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High-precision location and yield of North Korea's 2013 nuclear test

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[1] Using North Korea's 2009 nuclear test as reference and satellite imagery, we show that the location and yield of North Korea's 2013 nuclear test can be quickly and accurately determined based on seismic data. North Korea's 2013 nuclear test site is pinpointed by deriving relative location of North Korea's 2009 and 2013 nuclear tests and using the previously determined location of the 2009 nuclear test, while its yield is estimated based on the relative amplitude ratios of the Lg waves recorded for both events, the previously determined Lg-magnitude of 2009 nuclear test and burial depth inferred from satellite imagery. North Korea's 2013 test site is determined to be located at (41°17′26.88″N, 129°4′34.68″E), about 345 m south and 453 m west of its 2009 nuclear test site, with a geographic precision of 94 m. Its yield is estimated to be 12.2 ± 3.8 kt.

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1. Introduction

[2] On 12 February 2013, the Democratic People's Republic of Korea (North Korea) announced, without providing information of exact time, location, and yield, that it conducted a third nuclear test. On that day, the United States Geological Survey (USGS) reported detecting a magnitude 5.1 event in an aseismic region in North Korea (http://earthquake.usgs.gov/earthquakes/eventpage/usc000f5t0#summary).

[3] In the event of a nuclear test, source discrimination, location determination, and yield estimate of the test are the immediate issues facing the scientific monitoring community. Rapid and accurate determination of these parameters is, however, still hindered by many factors. In location determination, the traditional ways to locate an event still suffer large uncertainties due to our imperfect knowledge of seismic heterogeneities in the Earth's interior and lack of efficient methods to simulate high-frequency wave propagation in three-dimensional heterogeneous media at large distances. For example, the horizontal uncertainties of North Korea's 2013 nuclear test location reported by USGS and the Comprehensive Nuclear-Test-Ban Treaty Organization are ±11.2 km and ±16.2 km, respectively. In yield estimate, our lack of knowledge of burial depth, inaccurate consideration of path and station effects of wave propagation, and uncertain relationship between the seismic amplitude and yield could result in a large range of yield estimation. For example, the yield of North Korea's 2013 test is estimated at 19.8 kt, with minimum and maximal yields of 14.8 and 39.5 kt by some research groups (http://www.iris.edu/dms/nodes/dmc/specialevents/2013/02/12/north-korea-nuclear-explosion/); while the Federal Institute for Geosciences and Natural Resources, a state-run geology research institute in Germany, places the estimate to be 40 kt (http://www.bgr.bund.de/DE/Gemeinsames/Oeffentlichkeitsarbeit/Pressemitteilungen/BGR/bgr-130212_Kernwaffentest-Nordkorea.html).

[4] In this study, we show that, by combining modern methods of high-precision relocation and satellite imagery, and using the knowledge of a previous test (North Korea's 2009 test) as reference, it is possible to rapidly and accurately determine the location and yield of North Korea's 2013 test. In section 2, we review the previously determined location, magnitude, and yield of North Korea's 2009 test; in section 3, we present detailed analyses of relative location and magnitude difference between North Korea's 2009 and 2013 tests, and determine the location and yield of North Korea's 2013 nuclear test.

2. Review of the Previously Determined Location and Yield of North Korea's 2009 Nuclear Test

2.1. Location of North Korea's 2009 Nuclear Test

[5] North Korea's 2009 test was located by *Wen and Long* [2010] to be at (41°17′38.14″N, 129°4′54.21″E) (Table 1), with a geographic precision of 140 m. The location was derived based on the relative location between North Korea's 2006 and 2009 tests and satellite image identification of the 2006 test site [*Wen and Long*, 2010] (http://cryptome.org/eyeball/dprk-test/dprktest.htm). The relative location was obtained by minimizing arrival time differences of seismic Pn wave, the first arriving compressional wave that diffracts along the Earth's crust-mantle boundary, between North Korea's 2006 and 2009 tests, using seismic data recorded at seismic stations in the Global Seismographic Network and F-net in Japan. North Korea's 2009 nuclear test was located about 723 m north and 2235 m west of 2006 test (Figure 3). Similar results were also obtained by others using different methods [e.g., *Murphy et al.*, 2010; *Selby*, 2010].

