SUPPLEMENTAL ANALYSIS OF THE SEISMIC CHARACTERISTICS OF THE 2006 AND 2009 NORTH KOREAN NUCLEAR TESTS

John R. Murphy, Jeffry L. Stevens, Benjamin C. Kohl, Theron J. Bennett, and Brian W. Barker

Science Applications International Corporation

Sponsored by the U. S. Department of State

Award No. SAQMMA09C0250

ABSTRACT

In a previous study (Murphy et al., 2010), we conducted advanced analyses of the characteristics of the 2006 and 2009 North Korean nuclear tests using International Monitoring System (IMS) and other open seismic data sources. These studies focused on refining event locations, estimating source depths and yields, and evaluating the effectiveness of the various seismic identification criteria as applied to the observed data from these two explosions. While these studies were very productive and led to the development of some highly innovative analysis techniques that significantly advanced the seismic characterizations of these two nuclear tests, they also led to some additional questions that could not be conclusively addressed using the resources available at that time. Consequently, a supplemental research effort was initiated to further address these issues. These studies have included a review of United States Geological Survey (USGS) and foreign geologic publications to characterize the geologic and tectonic environment of the North Korean Punggye test site, a quantitative analysis of the uncertainties in the estimates of yield and depth of the two explosions based on broadband P wave spectral ratios, and theoretical modeling calculations and advanced surface wave analyses to address the observed Ms magnitude anomalies for the two North Korean tests.

With regard to the review of the geologic/tectonic environment at the Punggye test site, it has been inferred from the published data that the geologic media in the depth range encompassing the two nuclear tests at that site consist of hard igneous and older metamorphic rocks. This suggests that these explosions were conducted in “good coupling” media for purposes of seismic yield estimation, consistent with previous assumptions. The tectonic regime in the Punggye region is inferred to be predominantly extensional, with tension axes oriented NNW-SSE, consistent with the regional plate tectonic environment and published earthquake focal mechanisms. This tectonic characterization provides valuable constraints for our quantitative analysis of the observed Ms anomalies for the two North Korean tests.

The uncertainties in the estimates of source depths and associated yields for the two North Korean tests based on broadband regional P wave spectral ratios between the two explosions have been quantitatively addressed by computing formal statistical uncertainty bounds on the average observed P wave spectral ratio and estimating the ranges of source depths and yields consistent with these bounds. Variational analyses suggest that the 95% confidence level uncertainties in the estimated depths of 200 m for the 2006 test and 550 m for the 2009 test are on the order of ±100 m and ±175 m, respectively. Similarly, the associated yield estimates of 0.9 kt for the 2006 test and 4.6 kt for the 2009 test are inferred to have accuracies on the order of ±30 %.

In order to further investigate the Ms anomalies, a series of two-dimensional, axisymmetric nonlinear finite difference simulations have been carried out for the two North Korean tests. The simulations incorporated effects due to the nonlinear response of the free surface to the upgoing shock waves induced by the explosions, as well as effects due to various postulated tectonic prestress conditions. It was found that those simulations employing a tensile prestress, consistent with our review of the regional tectonic environment, led to predicted long period surface wave amplitudes that are in much better agreement with the observations, although the predicted Ms value for the 2009 explosion continues to be somewhat lower than the observed value.

OBJECTIVES

The North Korean (NK) nuclear test on May 25, 2009, and a smaller test on October 9, 2006, were recorded by the International Monitoring System (IMS) and other regional and teleseismic stations. Observed data from these two events were analyzed in a prior study (Murphy et al., 2010) using some innovative analysis techniques which generated several interesting conclusions related to monitoring relevant to refining event locations, estimating source depths and yields, and evaluating effectiveness of seismic identification criteria. The objective of this follow-on study has been to address in more detail some questions and issues raised by those previous analyses. In particular, the current investigation has been directed at improving understanding and characterization of the geologic/tectonic environment at the North Korean Punggye test site which affects the observed seismic signals, quantitative analyses to constrain depth estimates for the explosion tests and determine their uncertainties, better utilization of calibration data to improve Lg magnitude measurements and associated Lg yield estimates for the explosions, and modeling calculations and advanced analyses to better understand surface wave generation from the explosion sources.

RESEARCH ACCOMPLISHED

Geologic Factors Related to the NK Test Site

In our investigation of geologic/tectonic factors affecting seismic signals from the NK test site, we relied upon open source reference materials and reports on studies conducted by the USGS. In general, specific details on the NK test site and its geology are very sparse; however, a number of potentially relevant features have been identified (Table 1). The Sino-Korean craton, where the NK test site is located, has remained generally stable following several periods of metamorphism and intrusion during the Proterozoic (2500-540 Ma) with a later phase of graben formation accompanied by intrusions and volcanism during the Mesozoic (225-65 Ma) and Cenozoic (65 Ma to present). The latter, recent phase of tectonic activity affecting the NK test site area is associated with the pulling away of the Japanese island arc from the mainland forming the back-arc basin and causing a tensional stress regime throughout the Korean peninsula which persists today.

Table 1. Significance of geologic/tectonic factors in the vicinity of the North Korean test site for nuclear explosion monitoring.

