North Korea’s 2017 Test and its Nontectonic Aftershock

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Abstract Seismology illuminates physical processes occurring during underground explosions, not all yet fully understood. The thus-far strongest North Korean test of 3 September 2017 was followed by a moderate seismic event (mL 4.1) after 8.5 min. Here we provide evidence that this aftershock was a nontectonic event which radiated seismic waves as a buried horizontal closing crack. This vigorous crack closure, occurring shortly after the blast, is studied in the North Korea test site for the first time. The event can be qualitatively explained as rapid destruction of an explosion-generated cracked rock chimney due to cavity collapse, although other compaction processes cannot be ruled out.

Plain Language Summary North Korea detonated its strongest underground nuclear test in September 2017. It attracted the public interest worldwide not only due to its significant magnitude (6.3 mb) but also because it was followed 8.5 min later by a weaker event. Was the delayed shock a secondary explosion, an earthquake provoked by the shot, or something else? We answer these questions, thanks to unique data from near-regional broadband stations. We basically solve a simple problem—fitting observed seismograms by synthetics. The good fit means that we understand why and how the seismic waves are radiated. According to our model, the explosion created a cavity and a damaged “chimney” of rocks above it. The aftershock was neither a secondary explosion nor a triggered tectonic earthquake. It occurred due to a process comparable to a “mirror image” of the explosion, that is, a rock collapse, or compaction, for the first time documented in North Korea’s test site. Interestingly, shear fault motions, typical for natural earthquakes, were extremely small both in the explosion and in the aftershock. Small natural earthquakes also occur at the test site, and geotechnical works might trigger them. Thus, all studies related to rock stability of the site, and prevention of radioactive leakage, are important.

1. Introduction

Five tests were performed at North Korea’s Punggye-ri test site in 2006, 2009, 2013, and 2016 (twice). Their body wave magnitude (mB), reported by United States Geological Survey (USGS), increased from 4.3 in 2006 to 5.3 in 2016. Relative methods, including waveform interferometry (Murphy et al., 2013; Wen & Long, 2010; Zhang & Wen, 2013; Zhao et al., 2017), located the 2006–2016 events within an ~5 × 5-km region. Seismic estimates of burial depths (<800 m) were supported by satellite images of the entrance tunnels under Mt. Mantap (Murphy et al., 2013). The explosion yield estimate, which strongly trades off with depth, remained challenging (Koper et al., 2008). The full moment tensor (MT) inversion of the 2009 test revealed a nondouble-couple source (e.g., Ford et al., 2009b). Nonisotropic radiation, including shear motion, was observed in the 2013 test (Barth, 2014; Vavryčuk & Kim, 2014). The 2016 tests helped to delimit a significant uncertainty in the source parameters (Cesca et al., 2017). The uncertainty is due to poor resolution of the depth and certain moment-tensor components when a shallow nondouble-couple source is studied at long wavelengths (e.g., Bukchin et al., 2010; Henry et al., 2002). It yields significant trade-offs between moment magnitude Mw and the moment-tensor parts (double couple [DC], compensated linear vector dipole [CLVD], and isotropic [ISO]). Fortunately, resolvability of the source type (explosion, implosion, and crack) appears to be less affected, mainly if combining waveform data with first-motion polarities (Chiang et al., 2016). In the present paper the resolution is studied with a Bayesian approach (Hallo et al., 2017; Vackář et al., 2017), thus providing probability density functions (PDFs) of the source parameters.

Many nuclear tests in the past were accompanied by an underground collapse (e.g., Springer et al., 2002), but only a few studies of related seismic events were published, mostly before the 1980s. For example,
a sequence of weak events \( (m_b < 3.8) \) following the explosion at Amchitka was observed, eventually terminating with a large complex shock \( (m_b 4.9, 38 \text{ hr after the } \sim 5 \text{ Mt nuclear test CANNIKIN}) \) (Engdahl, 1972). The sequence was explained as due to a progressively deteriorating cavity and explosion-generated chimney, while the largest shock was attributed to a major, complete collapse, concurrent with surface subsidence. We study a similar event, as large as \( (m_L 4.1) \) but occurring shortly (8.5 min) after the 2017 test in North Korea.

