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Seismological Evidence for a Low-Yield Nuclear Test on 12 May 2010 in North Korea

by Miao Zhang and Lianxing Wen

Online Material: Location uncertainty estimation; figures of waveform comparison, location maps, and *Pg*/*Lg* spectral ratios; tables of earthquake parameters and *Lg*-wave amplitude ratios.

INTRODUCTION

Three nuclear tests (in 2006, 2009, and 2013) conducted by the Democratic People's Republic of Korea (North Korea) are all detected and confirmed by many governmental and international agencies (e.g., the U. S. Geological Survey [USGS] and the Comprehensive Nuclear-Test-Ban Treaty Organization [CTBTO]). The locations and yields of these tests have also been extensively studied by many research groups (e.g., Richards and Kim, 2007; Koper *et al.*, 2008; Zhao *et al.*, 2008, 2012, 2014; Murphy *et al.*, 2010; Wen and Long, 2010; Chun *et al.*, 2011; Zhang and Wen, 2013). However, it is under intensive debate among the governmental agencies and research groups whether North Korea has conducted other small nuclear tests. In particular, De Geer (2012) reported the detection of xenon and xenon daughter radionuclides between 13 and 23 May 2010 in four atmospheric radionuclide surveillance stations, located in South Korea, Japan, and the Russian Federation. He suggested the presence of barium-140 can be explained only by a sudden nuclear event, with the corresponding trinitrotoluene equivalent in a range of 50–200 t and the estimated time-zero at 6:00 + 18 hr/ − 30 hr UTC on 11 May 2010 (De Geer, 2012; see also Brumfiel, 2012). The fissile material of the possible mid-May 2010 nuclear test is indicated as uranium-235 rather than the plutonium-239 inferred from the radioxenon signal detected at Geojin in South Korea (De Geer, 2012, 2013), although Wright (2013) suggested they cannot be clearly discriminated from atmospheric transport modeling of the observed radionuclides. Other studies also obtained similar findings based on the detected types and ratios of isotopes (De Geer, 2013; Ihantola *et al.*, 2013; Wotawa, 2013; Wright, 2013). Based on 2 hr time slices, a more accurate time-zero is estimated to be 16:00 UTC on 12 May 2010 by Ihantola *et al.* (2013), which is limited between 9:00 UTC on 11 May 2010 and 13:00 UTC on 13 May 2010 based on its 95% uncertainty. Wright (2013) concluded that the most likely origin of the radionuclides is close to North Korea's nuclear test site (NKTS). Coincidentally, on 12 May 2010, the North Korean official daily morning newspaper *Rodong Sinmun* reported that North Korea succeeded in nuclear fusion on the Day of the Sun (http://www.kcna.co.jp/item/2010/201005/news12/20100512-05ee.html; last accessed July 2014), although the report was ridiculed by the South Korean and Western media (Brumfiel, 2012).

However, without seismic data or on-the-ground inspections to support the radioisotope data, it is impossible to verify where the isotopes come from (Brumfiel, 2012). The study of De Geer (2012) stirred a serious controversy about which representatives of the U.S. government and CTBTO refused to comment (Brumfiel, 2012; De Geer, 2013). So far, the first and only attempt to search for seismic signal of possible nuclear events in the reported period turned out to be negative (Schaff *et al.*, 2012). In that study, they tried to detect possible small nuclear tests in the NKTS by applying the three-component cross-correlation method on seismic waveforms recorded by station MDJ, using the 2006 and 2009 nuclear tests as the template. They failed to find any evidence for any underground explosion detectable at that station in the five specific days (14–16 April and 10–11 May) suggested by De Geer (2012). Thus, there has not been any seismological evidence to support the above radionuclide findings so far.

In the study of Schaff *et al.* (2012), only the seismic data from one station (MDJ) are used, and MDJ is at a distance of 370 km from NKTS. Their study does not exclude the possibility that a low-yield event may have escaped detection because of its weak signal at large distance or occurrence at other unchecked time windows. In this study, we search for possible events using regional seismic data recorded in April and May 2010 in northeast China, within 200 km of NKTS, and a newly developed event detection method called the match-and-locate (M&L) method (M. Zhang and L. Wen, unpublished manuscript, 2014). The M&L method is an effective method for small event detection by stacking cross correlograms between waveforms of the template events and potential small event signals in the continuous waveforms over multiple stations and components. Unlike the traditional match filter method, which assumes that the template event and slave event are sufficiently close that they generate effectively the same waveform (apart from a scale factor) and effectively the same time shift at all recording stations, the M&L method scans over potential small event locations around the template by making relative travel-time corrections based on the relative locations

