

## GEODETIC MONITORING

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

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Surveillance of clandestine nuclear tests relies on a global seismic network, but the potential of spaceborne monitoring has been underexploited. We used satellite radar imagery to determine the complete surface displacement field of up to 3.5 meters of divergent horizontal motion with 0.5 meters of subsidence associated with North Korea's largest underground nuclear test. Combining insight from geodetic and seismological remote sensing, we found that the aftermath of the initial explosive deformation involved subsidence associated with subsurface collapse and aseismic compaction of the damaged rocks of the test site. The explosive yield from the nuclear detonation with best-fitting source parameters for 450-meter depth was 191 kilotonnes of TNT equivalent. Our results demonstrate the capability of spaceborne remote sensing to help characterize large underground nuclear tests.

World peace benefits from adherence to internationally negotiated nuclear test ban treaties whose signatories 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 Treaty on the Non-Proliferation of Nuclear Weapons. North Korea has been conducting underground nuclear weapon tests with increasing intensity since 2006. On 3 September 2017, two seismic events separated by ~8.5 min were detected at 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 U.S. Geological Survey and the China Earthquake Networks Center determined a body-wave magnitude ( $m_b$ ) of 6.3 for the first event (NKNT 6), much larger than any of the five nuclear tests since 2006 (NKNT 1–5). Shortly thereafter, the scientific community started to determine the location, focal mechanism, and yield of the explosion by means of seismic waveforms and satellite optical imagery (1). Preliminary analysis revealed a predominantly isotropic explosive source located beneath Mount Mantap (1–3), which also hosted NKNT 2–5 (Fig. 1).

The source properties of previous North Korean underground nuclear tests have been extensive-

ly studied using seismic waveforms (4–12), 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 Earth's surface (13, 14) but its contribution to characterizing nuclear tests has been limited. NKNT 4, conducted on 6 January 2016, has been studied using SAR interferometry, but the interpretation of interferometric phase is difficult because of the single imaging geometry (15). Tracking the amplitude features of the SAR images (so-called pixel-offset tracking) is better suited when the interferometric phase is decorrelated (16). Moreover, pixel offsets can map displacement along the radar line-of-sight and 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 derivation of three-dimensional (3D) displacements (17–20). Here, we rely on detailed 3D displacements derived from submeter-resolution SAR images together with seismic waveform data to reveal the complex processes that took place during and in the immediate aftermath of NKNT 6.

We measured the surface displacements caused by NKNT 6 by cross-correlating high-resolution spotlight radar images acquired by the German TerraSAR-X satellite, with an azimuth resolution of 1.1 m and a slant-range resolution as fine as 0.45 m (fig. S1 and table S1). The accuracy of the offset measurement is about one-tenth of the imaging resolution (21). We combined the azimuth and range offsets from two ascending and two descending tracks to calculate the total 3D surface displacements produced during and in the immediate aftermath of the explosion on a 300 m × 300 m grid (Fig. 1 and figs. S3 to S5) (22). The horizontal motions of up to 3.5 m show a divergent pattern at the top of Mount Mantap with

