

High-precision Location of North Korea's 2009 Nuclear Test

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INTRODUCTION

On 25 May 2009, the Democratic People's Republic of Korea (North Korea) announced that it had conducted a second nuclear test, without providing information of exact time, location, and yield. On that day, the United States Geological Survey (USGS) reported detecting a magnitude 4.7 seismic tremor in an aseismic region in North Korea (<http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/us2009hbaf.php>; also archived copy at http://geophysics.geo.sunysb.edu/wen/NK/usgs_north_korea_2009_test.webarchive). The seismic waveform features recorded at the seismic stations around the globe for the event exhibit characteristics of an explosion. However, the exact location of the test remains elusive.

Seismic monitoring of underground nuclear explosions relies on seismic observations recorded by seismometers around the globe. Because seismic observations are influenced by the seismic properties along the paths of the wave propagation from the source to the seismometers, the accuracy of determination of an event location and time depends on the degree of our knowledge of the seismic properties in the interior of the Earth. The challenge in accurately determining the location of North Korea's nuclear tests stems from the fact that, due to the lack of seismic stations and seismicity in the region, the seismic structure is not known in enough detail that its influence can be well calibrated. For example, the horizontal uncertainty of the 2009 event location reported by the USGS is about ± 3.8 km (<http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/us2009hbaf.php>).

While our knowledge of the seismic structure in the region is unlikely to improve soon, in this study we demon-

strate a strategy that uses the forensic evidence registered by North Korea's 2006 nuclear test to determine the location of the 2009 test in high precision, and we present our determination of the location of the 2009 test.

SCIENTIFIC EVIDENCE, APPROACH, AND RESULTS

Scientific Evidence Registered by the 2006 Test

The possible location of North Korea's 2006 test is identified by satellite images (<http://cryptome.org/eyeball/dprk-test/dprk-test.htm>; also an archived copy at <http://geophysics.geo.sunysb.edu/wen/NK/eyeball.webarchive>) (Table 1). High-quality recordings of the 2006 test were observed for two seismic stations of the Global Seismographic Network, MDJ and INCN, and some seismic stations in the new Chinese Seismic Network (*e.g.*, Richards and Kim 2007; Kim and Richards 2007; Zhao *et al.* 2008; Koper *et al.* 2008). Through an extensive search of the seismic data in the public domain, we discovered that the 2006 test also registered high-quality seismic records in many seismic stations in the F-net in Japan (Figure 1).

Approach

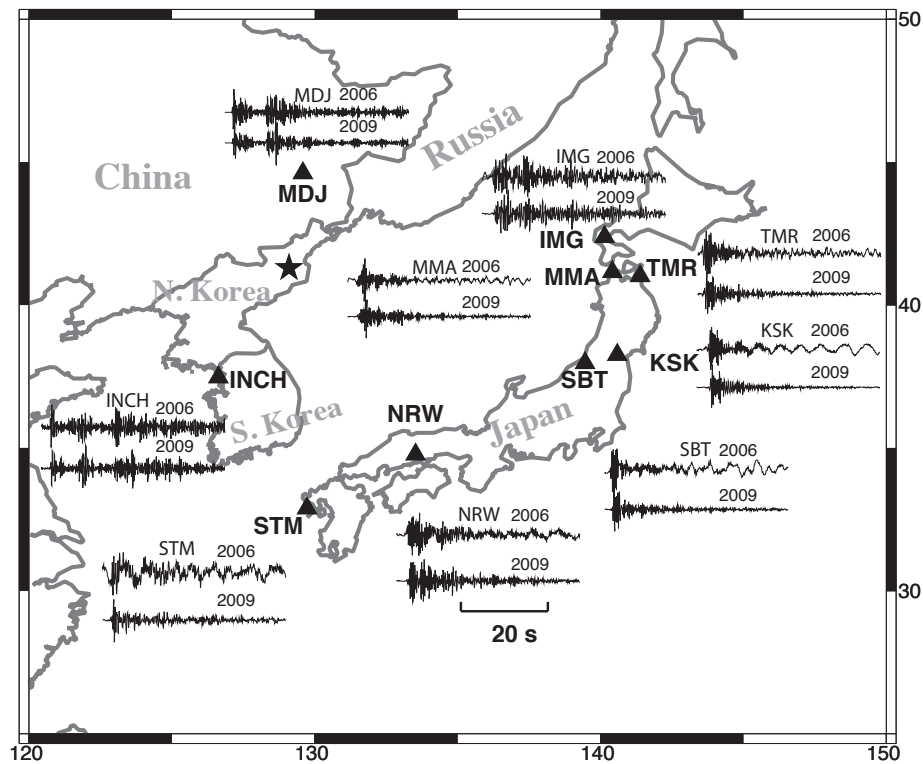
We use the observed arrival time difference of a particular seismic phase between the two tests to infer the relative location and origin time of the two tests. Such an approach allows high-precision determination of relative location and origin time between the two tests. We then determine the location and time of the 2009 test based on the inferred relative location and time of the two tests, and the location of the 2006 test identified by the satellite images and the origin time reported by the USGS (Table 1).