Geologic/Tectonic Factor	Description	Significance
Tectonic setting	Part of Sino-Korean craton	Stable platform areas are typically characterized by efficient generation and transmission of seismic signals used for detection, location, and yield estimation
Surface rocks	Hard, competent, mainly younger igneous or older metamorphic rocks	Expected good coupling of explosion source into transmitted seismic signals affects detection thresholds and yield estimates
Crustal structure	Rapid change in crustal thickness across test site area with potential low-velocity zone in volcanic areas to the northwest	Crustal anomalies affect seismic travel times and attenuation of seismic signals impacting detection thresholds, location accuracy, and yield estimates based on regional phases propagating through this area
Upper mantle	Low-velocity zone in upper mantle beneath Mt. Changbai volcanic area to the northwest	Upper mantle anomalies extending south into source area would affect seismic travel times and attenuation of seismic signals impacting detection thresholds, location accuracy, and yield estimates based on teleseismic phases
Stress conditions	Predominantly extensional stress (tension oriented NNW-SSE) throughout Korean peninsula indicated by plate tectonics and earthquake mechanisms	Potential for tectonic strain release combining with nuclear explosion source affects explosion yield estimates, particularly those based on LP signals (Ms or moment)

Small scale geologic maps for the Korean peninsula (Steinshouer et al. 1997) indicate the presence of Archean (3950-2500 Ma) and other Precambrian (>540 Ma) basement rocks in the general vicinity of the NK test site, along with Jurassic-Triassic (250-145 Ma) intrusive igneous rocks, as well as Cenozoic and Quaternary (<2.5 Ma) extrusive volcanic rocks extending towards the test site from Mt. Changbai to the northwest. Rock types in the test site area include limestone and dolomite basement rocks, granite and diorite intrusives, volcanic basalt flows, and metamorphic gneiss and schists. Best estimates indicate that rocks at the test site are low porosity, dense intrusive and extrusive igneous rocks (with granite considered the most likely source rock – i.e., "good coupling" media).

There is also evidence from geophysical and seismic measurements of potentially significant crust and upper mantle conditions in areas surrounding the NK test site. These include a rapid increase in crustal thickness from southeast to northwest based on regional gravity and seismic data (Song and Thae, 1993), a crustal low-velocity zone near Mt. Changbai (North Korea/China border area) based on seismic wide-angle reflection and refraction data (Song et al. 2007), and a more extensive low-velocity zone in the upper mantle extending outward from Mt. Changbai (just to the northwest of the NK test site) based on teleseismic P-wave tomography analyses (Lei and Zhao, 2005). However, P-wave spectra analyzed to date from the NK tests show little evidence of any effects from the latter.

Finally, as noted earlier, formation of the back-arc basin during the most recent phase of plate tectonic activity in the vicinity of the Korean peninsula has produced a tensional stress regime which appears to persist into the present time. In particular, earthquake focal mechanisms (Jin and Park, 2007; Kim and Kraeva, 1999) indicate that the active principal stress is tensional and oriented NNW-SSE with a secondary compression axis oriented ENE-WSW. As described below, the latter potentially causes a more complex source mechanism, as tectonic strain release accompanies the explosions, which affects the associated LP signals on which the Ms observations are based.

Uncertainty of Explosion Depth Estimates Determined from Teleseismic P Spectral Ratio

In our previous report (Murphy et al. 2010), it was noted that conventional analyses of teleseismic P wave spectral data recorded from the 2006 and 2009 NK nuclear tests do not have the resolving power to distinguish between source depths in the plausible range from 100 to 800 m. However, a new approach based on broadband P wave spectral ratios using data from common regional stations for the two explosions showed promise for identifying source depth differences. According to this method, regional P wave spectral ratios at individual stations are 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 (1971) explosion source model corresponding to different source depth hypotheses for the two explosions to determine a match.

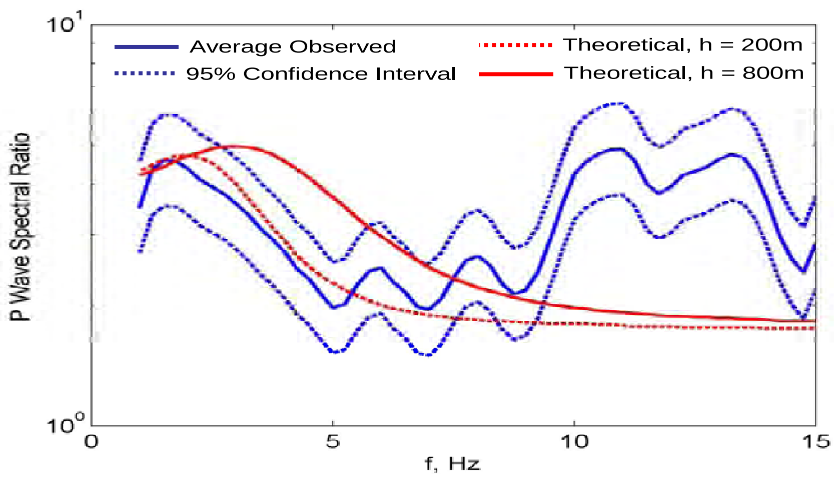

Figure 1. Comparison of the average observed broadband P wave spectral ratio, North Korea (2009) / North Korea (2006), and associated 95% confidence bounds with the theoretical Mueller/Murphy source spectral ratios computed assuming that both explosions were detonated at 200m depth and 800m depth. It can be seen that the hypothesis that both tests were detonated at the same depth is excluded by the observed high frequency spectral ratio data.