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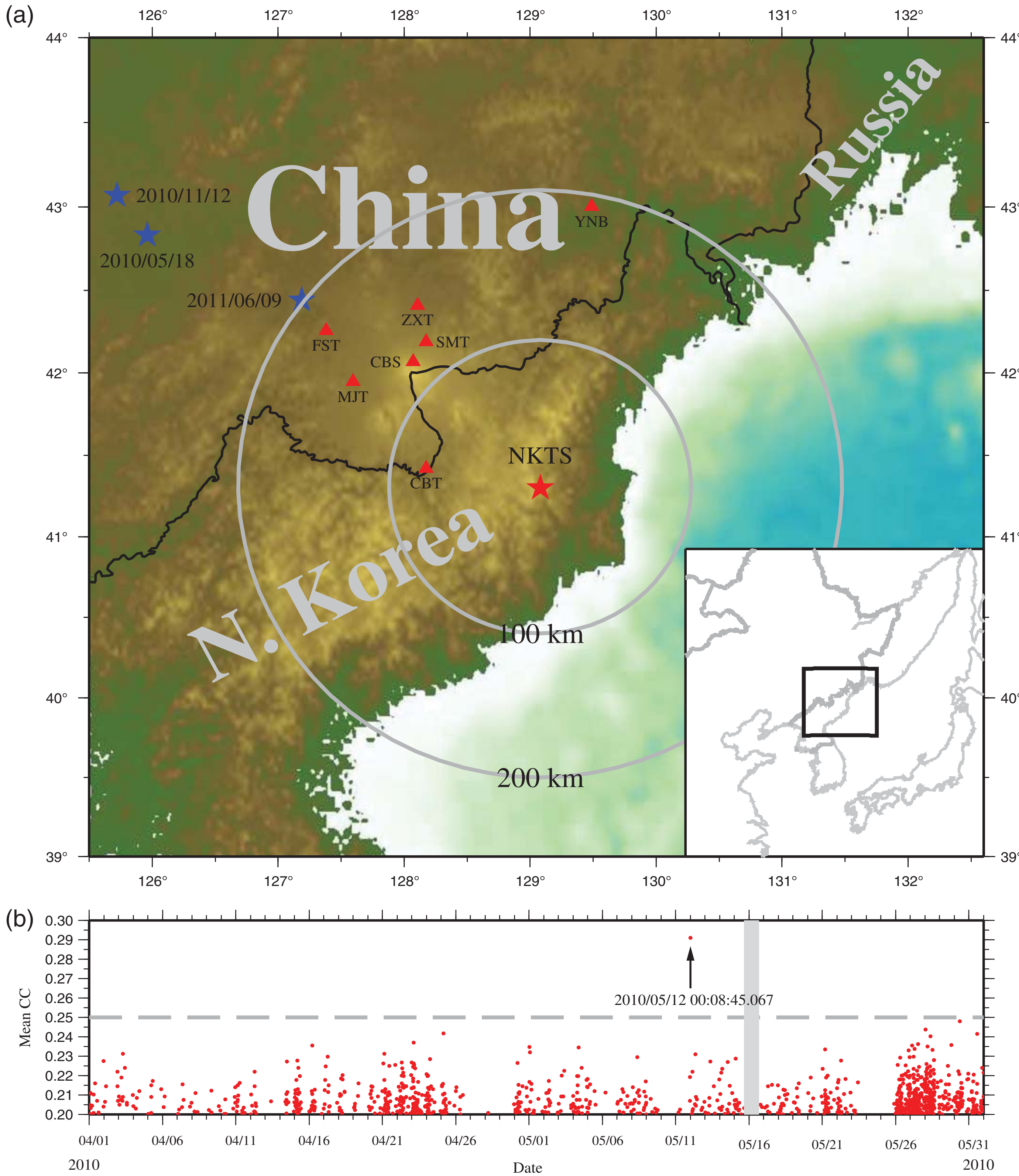


▲ **Figure 1.** (a) Location of North Korea's nuclear test site (NKTS, red star), seven seismic stations (red triangles) within 200 km of the test site, and three nearby earthquakes (blue stars) used in event type comparison. (Inset) A regional map of eastern Asia in which the black rectangle indicates the study area. (b) Maximal values of the stacked cross correlograms for every 0.001 s time interval (red dots) from 1 April 2010 to 31 May 2010 (only the values greater than 0.2 are plotted) and a detected event at 00:08:45.067 UTC on 12 May 2010 (dot labeled by the event origin time). Gray dashed line stands for the mean CC threshold of 0.25. Gray area indicates the time window of data gap (from 16:00 UTC on 15 May 2010 to 16:00 UTC on 16 May 2010).

