

Abstract

On September 3rd 2017 official channels of the Democratic People's Republic of Korea announced the successful test of a nuclear device. Only minutes after the alleged nuclear explosion at the Punggye-ri nuclear test site at 03:30:02 (UTC), hundreds of stations distributed all around the globe picked up strong and distinct seismic signals associated with an explosion. Our investigations locate the event within the test site at a depth of 0.6 km. The radiation and generation of P- and S-wave energy in the source region are significantly influenced by the topography of Mt. Mantap. Inversions for the full moment tensor of the main event reveal a dominant isotropic component accompanied by significant amounts of DC and CLVD terms, confirming the explosive character of the event. The analysis of the source mechanism of an aftershock around 8 min after the test in the direct vicinity suggests a cavity collapse. Measurements at seismic stations of the IMS result in a body wave magnitude of 6.2, which translates to a yield estimate of around 400 kt TNT equivalent. The explosive yield is possibly overestimated, since topography and source mechanism both tend to enhance the peak amplitudes of teleseismic P-waves.

Epicenter estimation

- epicenter location: 41.3007°N, 129.0728°E
- relative location error of 100 m
- location of the five previous test within a radius of 400 m

The REB localization uses 125 seismic stations of the IMS and results in an epicenter of 41.321°N and 129.035°E with an error ellipse area of 110 km². This relatively high error is generated by the fact that only eight IMS stations are located at distances of 400 up to 2100 km (Figure 1a). However, the incorporation of 25 additional seismic stations at regional distances cannot significantly improve the absolute location estimate, as the closest station MDJ is still 372 km away from the test site. Due to these large source-receiver distances, a further improvement of the absolute location accuracy is limited.