On 3 September 2017, at 03:30:01 UTC, the thus-far strongest North Korean test of \( (m_b 6.3) \) (USGS) was detonated near the previous explosions (Figure 1a). Later, at 03:38:31, an event of \( (m_L 4.1) \) (USGS) was reported at the test site. Here we analyze source processes of the recent explosion (mainshock) and its early \( (m_L 4.1) \) aftershock, hereafter referred to as Events 1 and 2, respectively. We focus predominantly on Event 2, and our main finding is its crack-closing nature, without any shear-slip signature. A deep insight into Event 2 is possible thanks to unique data from nearby broadband seismic stations. At more distant stations, Event 2 is obscured by noise and seismic coda of Event 1. At the end we also briefly mention a tectonic aftershock (Event 3) that occurred 20 days after the 2017 test. Basic parameters of the three events are given in Table S1a in the supporting information.

2. Methods

2.1. Inverting Waveforms for Full Moment Tensor

Seismic waveforms are inverted for full MT using software ISOLA (Sokos et al., 2016; Zahradník et al., 2017). Full MT is calculated by least-squares fitting of band-pass filtered displacement waveforms, accompanied by grid-searching of the centroid depth and time. A point-source approximation, the delta-function moment rate, and a 1-D velocity model are assumed for calculating full-wave Green’s functions by the discrete wavenumber method, including the near-field terms as well as all existing types of body waves and surface waves (Bouchon, 1981; Coutant, 1990). Each MT is represented by a weighted average of six elementary MTs: five DC tensors and one ISO tensor. Model parameters of the inverse problem are simply the weights \( a_1–a_6 \) of the elementary MTs. The weights are related to the components of the full MT (Křižová et al., 2013, equation (4)). The MT is decomposed into the DC, CLVD, and ISO parts, and their percentages are calculated. The percentages are used to determine a “tensility” factor (Vavryčuk, 2011): \( c = \text{sign}(\text{ISO}/\text{CLVD})\times100 \). The match between real and synthetic waveforms is quantified by variance reduction, and resolvability of the inverse problem is characterized by condition number.

Let the MT diagonal horizontal and vertical Cartesian components be \( M_{xx}, M_{yy}, M_{zz} \). Then the ISO and CLVD moments (Patton & Taylor, 2011) are calculated as \( M_1 = \text{trace}(\text{MT})/3 \), and \( M_{\text{CLVD}} = M_{zz} - M_1 \). We also employ their index \( K \), enabling classification of nuclear explosions: \( K = 2M_{zz}/(M_{xx} + M_{yy}) \). Major dipole of CLVD is vertical, \( M_{\text{CLVD}} > 0 \) or \( < 0 \) for extension and compression, respectively.
2.2. Analyzing Resolution of Moment Tensors

For any single source position (e.g., a given trial depth below epicenter), the full-MT calculation is a linear inverse problem, solved by the least-squares method, providing a best-fit solution. The posterior covariance matrix of model parameters $C_m$ is expressed via the Green's function matrix and data covariance matrix $C_d$. Hence, a Gaussian posterior PDF is known. The covariance matrix $C_m$, together with the best-fit solution, can be used to generate a suite of random MTs from the multivariate normal distribution. In this way, marginal probability density (histogram) can be obtained for any parameter, including the parameters which are nonlinearly related to MT, for example, DC%; ensemble plots of nodal lines can be also constructed.

If the source depth is included in the model parameters, the inverse problem is nonlinear. The least-squares waveform inversion is repeated at a series of trial source depths, each one with its own best-fit solution and own $C_m$. Total PDF is summed from the single-depth PDFs, which are properly normalized. The normalization constants (Hallo et al., 2017), derived in equation (10) of the cited paper, depend on the $C_m$ matrix and the waveform misfit at each depth. For each depth, a set of random MTs is generated, while the number of samples is proportional to the normalization constants. The union of the sample sets represents the total PDF. Therefore, histograms and nodal-line plots reflect also the uncertainty in the depth. This method has been recently included in ISOLA, to replace the previous uncertainty assessment via error ellipsoids (Zahradník & Custódio, 2012).

To estimate $C_d$ we use the simplest method, assuming $C_d = \sigma^2 I$, where $\sigma$ is standard data deviation (so-called data error) and $I$ is unit matrix. The “data” error refers jointly to effects of noise and inaccurate velocity model, where in our study the latter is predominant. We assume the data error $\sigma$ to be of the same order as the displacement amplitude at distant stations (Křížová et al., 2013). This is a simplifying approach, applicable in a relative assessment of the uncertainty of the depth, $M_w$, DC%, CLVD%, and ISO% values.

