Evaluation of a Seismic Event, 12 May 2010, in North Korea

by Won-Young Kim, Paul G. Richards, David P. Schaff, and Karl Koch

Abstract We assess seismological evidence bearing on claims that North Korea conducted a small nuclear test on 12 May 2010 in the vicinity of known underground nuclear tests (UNTs) in 2006, 2009, 2013, and 2016. First, we use $Lg$-wave cross correlation and more traditional methods to locate the 2010 event between about 4 and 10 km southwest of the 2009 test. Second, we compare the relative sizes of regional $P$ and $S$ waves, using stations within 400 km of the known North Korean nuclear tests, to assess the nature of the event.

We measured $P/S$ ratios at different frequencies, at first using data from the open station MDJ in northeast China, for training sets of earthquakes and of explosions. We developed a linear discriminant function (LDF) that, in application to $P/S$ measured at MDJ, is most effective in separating the earthquake and explosion populations. MDJ lacks usable data for the event of interest, but we obtained regional data from stations of the nearby Dongbei Broadband Seismographic Network (DBSN) for the 12 May 2010 event and for nearby UNTs conducted in 2006 and 2009. When our LDF is applied to DBSN data, and to data from stations SMT and NE3C in China, the LDF values measured from $P/S$ ratios from known explosions are explosion-like; but for the 12 May 2010 event, the LDF values are earthquake-like for frequencies between 6 and 12 Hz.

Our method for characterizing earthquakes and explosions on the basis of their regional signals can be widely applied. Measurements of $P/S$ based on the three-component waveform data provide better discrimination power than do those based on vertical-component data alone.

Electronic Supplement: Tutorial material on the Mahalanobis distance-squared measure, three-component linear discriminant function (LDF) analysis, tables of measurements of the $\log_{10} P/S$ spectral ratios obtained from waveforms recorded at station MDJ for the two training sets and three-component discrimination analysis, and figures of $\log (P/S)$ values measured at 8 Hz from vertical-component waveforms at station MDJ for two training sets and probability distributions for $D$.

Introduction

Several papers published during 2012–2015 have claimed there is evidence for a low-yield nuclear explosion conducted in Spring 2010 in North Korea close to the site of well-known nuclear explosions in 2006 (October), 2009 (May), 2013 (February), and 2016 (January and September). The original claim (De Geer, 2012) was based on the detection of radioxenons and radioxenon progeny nuclides at four sampling stations located at 10–1260 km outside the borders of North Korea. Five days in April and May 2010 were at first proposed as the candidate dates on which a nuclear test may have been carried out. Subsequent papers based on the radionuclide observations, and discussion of candidate locations from which atmospheric transport of radionuclides would fit those observations, focused on 11 May 2010 as the likely date of a claimed low-yield nuclear test in North Korea (De Geer, 2013; Wotawa, 2013; Wright, 2013).

Schaff et al. (2012) attempted to detect seismic signals from small explosions in North Korea on the specific days in 2010 proposed by De Geer. The seismic data recorded on those days by the nearest open station of the Global Seismographic Network (GSN), namely MDJ in northeastern China, were searched, applying three-component cross-correlation (CC) methods and using high-quality signals as templates (derived from known nuclear explosions in North Korea recorded at this same station). Schaff et al. (2012) assessed the capability of this method of detection and of simpler meth-
ods, all of which failed to find seismic signals that would be expected if scenarios proposed by De Geer were valid, and concluded, first, that no well-coupled underground explosion above about a ton occurred near the North Korean test site on these five days (14, 15, and 16 April; 10 and 11 May), and second, that any explosion would have to be very small (local magnitude less than about 2) to escape detection. An important issue emerging from this analysis was the practical difference between two types of detection threshold, namely between (a) estimating the present or future detection capability of a monitoring network, absent any templates similar to the signal one is attempting to detect, and (b) the detection capability for a specific time period in the past when it is known what data are available and for which templates do exist. Detection capability is much better in the latter situation.

In view of these previous studies and several additional papers interpreting the radionuclide data of 2010 in terms of a low-yield nuclear test, it was of considerable interest that Zhang and Wen (2015a) reported data from a small seismic event in North Korea, occurring on 12 May 2010 at about 00:08:45 UTC, which they claimed had occurred less than 1 km from the known tests of 2009 and 2013, and which they characterized unambiguously as a small nuclear explosion. The origin time is about nine minutes later than the time window for May 2010 searched by Schaff et al. (2012). Zhang and Wen used data from several seismographic stations in Jilin Province, China, in the distance range ~80–200 km from the North Korean test site. At present, the data these authors analyzed are not openly available. To detect the event, they used a method called “match and locate,” described further in Zhang and Wen (2015b), in which correlograms for different channels of seismic data are averaged using an appropriate template for each channel. The method allows templates to be drawn from more than one event, at different locations in the general source region of interest. The relative location of template events must be accurately known, and the match and locate method stacks correlograms for each point in a predetermined grid of candidate locations, using the appropriate delay for each point in the grid in a search for the grid point that maximizes the stack. In practice, the method searches a 2D horizontal grid at a fixed depth (the depth of the template events, presumed to be similar to the depth of the event being sought), with templates that in the present case are provided by known underground nuclear explosions (UNEs) in North Korea. Zhang and Wen (2015a) found a maximum mean CC value for a candidate location about 900 m south and 200 m west of the known UNE of 2009. They showed individual seismograms of the event as recorded on stations in Jilin Province, China, and assigned it a magnitude of 1.44 (based on Lg). On the basis of measured values of the spectral ratio between P and S waves, they claimed it to be a very small nuclear test explosion having a yield estimated at 2.9 tons (trinitrotoluene [TNT] equivalent), with very low uncertainty (only ±0.8 tons).

It is remarkable that the data streams and analysis methods used in modern seismology can now provide detection capability at magnitudes as low as the small event under discussion here. The first UNE conducted in North Korea (on 9 October 2006) had a seismic magnitude around 4 and was widely reported to have had a low yield—roughly 1 kt. The seismic event of 12 May 2010 was about two and a half units lower in magnitude and thus had signals about 300 times smaller than those of the small UNE of 2006. However, although Zhang and Wen are to be congratulated on finding this small seismic event, we present and analyze additional data indicating that it has characteristics different from those of a small, contained, single-fired explosion. We also discuss the likelihood of a somewhat different location, relative to the known North Korea UNEs. We comment on the procedure used by Zhang and Wen (2015a) for estimating yield of small underground explosions on the basis of their seismic signal strength and argue that there is substantial uncertainty in such estimates. Our principal source of additional data has been the Dongbei Broadband Seismographic Network (DBSN), installed in mid-2004 by Kin-Yip Chun and colleagues at several sites in northeast China in Liaoning and Jilin Provinces, just north of the border with North Korea.

Signals from the seismic event of 12 May 2010 reported by Zhang and Wen (2015a) can be seen in the openly available data acquired by a Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) instrument deployment, involving a temporary network of stations in northeast China known as the NECESS (Northeast China Extended Seismic Array, see e.g., Tao et al., 2014). Ford and Walter (2015) reported this confirmation, and they go on to make the case that if the location and magnitude of the 2010 event were as characterized by Zhang and Wen, then its detection at stations of the International Monitoring System (IMS) would be expected, using CC methods. It should also have been detected at the open station MDJ. The fact that it was not detected prior to work done by Zhang and Wen, and could not subsequently be confirmed with IMS or MDJ data, is a matter we discuss and explain in terms of a location for the event that is somewhat further away from prior UNEs than claimed by Zhang and Wen (2015a), or if it had taken place at a significantly different source depth.

Although it may be disconcerting that contrary interpretations have been published, with reference to a claimed event of significance in the context of monitoring for nuclear explosions, the larger picture is that (a) additional resources can often be brought to bear on such claims after a period of time; (b) it can then be possible to detect and characterize the nature of events more than 10 times smaller than has typically been reported (e.g., by the U.S. National Academy of Sciences, 2002, 2012) as the monitoring capability for various regions; and (c) contrary interpretations can potentially be resolved by on-site inspection. In the present case, new data have been obtained, are now openly available, and are analyzed in this article, indicating that the 12 May 2010 event exhibits the characteristics of a small natural earthquake, based on a specific set of assumptions and an application of standard statistical classification methods. We reaffirm a conclusion of Schaff et al. (2012) that no well-coupled underground explosion above about a ton occurred near the North Korean test site on days we have studied.
began operation in June 2004 and was removed in 2011, so it did not record the UNEs of 2013 or 2016. Furthermore, some station channels were nonoperational for events of interest. Station DB09 of the network was moved 7.19 km to the east-northeast in mid-2007 and renamed DB17, but overall it is clear that these stations were carefully sited and provided high-quality recordings. We used data from eight of the DBSN stations, shown in Figure 1, and their waveforms are presented and discussed in later figures. Ground motion was sampled at 100 samples/s, significantly higher than the 40 samples/s rate used continuously for MDJ and the NECESS Array stations.

For purposes of applying the $P/S$ spectral ratio to identify a seismic event, it is desirable to have spectral data from different populations (earthquakes and explosions) in the same region, recorded at the same stations, as well as good data at these stations for the event one is trying to characterize. We do not have this situation in the present case for analyzing the 12 May 2010 event. From station MDJ, we can compare $P/S$ spectral ratios for UNEs and chemical explosions, and for earthquakes, though not for the 12 May 2010 event. From the NECESS Array stations, we can compare $P/S$ spectral ratios for earthquakes, industrial explosions, and the 12 May 2010 event. From DBSN stations, we can compare $P/S$ spectral ratios for UNEs and the 12 May 2010 event. Furthermore, using the methods developed by Kim et al. (1997), we are able to use spectral measurements from vertical and horizontal components of recorded ground motion, which help stabilize the $P/S$ spectral ratios we report in this article, which are based on about 500 seismograms (72 recorded at MDJ, 24 at eight stations of the DBSN, and the remainder at 20 stations of the NECESS Array). This is significantly more than the number of seismograms used for $P/S$ spectral ratios reported by Zhang and Wen (2015a), for vertical components at stations SMT, that were used by them to compare the 12 May 2010 event to a pair of UNEs and three earthquakes. They did not give an objective criterion for classifying the event. We have been able to find earthquakes, in addition to those used by Zhang and Wen, which are significantly nearer to the North Korean test site, to provide a broader basis for comparison when using spectral ratios.

