EXPLOITATION OF THE IMS AND OTHER DATA FOR A COMPREHENSIVE, ADVANCED ANALYSIS OF THE NORTH KOREAN NUCLEAR TESTS

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ABSTRACT

On May 25, 2009, the North Koreans conducted a second underground nuclear test in the same area as their initial 2006 test. Preliminary analysis indicated that the explosive yield of the second test was roughly 5 times that of the first, and it was found to have been well-recorded by a variety of globally distributed seismic networks. We carefully analyzed the available short-period seismic data in an attempt to define accurate locations, depths and yields for these two North Korean nuclear tests. In order to determine accurate relative locations for the two events, we made very precise arrival time measurements at 35 stations that recorded both explosions with good signal to noise ratios. The location of the 2006 explosion was then held fixed at the previously determined preferred location and the relative location of the 2009 explosion was estimated using the Joint Hypocenter Determination (JHD), Double Difference (DD) and Differential Waveform Interferometry (DWIF) location algorithms. All of these relative location techniques yielded very similar results, indicating that the 2009 test was conducted about 2.5 km west-northwest of the 2006 test. These relative seismic locations were subsequently integrated with the local topographic data and satellite imagery to define what we believe to be very reasonable and accurate locations for these two explosions.

The corresponding source depths can not be reliably determined using the currently available arrival time data or the observed, narrowband network-averaged teleseismic *P* wave spectral data. Consequently, we implemented a new approach using broadband *P* wave spectral ratios of the two explosions at common regional stations to obtain estimates of the corresponding broadband source spectral ratios. The resulting network-averaged source spectral ratio was then compared with theoretical Mueller/Murphy based source spectral ratios to estimate best-fitting source depths and associated yields. The results of this analysis indicated that the two explosions could not have been detonated at any common depth in the plausible 100 to 800 m depth range and, in fact, the observed spectral ratio data are best fit by source depths of about 200 m for the 2006 test and 550 m for the 2009 test. The corresponding yield estimate for the May 25, 2009, explosion was then found to be about 4.6 kt.

The long-period surface wave Ms magnitudes for both the 2006 and 2009 tests appear to be anomalously large relative to historical experience, producing unreasonably large Ms yield estimates and problematic Ms/mb identification characteristics. A formal moment tensor inversion analysis of the available data indicated that release of tectonic strain energy by the explosion may have contributed somewhat to the observed anomaly. However, current estimates of the likely strength of this tectonic release are not large enough to fully explain the observed anomaly. Additional research will be required to determine whether unresolved CLVD secondary sources may account for the discrepancy. Identification of the 2009 and 2006 events as explosions based on high-frequency Pn/Lg ratios measured at regional stations are unambiguous; however, results for discrimination based on Ms-versus-mb are inconclusive (again probably due to secondary source contamination to Ms).

OBJECTIVES

The North Korean Test of May 25, 2009, was well recorded by the International Monitoring System and other regional and teleseismic stations. However several characteristics of the event were anomalous and warranted further study, in particular with regard to the unknown depth of burial of the event. The objective of the present study was to exploit IMS and other open data sources to conduct comprehensive, advanced analyses of the characteristics of these two North Korean nuclear tests. We focused on refining event locations, estimating source depths and seismic yields and evaluating the effectiveness of the various seismic event identification criteria as applied to these two explosions. Seismic data recorded at stations of the global IMS network were augmented with seismic data from key regional stations (< 20 degrees) obtained from the Incorporated Research Institutions for Seismology (IRIS) data management center, the Ocean Hemisphere Project Data Management Center (OPHDMC) and the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED).

RESEARCH ACCOMPLISHED

Data Resources

The May 25, 2009, underground nuclear test conducted by North Korea (Democratic People's Republic of Korea, DPRK) was located in the same general area of northeastern North Korea where a previous nuclear test was conducted in 2006. The two events appear to have been conducted in the same tunnel complex mined into Mount Mantap. The area is a relatively stable craton (the North China-Korean platform) with a basement of Archean (~2000 Ma BP) and Proterozoic (~1000 Ma BP) granite and metamorphosed rocks which are overlain by up to 1 km of Cenozoic (65 Ma BP - Present) volcanic basalts which are little deformed (USGS, 1967).

Although rather small in magnitude, the 2009 test was recorded by numerous global seismic stations. Seismic locations determined by the International Data Centre (IDC), US Geological Survey (USGS/NEIC), and independently in relative location analyses by SAIC (described below) are located in proximity to a tunnel entrance previously identified from satellite imagery analyses and believed to be associated with the 2006 explosion (GlobalSecurity.org, 2006; Schlittenhadt et al., 2010).

The primary and auxiliary seismic networks of the International Monitoring System (IMS) were the principal sources of data for the analysis conducted in this study. Signals from the 2009 test were detected globally on 56 IMS stations as reported in the Reviewed Event Bulletin of the International Data Centre. We supplemented the IMS data with key regional stations (< 20 degrees) from three sources:

- Incorporated Research Institutions for Seismology (IRIS) data management center
    - Global Seismograph Network (II and IU networks) - numerous stations at regional and teleseismic distances, in particular INCN (Inchon Korea)
    - New Chinese Digital Seismic Network (IC network) - numerous stations at regional distances, in particular MDJ (Mudanjiang, China) the closest station which recorded both events
    - Kazakhstan Network (KZ) - stations at regional distance
    - Kyrgyz Seismic Telemetry Network (KNET) - stations at regional distance
- Ocean Hemisphere Project Data Management Center (OP HDMC) - including TJN (Teajon, Korea) at a distance of about 500 km
- National Research Institute for Earth Science and Disaster Prevention (NIED) - a network of over 40 stations in Japan, all within regional distance.