Figure 1 shows a comparison of the observed P wave spectral ratio for the 2009 and 2006 NK nuclear tests determined (using the data from six common regional stations to determine the average and estimate the 95% confidence bounds) with the theoretical Mueller/Murphy source spectral ratios computed assuming that both explosions were detonated at 200 m depth and 800 m depth. It can be seen that the observed spectral ratio is statistically inconsistent with the hypothesis that both explosions were detonated at the same depth for any depth in the plausible depth range in that the corresponding theoretical solutions fall well outside the estimated

95% confidence bounds at high frequencies. On the other hand, as illustrated in Figure 2, the proposed theoretical solution corresponding to a depth of 200 m and associated yield of 0.9 kt for the 2006 test together with a depth of 550 m and associated yield of 4.6 kt for the 2009 test is found to be very consistent with the 95% uncertainty bounds on the average observed P wave spectral ratios.

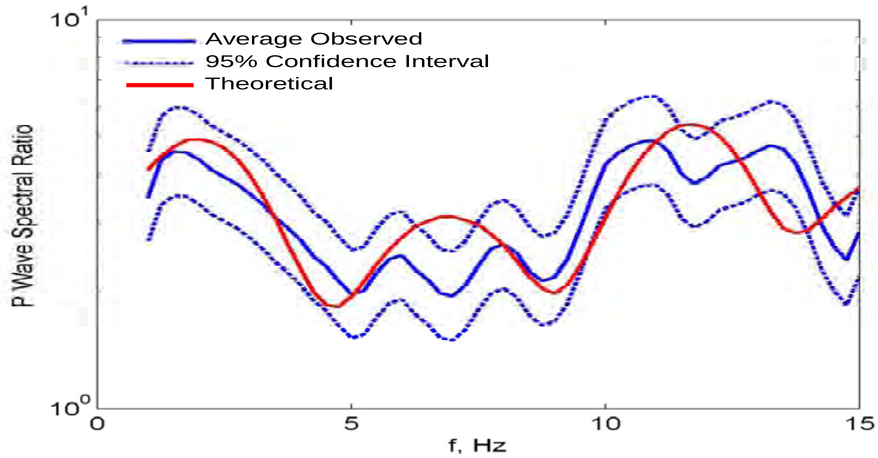

Figure 2. Comparison of the average observed broadband P wave spectral ratio, North Korea (2009) / North Korea (2006), and associated 95% confidence bounds with the best-fitting theoretical Mueller/Murphy source spectral ratio computed assuming that the 2009 test was conducted at a depth of 550m (W = 4.6kt), while the 2006 test was conducted at a depth of 200m (W = 0.9kt).

In addition to this matching, we performed a perturbation analysis to determine the sensitivity of the theoretical solution from the Mueller/Murphy model to variations in source yields and depths by varying one parameter at a time and holding the others fixed at the values in Figure 2, which appears to be close to an optimal fit. The results of that analysis indicated that even modest changes in explosion depths (over the range ± 100 m for the 2006 explosion or ± 175 m for the 2009 explosion) produce significantly worse fits to the observed spectral ratio data, particularly at high frequencies. Varying the yields of each explosion by ± 25% produced theoretical solutions for the ratios that tended to fall within the 95% confidence bounds of the observations, but the overall fits to the average values were clearly inferior. These results indicate that theoretical solutions corresponding to explosion source parameters much different from the “optimal” parameter values of Figure 2 are not consistent with the uncertainty estimates in the average observed P wave spectral ratios. We conclude that our yield estimates of 0.9 kt for the 2006 explosion and 4.6 kt for the 2009 explosion have accuracies on the order of 30%, assuming that seismic source coupling at the North Korean nuclear test site is comparable to that associated with the Mueller/Murphy granite source.

Relative Depth Determination from Waveform Correlation

To further corroborate the relative source depth differences for the NK nuclear tests, we used a waveform correlation method based on Differential Waveform Interferometry (DWIF). In this method the relative epicenter location was constrained to the best estimate from Murphy et al. (2010). The differential times between regional phases (Pg or Pn and Lg) for the two explosions at common local and regional stations were measured by cross-correlation of the traces and then time-shifting and stacking the correlation traces based on the event hypocenter hypothesis and slowness model of the source region. The best estimate for the source depth is then determined by a grid search for the event hypocenter hypothesis which maximizes the objective function, here defined as the maximum of the stack of the correlation traces.

The method was applied to 32 station-phase pairs for regional phases from the 2006 and 2009 NK explosions recorded mainly at continental stations in Asia along with selected stations in Japan. To determine the best relative depth, the computed root mean squares (RMS) of the residuals were compared for relative depths between -2.0 km and +2.0 km. Figure 3 shows the distribution of the RMS as a function of the relative depth. The results indicate that a minimum is achieved for the hypothesis in which the 2009 event occurred at a source depth 0.35 km deeper than the 2006 event. Although the DWIF methods do not provide formal depth uncertainties, the results do appear to strongly support the conclusion based on the P-wave spectral ratio observations presented above that the two NK nuclear tests had significantly different source depths and that a good estimate of the relative depth difference between the events is ~350 m.