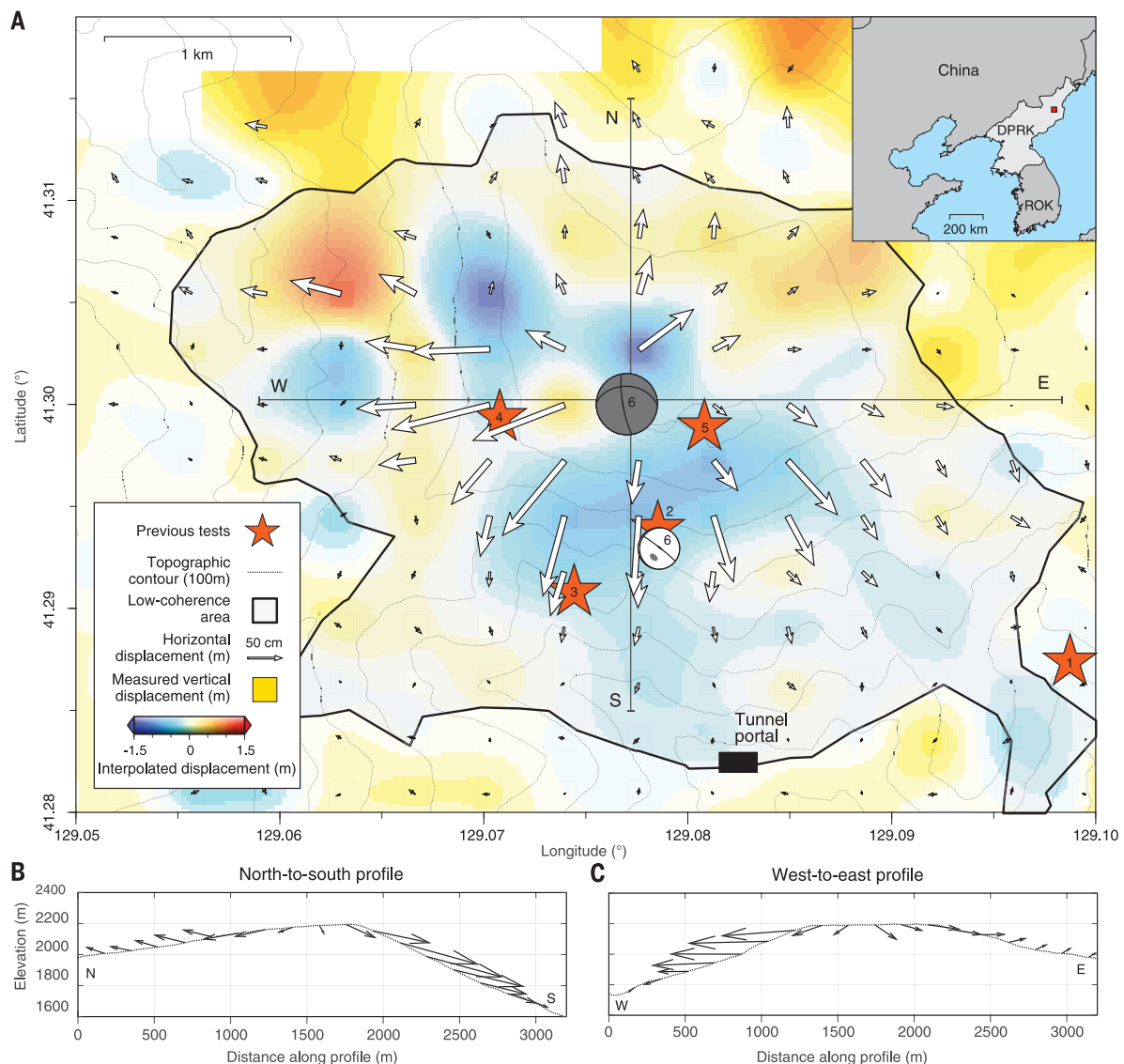
a central zone of subsidence of ~0.5 m. We decomposed the 3D displacements into vertical and horizontal directions along two topographic profiles across the top of Mount Mantap (Fig. 1). The along-profile displacements show that the horizontal displacement is generally larger where the topography is steeper (the west and south flanks). However, the direction of motion does not follow the slope of the terrain but is nearly horizontal. This indicates that although there is strong topographic control on the surface displacement field caused by the buried explosion, it does not resemble the slope-parallel motions expected from triggered landslides. Although optical imagery suggests isolated landslide deposits at the 10- to 100-m scale (23), these appear to be debris flows localized in preexisting channels that could not produce the large-scale horizontal motions we observed.

To resolve the horizontal location and depth of the detonation chamber, we set up numerical models that predict the surface displacements attributable to the expansion and subsequent collapse of an underground cavity embedded in a uniform elastic crust below realistic surface topography (24, 25) (Fig. 2). We constrained the 3D location of the source by minimizing the misfit between predicted and observed surface displacements (26, 27). The explosion and immediate collapse of a spherical cavity of 300 m radius that includes the detonation chamber and the surrounding damaged material reproduced the horizontal displacement well, but this was not sufficient to explain the small vertical motion around Mount Mantap. A third, mostly aseismic process involving 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 (28) 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 Mount Mantap). Incorporating the large-scale compaction source into the model does not influence our inferred epicenter of the explosion/collapse source much (22).