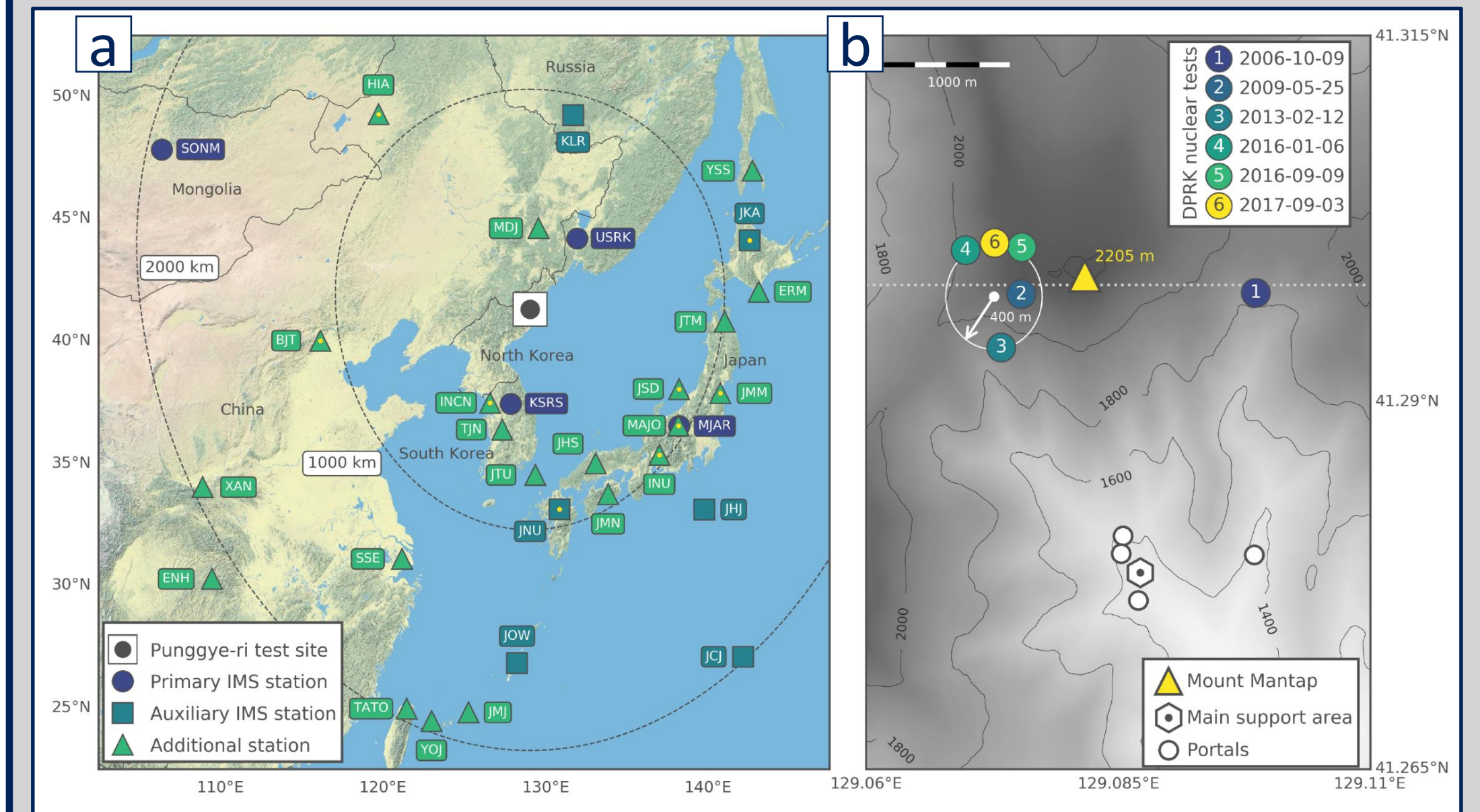


Figure 1: (a) Seismic stations of the International Monitoring System and other earthquake monitoring networks within a radius of 2100 km from the North Korean Punggye-ri nuclear test site. Stations that are used in the moment tensor analysis are marked with a small yellow dot. (b) Zoom into the Punggye-ri test site area. Numbered circles indicate the absolute locations of the six North Korean nuclear tests. The relative location error for each test is less than 100 m. The dashed line marks the profile to study the topographic influence of the Mt. Mantap massif on seismic energy generation and radiation from the 2017 test.

Nevertheless, relative location methods can be applied for a high-precision localization of the events. Here we apply a relative location procedure based on the cross correlation of seismograms from 33 regional seismic stations for the six North Korean tests (Figure 2). The relative locations of the six tests can be associated with absolute coordinates as soon as the geographical coordinates of one of the tests are known. The geographic, absolute location of the January 2016 nuclear explosion is fixed by means of radar interferometry data to the location of the maximum surface deformation observed after the test. The absolute epicenter location of the 2017 test from relative location procedures is consequently determined to be 41.3007°N, 129.0728°E (Figure 1b).