3. Seismic Evidence

We primarily used 12 nearest-to-source broadband seismic stations, at epicentral distances ~70–310 km (Figure 1b). Prior assessment of data quality included particle-motion analysis for checking sensor orientation and removal of records with instrumental disturbances (Zahradník & Plešinger, 2010). A suitable frequency range, featuring low noise and enabling full-wave modeling with simple velocity models, was found at
0.03–0.06 Hz. Two velocity models (Bassin et al., 2000; Ford et al., 2009b) presented in Table S2 were used, with only minor effects on the results. The models enabled waveform fitting of dominant (surface) waves without any artificial time shifts. At long wavelengths, as here, the inherent inaccuracy of epicenter (within ~5 km) is unimportant. Thus, we assumed a common epicenter for Events 1 and 2 at 41.30°N, 129.07°E. We used trial source depths at 0.5–2.5 km, with increment of 0.5 km. Source depth in this study is an effective depth for near regional stations and long-period waves, not exactly the burial depth. For the satisfactory match between real and synthetic waveforms in our source models, see Figure 2.

Twenty-four more distant stations up to ~1,100 km (Figure 1b) were used for checking first-motion polarities. Altogether, 30 polarities were reliably determined for Event 1, all positive, but none was clear enough for Event 2.

### 3.1. Mainshock (Event 1)

As in previous studies (Ford et al., 2009b), waveform matching was not sensitive to the source-depth variations, so the depth could not be resolved (the best-fitting solutions are in Tables S3 and S4). Strong trade-off between the source parameters is illustrated by the PDF in Figure 3; for histograms and nodal lines, see Figures S1–S3 in the supporting information. Moment magnitude $M_w$ trades off with depth, decreasing from 6 to 5.6 over the examined depth range of 0.5–2.5 km. At the 1.5-km depth, which might perhaps be preferred, in analogy with the seismic array study of the 2016 test (Cesca et al., 2017), the $M_w$ 5.7 is obtained; the full MT is given in Table S1b. The ISO part (ISO ~55–60%), together with the CLVD (CLVD ~30–45%), clearly dominates over the DC part (DC ~0–10%). Therefore, while not excluding small shear slip during the mainshock, we focus on the dominant sum of the CLVD and ISO parts. The equivalent body forces are illustrated in Figures 4a–4c. This model predicts compressive first arrivals on the entire focal sphere. We did not observe any reliable dilatation at the 30 stations of Figure 1b, but we cannot rule out any possible occurrence of dilatation at a few stations elsewhere, due to uncertainties discussed later. The explosion is well modeled by a triaxial extension, whose vertical dipole is ~2.7 times greater than the two equal horizontal dipoles at an assumed depth of 1.5 km, implying a relatively high index $K$ ~2.7 (or even higher, $K$ ~2.9 at a depth of 0.5 km). It means that the ratio of the CLVD and ISO moments (Patton & Taylor, 2011) is relatively high, $M_{CLVD}/M_I$ ~0.7. The a4–a6 model parameters corresponding to the dominant CLVD and ISO part can be found in Table S5. If considering also the small a1–a3 parameters of Table S5, the major extensional axis deviates from vertical by less than 10°.

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**Figure 3.** Resolution of source parameters of the (a) mainshock and (b) nontectonic aftershock. Bayesian analysis of the probability density function, treating the source depth and moment tensors as model parameters, shows significant trade-offs between the double-couple (DC), compensated linear vector dipole (CLVD), and isotropic (ISO) parts. The bottom-right frames of both panels refer to the $M_w$-DC trade-off. Random samples are shown as black dots. Best-fit solutions at five trial depths are also marked (red crosses).
Figure 4. Inferred interpretation of (a–c) mainshock and (d–f) nontectonic aftershock. Dominant body forces equivalent to seismic radiation are shown for an assumed depth of 1.5 km. The force couples are annotated with their relative size. Scaling factors for mainshock and aftershock are 5.33e17 and 3.40e16 Nm, respectively. The events radiated as an opening and closing horizontal crack, with a significant compensated linear vector dipole contribution. Schematic sketch (g) shows the structural elements and processes, discussed in the text. (h) Vertical components of normalized full-band raw data of Event 1 (red) and Event 2 (black). Traces of Event 2 are plotted with opposite sign; thus, the surface waves match with Event 1. It illustrates the “mirror-image” character of the two sources. Note also the absence of high-frequency body phases in the records of Event 2, similar to “collapse” events (Engdahl, 1972; Ryall & Savage, 1969; Willis, 1963). Origin time is at \( t = 0 \).
Before proceeding to aftershocks, which practically cannot be analyzed from more distant stations, we verify the mainshock results at 10 stations in Japan. Lower frequencies (0.02–0.04 Hz), as in Cesca et al. (2017), need to be used due to modeling problems at the considerably greater epicentral distances (750–1,100 km). The full MT derived from the 12 stations was used to forward simulate the observed data in a single 1-D model derived from Crust2.0 (Bassin et al., 2000), while assuming the source depth of 1.5 km (i.e., full MT derived from the 12 stations was used to forward simulate the observed data in a single 1-D model).

