

RESEARCH ARTICLES

SEISMOLOGY

Nuclear tests at Mt. Mantap have reactivated intraplate faults

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Underground nuclear explosions typically produce short-lived seismic sequences that decay rapidly after testing ceases. By contrast, seismicity near the Punggye-ri nuclear test site at Mt. Mantap in the Democratic People's Republic of Korea has persisted and intensified for years after the final large-yield explosion in 2017, evolving from diffuse activity to spatially organized distribution along fault-controlled structures. Analysis of 17 years of continuous waveform data reveals a progressive increase in seismicity and delayed reactivation of shallow faults. Earthquakes cluster beneath asymmetric topography, indicating progressive stress redistribution within a critically stressed crustal volume. These observations challenge conventional expectations, showing that under specific geological conditions, underground nuclear testing can drive multiyear fault reactivation and extend posttest seismicity well beyond the immediate aftermath of an explosion.

The Democratic People's Republic of Korea (DPRK) constructed the Punggye-ri nuclear test site at Mt. Mantap, Gilju County, North Hamgyong Province, northeastern DPRK (Fig. 1). Six underground nuclear tests were conducted at this site on 9 October 2006, 25 May 2009, 12 February 2013, 6 January 2016, 9 September 2016, and 3 September 2017 (1–8). The final test on 3 September 2017 was the largest, with an estimated yield of ~100 to 250 kilotons, and was reported by the US Geological Survey (USGS) as a body-wave magnitude (m_b) 6.3 seismic event, although estimates vary among agencies and magnitude scales. The reported hypocentral depth of the final test was 81 m relative to the surface elevation of the 6 January 2016 test (5). A local magnitude (M_L) 4.1 seismic event was reported ~8.5 min after the detonation and was interpreted as the collapse of the explosion cavity (9, 10). Satellite radar observations indicate that the 2017 test and its immediate posttest deformation produced up to ~3.5 m of divergent horizontal surface motion near the summit of Mt. Mantap, accompanied by ~0.5 m of localized subsidence (11).

Underground nuclear explosions (UNEs) generate well-documented seismic responses, including cavity collapse and clusters of small earthquakes that occur shortly after detonation (12–14). Such sequences typically decay rapidly as transient stress perturbations dissipate (15–18). During the period immediately after the sixth nuclear test and the associated cavity collapse at Mt. Mantap, only a few aftershocks were reported

(19–22). Most previous studies of DPRK's nuclear tests have focused on determining the location, timing, and yield of the explosions. Although some studies have described posttesting seismicity (19, 22, 23), the longer-term evolution, fault-scale organization, and physical mechanism of seismicity around Mt. Mantap remain incompletely resolved.

Here, we investigated the temporal and spatial evolution of the seismicity around Mt. Mantap using regional seismic data recorded in China and the Republic of Korea (ROK) since 2008. We constructed a new earthquake catalog using an approach that improves detection capability and enables high-precision hypocenter relocation. The results revealed the reactivation of at least two subparallel NNW-trending faults and allowed us to assess whether the observed seismicity reflects ongoing external forcing or time-dependent processes within a heterogeneous and critically stressed volume of the shallow crust.

Geological setting and historical seismicity

Geological information from the Punggye-ri test site is limited due to access restrictions and the scarcity of official reporting. The site is located in mountainous terrain marked by pronounced topographic relief and heterogeneous crystalline basement rocks (24–26). The test site and surrounding area are typical stable continental crust, characterized by low rates of deformation and sparse historical seismicity (see the materials and methods, fig. S1, and table S1). No crustal earthquakes have been documented within 50 km of the test site between 1 January 1904 and 3 September 2017 in major regional and global earthquake catalogs, including those of the Korea Meteorological Administration (27), China Earthquake Administration (28), USGS (10), and International Seismological Centre (29).