Estimates of Location and Magnitude for the 12 May 2010 Event

In this section, we use two methods to conclude that the 12 May 2010 event had its hypocenter within a few kilometers of the North Korean nuclear test site, most likely southwest of the 2009 test location at a distance that we estimate to be between 4 and 10 km, but first we note that Zhang and Wen (2015a), in application of their match and locate method, found a location only about 1 km to the southwest of the 2009 nuclear test, by maximizing the mean CC value for a stack of correlograms. The contours of their stack (their fig. 3A) appear not to have been sharply peaked at their preferred location for the event. Just how far apart the 2009 and 2010 events are is of interest in the context of under-
standing the capability of CC methods to enable detection of small events and high-quality location estimates.

Before discussing our own estimate of the location of the 12 May 2010 event, a simple and helpful indicator of its location can be derived from the horizontal particle motion in the P-wave arrival used at stations with clear signals, because the motion gives an approximate azimuth from which this longitudinal wave is arriving. Figure 2 shows a particle motion plot for the horizontal components of the regional P-wave at NE3C (a NECESS Array station). The azimuth is appropriate for a source near the North Korean nuclear test site.

Relative Location Estimates Based on Lg-Wave Cross Correlations

We used hypocentral estimates given in Zhang and Wen (2015a) for the 2006 and 2009 nuclear tests and the 2010 suspect event to determine Lg arrival times based on station distance and a group velocity of 3.5 km/s. Templates were used from the 2009 nuclear test because it was closer to the 2010 event than the 2006 explosion, and these templates were run on 10 min of continuous data from 2010. The correlation traces for the various stations are shown in Figure 3 for a ±10 s window centered on the arrival time at each station expected for the hypocenter proposed by Zhang and Wen (2015a). Five of the stations show maxima in this ±10 s window that have absolute time shifts less than 1.5 s. The three closest stations show detection maxima with peak times close to zero, which we take to be an indication that these are not just random detections among the stations but that there is a physical basis in terms of increased signal-to-noise ratios (SNRs).

The maximum correlation coefficients are all nevertheless quite low. The Lg signals are not obviously visible in the raw waveforms for most stations, but detailed studies (e.g., Schaff, 2008) have shown that detection via CC is achievable with signals significantly below the noise level. Low CC values may partly be due to the sample rate being 100 samples/s compared to the 20 samples/s that we have typically used in previous studies, but this higher sample rate makes the correlation values, even though low, more statistically significant because of the longer duration and greater time-bandwidth product for the template window of 50 s. (We do correlation in the time domain so the correlation function has a sample rate of 100 samples/s as well. Interpolation of the correlation function around the peak usually achieves precision that is about one-tenth of the sample interval.) The higher rate means there are more false alarms in a given time period because they scale linearly with sample rate. To do a thorough false alarm analysis and to quantify the statistical significance of these detections, continuous data records longer than 10 min need to be analyzed, but a rough estimate of the statistical significance of these detections can be made, based on the length of the lag windows searched over for a given maximum, even for these short (10 min) records. To do this, we count the single maximum of each of the five stations with peak lag times $t_{\text{peak}}$ having an absolute value less than 1.5 s. Then, we determine the nearest time $t_{\text{lag}}$ at which the CC value exceeds the local maximum for the lags searched over. The probability that the
original maximum was a false alarm can then be estimated as \( p = \text{absolute value of } \frac{t_{\text{peak}}}{t_{\text{lag}}} \). These values are shown in Table 1.

We found from work on the seismicity of China, Parkfield (California), and Kazakhstan that association even at just two stations is a powerful means of validating detections at single stations and reducing false alarms (Schaff, 2009; Schaff and Waldhauser, 2010; Slinkard et al., 2014). The combined probability of a false alarm coincidentally occurring at two or more stations can be determined by multiplying the individual probabilities at each station, because false alarms at different stations are independent from each other. From the last column of Table 1, we find a combined probability of \( 1.3 \times 10^{-11} \), indicating that the chance of a false detection occurring at all five of these stations, within a time window that includes the expected arrival of the \( Lg \) wave for an event with the hypocenter determined by Zhang and Wen (2015a), is very very low and that therefore the detections of an event on 12 May 2010 are highly likely to be true, from \( Lg \) signals alone.

The match and locate method of Zhang and Wen (2015b) effectively combines the detection, association, and location steps all together in one process to determine a single averaged correlation trace. They show their detection is statistically significant for two months of data assuming a sample rate of 100 samples/s and only one maximum value in this time period, the probability of such a detection occurring by chance is \( p = 1/60 \text{ days}/24 \text{ hours}/3600 \text{ s}/100 \text{ samples/s} = 2 \times 10^{-9} \). This shows the power of association in Table 1 because from just 10 min of data, we find a lower probability of occurring by chance (once in 25 years using 100 samples/s) compared to one in two months of data from a single trace.

To estimate a relative location of the May 2010 event with respect to the known 2006 UNE, we can use the lag times of the peak values as differential travel times, as has been done in a case study of the 1999 Xiuyan sequence in China (Schaff and Richards, 2004). We explore the sensitivity and robustness of relocating the pair of events (2009 and 2010) by adding stations of increasingly poor quality as determined by their deviation from the zero value we expect from reduced travel times of the \( Lg \) arrival, based on the hypocenter in Zhang and Wen (2015a). Three stations are needed as a minimum to solve for the three unknowns of the epicenter, but then, because these are exact solutions, with zero residuals, no formal error bars can be computed to determine the location quality.

Figure 4 shows several location estimates for the 2010 event relative to the 2009 nuclear test, including those based on our \( Lg \) double-difference (DD) analysis using different numbers of stations. The stars are the locations given in Zhang and Wen (2015a). The \( Lg \) location estimates for the four, five, and six station cases all agree with the 95% confidence error ellipse that is shown for the four-station case, but neither the three-station location nor the Zhang and Wen (2015a) location falls within this error ellipse. The four-station case has the smallest error bars and best fit for the residuals, but we find the data quality to be poorer than what we have typically used for \( Lg \) locations in other studies. The standard deviation of the residuals in the present case is 0.2618 s and is thus quite poor, for example, by comparison with results from a study using \( Lg \) to obtain relative locations for 3689 events over all of China in which the average residual standard deviation was only 0.0417 s (D. P. Schaff et al., unpublished manuscript, 2017; see Data and Resources). The estimated 95% confidence ellipse for the \( Lg \) location has semiaxes 3.91 and 0.50 km (using four stations). The azimuthal gap is 249°. The standard deviation of the residuals before location based on the hypocenters in Zhang and Wen (2015a) is 0.7519 s, so there is improvement by about a factor of 3 in the residuals to explain the Dongbei data with our best \( Lg \) relocation.

Table 1

<table>
<thead>
<tr>
<th>Station</th>
<th>CC</th>
<th>( t_{\text{peak}} ) (s)</th>
<th>( t_{\text{lag}} ) (s)</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBN08</td>
<td>0.08</td>
<td>0.18</td>
<td>46.46</td>
<td>0.0039</td>
</tr>
<tr>
<td>DBN06</td>
<td>0.06</td>
<td>0.19</td>
<td>10.74</td>
<td>0.017</td>
</tr>
<tr>
<td>DBN17</td>
<td>0.16</td>
<td>0.68</td>
<td>450</td>
<td>0.0015</td>
</tr>
<tr>
<td>DBN14</td>
<td>0.14</td>
<td>-1.10</td>
<td>450</td>
<td>0.0024</td>
</tr>
<tr>
<td>DBN15</td>
<td>0.08</td>
<td>-1.37</td>
<td>24.96</td>
<td>0.055</td>
</tr>
</tbody>
</table>

The combined probability of obtaining these results by chance for all stations is the product of the five separate \( p \) values, namely \( 1.3 \times 10^{-11} \).

CC, cross correlation.

Figure 4. Location estimates for the 2010 seismic event, using different data sets and double-difference (DD) methods based first on \( Lg \) CC and second on phase-pick data for \( P \) and \( S \) waves. The local coordinate system centers the origin on the location of the 2009 nuclear test.

Relative Location Based on Picks of \( P \) and \( S \) Arrivals
only for regional $P$ and $S$ waves from stations of the DBSN in the 158–206 km distance range. The square shows the estimated epicenter, which in this case is about 7 km to the southwest of the 2009 event. It is in general agreement with the epicenter location estimated independently using $Lg$-wave correlation data, that is, lying several kilometers to the southwest.

The root mean square (rms) residuals for the locations based on $P$- and $S$-wave picks are 0.189 s for the 2009 event and 0.117 s for the 2010 event. These can be compared with the standard deviation of the residuals for the $Lg$ location based on CC (0.2618 s). The standard deviation is related to the rms but differs in the numbers of degrees of freedom. The estimated 95% confidence error bars for the $P$- and $S$-wave locations are ±2.71 km east–west and ±0.79 km north–south. The error ellipse sizes and fit of the residuals are also in general agreement for the two independent location runs, that is, using $P$- and $S$-wave phase data and $Lg$ CC data.