Table 1
Location, Time, and Yield of North Korea's Nuclear Tests

Test	Date (yyyy/mm/dd)	Latitude (°N)	Longitude (°E)	Origin Time (hh:mm:ss.sss)	Magnitude	Yield
2006	2006/10/09	41.2874*	129.1083*	01:35:28.000[†]	3.93[‡]	0.48 kt[‡]
2009	2009/05/25	41.2939[§]	129.0817[§]	00:54:43.180[§]	4.53±0.12[‖]	7.0±1.9 kt[#]
2010	2010/05/12	41.2863**	129.0790**	00:08:45.067**	1.44±0.13**	2.9±0.8 t**
2013	2013/02/12	41.2908[#]	129.0763[#]	02:57:51.331[#]	4.89±0.14[#]	12.2±3.8 kt[#]

*Satellite images.
[†]U.S. Geological Survey.
[‡]Zhao *et al.* (2008).
[§]Wen and Long (2010).
[‖]Zhao *et al.* (2012).
[#]Zhang and Wen (2013).
**This study.

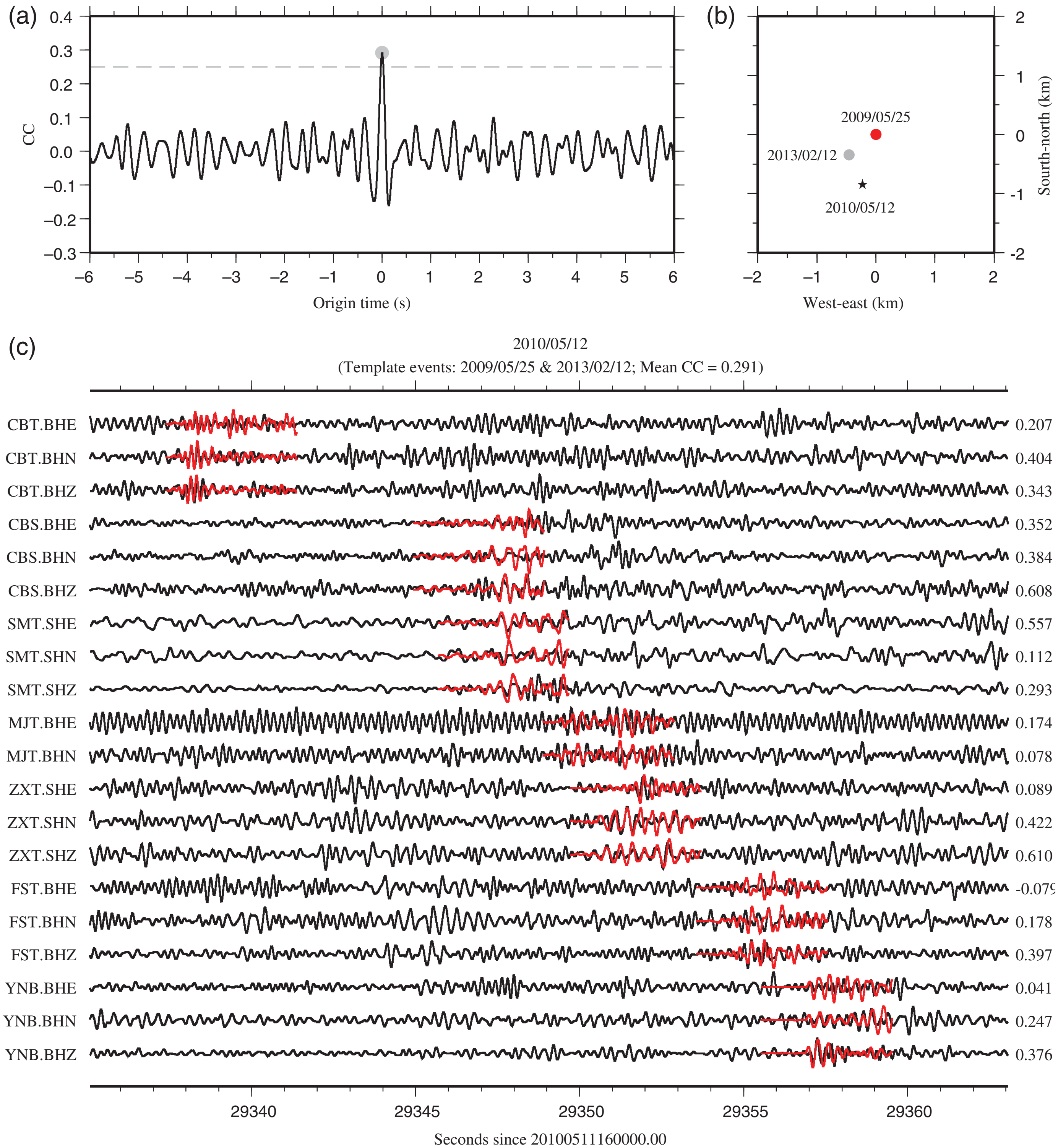
of the template event and the potential small event before stacking (M. Zhang and L. Wen, unpublished manuscript, 2014). It makes event detection more efficient and at the same time relocates the detected event with high precision. We detect a low-yield nuclear test on 12 May 2010 from the seismic data using the M&L method. We present details of the detection and location of the event; we further discriminate the event to be a nuclear test using the *Pg*/*Lg* spectral ratio and estimate its yield.