Construction of a local earthquake catalog

Continuous waveform data recorded since 2008 by regional seismic stations in northeastern China and the ROK, including stations located 80 to 200 km from the test site, enable the robust detection and relocation of small-magnitude earthquakes (Fig. 1B and table S2). We identified 1399 local earthquakes between 2008 and 2025 using matched-filter detection (see the materials and methods, figs. S2 to S19, and table S3), yielding a much greater number than reported in routine regional and global catalogs. The resulting catalog has a completeness magnitude (M_c) of ~1.3 (fig. S11). The procedures used for event detection, threshold determination, relocation, and uncertainty analysis are described in detail in the materials and methods.

Temporal evolution of seismicity

The earliest detected local earthquake occurred in 2013, after the third nuclear test. Seismicity remained sparse until 2017, when activity increased markedly after the sixth and largest detonation (Fig. 2 and movie S1). Unlike typical postexplosion sequences, which decay rapidly, seismicity at Mt. Mantap continued to increase for years after the final test. Both the earthquake rate and seismic moment release increased steadily through 2025. Cold War-era studies at the Nevada National Security Site in the United States and the Semipalatinsk Test Site in Kazakhstan (then part of the Soviet Union) documented explosion-triggered seismicity that persisted for days to weeks, typically confined to areas near ground zero and characterized by rapid decay (9, 15, 18, 30–33). By contrast, the sustained tectonic seismicity near Mt. Mantap began on 23 September 2017, roughly 3 weeks after the sixth test, and continued through the end of our study period in May 2025. The progressive increase in both the earthquake rate and the moment release rate indicates that the crust did not simply relax toward equilibrium after the final explosion; rather, seismicity expanded gradually as preexisting faults became active.

Spatial organization of seismicity

High-resolution relocation of 955 hypocenters revealed that post-2017 earthquakes delineate two subparallel structures extending NNW from the test site (Fig. 3 and movie S2). These events form coherent fault-scale structures rather than diffuse clusters. The western branch follows the projected continuation of a mapped fault south of the test site (25), suggesting the

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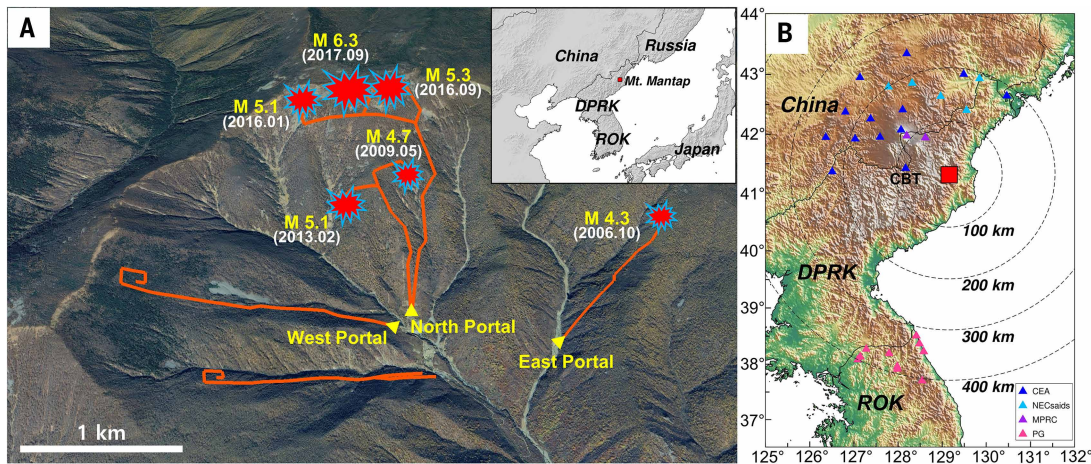


Fig. 1. Locations of the six nuclear tests by DPRK at Mt. Mantap and the distribution of seismic stations used in this study. (A) Locations of the six underground nuclear tests at Mt. Mantap. Red explosion symbols mark the locations of the six underground nuclear tests, with label size indicating USGS-reported body-wave magnitudes (m_b) and dates in year.month format (10). Relative to the surface elevation of the 6 January 2016 test, the reported hypocentral depths for tests 1 to 6 are 2215, 1087, 769, 1196, 1019, and 81 m, respectively (5). Orange lines mark inferred tunnel layouts leading to the detonation chambers (46). The background image is from Google Earth. Inset: location of Mt. Mantap in East Asia. (B) Distribution of seismic stations used in this study, colored according to the legend in the lower-right inset. The red square marks the plotting boundary shown in Fig. 3. Concentric circles denote distances 100 to 400 km from the test site. CBT marks the closest seismic station used in this study, located ~80 km from the test site. Representative seismic waveforms recorded at this station are shown in figs. S3 and S4.