Additional Discussion of Location Estimates for the 2010 Event

Based on the formal error ellipses shown in Figure 4, we can say with 95% confidence that the location of the 2010 event relative to the 2009 event is no closer than 3.8 km and no further than 9.5 km to the southwest. (The orientation of the $P$- and $S$-wave error ellipse should also be elongated in a northwest–southeast direction, like the $Lg$ CC error ellipse. We were not able to obtain singular value decomposition locations using $P$ and $S$ waves, so these locations are based on the least-squares method of inversion that returns only the diagonal elements of the covariance matrix in the cardinal directions.)

We can compare overall statistics for the 2010 relative event location with those of 3689 events in and near China for which we have recently obtained relative epicenter locations based on high-quality $Lg$ CC measurements (D. P. Schaff et al., unpublished manuscript, 2017; see Data and Resources). The average azimuthal gap is large in our study of all China, 205°, but the gap for the 2010 event is larger, at 249°. For all of China, the average of the semimajor axes ($= 0.42$ km) is much smaller than for the 2010 event ($= 3.91$ km), and the same applies to the average of the semiminor axes (0.09 km vs. 0.50 km). The fit for the residuals for events over all of China has a standard deviation of 0.0417 s, which is smaller than the sample interval of 0.05 s. The 3689 events are located within 1 km of at least one other event. Typically, D. P. Schaff et al. (unpublished manuscript, 2017; see Data and Resources) find that $Lg$ CC data lead to high-quality relative relocations only for interevent separations less than 1 km. The fact that the 2010 event has residuals more than six times higher than residuals for the high-quality $Lg$ CC data, in the study for all of China for events separated by 1 km or less, is strong additional evidence that the 2010 event is more than 1 km away from the 2009 event, besides the actual location estimate placing it about 4 km to the southwest. Further, but more indirect evidence that the 2010 event is more than 1 km away from the 2009 event, and/or is a different type of event such as an earthquake instead of an explosion, is that there were no CC data of sufficient quality to be used for differencing the $P$- and $S$-wave arrivals (so picks were used). Carmichael and Hartse (2016) describe how detection thresholds, based on CC methods, rise by up to a magnitude unit for sources located 4 km or more from one of the larger North Korean announced nuclear tests. Typically, CC data for $P$ and $S$ waves have been shown to be useful for interevent separation distances up to 2 km in northern California (Schaff et al., 2004; Schaff and Waldhauser, 2005; Waldhauser and Schaff, 2008).

We are reasonably confident in the $Lg$ correlation DD location because it agrees with the location estimate based on phase picks. These two locations were arrived at completely independently with two different data types and inversions (for $Lg$, we solve only for the epicenter in a different program, whereas for $P$ waves hypocenters are returned). The general direction from the 2009 event and the size of the ellipses agree from the two independent tests. The data are not high quality either for $Lg$ or for $P$, but we are fairly confident in our qualitative conclusions that the 2010 event occurs more than 1 km away from the 2009 event and likely is between 4 and 10 km to the southwest.

Another line of general evidence for greater than 1 km separation between the 2009 and 2010 events is the experience in obtaining a location for the 2009 explosion relative to that of 2006. In days immediately following the 25 May 2009 nuclear test, one of us (Kim) acquired data from more than 50 regional stations in China, South Korea, and Japan which had recorded both these first two tests by North Korea. For purposes of estimating a relative location, he used 83 travel-time pairs (48 from $Pn$, and 35 from $Sn$) at stations where the quality of CC of 2009 signals against those of 2006 was so low that travel-time picks appear to provide the best way to measure relative arrivals. He also used 36 waveform CC pairs derived from signals where CC methods appeared to be somewhat better than differencing arrival-time picks, but CC quality was still somewhat poor, and this is the relevant point, because these two explosions were estimated to be about 2.6 km apart, as reported in June 2009 at the Comprehensive Nuclear-Test-Ban Treaty Organization’s (CTBTO’s) International Scientific Studies (ISS) conference just a few weeks after the occurrence of the 2009 explosion. Seismic events at the same depth but more than about 2 km apart have regional signals that do not cross correlate well in bands such as 0.5–5 Hz that we are using for precision studies. There is even greater sensitivity to depth (i.e., CC values fall off faster with depth than they do with differences in epicenter).

Finally on this point, we note again a conclusion of Ford and Walter—that if the 2010 event were at the Zhang and Wen location, it would likely have had signals sufficiently similar to the explosion of 2009, and the 2010 event would be detectable using CC methods on IMS data.
Magnitude Estimates for the 12 May 2010 Event

The magnitudes given in Table 2 are based on rms amplitude ratios of a 2009 UNE template trace with known magnitude (4.53 according to Zhang and Wen, 2015a) and that of the detected signal window, about 50 s in length (P and S included). The magnitude is about 1.5 based on data from DBSN stations.

Characterization of the 12 May 2010 Event: Earthquake or Explosion

In this section, we describe features in several seismograms obtained for the 12 May 2010 event. We describe and apply a linear discriminant function (LDF), derived from the P/S spectral ratios at station MDJ, and apply it to data from DBSN. In a later section, we apply it to data from the only station (SMT) used by Zhang and Wen (2015a) to analyze spectra and from the best station (NE3C) of the NECESS Array. Our work was done first using only the vertical component of recorded motions and then, where possible, using horizontal as well as vertical records. We find that the event of interest consistently has P/S spectral features within the preferred frequency band, putting it into the earthquake population in the several different analyses we have conducted. Our strongest conclusions in this regard are those based on measurements made from three-component records.

We also comment on the method used by Zhang and Wen (2015a) to provide a yield estimate if the event is taken to be an explosion.

Observed Data from the Dongbei Broadband Seismographic Network

Seismic records on 12 May 2010 from several stations of the DBSN within about 230 km from the North Korean test site show signals consistent with the origin time and location reported by Zhang and Wen (2015a). The vertical-component record section given in Figure 5 shows possible signals from the event. The waveforms shown have been passed through a third-order Butterworth filter with cutoff frequencies at 0.8 and 10 Hz. Seismograms shown in Figure 5 and later are recordings of ground velocity, because the DBSN stations were equipped with broadband seismometers flat to velocity between periods ranging from 30 or 60 s to 0.02 s (0.017 or 0.033 Hz to 50 Hz; Chun and Henderson, 2009). At stations DB08 (Δ = 160 km and Az = 0°) and DB17 (Δ = 202 km and Az = 14°), arrival times of P and Lg waves are consistent with signals expected from the 12 May 2010 event. On the other hand, for signals at DB06 (Δ = 181 km and Az = 320°) and at DB05 (Δ = 193 km and Az = 306°), only the vertical records show P-wave arrivals, and two horizontal components show very weak signals nearly comparable to the noise. At DB10 (Δ = 209 km and Az = 29°), only signals arriving with Lg wavewave are visible, and no P waves are observed on any of the three components. Data quality varies between these stations, with indications of occasional noise bursts at DB04, DB06, and DB10 (Fig. 5). We place greater reliance on DB08 and DB09/DB17. Hence, P- and Lg-wave energy arrivals at several stations are consistent with the event on 12 May 2010 reported by Zhang and Wen (2015a).

A comparison of vertical records at DB08 from the 2006 and 2009 UNEs and the 12 May 2010 event is shown in Figure 6. P- and S-wave arrival times indicate that the three events occurred close to each other, but the relatively stronger S wave on the 12 May 2010 record suggests that they may not be the same type of source (Fig. 6). Three-component waveform data from the 2009 UNE and May 2010 events at DB17 and from the 2006 UNE recorded at DB09 suggest that the time and location of the claimed event on May 12 is broadly consistent with the report by Zhang and Wen (2015a; see Fig. 7). However, there are questions: is the 12 May 2010 event located as close to the 2009 underground nuclear test as claimed by Zhang and Wen (2015a)? Can the seismic data tell us if the event is an underground explosion as claimed by Zhang and Wen (2015a)?

Observed Data from the Northeast China Extended Seismic Array

The NECESS Array experiment deployed 127 seismographic stations in northeastern China during September 2009 to August 2011, and the waveform data (recorded continuously at 40 samples/s) are available from the Incorporated Research Institutions for Seismology Data Management Center.

Table 2: Result of Cross-Correlation Detector Using 2009 Underground Nuclear Test Signals as Templates

<table>
<thead>
<tr>
<th>Station</th>
<th>Channel</th>
<th>Magnitude (± 1 std.dev.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB08</td>
<td>HHZ*</td>
<td>1.66</td>
</tr>
<tr>
<td>DB06</td>
<td>HHZ</td>
<td>1.29</td>
</tr>
<tr>
<td>DB17</td>
<td>HH31</td>
<td>1.50(0.17)</td>
</tr>
<tr>
<td>DB10</td>
<td>HH32</td>
<td>1.51(0.04)</td>
</tr>
</tbody>
</table>

*HHZ indicates that only the vertical template was available.
1HH3 indicates the three components used: vertical, north–south, and east–west.
2Instrument gain was a factor of 4 smaller for the May 2009 explosion than for the event of May 2010.
3Instrument gain was a factor of 20 greater for the May 2010 event.
Only the station closest to the North Korean test site shows seismic signals from the 12 May 2010 event, which appear suitable for measurement of spectra. At this station, NE3C (Δ = 164 km and Az = 350°; see Figs. 1 and 2), P- and Lg-wave arrival times on all three components appear to be consistent with those of the Dongbei network station, DB08. Figure 8 compares records at DB08 and NE3C. Arrivals from the event of interest at other NECESS Array stations are of lower quality.

Because the NECESS Array recorded waveform data in continuous mode, we had an opportunity to examine the entire two years of archive data for additional possible events from the same area as the event of 12 May 2010. Using a 30-s-long waveform trace containing P and Lg waves of the 12 May 2010 event as a three-component template, we carried out waveform CC detection in a search for similar signals in two years of continuous data. Using a criterion of CC > 0.20, this process yielded 6373 energetic but dissimilar detections.
Visual inspection of most of the detections indicated that they are likely quarry blasts not near the North Korean test site. We found no similar events for the period from September 2009 through August 2011. Somewhat similar signals were detected on 6 June 2010 at 11:17:51, which were also found by Ford and Walter (2015). By comparison with the 12 May event, the 6 June event had magnitude about 2.3, and its signals are observed at other stations. A preliminary location for the event suggests that it is about 77 km northwest (Az = 292°) from the 2009 UNE.