DETECTION AND LOCATION OF A LOW-YIELD NUCLEAR TEST ON 12 MAY 2010

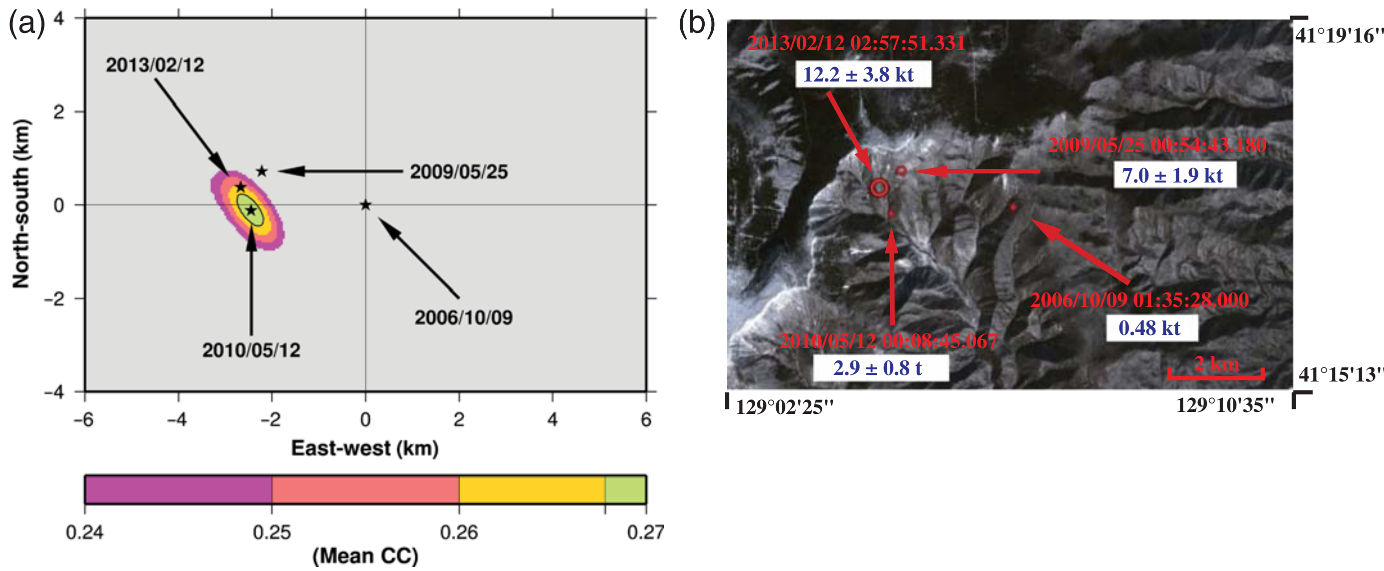
We use the M&L method to detect and locate possible nuclear tests through the seismic data recorded by the nearest seven three-component stations (except for the vertical component of station MJT, which had been changed over time) in Jilin province of the People's Republic of China from 1 April 2010 to 31 May 2010 (Fig. 1a). These stations are within 200 km of the test site and also recorded the seismic waves from North Korea's 2009 and 2013 nuclear tests. We convert the seismic data to ground velocity by removing the instrument response and then band-pass filter the ground velocity from 1 to 6 Hz. To improve the detection ability, we combine the 2009 and 2013 events as our templates (Table 1). For each potential location and occurring time, we shift the correlograms based on the predicted travel-time differences then stack the cross correlograms over all channels and average for both templates. Because source depth trades off event origin time in M&L detection when using a limited number of stations, we fix the depth to be zero and search for the potential event location in an area of 0.08° in latitude and 0.08° in longitude centered at the 2009 event, with an interval of 0.0002°. Waveforms of the *Pg* wave are used, and the *Pg* phase is adopted in the relocation procedure based on the IASP91 model (Kennett and Engdahl, 1991). A 4 s time window (1 s before and 3 s after the predicted *Pg*-wave arrival) is used as the template waveform window. Except for one origin time (00:08:45.067 UTC, 12 May 2010) that has a mean cross-correlation coefficient (CC) value of 0.291, all other origin times have mean CC values less than 0.25 (Fig. 1b). We regard the mean CC value of 0.291 as positive detection of an event, as it is significantly larger than the background mean CC values, satisfying the detection criterion similar to those set for event detection in many other studies (e.g., Peng and Zhao, 2009; M. Zhang and L. Wen, unpublished manuscript, 2014). The location is inferred based on the location of maximal mean CC value at 41.2863° N, 129.0790° E (Fig. 2b and Ⓔ Fig. S1b, available in the electronic supplement to this article). The detected 2010 event is located at 227 m west and 844 m south of the 2009 nuclear test and 227 m east and 499 m south of the 2013 nuclear test (Fig. 2b and Ⓔ Fig. S1b). The location uncertainty is determined to be 350 m, based on the analysis of the scaled-down seismic signals of past nuclear tests in the region (Fig. 3; Ⓔ see the analysis in the Contexts section of the electronic supplement).

