Forensic Seismology and the Comprehensive Nuclear-Test-Ban Treaty

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Abstract

One application of forensic seismology is to help verify compliance with the Comprehensive Nuclear-Test-Ban Treaty. One of the challenges facing the forensic seismologist is to discriminate between the many thousands of earthquakes of potential interest each year and potential Treaty violations (underground explosions). There are four main methods: (*a*) ratio of body- to surface-wave magnitudes, (*b*) ratio of high-frequency *P* to *S* energy, (*c*) model-based methods, and (*d*) source depth. Methods (*a*) and (*b*) have an empirical basis. The weakness of methods (*a*)–(*c*) is the lack of an equivalent elastic source for an underground explosion fired in the range of geological media found around the world. Reliable routine source-depth determination has proved difficult. However, experience gained in the past decade at identifying suspicious seismic sources suggests that although no single method works all of the time, intelligent and original application of complementary methods is usually sufficient to satisfactorily identify the source in question.

INTRODUCTION

CTBT: Comprehensive Nuclear-Test-Ban Treaty

IMS: International Monitoring System

OSI: On-Site Inspection

IDC: International Data Center

Global seismology is the study of elastic (seismic) waves to investigate a seismic source and the structure and processes within Earth. Usually, the seismic waves studied are caused by earthquakes, but seismic waves are also generated by nuclear explosions. It was recognized by experts, meeting in Geneva in 1958, that seismology could be the only way to detect and identify underground explosions, and thus could be used to help verify a treaty banning nuclear-test explosions.

Seismology and the Comprehensive Nuclear-Test-Ban Treaty

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) took more than 40 years to achieve and is considered to be the Holy Grail by arms control advocates (Marshall et al. 2001). The verification system for the CTBT has four pillars: the International Monitoring System (IMS), Consultation and Clarification, On-Site Inspection (OSI), and Confidence Building Measures. The IMS will consist of a global network of more than 300 stations sending data to the International Data Center (IDC) in Vienna, Austria.

The technical discussions on whether a CTBT could be adequately verified, which spanned the period from 1958 to the final negotiation of the Treaty in 1996, have been extensively reviewed elsewhere (Blandford 1977; Douglas 1981, 2007)—the main technical difficulty was the development of adequate seismological methods of identifying underground explosions (potential Treaty violations) from the many thousands of earthquakes that occur each year. The relative importance of seismology for Treaty verification is reflected by the fact that more than half (170 out of 321) of the IMS stations will be seismic stations. However, seismology alone cannot distinguish between single nuclear and chemical underground explosions—for this, diagnostic radionuclides are required. To detect and attribute the diagnostic radionuclides, the IMS network will comprise 80 radionuclide stations, and the Treaty has provisions for OSI.

Here, we use the term forensic seismology to describe seismology applied to CTBT verification using data mainly from global networks of seismic stations. The search for aftershocks from a suspected underground nuclear explosion as part of an OSI (Takano & Krioutchenkov 2001) could also be considered forensic seismology—examples of other applications of forensic seismology are briefly described in the sidebar Other Applications of Forensic Seismology. [The use of the term forensic comes from its definition as "pertaining to courts of justice." Forensic seismology is thus the application of seismological science to the elucidation of doubtful questions in such a court (Douglas 2007).]

The IMS and Seismology

The IMS network of stations will comprise 50 primary seismic stations providing continuous data and will be supported by 120 auxiliary seismic stations that provide data on request (Barrientos et al. 2001), 11 hydroacoustic stations (Lawrence et al. 2001), 60 infrasound stations (Christie et al. 2001), and 80 radionuclide stations (with particulate and noble gas sensors) (Matthews & Schulze 2001). The radionuclide part of the IMS will also be supported by 16 radionuclide laboratories (Karhu & Clawson 2001). The IDC receives data from the IMS network of stations and distributes these data and derived products (e.g., bulletins of seismic events) to states that are party to the Treaty (Bratt 2001).

At the IDC, the continuous waveform data (primary seismic, hydroacoustic, and infrasound) are searched for signals from a potential Treaty violation, and lists of detections are formed. These detections are then associated with events, and the event location, depth, and origin time (and other associated parameters, such as magnitude) are estimated (Bratt 2001). In general, the seismic signals are searched for signals from an underground explosion, the hydroacoustic for an explosion

OTHER APPLICATIONS OF FORENSIC SEISMOLOGY

The rapid expansion of seismometer observatories around the world has resulted in a growing number of examples of how seismic observations have been used to provide evidence to support investigations that are potentially judicial.

1. Seismic and acoustic signals (both recorded by a seismometer) from aircraft crashes can provide independent estimates of impact time and location, for example, the impacts from Pan Am Flight 103 at Lockerbie, Scotland in 1988 (crash site approximately 25 km southwest of the Eskdalemuir seismometer array), the impacts from Swiss Air passenger aircraft in shallow water at Peggy's Cove near Halifax, Canada, in 1998 (McCormack 2003), and the aircraft impacts into (and subsequent collapse of) the twin towers of the World Trade Center on September 11, 2001 (Kim et al. 2001).

2. Seismic and acoustic signals can provide independent estimates of the detonation time of terrorist explosions, such as from the Oklahoma City bombing in 1993 (Holzer et al. 1996) and from the truck bomb attack on the US Embassy in Nairobi, Kenya, in 1998 (Koper et al. 1999).

3. The amplitude of seismic and acoustic signals can be used to place constraints on the explosive yield (and coupling) of potentially judicial explosive sources (Koper et al. 1999). Experiments using controlled truck-bomb sources have refined initial estimates of the yield of the Nairobi bomb (equivalent to 2 to 6 tons of TNT) and resulted in initial scaling laws that could be used in future investigations (Koper et al. 2002).

in the ocean and the infrasound for an explosion in the atmosphere. However, it is becoming clear that there are many synergies between the waveform technologies that may be effectively exploited in the future. The IDC is also required by the Treaty to routinely screen-out events considered to be consistent with natural phenomena or non nuclear, man-made phenomena.

As noted above, analysis of the data from the waveform technologies alone does not uniquely identify a source as nuclear. The smoking gun may come from data provided by the radionuclide stations, an OSI, or even from National Technical Means, should a state choose to share such means to help verify a Treaty violation.

In this article, we focus on the methods available to the forensic seismologist for source identification. We discuss examples of special analysis of the so-called seismic problem events (**Figure 1**), which some consider inevitable under a CTBT (Sykes 2002). We also discuss announced underground nuclear tests that have occurred since the Treaty was opened for signature in 1996, including that by the Democratic People's Republic of Korea (DPRK) on October 9, 2006 (and preceding false alarms).

We show that, in practice, the forensic seismologist often utilizes not only data from the IMS network of stations and products from the IDC (Douglas et al. 1999, Bowers et al. 2001), but also data from non-IMS networks of stations (Richards & Kim 1997, Hartse 1998, Bowers 2002, Kim & Richards 2007). Non-IMS networks may be other international, regional, and national seismometer networks originally deployed for non-CTBT verification purposes, such as earthquake hazard assessment, or for basic seismological research (van der Vink & Park 1994, Richards & Kim 1997, Kim & Richards 2007). There is now wide access to data from numerous seismic stations via the Internet (Kradolfer 2000).

SOURCE IDENTIFICATION METHODS

There have been several substantial reviews of research into the problem of discriminating between earthquakes and underground explosions (Blandford 1977; Douglas 1981, 2007). Early

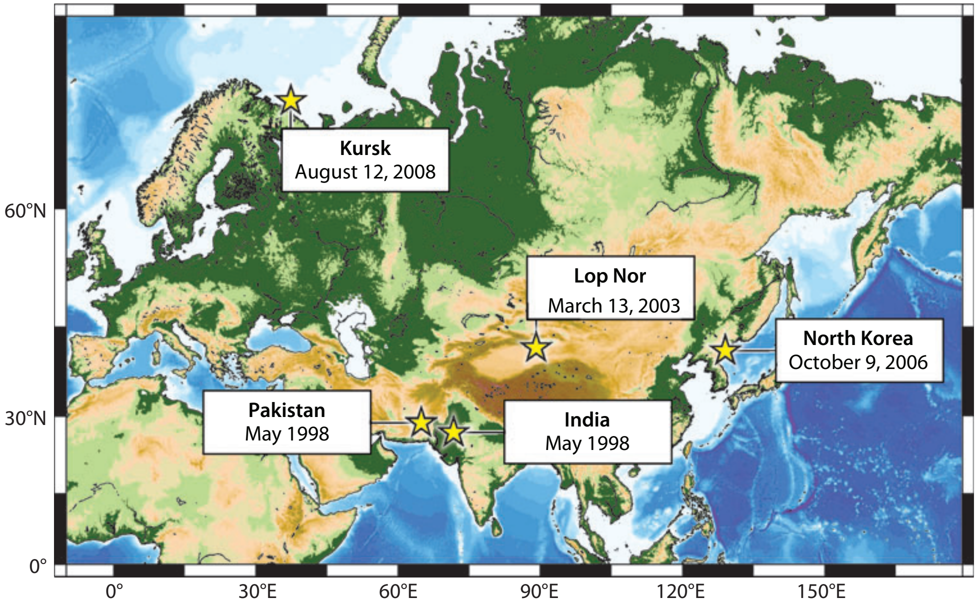


Figure 1

Locations of some seismic disturbances that have been of interest to forensic seismologists over the past decade.

work concentrated on seismic methods using signals recorded at regional distances in the western United States, defined as distances <1700 km (National Academy of Sciences 2002). Initial results were not encouraging. However, clear *P* signals were seen by an experimental seismometer array deployed in Wyoming, United States, from presumed underground nuclear explosions (UNEs) in Kazakhstan and Algeria, leading to the realization that signals detected at large distances, i.e., 3000–10,000 km, from the source (known as teleseismic signals) could be used for discrimination (Richards & Zavales 1996, Douglas 2007). The main teleseismic discriminants that emerged from subsequent research are source depth, *P* complexity (simplicity), and the ratio of body- to surface-wave magnitude (m_b:M_s).

