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Preface to the Focus Section on North Korea's September 2017 Nuclear Test and Its Aftermath

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Disclaimer

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On September 3, 2017 a large seismic event was detected near the Punggye-ri nuclear test site in North Korea (officially known as the Democratic People Republic of Korea or DPRK) by several geophysical monitoring institutions (for example, the USGS announced it as m_b 6.3 event, the CTBTO announced it as a m_b 6.1 event). Within a few hours North Korea declared it had carried out its sixth underground nuclear explosion, a test of a hydrogen bomb.

This 2017 seismic event immediately attracted the attention of the global geophysical community for a number of reasons beyond its declared nuclear source. First it was an order of magnitude larger than any of the five previous declared nuclear tests the DPRK had carried out in October 2006, May 2009, February 2013, January 2016 an September 2016. Second it was followed about eight and half minutes later by a second seismic event that appeared to be a collapse (for example the USGS reported it this way as a M_L 4.1 seismic event). Third, in the days to weeks following the test several small seismic events were reported by a number of monitoring agencies (e.g., the USGS reported events on 9/23/17, M_L 3.6 and 10/12/17 M_L 2.9) in the vicinity of the test site. These small events attracted widespread attention as to their nature and relationship to the test site geology.

Scientists around the world immediately began analyzing the available data. In addition to a flurry of international technical communications, a special event page was established at the Incorporated Research Institutions for Seismology (https://ds.iris.edu/ds/nodes/dmc/specialevents/2017/09/03/2017-north-korean-nuclear-test/), and a late breaking special session was convened at the December 2017 American Geophysical Union (AGU) meeting in New Orleans. The idea for this special focus section in Seismological Research Letters (SRL) grew out of discussions in preparation for the AGU meeting and a call for SRL papers with a due date of May 1, 2018 was announced shortly afterward. We thank the many scientists representing a variety of disciplines and institutions that responded to the call for papers for this SRL section and participated in the review process. This special section consists of 17 papers covering a full range of topics from surface observations, acoustic observations through detailed seismological investigations of the nuclear test, the post-test collapse and the additional seismic events, including event detection, location, depth and yield estimation and source type discrimination.

The September 2017 DPRK seismic events caused a variety of surface disturbances that are the subject of investigation by Pabian and Coblentz (2018) in this special section. They use satellite SAR, commercial satellite optical imagery and a short official video to investigate slumping or compression of the top 200m of Mt. Mantap associated with the 2017 test. They note two zones of slippage or subsidence in SW top corner of Mt. Mantap, but they think those zones cannot be interpreted as a "collapse crater" that was a result of a "cave-in" above any nuclear test created cavity and/or associated tunneling. Other studies not in this special section have modeled the 2017 explosion and collapse (e.g. Wang et al., 2018) and made connections to surface effects.

The surface disturbances associated with the 2017 test also produced acoustic (infrasound) signals in the atmosphere that were detected at about 400 km away at an infrasound array of the CTBT International Monitoring System (IMS) as shown by Assink et al. (2018). They found that in addition to signals generated from the epicentral region, there were also signals generated by the Hamgyong mountain range, the Tumen River delta and the Japan basin and seamounts. They note that due to the seasonal atmospheric conditions, there was a weak stratospheric vortex that complicated the signal propagation to the remote stations. This prevented the analysis of the acoustic signals to assess the event depths.

Several of the papers in this section use detailed waveform correlation to derive relative phase timing to obtain high precision relative location of the six declared nuclear tests. Here Gibbons et al. (2018), Yao et al. (2018a), Zhao et al. (2018) and Myers et al., (2018) each provide clear patterns for the relative locations of the six tests based on their relative timing. Each faces the challenge of tying the pattern to an absolute location point to anchor the relative configuration. While the overall locations are close to each other, there are small differences related to how the absolute location analysis was carried out. For example, Myers et al. (2018) tie the locations to modeling of the source of the presumed InSAR signal from the January 2016 nuclear test and Yao et al. (2018a) tie directly to the January 2016 InSAR signal location, whereas Zhao et al. (2018) tie to the presumed location for the first 2006 declared nuclear test.

Using the high-precision locations, Pasyanos and Myers (2018) then use topography and locations of the tunnel entry points to estimate the depths of the test. In addition, they use regional phase coda envelopes to try to break some of the location/depth/yield tradeoffs. They explore four different explosion models and estimate the 2017 explosion yield is about 125 kt (range 103-150 kt) at a depth of about 600 m.