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) (22). With the calibration from the first event and careful *P*-wave arrival picks of the second event (figs. S7 and S8), our grid search showed that the second event occurred 8 min 31.79 s after the first event and was located about 700 m to the south.

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**Fig. 1. Three-dimensional displacement associated with the 3 September 2017 North Korea nuclear test (NKNT 6).** (A) 3D displacements derived from radar imagery. Arrows indicate horizontal displacement; color indicates vertical motions spanning the explosion and ~1 week of additional deformation. The uncertainties are shown in fig. S4 and provided in data S1 with the displacements. The 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 km<sup>2</sup> (figs. S1 and S2). Thin gray lines are topographic contours at 100-m intervals. The red square in the upper right inset shows

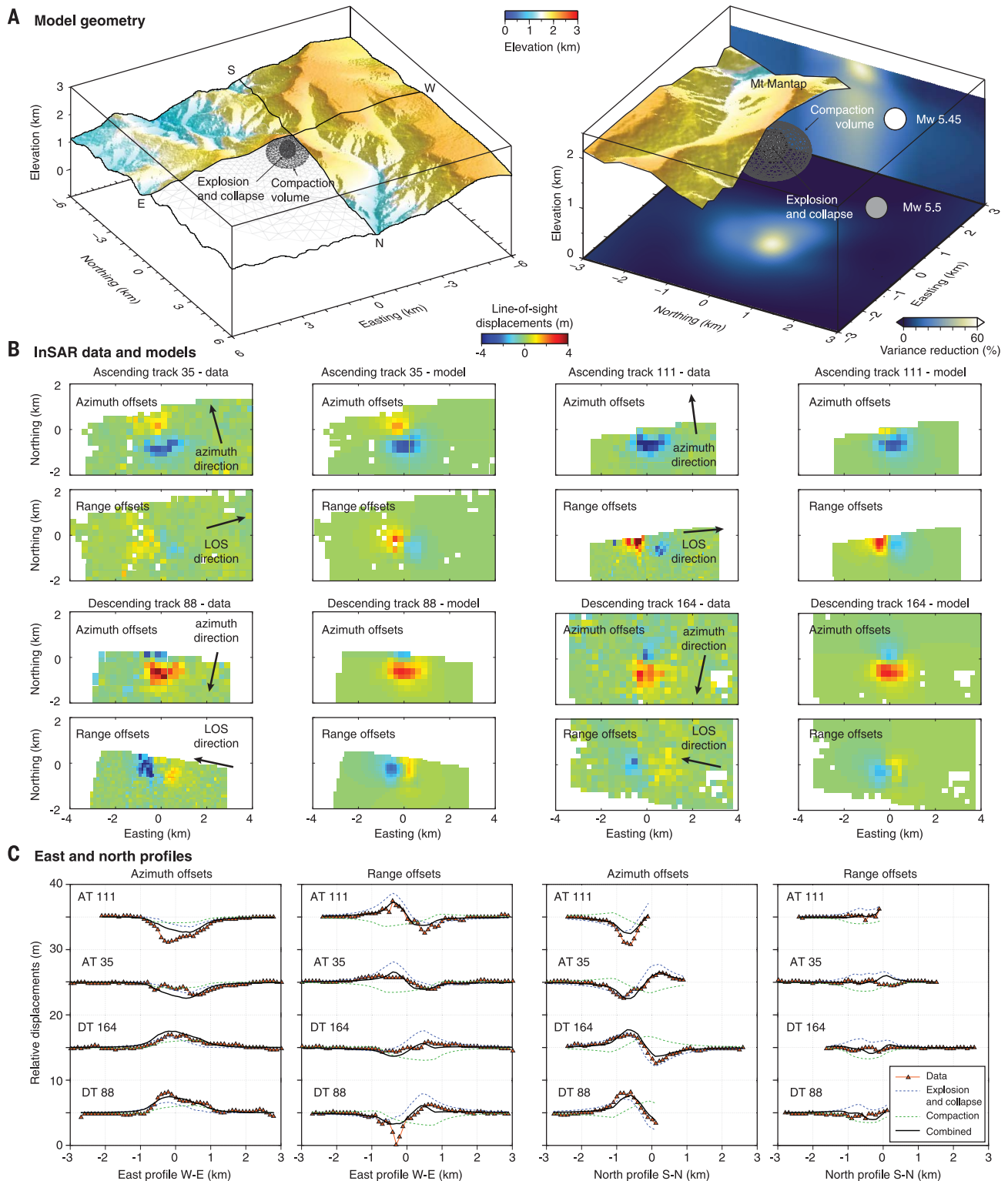
the location of Mount Mantap (DPRK, Democratic People's Republic of Korea; ROK, Republic of Korea). Red stars indicate the locations of NKNT 1–5 (1, 6, 9, 15, 37), among which NKNT 2–5 were all located within the NKNT 6 low-coherence region; NKNT 1 on 9 October 2006 was in a different location (5). Beach 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) 2D (horizontal along the profile and vertical) displacements along two profiles across the top of Mount Mantap from north to south and from west to east, respectively. No vertical exaggeration in (B) or (C).