Characterization of the 12 May 2010 Event from Spectral Features

A previous study found eight shallow earthquakes with magnitudes 2.5–4.1 that occurred during 1989–2005 within about 200 km of the North Korean test site (see fig. 1 of Kim and Richards, 2007). That study also found signals at MDJ from four known chemical explosions conducted in the summer of 1998 not far from the test site, as part of a PASSCAL experiment led by Francis Wu (Song et al., 2007). They were 1 or 2 ton (TNT equivalent) single-hole shots ranging in magnitude from about 1.0 to 2.0; their signals at MDJ appear as figure 6 in Schaff et al. (2012).

In studies of earthquakes and explosions that we have conducted for northeastern China and the Korean peninsula, waveform data have been provided from a variety of stations including BJT, HIA, and MDJ in China and INCN in South Korea. Data for these GSN stations are archived by the IRIS-DMC. In general, for discrimination studies we would wish to work with as much data as reasonably possible and in particular to use high-sample-rate records if available. We note that for some events in the region there are triggered data sets (notably from MDJ) sampled at 80 samples/s. However, for practical purposes of developing a straightforward strategy for applying the P/S discriminant method to signals from the 12 May 2010 event, it is necessary to make some choices on what data subsets will be used and not use all available data. Such choices are guided by the facts that: (a) we have direct access to only a limited number of stations that recorded the event of interest, namely, those of the DBSN, that also recorded signals from nearby known nuclear explosions; (b) at present we do not have access to DBSN data from earthquakes in the region; and (c) our station with the most extensive archive of earthquake and explosion records, namely MDJ, did not provide useful records of the 12 May 2010 event. (At the time of expected arrival at MDJ, of signals from this event of interest, there appears to be an Lg
arrival from a different event, obscuring the record.) Though the archive for MDJ includes some triggered higher-sample-rate records (80 samples/s), it is consistently reliable for events recorded in the 40 samples/s continuous data stream.

In these circumstances, our strategy has been to build up a training set of signals at MDJ for both explosions and earthquakes in the region and then to find the frequencies at which the observed values of the $P/S$ spectral ratio provide the best separation of the two populations (explosions and earthquakes), using standard statistical methods for event classification. We have then used this knowledge to evaluate the $P/S$ spectral ratios measured from DBSN stations, noting that their azimuthal direction from the North Korean test site region is similar to that for station MDJ.

To carry out such a strategy, we identified 12 earthquakes and 12 explosions in northeastern Korea and northeastern China, mostly within about 200 km from the test site, to carry out multivariate discriminant function analysis. The events we use as training sets are listed in Tables 3 (for explosions) and 4 (for earthquakes), and their locations are indicated in Figure 1. In addition to the UNEs of 2006, 2009, and 2013, and the chemical explosions of 1998, we included industrial explosions in two separate regions of North Korea (in Table 3, the events numbered 8, 9, and 10; and then numbers 11 and 12).

Three-component waveform data at station MDJ are fairly good for all 24 events. Other GSN stations, INCN and BJT, show weak seismic signals with relatively poor SNRs.

$P/S$ Spectral Amplitude Ratio on Vertical-Component Records

Numerous regional seismic event discrimination studies have shown that the high-frequency (usually higher than 3–4 Hz), $P/S$ spectral amplitude ratios of regional $P$ ($P_g$ or $P_n$) and $S$ ($S_g$, $S_n$, or $L_g$) waves are observed over distances ranging from a few kilometers up to about 2000 km and provide an efficient method to classify regional earthquakes, quarry blasts, and UNEs (e.g., Kim et al., 1993, 1997; Hartse et al., 1997, among many others). The high-frequency $P/S$ spectral ratios on vertical-component regional records have been used successfully with a misclassification probability of a few percent (e.g., Kim et al., 1993). Distance corrections have also been applied to $P/S$ ratios, significantly improving the discrimination power, particularly if the events have data recorded over a wide distance range (e.g., from 3° to 17°). In particular, Kim et al. (1997) and Pasyanos and Walter (2009) have demonstrated improvement in discrimination capability when $P/S$ spectral ratios have been corrected for attenuation effects in a region that exhibits significant variation in attenuation (parts of central and south Asia).

Figure 9 shows vertical-component log$_{10}(P_g/L_g)$ spectral amplitude ratios at discrete frequency points between 1 and 15 Hz used in discrimination analysis for 12 earthquakes and 12 explosions (five chemical explosions, four shots known to have been conducted in single holes, and three North Korean nuclear tests) recorded at MDJ. To calcu-
late P/S spectral amplitude ratios, \( P_g \) and \( L_g \) signals are windowed with a Gaussian weighting function centered at group velocities around 5.9–6.0 and 3.3–3.4 km/s, respectively. A standard deviation of \( \sigma_{ref} = 2.5 \) s is used for the \( L_g \) Gaussian window at a reference distance of \( \Delta_{ref} = 100 \) km. The window includes \( L_g \) arrivals with group velocities between 3.66 and 3.09 km/s in its \( \pm \sigma \) width centered at 3.35 km/s, and the Gaussian window is truncated at \( \pm 1.96\sigma \) (≈95%), which includes signals within the group velocity range from 4.0 to 2.88 km/s. Window lengths at different distances are scaled by \( \sigma = \sigma_{ref} \times \Delta/\Delta_{ref} \). Thus, the time window used for \( L_g \) has the same group velocity window regardless of distance. The \( P_g \) window length of \( \sigma_{ref} = 2.0 \) s is used, so that the \( P_g \) window includes \( P \) arrivals with group velocities between 6.7 and 5.3 km/s, regardless of distance when centered at 5.9 km/s. The \( P_g \) and \( L_g \) signals, weighted by the Gaussian functions, are fast-Fourier transformed. The resulting amplitude spectra are smoothed with another Gaussian function having \( \sigma = 1 \) Hz and are resampled at every 1 Hz interval from 1 to 15 Hz. From 15–16 Hz is a conservative upper limit of the seismic data available from MDJ and other GSN-type stations in the region, because stations recorded seismic data continuously at 40 samples/s and occasionally at 80 or 100 samples/s in trigger mode. For the two training sets of 12 earthquakes and 12 explosions, seismic data with high SNR were selected for \( P/S \) spectral ratio analysis. However, \( P \) or \( S \) arrivals from two low-magnitude single-hole explosions in the training set at high frequencies (above 10 Hz) fall below the ambient noise on some records, and for this reason the \( P/S \) ratios at high frequencies were deemed to be less reliable. The vertical-component \( P/S \) spectral amplitude ratios from two UNEs and the 12 May 2010 event recorded on Dongbei stations (DBSN) in northeastern China along the China–North Korea border region are also plotted. Among

### Table 3
Explosions Analyzed

<table>
<thead>
<tr>
<th>ID</th>
<th>Date (yyyy/mm/dd)</th>
<th>Time (hh:mm:ss.ss)</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Magnitude (( M_L ))</th>
<th>Explosion Type/Information Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2006/10/09</td>
<td>01:35:28.00</td>
<td>41.287</td>
<td>129.108</td>
<td>3.93</td>
<td>UNE/Z&amp;W2015</td>
</tr>
<tr>
<td>2</td>
<td>2009/05/25</td>
<td>00:54:43.18</td>
<td>41.294</td>
<td>129.082</td>
<td>4.53</td>
<td>UNE/Z&amp;W2015</td>
</tr>
<tr>
<td>3</td>
<td>2013/02/12</td>
<td>02:57:51.33</td>
<td>41.291</td>
<td>129.076</td>
<td>4.89</td>
<td>UNE/Z&amp;W2015</td>
</tr>
<tr>
<td>4</td>
<td>1998/08/12</td>
<td>15:00:08.10</td>
<td>42.865</td>
<td>128.223</td>
<td>1.0</td>
<td>SHCE/Wu</td>
</tr>
<tr>
<td>5</td>
<td>1998/08/18</td>
<td>14:00:06.69</td>
<td>42.914</td>
<td>129.324</td>
<td>2.0</td>
<td>SHCE/Wu</td>
</tr>
<tr>
<td>6</td>
<td>1998/08/19</td>
<td>15:00:07.79</td>
<td>42.091</td>
<td>128.739</td>
<td>1.9</td>
<td>SHCE/Wu</td>
</tr>
<tr>
<td>7</td>
<td>1998/08/25</td>
<td>15:00:07.46</td>
<td>42.427</td>
<td>126.748</td>
<td>1.0</td>
<td>SHCE/Wu</td>
</tr>
<tr>
<td>8</td>
<td>2010/01/15</td>
<td>06:18:01.44</td>
<td>41.7488</td>
<td>126.9143</td>
<td>2.9</td>
<td>CE/ISC</td>
</tr>
<tr>
<td>9</td>
<td>2011/01/05</td>
<td>05:46:05.66</td>
<td>41.7317</td>
<td>126.9674</td>
<td>2.8</td>
<td>CE/ISC, KIGAM</td>
</tr>
<tr>
<td>10</td>
<td>2011/02/18</td>
<td>15:25:58.15</td>
<td>41.7345</td>
<td>126.8917</td>
<td>3.5</td>
<td>CE/ISC</td>
</tr>
<tr>
<td>11</td>
<td>2011/05/19</td>
<td>09:38:21.58</td>
<td>42.2512</td>
<td>129.3803</td>
<td>2.6</td>
<td>CE/ISC</td>
</tr>
<tr>
<td>12</td>
<td>2012/01/21</td>
<td>07:54:45.59</td>
<td>42.2306</td>
<td>129.3680</td>
<td>2.6</td>
<td>CE/ISC</td>
</tr>
<tr>
<td>13</td>
<td>2010/05/12</td>
<td>00:08:45.07</td>
<td>41.286</td>
<td>129.079</td>
<td>1.44</td>
<td>Claimed UNE/Z&amp;W2015</td>
</tr>
<tr>
<td>14</td>
<td>2016/01/06</td>
<td>01:30:01.4</td>
<td>41.305</td>
<td>129.039</td>
<td>5.1</td>
<td>UNE/PDE</td>
</tr>
</tbody>
</table>

Our basic training set for explosions is comprised of the first twelve events here. Additional analysis included events 13 and 14. UNE, underground nuclear explosion; Z&W2015, Zhang and Wen (2015a); SHCE, single hole chemical explosion; CE, chemical explosion; ISC, International Seismological Centre; KIGAM, Korea Institute for Geosciences and Mineral Resources; PDE, Preliminary Determination of Epicenters.