The corresponding mean CC of the detected 2010 event exhibits a distinct impulse in the stacked cross correlogram (Fig. 2a), indicating the seismic signal is coherent in time in the individual channels. The maximal mean CC value is well localized in a small region in the mean CC distribution over all potential locations (Fig. 3a), indicating reliable detection and high-resolution relocation of the detected event. Waveform matching between the detected event and the template event is good and consistent for both template events, as illustrated by almost all positive CC values over all channels for both template events (Fig. 2c and Ⓔ Fig. S1c).

Both *Pg* and *Lg* waves are clearly recorded in all seven stations for the 2009 and 2013 nuclear tests (Fig. 4a,b). These two phases are also clearly visible in the recordings of most stations for the 2010 event (Fig. 4c and Ⓔ Fig. S2). The *Lg* phases of the 2010 event are observed distinctly at stations SMT and CBS in a relatively broad frequency band from 1 to 20 Hz (Fig. 4c) and at stations MJT, ZXT, FST, and YNB in the frequency band from 1 to 5 Hz (Ⓔ Fig. S2a). The *Pg* phases of the 2010 event are clearly visible at stations CBT and SMT over 5 Hz and stations YNB and ZXT in higher frequency bands (5–10 Hz and 15–20 Hz for YNB and 5–15 Hz for ZXT) (Ⓔ Fig. S2). Further detailed analysis



▲ **Figure 2.** (a) Stacked correlogram for the detected event at 00:08:45.067 UTC on 12 May 2010, (b) locations of the determined 12 May 2010 event (black star) and two template nuclear tests (red circle, 25 May 2009; gray circle, 12 February 2013), and (c) the template nuclear test waveforms (red traces, 25 May 2009) plotted in comparison with the continuous waveforms (black traces) along the predicted arrival times of the detected event on 12 May 2010. The gray dashed line in (a) indicates the mean CC threshold (0.25) of detection. In (c), each trace is labeled with station name on the left and CC value on the right, and the total mean cross-correlation coefficient (CC) computed in match and locate (M&L) is labeled under the subtitle. Ⓔ The seismogram comparison between the other template (12 February 2013) and the continuous waveforms is shown in Figure S1.



▲ **Figure 3.** (a) Best-fitting location of the 12 May 2010 nuclear test (star labeled as 2010/05/12, which corresponds to the maximal mean CC value in M&L detection) relative to the locations of template 2009 and 2013 tests (stars labeled as 2009/05/25 and 2013/02/12), plotted centered at the location of 2006 test (star labeled as 2006/10/09). The mean CC values in the neighboring locations of the inferred 2010 test site are plotted in color (only the regions with mean CC > 0.24 are presented). The black ellipse represents the confidence level of the 2010 test location within 94.3% of the maximal mean CC (Ⓔ see the analysis in the electronic supplement). (b) Locations (circles), origin times (labeled red), and yields (labeled blue) of the 2006, 2009, 2010, and 2013 nuclear tests, plotted on a Google Earth map (image on 23 January 2013) of the area shown in (a), centered at the 2006 test site identified by the satellite images. The sizes of the 2009 and 2013 symbols are proportional to their yields. The event parameters for North Korea's four nuclear tests are shown in Table 1.