Because of the azimuthal gap in the station coverage, the east-west location ( $\pm 700$  m) is less well constrained relative to the north-south separation ( $\pm 200$  m 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 Mount 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 an isotropic component (i.e., explosive or implosive volume source), a compensated linear vector dipole (CLVD) component (i.e., ring faulting along a certain axis, such as a collapse), and double-couple component (i.e., shear dislocation on a planar fault) (22). Our preferred solution of the first event indicates a moment of  $9.5 \times 10^{16}$  N·m (moment magnitude  $M_w = 5.24$ ), a 50 to 90% positive isotropic component, and relatively small CLVD or double-couple contributions (figs. S10 to S13). The second seismic event ( $M_w =$

4.5) has a large negative isotropic component (~50 to 70% of the total moment) (figs. S14 and S15). Although 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 sought more information about the moment tensor of the second event by directly comparing the waveforms with those of the



**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 the explosion and immediate collapse, using a sphere of 300 m radius with a centroid located at a depth about 450 m below Mount Mantap. We model the aseismic subsidence detected with geodetic data about a week after the seismic events 1 and 2 with an ellipsoid of dimension 800 m  $\times$  800 m  $\times$

470 m (semi-axes), centered at 100 m deeper than the explosive source. The isotropic components of the moment tensors are represented as beach balls. (B) The interferometric SAR (InSAR) observed and simulated surface displacements. (C) The west-east and south-north profiles of the surface displacements from the SAR observations and the best-fitting models. The dashed profiles represent the contributions of the explosion/collapse (event 1) and the subsequent aseismic compaction on the surface displacement. We ignore the deformation caused by event 2.

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 ( $\sim 0.2$  to  $0.9$  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).