For teleseismic discriminants, the identification threshold is usually taken as approximately half a magnitude unit above the event-detection threshold. The threshold for detection by at least three stations in the IMS primary seismic network is <3.5 m_b for the vast majority of the continental land mass 90% of the time (National Academy of Sciences 2002).

UNE: underground nuclear explosion

m_b**:** body-wave magnitude (based on the *P* wave amplitude and period)

M_s**:** surface-wave magnitude (based on the Rayleigh wave amplitude and period)

Since the late 1970s, there has been concerted research into discriminants that are effective using signals recorded at regional distances, especially by the United States (Blandford 1981). Research has shown that discriminants based on the spectral amplitude ratio of a single regional phase can be ineffective (Blandford 1981, 1996), but that at high frequencies (>2 Hz) *P*/*S* amplitude ratios are a promising discriminant (Blandford 1996).

The shift from teleseismic back to regional discrimination appears to have been driven by the requirement to detect seismic signals from, and identify, UNEs with $m_b < 4$. Signals from at least three stations are usually required to be associated to form an event and estimate its location. Given the distribution of seismic stations in the IMS network, it is likely that, for a source located on the continental land mass, at least one station at regional distances will have clear signals. Thus, it has been argued that there may be little difference in the event-detection and -identification thresholds for regional discriminants (National Academy of Sciences 2002), providing discriminants applied at a single station at regional distances can be considered reliable.

Further, non-IMS seismic networks allow the event-detection threshold to be lowered below 3 m_b for many parts of the world (National Academy of Sciences 2002) and increase the chance of applying regional discriminants averaged over more than one station. It is estimated that, globally, on average, there are more than 60,000 earthquakes a year with $m_b \geq 3$, compared with approximately 7000 with $m_b \geq 4$. Lowering the detection threshold brings additional challenges, not only caused by the significant increase in natural earthquakes that need to be considered, but also because it is estimated that there are a few hundred mining explosions a year with $m_b \geq 3$ (National Academy of Sciences 2002).

REB: Reviewed Event Bulletin

TNT: trinitrotoluene

In addition to earthquakes and large mining explosions, mine tremors appear explosion-like on many traditional discriminants (Blandford 1996). Research suggests that such problem events may be resolved using a combination of the first motion of teleseismic *P* (Bowers & Douglas 1997), combined body- and surface-wave modeling (Bowers & Walter 2002), and regional P/L_g amplitude ratios (Bennett & McLaughlin 1997).

The IDC currently operates an experimental event screening process (identification of events considered consistent with natural phenomena or nonnuclear, man-made phenomena) for all events in the analyst Reviewed Event Bulletin (REB) with network-averaged $m_b \geq 3.5$ (Fisk et al. 2002). The REB is produced by interactive analyst review of an automated event bulletin. The experimental process has provisional criteria for screening using m_b:M_s, depth, location (onshore/offshore, with a minimum water depth constraint and nonobservation of unblocked underwater explosion-like hydroacoustic signals), and regional high-frequency *P*/*S* amplitude ratios. There are more than 20,000 earthquakes each year with $m_b \geq 3.5$, so the global event screening process adopted at the IDC will probably need to be highly automated to be cost-effective.

A key challenge for effective routine event screening is to define the explosion population under a CTBT. The vast majority of presumed UNEs conducted have been fired at a depth sufficient for containment of radioactivity, with little consideration of whether there is a permanent surface expression or seismic waves are detected; detection via seismic signals or surface disturbance is likely to be considered by a potential violator of the CTBT. Even for the well-instrumented tests, it is not fully understood how underground explosions generate seismic waves (Douglas 2007). Further, as Douglas (2007) states,

> [t]he lack of understanding of the explosion source adds to the difficulty of setting screening criteria. The available recordings from explosions are not some random sample from a population of possible signals. Most of the explosions have been fired at a small number of test sites, so statistical comparisons of earthquake and explosion signals may be unreliable.

However, it may be that not only do large tamped chemical and equivalent-yield UNEs produce similar seismic signals, but they also appear to follow similar scaling laws (Denny & Johnson 1991). Thus, experiments using small chemical explosions [a few tons equivalent or less of trinitrotoluene (TNT)] may help inform us about how larger-yield UNEs generate seismic waves. One disadvantage of small-scale experiments is that gravity does not scale, so containment rules (overburden pressure is usually assumed to be proportional to the cube-root of yield) and spall effects will not necessarily be accurately reproduced.

For the forensic seismologist, an attractive alternate to the event screening strategy is to routinely attempt to detect statistical outliers to the earthquake population using promising discriminants (Fisk et al. 1996). Resources can then be targeted at identifying outliers in regions of interest through special studies. Regularized discrimination analysis can be applied to combine candidate discriminants, allowing for the level of explosion calibration information available, i.e., the transition from outlier detection to classical discrimination (Anderson & Taylor 2002, Anderson et al. 2007).

Some recent advances and remaining challenges for three of the experimental screening criteria and candidate outlier detection discriminants are described below. The basic concepts and physics on which these criteria are based have been used, along with waveform modeling and inversion techniques, to resolve many problem events in special studies. The remainder of this article gives examples of special studies to demonstrate the variety of methods available to the forensic seismologist helping to verify compliance with the CTBT.

Depth

The depth criterion is based on the idea that there is a physical limit to the depth at which a potential violator could place a nuclear explosive device. For example, if the estimated source depth is >10 km with 95% certainty, then the source is likely to be natural (Blandford 1977).

For depth estimates using only teleseismic *P* onset times, the estimated depth tends to trade off with the origin time. When times from regional distance stations are available, the depth estimates are also typically unreliable for depths less than 50 km and tend to have large uncertainty (Fisk et al. 2002).

Approximately 15% of REB events are screened out using the experimental depth screening criterion (Fisk et al. 2002). The experimental depth criterion is nominally a one-sided test that the depth is >10 km at the 97.5% confidence interval. The current implementation has a constant factor (to account for model uncertainty, e.g., +20 km), which is expected to reduce over time as better models are developed (Fisk et al. 2002).

Depth phases, such as free-surface reflections *pP* and *sP*, should provide precise and reliable depth estimates. However, reliable routine identification has turned out to be harder than expected. Nonetheless, when candidate depth phases can be identified at three or more teleseismic stations, then the amplitude ratios *pP*/*P* and *sP*/*P* have been widely used to assess whether these are consistent with an earthquake model (double couple source) at a given depth (Pearce 1980, Douglas et al. 1999).

If the amplitude ratios are consistent with the earthquake model, then further confidence can be gained in this interpretation by forward modeling (Douglas et al. 1972, Douglas 2007). Care must be taken to ensure that an appropriate source-region model is used. The growing availability of reliable geophysical models can further increase confidence in the modeling results (Bowers et al. 2000). The most promising advances probably lie in the development of semiautomated tools to help guide the analyst to routinely pick candidate depth phases (Murphy & Barker 2006, Heyburn & Bowers 2008), the consistency of which can be assessed by the application of a set of validation rules using regional models (Heyburn & Bowers 2008).

Observations of the near-regional phase R_g at frequencies approximately 0.5–1.0 Hz are diagnostic of a shallow source (depth less than approximately 3 km) (Bowers 1997, Myers et al. 1999, Kim & Richards 2007). However, 0.5 Hz R_g tends to be highly attenuated by scattering and nonelastic attenuation, and is rarely observed at distances greater than 150 km. Indeed, there is some evidence that R_g scattering close to the source is part of the explanation of L_g generation by underground explosions (Blandford 1996, Myers et al. 1999).

The amplitude spectra of long-period surface waves (0.01–0.14 Hz) recorded at regional (and teleseismic) distances can have significant depth resolution if the earthquake mechanism and depth results in a notch in the Rayleigh spectrum (Douglas et al. 1971b, Patton 1998). Further research is required to investigate the origin of Rayleigh spectral notches from underground explosions before consideration as a routine screening method. However, analysis of surface-wave amplitude spectra from a network of regional stations with good azimuthal coverage can increase confidence in the resolution of problem events such as the March 13, 2003 Lop Nor disturbance (see Earthquake Near Lop Nor, March 13, 2003, below).

P wave: primary seismic body-wave

NEIC: National Earthquake Information Center

m_b:M_s

It became clear from observations made in the 1960s that for a given distance-corrected short-period (~1 s) P wave amplitude (m_b), the distance-corrected long-period (~20 s) Rayleigh-wave amplitude (M_s) from presumed UNEs is generally smaller than from earthquakes. These observations formed the basis of the m_b:M_s discriminant, although it was recognized early on that there are some earthquakes that generate weak Rayleigh waves and so appear anomalous, or explosion-like, on m_b:M_s (Douglas 1981). Network-averaged m_b and M_s for discrimination and screening need to be calculated assuming a shallow source (applying the amplitude-distance curves for zero depth), as m_b and M_s are source-depth dependent. The network-averaged m_b and M_s also need to be corrected for network data censoring effects. This can be achieved using maximum-likelihood techniques (Lilwall 1987, Zaslavsky-Paltiel & Steinberg 2008).

Station and path corrections can be determined and applied to station m_b and M_s to reduce individual magnitude bias and uncertainty in the network average (Marshall et al. 1979). However, when deriving corrections to station magnitudes, care must again be taken to account for data censoring (Lilwall 1987, Zaslavsky-Paltiel & Steinberg 2008) and identify possible trade-offs between static corrections and the effects of nonisotropic radiation, especially if using earthquakes for calibration (Bowers & Douglas 1998).

During development of the m_b:M_s experimental screening criterion, it was recognized that there is potential bias between the automatically measured network-averaged m_b and M_s at the IDC, and the respective magnitudes measured by an analyst from short- and long-period seismograms as reported in global seismic event bulletins such as that by the National Earthquake Information Center (NEIC). An initial study of magnitudes from earthquakes showed that the IDC network-averaged m_b and M_s was, on average, 0.4 and 0.1 units, respectively, less than those reported by the NEIC (Fisk et al. 2002). Because the NEIC has m_b and M_s observations from a large number of presumed UNEs, the average NEIC/IDC magnitude biases from earthquakes were used to infer the equivalent IDC explosion m_b:M_s and hence define the experimental screening line (Fisk et al. 2002).

