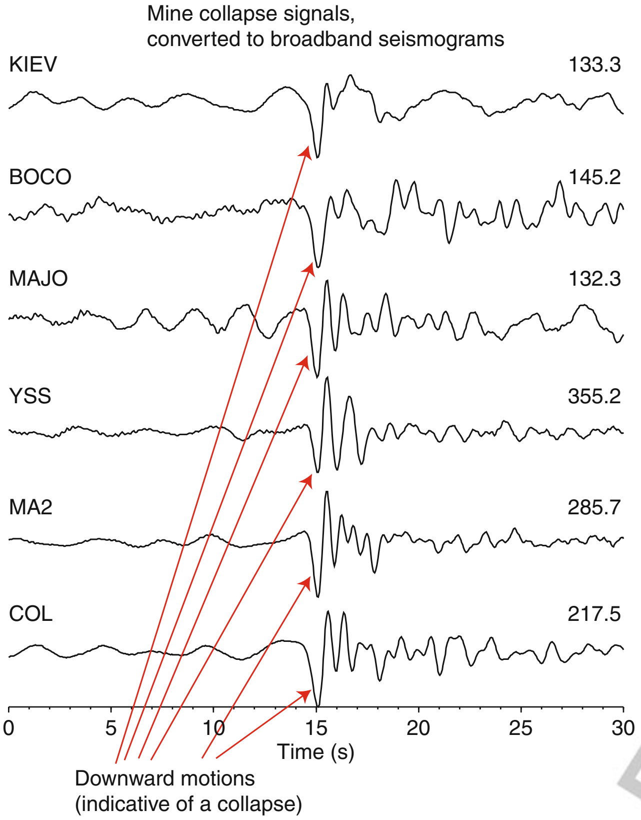
Seismic Monitoring of Nuclear Explosions, Figure 4 Spectral ratios are shown, for the two nuclear explosions carried out by North Korea in 2006 and 2009, as measured from waveforms recorded at station MDJ in China (distance, about 370 km). They are compared with these ratios for a small group of earthquakes, and another group of chemical explosions, all in the vicinity of North Korea's nuclear test site. Colored bars represent ±1 standard deviation in the ratios for chemical explosions (*yellow*), and small earthquakes (magenta). The spectral ratios for events in North Korea on October 9, 2006, and on May 25, 2009, are both explosion-like. (Courtesy of Won-Young Kim.)