Emphasis was on obtaining broadband waveform data from stations that recorded signals from both the 2006 and 2009 events. This supported the detailed comparative analysis conducted in much of this report.

Location

The objective of this part of the study was to obtain a best estimate of the absolute locations and depths of both nuclear tests using seismic location methods. The lack of historical calibration data from the North Korea test site limits the accuracy of single event location methods. Even with good regional structure models, biases of several kilometers can be expected. Our approach was to first determine the relative locations between the events. We used three relative location algorithms that complement each other in terms of the data, earth structure model and objective function. In the second stage of our location analysis, we used the relative locations between the events as a constraint to aid in pinpointing the absolute location. We used high-resolution topographic data along with constraints on depth-of-burial and the relative location to derive the most likely absolute locations of the two events.

Waveform Correlation-Based Relative Location - The method builds on the basic concept that the relative location of a new event with respect to one or more reference events can be obtained from differential times of common event-station-phase pairs (Snieder,and Vrijlandt, 2005). Waveform cross-correlation is used to measure the differential times. Rather than pick the lag of the maximum of the correlation trace (which is susceptible to errors due to cycle skipping) to obtain a differential time, the Differential Waveform Interferometry (DWIF) method involves time-shifting the correlation traces for a given event location hypothesis using a slowness model of the source region, and stacking the correlation traces. A grid search is performed to determine the event origin time and hypocenter that maximizes the objective function. The individual correlation traces are weighted by the statistical significance of the correlation results, hence event-station-phase pairs that do not correlate well are implicitly down-weighted and no a priori rejection of data or outlier rejection is required. In the first phase of the processing the correlation processing is performed using phase-dependent rules (filter band, window-length) allowing the use of all common body-wave phases (regional, primary, secondary). All stations with waveform recordings and a good SNR signals for both events were used in the processing.

In the second phase of the processing, the individual correlation traces were time-shifted using a source slowness model, according to a relative location and origin time hypothesis. The peak of the stack of the correlation traces was used as the objective function. A grid search was performed for all relative locations and origin times to maximize the objective function. Figure 1 shows a slice through the objective function grid at fixed relative depth = 0. The breadth of the peak is controlled by the frequency content of the waveform data. For the best location the RMS residual in the peaks of the correlation traces was reduced from about 0.160 seconds to 0.023 seconds.

To assess the uncertainty in the solution we performed a bootstrap experiment. For each case we randomly selected half of the stations and performed the relative location using the same approach as for the full station network. The error ellipse (0.26 x 0.23 km) was defined as the ellipse that enclosed 90% of the bootstrap experiment locations.

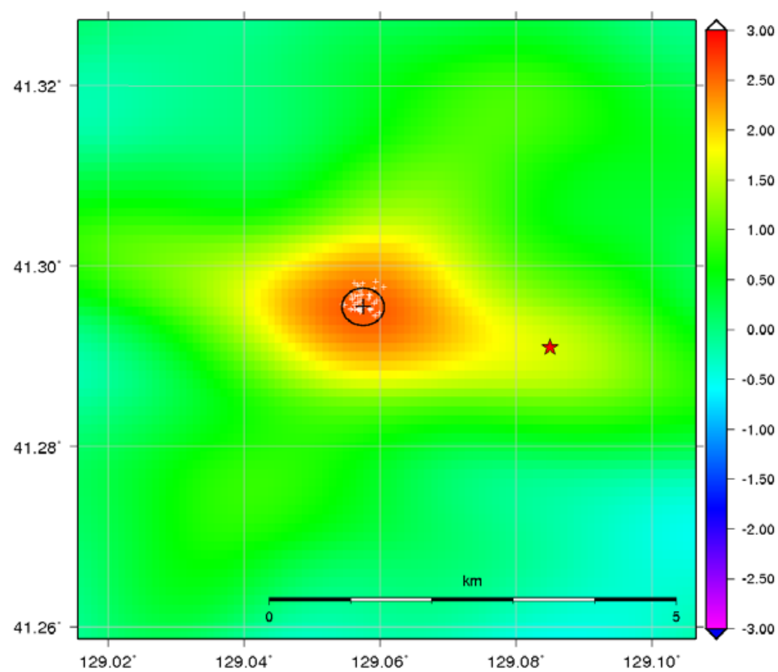

Figure 1. Color-contoured slice through the 3-D objective function grid at constant relative depth (0) at a fixed origin time. The red star marks the location of the October 9, 2006, that was used a fixed reference point in the algorithm. The black "+" marks the best location and the white "+" mark the results of a boot-strap experiment involving subsets of stations to quantify the uncertainty. The black ellipse represents a 90% confidence ellipse based on the bootstrap results.