The relative source depth difference determined from this method and the spectral ratios has implications for the absolute locations for the 2006 and 2009 events. In our prior study (Murphy et al. 2010), we conducted a topographic analysis of the source area and derived potential locations based on overburden requirements necessary for containment with the relative epicenter locations between the events constrained and assuming that both events were placed in horizontal tunnels extending into the mountain from the same adit. Imposing the new constraint that the 2009 event was about 350 m deeper than the 2006 event would require that the two explosions were located several hundred meters to the east and south of the prior locations, as shown in the right panel of Figure 3.

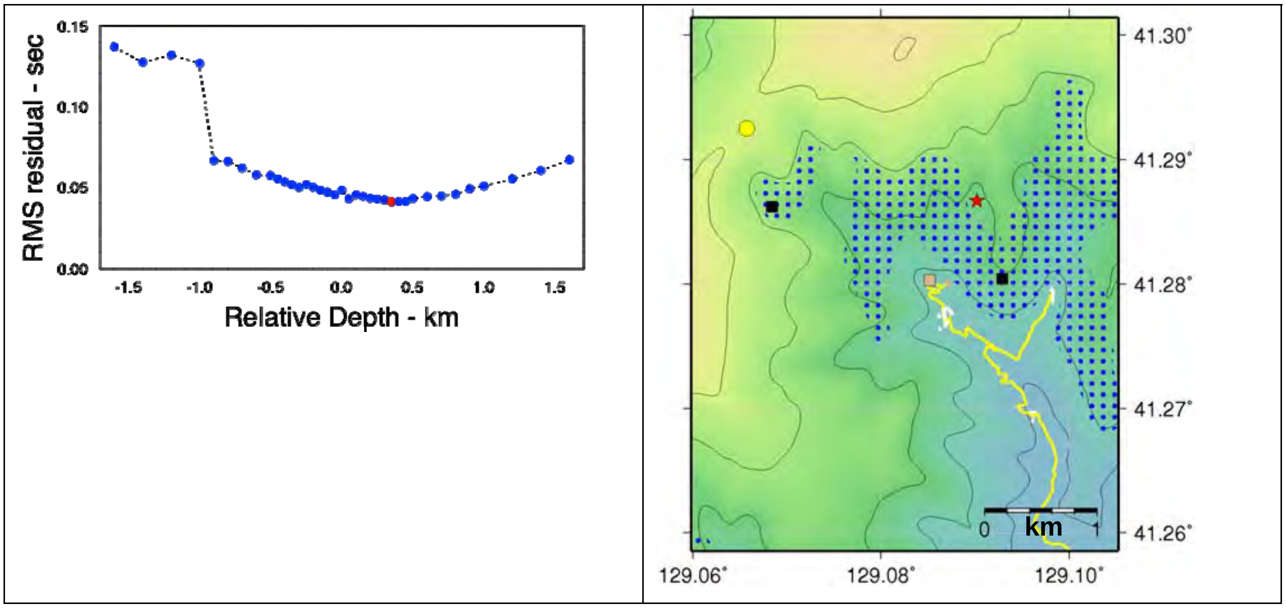

Figure 3. RMS of the residuals of the relative arrival times plotted against relative depth hypotheses (left panel). The minimum RMS (red circle) is found for a relative absolute depth of 0.35 km, that is, the data suggest that the 2009 event occurred 350 meters deeper than the 2006 event. Right panel shows the tunnel adit (beige square) and candidate locations (blue hatched area) based on topographic analysis of the containment depth requirements, relative epicenter locations, and the newly derived relative depth estimate. Best estimates of the absolute locations (black squares) were derived by shifting the Murphy et al. (2010) solutions (2006 – red star, 2009 – yellow circle) to the southeast.

Refined Yield Estimates from Lg Magnitudes

In our previous study (Murphy et al. 2010) we cited bulletin data from the USGS/NEIC (2010) which reported a very small Lg magnitude, 3.6 mb(Lg) for the 2009 North Korean nuclear test based on observations from four regional stations and the same Lg magnitude for the 2006 test based on observations from three stations. That magnitude corresponded to a very low yield estimates ($W \approx 0.1$ kt) for the two explosions, based on mb(Lg)-vs-yield relationships for explosion sources in water-saturated rock (Nuttli, 1986a, b). Two obvious issues for the mb(Lg) measurements reported by the USGS were that the station sets were different between events and the attenuation relationship used to correct Lg amplitude for distance, as applied by the USGS, is not dependent on the region where the event is located or on the paths specific to the stations where the Lg measurements were made.