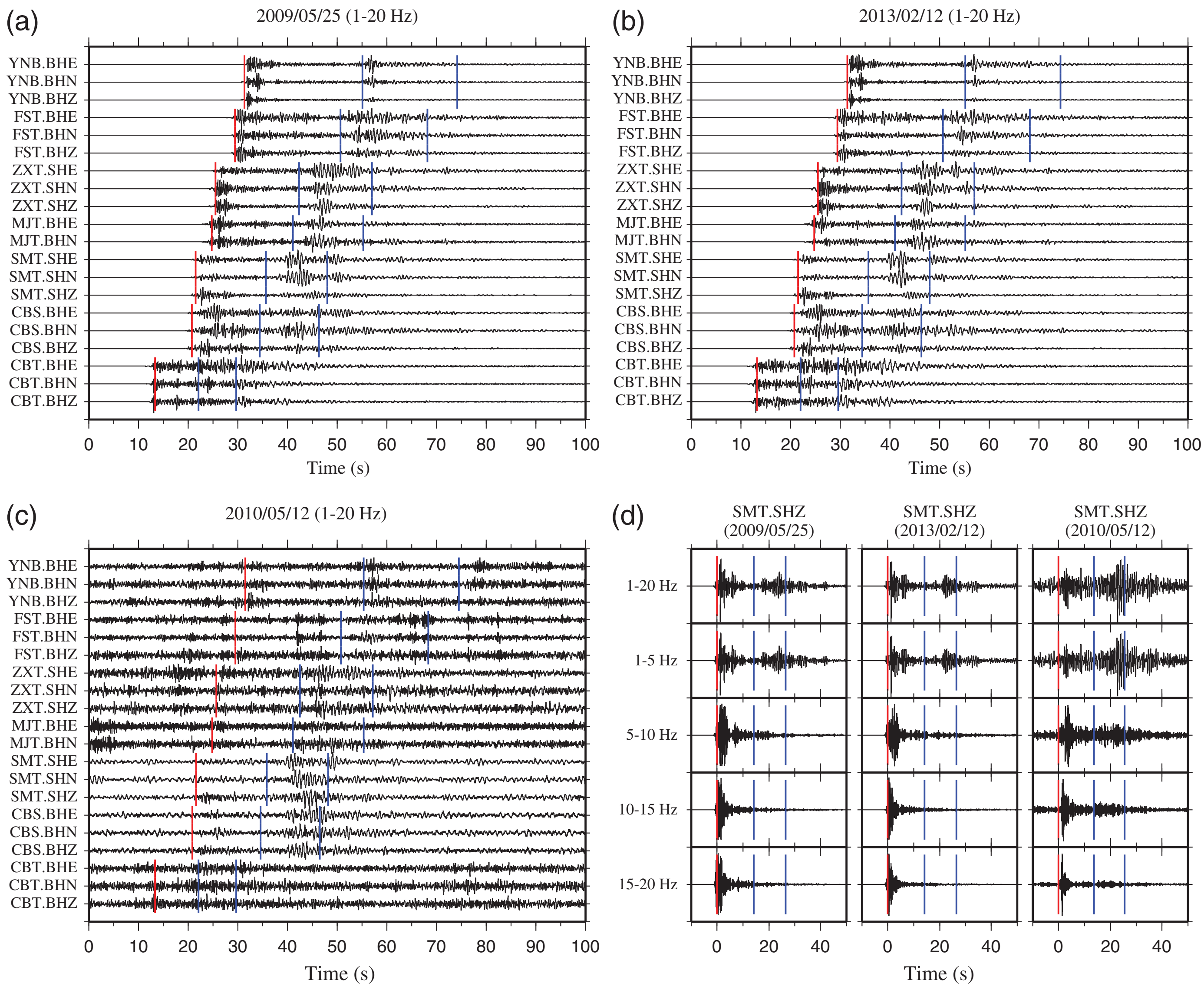
for the seismic recordings at borehole station SMT suggests that, although the relative amplitudes of *Pg* and *Lg* waves are similar at various frequency bands between the 2009 and 2013 tests, the *Lg* wave for the 2010 test has relatively larger amplitudes at the frequencies below 10 Hz (Fig. 4d). These waveform characteristics may be due to these reasons: (1) the local background noise may affect the waveform characteristics differently at different frequency bands, (2) the explosion characteristics of *Pg*/*Lg* behavior shift toward higher frequencies for a smaller explosion, and (3) the 2010 test may be a decoupled event. We will further elaborate the last two possible reasons later in this paper.

