The rise, collapse, and compaction of Mt. Mantap from the 3 September 2017 North Korean nuclear test

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Title: The rise, collapse, and compaction of Mt. Mantap from the 3 September 2017, North Korean nuclear test

Authors: Teng Wang^{1*}, Qibin Shi^{1,2}, Mehdi Nikkhoo³, Shengji Wei^{1,2*}, Sylvain Barbot^{1,2}, Douglas Dreger^{4*}, Roland Bürgmann⁴, Mahdi Motagh^{3,5} and Qi-Fu Chen⁶

Affiliations:

¹ Earth Observatory of Singapore, Nanyang Technological University, Singapore

² Asian School of Environment, Nanyang Technological University, Singapore

³ GFZ, German Research Centre for Geosciences, Potsdam, Germany

⁴ Department of Earth and Planetary Science, University of California, Berkeley, California, USA

⁵ Institute for Photogrammetry and GeoInformation, Leibniz Universität Hannover, Hannover, Germany

⁶ Key Laboratory of the Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

*Corresponding authors: wang.teng@ntu.edu.sg, shjwei@ntu.edu.sg, dreger@seismo.berkeley.edu.

Abstract: Surveillance of clandestine nuclear tests relies on a global seismic network, but the potential of spaceborne monitoring has been underexploited. Here, we determined the complete surface displacement field of up to 3.5 m of divergent horizontal motion with 0.5 m of subsidence associated with North Korea's largest underground nuclear test using satellite radar imagery. Combining insight from geodetic and seismological remote sensing, we found that the aftermath of the initial explosive deformation involved subsidence associated with sub-surface collapse and aseismic compaction of the damaged rocks of the test site. The explosive yield from the nuclear detonation with seismic modeling for 450m depth was between 120-304 kt of TNT equivalent. Our results demonstrate the capability of spaceborne remote sensing to help characterize large underground nuclear tests.

Main Text: World peace benefits from the adherence to internationally negotiated nuclear-test-ban treaties that strive to promote the nonproliferation of nuclear weapons. In 2003, the Democratic People's Republic of Korea (North Korea) became the first country to withdraw from the 1968 Non-Proliferation treaty and started to conduct underground nuclear weapon tests with increasing intensity since 2006. On 3 September 2017, two seismic events separated by ~8.5 minutes were detected in the North Korea's Punggye-ri nuclear test site. Soon thereafter, North Korea's state media reported the successful firing of a two-stage thermonuclear bomb test. The US Geological Survey and China Earthquake Networks Center determined a body wave magnitude (m_b) of 6.3 for the first event (NKNT 6), much larger than the five nuclear tests since 2006 (NKNT 1-5). Shortly after, the scientific community started to determine the location, focal mechanism, and yield of the explosion using seismic waveforms and satellite optical imagery (1). Preliminary analysis revealed a predominantly isotropic explosive source located beneath Mt. Mantap (1,2), which also hosted NKNT 2-5 (Fig. 1).

The source properties of previous North Korean underground nuclear tests have been extensively studied using seismic waveforms (3-12), but surface displacements associated with these explosions are rarely reported. Remote sensing with Synthetic Aperture Radar (SAR) is a powerful technique for monitoring deformation of the Earth's surface (14,15) but its contribution to characterizing nuclear tests has been limited. The NKNT 4 conducted on 6 January 2016 has been studied using SAR interferometry, but the interpretation of interferometric phase is challenged due to the single imaging geometry (16). Tracking the amplitude features of the SAR images (so called pixel-offset tracking) is better suited when the interferometric phase is decorrelated (17). Moreover, pixel offsets can map displacement along the radar line-of-sight (LOS) and the satellite flying (azimuth) directions. In contrast to offset tracking of optical images, the SAR range offset is sensitive to the vertical displacement because of the slant-range imaging geometry, allowing for deriving three-dimensional (3D) displacements (18-21). Here we rely on detailed 3D displacements derived from sub-meter

1 resolution SAR images together with seismic waveform data to reveal the complex processes
2 that took place during and in the immediate aftermath of NKNT 6.

3
4 We measured the surface displacements caused by NKNT 6 by cross-correlating high-resolution
5 spotlight radar images acquired by the German TerraSAR-X satellite, with an azimuth resolution
6 of 1.1 m and a slant-range resolution as fine as 0.45 m (fig. S1, Table S1). The accuracy of the
7 offset measurement is about 1/10 of the imaging resolution (22). We combined the azimuth
8 and range offsets from two ascending and two descending tracks to calculate the total 3D
9 surface displacements produced during and in the immediate aftermath of the explosion on a
10 300-by-300 m grid (Fig. 1 and fig. S3-S5, 23). The horizontal motions of up to 3.5 m show a
11 divergent pattern at the top of Mt. Mantap with a central zone of subsidence of ~ 0.5 m. We
12 decomposed the 3D displacements into vertical and horizontal directions along two
13 topographic profiles across the top of Mt. Mantap (Fig. 1). The along-profile displacements
14 show that the horizontal displacement is generally larger where the topography is steeper (the
15 west and south flanks). However, the direction of motion does not follow the slope of the
16 terrain but is nearly horizontal. This indicates that while there is strong topographic control on
17 the surface displacement field caused by the buried explosion, it does not resemble the slope-
18 parallel motions expected from triggered landslides. While optical imagery suggests isolated 10-
19 100 m scale landslide deposits (24), these appear to be debris flows localized in pre-existing
20 channels that could not produce the large-scale horizontal motions we observed.