Waveform Alignment and JHD, DD - Relative arrival times for two events recorded with adequate SNR at a given station can often be measured precisely by waveform alignment either manually or with cross correlation (Fisk, 2002). We measured such relative arrival times manually for all stations with recordings of both explosions. Figure 2 shows the initial part of the waveform sections of the 2009 event (in red) relative to those of the 2006 event (in blue) The difference in arrival times for the station-phase pairs (differential times) picked in this manner were very consistent. Figure 2 plots the residual of the differential times with respect to the average differential time. It shows that the picks for the 2009 event for stations in the north-west quadrant are systematically early relative to the 2006 arrivals, indicating that the 2009 test must have been located to the northwest of the 2006 test.

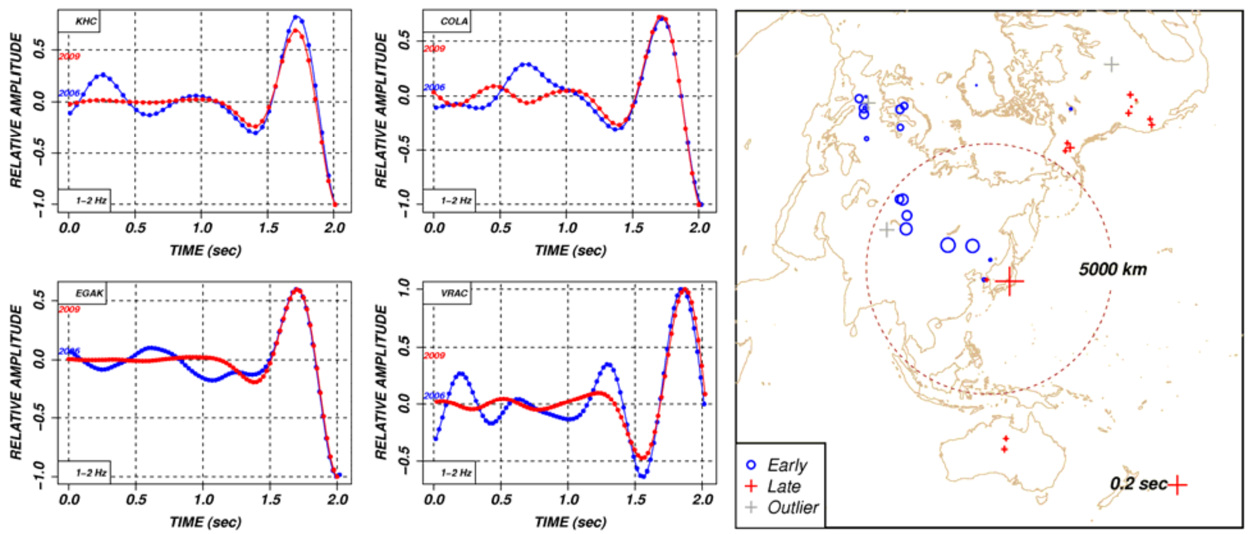

Figure 2. Waveforms for the two explosions at four stations manually aligned (left). Residuals of the differential times plotted for the IMS and IRIS stations (right). The early arrivals for the stations to the northwest support the conclusion that the 2009 event occurred to the northwest of the 2006 event.

We calculated relative epicenters of the two explosions using the algorithm (jhd89) developed by Dewey (1972). Only first arrival *P* phases were used. The epicenter of the 2006 explosions was fixed at 41.291 N and 129.085 E and at zero depth (Bennett et al, 2006) throughout the calculations. To detect and remove possible errors in the data we applied Grubbs' outlier test (Grubbs, 1950). Arrivals for the stations with an outlying residual (p-value larger than 0.05) were removed iteratively before the next JHD run with the arrivals of the remaining stations.

We also applied the double difference method using the hypoDD software (version 1.1) (Waldhauser and Ellsworth, 2000) to data at stations within about 10 degrees. Convergence of the calculations were found to be dependent on the depths of the starting solutions, but epicenters of converging solutions generally agreed with JHD solutions. The epicenter of the 2009 explosion for starting depths at zero for both explosions was 41.2983 N 129.0616 E, after the epicenter solutions of the two explosions were shifted so that the epicenter of the 2006 explosion coincided with the "ground truth" used in the JHD calculations. In all 41 stations were used in this solution after applying an outlier cut-off at 1.96 standard deviations (95%).

Table 1. Comparison of the relative location results. The double difference solution (DD) used regional stations including the NIED stations. JHDNIED used the same stations as the DD run, JHDALL used all stations and JHD used regional and teleseismic IMS and IRIS stations.

Auth	Date Time	Latitude	Longitude	Smaj	Smin	Az
fixed	2006/10/09 01:35:29.90	41.291	129.085	0.13	0.12	90
DD	2009/05/25 00:54:44.90	41.2986	129.0616	0.13	0.12	90
JHDNIED	2009/05/25 00:54:45.30	41.2945	129.0687	0.88	0.22	132
JHDALL	2009/05/25 00:54:45.30	41.2983	129.0608	0.16	0.16	1
JHD	2009/05/25 00:54:45.10	41.2968	129.0605	0.25	0.20	62
DWIF	2009/05/25 00:54:45.17	41.2955	129.0575	0.26	0.23	2

Topographic Analysis - The relative location computations yielded a relative location of the May 25, 2009, event of about 2.5 km to the west-northwest of the October 9, 2006, event. All computations were based on fixing the October 9, 2006, to the location of Bennett et al. (2006) as shown in Figure 3. The fixed location reported by Bennett et al. (2006) was estimated as being about 1 km into the mountain from the known tunnel adit in the direction of maximum relief. This placed the 2006 event directly to the north of the adit. This assumed location of the 2006 explosion results in a location for the 2009 on the other side of ridge from the adit (Figure 3). This seems unlikely and suggests that the presumed location of the 2006 may be biased.