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 modern methods using the information between earthquake doublets (*e.g.*, Poupinet *et al.* 1984; Ito 1985; Fremont and Malone 1987; Deichmann and Garcia-Fernandez 1992; Poupinet *et al.*

TABLE 1
Location and Time of North Korea's Nuclear Tests

Test	Date (year/mm/dd)	Latitude (°N)	Longitude (°E)	Origin Time (hh:mm:ss)
2006	2006/10/09	41.2874 ¹	129.1083 ¹	01:35:28.000 ²
2009	2009/05/25	41.2939	129.0817	00:54:43.180

1. from satellite images
2. from USGS



▲ **Figure 1.** Map showing North Korea's nuclear test site (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 name and the year of the test. Seismic data are bandpass-filtered in a frequency range of 4–9 Hz.

2000; Waldhauser and Ellsworth 2000; Schaff and Richards 2004; Zhang *et al.* 2005), 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 is sensitive primarily to the relative change of event location. Waveform doublets also allow accurate travel time measurement to be made by the waveform cross-correlation technique because of the 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 two tests essentially constitute a nuclear doublet and the additional observational pairs between the two tests discovered in the F-net stations in Japan make good azimuthal coverage possible for high-precision determination of the relative location of the two tests (Figure 1).

Relocation Results

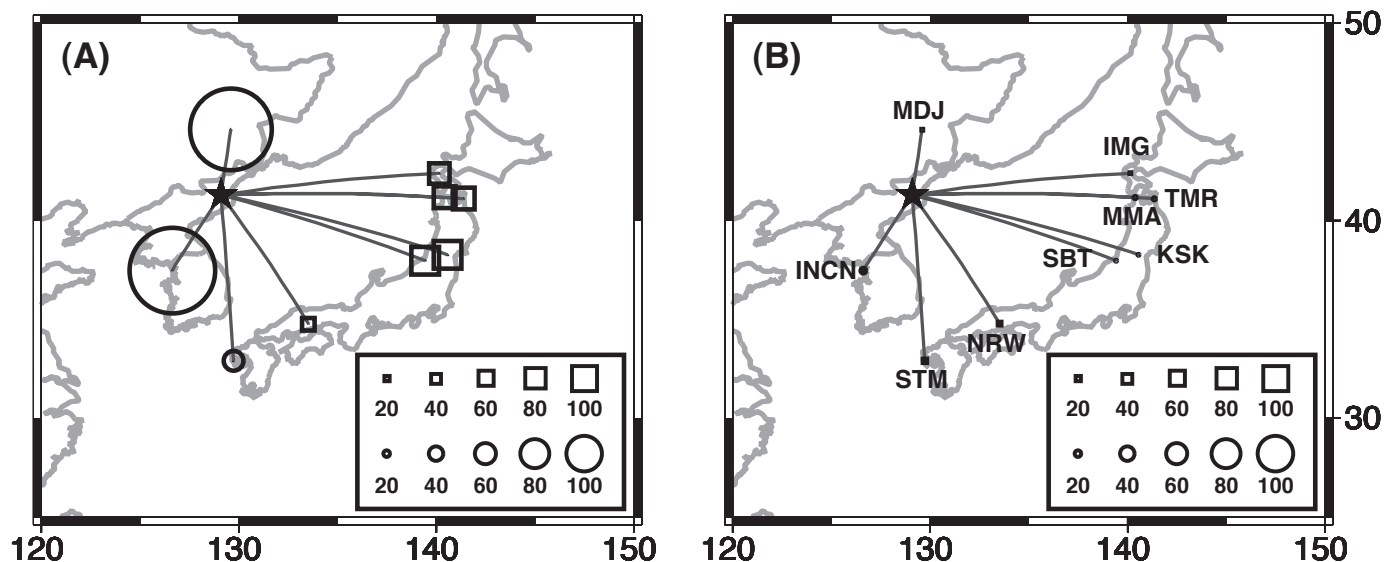
The seismic phase we used is the P_n wave, the first arriving compressional wave that diffracts along the Earth's crust-mantle boundary. The travel time differences of the P_n phases between the two tests are obtained by cross-correlating the observed waveforms between the two tests and are presented in 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.