DISCRIMINATION OF THE 12 MAY 2010 NUCLEAR TEST BASED ON *PG*/*LG* SPECTRAL RATIO

P/*S*-type spectral ratios of regional phases (e.g., *Pg*/*Lg*, *Pn*/*Lg*, *Pn*/*Sn*) are usually used in event discrimination of explosions from earthquakes (Walter *et al.*, 1995; Xie, 2002; Richards and Kim, 2007; Zhao *et al.*, 2008, 2014). For example, Richards and Kim (2007) showed that the *Pg*/*Lg* spectral ratios of the North Korea's 2006 nuclear test are very different from earthquakes. We analyze the *Pg*/*Lg* spectral ratio of the vertical seismograms recorded by the borehole short-period station SMT (0.5–50 Hz), which is the station that possesses the highest signal-to-noise ratio (SNR) above 1 Hz (Fig. 4d and Ⓔ Fig. S2). Three nearby earthquake waveforms are also collected and analyzed for spectral comparison (Fig. 1a and Ⓔ Table S1). A 7 s time window (2 s before and 5 s after the predicted *Pg*-wave arrival) is used as the *Pg* window, and we use group velocities of 3.50–2.60 km/s to pick the *Lg* waves (Chun *et al.*, 2009) (Fig. 4). A 20% cosine taper is used for both *Pg* and *Lg* phases. We calculate displacement Fourier spectra of these six events after removing instrument responses (Ⓔ Fig. S3). Only the spectral estimates with SNR > 2 are used in smoothed spectral ratios, following the approach of Zhao *et al.* (2008). The spectral SNR is defined as the ratio of power spectral density of *Pg* or *Lg* with respect to that of pre-*P* noise (Xie, 2002). Here, we have ignored distance corrections because distance differences from these events are small and attenuation in the region is low (Kim and Richards, 2007; Richards and Kim, 2007; Zhao *et al.*, 2013). The smoothed spectral ratios for these six events clearly separate the 2009 and 2013 explosions from the earthquakes at frequencies above 2 Hz and the 2010 event above 5 Hz (Fig. 5). The separation of the 2010 event spectrum at a higher frequency is consistent with the conclusion that the frequency range of the spectral ratio of explosion separation from the earthquake shifts higher for smaller explosions (Xie, 2002; Fisk, 2006). In addition, the *Pg*/*Lg* spectral ratio would also be affected by cavity coupling and burial depth (Murphy *et al.*, 1997; Fisk, 2006).

YIELD ESTIMATION OF THE 12 MAY 2010 NUCLEAR TEST

We follow the procedure in Zhang and Wen (2013) to estimate the yield of the 2010 test. We first calculate the *Lg*-wave

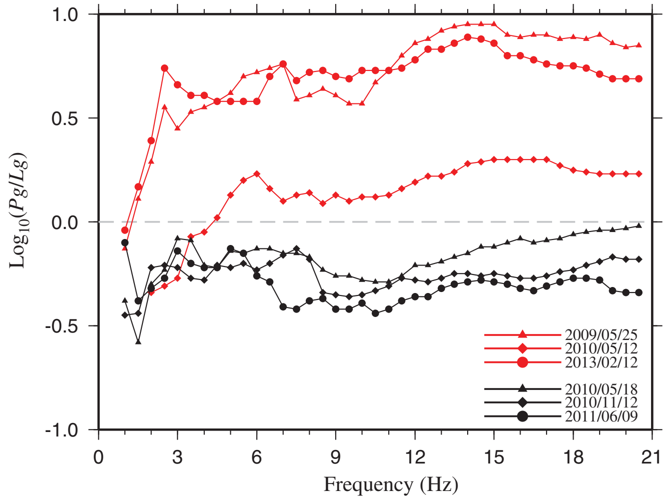


▲ **Figure 4.** (a)–(c) Displacement seismograms (1–20 Hz) of the template (a) 2009 and (b) 2013 tests and (c) the detected 2010 test recorded at the nearest seven stations within 200 km of the test site shown in Figure 1a. Station names are labeled on the left side of each trace. (d) Comparisons of displacement seismograms are shown in different frequency bands (labeled on the left) for the 2009, 2013, and 2010 tests recorded at borehole station SMT. The predicted template *Pg*-phase arrival times are marked with red lines, and the predicted *Lg*-wave time windows are marked by two blue lines corresponding to the group velocities of 3.50 and 2.60 km/s, respectively.

magnitude using the amplitude ratios of the *Lg* waves observed between the 2009 and 2010 tests; we then estimate the yield of the 2010 test based on a modified empirical *Lg*-magnitude–yield–depth relationship using the calculated *Lg* magnitude and the burial depth inferred from satellite imagery. The *Lg* magnitude of the 2009 test was estimated after correcting the path and station effects (Zhao *et al.*, 2012). Because the separation of the 2009 and 2010 nuclear tests is just 873 m, the path effect and station corrections are the same for the same station between the two tests. The *Lg* waves recorded at the borehole station SMT are chosen to estimate the *Lg* magnitude and yield, because of their high SNR in each frequency band (Ⓔ Fig. S2).