2.2. Yield Estimation of North Korea's 2009 Nuclear Test

[6] Much effort has been devoted to estimate the yield of North Korea's 2009 test. *Murphy et al.* [2010] estimated the yield of the 2009 test to be 4.6 kt, if detonated at a depth of 550 m. However, they pointed out that there was a significant trade-off between the assumed burial depth of the test

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Table 1. Location, Time, Lg-Magnitude, and Yield of North Korea's Nuclear Tests

Test	Date (year/mm/dd)	Latitude (°N)	Longitude (°E)	Origin Time (hh:mm:ss)	Lg-Magnitude	Yield (kt)
2006	2006/10/09	41.2874[a]	129.1083[a]	01:35:28.000[b]	3.93[d]	0.48[d]
2009	2009/05/25	41.2939[c]	129.0817[c]	00:54:43.180[c]	4.53 ± 0.12[e]	7.0 ± 1.9[f]
2013	2013/02/12	41.2908[f]	129.0763[f]	02:57:51.331[f]	4.89 ± 0.14[f]	12.2 ± 3.8[f]

[a]Satellite images.
[b]United States Geological Survey.
[c]*Wen and Long* [2010].
[d]*Zhao et al.* [2008].
[e]*Zhao et al.* [2012].
[f]This study.

and yield estimation. The observed seismic data could not distinguish between an explosion with a 2.7 kt yield at a depth of 200 m and a 4.8 kt yield at a depth of 800 m. *Rougier et al*. [2011] combined the results from the hydrodynamic simulation and near-field observations and obtained the minimum yield and depth of burial for the 2009 test as 5.7 kt and 375 m. *Chun et al*. [2011] obtained m_b(Lg) of the 2009 test to be 4.86 ± 0.13 and yield to be 6.51 kt under the minimum burial depth assumption based on a magnitude-yield relationship used by *Bowers et al*. [2001]. *Zhao et al*. [2012] investigated the yield of North Korea's 2009 test using a regional network in northeast China and South Korea. They first estimated the Lg-magnitude of the event based on the Lg-wave amplitudes observed in the seismic data. They then employed a modified fully coupled magnitude-yield relationship [*Bowers et al*., 2001] to estimate the yield of the 2009 test. In their study, the Lg-wave amplitudes were corrected for the path effects using a crust attenuation Q model [*Xie et al*., 2006], and the Lg-magnitude was further calibrated for the station effects using a historical event dataset related to the seismic network. They estimated Lg-wave magnitude of the 2009 test to be $m_b(Lg) = 4.53 \pm 0.12$ and the yield approximately 2.35 kt under the minimum burial depth assumption.

3. Determining the Location and Yield of North Korea's 2013 Nuclear Test Using its 2009 Test as Reference and Satellite Imagery

3.1. Location of North Korea's 2013 Nuclear Test

[7] We first use the observed arrival time difference of Pn phase between the two tests to infer the relative location and origin time of North Korea's 2009 and 2013 nuclear tests. Such approach allows high-precision determination of relative location and origin time between the two tests. We then determine the location of the 2013 test, based on the inferred relative location of the two tests and the location of the 2009 test identified by *Wen and Long* [2010] (Table 1).

[8] We use a method developed by *Wen* [2006] to determine the relative location and origin time of the two tests. The method uses the arrival time difference of a particular seismic phase between a waveform doublet, defined as a pair of seismic events occurring at different times but in close location and exhibiting similar waveforms, to determine the relative location and origin time of the doublet. It is similar to the modern methods using the information between earthquake doublets [e.g., *Poupinet et al*., 1984] chemical explosions [*Phillips et al*., 2001] and nuclear tests [e.g., *Waldhauser et al*., 2004]. Because the doublets occur very close in location, the relative travel time and waveform difference between the waveform doublets are sensitive primarily to the relative change of event location. Waveform doublets also allow accurate travel time measurements to be made by the waveform cross-correlation technique because of similarities of the waveforms. It is thus a powerful tool for high-precision studies of relative location and time of the doublets. In the present case, North Korea's 2013 and 2009 tests essentially constitute a nuclear doublet, and the available observational pairs between the two tests recorded in Chinese National Seismic Network in China and the F-net stations in Japan provide good azimuthal coverage for high-precision determination of the relative location of the two tests (Figure 1).