The mirror-image character of the two MTs (inferred at long periods), that is, MT1 = const. MT2, where the constant is negative, const = −16, and subscripts refer to Events 1 and 2, is best justified in Figure 4h. In that plot we demonstrate normalized raw data of vertical components, that is, full-band records of Events 1 and 2, while Event 2 is shown with opposite sign, thus producing a very good match in the surface-wave group with Event 1. Moreover, the same figure illustrates a clear deficiency of high-frequency body phases in the raw records of Event 2, relative to Event 1.

3.2. Nontectonic Aftershock (Event 2)

The DC part of the aftershock is very small (Figures 3 and S1–S3 and Tables S4 and S5); that is why we call it nontectonic aftershock. The event exhibits striking complementarity to Event 1, as illustrated in Figures 4d–4f, where the ratio of the dominant CLVD and ISO is practically the same as for Event 1. Note the negative signs; CLVD < 0 implies that the major axis is compressive, while ISO < 0 is an implosion. Thus, apart from its size, Event 2 is a mirror image of Event 1. It represents a symmetric, triaxial compression, with horizontal dipoles being one-third of the vertical dipole. The full-MT beach ball would be empty; all first arrivals should be dilatations. However, as explained, this latter feature cannot be verified due to natural noise and coda of Event 1. The resulting K-index is similar to Event 1.

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3.3. Tectonic Aftershock (Event 3)

Strongly contrasting with the small DC part of Events 1 and 2 is an aftershock of Mw 3.6 (USGS), occurring nearby on 23 September, that is, 20 days after the test. A significant generation of Love waves is clearly seen in Figure 2c. We were able to match waveforms of this small event with a DC-constrained model at 0.08–0.12 Hz, and we found sensitivity to variation of the trial source depth, as usually observed for tectonic (high-DC) events. The preferred depth was 3.5 km. The inversion, supplemented by first-motion polarities revealed a normal-faulting focal mechanism, presented in Table S1a. Two smaller events occurred between 19 and 23 September, but their focal mechanisms could not be calculated.

4. Interpretation

Formal interpretation of the inferred body forces is straightforward. Both events can be described in terms of a tensile source model (Julian et al., 1998; Vavryčuk, 2011). For DC < 10%, the "tensility" factor c > 0.9 implies that Events 1 and 2 are almost pure extensive and compressive sources, that is, opening or closing cracks, respectively. The CLVD and ISO parts of the tensile models are related via P and S wave velocities at the source (Vavryčuk, 2011). Applying this concept to our model of Figure 4, for both events, we obtain a somewhat lower Vp/Vs ratio of the aftershock at all trial depths (Tables S3 and S4). This means that if a change in material parameters occurred in the source zone due to material failure (Patton & Taylor, 2011), it was small.

Physical explanation as to why a tensile model well suits both events is possible, thanks to recent understanding of explosive processes (Patton & Taylor, 2008, 2011). Primary effects of buried nuclear explosions are cavity formation and damage to the surrounding medium by shock waves. Various secondary effects include interactions with the free surface, hydrodynamic flows, rotations, vertical parting of horizontal layers, extensional block motions, heaving and bulking at depth, cavity rebound, and gravitational unloading of the...
spalled surface layers (Figure 4g). In this light, the ISO part of Event 1 appears to arise from cavity formation and nonlinear failure in the shot vicinity (Patton & Taylor, 2011), while CLVD is due to shock-induced, deep-seated vertical extensional deformations and horizontal contractions around the explosion (Patton & Taylor, 2008).