We conducted a topographic analysis of the area using ASTER Global Digital Elevation Model. These terrain data are sampled with a posting interval of 30 m, and an accuracy of 7-14 m making them comparable to NIMA DTED level 2. The potential locations of the 2009 event were selected by identifying the areas with sufficient overburden that have positions relative to potential possible 2006 event locations as constrained by the relative location results. The result is shown in Figure 4, i.e. the blue hatched area is the only area that is consistent with all three constraints:

1. The 2006 event had 100 - 300 m of overburden relative to the adit elevation, based on a yield of 1.1 kt and a depth of burial of 200 meters from the Pn spectral ratio analysis (see below)
2. The 2009 event had 350 - 750 m of overburden relative to the adit elevation, based on a yield of 4.6 kt and a depth of burial of 550 meters from the Pn spectral ratio analysis (see below)
3. The 2009 events was about 2.5 km to the west-northwest of the 2006 event (location result)

Much of the hatched area in Figure 4 is beyond the ridge line relative to the adit. Figure 4 shows our best estimate of the locations of both events. This result gives a depth of burial of about 180 meters for the 2006 event and 600 meters for the 2009 event.

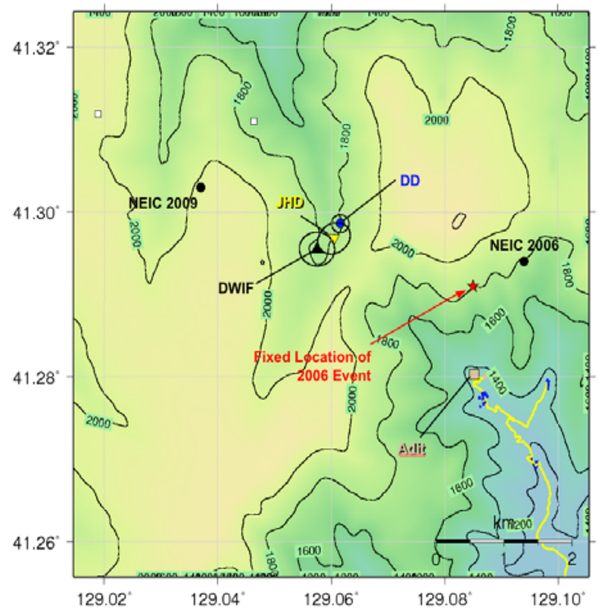

Figure 3. Locations of the May 25, 2009 event assuming a fixed location for the October 9, 2006 event based on Bennett et al. (2006). It places the 2009 event beyond the area of maximum overburden relative to the adit, indicating a probable bias in the fixed location for the 2006 event.

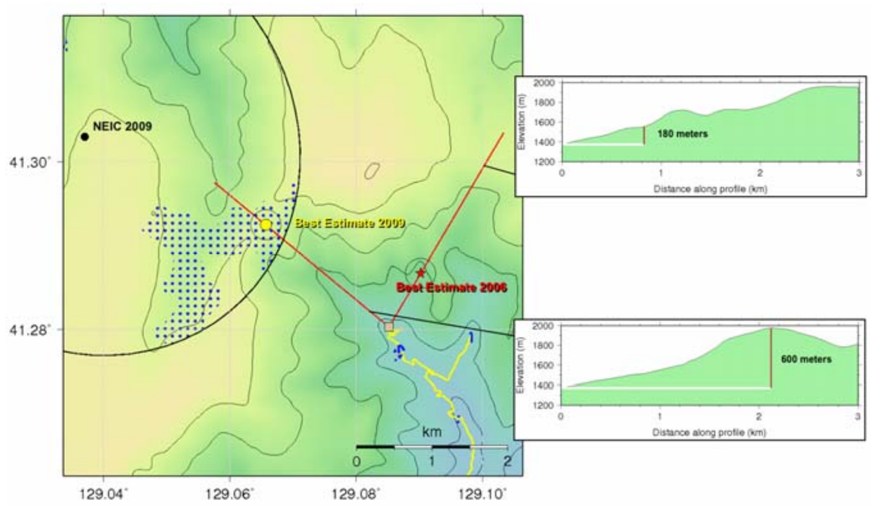

Figure 4. Best estimates for the locations resulting from the topographic analysis, assuming that the tunnel for the 2009 event did not go beyond the area of maximum relief. The best estimates put the 2006 and 2009 events at 41.2867° N, 129.0902° E and 41.2925° N, 129.0657° E respectively.