21 To resolve the horizontal location and depth of the detonation chamber, we set up numerical
22 models that predict the surface displacements due to the expansion and subsequent collapse of
23 an underground cavity embedded in a uniform elastic crust below realistic surface topography
24 (25,26) (Fig. 2). We constrained the 3D location of the source by minimizing the misfit between
25 predicted and observed surface displacements (27,28). The explosion and immediate collapse
26 of a 300 m radius spherical cavity that includes the detonation chamber and the surrounding
27 damaged material reproduced the horizontal displacement well but was not sufficient to
28 explain the small vertical motion around Mt Mantap. A third, mostly aseismic process involving
29 the compaction of a larger volume is invoked to explain the low uplift (Fig. 2A and fig. S6). A

similar compaction process has been inferred from the seismic analysis of other explosions (13) and was observed in the weeks to months following underground nuclear tests conducted in Nevada (29). As we do not have any constraints on the geometry of the compaction zone, we assumed a generalized ellipsoidal geometry for it and inferred its dimensions by using the geodetic observations. We estimated the explosive source to be located at 129.078-°E/41.300°N±50 m, 1750±100 m above mean sea level, i.e., 450±100 m below the top of Mt. Mantap. Incorporating the large-scale compaction source into the model does not significantly influence our inferred epicenter of the explosion/collapse source (23).

Assuming that the hypocenter of the first event coincides with the center of the spherical cavity we refined the relative location for the second seismic event using local seismic waveform records from the NorthEast China Seismic Array to Investigate Deep Subduction (NECSAIDS) (30) and regional data from South Korean sites archived at the Incorporated Research Institutions for Seismology (IRIS) (Fig. 3A) (23). With the calibration from the first event and careful P-wave arrival picks of the second event (figs. S7-S8), our grid search showed that the second event occurred 8 min 31.79 s after the first event and is located about 700 m to the south. Due to the azimuthal gap in the station coverage, the east-west location (±700m) is less well constrained compared with the north-south separation (±200m with 96% confidence) (Fig. 3C and fig. S9). The refined location of the second implosive event is beneath the area of large subsidence and southward horizontal motion under the south flank of Mt. Mantap, between the initial explosion and the south portal of the tunnel system (Fig. 1).

We applied the generalized Cut-And-Paste (gCAP) method (31) to the regional and local waveform data to invert for the full moment tensor solutions of the two seismic events, including isotropic (i.e., explosive or implosive volume source), compensated-linear-vector-dipole (CLVD) (i.e. ring faulting along a certain axis, like a collapse), and double-couple (i.e., shear dislocation on planar fault) components (23). Our preferred solution of the first event indicates a moment of 9.5×10^{16} N m ($M_w=5.24$) and a 50-90% positive isotropic component, and relatively small CLVD or double couple contributions (figs. S10-S13). The second seismic event

($M_w=4.5$) has a large negative isotropic component (~50-70% of the total moment) (figs. S14-15). While we obtained a high waveform cross-correlation coefficient between the data and synthetics for most of the waveform components of the first event (e.g. Fig. 3B), the noise level for the second event is larger, resulting in a much smaller variance reduction of the observations (fig. S16). To overcome this limitation of the data, we drew insight on the moment tensor of the second event by directly comparing the waveforms with those of the first event. We multiplied the amplitude of the vertical-component waveforms of the second event by a factor of -60 and compared them with the waveforms of the first event at higher frequencies (~0.2-0.9 Hz). The result (Fig. 3D and fig. S16) shows very high waveform cross-correlation coefficients, even for some coda waves, supporting the close locations but opposite isotropic polarities of the two events (2).

Combining the depth constraints from geodesy and energy constraints from seismology, we can refine the explosive yield of the nuclear explosion (32,33). We assumed the seismic velocity model MDJ2 (4) for the elastic earth structure. We based the overburden pressure on the best-fitting centroid source depth of 450 ± 100 m from the geodetic modeling. The medium in which the device was detonated was likely the granodiorite that lies beneath the stratified volcanic rocks that make up the high elevations of Mt. Mantap (8). We assumed a gas porosity of 1% for granitic rocks (35). Considering an isotropic seismic moment of magnitude $M_w=5.05$ (the mean value of solutions fitting within 95% of the maximum fit for a source depth of 450m) and the possible range of source depths of 350-550 m, the yield estimates range between 171-209 kt of TNT equivalent, with 191 kt corresponding to the best-fitting source parameters from geodetic and seismic data (Fig. 3E). Doubling the gas porosity results in an 8% increase in the magnitude of estimated yield.