However, subsequent studies have shown that there is negligible difference between NEIC and IDC network-averaged m_b from presumed UNEs (Granville et al. 2002, Bowers et al. 2002). The offset in NEIC and IDC network-averaged m_b from earthquakes with NEIC $m_b \geq 5$ can be explained by the different procedures used by the respective centers and the tendency for the depth assigned to a common event by the NEIC to be greater than that assigned by the IDC (Granville et al. 2005).

There is also a clear magnitude dependence to the IDC/NEIC network-averaged m_b and M_s bias. This can be attributed, at least in part, to data censoring effects of the different IDC and NEIC station networks (Stevens & McLaughlin 2001, Zaslavsky-Paltiel & Steinberg 2008). Simulation can provide insight into the network-dependent threshold above which data censoring can be considered negligible. Preliminary results from simulation of network-averaged m_b, suggest that the threshold is approximately 4.5 m_b and 5.5 m_b for the (incomplete) IMS primary and NEIC-type networks, respectively.

M_s for discrimination was originally defined based on Rayleigh amplitudes at periods around 20 s (Douglas 2007). M_s at the IDC is defined in a similar way (Rezapour & Pearce 1998) and is utilized in the experimental screening process (Stevens & McLaughlin 2001, Fisk et al. 2002). Rayleigh waves from small underground explosions (with $m_b \sim 4.5$) are weak and are likely to go undetected unless stations are at regional distances (the IMS auxiliary network and non-IMS networks have proved to be valuable for detecting surface waves from problem events, as we demonstrate later).

NTS: Nevada Test Site

For continental propagation at regional distances, the largest amplitude is often the Airy phase, with a dominant period significantly less than 20 s. To allow analysts to report M_s from seismograms from small disturbances recorded at regional and teleseismic distances, and from more dispersed waveforms following oceanic and mixed paths, a variable-period path correction was developed (Marshall & Basham 1972).

Recently, a variable-period M_s measurement has been proposed based on bandpass Butterworth filters applied in the time domain (Russell 2006, Bonner et al. 2006). Such a method appears to be easily operationally implemented and can be regionalized (Russell 2006). A preliminary inversion of global M_s measurements reported in the REB, for empirical station terms and two-dimensional (2D) path corrections, shows a strong correlation between the path correction and distinct known tectonic regions (Selby et al. 2003).

One of the challenges of M_s measurement is that surface waves from large earthquakes can have durations of many hours and can potentially obscure surface waves from seismic disturbances of interest (Douglas 2007). For example, the surface waves from the Pakistani announced UNE of May 30, 1998 were obscured by those from an earthquake in Afghanistan approximately 30 min earlier (Barker et al. 1998). Another problem is association, especially if the surface wave processing is automated, as in the experimental IDC process. Robust methods of measuring Rayleigh wave back azimuth have been shown to increase confidence in association (Selby 2001).

A problem that may fundamentally limit the usefulness of m_b:M_s for event screening is that the explosion and earthquake populations may converge for $m_b \leq 4.5$. This convergence has been observed (Douglas 1981) and modeled (Stevens & Day 1985). However, there are workers who observe divergence for the earthquake and explosion populations in the Nevada Test Site (NTS) region (Bonner et al. 2006). New data from the DPRK underground explosion presented later in this article may help throw some more light on this subject for the Eurasian region.

Teleseismic P amplitudes are highly sensitive to attenuation in the mantle (Marshall et al. 1979), and signals with small amplitudes often show complex P wave forms (Douglas 2007). However, the scaling of observations of network-averaged m_b with yield from announced UNEs are explained to the first order by the Mueller-Murphy model of the UNE seismic source function (Mueller & Murphy 1971, Murphy 1996). The coupling in the Mueller-Murphy model is dependent on the source medium and depth (unlikely to be well known to the investigating forensic seismologist). Furthermore, a regression analysis of data from underground explosions concluded that only the low-frequency level and corner frequency of the underground explosion source amplitude spectrum could be constrained (Denny & Johnson 1991). So it seems the underground explosion source function for seismic waves is not yet well understood (Douglas 2007).

A further concern is the effect on m_b:M_s of what is commonly referred to as tectonic release—observations of long-period horizontally polarized S and surface waves not predicted by simple elastic underground explosion models (Toksöz & Kehrer 1972). These anomalous observations include Love waves and Rayleigh waves with polarity reversed relative to that expected from an underground point elastic–explosion source (Toksöz & Kehrer 1972, Rygg 1979). The anomalous observations are often interpreted by assuming a point elastic explosion with an additional double-couple source (Ekström & Richards 1994). However, this interpretation is nonunique (Stevens & Murphy 2002).

Empirically, presumed UNEs that show anomalous surface waves that have been studied (Toksöz & Kehrer 1972, Ekström & Richards 1994, Fisk et al. 2002) do separate from the earthquake population on m_b:M_s. However, the modeling study by Stevens & Day (1985), suggesting convergence of the explosion and earthquake m_b:M_s populations around $m_b \sim 4.5$, does not include tectonic release in the explosion source model.

Physical mechanisms proposed to explain the anomalous surface wave observations from presumed UNEs are mainly related to nonlinear effects in the zone immediately surrounding the explosion. Such mechanisms include (*a*) nonspherical effects due to heterogeneous and anisotropic material, (*b*) cracking and block movement along preexisting lines of weakness, and (*c*) tectonic release by the relaxation of preexisting stresses in the nonelastic zone surrounding the explosion (Patton 1991). Triggering of earthquakes on faults in the vicinity of the explosion has also been proposed.

It may be that at least some of the differences reported in the m_b:M_s explosion populations for Eurasia and NTS (Marshall & Basham 1972, Bonner et al. 2006) may be explained by differences in the physical causes of the observations often attributed to tectonic release. Until the explosion source model and physical causes of anomalous surface waves are understood and quantified, the theoretical basis of m_b:M_s for underground explosions remains unresolved. In later sections, we show anomalous surface waves from the announced UNEs detonated in India and Pakistan on May 11 and 28, 1998, respectively.

Regional *P*/*S* Amplitude Ratios

The spatial distribution of IMS and non-IMS seismic stations means it is likely that, for a source located on the continental land mass, at least one station at regional distances will have clear signals. If the aim is to identify UNEs with $m_b < 3.5$, then methods utilizing seismic signals recorded at regional distances provide a valuable tool for the forensic seismologist. The most promising methods utilize *P*/*S* amplitude ratios.

Empirical observations. Research since the early 1980s suggests that the regional *P*/*S* amplitude ratio at high frequencies ($f > 2$ Hz) shows promise as a discriminant (Walter et al. 1995, Blandford 1996, Fisk 2006) but is highly region-dependent (due to crustal and upper mantle structure). Usually the amplitude ratio is measured from *P* and *S* recorded on the vertical component only, although some studies have shown that three-component amplitude measurements can improve discrimination (Kim et al. 1997). If there is strong scattering, then it is unlikely to matter from which component the amplitude is measured, and the *P*/*S* ratio is stable (Blandford 1996) as the *P* and *S* source-radiation patterns are obscured (Zhang et al. 2002). However, if there is weak scattering, then three-component measurements may be able to exploit differences in the *P* and polarized-*S* radiation patterns from earthquake and explosion sources (Lilwall 1988, Bowers et al. 2001, Bowers 2002).

There appears to be some variation in the definition of regional distance, Δ. For example, the National Academy of Sciences (2002) prefers $\Delta \leq 15°$, whereas the experimental regional screening process at the IDC uses *P* and *S* recorded at stations with $3° \leq \Delta \leq 17°$ (Bottone et al. 2002).

Studies show that there can be large variations in the amplitudes observed at sensors separated by less than 100 km. At source-receiver distances of approximately 20°, *P* amplitudes in the 1–3 Hz passband, from a presumed UNE and an earthquake, vary by a factor of up to eight across the NORSAR array in Norway, whereas *S* amplitudes appear to vary little (Ringdal et al. 2001). At a source-receiver distance of approximately 10°, *P* amplitudes in the 0.2–8.0 Hz passband recorded by the Kyrgyzstan network vary by a factor of 20 (Xie & Patton 1999). Both observations of variations in P amplitudes have been attributed to strong three-dimensional (3D) structure in the vicinity of the recording network. Possible variations in P and S amplitudes need to be considered if data from surrogate stations are used to help calibrate new IMS stations. For example, the seismic station MAKZ in east Kazakhstan (calibrated by Bottone et al. 2002) is 24 km from the IMS station MKAR used by the IDC experimental regional screening process.

Path corrections and transportability. To account for the regional variations in propagation of P and S, various schemes have been proposed to determine empirical distance-dependent corrections. It was found that using optimal spatial prediction [often referred to as kriging (Schultz et al. 1998)] based on the observed P/S ratios in common fixed passbands significantly improved discrimination (Rodgers et al. 1999b)

The experimental regional screening process at the IDC uses a fixed passband 6–8 Hz and P_n/S_{max} ratios, where S_{max} is either S_n or L_g, with a minimum signal-to-noise criterion for each phase (Bottone et al. 2002). The kriging algorithm used to derive the station-specific 2D correction surfaces for P_n/S_n and P_n/L_g ratios used by the IDC process converges to the global mean value (for earthquakes) when no calibration data are available and to the local mean when there are sufficient calibration data. Intermediate values depend on an exponential distance-damping function defined by a correlation length estimated to be 5–7° from the data by semivariogram modeling (Bottone et al. 2002).

The associated uncertainty surfaces are based on a calibration variance and the variance from the earthquake data residuals, both estimated by semivariogram modeling (Bottone et al. 2002). To calculate the experimental screening score (criterion), the explosion P/S variance also needs to be set. This can be estimated from an UNE dataset by semivariogram modeling, but we must consider the possibility that the available presumed UNE dataset may not be drawn from the same population as UNEs under a CTBT. If P/S is available from more than one station, then the scores can be averaged (Bottone et al. 2002).