### Table 4
Selected Earthquakes Analyzed

<table>
<thead>
<tr>
<th>ID</th>
<th>Date (yyyy/mm/dd)</th>
<th>Time (hh:mm:ss.ss)</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Depth (km)</th>
<th>Magnitude (( M_L ))</th>
<th>Information Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1994/01/25</td>
<td>08:51:38.2</td>
<td>42.23</td>
<td>127.12</td>
<td>04</td>
<td>4.0</td>
<td>NK</td>
</tr>
<tr>
<td>2</td>
<td>2004/12/16</td>
<td>18:59:14.5</td>
<td>41.79</td>
<td>127.94</td>
<td>10</td>
<td>4.0</td>
<td>PDE</td>
</tr>
<tr>
<td>3</td>
<td>2007/12/31</td>
<td>21:33:38.0</td>
<td>40.41</td>
<td>127.25</td>
<td>0</td>
<td>3.2</td>
<td>KMA</td>
</tr>
<tr>
<td>4</td>
<td>2009/08/05</td>
<td>12:08:12.6</td>
<td>42.349</td>
<td>127.223</td>
<td>10</td>
<td>3.8</td>
<td>ISC</td>
</tr>
<tr>
<td>5</td>
<td>2010/05/18</td>
<td>04:08:10.3</td>
<td>42.83</td>
<td>125.96</td>
<td>10</td>
<td>3.7</td>
<td>Z&amp;W2015</td>
</tr>
<tr>
<td>6</td>
<td>2010/10/09</td>
<td>05:45:14.7</td>
<td>42.352</td>
<td>128.388</td>
<td>10</td>
<td>3.4</td>
<td>ISC</td>
</tr>
<tr>
<td>7</td>
<td>2010/10/09</td>
<td>06:07:09.2</td>
<td>42.370</td>
<td>128.420</td>
<td>5</td>
<td>3.6</td>
<td>ISC</td>
</tr>
<tr>
<td>8</td>
<td>2011/07/07</td>
<td>11:11:39.7</td>
<td>40.062</td>
<td>128.199</td>
<td>18</td>
<td>3.5</td>
<td>KIGAM</td>
</tr>
<tr>
<td>9</td>
<td>2010/11/12</td>
<td>02:10:44.8</td>
<td>43.00</td>
<td>125.89</td>
<td>7</td>
<td>2.8</td>
<td>Z&amp;W2015</td>
</tr>
<tr>
<td>10</td>
<td>2011/06/09</td>
<td>01:10:35.1</td>
<td>42.44</td>
<td>127.19</td>
<td>6</td>
<td>3.3</td>
<td>Z&amp;W2015</td>
</tr>
<tr>
<td>11</td>
<td>2011/12/26</td>
<td>13:34:08.6</td>
<td>42.381</td>
<td>127.246</td>
<td>0</td>
<td>3.6</td>
<td>ISC</td>
</tr>
<tr>
<td>12</td>
<td>2014/08/04</td>
<td>21:16:36.0</td>
<td>40.110</td>
<td>127.200</td>
<td>0</td>
<td>2.5</td>
<td>KMA</td>
</tr>
</tbody>
</table>

Earthquakes 5, 9, and 10 were used by Zhang and Wen (2015a). KMA, Korea Meteorological Administration; NK, North Korea Institute of Seismology.
P smaller than the noise amplitude, so the reliable in those frequencies (see Figs. 6, 8, and 9).

and the DBSN stations, only two, DB08 and DB17, show clear explosions (triangles) comprised of four single-hole explosions, five large industrial explosions, and three known nuclear tests. The data for the earthquakes and chemical explosions are from MDJ, but two underground explosions (2006 and 2009; blue open squares) and the 12 May 2010 event (red squares) are from Dongbei network data (see Fig. 1); stations DB08 and DB17 are used for the analysis. A mean spectral value for each discrete frequency point is plotted both for earthquakes (black circle) and for explosions (black triangle), with a bar representing the scatter (±1 std.dev.). The spectral ratio at 12 Hz of DBSN data is less reliable for the 12 May 2010 event due to an almost null value for the Lg window on the vertical component for station DB08. The P/S ratio at 12 Hz, excluding DB08 measurement, is plotted with a green square for comparison.

Selection of the Most Effective Frequencies for Purposes of Event Discrimination

As mentioned in the previous section, many studies of P/S spectral ratios have employed data in the 1–5 Hz band, whereas Kim et al. (1993, 1997) and Kim and Richards (2007) have shown the utility of 5–15 Hz data in separating earthquakes from explosions when such higher frequencies are available. To explore the discrimination power of P/S spectral ratios at various frequencies, we use the Mahalanobis distance-squared measure between the multivariate means of the earthquake and explosion populations, which is related to misclassification probabilities (as shown, e.g., by Kim et al., 1993).

Thus, we are working here with $f_{\text{Eq}}(r)$ and $f_{\text{Ex}}(r)$ as the probability densities of measurable features of the two types of events, in which $r$ is a column vector representing log$_{10}(P/S)$ values, sampled at $d$ different frequencies. We follow the formalism as described, for example, in the textbook by Seber (1984). The mean data vector and covariance matrix associated with the training set of 12 earthquakes are $\mu_{\text{Eq}} = (1/12) \sum_{i=1}^{12} r_{\text{Eq}}$ and $S_{\text{Eq}} = (1/11) \sum_{i=1}^{12} (r_{\text{Eq}} - \mu_{\text{Eq}})(r_{\text{Eq}} - \mu_{\text{Eq}})^T$ and similarly for the training set of explosions to obtain $\mu_{\text{Ex}}$ and $S_{\text{Ex}}$, in which $T$ denotes a transpose.

We evaluate an LDF $D(r)$ under the assumptions that sample distributions are normal, the two covariance matrices (describing the scatter of values measured for the two training sets) are effectively the same, and the events in the training sets are correctly classified. This linear function is

$$D(r) = \lambda^T [r - (\mu_{\text{Eq}} + \mu_{\text{Ex}})/2].$$

in which $\lambda = S^{-1}(\mu_{\text{Ex}} - \mu_{\text{Eq}})$ and $S$ is the average of $S_{\text{Eq}}$ and $S_{\text{Ex}}$. Conceptually, if $r$ is a data set for a particular event, then $D(r)$, which is a scalar, is a dimensionless measure of the distance between $r$ and the average of the two training sets, expressed in standard deviation units. Further discussion of $D(r)$ is given in a tutorial section in the electronic supplement to this article. If, a priori, we make the simple assumption that a new event is equally likely to be an earthquake or an explosion, then an event with $D(r) > 0$ is taken to be an explosion, and an event with $D(r) < 0$ is taken to be an earthquake. Our definition of $D$ is the negative of that used by Kim et al. (1993, 1997). This change is motivated by the tutorial discussion given in the electronic supplement, and noting that typically the log$_{10}(P/S)$ values of explosions are higher than those of earthquakes, so components of the vector $\mu_{\text{Ex}} - \mu_{\text{Eq}}$ are positive.

The Mahalanobis distance-squared measure between population means $\Delta^2$, given by $\Delta^2 = D(\mu_{\text{Eq}}) - D(\mu_{\text{Ex}})$, is calculated and contoured in Figure 10 for different choices of the LDF, using 1, 2, 3, 4, and 5 variables (values of $d$, the number of discrete frequencies) for frequencies in the 1–15 Hz range. Although misclassification probabilities tend to decrease as $d$ increases, the computational effort to provide a vector observation goes up with $d$. Both the precision of estimation and the robustness of the LDF fall off with increasing $d$. LDF analysis and related $F$-statistics work well for two groups (earthquakes and explosions) with parameters less than five and number of observations (events) greater than or equal to five.
than nine in all groups (Seber, 1984). We have therefore selected $d = 4$ as the optimum number of parameters for our LDF analysis using $P/S$ ratios in this study. Furthermore, we have worked within a simple framework in which the multivariate means of the explosion and earthquake populations are found to be significantly different, and the covariance matrices of the two groups (i.e., the scatter of the two populations) are effectively the same. We recognize the merit of working with a subset of the $d$ variables in $P/S$ ratios that are based on lower frequencies whenever these can be effective, because low-frequency $P/S$ ratios may be less subjected to frequency-dependent amplitude attenuation during wave propagation, and because data at the lower frequencies may be more readily acquired (e.g., at more stations), but it is clear from Figure 9 that the two populations tend to separate better at the higher frequencies, which are available for our use in the present case.

Figure 10. The discrimination power of vertical-component $P/S$ spectral ratios, observed at MDJ at discrete frequencies between 1 and 15 Hz, is shown here in terms of the Mahalanobis distance between the multivariate means of the two populations, earthquakes and explosions. The horizontal axis (number of frequencies) represents choices from 1 to 5 discrete frequencies, used for linear discriminant function (LDF) analysis to obtain the Mahalanobis distance and associated misclassification probability. The vertical axis is the average frequency for each run. For example, if choosing four parameters, discrete frequencies 6, 7, 8, and 9 Hz are taken for LDF analysis (with average 7.5 Hz), then 7–10 Hz (7, 8, 9, and 10 Hz with average 8.5 Hz), and 8–11 Hz, and so on.