The source characteristics we derived from surface displacement and seismic waveforms are in remarkable agreement. The divergent horizontal motions and the moment tensor of the first event consistently suggest a predominant isotropic explosive source buried at shallow depth. The moment of the geodesy-derived models, assuming an empirical rigidity of 5.7 GPa (36), is $M_w=5.5$, larger than the one inferred seismically ($M_w=5.24$), because it includes slow

1 deformation that did not generate seismic waves - with a total volume change of 0.01 km^3 . The
2 seismic analysis of the second event reveals an implosive seismic source that occurred south of
3 the first event with a dominant negative isotropic component, suggesting an inverse process of
4 the main explosion. This may reflect the combination of negative isotropic compaction of the
5 over-pressured cavity and/or vertical collapse of the explosion chimney and nearby tunnel
6 segments due to gravity, contributing to the subsidence on the south flank of Mt. Mantap (Fig.
7 4). The larger-scale compaction source in the geodetic model is independent of the first and
8 second seismic events, and the post-explosion compaction of surrounding rocks may continue
9 aseismically for an extended period, as seen in the Nevada underground nuclear test site with
10 initial subsidence rates of $\sim 1\text{-}7 \text{ cm/yr}$ (29).

11
12 Our 3D surface displacement measurements and elastic modeling incorporating realistic
13 topography allow for locating the main explosive event within $\pm 50 \text{ m}$ assuming a uniform elastic
14 medium, but a non-uniform structure and small-scale surficial processes (e.g., landslides) may
15 bias our results. As the largest deformation occurred above the explosive source due to the
16 chimneying and spalling effect (13), the centroid of the modeled geodetic source may locate
17 above the actual detonation point. Following the explosion, water was observed to be flowing
18 from the tunnel portal (24). Assuming a slope of 2-4 degrees to provide drainage, the depth
19 implied from the elevation of the tunnel entrance is about 600-700 m below the surface,
20 consistent with a detonation point about 150 m deeper than the centroid of geodetic model.

21
22 Combining the available space-borne geodetic and seismic records provided new insights into
23 the mechanics of deformation surrounding North Korea's sixth underground nuclear test,
24 revealing the explosion, collapse, and subsequent compaction sequence (Fig. 4). The modeling
25 of the geodetic observations reduces the epicentral and depth uncertainties that otherwise
26 hinder the analysis of seismic waveforms. The derived horizontal location of the first event is
27 important to relatively relocate the second event, which likely indicates the collapse of the
28 tunnel system of the test site. The inclusion of geodetic data also helps resolving the aseismic
29 deformation processes that may follow nuclear tests. Finally, our findings demonstrate the

1 capability of monitoring shallow underground nuclear tests using remote-sensing observations
2 and seismic sensors.

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3 **Authors contributions:** T.W. analyzed SAR images provided by M.M, Q.S. and S.W. conducted
4 the seismic analysis using the data collected by Q-F. C., M.N. and S.B conducted the geodetic
5 modeling, D.D. estimated the yield, T.W., M.N., S.B., R.B., and M.M contributed to the
6 interpretation of SAR offsets and geodetic models; Q.S., S.W., D.D. and Q-F. C. contributed to
7 the interpretation of seismic waves and moment tensors. T.W. drafted the manuscript with
8 inputs from all co-authors. **Competing interests:** All authors declare no conflicts of interest.

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13 supplementary material. Tele-seismic data are archived at the Incorporated Research
14 Institutions for Seismology (IRIS).

Fig. 1. Three-dimensional (3D) displacement associated with the 3 September 2017 North Korean Nuclear Test (NKNT 6). (A) 3D displacements derived from radar imagery with arrows indicating horizontal, color indicating vertical motions spanning the explosion and ~1 week of additional deformation. The uncertainties are shown in Fig. S4 and provided in Dataset S1 with the displacements. Black outline derived from ALOS-2 coherence loss indicates the substantial surface disturbance and large displacement gradients caused by the explosion over an area of ~9 km² (figs. S1-S2). Thin gray lines are topographic contours at 100-m intervals. Red square in the upper right inset shows the location of Mt. Mantap. Red stars indicate the locations of NKNT 1-5 (1,6,9,16), among which NKNT 2-5 were all located within the NKNT-6 low-coherence region, NKNT 1 on 9 October 2006 was in a different location (5). Beach balls show locations and focal mechanisms of the M_w 5.24 and M_w 4.47 events on 3 September 2017. (B) and (C)

- 1 show 2D (horizontal along the profile and vertical) displacements along two profiles across the
- 2 top of Mt Mantap from north to south, and from west to east respectively. The elevations along
- 3 the vertical axis in (B) and (C) are on scale.
- 4

Fig. 2. Model geometry and fit to the observed surface displacements. (A) Perspective view of the model with topography and variance reductions as a function of centroid position (both cross-sections are centered on the best fit location). We represent the first event, combining

1 the explosion and immediate collapse, using a sphere of 300 m radius with a centroid located at
2 a depth about 450 m below Mt Mantap. We model the aseismic subsidence detected with
3 geodetic data about a week after the seismic events 1 and 2 with an ellipsoid of dimension
4 800x800x470 m semi-axes, centered at 100 m deeper than the explosive source. The isotropic
5 components of the moment tensors are represented as beach balls. (B) The observed and
6 simulated surface displacements. (C) The west-east and south-north profiles of the surface
7 displacements from the SAR observations and the best-fitting models. The dashed profiles
8 represent the contributions of the explosion/collapse (Event 1) and the subsequent aseismic
9 compaction on the surface displacement. We ignore the deformation caused by Event 2.