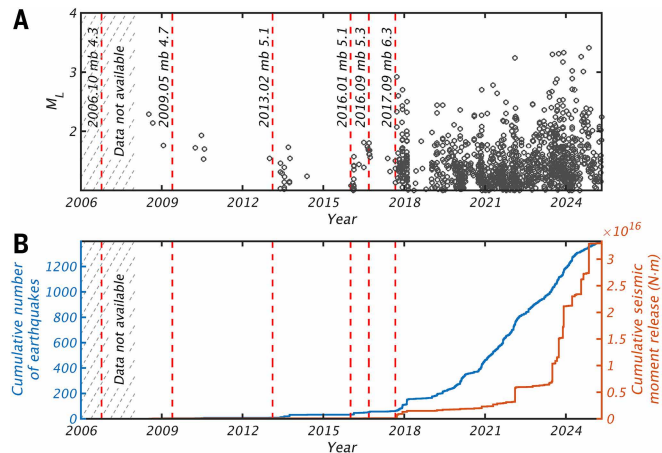


Fig. 2. Temporal evolution of seismicity at Mt. Mantap during and after the six UNEs. (A) Origin times and local magnitudes (M_L) of earthquakes (open circles) at Mt. Mantap. Dashed red lines mark the origin times (in year.month format) of the six UNEs and their USGS-reported body-wave magnitudes (m_b). (B) Cumulative number of earthquakes (blue curve) and cumulative seismic moment release (orange curve). Dashed vertical red lines mark the six DPRK's nuclear tests as in (A). Seismicity persisted after the final large-yield test in 2017 and accelerated over time.

reactivation of a preexisting fault. The eastern branch does not correspond to any mapped fault but displays a clear fault-like geometry. The seismicity clusters preferentially beneath steep topographic slopes and remains largely confined to a topographically bounded zone extending from the test site, with only a small number of earthquakes on the other side of the highest elevations. These same structures remain active across successive intervals (Fig. 4 and movie S1). Relocated depths are shown in Figs. 3 and 4 for descriptive completeness, and the distribution of relocated depths is summarized in fig. S19. Because absolute focal depths are poorly constrained by the available regional station geometry, our interpretation relies primarily on the plan-view structural organization and time-resolved evolution of seismicity. Beginning in 2023, a small number of earthquakes occurred at depths of ≥ 2 km between the two branches. P-wave first-motion polarities and S/P amplitude ratios for a selected larger 2023 event yielded a candidate earthquake-like double-couple mechanism dominated by oblique strike-slip