Discrimination Power of Vertical-Component $P/S$ Spectral Ratios at MDJ

For vertical-component $P/S$ ratios, frequencies between 6 and 12 Hz will carry most of the classification power, as indicated in Figure 10. The shaded contours are for values of Mahalanobis $\Delta^2$, and they show the classification power of each frequency for chosen sets of 1, 2, 3, 4, and 5 frequency values, resulting in progressively higher Mahalanobis distance-squared values, as expected. From Figure 10, we consider three frequencies in the band from 7 to 11 Hz (i.e., at 7, 9, and 11 Hz) and for four frequencies between 6 and 11 Hz as the most robust region for discrimination. At lower frequencies, values in the 3–5 Hz and 2–5 Hz range are most robust for three and four frequency values, respectively. Ranges including 5–6 Hz are not good, because for them the covariance matrices of the two populations are not the same (Seber, 1984; Kim et al., 1993). For the case of four variables used and discrete frequencies between 6 and 9 Hz, the analysis is based specifically on 6, 7, 8, and 9 Hz. In this case, all earthquakes and explosions are correctly classified on the basis of MDJ data, and the Mahalanobis distance squared is $\Delta^2 = 20.7$, with misclassification probability of 1.15%. Adjacent frequency bands also provide strong discrimination power: 7–10 Hz ($\Delta^2 = 19.9$; misclassification probability = 1.29%) and 8–11 Hz ($\Delta^2 = 19.2$; misclassification probability = 1.42%). Broad frequency bands between 6 and 12 Hz provide strong classification power with small misclassification probabilities of about 1.1%–1.9% (Fig. 10).

Our discussions below are based on use of four frequencies, but here we note that if three variables in the frequency band 8–10 Hz are used (i.e., 8, 9, and 10 Hz), the Mahalanobis distance squared is $\Delta^2 = 19.2$, and all earthquakes and explosions are correctly classified with misclassification probability = 1.42%. Using 7, 8, and 9 Hz, we find $\Delta^2 = 18.3$ and misclassification probability = 1.62%; using 9, 10, and 11 Hz, $\Delta^2 = 16.5$ and misclassification probability = 2.1%. Thus, use of three frequencies yields reasonable discrimination power, although we have chosen in the analysis below to work with four frequencies.

Linear Discriminant Function from Vertical-Component $Pg/Lg$ Ratios

The best LDF from the vertical-component $Pg/Lg$ ratio measured from the sample data sets consisting of 12 earthquakes and 12 explosions is obtained for discrete frequencies 6–9 Hz. For each event, vertical-component $\log_{10}(Pg/Lg)$ ratios at frequencies of 6, 7, 8, and 9 Hz correspond to the variables $r_1$, $r_2$, $r_3$, and $r_4$, respectively. The LDF is obtained as

$$D(r) = -7.46 + 12.88r_1 + 4.28r_2 - 26.81r_3 + 40.19r_4,$$

for which $\Delta^2 = 20.7$ and the misclassification probability is 1.15%.
known explosions recorded by this network are correctly
to the two known nuclear tests at the North Korean test site,
Dongbei network stations. These two
cords show a mean of about 3.2 (logarithmic value around
tical-component
D
D

This method is simply to rotate the observed north–
south– and east–west–component seismogram pairs to obtain
radial (R) and tangential (T) components. The P/S ratios of
three-component records are then formed for each station by
defining $P/S = (P_Z^2 + P_R^2)^{1/2}/(S_Z^2 + S_R^2 + S_T^2)^{1/2}$, in which
subscripts indicate the component. For example, $P_Z$ indicates
the spectral amplitude of $P$ waves on the vertical component
($Z$), and $S_R$ indicates the spectral amplitude of $S$ waves on the
radial component. A single three-component P/S ratio is
obtained for each discrete frequency. This approach uses
the observation that explosive sources tend to excite relatively
strong and impulsive $P$ waves and weak shear waves, whereas
earthquakes as shear-dislocation sources tend to generate
weak $P$ waves but relatively energetic $S$ waves, particularly on
the transverse component. Figure 12 shows three-component
$\log_{10}(P_g/L_g)$ spectral amplitude ratios at discrete frequency
points between 1 and 15 Hz used in discrimination analysis for
our sample data set of 12 earthquakes and 12 explosions.

When a $P$ wave or $S$ wave is incident upon a seismom-
eter sited near the Earth’s free surface, the recorded ground
motion consists of a superposition of $P$ and $S$ waves (there
are reflected $P$ and $S$ waves as well as the incident wave).
Kim et al. (1997) showed that a slight improvement in
discrimination capability can be achieved, if, instead of using
rotated components, an additional correction is made, namely,
removing the effect of the $P$ and $S$ waves reflected at the free
surface (see also problem 5.7 of Aki and Richards, 2009),
but such a correction entails making additional assumptions,
for example, on near-surface structure, and on the horizontal
slowness of the recorded waves. The additional capability
may not be worth the trouble associated with making the additional
assumptions.

The three-component $\log_{10}(P_g/L_g)$ spectral amplitude
ratios from the earthquake and explosion populations overlap
significantly at frequencies 1–4 Hz, but the spectral ratios

tics and are correctly classified, as shown in Figure 11,
indicating that high frequency, vertical-component $P_g/L_g$ spectral ratios are capable of
classifying earthquakes from explosions in the north-
eastern North Korea–northeastern China region. We also
tested the claimed event of 12 May 2010 recorded at Dongbei
network stations DB08 and DB17, using the above discrimi-
nant function. We found that the claimed event on 12 May
2010 was classified as an earthquake (the red square in Fig. 11),

Based on our study of vertical-component waveforms.

**Figure 11.** LDF analysis of the vertical $P/S$ ratio from 12 earth-
quakes (circles) and 12 explosions (shaded triangles) using four
frequencies: 6, 7, 8, and 9 Hz. All the training data, from earthquakes
and explosions, are correctly classified; the Mahalanobis distance is
$\Delta^2 = 20.6$, and the total misclassification probability is 1.15%.
Discriminant scores of 12 earthquakes and 12 explosions of the training
data are plotted with their mean log $P_g/L_g$ ratios. Note that the
two populations are also separated by a mean vertical-component
log $P_g/L_g$ ratio of about 0.2. Vertical lines denoted as Eq and Ex
are the projection of the multivariate means of the earthquake and
explosion population, respectively. The vertical line $D_0$ is the classi-
fication line. Using the LDF obtained for MDJ, the two UNEs (blue
squares) for which we have signals recorded at DBSN are correctly
classified, and the 12 May 2010 event is classified as an earthquake
(red square). Event IDs are as listed in Tables 3 and 4.

Values of $D(r)$ may be called the discriminant score and are plotted in Figure 11 with respect to the mean
log $P_g/L_g$ spectral amplitude ratio of each event. The vertical line $D_0$ is the line $D(r) = 0$, which serves to classify
events when the a priori probability of the two populations is the same. The distance between Eq and Ex is the Mahala-
nobis $D$-squared measure of distance between two popula-
tions. It follows from the logarithmic values in Figure 11
(also, from Fig. 9) that all the earthquake records from various
paths in northeastern China and North Korea have a mean ver-
tical-component $P_g/L_g$ spectral ratio of about 0.6 (and a mean
logarithmic value around −0.1), whereas the explosion rec-
ords show a mean of about 3.2 (logarithmic value around
+0.5) in the frequency band from 6 to 9 Hz.

Classification of Known Underground Nuclear Tests
and of the Claimed Event on 12 May 2010

We tested the performance of the high-frequency dis-
criminant function described in equation (1) by applying it
to the two known nuclear tests at the North Korean test site,
which were recorded at Dongbei network stations. These two
known explosions recorded by this network are correctly
Figure 12. Similar to Figure 9 but now using three-component log$_{10}(P_g/L_g)$ spectral amplitude ratios. The spectral ratio data for the earthquakes and chemical explosions are from MDJ, but two underground explosions (2006 and 2009; blue squares) and the 12 May 2010 event (red square) are from Dongbei network data (stations DB07, DB08, DB09, and DB17). A mean spectral value for each discrete frequency point is plotted both for earthquakes (black circle) and for explosions (black triangle), with a colored bar representing the scatter (±1 s.d.). This use of three-component data achieves better separation of the explosion and earthquake populations than was found in Figure 9, which was based on vertical-component data only.

from the two populations are fairly well separated at frequencies greater than 5 Hz (Fig. 12). The overlap and separation of high-frequency spectral ratios from these two populations are also generally observed for other regions, such as southern Korea (Kim et al., 1998) and nuclear test sites in China (Hartse et al., 1997) and Nevada (Walter et al., 1995).

Three-component $P/S$ spectral amplitude ratios are generally similar to those measured from vertical components in broad frequency bands: $P/S$ ratios of the earthquakes are fairly well separated from those of explosions at frequencies above 5 Hz. The average $P/S$ ratio of earthquakes in the 1–15 Hz band is about 0.4, whereas the mean $P/S$ ratios of explosions in the same frequency band is about 1.5 (see Fig. 12), but the discrimination capabilities when using three-component data are somewhat improved (over use of vertical components only), as we discuss in the next section.

Discrimination Power of Three-Component $P/S$ Spectral Amplitude Ratios at MDJ

We evaluated the discrimination power of three-component $P/S$ ratios using methods similar to those applied to the vertical-component data. The resulting discrimination power is shown at various discrete frequencies, and for different numbers of parameters used, in Figure 13. Broad frequency bands between 6 and 12 Hz, with 3 and 4 parameters used for the LDF, provide strong classification power with very small misclassification probabilities (~0.5% – 1.27%). Further details on the discrimination power obtained with different choices of frequency are provided in the electronic supplement. We next go forward using our best choice.