10

Fig. 3. Analysis of seismic waves. (A) Station map of broadband seismometers with four stations in B and D highlighted in red. The black and red stars are the epicenter location of the first and second event, respectively. (B) Moment tensor solutions for the first explosive (left) and the second implosive (right) event, with vertical component of two representative stations shown at the bottom. Both data and synthetics are filtered between 0.02 and 0.045 Hz. Station names are shown at the beginning of waveform pairs and distance (in km) and azimuth (in degree) are indicated below. (C) Grid search result (under L1 norm) for relocating the second event relative to the first event (black star). Marginal distribution for the epicentral position are plotted along the northing and easting axes. (D) Vertical component waveform comparison between the first (black) and the second (red) event at two representative stations, with the second event waveforms multiplied by -60. (E) Explosive yield with historical nuclear tests. The black dots and error bars show yields estimated based on the mean and standard deviation of tabulated moment within 95% of the best fitting solutions with depths of 300, 450 and 600 m respectively.

Fig. 4. Summary deformation scenario for the 3 September 2007 North Korea's Nuclear test.

The unfolding of events includes the succession of (A) explosive, (B) collapse, and (D) compaction processes, with different associated surface displacements. The implosive source (C) may be shallow and only contribute localized surface displacements. The radar imagery reveals the deformation (arrows in D) resulting from the three processes.

Supplementary Materials for

The rise, collapse, and compaction of Mt. Mantap from the 3 September 2017,
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Teng Wang^{1*}, Qibin Shi^{1,2}, Mehdi Nikkhoo³, Shengji Wei^{1,2*}, Sylvain Barbot^{1,2}, Douglas
Dreger^{4*}, Roland Bürgmann⁴, Mahdi Motagh^{3,5} and Qi-Fu Chen⁶

Affiliations:

¹ Earth Observatory of Singapore, Nanyang Technological University, Singapore

² Asian School of Environment, Nanyang Technological University, Singapore

³ GFZ, German Research Centre for Geosciences, Potsdam, Germany

⁴ Department of Earth and Planetary Science, University of California, Berkeley, California,
USA

⁵ Institute for Photogrammetry and GeoInformation, Leibniz Universität Hannover, Hannover,
Germany

⁶ Key Laboratory of the Earth and Planetary Physics, Institute of Geology and Geophysics,
Chinese Academy of Sciences, Beijing, China

correspondence to: wang.teng@ntu.edu.sg, shjwei@ntu.edu.sg, dreger@seismo.berkeley.edu

This PDF file includes:

Materials and Methods

Figs. S1 to S16

Tables S1 to S3

Other Supplementary Materials for this manuscript includes the following:

Databases S1 and S2

Materials and Methods

Synthetic Aperture Radar (SAR) image processing and 3D displacement calculation

The Japanese ALOS-2, the European Sentinel-1A/B, and the German TerraSAR-X satellites all acquired SAR images spanning the sixth North Korean Nuclear Test (NKNT 6), conducted on 3 September 2017 at the Punggye-ri test site (Fig. S1 and Table S1). All these images are publicly available, either obtained free of charge (Sentinel-1) or via data allocations for scientific projects (ALOS-2 and TerraSAR-X), see the acknowledgment in the main text for details. The resolution of Sentinel-1 data is too low to reveal any reliable information for this case.

A pair of ascending ALOS-2 images spanning the NKNT 6 was co-registered to generate an interferogram and a coherence map using our InSAR processing system (38,39). The near-field interferometric phases are completely decorrelated due to the large displacement and substantial surface disturbance from the explosion, and therefore impossible to unwrap (Fig. S2A). Nevertheless, the level of coherence can be used to indicate the area of the surface disturbances caused by the explosion (Fig. S2B).

Four pairs of TerraSAR-X images from the German Aerospace Center (DLR) were processed to map the surface displacement associated with the underground nuclear test. Two pairs of TerraSAR-X Spotlight images covering the south part of the test area were acquired from ascending orbits (satellite travelling north) and descending orbits (satellite traveling south) with resolution of 1.1 m in azimuth and 0.45 m in range (the line-of-sight direction), and two additional pairs covering the whole test area were acquired from ascending and descending orbits with resolution of 1.1 m in azimuth and 0.9 m in range (For dataset information, see Fig S1 and Table S1). These images provide a unique dataset to calculate a complete 3D displacement map caused by the nuclear explosion (Fig. 1).