Yield Estimation from Teleseismic *P* Data

The teleseismic *P* wave data recorded from the May 25, 2009, North Korean nuclear test were analyzed using the model-based network-averaged *P* wave spectral yield estimation procedures summarized by Murphy and Barker (2001). Figure 5 shows a comparison of the observed network - averaged *P* wave spectrum for the May 25, 2009, explosion with that observed for the previous October 9, 2006 North Korean nuclear test based on data recorded at nine common teleseismic stations. The spectral amplitude levels for the 2009 test are about a factor of four larger than those observed from the 2006 test over this short-period band (0.5 - 2.5 Hz). The observed network - averaged teleseismic *P* wave spectrum for the 2009 nuclear test are compared with the corresponding best fitting theoretical predictions obtained using the Mueller/Murphy explosion seismic source model in Figure 6, assuming a source depth of 200 m in hardrock and frequency-dependent attenuation models appropriate to the Semipalatinsk Test Site (Semi) and the Nevada Test Site (NTS). Figure 6 shows that the yield estimate varies by about a factor of two (2.7 kt versus 5.3 kt) depending on the attenuation model. Further, the Semi model with an associated yield estimate of 2.7 kt provides a much better overall fit to the observed spectrum.

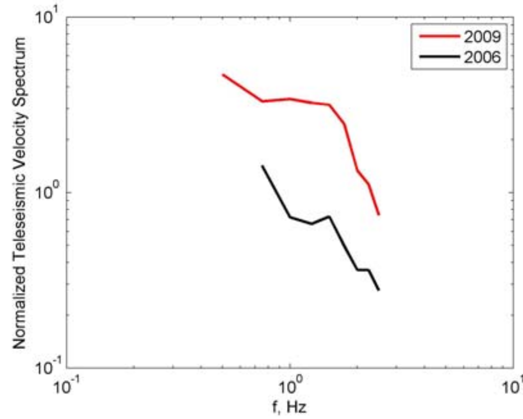

Figure 5. Comparison of the network-averaged, teleseismic *P* wave spectra determined from data recorded at a common set of stations from the North Korean nuclear tests of May 25, 2009, and October 9, 2006. It can be seen that the spectral amplitude levels for the May 25, 2009 test are about a factor of 4 larger, on average, than those for the October 9, 2006 test over the frequency band extending from 0.5 to 2.5 Hz.

The observed network-averaged teleseismic *P* wave spectrum for the 2009 test is compared with the best fitting predictions for hypothetical Mueller/Murphy sources at depths of 200m and 800m in Figure 7. The two theoretical predictions are essentially identical over the available 0.5 to 2.5 Hz frequency band. That is, the observed teleseismic spectral data do not have the resolving power to distinguish between the alternate hypotheses of a 2.7 kt explosion at a depth of 200m and a 4.8 kt explosion at a depth of 800 m.

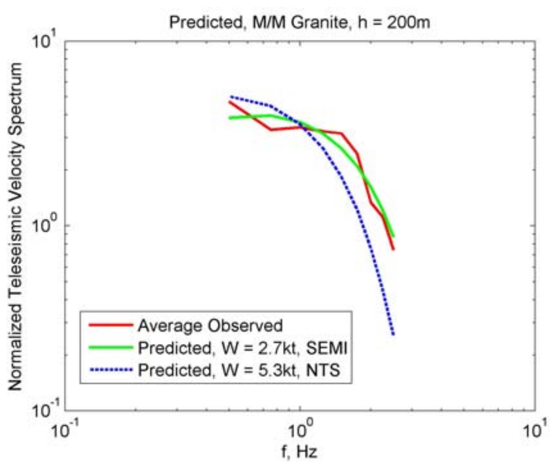

Figure 6. Network-averaged teleseismic *P*-wave spectrum for the May 25, 2009 North Korean nuclear test compared with the best-fitting Mueller/Murphy source models, assuming a depth of 200m and attenuation models for the Semipalatinsk and NTS test sites. The Semipalatinsk model is much more consistent with the observed spectra.

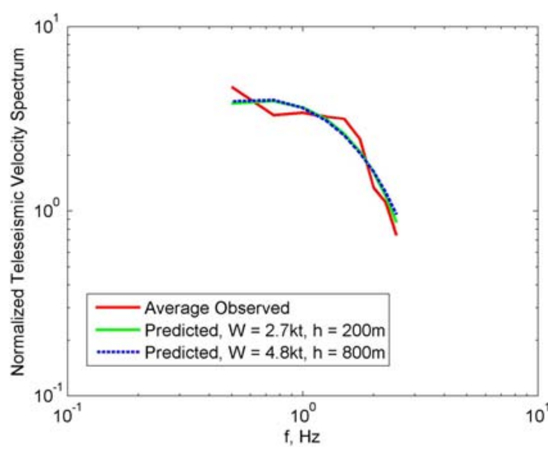

Figure 7. Network-averaged teleseismic *P*-wave spectrum for the May 25, 2009 North Korean test compared with the best-fitting Mueller/Murphy model assuming depths of 200 and 800m. The observed data do not have the resolving power to distinguish between the hypotheses of a 2.7 kt test at 200m depth and a 4.8 kt explosion at 800m.