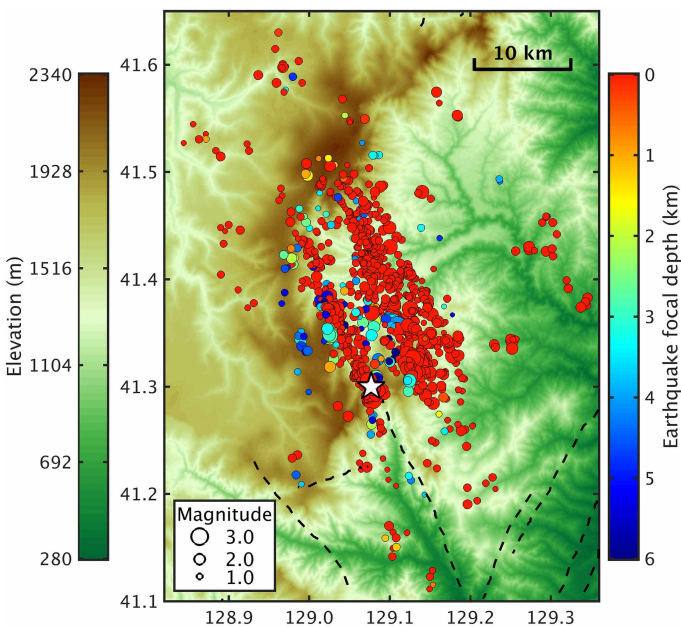


Fig. 3. Spatial distribution of earthquakes around Mt. Mantap during and after the six UNEs. Circle size scales with earthquake magnitude, and color indicates focal depth (km). The white star marks the location of the largest underground nuclear test in 2017. Dashed lines are digitized fault traces from the Geological Map of Korea (25).

motion with a minor normal component; one nodal plane is broadly parallel to the local NNW-trending seismicity (fig. S20). Together, these observations reveal persistent, spatially organized fault reactivation.

Delayed crustal response

Previous investigations of explosion-triggered seismicity generally revealed rapidly decaying aftershock sequences or short-lived earthquake swarms confined to localized damage zones (9, 15, 18, 31–33). The Mt. Mantap sequence, by contrast, shows an increase in seismicity over several years and progressive structural organization, pointing to processes that extend beyond short-lived explosion-related responses.

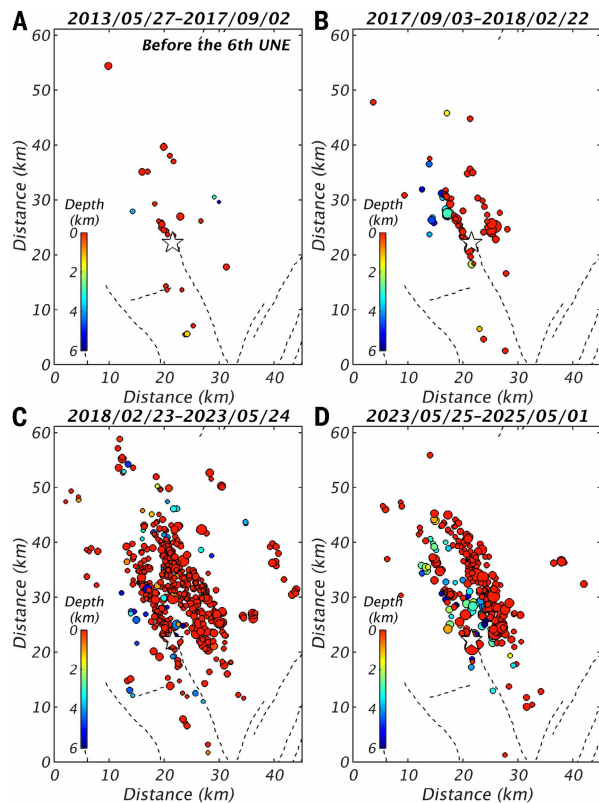


Fig. 4. Spatiotemporal evolution of the seismicity around Mt. Mantap. (A to D) Earthquake locations projected in a local coordinate system for four time periods: 27 May 2013 to 2 September 2017, which is before the sixth UNE (A), 3 September 2017 to 22 February 2018 (B), 23 February 2018 to 24 May 2023 (C), and 25 May 2023 to 1 May 2025 (D). Circles denote earthquake epicenters, with symbol size proportional to magnitude (as in Fig. 3) and color indicating focal depth (km). The white star marks the location of the largest underground nuclear test in 2017. Dashed lines are digitized fault traces from the Geological Map of Korea (25). The seismicity evolved from sparse background activity (A) to activity along well-defined fault-scale structures [(B) to (D)] as seismicity increased after the 2017 nuclear test.

The Mt. Mantap test site is located within stable continental crust characterized by low rates of deformation and long-lived inherited structures (34, 35). In such tectonic settings, faults may remain seismically quiet for extended periods, yet they are susceptible to reactivation when transient stress or damage-related perturbations are superposed on a heterogeneous, prestressed crust. Even small stress changes can promote slip if faults are already near failure (36–39). Our observations indicate that repeated underground explosions modified the local stress field and progressively damaged the shallow crust, facilitating the delayed reactivation of preexisting structural weaknesses rather than producing only short-lived, localized responses.