[9] The travel time differences of the Pn phases between the two tests are obtained by cross-correlating the observed waveforms between the two tests (Figure 2a and Table 2). The data time series of the two tests are time interpolated to an evenly spaced time series with a time sampling rate of 0.0025 s before the cross-correlations are performed.

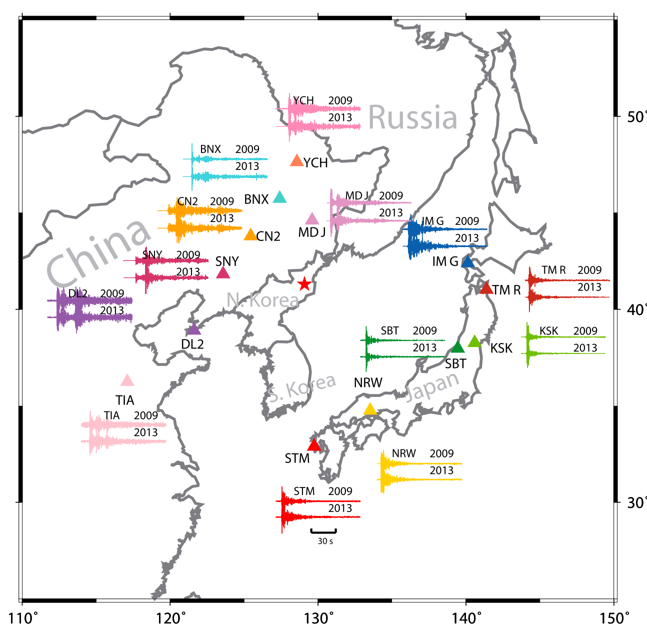

Figure 1. Map showing North Korea's 2009 and 2013 nuclear test sites (red star), seismic stations (triangles) that recorded high-quality waveforms for both tests, and observed vertical components of seismic waveforms. Seismic waveforms are self-normalized and labeled with station names and the year of the test. Seismic data are bandpass-filtered in a frequency range of 4–9 Hz.

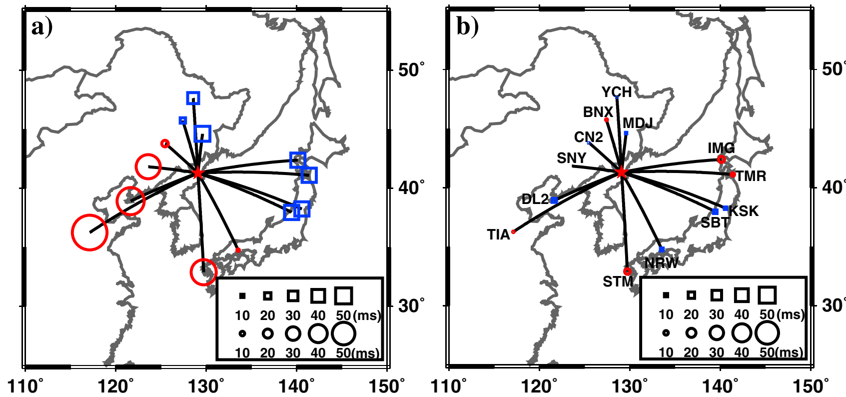

Figure 2. (a) Measured difference in absolute arrival time (circles and squares) of the Pn phases between the North Korea's nuclear tests in 2009 and 2013, plotted centered at the location of each station, along with the great circle paths (black traces) from the nuclear sites (star) to the stations (labeled with station names in Figure 2b). For plotting purpose, the arrival time differences are plotted with respect to a difference of the test times that generates a zero mean of the travel time differences for all the stations. The circles indicate that the Pn phases in the 2013 test arrive relatively earlier than their counterparts in the 2009 test, while the squares show the opposite (scale shown in the inset in the unit of ms). (b) Travel time residuals between 2009 and 2013 nuclear tests, after corrections using the best-fitting relative location (Figure 3a) and origin time (Table 1) for the 2013 test. The differential travel times in Figures 2a and 2b are also listed in Table 2, with Δt^0 in the table for those in Figure 2a and Δt^1 for those in Figure 2b.