Alternatively, various P/S ratios can be formed from the regional P phases P_n, P_g, and S phases S_n, L_g, either in common or different (cross-spectral) passbands for P and S. It may be that for a particular region a certain combination offers the most promising discriminant (Walter et al. 1995, Fan et al. 2002, Rodgers & Walter 2002), or a number of combinations are to be considered as part of an outlier detection strategy (Fisk et al. 1996).

A model-based approach with source (earthquake model) and distance (path) frequency-dependent corrections has been developed for each regional phase, P_n, P_g, S_n, and L_g (Taylor et al. 2002, Walter & Taylor 2001), for a single station. This approach allows the whole spectrum of the source and path effects to be modeled for each regional phase, allowing flexibility. The model constrains the regional mean, upon which the calibration data can be kriged. Further, the model-based approach allows the mean of the path effects for each phase to be predicted from geophysical experience in poorly or uncalibrated regions (Taylor et al. 2002). This predictive potential is attractive, as initially poor and uncalibrated regions are likely to be the norm for global monitoring under a CTBT. Over time, models should improve (e.g., resolving the trade-off between geometrical spreading and nonelastic attenuation), and the number of calibration events could increase, either through confidence-building measures or through serendipity.

Several workers have reported improved discrimination if the P/S ratios are averaged over a network (Walter et al. 1995, Blandford 1996, Xie & Patton 1999). It has also been shown that network-averaged P_n, S_n, and L_g relative spectra from pairs of nearby explosions and earthquakes (so path effects cancel) at Lop Nor, China, with different magnitudes, are easier to interpret than at a single station (Fisk 2006). Network-averaged P/S ratios might be preferred given the potential variation in P amplitude described above. Significant P amplitude variation may confound the screening, discrimination, or outlier strategies if not represented by the correction and uncertainty surfaces.

Another challenge is to correctly associate P and S phases with the event under consideration. There is at least one example of an automated process resulting in misassociation of P and S with the May 28, 1998, Pakistani announced UNE and apparent subsequent failure of the P/S discriminant (Jenkins & Sereno 2001, Bowers et al. 2002).

S wave: secondary or shear seismic body-wave

Research into how explosions generate *S* waves. Over the past decade or so there has been a concerted effort, especially by United States researchers, to attempt to understand how explosions generate high-frequency S waves. The main candidate mechanisms proposed are:

1. interaction of curved P wavefronts with the free-surface above the source (Lilwall 1988) and regional phase propagation in realistic 3D earth structure with topography (Myers et al. 2003);
2. scattering from R_g-to-S. This may be significant in the 1–5 Hz passband and depends on the explosion source depth (Myers et al. 1999);
3. significant deviations from a point explosion source in an elastic medium with a free surface, such as the effect of spall (Blandford 1996, Stevens et al. 2006);
4. cracking in some volume surrounding the detonation point (Blandford 1996).

There are an increasing number of studies that suggest the corner frequency of regional S_n and L_g from underground explosions is significantly less than the corresponding P corner frequency (Xie & Patton 1999, Fisk 2006, 2007). Differing P and S corner frequencies would suggest that P-to-S conversion is not the dominant mechanism for S generation from underground explosions, as such a mechanism would be expected to produce S spectra with the same corner frequency as P (Fisk 2006). Further, recent observations and modeling suggest R_g-to-S scattering may be less important than previously thought (Stevens et al. 2006).

Fisk (2006) conjectured that the S-wave spectrum from underground explosions in hard rock can be represented by the Mueller-Murphy explosion P wave source spectrum (Mueller & Murphy 1971), with S-wave corner frequency lower than P by the ratio of P to S wave speeds in the material around the source. Combining the Fisk conjecture for the explosion source with standard earthquake source models seems to explain why P/S discriminants perform well at frequencies above approximately 2 Hz but not at lower frequencies (Fisk 2006).

One implication of the Fisk conjecture is that the S waves are generated either at or in the immediate vicinity of the source (Fisk 2006). The conjecture also predicts that P/S criteria should only be reliable at frequencies around and above the P corner frequency, i.e., a magnitude and explosion source-depth dependence. Yet another consequence of the conjecture is that such scaling of S corner frequencies from explosions is unlikely to be consistent with nonlinear spall effects, given the scaling appears to hold for differing emplacement media (e.g., tunnel versus shaft) and firing depths (Fisk 2006).

The physical cause of S waves from underground explosions remains poorly understood. Current research efforts seem to be concentrating on the following:

1. attempting to quantify the uncertainty in and resolving the trade-off between parameters describing the path and station effects (required to estimate the explosion source function);
2. confirming the observations that suggest the underground explosion S corner frequency is less than and proportional to that of P;
3. explaining the observations of high-frequency S, L_g, and surface waves (often showing evidence of tectonic release) from presumed UNEs.

INDIAN UNDERGROUND TEST OF MAY 11, 1998

UTC: Universal Coordinated Time

kt: equivalent energy released by a kiloton of TNT ($\sim 4.2 \times 10^{12}$ J)

A seismic disturbance, located at 27.081°N, 71.738°E with origin time 10:13:44.2 UTC (subsequently referred to as IND 980511), is directly associated with the announcement by India of the simultaneous detonation of three devices with nuclear yields of 43, 12, and <1 kilotons (kt) (Barker et al. 1998).

High frequency *P*/*S* ratios (>2 Hz) for IND 980511 indicate that the disturbance is an outlier to the earthquake population defined by common regional phase-ratio discriminants, such as P_n/L_g and P_n/S_n. Interestingly, these discriminants also seem effective at frequencies as low as 0.5–2.0 Hz (Rodgers & Walter 2002).

Surface waves generated by IND 980511 were observed at many stations across Eurasia. Unfortunately, Rayleigh waves reported in the NEIC bulletin were subsequently shown to be misassociated (i.e., they originated from a different seismic disturbance); this misled some authors (Evernden 1998, Sikka et al. 2001). Using carefully associated Rayleigh waves, the network-averaged M_s for IND 980511 is 3.32 (Douglas et al. 2002).

The prototype IDC REB reported a network-averaged m_b of 5.0, but did not report any associated M_s measurements. Using a network-averaged $M_s = 3.3$, IND 980511 is an outlier to the earthquake population on an m_b:M_s plot (**Figure 2**) and is not screened out using the experimental m_b:M_s criteria (Fisk et al. 2002). Thus, the seismic waves generated by IND 980511 are consistent with an explosion source. However, modeling of the surface waves recorded at non-IMS stations NIL (Pakistan) and HYB (India) showed that the Rayleigh waves observed had the opposite polarity from that expected from a simple elastic explosion source (Rodgers et al. 1999a). Subsequent work demonstrated that Rayleigh waves were reversed at all stations where they were observed (Selby et al. 2004), with the best-fit model having reversals at all azimuths.

The reversed polarity of Rayleigh waves from presumed UNEs was briefly described in the section entitled m_b:M_s, and it has been observed at NTS (Toksöz & Kehrer 1972) and at the Shagan River test site, eastern Kazakhstan (Rygg 1979, Herrin & Goforth 1986). The reversals are believed to be due to the interference of the Rayleigh waves from the explosion source, with the Rayleigh waves due to the accompanying tectonic release usually modeled as a double couple. Ekström & Richards (1994) calculate Rayleigh and Love radiation patterns from 71 presumed UNEs at Shagan River. Only four of these explosions show Rayleigh reversal at all azimuths (the smallest having 5.29 m_b); a further three have a Rayleigh radiation pattern dominated by reversals.

If Rayleigh waves generated by tectonic release can be larger than those from the point explosion source, it is not clear why the m_b:M_s criterion should work for explosions of any size. Toksöz & Kehrer (1972) consider this issue and conclude that tectonic release does not affect the network-averaged M_s if good azimuthal coverage is available. However, Toksöz & Kehrer (1972) constrain tectonic release at NTS to be a strike-slip mechanism, and their argument does not appear to apply where the tectonic release is not believed to be strike-slip—e.g., Shagan River (Ekström & Richards 1994) and IND 980511. To conclude, the study of long-period waveforms from IND 980511 confirms that the mechanism for the generation of surface waves by underground explosions is not understood, and that this has implications for the applicability of the m_b:M_s criterion.

PAKISTANI UNDERGROUND TEST OF MAY 28, 1998

Pakistan announced that it had conducted an underground nuclear test involving five explosive devices on May 28, 1998 (subsequently referred to as PAK 980528). The location is reported as