Possible mechanisms

The observations at Mt. Mantap cannot be explained solely by test frequency or cumulative explosive yield or by classical stress-triggering mechanisms. Dynamic stress perturbations would induce a near-immediate seismic response (40–42), whereas the most pronounced acceleration in seismicity at Mt. Mantap occurred years after the final detonation. Likewise, static stress changes from the final test are insufficient to account for the delayed emergence of organized fault-scale activity at distances 10 to 30 km from the detonation points (see the materials and methods) (36, 43). Instead, the observations suggest a time-dependent crustal response in which cumulative damage and progressive stress redistribution within the shallow crust evolved over extended periods (38, 44). According to this

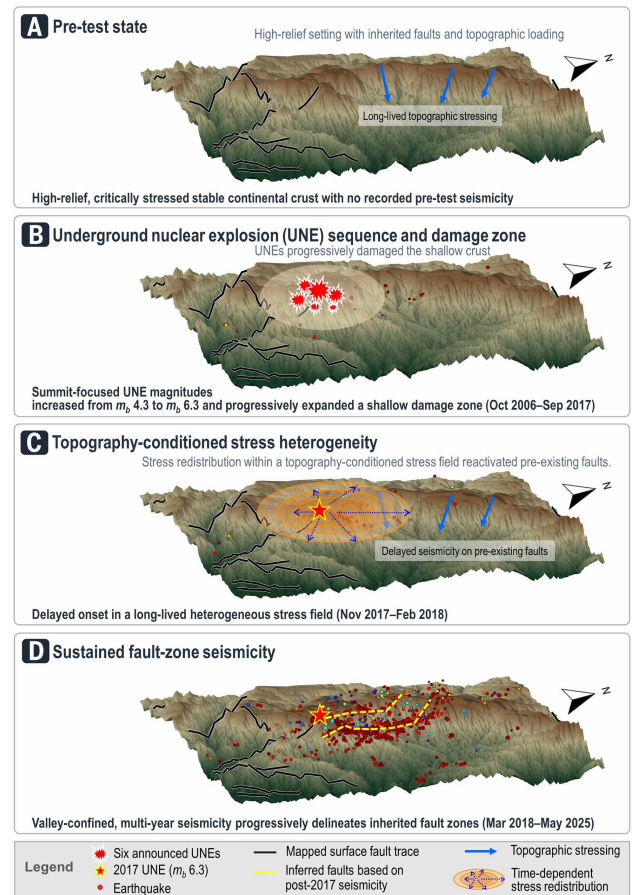


Fig. 5. Proposed evolution of delayed topography-conditioned fault-zone seismicity beneath Mt. Mantap. (A) Before underground nuclear testing, the Mt. Mantap area was a high-relief mountain-front setting in a region of critically stressed stable continental crust. Surface faults had been mapped, but no pretest seismicity was recorded. Long-lived topographic stressing is inferred to have produced considerable spatial variability in shallow-crustal normal stress and shear stress. (B) The six announced UNEs between October 2006 and September 2017 were concentrated beneath the summit and progressively enlarged a shallow damaged crustal volume. Relative to the surface elevation of the 6 January 2016 test, the reported hypocentral depths for the six UNEs are 2215, 1087, 769, 1196, 1019, and 81 m, respectively (5). The size of the symbols increases schematically with USGS-reported body-wave magnitude (m_b). (C) After the final test, explosion- and collapse-related damage and time-dependent stress redistribution evolved within a topography-conditioned stress field during the posttest delay interval from November 2017 to February 2018, preceding the sustained fault-zone seismicity shown in (D). (D) Since March 2018, valley-confined, multiyear seismicity has remained concentrated along structurally favorable fault segments, progressively delineating inherited fault zones while remaining comparatively limited outside of the principal topographically confined area. Mapped surface fault traces are shown as solid black lines, faults inferred from post-2017 seismicity as dashed yellow lines, topographic stress loading as solid blue arrows, and time-dependent stress redistribution as orange contours with dotted blue arrows. This diagram is intended as a conceptual synthesis; the fault geometry, plotted earthquake depths, and stress fields are schematic. Earthquake symbols are colored by relative relocated depth, with red indicating shallower events and blue indicating deeper events, as in Figs. 3 and 4.