We search for the best-fitting relative location and origin time for the 2009 test that minimize the travel time residu-

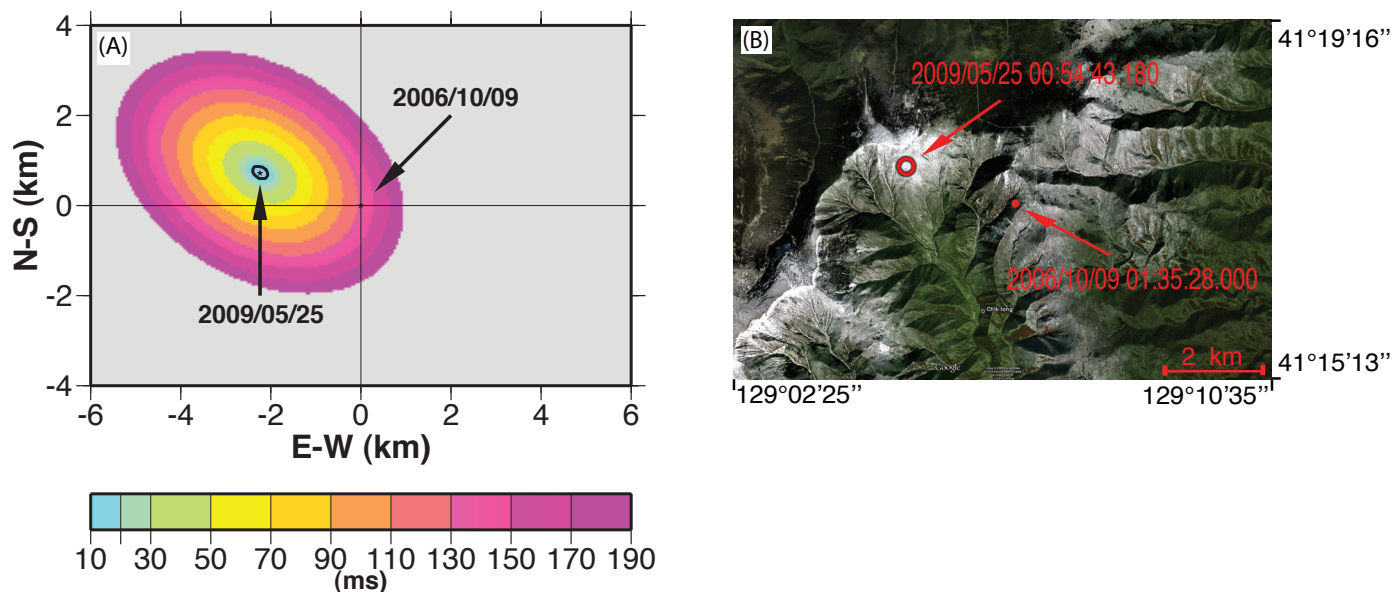
Station Name	Latitude (°N)	Longitude (°E)	Δt^0 (ms)	Δt^1 (ms)
TMR	41.1016	141.3830	86	-9
MDJ	44.6170	129.5910	-229	6
MMA	41.1619	140.4110	86	-9
KSK	38.2585	140.5830	111	-2
IMG	42.3928	140.1410	81	4
INCN	37.4776	126.6240	-240	-17
SBT	37.9683	139.4500	111	-3
NRW	34.7682	133.5330	51	13
STM	32.8870	129.7240	-54	15