We co-registered the four datasets separately using their orbital information and a 30 m-resolution digital elevation model (DEM) from SRTM DEM (38). To estimate pixel offsets due to the explosion and possible subsequent collapse, we calculated the cross-correlation between distributed sub-images on the co-registered radar amplitude images. Cross-correlation windows with a dimension of 32-by-32 pixels were uniformly distributed to compute image offsets due to the explosion. The peak location in the obtained cross-correlation surface indicates the pixel offsets between the two sub-images in two dimensions (17). The TerraSAR-X range offsets from the ascending and descending orbit images measure ground displacement in their radar line-of-sight directions, which are about 34-48 degrees from the vertical with a component towards the west and east, respectively. The azimuth offsets measure along-track components, which are close to the north-south direction. We downsampled these offsets points using 200-250 m uniformly distributed grids to further improve the signal-noise-ratio. We calculated the standard deviation of offsets points outside of the disturbance area before and after downsampling (Table S1, Dataset S1).

To calculate the 3D displacement, we defined a grid with 300 m spacing across the test site. Values from the offsets along up to eight directions were combined to invert for the displacement

1 in west-east, south-north and vertical directions for each grid element (Fig. 1, Fig. S5, Dataset
2 S1) (18,19). Where we have displacements from more than three independent measurements, we
3 calculated the standard deviation from the residues of the 3D displacement decomposition (Fig.
4 S4). The 3D displacement measurements were also decomposed along profiles into horizontal
5 motions parallel to the profile and vertical displacements (Fig. 1B and 1C). We then interpolated
6 the 3D displacement into a regular grid with 100 m resolution as shown in Fig. 2A and Fig. S3
7 with different components.

8 9 Dislocation modeling of the geodetic data

10
11 To infer the parameters of the deformation source associated with the 3 September 2017
12 underground nuclear test in North Korea, we applied the point-source version of the compound
13 dislocation model (the point CDM) (26) to the observed surface displacements. The point CDM
14 is a half-space source model in which a flat free surface is implemented analytically. In principle,
15 this procedure can be viewed as correcting the full-space solution for the free surface effect
16 through adding some analytical correction terms to it. For irregular surface topographies,
17 however, this needs to be performed numerically. For this purpose, we first simulated the surface
18 topography as a continuous mesh of triangular dislocations (TDs) (25). Then, using the TD mesh
19 in a numerical scheme based on the boundary element method (BEM), we calculated the
20 corrections that implement the effect of the realistic surface topography on the calculated surface
21 displacements in our models (40,41).

22
23 Also, through a minor modification in the point CDM formulation, we allowed for arbitrary
24 positive and negative signs for the potencies. This way, one single point CDM was capable of
25 simulating the superimposed effects of expansion and contraction due to the initial explosion and
26 subsequent vertical collapse of the explosion chimney, respectively.

27
28 We used this source model in a nonlinear inversion scheme based on the genetic algorithm
29 (27,28) and inverted the surface displacements for the source parameters, including the
30 horizontal location and depth as well as the potencies along the three axes of the source model
31 (see Table S2). The presence of significant topographic effects in the surface displacements and
32 accounting for these effects in the model provided strong constraints on the source depth in the
33 inversions. The optimal model from this step fitted the best to the azimuthal offset data, yet the
34 amplitude and extent of the model residuals for the range offsets were significant. This is
35 because the azimuthal offsets exclusively depend on the horizontal displacements and the range
36 offsets depend on both horizontal and vertical displacements.

37
38 The temporal resolution of our geodetic data, however, provides only a snapshot of the
39 deformation signal, which is the superposition of the explosion, collapse and compaction
40 processes. Therefore, the exact nature of the compaction source and its contribution to the total
41 deformation signal cannot be resolved uniquely through inversions of the available geodetic data.
42 However, we were able to simulate the general pattern of the deformation as a two-source model,
43 one is the explosion plus collapse on the top, and the other is the compaction in a larger area
44 (Fig. S6). Using numerical integration, we first extended the inferred point CDM to a finite
45 ellipsoidal source which simulated the source of explosion and collapse with a better fit to the
46 data. We then implemented a zone of compaction as a large ellipsoidal source, which surrounded

the first inferred source of explosion and collapse. Best results were achieved for a large cavity of rather isotropic compaction, which contained almost the entire uppermost edifice of Mt. Mantap from the top to a few hundred meters below the inferred source of explosion and collapse (see Fig 2, Fig. S6 and Table S3).

It must be noted that the incorporation of the source of compaction into the model did not significantly influence the inferred depth of the first source from the inversions, and was just to suggest one possible mechanism, which could explain the overall pattern of observed horizontal and vertical surface displacements in one framework under a few reasonable assumptions.