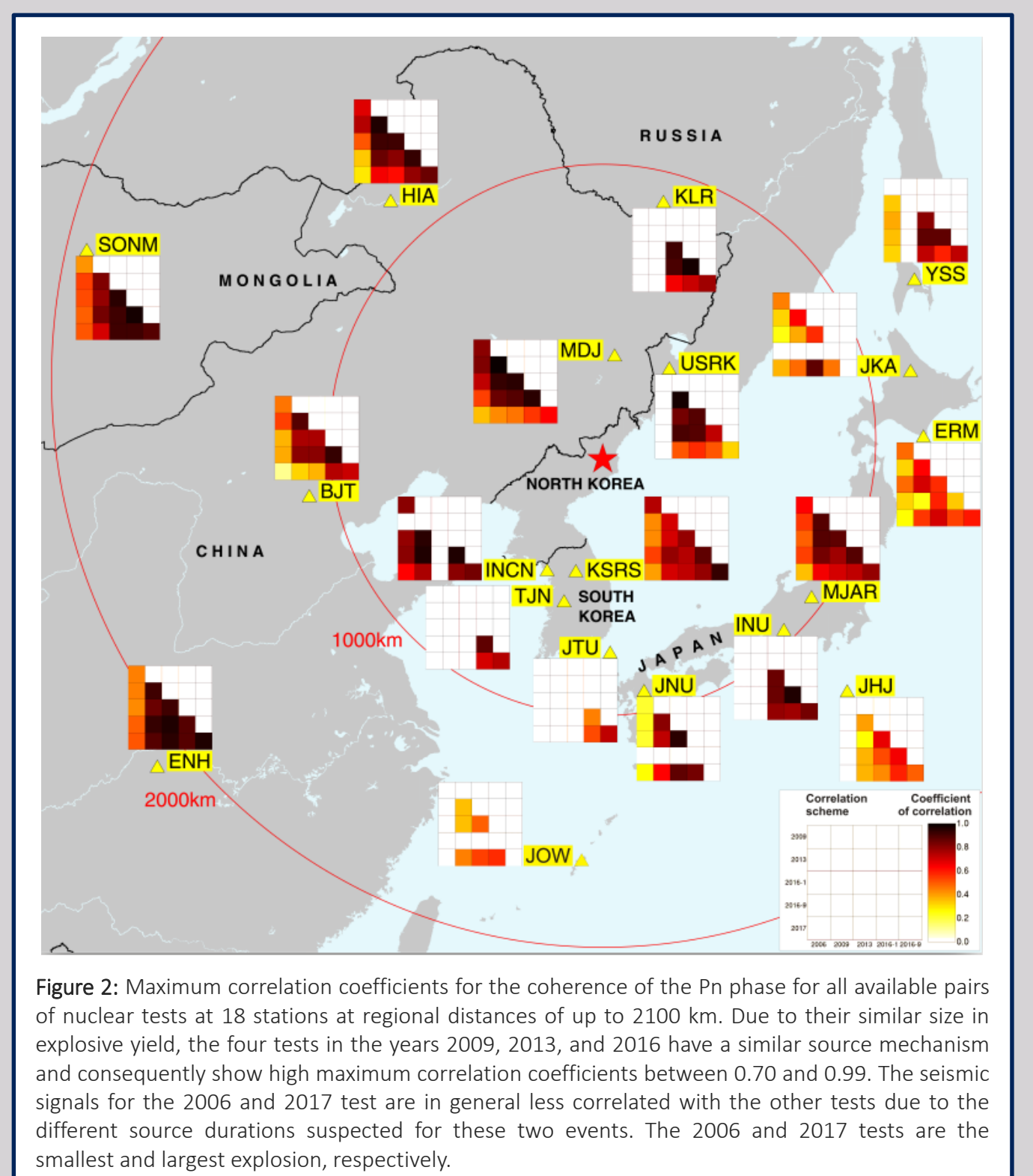


Figure 2: Maximum correlation coefficients for the coherence of the Pn phase for all available pairs of nuclear tests at 18 stations at regional distances of up to 2100 km. Due to their similar size in explosive yield, the four tests in the years 2009, 2013, and 2016 have a similar source mechanism and consequently show high maximum correlation coefficients between 0.70 and 0.99. The seismic signals for the 2006 and 2017 test are in general less correlated with the other tests due to the different source durations suspected for these two events. The 2006 and 2017 tests are the smallest and largest explosion, respectively.

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Depth and seismic moment

- estimation of depth by depth-phase modeling: 400-800 m
- seismic moment magnitude M_w : 5.55

The source depth is needed to estimate the explosion process and strength of the seismic source. However, constraining the depth of a shallow source is difficult from regional and teleseismic data without a close station within a focal depth's distance from the source. The modeling of the wavelet consisting of a surface-reflected P phase, the so-called depth phase, and STF can potentially help in such a case. Such a wavelet modeling approach resembles the inverted and time-shifted STF and needs high-frequency waveforms above 1 Hz to resolve the onset of the depth phase, and it may be difficult to perform this from single station recordings if the signal-to-noise ratio is poor at teleseismic distances. An approach uncommon for nuclear test studies is used, which was established for the analysis of induced seismicity, where waveform beams are calculated at several small-aperture, short-period arrays to enhance the SNR (Figure 3a). The beam waveforms represent a superposition of direct and reflected waves. The depth of the explosion is estimated by comparing observed and synthetic beam wave-forms (Figure 3d), which are calculated for the best moment tensor solution, a common STF and varying depths.