We first deconvolve the instrument response from the observed vertical component of station SMT and then convolve the seismograms with the World-Wide Standardized Seismograph Network instrument response. Three different methods are used to measure their relative amplitude ratios: integrated envelope, third-peak amplitude, and the root mean square amplitude (Zhang and Wen, 2013). Based on the *Lg*-wave amplitude ratio (Ⓔ Table S2), the *Lg* magnitude of North Korea's 2010 nuclear test is inferred to be $m_b(Lg) = 1.44 \pm 0.13$, including the uncertainty of ± 0.12 inherited from Zhao *et al.* (2012) and an uncertainty of ± 0.04 from the variation of estimation of relative *Lg*-amplitude ratio between the two tests.

A modified empirical *Lg*-magnitude–yield–depth relationship $m_b = 1.0125 \log(Y) - 0.7875 \log(h) + 5.887$ had been adopted by Zhang and Wen (2013), in which m_b is *Lg* magnitude, h is burial depth, and Y is yield, which included



▲ **Figure 5.** *Pg/Lg* spectral ratios of three nuclear tests (red symbols) and three nearby earthquakes (black symbols) (shown as blue stars in Fig. 1a, Ⓔ Table S1 in the electronic supplement) for the seismic data recorded at borehole station SMT.

the traditional magnitude–yield relationship in NKTS (Bowers *et al.*, 2001; Zhao *et al.*, 2008, 2012, 2014; Schaff *et al.*, 2012) and the depth correction proposed by Patton and Taylor (2011). The burial depth is estimated from the difference of the surface elevation between the associated tunnel entrance and the identified test location. Based on the location of the 2010 nuclear test, we regard "the west portal" identified by Pabian and Hecker (2012) as the most likely tunnel entrance to the test. The surface elevations of the west portal and the identified test location of the 2010 event are 1400 and 1630 m, respectively (Ⓔ Fig. S6). We thus inferred the burial depth of the 2010 nuclear test to be 230 m, that is, the elevation difference between the tunnel entrance and the test site. By applying the above modified empirical *Lg*-magnitude–yield–depth relationship, the yield of the 2010 test is estimated to be 2.9 ± 0.8 t, based on a burial depth of 230 m.

DISCUSSION

De Geer (2012) suggested there might be another low-yield nuclear test in mid-April 2010, carried out in the same chamber of the mid-May event. We did not detect any potential event in the seismic data in mid-April (Fig. 1b). Although we could not exclude the possibility that the magnitude of the postulated event was too small to be detected, it is also possible that the event did not occur. The existence of a mid-April event was proposed to explain the disagreements of the xenon ratio between the data and De Geer's model. In later studies, the xenon signatures are also explained by an underground nuclear explosion in mid-May 2010 without postulating an early event (De Geer, 2013; Wright, 2013).

The origin time we have determined is within the time window based on the analysis of radionuclide isotope ratios (Ihantola *et al.*, 2013). However, the yield of the 2010 test estimate based on the seismic data (2.9 ± 0.8 t) is much smaller than the 50–200 t suggested by De Geer (2012) or a few hundred tons inferred based on radionuclide activity calculations (Wright, 2013). If the inferred yield based on radioisotopes holds true, the large difference in yield estimates may suggest that the 2010 test is at least partially decoupled, consistent with the indication from the noble gases as suggested by De Geer (2013). Our study demonstrates the scientific capability of monitoring low-yield nuclear tests by combining seismic and radionuclide isotope data.

CONCLUSION

We detect and locate a low-yield nuclear test conducted on 12 May 2010 by North Korea. We apply the M&L method and search for potential events in the continuous seismic data recorded in seven stations within 200 km of North Korea's test site from 1 April 2010 to 31 May 2010, using North Korea's 2009 and 2013 tests as templates. A detectable event occurred at 00:08:45.067 UTC on 12 May 2010, located at 41.2863° N 129.0790° E with a geographic precision of 350 m. The detected 2010 event is about 227 m west and 844 m south of the location of North Korea's 2009 nuclear test; about 227 m east and 499 m south of the location of its 2013 nuclear test. *Pg/Lg* spectral ratios of the event further indicate it is explosive in nature. We estimate the yield of the event to be 2.9 ± 0.8 t, based on the *Lg*-wave amplitude ratio between the 2009 and 2010 tests and the burial depth inferred from satellite imagery. Our study provides seismological evidence for a low-yield nuclear test in North Korea on 12 May 2010, supporting the radionuclide isotope observations, and demonstrates the scientific capability of monitoring low-yield nuclear tests by combining seismic and radionuclide isotope data.

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