Linear Discriminant Function Based on the Three-Component $P_g/L_g$ Ratio

The best LDF from the three-component $P_g/L_g$ ratio for the sample data sets, consisting of 12 earthquakes and 12 explosions recorded at station MDJ, is obtained for four discrete frequencies in the 6–9 Hz band. For each event, let three-component log$_{10}(P_g/L_g)$ ratios at frequencies of 6, 7, 8, and 9 Hz correspond to the variables $r_1$, $r_2$, $r_3$, and $r_4$, respectively. The LDF we obtain is

\[
D(r) = -4.33 + 14.43r_1 - 16.77r_2 - 12.04r_3 + 45.91r_4,
\]

with $\Delta^2 = 25.6$. All earthquakes and explosions in our training sets are classified correctly (Fig. 14), and the misclassification probability is only 0.57%. We can now use this LDF to classify seismic events in northeastern North Korea and northeastern China.

Classification of Known Underground Nuclear Tests and the Claimed Event on 12 May 2010

We tested the performance of the above high-frequency discriminant function (equation 3), by applying it to the data set of two known nuclear tests at the North Korean test site recorded at Dongbei network stations. We found that two known explosions are correctly classified (Fig. 13). We also evaluated the seismic event on 12 May 2010 recorded at Dongbei network stations (DB08 and D17), using the above discriminant function, finding that the event is then classified as an earthquake (Fig. 14).

Lack of Effects due to Distance and Magnitude, on the Measured Spectral Ratio

Figure 15 shows the measured three-component $P/S$ ratios plotted against epicentral distance. In cases where high frequencies are significantly attenuated, there can be a distance dependence in the ratio and it may then be useful to make a correction to the observed spectral ratio (as done for example by Kim et al., 1997; Hartse et al., 1998; Walter and Taylor 2001; Taylor et al., 2002; Pasyanos and Walter 2009; and Pasyanos et al., 2012), to account for the fact that the denominator (based on S-wave data) may attenuate with distance differently from the numerator (based on $P$), but we have not made a correction for distance, because earthquakes and explosions in the 150–550 km distance range show no clear distance dependence of the ratios, and the training set data have comparable distance ranges and are tightly distributed. The 12 earthquake events have an average epicentral
distance of 368 ± 96 km, whereas the average distance for the 12 explosions is 320 ± 71 km (Fig. 15a).

$P/S$ ratios of the earthquakes and explosions show separation along a horizontal line, namely $\log_{10}(P_g/L_g) \approx -0.1$ (the data here are for chemical explosions, single-hole shots, UNEs, UNEs recorded at DBSN, and the claimed event on 12 May 2010).

To conclude on this point, in the present case distance corrections can be ignored, because all events are typically within 200 km from each other, and the paths have very low attenuation.

The lack of dependence of $P/S$ ratios on magnitude, in the magnitude range we are using, was studied in detail by Pan et al. (2007, pp. 553), who wrote that:

Applicability of regional $P/S$ amplitude ratios for the discrimination of low-magnitude seismic events was tested and proved using earthquakes and explosions in central Asia. Results obtained show that regional $P/S$ amplitude ratios which may discriminate medium or large magnitude events well are also applicable to low magnitude events...

The $P/S$ ratio of each record is plotted against event magnitude in Figure 15b. Again there is no clear correlation of $P/S$ ratios on magnitude, and we have made no correction for a magnitude effect. The low magnitude of the 12 May 2010 event is comparable to magnitudes of the small single-fired chemical explosions in our training set (events numbered 4–7 in Table 3); its $P/S$ spectral ratio, averaged over the frequencies 6–9 Hz, at stations DB08 and DB17, is lower (and hence more earthquake-like) than this ratio for any of these four chemical explosions at the MDJ station.

Event Magnitude and Relationships between Magnitude, Depth, and Yield (for Explosions)

Zhang and Wen (2015a) assign an Lg magnitude of 1.44 to the 12 May 2010 event. Taking the event to be an explosion, they interpret this magnitude to obtain a yield estimate on the basis of several assumptions, including:

- use of a relationship between the teleseismic $P$-wave magnitude and log (yield) proposed by Bowers et al. (2001) for underground explosions at Novaya Zemlya, $m_b = 4.25 + 0.75 \log Y$ for $Y$ in kilotons for $Y \geq 1$ kt;
Figure 15. The mean $\log_{10}(P/S)$ values between 6 and 9 Hz measured from three-component records are plotted against (a) epicentral distance and (b) magnitude. Earthquakes (circles) and different types of explosions: chemical explosions (inverted triangles), single-hole shots (triangles), UNEs (black star), UNEs recorded at DBSN (blue stars at stations DB07, DB09, DB10, and DB17), and the claimed event on 12 May 2010 (red squares at DB08 and DB17). $P/S$ ratios of the earthquakes and explosions show separation along $\log_{10}(Pg/Lg) = \sim 0.1$. There is no clear correlation of $P/S$ ratios with either distance or magnitude, within the different types of seismic event, and we have chosen not to make any distance or magnitude correction to the measured ratios prior to applying our methods of event classification.

- correcting their magnitude for a depth effect as proposed by Denny and Johnson (1991) and Patton and Taylor (2011), which for a $P$-wave $m_h$ amounts to adding the term $-0.7875 \log[h/120Y_{1/3}]$ to the right side of the magnitude–yield relation for an explosion conducted at a depth $h$ (in meters) rather than at the standard depth of $120Y_{1/3}$; and
- taking the source depth $h$ to be 230 m on the basis of differencing surface elevations associated with the entry and the end of a presumed adit.

But the numbers 4.25, 0.75, 0.7875, and 230 all have uncertainties in the original studies from which they were derived, with further uncertainties in application to nuclear explosions at the North Korean test site; the application of a $P$-wave magnitude correction for depth to a magnitude based on $Lg$-waves is questionable; and the underlying assumption of a one-to-one correspondence between a magnitude and yield at a particular depth, without regard to coupling conditions or knowledge of local geology or cavity gases, is inappropriate. The overall uncertainty of yield estimation in practice, even accepting the event to be an underground explosion of some sort (chemical or nuclear), is therefore considerable. According to an Office of Technology Assessment (OTA) report of the US Congress (1988), yield estimates are typically associated with a factor of uncertainty. For a yield estimate given as $\hat{Y}$ and $F$ as the factor of uncertainty, the actual yield lies within a 95% confidence interval given by $\hat{Y}/F \leq Y(\text{actual}) \leq \hat{Y} \times F$, and $F$ is about 2 in the case of estimates based on teleseismic $P$ waves. Refinements have been made in the case of well-studied test sites, but even with a unified yield estimate based on a variety of seismological methods, the factor of uncertainty is still around 1.3, according to the same OTA report, and this is in the context of estimating the yield of a large underground explosion (tens of kilotons). For all explosions, yield estimates are subjected to uncertainties associated with the degree of coupling of nuclear energy into seismic waves, and such coupling is potentially easier to modify for small explosions than for multikiloton explosions. There is also the fact that just a few regional seismic signals are being used in the present case, with no opportunity to average tens or hundreds of teleseismic signals to obtain a reliable magnitude, as would be the case for a multikiloton event.

To summarize here, the yield of tamped explosions with magnitude in the range around 1.5 is on the order of one ton (TNT equivalent), but with considerable uncertainty, perhaps as much as a factor of 5.

Discussion

During the late stage of Comprehensive Nuclear-Test-Ban Treaty (CTBT) negotiations in the 1990s, three categories of network were under consideration for treaty verification. These were variously called alpha, beta, and gamma networks or primary, auxiliary, and supplementary networks. The primary and auxiliary networks have become a reality as components of the IMS of the CTBTO. As noted, for example, by the US National Academy of Sciences (2012), the IMS and the associated International Data Centre are now providing verification capability that is significantly better than had been anticipated in the 1990s.

The event on which we focus in this article, at magnitude $\sim 1.5$, has seismic signals about 300 times smaller than those of North Korea’s first nuclear test, conducted in 2006. We have been led to write a lengthy article, analyzing such a very small seismic event, for two main reasons. First, the event has been characterized as a small nuclear explosive test, and we deem this conclusion to be unsupported by the seismological evidence available to us for reasons we have now presented (Figs. 11 and 14) and which we augment in this section. Second, it is surely important to convey a sense of current capabilities when reporting on signals from a region for which extensive supplementary data are available. We advocate for open access to such data, given its potential to help clarify the nature of problem events.
Figure 16. Same as Figure 11 (vertical-component LDF analysis), except that we have added points derived from data recorded by station SMT (shown in Fig. 1) used by Zhang and Wen (2015a, data given in their figure 5) and from the NECESS Array station NE3C. The six points based on SMT data are shown in yellow, and they correctly place the nuclear explosions of 2009 and 2013 in the explosion population (yellow triangles), and the three earthquakes in the training set from Table 4 recorded by SMT are in the earthquake population (yellow circles), but the event of 2010 is now with the earthquakes (yellow square). The point based on data from station NE3C (green square) is for the 2010 event, and it is also with the earthquakes. In Figure 16, we have added these six points, derived from the data of Zhang and Wen, to points shown in Figure 11. Based on measurements made from SMT seismograms, the known earthquakes and explosions fall appropriately into their respective populations, and the 12 May 2010 event falls among the earthquakes. In Figure 16, we also show a point derived from the NE3C station of the NECESS Array for the event of interest. It is somewhat of an outlier among the earthquakes, but on the side away from being explosion-like.