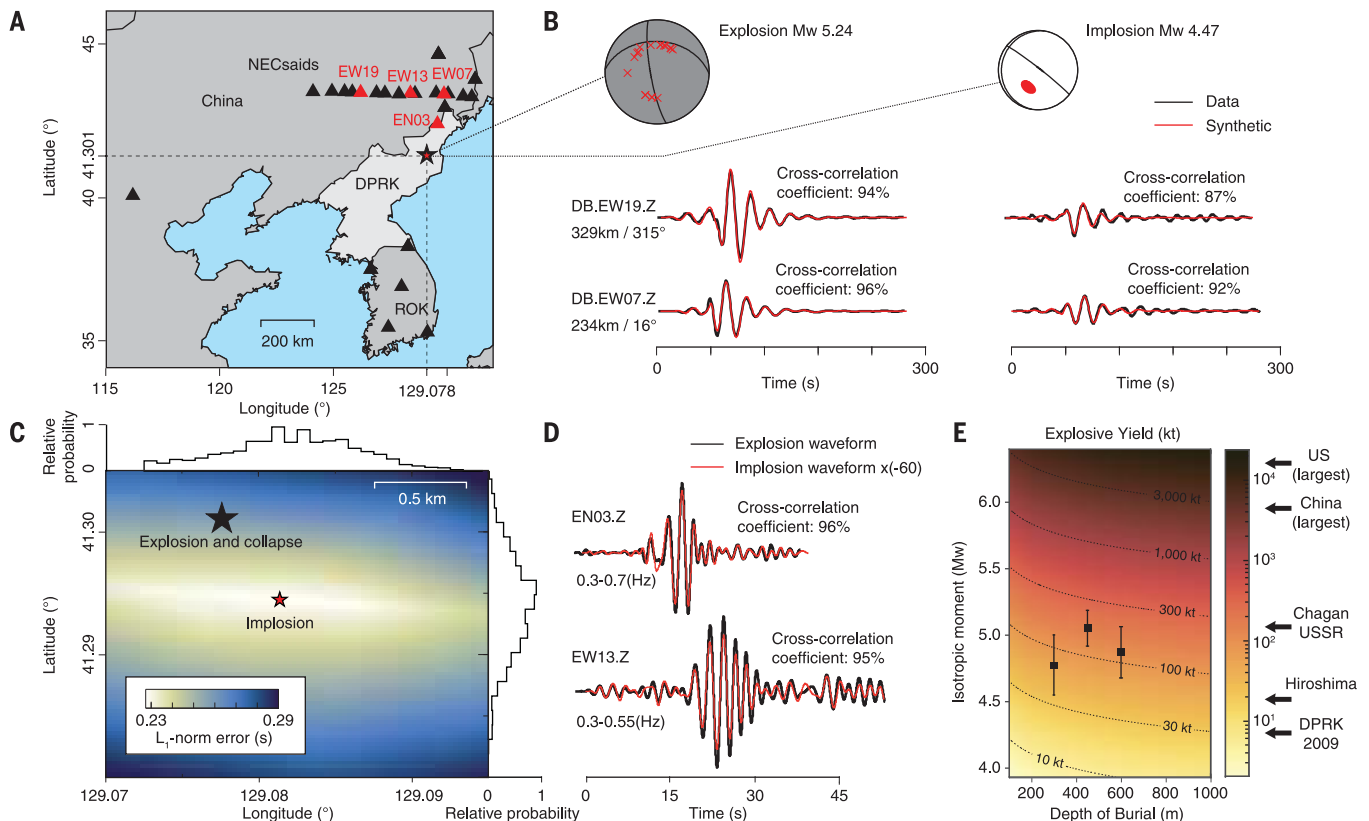
Combining the depth constraints from geodesy and energy constraints from seismology, we can refine the explosive yield of the nuclear explosion (32–34). We assumed the seismic velocity model MDJ2 (4) for the elastic Earth structure. We based the overburden pressure on the best-fitting centroid source depth of  $450 \pm 100$  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 Mount Mantap (8). We assumed a gas porosity of 1% for granitic rocks (35). Considering an isotropic seismic  $M_w = 5.05$  (the mean value of solutions fitting within 95% of the maximum fit for a source depth of 450 m) and the possible range of source

depths of 350 to 550 m, the yield estimates range between 171 and 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 the 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 deformation that did not generate seismic waves, with a total volume change of  $0.01 \text{ km}^3$ . The seismic analysis of the second event reveals an implosive seismic source that occurred south of the first event with a dominant negative isotropic component, suggesting an inverse process of the main explosion. This may reflect the combination of negative isotropic compaction of the over-