Source Depth Estimation from *Pn* Spectral Ratio Analysis

In principle, broadband regional *P* wave data recorded from these explosions can provide the information needed to distinguish between different source depth hypotheses. However, in order to use such data to accurately infer source characteristics, it is necessary to first correct for frequency-dependent propagation path effects, and that cannot currently be done with confidence for the regional distance stations that recorded the two North Korean nuclear tests. One approach to eliminating the uncertainties associated with correcting for frequency-dependent propagation effects is to compute *P* wave spectral ratios of the two explosions at common regional stations. For closely-spaced explosions, the propagation path effects are essentially the same, and computing the *P* wave spectral ratios cancels them out to give estimates of the broadband seismic source spectral ratio between these two explosions. The individual regional station *P* wave spectral ratios can then be averaged to obtain a robust estimate of the source spectral ratio that can be compared with the theoretical source spectral ratios predicted by the Mueller/Murphy explosion source model corresponding to different source depth hypotheses for the two explosions.

This analysis procedure was applied to the broadband *P* wave data recorded from the two explosions at regional stations KSRS, MDJ, INCN, TJN and MAJO. The average observed regional *P* wave source spectral ratio, North Korea (2009)/North Korea (2006) is shown in Figure 8 over the frequency range from 1 to 15 Hz, where it is compared with the theoretical Mueller/Murphy source spectral ratios computed by assuming that both explosions were detonated at the same depth of 200m or 800m. The hypothesis that the two North Korean tests were detonated at the same depth anywhere in the plausible depth range is completely inconsistent with the observed spectral ratio data. In fact, it has been found that the observed spectral ratio data are much more consistent with the hypothesis that the 2006 test was conducted at a depth of about 200m, while the 2009 test was conducted at a depth of about 550m. This is shown in Figure 9 where the average observed spectral ratio is compared with the alternate theoretical Mueller/Murphy source spectral ratio obtained by modeling the 2009 test as a 4.6 kt explosion at a depth of 550m and the 2006 test as a 0.9 kt explosion at a depth of 200m.

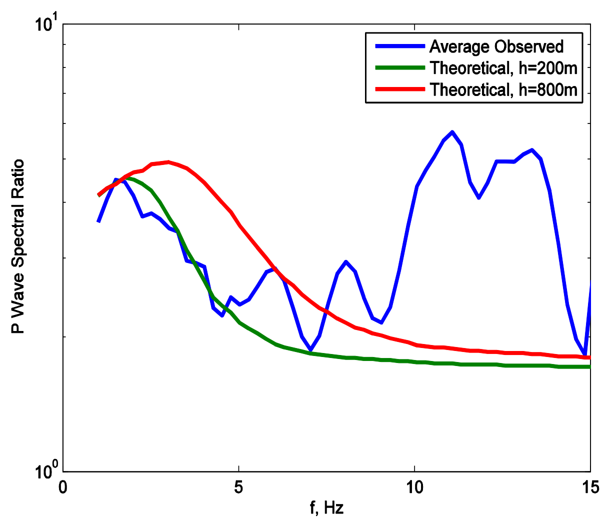

Figure 8. The average observed (KSRS, MDJ, INCN, TJN, MAJO) regional *P*-wave source spectral ratio North Korea(2009)/North Korea(2006) compared with the Mueller/Murphy source spectral ratios computed assuming that both explosions were detonated at 200m depth and at 800m depth. The hypothesis that both tests were detonated at the same depth is inconsistent with the observed high frequency spectral ratio data.

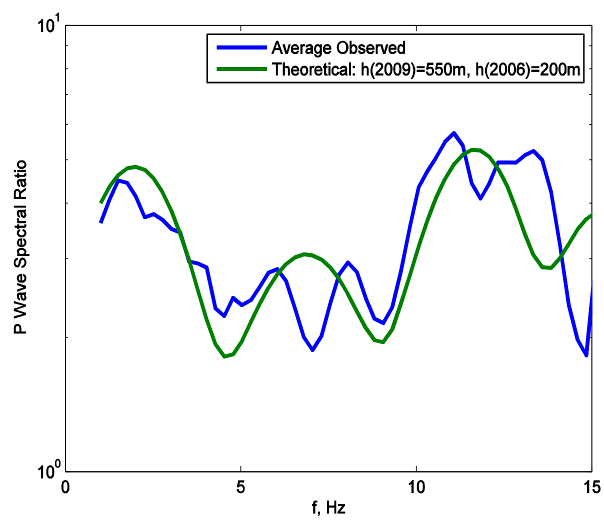

Figure 9. The average observed (KSRS, MDJ, INCN, TJN, MAJO) regional *P*-wave source spectral ratio North Korea(2009)/North Korea(2006) compared with the theoretical Mueller/Murphy source spectral ratio computed assuming that the 2009 test was conducted at 550m (W=4.6kt), while the 2006 test was conducted at 200m (W=0.9kt), with a pP/*P* amplitude ratio of 0.3 for both explosions. The hypothesis of significantly different depths for the two explosions is much more consistent with the observed high frequency spectral ratio data.

Effects of the surface reflected pP phases were included, with the pP/*P* amplitude ratios held at 0.3, consistent with previous experience with shallow explosions at other nuclear test sites (Murphy and Barker, 2001). These calculations predict a source spectral ratio that agrees remarkably well with the average observed spectral ratio over the entire band extending from 1 to 15 Hz. That is, the hypothesis of significantly different source depths for the two North Korea nuclear tests is much more consistent with the observed regional *P*-wave spectral ratio data than is the alternative, that the tests were conducted at the same depth.