interpretation, the explosions altered the stress field and fracture network in the shallow crust, initiating a prolonged phase of structural adjustment. Over time, stress redistribution gradually activated nearby faults, and the seismicity became organized into a broader fault network rather than remaining confined to localized damage zones.

Three-dimensional elastic stress modeling of topographic loading at Mt. Mantap further supports this interpretation by showing how the mountain's asymmetric relief can precondition the shallow crust (see the

materials and methods and figs. S21 to S25). Topographic loading here refers to stress perturbations caused by the weight of high terrain and by horizontal tractions associated with steep slopes. The pronounced asymmetric surface relief of the test site generates strong spatial heterogeneity in shallow-crustal normal- and shear-stress fields locally on the order of tens of megapascals in the near-surface crust (45) (figs. S21 to S25). Because normal stress controls fault clamping and shear stress promotes slip, this heterogeneity creates spatially variable proximity to failure. The relocated earthquakes cluster not simply beneath the largest topographic loads, but where stress gradients and elevated shear stress overlap mapped or inferred inherited faults (fig. S22). Thus, topography is not invoked as active tectonic loading or as a sole trigger, but as a persistent mechanical framework that helps to localize delayed reactivation of fault segments affected by explosion-related damage and progressive stress redistribution.

Topographic relief, therefore, helps to localize the delayed seismic response. Stress perturbations associated with repeated underground explosions can then promote reactivation along favorably oriented inherited structures, progressively integrating them into a connected fault network. The resulting spatial organization of seismicity reflects cumulative stress redistribution within the heterogeneous shallow crust rather than continued external forcing or instantaneous dynamic triggering. This evolutionary interpretation is summarized in Fig. 5, which links high-relief topography, repeated summit-centered underground explosions, delayed fault reactivation, and the progressive emergence of valley-confined/fault-controlled seismicity.

Implications for anthropogenic perturbations

The Mt. Mantap sequence demonstrates that UNEs can produce long-lasting crustal effects in a heterogeneous and critically stressed environment. Rather than generating only short-lived aftershock sequences, such perturbations can initiate the delayed reactivation of intraplate faults that unfold over years. The delayed fault-controlled seismicity at Mt. Mantap has important implications for the long-term monitoring of underground nuclear test sites, including verification efforts under the Comprehensive Nuclear-Test-Ban Treaty. Seismicity occurring years after detonation may complicate attribution and blur distinctions between explosion-related and tectonic events. Sustained monitoring and physically informed interpretation are therefore essential when evaluating late-stage seismic activity in the vicinity of legacy test sites. More broadly, these observations underscore the importance of preexisting stress heterogeneity and structural inheritance in governing the crustal response to transient perturbations. Anthropogenic perturbations introduced into critically stressed regions of the Earth's crust may not only produce immediate or short-lived effects, but may also trigger time-dependent structural evolution, extending their seismic impact well beyond the duration of the direct perturbation.

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Figs. S1 to S26; Tables S1 to S3;
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Editor's summary

North Korea conducted six underground nuclear tests between 2006 and 2017 at the Punggye-ri test site. The largest, final explosion was an equivalent magnitude 6.3 seismic event and deformed the mountaintop by about 3 meters. Most studies have focused on characterizing the explosion events, but Fan *et al.* took a longer view. Their 17-year earthquake catalog identified about 1400 local earthquakes between 2008 and 2025, with a notable acceleration of events and magnitudes after the 2017 test. Delayed reactivation of shallow faults indicates that cumulative damage from the explosions has redistributed crustal stress in the region. —Angela Hessler

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