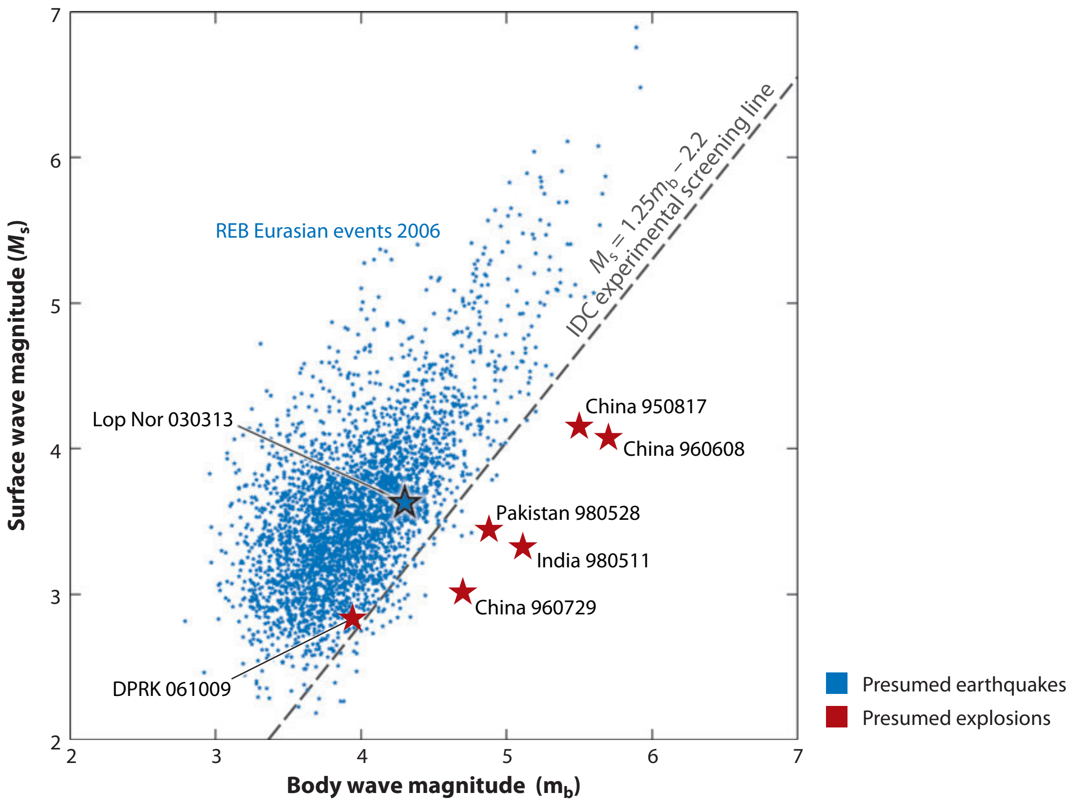


Figure 2

m_b:M_s for recent Eurasian underground explosions and earthquakes. Magnitudes for earthquakes shown are from the Reviewed Event Bulletin (REB) except for Lop Nor 030313 (Selby et al. 2005). Magnitudes for the explosion in North Korea (DPRK 061009) are from Selby & Bowers (2007), and for the explosions in India 980511 and Pakistan 980528 are from Bowers et al. (2002), except M_s for India 980511, which is from Douglas et al. (2002). For the Chinese explosions, m_b is from the REB and M_s is from Bonner et al. (2006).

28.792°N, 64.948°E from satellite imagery (Albright et al. 1999), with an origin time of 10:16:17.0 UTC estimated from seismic signals (Barker et al. 1998). The prototype IDC REB reported network-averaged m_b and M_s of 4.9 and 3.6, respectively. PAK 980528 was not screened out using the experimental m_b:M_s criteria (Fisk et al. 2002) and was not considered for the experimental *P/S* screening (Bottone et al. 2002), presumably because data from NIL were not available. Nonetheless, PAK 980528 appears to be more earthquake-like than the vast majority of presumed UNEs considered when the experimental m_b:M_s screening criteria was developed.

As briefly mentioned earlier, Jenkins & Sereno (2001) failed to identify PAK 980528 as an explosion using regional high-frequency *P/S* amplitude ratios. The apparent failure of the high-frequency *P/S* criteria seems to be due to the misassociation of *P* from a near-regional earthquake to *S* from PAK 980528 (Bowers et al. 2002).

Bowers et al. (2002) estimated a network-averaged M_s equal to 3.44 from carefully associated Rayleigh waves using a variable-period method with path-corrections (Marshall & Basham 1972), noting that PAK 980528 falls between the historical presumed UNE and earthquake populations for Eurasia (**Figure 2**). Thus, PAK 980528 may arouse suspicion using the m_b:M_s criteria, but it is also consistent with deep-lithospheric Eurasian earthquakes.

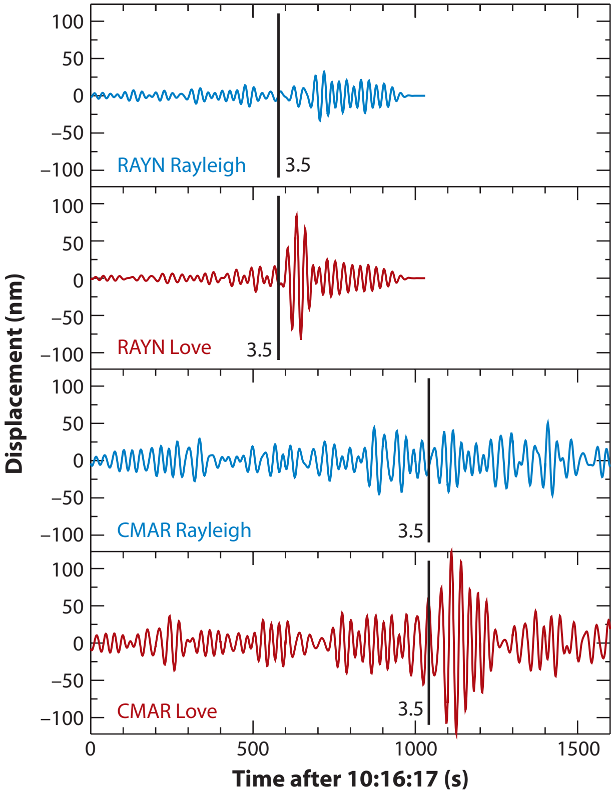


Figure 3

Surface-wave seismograms from the underground explosion in Pakistan on May 28, 1998 recorded at stations RAYN (Saudi Arabia) and CMAR (Thailand). Seismograms are filtered in the passband 0.025–0.045 Hz. At both stations, the Love waves (*red*) are larger than the Rayleigh waves (*blue*). The vertical line indicates the time of arrival for a group wave speed of 3.5 km/s.

Although *P* onset times from 63 stations were reported in the prototype IDC REB for PAK 980528, the vast majority of the teleseismic *P* waves recorded from PAK 980528 are unusually complex compared with those typically observed from underground explosions. Further, there are strong Love waves recorded at the non-IMS station in Saudi Arabia (RAYN) and an IMS station in Thailand (CMAR) (**Figure 3**), indicating that there was significant tectonic release. However, simple *P* seismograms were recorded by at least three IMS stations (in Australia, Antarctica, and the United States). Bowers et al. (2002) showed that these three simple *P* seismograms are inconsistent with an earthquake source at a depth of at least 5 km, implying that the source is shallow and thus should arouse suspicion using the m_b:M_s criteria.

KURSK SUBMARINE DISASTER, AUGUST 12, 2000

Seismologists at the NORSAR group in Norway reported two nearly colocated seismic disturbances on August 12, 2000, with epicenters in the Barents Sea (Ringdal et al. 2000). Seismic disturbances in the Barents and Kara Sea regions (**Figure 1**), which have a low level of natural seismicity, are of interest due to the proximity of the Russian nuclear test site at Novaya Zemlya (Koper et al. 2001). The first and second seismic disturbances have local magnitudes of 1.5 and

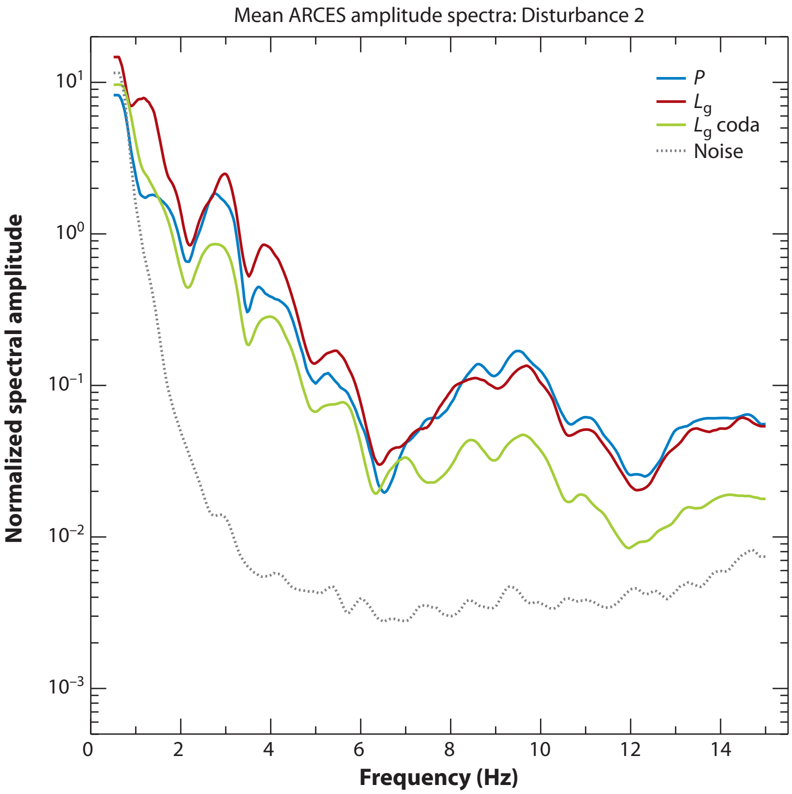


Figure 4

Array-averaged amplitude spectra from time windows corresponding to *P*, L_g, and L_g coda from the second disturbance associated with the sinking of the Kursk submarine on August 12, 2000. The amplitude spectrum of the noise preceding the *P* onset of the signal from the second disturbance (i.e., the coda from the first disturbance) is also shown.

3.5 respectively (Ringdal et al. 2000). *P* signals from the larger second disturbance were detected as far away as Alaska and reported in the REB.

Seismic signals from the two disturbances were clearly recorded by the IMS seismometer array (25 sensors) in northern Norway (ARCES). ARCES is approximately 470 km from the reported location of the tragic sinking of the Kursk submarine at 69.6166°N, 37.5708°E (Schweitzer 2002). The epicenter of the second disturbance estimated by NORSAR is within 6 km of the reported location, and hence the seismic signals observed were associated with the sinking of the Kursk (Ringdal et al. 2000).

The origin time of the second disturbance is estimated as 07:30:42.4 UTC; relative times measured using cross-correlation show the first disturbance occurred 135.8 s earlier, located within a few hundred meters of the second. Further, the relatively high cross-correlation coefficients for *P* and *S* at ARCES have been interpreted as indicating similar, but not identical, source and propagation characteristics (Schweitzer 2002).