Surface Wave Magnitude Anomaly

The two North Korean nuclear tests generated larger than expected surface waves relative to Ms-yield relations derived from historical nuclear explosions. The events were somewhat unusual compared to the body of historical explosion surface wave measurements in that they were small and in high velocity hard rock. Most of the historical events are in lower velocity material at NTS, or larger events at both NTS and foreign test sites. A large fraction of the foreign events were at the Soviet Semipalatinsk test site, and many of those events show evidence of compressive tectonic strain release, which has the effect of reducing surface wave amplitudes. So, it is not immediately clear whether the larger surface waves from the North Korean event are highly anomalous, or incorrectly estimated from larger explosions in different media and tectonic settings.

***Ms Measurements* -** We used the Russell (2006) Butterworth filtered surface wave magnitude formula to estimate Ms using measurements from both Rayleigh and Love waves at six regional seismic stations (BJT, ENH, HIA, INCN, KS31 and MDJ) that recorded useable long-period data for both North Korean nuclear tests. Note that for the 2006 test, the Love wave measurements should be regarded as upper bounds as Love waves were close to or below the noise level at all stations. The magnitudes determined for these two events are listed in Table 2. The Ms/yield relation (Ms = 2.10 + 1.0 log W) derived by Stevens and Murphy (2001) results in a yield estimate of 32 kt for the 2009 event which is completely inconsistent with the body-wave estimate from above. The relative Ms-based yields between the 2006 and 2009 are consistent with the relative yield from body wave measurements indicating that the source of the absolute Ms anomaly must be common to both events.

Table 2. Surface wave magnitudes from North Korean explosions (10-20 second average)

Event	Rayleigh $M_{s(b)}$	Love $M_{s(b)}$
Event 1 – 10/9/2006	2.93 ± 0.20	< 2.58 ± 0.27
Event 2 – 5/25/2009	3.66 ± 0.10	3.07 ± 0.11

***Analysis of the Ms Anomaly* -** One effect that has been shown to bias Ms values observed from explosions at other test sites is the triggering of the release of pre-existing tectonic strain energy by the explosion. That is, tectonic strain energy stored in the medium prior to the explosion can be released by the effects of the explosion shock waves, producing a secondary source of long-period surface waves that can either add to or subtract from the direct explosion induced surface waves, leading to anomalous Ms values. Since such secondary tectonic sources are expected to produce long-period transverse Love waves, while pure explosions are not, observations of significant transverse component Love waves on recordings from explosions provides strong evidence for explosion-induced "tectonic release." Accurate characterization of any secondary sources of surface waves is important in seismic monitoring, and moment tensor inversion analysis provides the formalism needed to characterize such secondary sources.

To examine the possible effect of tectonic release on surface wave amplitudes observed from the two North Korean tests, we performed moment tensor inversions for the two events. To do this, we performed a search for best fit to all the data in the 10-20 second period band while varying the isotropic moment, CLVD moment and shear moment tensor components, excluding the vertical dip slip moment tensor components which vanish at the free surface. We find the following:

Table 3. Moment tensor inversion results for North Korean explosions ($\times 10^{14}$ N-m)

Event	Mxx	Myy	Mzz	Mxy
Event 1 – 10/9/2006	4.30	5.56	3.68	-0.50
Event 2 – 5/25/2009	25.12	27.63	18.84	-4.27

Table 4 lists the moment tensor in terms of the isotropic moment and the shear components. The CLVD as defined here will generate larger surface waves if it is positive, since at shallow depths the horizontal strain is the principal generator of surface waves. The CLVD component is small, but is positive and therefore enhances surface waves.

Table 4. Moment tensor inversion results for North Korean explosions (x10^{14} N-m)

Event	M_I	M_{CLVD}	Mxx-Myy	Mxy
Event 1 – 10/9/2006	4.51	1.25	-1.26	-0.50
Event 2 – 5/25/2009	23.86	7.54	-2.51	-4.27

The effects on the individual station Ms values predicted by the tectonic release moment tensor solution for the 2009 test vary from no change up to a change of 0.17 magnitude units. The net effect is predicted to increase the network-averaged Ms value by only 0.06 magnitude units, which is much too small to explain the observed anomaly. However, it should be noted that since the CLVD component does not generate Love waves, it is not well constrained in the inversion; and a larger CLVD component would generate larger Ms. That is, an explosion with the same isotropic moment and a larger CLVD would generate larger surface waves with the same Love waves, no additional Rayleigh wave azimuthal variation and only a small change in spectral shape. This possibility will need to be systematically evaluated in any future studies of the observed Ms anomalies.

In summary, the Ms values observed for the North Korean explosions were much higher than expected based on past experience with explosions at other test sites. The inferred non-isotropic contributions to the long-period sources for the North Korean explosions relative to Semipalatinsk are of opposite sign, and account for part of this difference. Uncertainties in the extrapolation from the experimental database of mostly larger explosions in lower velocity media may also contribute to the apparent anomaly. Nevertheless, it is not clear that there is any plausible combination of these two factors that is adequate to explain the observed offsets. Additional research will be required to more fully investigate possible sources of these observed Ms anomalies for the two North Korean nuclear tests.