Relative relocation of the second event

We used regional waveform data recorded by a temporary broadband network installed in northeast China (30) and a few stations in the national broadband network of China and South Korea (Fig 3A) to refine the location of the second event, relative to the epicenter of the main event. We used the main event epicenter location derived from the surface displacement field. Since the P-wave arrival times of the main event can be very well picked (Fig. S7), we firstly used these arrival picks to calibrate the paths and then applied the corrections to relocate the second event in a grid search optimization, similar to a master-event relocation, e.g. (42). Because these two events are very close to each other, according to preliminary USGS reports, the master event approach is a good option for relocation. However, due to the coda wave from the main event, it is more difficult to pick the P-wave arrivals for the second event at these regional stations. To obtain reliable arrival picks, we filtered the data of the second event to relatively high frequency ranges (approximately 1.0-8.0 Hz) to improve the picks (Fig. S8). With these picks, our relocation results using L1 and L2 norm for error calculation are shown in Fig. S9. Both results show that the second event is located about 700 m to the south of the main event, but the EW component of the location estimates differ by ~700m. This difference is not unexpected, as the error ellipses are elongated in the E-W direction, primarily because there are no seismic stations in this direction. To better estimate the uncertainty of the relocation, we add random Gaussian noise to the arrival picks of the second event, assuming the maximum picking error of ± 0.3 s. We repeat this process 1000 times and produce 1000 relocations (gray dots in Fig. S9), these locations also show elongated error ellipses (95% confidence levels of the distributions) similar to that from the grid search result using original picks (background color). We finally use the location from L1-normal solution for the second event (Fig. 3C in the main text).

Moment tensor inversion

To constrain the moment tensor solution of the main event, we conducted waveform inversion on the regional seismic waveform data using a generalized Cut-And-Paste method (gCAP) (31). The regional stations are the same as we used in the relocation procedure. We removed the instrument response from the raw data, converted the data into ground velocity, and then rotated the horizontal components into radial and tangential components. In the gCAP algorithm, the three-component waveform data at each station is cut into Pnl segments (vertical and radial components) and surface wave segments (vertical and radial component for Rayleigh

1 wave and tangential component for Love wave), and fitted with the 1D synthetics. Each
2 component can have its own time shift to align the data and the synthetics, which can greatly
3 reduce the sensitivity of the inversion to the imperfect velocity model. We used a modified 1D
4 velocity model for most of the stations, except BJT and HIA, for which we used the PREM
5 model (43).
6

7 We filtered the Pnl waves to 0.01-0.06 Hz and surface waves to 0.02-0.045 Hz, which are
8 the frequency ranges that can fit most of the components with decent cross-correlation
9 coefficients (>0.9 on average). During the inversion, we experimentally place the source at the
10 depth of 0.45 km as constrained by the geodetic data modeling, and grid searched for the best
11 percentage of the deviatoric CLVD component (compensated linear vector dipole) (44), and
12 isotropic volume-change component (Fig. S10). Our inversion result prefers a large percentage
13 (80%) of the positive isotropic component (explosion) in the full moment tensor solution and a
14 total moment magnitude of 5.24 (Fig. S11). However, the waveforms cannot be fitted well if we
15 assume a 100% isotropic source (Fig. S10). The CLVD indicates a component of collapse in the
16 vertical direction. Possible causes include: 1) triggering of tectonic faults, 2) heterogeneous
17 stress in the source region, 3) non-elastic deformation, 4) 3D velocity structure and topography
18 effects. Because the non-isotropic component is very small, it is difficult to distinguish the
19 contribution of these factors with the data we have. Also note that there are some trade-offs
20 between isotropic and the CLVD component (Fig. S10).
21

22 To test the impact of topography, we also use Spectral Element Method (SEM) (46) to
23 simulate 3D synthetics with topography imposed on a background 1D velocity model (Fig. S12).
24 We place a pure explosion source at the depth of 450m and generate synthetics at the stations
25 used in the moment tensor inversion. We filter both the 3D and 1D synthetics to the same
26 frequency ranges as we used in the inversion and display one of example station (EW06) in Fig.
27 S13. As shown, the difference between the 3D and 1D synthetics in tangential component is very
28 small at this frequency range, primarily because the corresponding wavelength (tens of
29 kilometers) is much longer than that in the topography features (a few kilometers).
30

31 Similar to the P-wave arrival picks, the full moment tensor inversion of the second event is
32 also more difficult due to the coda from the first event. With careful selection of the waveform
33 components and frequency ranges, we can still obtain good fits for the Rayleigh waves at more
34 than 10 stations, in particular for the vertical component (Fig. S15). A grid search for the
35 isotropic and CLVD components of the second event indicates strong trade-offs between the two
36 components, and the inversion did not converge as good as for the first event and the variance
37 reduction is apparently lower (Fig. S15). Despite more local minimums present in the Hudson
38 source type plot, the inversion still shows a concentration of minimums near a strong negative
39 isotropic component value ($\sim -55\%$, implosion) with a moment magnitude of 4.5 (Fig. S14). To
40 verify this result we multiplied the amplitude of the vertical-component waveforms of the second
41 event by a factor of -60 (note the sign flip), and compared them with the waveforms of the first
42 event at higher frequencies (~ 0.2 -0.9 Hz). The result (Fig. S16) shows very high waveform
43 cross-correlation coefficients, even for some coda waves. The strong similarity of the flipped
44 high-frequency waveforms therefore provides additional evidence for a large negative isotropic
45 component of the second event, as well as for the close proximity of the two events.
46

Source Radius and Yield estimation

We considered the uncertainty in the isotropic scalar moment in estimating the source radius and explosive yield. First, all solutions fitting within 95% of the best fitting solution (e.g. Figure S10) were tabulated, and then the mean and standard deviation were estimated. The mean and standard deviation of the isotropic moment was determined to be $M_w 5.05 \pm 0.13$. Using the relationship, $M_0^{iso} = (\lambda + 2\mu) \delta V$ and the equation for the volume of a sphere, where the two Lamé coefficients are assumed from the V_p , V_s and density values from model MDJ2 (4) the cavity radius is estimated to be 51m.