Figure 4 shows the array-averaged amplitude spectra from signals recorded at ARCES from the second disturbance. The *P*, L_g, and L_g coda show a common modulation with a regular interval frequency of approximately 1.45 Hz, and clear spectral notches at approximately 6 and 12 Hz. Given the very different propagation paths, the similarity of the modulation and notches in the regional phase amplitude spectra suggests that these are related to the seismic source.

The 1.45 Hz modulation frequency is diagnostic of the bubble pulse from an underwater explosion (Koper et al. 2001, Sebe et al. 2005). Many decades of experience with underwater chemical explosions suggest the yield can be estimated from the bubble-pulse frequency if the source depth is known. It turns out that the notches in the ARCES amplitude spectra (**Figure 4**) constrain the source depth.

Figure 5 shows notches in synthetic far-field amplitude spectra that are dependent on the source depth in a water layer over a solid half-space. We can see that for a water layer 120 m thick, synthetic spectral notches at approximately 6 and 12 Hz are seen if the source is on the sea floor. Similar observations and modeling lead to the conclusion that the second Kursk explosion occurred on the sea floor (Koper et al. 2001, Schweitzer 2002, Sebe et al. 2005). The depth/bubble-pulse frequency and seismic magnitude give a yield estimate roughly equivalent to approximately five tons of TNT (in the range of two to eight tons).

Similar analysis of the regional phase amplitude spectra of signals recorded at ARCES from the first disturbance is not possible due to the poor signal-to-noise ratio. However, the similarity of the signals from the first and second disturbances suggests that the source of the first disturbance is also an explosion. Semblance analysis of the beamformed regional phases suggests the beamformed *P* amplitude spectrum is reliable over the passband 2–10 Hz. The beamformed *P* spectrum shows no evidence of a bubble pulse, or of a notch at approximately 6 Hz, which is consistent with the first explosion occurring at a depth of approximately 80 m or less (**Figure 5**) and being completely contained by the hull of the submarine. The estimate of the yield from seismic magnitude of the first explosion is in the range of 2 to 80 kg of TNT. However, decoupling experiments underwater show signals are muffled by a factor of between 5 and 10 (Khristoforov 1996). If the potential muffling effect of the submarine's hull is considered, the yield estimate of the first explosion is revised to the range of 10 to 800 kg of TNT.

Several authors have referred to observations of negative first-motion of *P* from the second Kursk disturbance, which is more consistent with an implosion than an explosion source (Koper et al. 2001, Schweitzer 2002). Schweitzer (2002) compares filtered (passband 1.5–8.0 Hz) beamformed *P* onsets at IMS seismometer arrays ARCES and FINES (Finland) from the second Kursk disturbance, with those from a local-magnitude 2.5 underwater explosion conducted by the Russian navy. The *P* onsets on the filtered seismograms from the explosion are clearly impulsive with positive first motion, whereas those from the second Kursk disturbance are apparently negative (Schweitzer 2002).

Figure 6 shows the beamformed ARCES and FINES seismograms from the second Kursk disturbance, both unfiltered and optimally filtered to suppress sinusoidal noise (Douglas 1997). It seems clear that the first motions are positive, and hence consistent with an explosive source. **Figure 6** also shows the FINES seismogram filtered to simulate a wide-band velocity seismograph. It becomes clear that the rise-time of the *P*-pulse is comparatively slow relative to an impulsive onset, resulting in weak first motion in the short-period seismograph passband. The forensic seismologist should be aware of the potential pitfalls of attempting to read first motion from bandpass filtered seismograms, or narrow-band seismograph systems (Douglas et al. 1997).

It has been known for decades that underwater explosions are remarkably efficient at generating seismic signals at long range—a 10-ton chemical explosion fired in the North Sea in July 1971 generated teleseismic *P* waves detected in Brazil and Australia (Jacob & Willmore 1972). Thus, the data from the IMS seismic network can be used to detect and identify small explosions fired underwater in areas where paths to the hydroacoustic network are blocked.

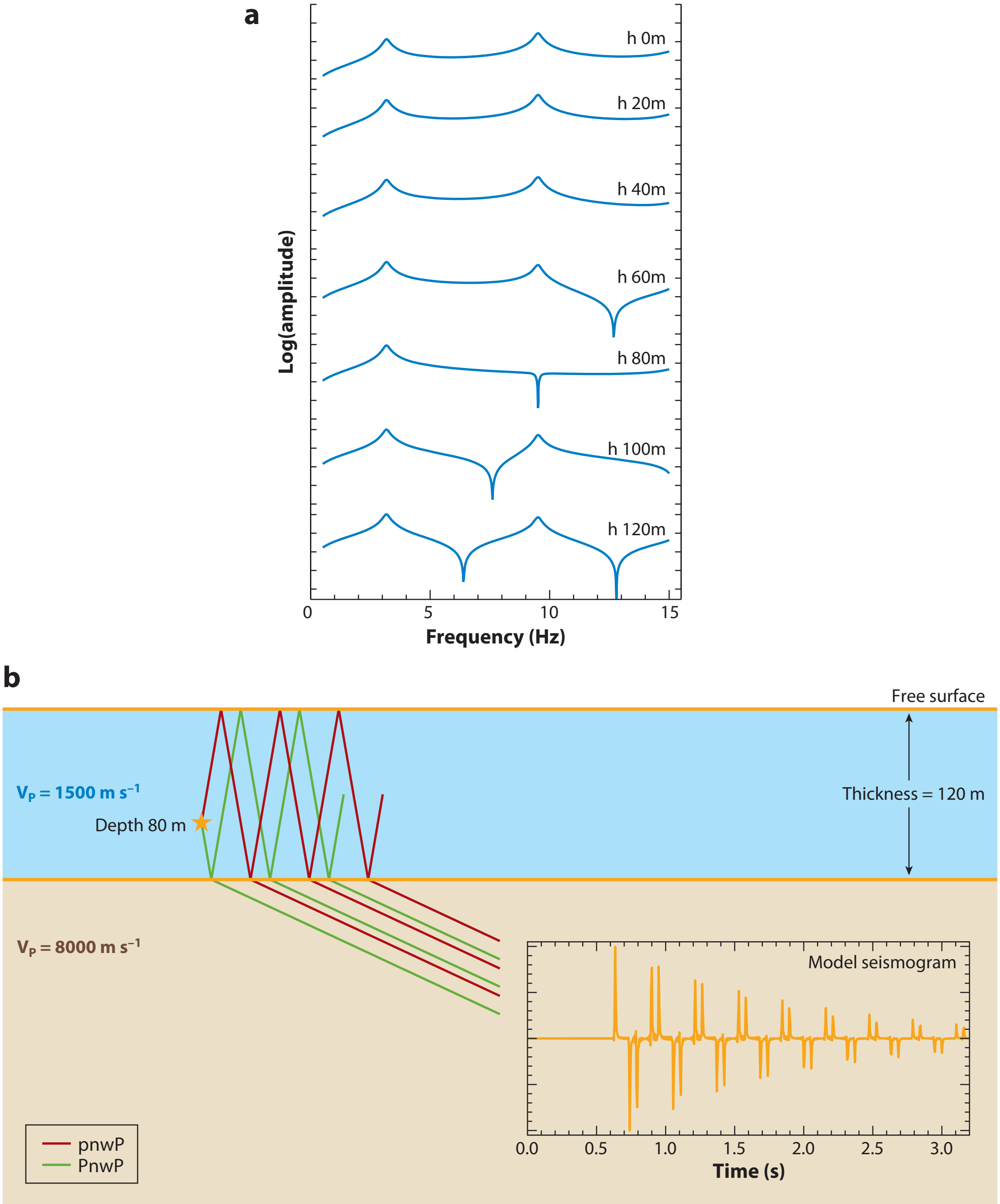
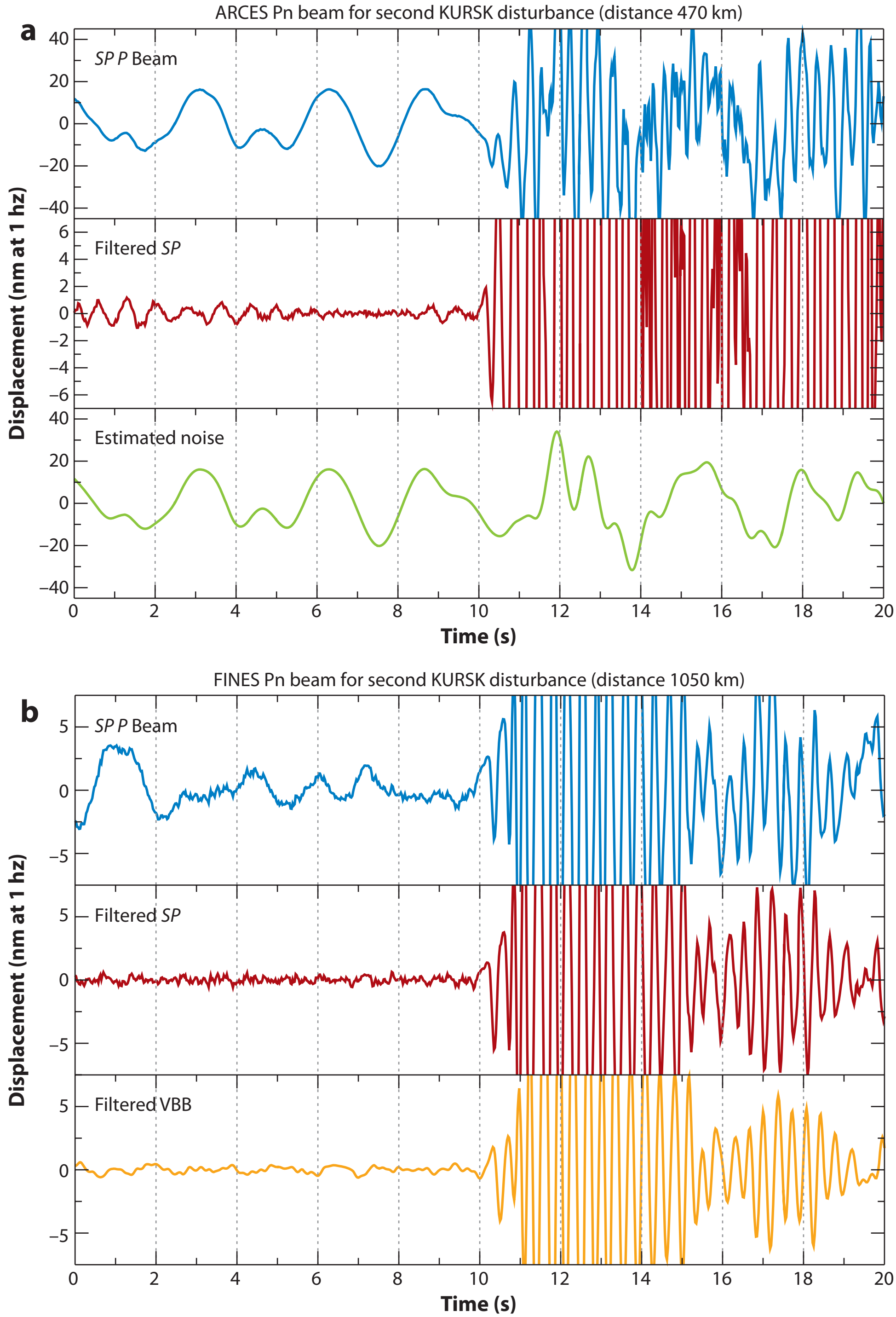