CONCLUSIONS AND RECOMMENDATIONS

On May 25, 2009, the North Koreans conducted a second underground nuclear test at a location very close to that of their initial 2006 test in a remote, mountainous region of northeastern North Korea. The objective of the present study was to exploit IMS and other open data sources to conduct comprehensive, advanced analyses of the characteristics of these two North Korean nuclear tests. The focus was on refining event locations, estimating source depths and seismic yields and evaluating the effectiveness of the various seismic event identification criteria as applied to these two explosions. Seismic data recorded at stations of the global IMS network were augmented with seismic data from key regional stations (< 20 degrees) obtained from the Incorporated Research Institutions for Seismology (IRIS) data management center, the OPHDMC and the NIED. The principal findings of these analyses with regard to the characterization of the North Korean nuclear tests can be summarized as follows:

- Available seismic arrival time data from the 2006 and 2009 tests were analyzed using a variety of state-of-the-art relative location techniques. All of the resulting solutions yielded very similar locations, indicating that the 2009 test was conducted about 2.5 km west-northwest of the 2006 test. Supplemental topographic data for the site were used to further constrain the absolute locations with respect to the tunnel adit entry identified from open source overhead imagery.
- Teleseismic *P* wave spectral data were inverted using a model-based procedure to determine the yield of the 2009 test as varying from 2.0 to 4.8 kt. over the plausible depth range from 100 to 800 m.
- Since the uncertainty in source depth leads to considerable uncertainty in the yield estimate, a new technique based on broadband source spectral ratios was developed to better constrain the depths of the 2006 and 2009 explosions. The results of this analysis indicate that the two explosions could not have been conducted at any common depth in the plausible 100 to 800 m range; and, in fact, the observed spectral ratio data are best modeled by source depths of about 200 m for the 2006 test and 550 m for the 2009 test. The corresponding yield estimates for the 2006 and 2009 tests are 0.9 kt and 4.6 kt., respectively.
- The long-period surface wave Ms magnitudes for both the 2006 and 2009 tests appear to be anomalously large relative to historical experience, producing unreasonably large Ms yield estimates and problematic Ms/mb identification characteristics. A formal moment tensor inversion analysis of the available data has indicated that release of tectonic strain energy by the explosion may have contributed somewhat to the observed anomaly. However, current estimates of the likely strength of this tectonic release are not large enough to fully explain the observed anomaly. Additional research will be required to determine whether unresolved CLVD secondary sources any account for the discrepancy.

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REFERENCES

Bennett J, North B, Kohl B, Murphy J, Stevens J, Bondar I, Fisk M, Bahavar M, Barker B, Israelsson H and V Oancea, (2006). Analysis of IMS data from the North Korean (DPRK) Nuclear Test of October 9, 2006, SAIC, *SAIC Technical Report* SAIC-06/2203.

Dewey, J. W. (1972). Seismicity and tectonics of western Venezuela, *Bull. Seismol. Soc. Am*. 62: 1711–1751.

Fisk, M. D. (2002). Accurate locations of nuclear explosions at the Lop Nor test site using alignment of seismograms and IKONOS satellite imagery, *Bull. Seism. Soc. Am.* 92: 2911–2925.

GlobalSecurity.org (2006). Weapons of Mass Destruction (WMD): Possible North Korean nuclear test site near Punggye-yok, online at http://www.globalsecurity.org/wmd/world/dprk/kilju-punggye-yok.htm.

Grubbs, F. E. (1950). Sample criteria for testing outlying observations, *Ann. Math. Stat*. 21: 27–58.

Mueller, R. A. and J. R. Murphy (1971). Seismic characterization of underground nuclear detonations. Part 1: Seismic scaling law of underground nuclear detonations, *Bull. Seismol. Soc. Am*. 61: 1675–1692.

Murphy, J. R. and B. W. Barker (2001). Application of network-averaged teleseismic *P*-wave spectra to seismic yield estimation of underground nuclear explosions, *Pure Appl. Geophys*. (PAGEOPH) 158: 2123–2171.

Russell, D. R. (2006). Development of a time-domain, variable period surface-wave magnitude measurement procedure for application at regional and teleseismic distances. Part I: Theory, *Bull. Seismol. Soc. Am*. 96: 665–677.

Schlittenhadt, J., M. Canty, and I. Gruenberg (2010). Satellite Earth observations support CTBT monitoring: Case studies including the nuclear test in North Korea of Oct. 9, 2006, and comparison with seismic results, *Pure Appl. Geophys.* (PAGEOPH), 10.1007/s00024-009-0036-x.

Snieder, R. and M. Vrijlandt (2005). Constraining the source separation with coda wave interferometry: Theory and application to earthquake doubles in the Hayward fault, California, *J. Geophys. Res.* 10: B04301.

Stevens, J. L. and J. R. Murphy (2001). Yield estimation from surface wave amplitudes, *Pure and Applied Geophysics* (PAGEOPH) 158: 2227–2251.

US Geological Survey (1966-1969). Military Geology Branch Atlases of Asia and Eastern Europe to Support Detection of Underground Nuclear Testing, prepared for DARPA.

Waldhauser, F. and W. L. Ellsworth, (2000). A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am* 90: 1353–1368.