It should be noted that the larger source radius of the geodetic modeling is the result of the integrative effect of all of the deformation processes that affect the surface displacement field, namely the explosion, collapse and compaction, as discussed in the paper. There are some trade-offs between the inferred parameters of the sources in the deformation model. The trade-offs could result in an overestimation of the geodetically estimated volume. Therefore, we did not use the radius derived from this volume for yield estimation. The seismic data have the resolution for separating the explosion and collapse precisely. Also, the isotropic moment is determined by inverting the regional waveform assuming different source depths. When the source is located at 600m, we got very similar total moment as the other depth, however, the isotropic percentage is smaller, therefore the corresponding isotropic moment is also smaller, resulted in smaller yield than depth of 450 m shown in Fig. 4E.

The Denny and Johnson model (33,34) relates the explosive yield to the isotropic scalar seismic moment, the V_p , V_s and density at the source, the overburden pressure and the gas porosity of the medium. We have assumed the MDJ2 model (4) for the elastic parameters, the overburden pressure is based on the best fitting geodetic centroid of 450 m. The medium in which the device was detonated is likely the granodiorite that lies beneath the stratified volcanic rocks that make up higher elevations of Mt. Mantap. We assumed a gas porosity of 1% for granitic rocks (35). For the mean isotropic scalar moment of solutions fitting within 95% of the best fit solution at 450m depth the explosive yield is estimated to be 191 kt, with a 1 standard deviation range of 120-304 kt. Our preferred explosive yield for the event is 191 kt from the mean of acceptable solutions, however for completeness the yield of the best fitting solution (isotropic $M_w=5.15$) is 265kt.

Fig. S1

Punggye-ri nuclear test site with datasets. Green and blue lines indicate the coverage of Japanese ALOS-2 and German TerraSAR-X image coverages respectively. Yellow stars indicate the locations of NKNT 1-5 from (1,6,9,16).

Fig. S2

ALOS-2 interferogram (A) and coherence map (B). Yellow stars indicate the location of NKNT 1-5. Black circle is south portal. Red dots are low coherence pixels, from which the boundary polygon (red lines) was calculated.

Fig. S3

Horizontal and vertical displacements of grid-points spaced 100 m apart obtained from pixel offsets of four pairs of ascending and descending orbit TerraSAR-X images spanning NKNT 6 with topographic contours.

Fig. S4

Standard deviations (std) derived from the 3D displacement decomposition. Note that only patches with measurements from more than 3 independent directions can be used to calculate residual standard deviations.

1

2

3 Fig. S5

4 3D displacements calculated within 300-by300m grid before interpretation plotted with locations
 5 published from other institutes and this study. Locations are inferred from
 6 <http://weilab.uri.edu/nk6/>.

7

8

Fig. S6

3D displacements predicted from our elastic model with explosion/collapse source, compaction source, and two sources combined.

Fig. S7

P-wave first arrival picks for the first event on the vertical components. The station names are indicated at the end of each seismogram.

Fig. S8

P-wave first arrival picks for the second event. Note that the waveform data has been filtered to relatively high frequency ranges (~1-8 Hz) shown to the right of each trace.

Fig. S9

Relative relocation results of the second event by using path calibrations from the first event. The error of L1 and L2 norms are shown in the left and right, respectively. The black star indicates the epicenter location of the first event based on the deformation data, which is also the reference location. The red star shows the preferred location of the second event determined by grid search. The gray dots are the grid search results using the perturbed arrival times of the second event, assuming a random Gaussian distribution error in arrival time picks. We assume the maximum picking error is $\pm 0.3s$, and the sampling process was conducted 1000 times (corresponding to 1000 gray dots). The ellipses represent the 95% confidence levels of the distributions of gray dots.