Figure 5

(*a*) Amplitude spectra for varying source depths in the model below. (*b*) Model and example synthetic seismogram for an impulsive seismic source (at a depth of 80 m) in a water layer (120 m thick) over a half-space.


ARCES Pn beam for second KURSK disturbance (distance 470 km)
a
SP P Beam
Filtered SP
Estimated noise
Displacement (nm at 1 hz)
Time (s)
FINES Pn beam for second KURSK disturbance (distance 1050 km)
b
SP P Beam
Filtered SP
Filtered VBB
Displacement (nm at 1 hz)
Time (s)

EARTHQUAKE NEAR LOP NOR, MARCH 13, 2003

The REB reported a seismic disturbance on March 13, 2003 near the Chinese nuclear test site at Lop Nor (epicenter 41.776°N, 89.078°E, origin time 15:07:08.3 UTC, 4.3 m_b), subsequently referred to as Lop Nor 030313. The REB associated *P* waves from 21 IMS stations, but no M_s was reported. The location of this seismic disturbance and the remarkably simple short-period teleseismic *P* waves, all with upward first motion (i.e., explosion-like), warranted further investigation.

Selby et al. (2005) identify Lop Nor 030313 as an earthquake with m_b:M_s (**Figure 2**) using the variable-period M_s measurement, with path corrections (Marshall & Basham 1972). M_s was measured from Rayleigh waves recorded by 12 stations, with network-averaged M_s of 3.63 (Selby et al. 2005). Selby et al. (2005) were able to obtain data from 16 stations within 30° of the Lop Nor 030313 epicenter. Although most of these 16 stations are not IMS stations, they can be considered substitutes for the completed IMS seismic network in the region (Selby et al. 2005). Modeling the surface-wave (especially Rayleigh) amplitude spectra from these 16 stations, Selby et al. (2005) demonstrate that Lop Nor 030313 is an earthquake with a 40° reverse-dip-slip mechanism at a depth of approximately 6 km. This result is further supported by full waveform modeling of three-component data from a non-IMS station WMQ, at a distance of approximately 250 km (Selby et al. 2005).

Historically, m_b:M_s has been a robust discriminant for disturbances with $m_b > 4.5$ (although perhaps not at smaller magnitudes). The cause of differences between the m_b:M_s ratio for earthquakes and explosions has been discussed in several papers (Douglas et al. 1972, Stevens & Day 1985, Douglas 2007). Douglas et al. (1972) demonstrate that shallow earthquakes with near-45° reverse-dip-slip mechanisms might be expected to be anomalous on the m_b:M_s criteria because (*a*) *P* waves will show upward first motion at all teleseismic stations (as will *P* waves from UNEs), (*b*) for source depths less than approximately 10 km, it is difficult to clearly identify the depth phase *pP* (and for very shallow sources *pP* will constructively interfere with *P*, increasing m_b), (*c*) Rayleigh wave amplitude spectra for this type of focal mechanism have a zero or null at a period dependent on the source depth and azimuth to the recording station (Tsai & Aki 1970; Douglas et al. 1971a,b), and this may reduce M_s.

The modeling of Rayleigh wave amplitude spectra has successfully been used to estimate the focal mechanisms and depths of several earthquakes (in addition to Lop Nor 030313) in northwest China (Fox et al. 2005). It appears that the method is especially applicable to shallow continental dip-slip earthquakes, which may be difficult to identify using the m_b:M_s criterion.

NORTH KOREA 2004–2006

Concerns about the development of nuclear weapons by North Korea (DPRK) were heightened by its withdrawal from the Nuclear Non-Proliferation Treaty in April 2003. The possibility that the DPRK might test a nuclear weapon led to increased interest in seismic monitoring of the

Figure 6

P onsets from the second disturbance associated with the sinking of the Kursk submarine on August 12, 2000. (*a*) Comparison of the unfiltered short-period array beam at ARCES with the same trace filtered to estimate the signal assuming the noise is a sinusoid (Douglas 1997), and the estimated noise. (*b*) Comparison of the unfiltered short-period array beam at FINES with the signal estimated using the method of Douglas (1997). The bottom trace is the filtered beam-signal estimate converted to an instrument response that is proportional to velocity.

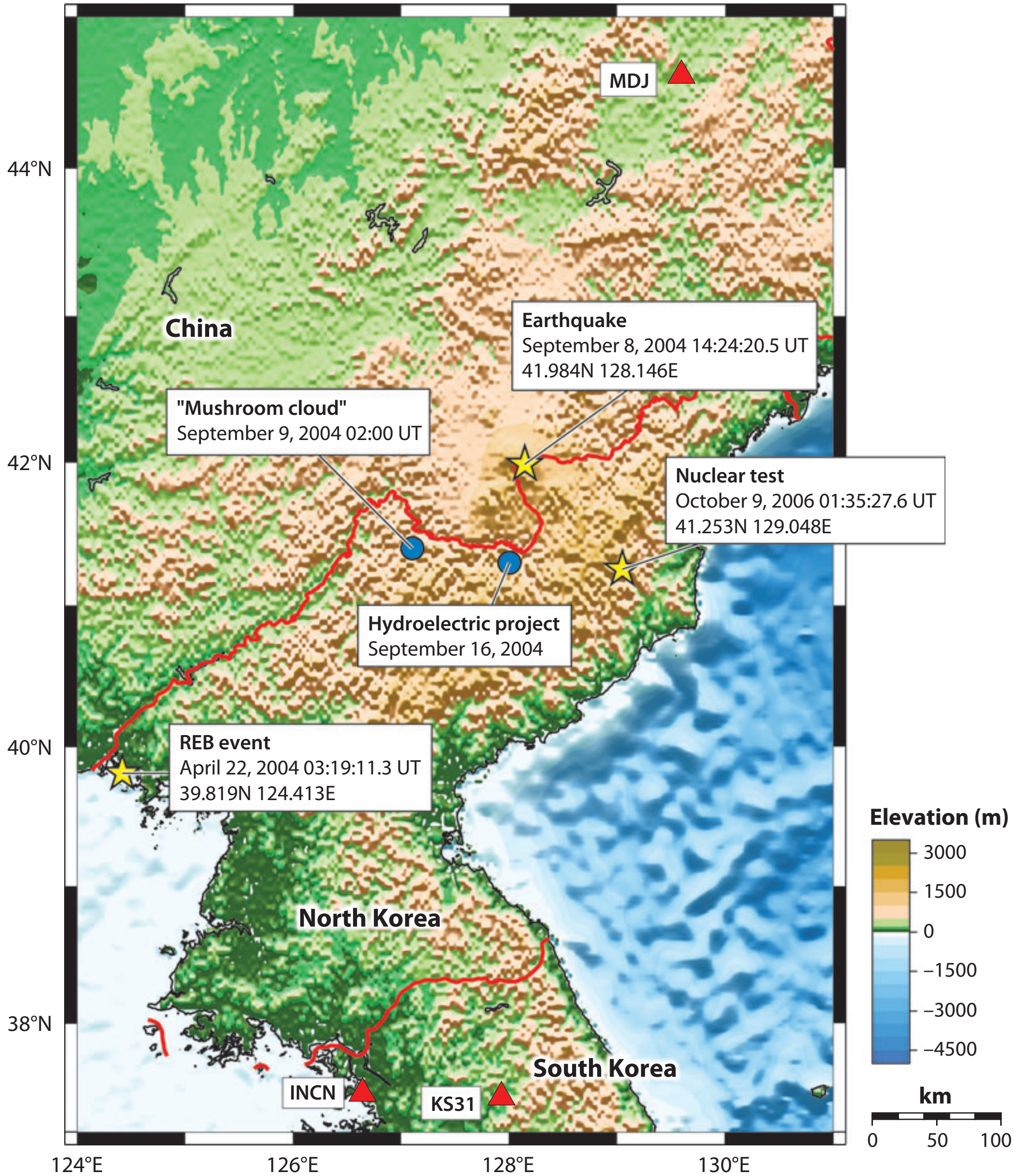


Figure 7

Locations of what turned out to be seismic nonevents and genuine seismic events of interest to the forensic seismologist in the North Korean region over the past five years.

region. During 2004, two events occurred for which the application of forensic seismological techniques was able to help clarify confusing press reports.

On April 22, 2004, a large explosion occurred near the railway station at Ryongchon in north-western North Korea (see **Figure 7**). Little is known about the explosion, although the North Korean news agency KCNA reported that it was an accident caused by an electrical contact during the shunting of wagons loaded with ammonium nitrate fertilizer (KCNA 2004, BBC 2004a). Press reports (Chosun 2004a), apparently based on seismological findings, suggested that the size of the explosion was much larger than reported by the DPRK government. However, analysis of the data showed that no seismic signals could convincingly be demonstrated to originate from this explosion.