Δt^0 measured differential travel time with a zero mean; Δt^1 differential travel time after correcting for the best-fitting location of the 2009 test.

als of the P_n observations between the two events. The search region for the relative location of the 2009 test is an area of 10 km (N-S direction) \times 10 km (E-W direction) centered at the identified location of the 2006 test. The search grid intervals are 1 m in the N-S and E-W directions. Such a procedure places the best-fitting location of the 2009 test at 723 m north and 2,235 m west of the 2006 test (Figure 3A). The best-fitting ori-



▲ **Figure 2.** A) Measured difference in absolute arrival time (circles and squares) of the P_n phases between North Korea's nuclear tests in 2006 and 2009, plotted centered at the location of each station, along with the great circle paths (black traces) from the nuclear sites (stars) to the stations (labeled with station names in B). For plotting purposes, 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 P_n phases in the 2009 test arrive relatively earlier than their counterparts in the 2006 test, while the squares show the opposite (scale shown in the inset in the unit of ms). B) Travel time residuals between the 2006 and 2009 nuclear tests, after corrections using the best-fitting relative location (Figure 3A) and origin time (Table 1) for the 2009 test. The differential travel times in A and B are also listed in Table 2, with Δt^0 in the table for those in A and Δt^1 for those in B.



▲ **Figure 3.** A) Best-fitting location of the 2009 test (star labeled as 2009/05/25) relative to the location of the 2006 test (star labeled as 2006/10/09) that minimizes the RMS travel time residual of the P_n phases observed in the stations in Figure 1 between the two tests, along with the RMS travel time residuals (only those less than 190 ms are plotted) as a function of relative location of the 2009 test. The black ellipse represents the 95% confidence ellipse for the 2009 test location based on the chi-square distribution. B) Locations (circles, with their sizes proportional to the relative yield determined from the relative P_n amplitudes between the two tests) and origin times of North Korea's 2006 and 2009 tests, plotted on a Google Earth map centered at the 2006 test site identified by the satellite images. The event parameters for the 2006 test and their sources are shown in Table 1; so are the determined event parameters for the 2009 test.

gin time for the 2009 test is 25 May 2009, 00:54:43.180 UTC. The best-fitting location and origin time of the 2009 test significantly reduce the root-mean-square (RMS) travel time residual to 10 milliseconds (ms) (Figure 3A) and the travel time residuals at each individual station to a maximum of 17 ms (station INCN) between the two tests (Figure 2B and Table 2). A travel time residual of 17 ms for the Pn phases corresponds to a difference of 140 m in distance. The geographic precision of the relocation is thus determined to be 140 m. The inferred location of the 2009 test is (41°17'38.14"N, 129°4'54.21"E) (Table 1) and is shown on a Google map in Figure 3B.

Our relocation results are affected little by the uncertainties of the reference Earth's velocity models 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 determination of location. 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. Our determination of the absolute origin time of the 2009 test would depend on the accuracy of the reported time for the 2006 test (Table 1).

CONCLUSION

Our study demonstrates that the forensic evidence registered by a nation's past nuclear tests can be used to accurately determine the location of its future test, with a geographic precision on the order of 140 m. Using the forensic seismic evidence registered by North Korea's 2006 nuclear test and the satellite images, we locate the 2009 test at 723 m north and 2,235 m west of the 2006 test and at 41°17'38.14"N, 129°4'54.21"E. This study also, in practice, identifies the seismic coverage needed and available for future monitoring of North Korea's nuclear tests. Since the seismic data we use are in the public domain and can be available in real time, the determination can be made in real time. In the view of modern seismology, it is not just that each new nuclear test a nation conducts would be confidently detected. High-precision location would reveal, in real time and at great accuracy, an increasingly complete view of the geographic network of a nation's nuclear test infrastructure. ☒

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