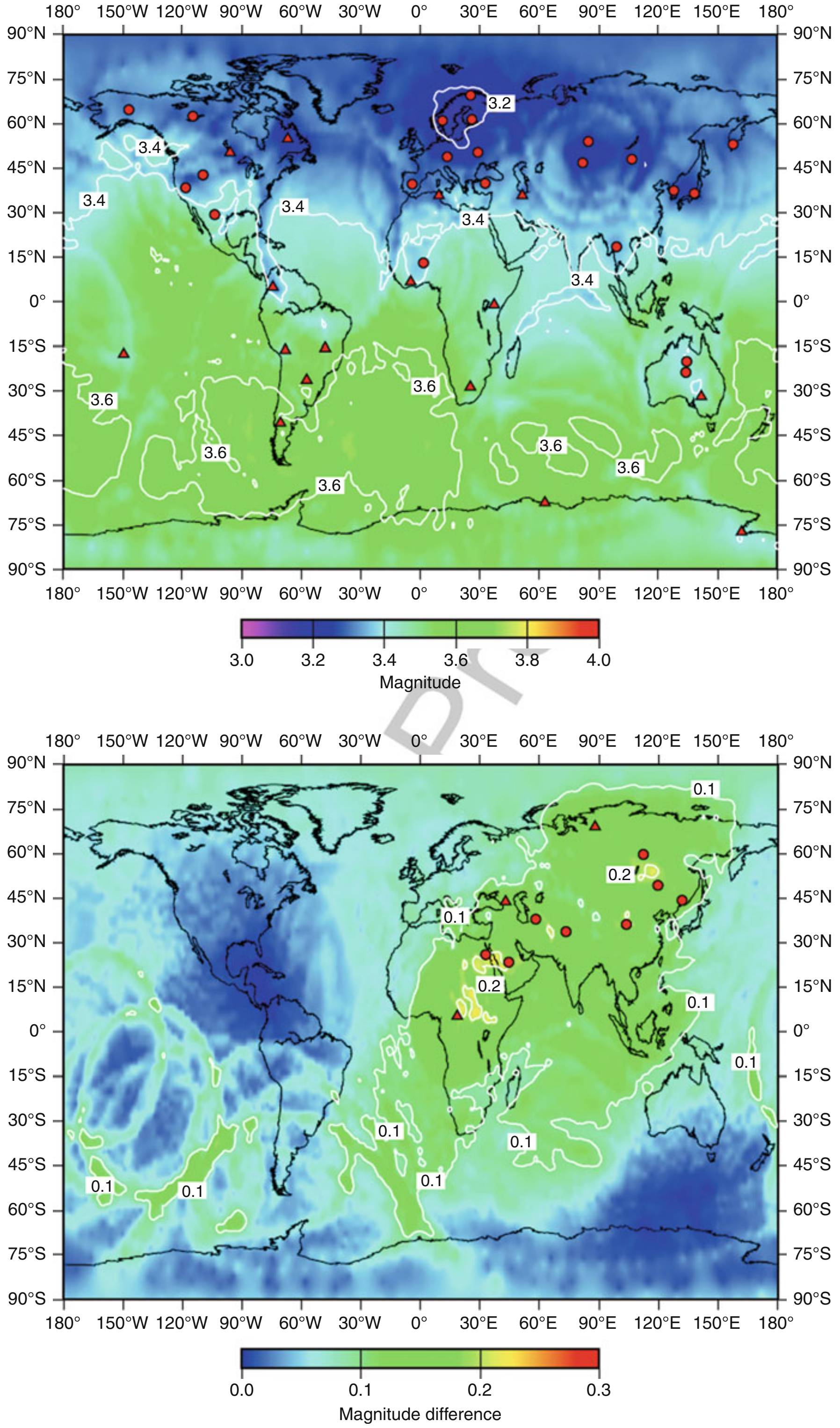
Seismic Monitoring of Nuclear Explosions, Figure 5 Seismic magnitude m_b vs. announced yield, for 17 Nevada Test Site nuclear explosions in tuff and rhyolite. The straight line here, which fits the data quite well, can be used to make a yield estimate of other events at this test site, in similar rock, if the seismic magnitude is known. (Data from Nuttli, 1986.)



Seismic Monitoring of Nuclear Explosions, Figure 6 A global map showing stations recording teleseismic *P*-waves from a mine collapse in Wyoming. Its body wave magnitude was 5.3, and surface wave magnitude was 3.7. This combination is explosion like, as shown in Figure 3. (From Bowers and Walter, 2002.)



Seismic Monitoring of Nuclear Explosions, Figure 7 The *P*-wave signals of the Wyoming mine collapse are shown at six teleseismic stations, processed to bring out the fact that the first motion of the ground at these stations is downward, indicative of an implosion rather than explosion (for which the first motion would be upward). (From Bowers and Walter, 2002.)



Seismic Monitoring of Nuclear Explosions, Figure 8 Maps showing the detection capability of the IMS primary seismographic network. The upper figure shows the capability of the network in late 2007, with 38 stations sending data to the IDC. The capability is represented by the magnitude of the smallest seismic event that would be detected with a 90% probability by three stations or more. The lower figure shows the estimated improvement over this capability that could be achieved by bringing 11 of the remaining 12 primary seismic stations into operation. (From Kværna and Ringdal, 2009.)

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AU2	’Bowers and Walter (2002)’ is cited in text but not given in the reference list. Please provide details.	
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