The LDFs we have obtained, in equations (2) and (3), share a characteristic that was exhibited in our earlier studies (Kim et al., 1993, 1997), namely, that these formulas involve a mix of signs, positive and negative, for the various contributing $r_i$ values. The equations define hyperplanes that separate the two populations, earthquakes from explosions. The $D(r)$ measures are quite robust, because we obtain similar results with alternative choices of which frequencies to use and how to weight them. The average values of $\log_{10}(P/S)$ given on the vertical axes of Figures 11, 14, and 16 represent a quite different linear combination of $r_i$ values, and these average values also lead to separated earthquake and explosion populations, albeit with somewhat greater misclassification potential than with use of the horizontal-axis values derived from equations (2) and (3).

A key assumption of the Mahalanobis analysis in this article is that an LDF developed from training sets of MDJ data is suitable for application to waveform data (recorded at regional distances over low-attenuation paths) from other stations. The NECESS Array stations appear to provide us with an opportunity to evaluate this assumption, and to this end we have examined spectral ratios for 125 examples of three-component $P/S$ from six earthquakes and six explosions, using waveforms drawn from 20 NECESS Array stations. The data are far from ideal, in that this was a temporary deployment, too short (from September 2009 to August 2011) to enable study of larger training sets, and it did not acquire data from any one of the known UNEs in North Korea. Nevertheless, it was interesting to carry out an LDF analysis of the training sets for NECESS Array data and to find that $P/S$ spectral ratios between 6 and 11 Hz provided the greatest Mahalanobis separation between the two population means. The $\Delta^2$ value was even greater than was the case for MDJ data (discussed in Fig. 14).

Seber (1984) suggests that LDF analysis should be good for at least nine events in each population when using fewer than five parameters (frequencies, in our case), but we went ahead with our somewhat smaller test data sets and tested for portability of the LDF. The first test was to classify the 12 explosions and 12 earthquakes of Tables 3 and 4 by applying the NECESS Array LDF to MDJ data. All 12 explosions...
were correctly classified, but about half of the earthquakes were classified as explosions. A second test was to use the MDJ LDF to classify the six earthquakes, four explosions, and two unknown events, which provided the NECESS Array LDF. All earthquakes were correctly identified, but in this case two of the explosions were misclassified, due, we suggest, to lower-quality waveforms and to the unknown nature of some of the events.

To summarize, our efforts to use NECESS Array data were frustrated by the quality of data and lack of training events available for obtaining a reliable LDF.

Our objective criterion for identifying the event has been its Mahalanobis score (negative for an earthquake and positive for an explosion), established on the basis of having just two classes of events, as developed via training sets using MDJ data, but then we might ask if there are other types of seismic event, with characteristics that are not obviously associated with the events in our Table 3 (explosions) or Table 4 (earthquakes). For example, on the basis of observed P/S spectral ratios, how would we expect to classify an unusually deep small earthquake, or a small explosion, that was ripple-fired rather than single-fired and/or was conducted at or just above the surface rather than at the contained depth of known nuclear explosions in North Korea? Should we expand the number of source types or expand the characteristics of the two types we have worked with to include the characteristics of such unusual earthquakes and explosions in our training sets? We raise these questions to make clear that in this article we are not stating there is rigorous evidence that the seismic event of 12 May 2010 was an earthquake, but rather that it appears to have been an earthquake on the basis of considerably more seismological data, and objective analysis, than has been provided by Zhang and Wen (2015a).

In the course of our work, we have been asked if the 12 May 2010 event could be from a decoupled explosion. Consideration of this possibility seems not to be relevant in the present case, at least for decoupled explosions conducted with the goal of reducing signal amplitudes radiated in all directions and thus with the explosive device not near the cavity walls. Such decoupled explosions are found to generate signals with P/S spectral ratios even higher than for signals from tamped explosions (Blandford, 1996), and our observation for the May 2010 event is that its P/S spectral amplitudes were lower than for tamped explosions. But then, could the event have been a partially decoupled explosion conducted asymmetrically in its cavity? There is limited practical experience to show that such an explosive source generates S waves more efficiently (hence appearing more earthquake-like) than for a decoupled explosion at the center of a spherical cavity. Stevens and Baker (2009) describe a 1-ton chemical explosion conducted in Kyrgyzstan in 1960, offset from the center of a spherical cavity with radius 4.92 m. Theory and very limited data from this shot indicate S waves comparable to P waves at around 10 Hz. The S-wave source is effectively a dipole and therefore would be expected to exhibit amplitudes decreasing significantly at low frequency, a feature we do not observe for DBSN data.

Ultimately, the characterization of a small seismic event by a method such as one described here may not be deemed to provide sufficient evidence on the nature of a problem event in the context of the CTBT after entry into force but may serve purely as an indicator. In the presence of conflicting indicators, such as from radionuclide and seismic monitoring, the need for clarification may be a basis for requesting an on-site inspection.

Looking ahead, there is the prospect of being able to analyze additional data, but from the Dongbei network, which was deployed for about seven years. When relevant data become available, we plan to apply our evaluation of P/S spectral ratios directly to data from the Dongbei network using training sets from earthquakes and explosions derived from the same stations for which we have signals of the 12 May 2010 event. From the Dongbei waveform archive, we would expect to learn whether there are other small seismic events near the North Korean test site. The LDF method we employed in this study has the merit of allowing new training data to be added to existing data to update the LDF, thus enabling a process of learning from the new data.

Our analysis of discrimination capability in this article has emphasized an application to one particular event, but our method potentially has wide application. For example, many data centers that prepare catalogs of seismic events, from waveform data acquired by regional or local networks, are concerned not to include explosions from industrial or construction activities, because the catalog may be intended for studies of tectonic activity—that is, it should contain only natural earthquakes. Our discrimination method based on equations (2) or (3) can be very suitable for such an application.

We wish to emphasize the very small size of the event in May 2010 studied here. With signals about 3.5 magnitude units smaller than those of nuclear tests in 2013 and 2016 (January), its seismic signals are about 3000 times smaller. The event is on the margins of what can be detected and identified and is thus useful as an indication of those margins. It is remarkable that significant data exist, enabling our effort to characterize such a very small event. At this low size, we are stretching current monitoring capability to new low levels, below those described, for example, in the latest report of the US National Academy of Sciences (2012; Figs. 2–7 and related discussion of monitoring for CTBT compliance).

The need to address problem events has historically been the way in which the monitoring community has been prompted to develop new methods, which, if demonstrated to be successful, have eventually come into operational use. Over time, we can expect monitoring capability to improve, both for broad areas and for particular regions of interest.

Summary and Conclusions

First, to locate the 12 May 2010 seismic event, we analyzed $L_g$-wave CC measurements and phase picks from temporary stations to conclude that the event is more than 1 km from the 2009 nuclear test and is most likely located between about 4 and 10 km to the southwest of this known explosion in North Korea.
Second, to assess the nature of the event, we analyzed waveform data from a GSN station, MDJ in northeastern China, for events at distances from about 200 to 600 km, including earthquakes and chemical and nuclear explosions in and near the northern regions of North Korea, to identify an LDF based on measurements at MDJ of $P$-to-$S$ spectral ratios ($P/S$) that could most effectively be used to discriminate between small earthquakes and small explosions. We then applied that experience, acquired from station MDJ, to a limited set of seismic signals recorded by the DBSN, which included those from two known nuclear explosions in North Korea and from a small seismic event ($M \sim 1.5$) on 12 May 2010 near the North Korean test site, reported by Zhang and Wen (2015a), which they claimed to be a small nuclear explosion. When our LDF is applied to DBSN data and to data from stations SMT and NE3C in China, the LDF values measured from $P/S$ ratios from known explosions are explosion-like, but for the event of 12 May 2010, the LDF values are earthquake-like for frequencies between 6 and 12 Hz. In the present case and taking account of SNRs (which degrade at higher frequencies), the band from 6 to 9 Hz appears to provide the best discrimination capability.

Thus, we find the event of interest to have the characteristics of an earthquake, on the basis of the best seismological data we have been able to obtain, which includes the $P/S$ spectral measurements reported by Zhang and Wen (2015a). This is a preliminary conclusion, which we and others can examine further if additional data from DBSN and from other stations in the region become available.

Our results suggest that vertical- and three-component $P/S$ spectral ratios provide an efficient method for classifying earthquakes and explosions in northeastern North Korea and northeastern China down to only a few tons TNT equivalent.

From our work, there is at present still no explosive seismic event to associate with the known radionuclide anomalies reported by De Geer (2012). The event first detected and reported by Zhang and Wen (2015a), being found here to have earthquake-like features, appears not to be an appropriate candidate for consideration as a decoupled explosion.

Data and Resources

Waveform data from the Global Seismograph Network (GSN) stations—MDJ (Mudanjiang, China) and INCN (Incheon, Korea)—and from stations of the Northeast China Extended Seismic (NECESS) Array were obtained from the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC; www.iris.edu/SeismiQuery/by_station.html, last accessed January 2016). Waveform data from the Dongbei Broadband Seismographic Network (DBSN) were kindly provided by Kin-Yip Chun, formerly of the University of Toronto. Earthquake catalog data used are acquired from the International Seismological Centre and the U.S. Geological Survey (www.isc.ac.uk/iscbulletin/search/catalogue/ and https://earthquake.usgs.gov/data/pde.php, last accessed January 2016). Seismographic networks and data centers in the region include the Korea Meteorological Administration (KMA; www.kma.go.kr/weather/earthquake/domesticlist.jsp, last accessed January 2016) and the Korea Institute of Geology and Mineral Resources (KIGAM) (quake.kigam.re.kr/pts/db/db.html, last accessed January 2016). High-quality $Lg$ cross-correlation measurements are obtained from the unpublished manuscript of D. P. Schaff, P. G. Richards, M. Slinkard, S. Heck, and C. Young (2017): “$Lg$-wave cross-correlation and epicentral double-difference location in and near China,” in preparation for submission to Bulletin of the Seismological Society of America.

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