The seismograms in each pair are aligned according to the cross-correlation travel time shifts and are further eye-checked for possible cycle skipping. We search for the best-fitting relative location and origin time for the 2013 test that minimize the travel time residuals of the Pn observations between the two events. The search region for the relative location of the 2013 test is a 10 km (N-S direction) × 10 km (E-W direction) centered at the identified location of the 2009 test. The search grid intervals are 0.1 m in N-S and E-W directions. The relocation procedure places the best-fitting location of the 2013 test to be 345 m south and 453 m west of the 2009 test (Figure 3a). The best-fitting origin time for the 2013 test is 12 February 2013, 02:57:51.331 UTC. The best-fitting location and origin time of the 2013 test significantly reduce the root-mean-square (RMS) travel time residual to 8 ms (Figure 3a), and the travel time residuals at each individual station to a maximum of 13 ms (station IMG), between the two tests (Figure 2b and Table 2). The precision of the relative location between the two tests is determined to be 94 m based on the 95% confidence ellipse of the relocation travel time residuals (Figure 3a). The inferred location of the 2013 test is at (41°17′26.88″N, 129°4′34.68″E) (Table 1) and is shown on Google Earth (image on 23 January 2013), along with the locations of two previous nuclear tests (Figure 3b).

[10] Our relocation results are affected little by the uncertainties of the reference Earth's velocity models that we used. Using the Preliminary Earth Reference Model [*Dziewonski and Anderson*, 1981] or AK135 [*Kennett et al.*, 1995] as the Earth's reference model essentially yields the same results. The Pn differential travel times are affected by the compressional wave velocities assumed in the top of the Earth's mantle, which has been reported to vary from 7.7 to 8.3 km/s. Such two end-member velocities would introduce an uncertainty of 88 m in the relocation result. The uncertainty is within the range of the travel time residuals in each individual station after the relocation (Table 2). We attribute those differential travel time residuals partially to the uncertainty of compressional velocities in the top of the mantle.

[11] With the actual locations of the tests identified (Figure 3), we estimate their burial depths based on elevation data as derived from Google Earth, using the difference of the surface elevations between the associated tunnel entrances and the identified test locations. The surface elevations of the inferred 2009 and 2013 test locations are 2010 m and 1830 m, respectively. Although three tunnel entrances have been previously identified in the immediate vicinity as being capable of supporting underground nuclear testing, only one tunnel entrance, "the west portal" as identified and suggested by *Pabian and Hecker* [2012], could be associated with (and most likely used to support) both of these tests. The elevation of that identified tunnel entrance is 1400 m. The burial depths of the 2009 and 2013 tests are thus determined to be about 610 m and 430 m, respectively, based on the elevation differences between the test locations and the tunnel entrance.

Table 2. Pn Differential Travel Times at Each Seismic Station[a]

Station Name	Latitude (°N)	Longitude (°E)	Δt^0 (ms)	Δt^1 (ms)
YCH	47.6345	128.5650	34	1
BNX	45.7390	127.4030	16	−5
CN2	43.8000	125.4500	−14	2
MDJ	44.6200	129.5900	47	4
SNY	41.8278	123.5780	−54	0
DL2	38.9062	121.6280	−60	12
TIA	36.2500	117.1000	−76	−3
TMR	41.1016	141.3830	44	−8
KSK	38.2585	140.5830	44	7
IMG	42.3928	140.1410	44	−13
SBT	37.9683	139.4500	44	11
NRW	34.7682	133.5330	−6	9
STM	32.8870	129.7240	−56	−12

[a]"Δt^0" measured differential travel time with a zero mean; "Δt^1"differential travel time after corrected for the best-fitting location of 2013 test.