Fig. S10

Grid search results for the CLVD and isotropic components of the first event using GCAP method. The Variance Reduction (VR) from the inversion is color coded on the Hudson source type plot (45). The white circle indicates the preferred moment tensor (see more details of moment tensor and waveform fits in Fig.S10). The black dot displays the preferred moment tensor solution from (2), the gray dot displays the moment tensor from an independent inversion result reported during AGU meeting 2017 (Dreger et al., Source-Type Inversion of the September 03, 2017 DPRK Nuclear Test 2017).

mdj2prem_0.45; FM 273 41 16; Mw 5.24
rms 6.558e-05
Variance reduction 89.1

sec

0 60 120 180 240 300 360

Fig. S11

Waveform fits for the preferred moment tensor solution for the first event. Station names are indicated at the beginning of waveform comparisons, with epicenter distance (front) and azimuth (back) shown below the station name. Black traces are observed waveforms and red traces are

1 predicted waveforms. The numbers below each waveform segment are time shift in s and
2 waveform cross-correlation coefficient in percentage.
3
4

5
6
7 **Fig. S12**

8 A portion of velocity model setup for the 3D Spectral Element Method (SEM) simulations with
9 topography. The pink dot represents the epicenter location used for the simulation. A 1-D
10 velocity model (MDJ2 model (4)) is used as the background model.
11
12

Fig. S13

Waveform comparisons between the three component 3D synthetics (red) with topography and 1D synthetics (blue). Note the very small difference in the tangential component.

Fig. S14

Grid search results for the CLVD and isotropic components of the second event using GCAP method. The Variance Reduction (VR) from the inversion is color coded on the Hudson source type plot (45). The white circle indicates the preferred moment tensor (see more details of moment tensor and waveform fits in Fig.S12).

prem_0.5; Pnl 0.02~0.2 Sur 0.02~0.1; FM 182 10 130; Mw 4.47

rms 6.332e-05;

Variance reduction 58.1

sec

0 60 120 180 240 300 360

Fig. S15

Waveform fits for the preferred moment tensor solution for the second event. Stations names are indicated at the beginning of waveform comparisons, with epicenter distance (front) and azimuth (back) shown below the station name. Black traces are observed waveforms and red traces are predicted waveforms. The numbers below each waveform segment are time shift in s and waveform cross-correlation coefficient in percentage.

Fig. S16

Vertical component waveform comparison between the first and the second event. Here the sign of the second event waveforms are flipped and the amplitude is enlarged by a factor of 60. The station names are shown at the beginning of each waveform pair with azimuth (in degree) and distance (in km) shown at the bottom and top, respectively. The waveform cross-correlation coefficients in percent and frequency ranges are displayed to the right of each trace.

Table S1.

SAR images processed. AT means ascending tracks, DT means descending tracks.

Satellites	Track	Resolution Az/Ra	Incidence Angle	Date yyyymmdd	Useful information	std (m) before/after downsampling
TerraSAR-X	DT88	1.1 m 0.45 m	48.3	20170824 20170904	Azimuth offsets Range offsets	Az: 0.98/0.29 Ra: 0.51/0.21
TerraSAR-X	AT111	1.1 m 0.45 m	46.2	20170826 20170906	Azimuth offsets Range offsets	Az: 0.70/0.16 Ra: 0.36/0.20
TerraSAR-X	DT164	1.1 m 0.86 m	35.6	20170602 20170909	Azimuth offsets Range offsets	Az: 1.10/0.27 Ra: 1.15/0.23
TerraSAR-X	AT35	1.1 m 0.86 m	33.7	20170605 20170912	Azimuth offsets Range offsets	Az: 0.77/0.20 Ra: 1.31/0.18
ALOS-2	AT130	5 m 6 m	36.3	20170727 20170907	coherence	x

Table S2.

Source parameters of an axisymmetric point CDM ($\Delta V_x = \Delta V_y$) under realistic topography. “H” is the elevation of the source centroid above mean sea level (MSL). The reference location is 129.077598 E, 41.300653 N.

E (km)	N (km)	H (km)	Potency $\Delta V_x = \Delta V_y$ (km ³)	Potency ΔV_z (km ³)
0.050±50m	-0.150±50m	1.743±100m	0.003056	-0.000187

Table

Source

parameters of the two deformation sources in the finite-source model. The centroids of both sources have the same coordinates as the point CDM in Table S1.

Source	Source semi-axes (m)	ΔV_x (km ³)	ΔV_y (km ³)	ΔV_z (km ³)
Explosion and collapse	$a_x = a_y = a_z = 300$	0.009008	0.007862	0.001288
Compaction	$a_x = a_y = 800$ $a_z = 460$	-0.006407	-0.004498	-0.005396

Additional Dataset S1

geo.zip, contains downsampled SAR offsets data points and 3D displacements:

TSX_AT111_az.geo
 TSX_AT111_ra.geo
 TSX_AT35_az.geo
 TSX_AT35_ra.geo
 TSX_DT164_az.geo
 TSX_DT164_ra.geo
 TSX_DT88_az.geo

1 TSX_DT88_ra.geo
2
3 Data files with 11 columns: longitude, latitude, deformation in cm, cos(E), cos(N), cos(U), cross-
4 correlation, variance calculated within downsampling grid, area of the downsampling grid in
5 km², number of points within the downsampling grid, elevation.
6
7 def3d.xy
8
9 Data files with 6 columns: longitude, latitude, elevation, west-east deformation, south-north
10 deformation, down-up deformation, west-east std, south-north std, down-up std.
11
12 **Additional Dataset S2**
13
14 NorthKorea_20170903_0330.zip
15
16 Regional waveform data and instrument response of the two events recorded by NorthEast China
17 Seismic Array to Investigate Deep Subduction (NECsaisd).
18