On September 12, 2004 the media reported (BBC 2004b) that a mushroom cloud had been observed in North Korea near the border with China (**Figure 7**). It was also reported that seismic signals had been detected and may have been associated with the cause of the mushroom cloud. Analysis of waveform data demonstrated that the only seismic event detected in the area concerned was located near 42.0°N, 128.1°E (see **Figure 7**), which was more than 100 km from the supposed mushroom cloud location. The DPRK claimed that the mushroom cloud was due to demolition activity related to a hydroelectric project, which was at a third location (**Figure 7**). Subsequently, consensus emerged that the mushroom cloud was likely a natural formation (Chosun 2004b).

Underground Test of October 9, 2006

The DPRK announced it had conducted an underground nuclear test on October 9, 2006 (KCNA 2006); the resulting seismic disturbance is subsequently referred to as DPRK 061009. This was the first nuclear explosion announced since May 1998, ending a de facto global moratorium that had lasted for more than eight years. The location and origin time of the explosion were well resolved by teleseismic and regional data soon after the explosion occurred (CTBTO 2007), demonstrating the ability of the IMS to detect explosions of $m_b \sim 4$. The United Kingdom National Data Center (NDC) estimated the epicenter of the explosion as 41.253°N, 129.048°E, with an origin time of 01:35:27.6 UTC. DPRK 061009 has a maximum-likelihood $m_b = 3.94$ and $M_s = 2.83$ (Selby & Bowers 2007). Other agencies calculated similar values. DPRK 061009, an announced nuclear explosion in a new location, provided the opportunity to test the power of forensic seismology to identify an explosion source in a new geological context.

Depth. Unless local stations are available, the depth of a shallow seismic source is difficult to estimate from the phase onset times because the depth trades off with origin time. However, there are some indications that the source of DPRK 061009 was shallow. The clear R_g phase observed at non-IMS station MDJ (China) suggests a shallow source; R_g is not observed at this station from a nearby mid-crustal depth earthquake (Kim & Richards 2007). There are simple teleseismic *P* seismograms at several stations (**Figure 8**), lacking evidence of clear depth phases *pP* and *sP*. These seismic observations suggest that DPRK 061009 is either a shallow earthquake or an explosion. Further, teleseismic *P* polarities together with the phase of Rayleigh waves observed at the closest stations (**Figure 8**) are consistent with a shallow simple elastic explosion source model, although they are not sufficient to formally rule out a shallow earthquake source.

Regional *P/S* ratios. Two studies (Kim & Richards 2007, Walter et al. 2007) report that DPRK 061009 is an outlier to the earthquake population defined using regional high frequency *P/S* ratios. However, as described in the section entitled Regional *P/S* Amplitude Ratios, this criterion is empirical, and its physical basis is not fully understood.

m_b:M_s. **Figure 2** shows m_b versus M_s for several recent Eurasian presumed UNEs and Eurasian earthquakes during 2006 from the IDC REB. Unlike the explosions in India, Pakistan, and China, DPRK 061009 falls on the edge of the earthquake population from the REB. This leads to doubts that the experimental screening criterion used by the IDC is applicable to seismic disturbances with small magnitude. Currently, it is unclear whether DPRK 061009 is anomalous, or whether the

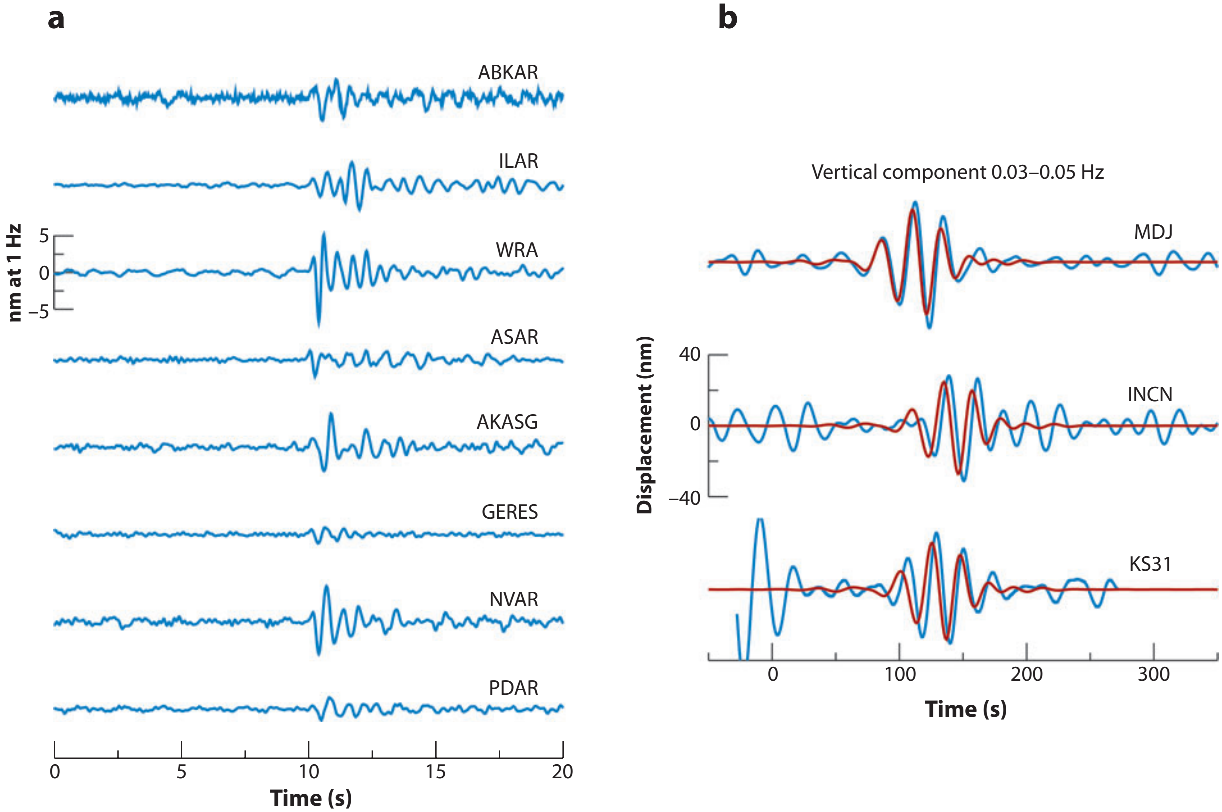


Figure 8

(*a*) Observed teleseismic *P* waves (*blue*) recorded globally, and (*b*) regional distance Rayleigh waves from DPRK 061009 (*blue*). The red traces on the right are the synthetic seismograms for a point explosion source with a scalar moment of 2.0×10^{14} Newton-meters.

m_b:M_s ratio is as expected for an explosion with small magnitude. The IDC experimental screening line (shown in **Figure 2**) was devised under the assumption that m_b and M_s scale differently with yield, whereas an explosion model (Mueller & Murphy 1971) suggests that they should scale in the same way. The inconsistency results from a failure to understand the overall relationship of M_s to yield. Clearly, the theoretical basis of the m_b:M_s criterion is not understood.

SUMMARY POINTS

1. The IMS is an important part of the CTBT verification regime. On completion, the IMS network will comprise 337 facilities, 170 of which will be seismic stations.
2. The application of the analysis of seismic data to support verification of the Treaty has been called forensic seismology and its main application is the identification of underground explosions from the thousands of earthquakes of potential interest that occur each year.
3. There are four main tasks for the forensic seismologist: (a) signal detection, (*b*) association of signals, (*c*) source location, and (*d*) source identification.

4. There are four main complementary methods for source identification: (*a*) source depth, (*b*) ratio of m_b to M_s, (*c*) ratio of high-frequency (>2 Hz) *P* to *S* energy, and (*d*) model-based methods.
5. The m_b:M_s and high-frequency *P*/*S* criteria are empirically based on observations of signals from presumed UNEs and earthquakes. Whereas models of the earthquake source explain the observations reasonably well, current equivalent-elastic models of the UNE do not.
6. Source-depth estimation is often difficult and unreliable, and model-based methods are also subject to large uncertainties in the appropriate equivalent-elastic model for UNEs fired in the diverse geological environments around the world.
7. Experience gained by forensic seismologists in the past decade at identifying suspicious seismic sources using data from IMS and non-IMS stations suggests that although no single method works all of the time, intelligent and original application of the complementary methods available is usually sufficient to satisfactorily identify the seismic source in question.
8. Identifying a single underground explosion as nuclear or chemical is not possible using seismology; diagnostic radionuclides must be detected. The IMS has a network of 80 radionuclide stations for this purpose, and there is provision for on-site inspection to confirm violations of the Treaty.

FUTURE ISSUES

1. Development of equivalent-elastic models for UNEs in diverse geological media that explain how explosions generate high-frequency *P* and *S* waves and long-period Rayleigh and Love waves is necessary.
2. Development of realistic 3D models of the Earth (recent developments on resolving upper-mantle and crustal structure are described in this volume by M. Ritzwoller in the review, "Earth Structure from Seismic Noise") and the generation of synthetic seismograms from realistic earthquake and UNE sources in 3D models are necessary.
3. It is important to identify the seismic source by solving the inverse problem using multiple datasets (e.g., high-frequency *P* and *S* and long-period Rayleigh and Love waves), which, if inverted, individually currently give contradictory solutions, presumably because the models and/or parameters used are inappropriate.

DISCLOSURE STATEMENT

AWE Blacknest operates the National Data Center, on behalf of the United Kingdom National Authority to the CTBT Organization, under contract with the Ministry of Defence (MoD). The views expressed in this article are those of the authors and are not necessarily those of AWE, MoD, or the United Kingdom government.

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http://www.ctbto.org. CTBT Organisation Web site
http://www.iss.niiit.ru/ksenia/catal_nt/index.htm. Catalog of worldwide nuclear testing

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