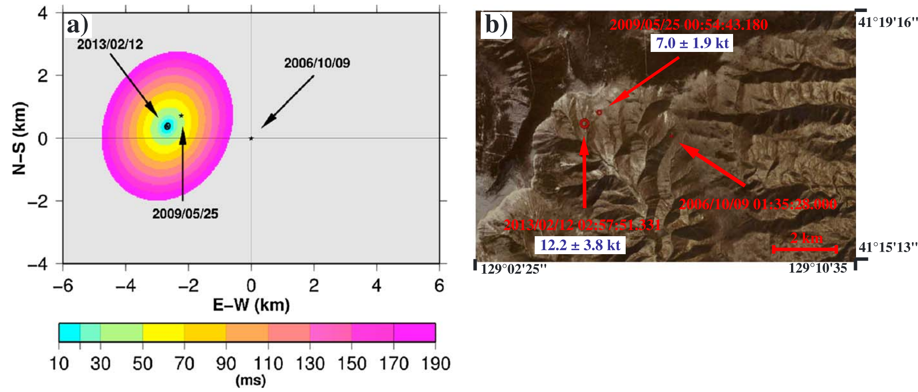

Figure 3. (a) Best-fitting location of the 2013 test (star labeled as 2013/02/12) relative to the location of 2009 test (star labeled as 2010/05/25) that minimizes the RMS travel time residual of the Pn phases observed in the stations in Figure 1 between the two tests, plotted centered at location of 2006 test (star labeled as 2006/10/09), along with the RMS travel time residuals (only those less than 190 ms are plotted) as a function of relative location of 2013 test. The black ellipse represents the 95% confidence ellipse for the 2013 test location based on the chi-square distribution. (b) Locations (circles, with the sizes of 2009 and 2013 symbols proportional to their yields (labeled blue)) and origin times (labeled red) of the 2006, 2009, and 2013 tests plotted on a Google Earth map (image on 23 January 2013) (corresponding area in Figure 3a) centered at the 2006 test site identified by the satellite images. The event parameters for North Korea's three nuclear tests and their sources are shown in Table 1.

3.2. Yield of North Korea's 2013 Nuclear Test

[12] The yield of a nuclear test can be estimated using different portions of seismic signals [e.g., *Murphy*, 1977; *Nuttli*, 1986]. In the present case, we use regional Lg-wave amplitude to estimate the yield of the 2013 test for the following reasons: (1) Lg waves exhibit large and stable amplitudes in the regional distances for the seismic data recorded in China, while the teleseismic body wave amplitudes could be affected by strong scattering from the surface topography near the test sites, (2) the path and station effects have been carefully corrected in their estimation of Lg-magnitude of the 2009 test [*Zhao et al.*, 2012], and (3) the Lg-magnitude-yield relationship was also calibrated with several known chemical explosions in the region [*Zhao et al.*, 2012]. There is a difference in Lg-magnitude estimates between the studies of *Chun et al*. [2011] and *Zhao et al*. [2012], because different Lg Q models and seismic stations were used between the two studies. We use *Zhao et al*. [2012] study as reference, because the path and station effects have been carefully corrected in their estimation of Lg-magnitude of the 2009 test; and, more importantly, the Lg-magnitude-yield relationship was calibrated and verified with several known chemical explosions using the Lg-magnitudes estimated based on their Q models and station corrections. We estimate the yield of the 2013 test in two steps: we first estimate the Lg-wave magnitude of the 2013 test using the amplitude ratios of the Lg waves observed between the 2009 and 2013 tests and the Lg-magnitude estimation of North Korea's 2009 nuclear test by *Zhao et al*. [2012]; we then calculate the yield of the 2013 test based on a modified empirical Lg-magnitude-yield-depth relationship using the estimated Lg-magnitude and inferred burial depth of the test.