As part of our current investigation to help clarify the utility of Lg magnitude measurements for use in determining the yields for the 2009 and 2006 NK nuclear tests, we analyzed observations from six regional stations (Figure 4) at distances 3.3°-10.3° which recorded both the 2009 and 2006 explosions. The vertical component records at these six stations all show clear Lg phase signals in the appropriate group velocity window and dominant frequencies of ~2 Hz, which were used for the Lg amplitude measurements. We initially applied an attenuation relationship developed by Kohl et al. (2004) using calibration data from the whole of the Korean peninsula which produced mb(Lg) magnitude measurements which varied considerably between stations (with an apparent pattern to the variations) and consistent magnitude differences between the 2009 and 2006 explosions at the individual stations. Furthermore, the Lg magnitude measurements tended to be biased low relative to other magnitude measures. We have subsequently applied an alternative Lg attenuation relationship based on work by Chun and Henderson (2009) which used calibration data from the North Korea/China border region. The mb(Lg) results for the two NK events at the six regional stations are summarized in Table 2.

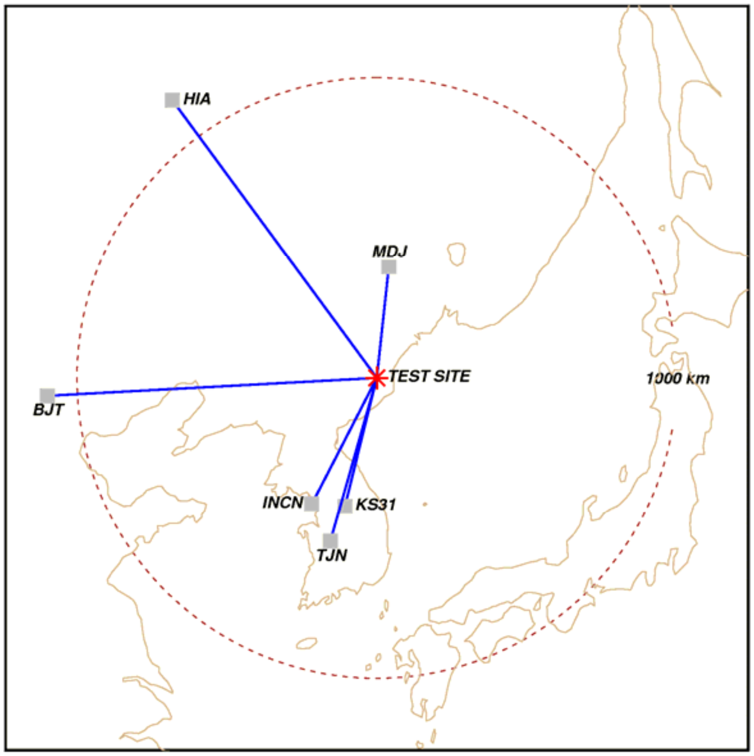

Figure 4. Map showing the locations of six regional stations which recorded Lg signals from both the 2009 and 2006 North Korean nuclear explosions.

Table 2. Lg magnitudes determined using the Chun and Henderson (2009) attenuation model for the Korean peninsula.

Station	Distance	2006 m_b(Lg)	2009 m_b(Lg)
MDJ	3.34	4.43	5.11
KS31	3.95	3.81	4.39
INCN	4.25	4.08	4.36
TJN	5.09	4.11	4.32
BJT	9.90	4.12	4.54
HIA	10.33	4.10	4.87
Average		**4.11**	**4.60**

It can be seen that the network-averaged mb(Lg) values for the two events are now in very good agreement with the values reported for mb by the International Data Center (IDC) (4.1 mb for the 2006 event and 4.5 mb for the 2009 event), providing an indication that we have improved the calibration of the mb(Lg) measure for the region. Although a previously observed low bias for the mb(Lg) values at the southern stations relative to the northern stations has largely disappeared, there is still some evidence of lower magnitudes at the southern stations (mainly for the 2009 event) which suggests that some additional refinements of the Lg path attenuation could be warranted for these stations.

To determine the yields associated with the Lg magnitudes, we used the Lg magnitude-vs-yield relation from Patton (1988) for Nevada Test Site (NTS) explosions below the water table:

$$mb(Lg) = 4.18 + 0.76 \log W$$

Resulting yields are shown in Table 3 for the 2009 and 2006 NK explosions and show relatively good agreement with yields for these events based on other methods.

Table 3. Yield estimates (kt) from mb(Lg) using the Patton (1988) magnitude vs. yield relations and the average magnitudes from Table 2.

mb(Lg) versus Yield Relation	2006 – Yield (kt)	2009 – Yield (kt)
Patton (1988)	**0.81**	**3.55**

Modeling and Analysis of Surface Waves for NK Nuclear Tests

As noted in Murphy et al (2010) and elsewhere, the North Korean nuclear tests generated anomalously large surface waves, inconsistent with simple explosion source models. As part of the current study, we have been investigating possible causes for the large surface waves and attempting to identify the physical mechanisms that are most likely responsible. Surface wave amplitudes are controlled primarily by the horizontal strain at the source, and are increased or decreased by tectonic strain release or other local physical effects that can cause the horizontal strain to vary. Large surface waves from the North Korean tests imply that horizontal strains were larger for these events than for most of the other explosions in the historical data set. The most likely explanation is tectonic strain release, although other possible explanations include enhanced horizontal offsets due to the presence of weaker source rock or increased resistance to horizontal rebound due to altered explosion dynamics.