Using different methods, Stevens and O'Brien (2018) estimate a yield 180 kt from relative surface wave M_s amplitude and a burial depth of 730 m. Yao et al. (2018a) estimate the yield at 109 +/- 49 kt using Lg magnitude and an inferred burial depth of 770 m between the elevations of the tunnel entrance and the located test position. Stroukova (2018) estimates a range of yields between 150-300 kt with depths close to 800 m using several different models. We note that in the absence of calibration information, those estimates fall into the expected uncertainty on the order of a factor of two in the absolute yield.

As noted by Stevens and O'Brien (2018) the amplitudes of the surface waves of the DPRK tests appear to be anomalous relative to the global population. They conduct numerical modeling studies of the interaction of explosions with topography, noting that explosions conducted within mountains have reduced surface wave amplitudes as compared with those conducted below the base of mountains or in flat topography. They argue that this may explain the differences between DPRK surface wave behavior and what has been observed at other test sites.

Several of the papers in this section address the small seismic events that appear in the vicinity of the DPRK test site (Kim et al. 2018; Schaff et al. 2018; Gibbons et al. 2018; Dodge, 2018; Yao et al. 2018b). They adopt different template matching methods, with Kim *et al*. (2018) and Schaff *et al*. (2018) using a correlation method (e.g., Harris, 1991), Gibbons et al (2018) using an array correlation method (Gibbons and Ringdahl, 2006), Dodge (2018) using a subspace detector method (Harris, 2006) and Yao *et al*. (2018b) using a match and locate method (Zhang and Wen, 2015). All these studies find new additional seismic events not reported by agencies such as the USGS and the CTBTO. Kim et al. (2018) report on 3 additional seismic events in addition to 10 reported by other agencies after the 2017 test and collapse. Yao et al. (2018b) using the more local data available in China finds a total of 88 events after the 2017 test. Dodge (2018) finds correlated events prior to the 3 September 2017 nuclear test in addition to those after the test, with related events perhaps as early as 2013. Most of the events found are in common between the papers, although some discrepancies exist possibly due to difference in templates (events chosen, window lengths, frequency bands) and available data used in the analysis.

All of these papers show there is not a clear Omori law pattern to these events that might be associated with the 2017 nuclear test. Kim et al. (2018), Schaff et al. (2018), Yao et al. (2018b) and Dodge (2018) all locate these events about 4-8 Km north of the DPRK test site. In addition, Schaff et al. (2018) and Yao et al. (2018b) show a subset of these events appear to trace out a north striking fault region. Kim et al. (2018), Zhao et al. (2018) and Walter et al. (2018) show that P/S ratios from these small events are consistent with them being regular earthquakes. Given their location and timing, the relationship of these apparent earthquake events to the DPRK nuclear testing remains intriguing but unresolved. Yao et al. (2018b) argue they may be triggered events related to testing, and this is possible, but some findings remain to be explained, such as the reported presence of events as early as 2013 by Dodge (2018) and the unique seismicity pattern. A better understanding of these apparent earthquakes near and north of the DPRK test site should be a topic of future work.

A number of papers address regional discrimination methods to identify event source type. Walter et al. (2018) use low/high frequency ratios to identify the relative lack of high-frequency energy in Nevada and DPRK post nuclear test collapse events. They note that a combination of P/S ratios and low/high frequency ratios may be able to uniquely identify collapses for small events where waveform modeling identification may not be possible. Kim et al. (2018), Zhao et al. (2018) and Walter et al. (2018) all show P/S ratios clearly separate the nuclear tests from both tectonic earthquakes and the collapse event. As noted above these papers also show or imply the 9/23/17 and 10/12/17 events reported by the USGS and the events correlated with those discussed above have P/S ratios consistent with earthquakes.