[13] Because the separation of the 2009 and 2013 tests is just about 570 m (Figure 3), the path effects and station corrections are the same for a same station between the two tests. The Lg-magnitude difference of the two tests is thus scaled with their Lg-wave amplitude ratio, i.e.,

$$m_{b,2013} = m_{b,2009} + \log(R) \tag{1}$$

where $m_{b,2009}$ and $m_{b,2013}$ are the Lg-magnitudes of North Korea's 2009 and 2013 tests, respectively, and R is the estimated Lg-wave amplitude ratio between the 2013 and 2009 nuclear tests. $m_{b,2009} = 4.53 \pm 0.12$ [*Zhao et al*., 2012].

[14] We follow the same data processing procedures in *Zhao et al*. [2012] and estimate the Lg-amplitude ratios between the two tests at eight (MDJ, CN2, SNY, BNX, DL2, HEH, BJT, and HIA) of the nine stations used in *Zhao et al*. [2012] (Figure 4). We first deconvolve the instrument response from the observed broadband vertical component seismograms and then convolve the seismograms with the World-Wide Standardized Seismograph Network instrument response. We then pick Lg waves in a group velocity window between 3.6 and 3.0 km/s and measure their amplitudes through three different methods: integrated envelope [*Salzberg and Marshall*, 2007; *Zhao et al*., 2012], third-peak amplitude [*Nuttli*, 1973, 1986], and the root mean square (rms) amplitude [*Ringdal et al*., 1992; *Zhao et al*., 2012]. The rms amplitude is also corrected for the pre-P noise. Average Lg-wave amplitude ratios between the 2013 and 2009 tests estimated using these three methods are 2.29 ± 0.38, 2.34 ± 0.39, and 2.36 ± 0.41, respectively (Table 3). We take the average of the measurements by these three methods, $R = 2.33 \pm 0.39$, as our estimate of Lg-amplitude ratios between the two tests. Lg-magnitude of North Korea's 2013 nuclear test is inferred to be m_b (Lg) = 4.89 ± 0.14 based on equation (1), including the uncertainty of ± 0.12 inherited from *Zhao et al*. [2012] and an uncertainty of ± 0.07 from the variation of estimation of relative Lg-amplitude ratios between the two tests.

[15] Empirical hard rock magnitude-yield relationships for fully coupled nuclear explosions were reported by many studies [e.g., *Ringdal et al*., 1992; *Bowers et al*., 2001]. *Zhao et al*. [2008, 2012] examined various empirical relationships and concluded that the empirical relationship provided by *Bowers et al*. [2001] fit the North Korea's test site best:

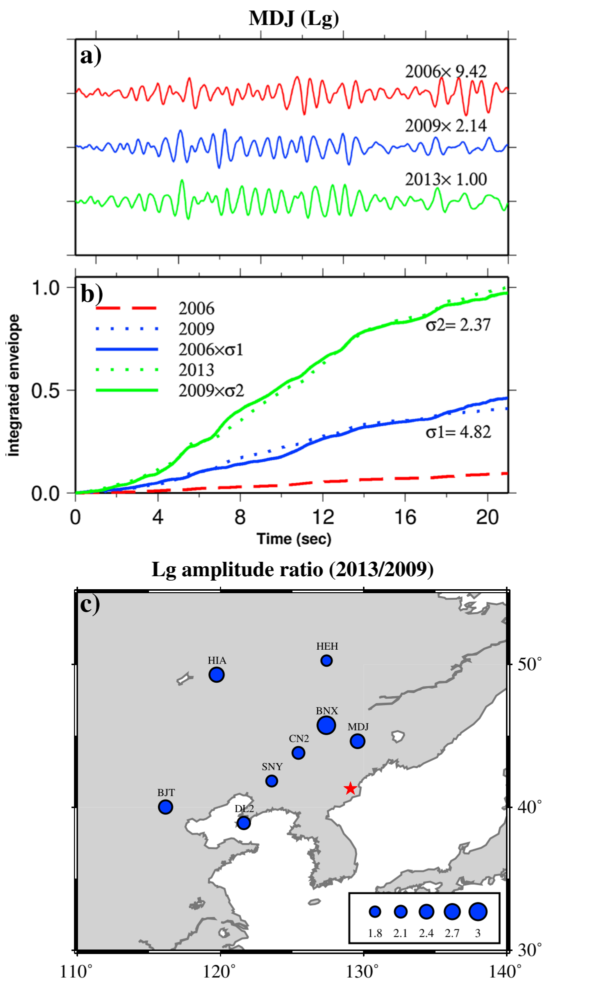

Figure 4. (a) Seismic Lg-waveforms recorded at station MDJ for three nuclear tests as an example, each trace is normalized to the recording of the 2013 test with the normalization constants labeled at the upper right of each trace. (b) Integrated amplitude envelopes of Lg waves of North Korea's three nuclear tests in 2006, 2009, and 2013. The curves from the 2006 and 2009 tests have been multiplied by a factor of σ1 (4.82) and σ2 (2.37) to match those from 2009 and 2013 tests, respectively. (c) Map showing North Korea's nuclear test site (red star), stations (solid circles) used to calculate amplitude ratios of Lg waves between the 2013 and 2009 nuclear tests, and Lg-amplitude ratios (solid circles, with their radii proportional to the measured amplitude ratios).

$$m_b = 4.25 + 0.75 \log Y \tag{2}$$

for a standard minimum burial depth 120 m and a 1 kt explosion.

[16] For a nuclear test with an actual burial depth h and a yield Y, *Patton and Taylor* [2011] proposed a correction term to equation (2) using the scaling relationship proposed by *Denny and Johnson* [1991]:

$$-0.7875 \log\left(\frac{h}{120Y^{1/3}}\right)$$

[17] This depth correction term was derived based on body wave magnitude. In the seismic data along the paths we study, *Zhao et al*. [2012] showed that the magnitudes derived from the Lg waves are linear with those derived based on the body waves. We thus adopt this depth correction term for the relationship between the Lg-magnitude and yield for North Korea's nuclear tests. With the depth correction, the magnitude-yield relationship becomes

$$m_b = 1.0125 \log(Y) - 0.7875 \log(h) + 5.887 \tag{3}$$

[18] According to equation (3) and the inferred depth of the 2013 test (430 m), we estimate the yield of the 2013 test to be 12.2 ± 3.8 kt from m_b(Lg) = 4.89 ± 0.14. The yield of the 2009 test is reestimated to be 7.0 ± 1.9 kt based on a burial depth 610 m.

4. Conclusions

[19] We determine the location and yield of North Korea's 2013 nuclear test using the 2009 test as reference based on seismic data and satellite imagery. The location of North Korea's 2013 nuclear test site is obtained based on inferred relative location of North Korea's 2009 and 2013 nuclear tests and the previously determined location of the 2009 nuclear test, while its yield is estimated based on the Lg-magnitude difference between the two tests, the previously determined Lg magnitude of the 2009 nuclear test and the burial depth inferred from satellite imagery as presented on Google Earth. North Korea's 2013 nuclear test is determined to be located at (41°17′26.88″N, 129°4′34.68″E), about 345 m south and 453 m west of its 2009 nuclear test site, with a geographic precision of 94 m. The yield of the test is estimated to be 12.2 ± 3.8 kt. Our analyses indicate that the location and yield of a nuclear test can be quickly and accurately determined using seismic data, information of previous tests, and satellite imagery.

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Table 3. Lg-Wave Amplitude Ratio at Each Station (2013/2009)[a]

		Amplitude Ratio		
Station	Distance (km)	Integrated Envelope	TP	rms
BJT	1100.20	2.34	2.42	2.45
HIA	1146.86	2.49	2.74	2.61
MDJ	369.74	2.37	2.19	2.35
BNX	510.38	3.07	2.67	3.16
HEH	1002.37	1.86	1.58	1.84
CN2	406.60	2.14	2.50	2.01
DL2	688.81	2.13	2.03	2.26
SNY	462.412	1.95	2.58	2.17
Average	710.92	2.29	2.34	2.36
S.D.	324.70	0.38	0.39	0.41

[a]"Average" and "S.D." are the average value and standard deviation, respectively.

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