Additional support for our high-$K$ model comes from magnitudes, determined independently of this study. Considering the $M_S$-$m_b$ plot, used for discrimination purposes, a high-$K$ event should be situated well below the screening lines (Selby et al., 2012). Indeed, we found such a remarkable feature of Event 1 (Figure S5a).

Event 2 can be formally interpreted as a purely compressive, crack-closure source. It resembles certain mining-induced seismic events. For example, a prevailing vertical compressive dipole is a suitable body-force equivalent of a pillar burst, while a single force is a plausible model of cavity collapse (Šílený & Milev, 2008; Smith, 1963). At long wavelengths, as in our study, a single vertical force and a horizontal crack closure are indistinguishable (Day & McLaughlin, 1991). A cavity collapse following the nuclear test ATRISCO was modeled as closing crack (Ford et al., 2009a), and references to mine collapses can be found in the same paper. Although the cavity itself is not likely to collapse within seconds, owing to the melted-rock envelope formed during detonation (Patton & Taylor, 2011), it usually deteriorates later. Vapor is released, and a chimney of cracked material is formed (Figure 4g) and migrates upward, usually within minutes or hours (Hawkins, 2011). Seismic events attributed to cavity deterioration and chimney collapse have been known (e.g., Engdahl, 1972; Ryall & Savage, 1969; Willis, 1963). They have been characterized by a relatively low-frequency radiation, as observed in this paper (Figure 4h). Moreover, collapse events observed in the 1960s and 1970s were reported to have symmetric sources, generating insignificant Love waves (Toksoez et al., 1971), as also observed here (Figure 2b). Therefore, we can qualitatively interpret the crack-closure model of Event 2 in several ways; for example, (i) Cavity deterioration and its filling by the damaged chimney material represented the observed crack closure. (ii) Due to progressive filling of the deteriorated cavity, an empty space was created inside the chimney above the cavity, and this space was then closed by a downward movement of the resting top part of the damaged chimney. Using the crack model, originally developed for spall (Day & McLaughlin, 1991), the empty space can be roughly estimated as $1 \times 10^6$ cubic meters.

5. Conclusion and Outlook

The 2017 test (mainshock, Event 1) and the nontectonic aftershock occurring 8.5 min later (Event 2) were subjected to a long-wavelength moment-tensor study. The study included a careful resolution analysis of the source parameters, that is, the source depth, DC%, CLVD%, ISO%, and $M_w$, revealing their significant mutual trade-offs (Figure 3). Both events featured a very small DC part (especially Event 2). Event 2 is strongly contrasting with a small normal-faulting, tectonic earthquake (Event 3) that occurred nearby 20 days after the test.

In terms of body-force equivalents, the seismic wave radiation of Events 1 and 2 points to “mirror-image” processes of a crack opening and crack closure, respectively. Their CLVD/ISO ratio is significant. The compressional nature of the aftershock can be possibly explained as due to various compaction processes known to follow nuclear explosions, for example, sudden closure of an open space created in the explosion-generated chimney after the cavity collapse. The collapse character of Event 2 is also supported by a remarkable lack of high-frequency body-wave radiation relative to Event 1 (Figure 4h), in agreement with previous observations (Engdahl, 1972).

As Chiang et al. (2016) we conclude that in spite of the significant parameter tradeoffs, discussed in Figure 3, the source-type interpretation in terms of the crack models is stable, not critically suffering from the well-known free-surface long-period resolution problems. The stability is best documented by strong dominance of the vertical CLVD and ISO parts, found across all tested depths in a broad interval of condition numbers (Tables S3 and S4). Naturally, the successful interpretation was possible in this paper also thanks to the relatively low-noise data, and thanks to validation at Japan stations. Event 2, complicated by the preceding Event 1, and not allowing validation in Japan, would not be interpreted as safely as Event 1 if not observing the mentioned “mirror imaging” in Figure 4h, which is a strong observational result at relatively short periods (< 5 s), beyond the modeling range. First motion polarities, which would further stabilize the source-type interpretation (Chiang et al., 2016), were unfortunately not readable for Event 2 at all.
Seismic models, like in this paper, provide only partial understanding of the underground explosions. Physicochemical models are needed to fully explain the involved processes and to illuminate environmental aspects, such as release and migration of radionuclides, possibly contaminating groundwater (Tompson et al., 2002).

References