To gain a better understanding of the source, we ran two-dimensional finite difference calculations of the North Korean explosions using the yield and depth estimates noted above (i.e. depth = 550 m and W = 4.6 kt for the 2009 explosion and depth = 200 m and W = 0.9 kt for the 2006 explosion). The calculations were based on a material model for granite derived from Degelen mountain explosions (Stevens et al. 2003). The calculated regions of nonlinear deformation corresponding to material yielding for the two NK explosions are shown as the top pair of illustrations in Figure 5, with the 2006 explosion on the left and the 2009 explosion on the right. Because the explosions are overburied for their yield, the nonlinear deformation away from the explosion is quite modest, particularly for the 2009 explosion, which is nearly spherical.

Tectonic strain release refers to relaxation and motion of the medium surrounding the explosion associated with local or regional stresses, not generated by the explosion itself. These tectonic prestresses cannot be so large that the material fails, creeps, cracks, or slips; on the other hand, they are likely to be at or close to these failure levels in any region with active tectonics. The model for prestress release includes the material surrounding the explosion moved by the combination of the explosion plus the tectonic shear stresses relaxed in the surrounding material (out to about the elastic radius). In addition, tectonic stresses have the additional effect of increasing (if compressive) or reducing (if tensile) the overburden pressure as a function of depth, which results in enhanced rock failure (and associated enhanced surface waves) in tension or in reduced rock failure (and associated lower surface waves) in compression.

To understand the effects of prestress release, we ran additional finite difference calculations for the North Korean explosion models, adding compressive and tensile prestress. These two calculations involved a complex source model obtained by combining the explosion source with an axisymmetric horizontal stress with maximum value of ± 150 bars, and maximum absolute value of ¾ of the overburden pressure. The results of these calculations are shown in the middle and bottom pairs of illustrations in Figure 5 for the 2006 NK explosion on the left and the 2009 explosion on the right. As described above, the compressive prestress has the effect of reducing the amount of nonlinear deformation, while the tensile prestress increases the nonlinear deformation; and this is clearly evident in the results from the calculations.

The effect on surface wave amplitudes and Ms of these kinds of tectonic stress release were determined using synthetic seismograms calculated using the representation theorem and appropriate Green's functions to produce seismograms at a distance of 1150 km from the sources for each of the 6 finite-difference calculations from Figure 5. The Ms values determined by applying standard Ms methods (Russell, 2006) to the synthetics are shown in Table 4. The results show that the tensile prestress release (consistent with North Korean tectonics described above) increases Ms by about 0.3 magnitude units in both cases. Compressive prestress release (not expected for this region but likely in other areas) causes a reduction in Ms of about 0.15 magnitude units for both events.