Several papers make use of regional waveform modeling and focal mechanism information to perform moment tensor analysis on these events. Liu et al. (2018b) invert a mean source moment tensor model of all six North Korea's nuclear tests based on synthetic waveform fitting the seismic records that are averaged from all the tests, Chiang et al. (2018) and Alvizuri and Tape (2018) perform individual event modeling waveforms and first motion modeling specifically for the 2017 test and collapse, and Yao et al. (2018a) take an approach of using the collapse event 8.5 minutes later as reference to eliminate the path effects and obtained a source solution based on the observed noncircular Rayleigh wave radiation pattern and Love/Rayleigh amplitude ratios. All these studies suggest that the source of the 2017 test consists of a dominant isotropic component related to the explosion and an additional component associated with a secondary source. However, they differ on the nature of the secondary source, with Liu *et al*. (2018b) suggesting an oblique compensated linear vector dipole (CLVD) source related to medium damage after the test, Alvizuri and Tape (2018) a sum of a double couple and a crack tensor whose plane is near horizontal, and Yao *et al*. (2018a) either an oblique CLVD or a double couple explaining the data equally well. Yao *et al*. (2018a) further propose a deformation scenario where the 2017 test generated a prompt source medium damage expanding away from the test center mostly along the direction of 320° represented by an oblique CLVD. Then they suggest the deformed rocks collapsed toward the test center along the weakness direction in an opposite way represented by the collapse event 8.5 minutes later as suggested earlier by Tian et al. (2018). Alvizuri and Tape (2018), Chiang et al. (2018), and Liu et al. (2018) all show that moment tensors clearly discriminate the 2017 declared nuclear test from the post-test collapses and earthquakes on source type plots (e.g. Ford et al, 2009). These papers show moment tensor modeling can be a routine part of monitoring.

Chiang et al. (2018) and Alvuzuri and Tape, (2018) identify the event eight and half minutes after the explosion as a collapse mechanism consistent with a closing crack or two-sided vertical point force model. This is consistent with papers outside this special issue by others (e.g. Tian et al., 2018; Wang et al., 2018). Chiang et al. (2018) show the volume of the collapse cavity needed to match the moment tensor modeling is consistent with that expected to be produced by vaporization during the nuclear explosion, where as if a tunnel collapse was the source significant lengths of tunnel collapse (roughly 10 km) would be necessary.

Finally, Stroukova (2018) makes use of the six explosions recorded at common stations to perform a non-parametric inversion for source spectra and a common spectral path/site effect. She finds the DPRK source spectra are consistent with Mueller and Murphy (1971) and Denny and Johnson (1991) explosion source models with omega to the minus two falloff.

The DPRK is not one of the 183 current signatories of the Comprehensive-Nuclear-Test-Ban Treaty (CTBT) and it is the only country that has conducted underground nuclear explosions in this century. In May 2018 DPRK invited journalists to view chemical explosions at its test site that it declared would damage its test site and limit its future capability to test nuclear weapons. While the future of nuclear testing in DPRK and indeed the rest of the word is subject to ongoing political discussions, monitoring science continues to advance.

As shown in these papers, a remarkable amount of detail about nuclear testing can be determined remotely. These SRL special section papers highlight significant advancements in scientific approaches of studying seismic sources: 1) high-precision relative location methods utilizing geodetic constraints allows the determination of a nuclear test location to reach a precision of an order of 100 m, 2) with the precise event location known and coupled with satellite imagery, the burial depth, an essential event parameter for yield estimate of a nuclear test, can be accurately determined, 3) with the approach of using a neighboring event as reference, our confidence of deciphering the secondary source accompanying a nuclear test is increased to new levels, and 4) template matching can dramatically lower detection thresholds, and reveal heretofore unknown earthquake activities or small-yield nuclear tests in and around nuclear test sites.

Perhaps in the future, when details about the DPRK tests are more fully revealed, we will be able to better assess the strengths and weaknesses of the analyses presented here. In the meantime, the techniques developed and demonstrated in the papers in this special section are available for future nuclear test monitoring, and in many cases already being used, to better understand and monitor the hazards posed by tectonic earthquakes worldwide.

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Order of papers:

1) Walter and Wen – Preface
2) Pabian and Coblenz – surface effects
3) Assink et al. – acoustic/infrasound
4) Gibbons et al - location
5) Zhao et al - location
6) Myers et al – location
7) Pasyanos and Myers – Yield/depth/location
8) Stevens and O'Brien – surface wave modeling
9) Yao et al 2018a
10) Kim et al
11) Shaff et al
12) Dodge
13) Walter et al

14) Alvuzuri et al
15) Chiang et al
16) Liu et al
17) Stroukova