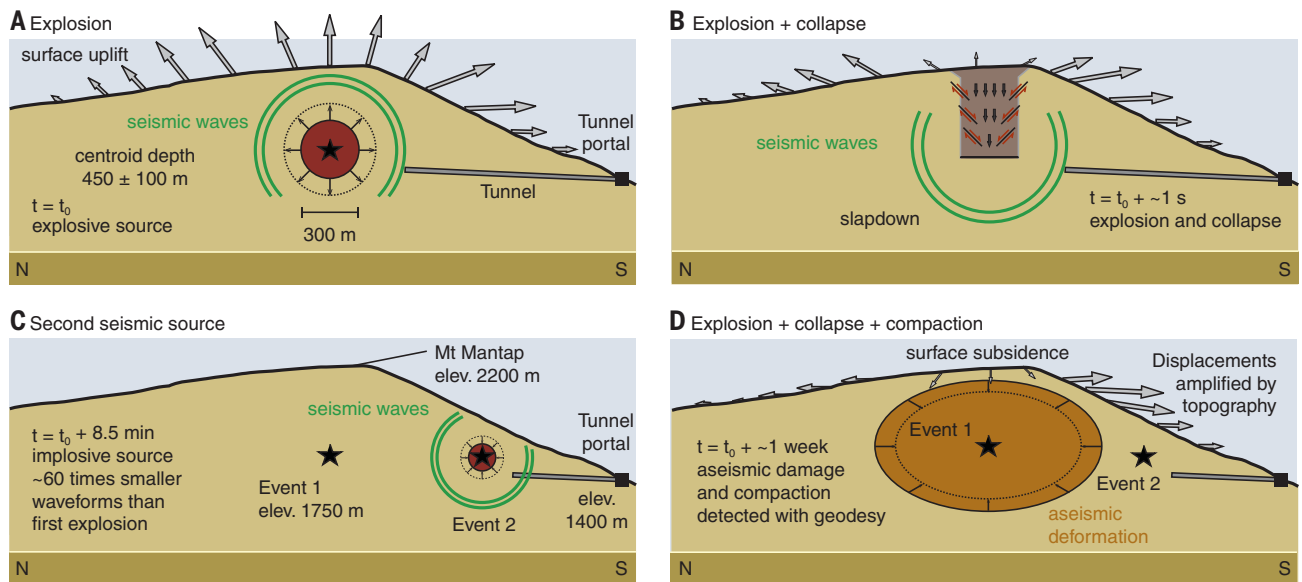
pressured cavity and/or vertical collapse of the explosion chimney and nearby tunnel segments due to gravity, contributing to the subsidence on the south flank of Mount Mantap (Fig. 4). The larger-scale compaction source in the geodetic model is independent of the first and second seismic events, and the post-explosion compaction of surrounding rocks may continue aseismically for an extended period, as seen in the Nevada underground nuclear test site with initial subsidence rates of  $\sim 1$  to  $7 \text{ cm/year}$  (29).

Our 3D surface displacement measurements and elastic modeling incorporating realistic topography allow for locating the main explosive event within  $\pm 50 \text{ m}$ , assuming a uniform elastic medium, although a nonuniform structure and small-scale surficial processes (e.g., landslides) may bias our results. Because the largest deformation occurred above the explosive source as a result of the chimneying and spalling effect (28), the centroid of the modeled geodetic source may be located above the actual detonation point. After the explosion, water was observed to be flowing from the tunnel portal (23). Assuming a slope of  $2^\circ$  to  $4^\circ$  to provide drainage, the depth



**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 locations of the first and second event, respectively. (B) Moment tensor solutions for the first explosive event (left) and the second implosive event (right), with the 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; distance (in kilometers) and azimuth (in degrees) are indicated below. (C) Grid search result (under  $L_1$  norm) for

relocating the second event relative to the first event (black star). Marginal distributions 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 in the context of historical nuclear tests. The black dots and error bars show yields estimated according to the mean and standard deviation of tabulated moment within 95% of the best-fitting solutions with depths of 300 m, 450 m, and 600 m, respectively.



**Fig. 4. Summary deformation scenario for the 3 September 2017 North Korea nuclear test. (A, B, and D)** The unfolding of events includes the succession of explosive (A), collapse (B), and compaction (D) processes, with

different associated surface displacements. **(C)** The implosive source may be shallow and may only contribute localized surface displacements. The radar imagery reveals the deformation [arrows in (D)] resulting from the three processes.

implied from the elevation of the tunnel entrance is about 600 to 700 m below the surface, consistent with a detonation point about 150 m deeper than the centroid of the geodetic model.

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

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#### SUPPLEMENTARY MATERIALS

[www.sciencemag.org/content/361/6398/166/suppl/DC1](http://www.sciencemag.org/content/361/6398/166/suppl/DC1)  
Materials and Methods

Figs. S1 to S16

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### Nuclear testing under the radar

North Korea conducted its sixth underground nuclear weapons test in September 2017. The seismic waves generated from the test allow for triangulation and explosive yield estimates. However, Wang *et al.* show that synthetic aperture radar (SAR) should be added to the arsenal of techniques used to detect and characterize nuclear tests. SAR tracks deformation from space, which resulted in a better constraint of source parameters by using deformation from the nuclear test and the subsequent collapse of Mount Mantap. The test occurred at a depth of about half a kilometer, with an explosive yield around 10 times that of the Hiroshima explosion.

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