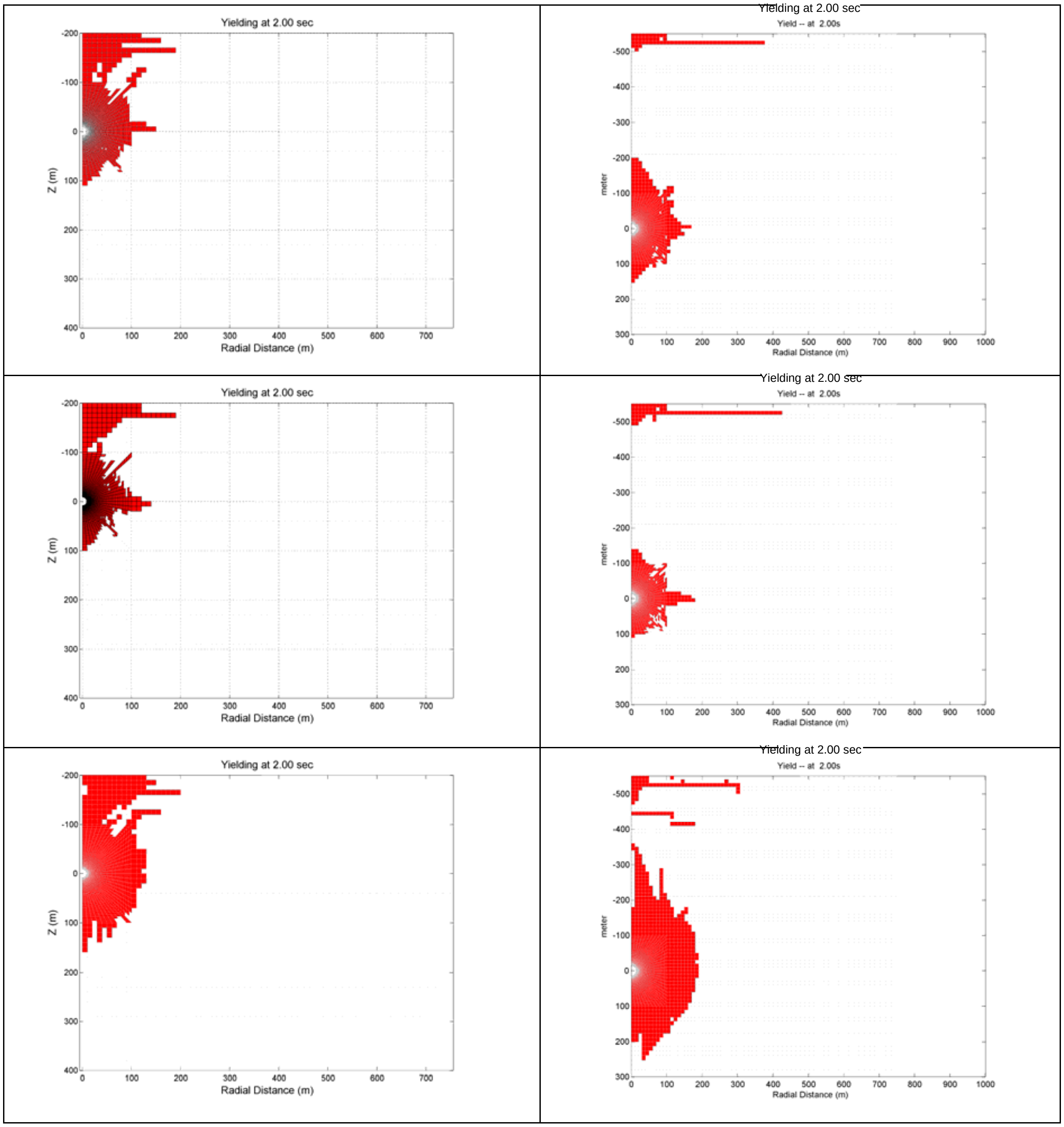

Figure 5. Regions of yielding from axisymmetric calculations of the North Korean nuclear explosions 2006 (left) and 2009 (right) without prestress (top), with compressive prestress (middle) and with tensile pre-stress (bottom). Note: There is an approximate factor of 1.4 difference in scale between the figures for the 2006 and 2009 calculations.

Table 4. Calculated surface wave magnitudes.

Event	Observed M_S	M_S no prestress	M_S compressive prestress	M_S tensile prestress
NK2006	2.93	2.46	2.32	2.67
NK2009	3.66	3.04	2.89	3.31

Figure 6 shows these calculated magnitudes derived from the finite difference model calculations for the North Korean nuclear tests along with the observed Ms magnitudes from the NK tests as well as other historical Ms vs. yield observations from a range of source areas. For the two NK events, the tensile prestress release increases Ms substantially, reducing the difference with respect to the observed Ms from 0.47 to 0.26 magnitude units for the 2006 event, and from 0.62 to 0.35 units for the 2009 event. Furthermore, compressive prestress decreases Ms almost back to the slope 1 line, demonstrating that prestress can indeed cause large variations in Ms. Although tensile tectonic stress release provides a likely explanation for the large Ms of the North Korean events, the calculated surface wave amplitudes are still only about ½ of the observed amplitudes; so, further study is indicated.

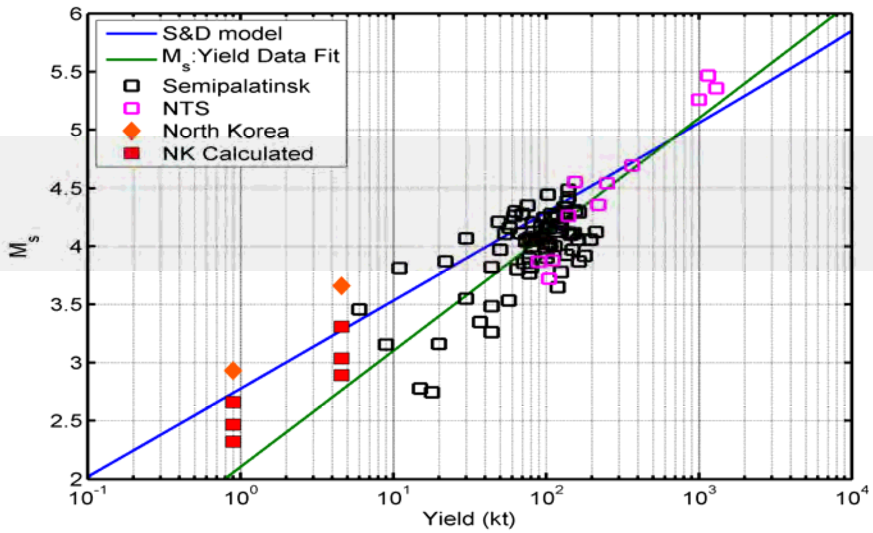

Figure 6. Calculated M_S with and without tectonic release plotted together with NK and historic data.

CONCLUSIONS AND RECOMMENDATIONS

Supplemental analyses were conducted for a number of issues identified during our previous study of seismic characteristics of the 2006 and 2009 North Korean nuclear tests. These included review of USGS and foreign publications addressing the geologic/tectonic environment of the Punggye test site, refinement and analysis of uncertainties in depth and yield estimates for the explosions utilizing broadband P wave spectral ratios, a refined relative depth and location analysis using high-resolution differential travel-time data from local and regional seismic stations, improved calibration of Lg attenuation to better determine Lg magnitudes and related yield estimates, and theoretical modeling and analysis of surface waves to address the observed Ms anomalies for the two NK tests. The principal findings of these studies can be summarized as follows:

- Available geologic information suggests that the 2006 and 2009 explosions were conducted in “good coupling” media for purposes of seismic yield estimation and that the tectonic environment in the Punggye region is predominantly extensional which constrains the effect of tectonic prestress release on Ms from the NK explosions.

- Formal uncertainty and variational analyses of the effects of explosion source depth and yields on broadband P wave spectral ratios confirm that the 2009 test was likely (95% confidence) conducted at significantly greater depth (~550 ± 175 m) than the 2006 test (~200 ± 100 m) and that yield estimates of 0.9

kt for the 2006 test and 4.6 kt for the 2009 test based on these same data have accuracies on the order of ± 30%.

- Waveform correlation analyses of high-resolution data from additional local and regional stations from the 2009 and 2006 NK tests indicate that travel time residuals are minimized for a solution in which the 2009 explosion has a source depth 350 m deeper than the 2006 test (in agreement with the conclusion cited above based on the P-wave spectral ratio analyses).

- Application of a revised Lg attenuation model more appropriate to the North Korean region leads to Lg magnitudes and associated Lg yield estimates that agree better with teleseismic P wave observations.

- Theoretical, two-dimensional axisymmetric nonlinear finite difference simulations to assess the effects of free surface interaction and tectonic release on LP surface waves and associated Ms observations for the 2006 and 2009 NK tests lead to Ms values that better match observed values for calculations incorporating the release of tensile prestress as part of the complex source, although the Ms value for the 2009 test continues to be anomalously low.

ACKNOWLEDGEMENTS

Seismic data from the IDC/IMS, Ocean Hemisphere Project Data Management Center, National Research Institute for Earth Science and Disaster Prevention, and Incorporated Research Institutions for Seismology Data Management Center were used in this study. We are also grateful to Rongsong Jih of the Department of State for his support and recommendations during the course of this project and to Rod Matzko for providing access to related USGS documents. The results reported in this paper are the opinions of the authors, and do not reflect the position of the U. S. Government.

REFERENCES

Chun, K.-Y., and G. A. Henderson (2009). Lg attenuation near the North Korean border with China, Part II: Model development from the 2006 nuclear explosion in North Korea, *Bull. Seismol. Soc. Am.*, 99: pp. 3030–3038.

Jin, J., and P.-H. Park (2007). Tectonic activities and deformation in South Korea constrained by GPS observations, *Int. J. Geol.*, 1: 11–15.

Kim, S.-G., and N. Kraeva (1999). Source parameter determination of local earthquakes in Korea using moment tensor inversion of single station data, *Bull. Seismol. Soc. Am.*, 89: pp. 1077–1082.

Kohl, B., B. Barker, J. Bennett, I. Bondar, M. Fisk, H. Israelsson, K. McLaughlin, W. Nagy, M. Skov, J. Stevens, X. Yang, and B. Zuzolo (2004). Application of advanced seismo-acoustic technologies to regional monitoring of North Korea, *SAIC Technical Report SAIC-04/2200,* submitted to U.S. Army Space and Missile Defense Command, May.

Lei, J., and D. Zhao (2005). P-wave tomography and origin of the Changbai intraplate volcano in northeast Asia, *Tectonophysics*, 397: pp. 281–352.

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: pp. 1675–1692.

Murphy, J. R., B. C. Kohl, J. L. Stevens, T. J. Bennett, and H. G. Israelsson (2010). Exploitation of the IMS and other data for a comprehensive, advanced analysis of the North Korean nuclear tests, in *Proceedings of the 2010 Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-10-05578, Vol. 1, pp. 456–465.

Nuttli, O. W. (1986a). Yield estimates of Nevada test site explosions obtained from seismic Lg waves, *J. Geophys. Res*., 91: pp. 2137–2151.

Nuttli, O. W. (1986b). Lg magnitudes of selected East Kazakhstan underground explosions, *Bull. Seismol. Soc. Am.*, 76: pp. 1241–1251.

Patton, H. (1988). Application of Nuttli's method to estimate the yield of the Nevada test site explosions recorded by the Lawrence Livermore National Laboratory's seismic system, *Bull. Seismol. Soc. Am.*, 78: pp. 1759–1772.

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: pp. 665-677.

Song, P.-C., and O.-I. Thae (1993). Deep structure of the crust, in *Geology of Korea*, Foreign Language Books Publishing House, Pyongyang, North Korea.

Song, J., E. Hetland, F. Wu, X. Zhang, G. Liu, and Z. Yang (2007). P-wave velocity structure under the Changbaishan volcanic region, NE China, form wide-angle reflection and refraction data, *Tectonophysics*, 433: pp. 127–139.

Steinshouer, D., J. Qiang, P. McCabe, and P. Ryder (1997). Maps showing geology, oil and gas fields, and geologic provinces of the Asia Pacific region, *USGS Open-File Report 97-470F*.

Stevens, J. L., N. Rimer, H. Xu, G. E. Baker, and S. M. Day (2003). Near field and regional modeling of explosions at the Degelen test site, *SAIC Final Report SAIC-02/2050*, submitted to U.S. Defense Threat Reduction Agency *DTRA-TR-03-3*, January.