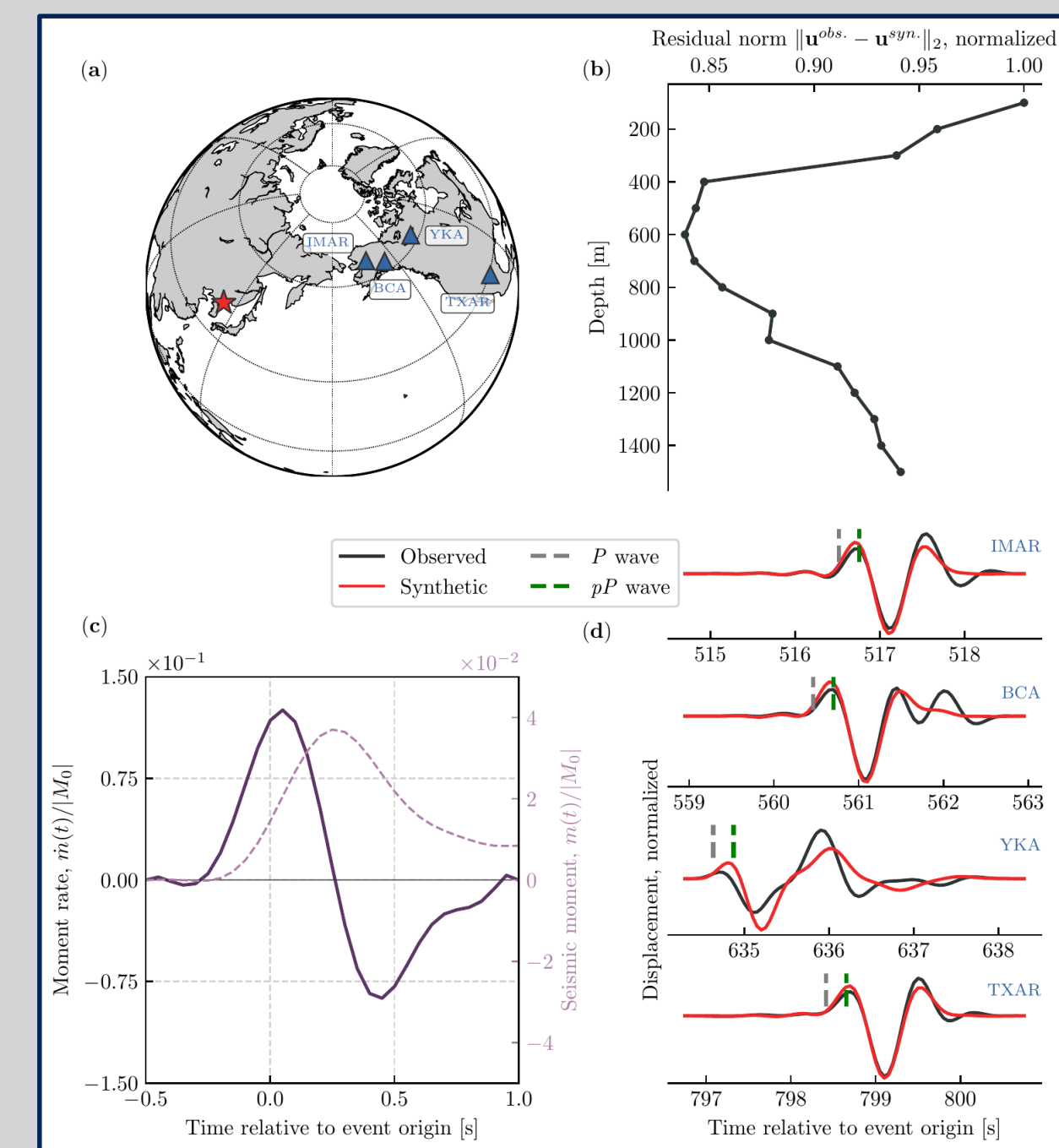


Figure 3: (a) Setup of the depth analysis with the 2017 North Korean nuclear test marked as a red star and the four small-aperture, short-period arrays marked as black triangles. The epicentral distances to arrays IMAR, BCA, YKA, and TXAR are 48°, 54°, 65°, and 94°, respectively. (b) Residuals between observed and synthetic waveforms (L2 norm) as a function of depth of the explosion. (c) Least squares source time function associated with the best-fit regularized solution. Solid and dashed lines are the normalized moment rate and moment function, respectively. (d) Observed (black) and synthetic (red) waveforms for the best-fit regularized solution at 600 m depth. The gray and green dashed lines indicate the theoretical arrival times of the P and pP phases, respectively. The traces are bandpass-filtered between 0.5 and 2.5 Hz.

Magnitude and yield estimation

- seismic body wave magnitude m_b : 6.2
- estimated explosive yield of around 400 kt TNT equivalent

The determination of m_b is the prerequisite for a reliable estimation of the yield of a nuclear explosion. In order to obtain comparable results for the past six North Korean events, is calculated from waveform peak values measured at always the same 15 IMS seismic stations that recorded all six events. For the 2017 test a m_b of 6.2 is calculated. This translates into a yield estimation of around 400 kt TNT equivalent (Figure 4).

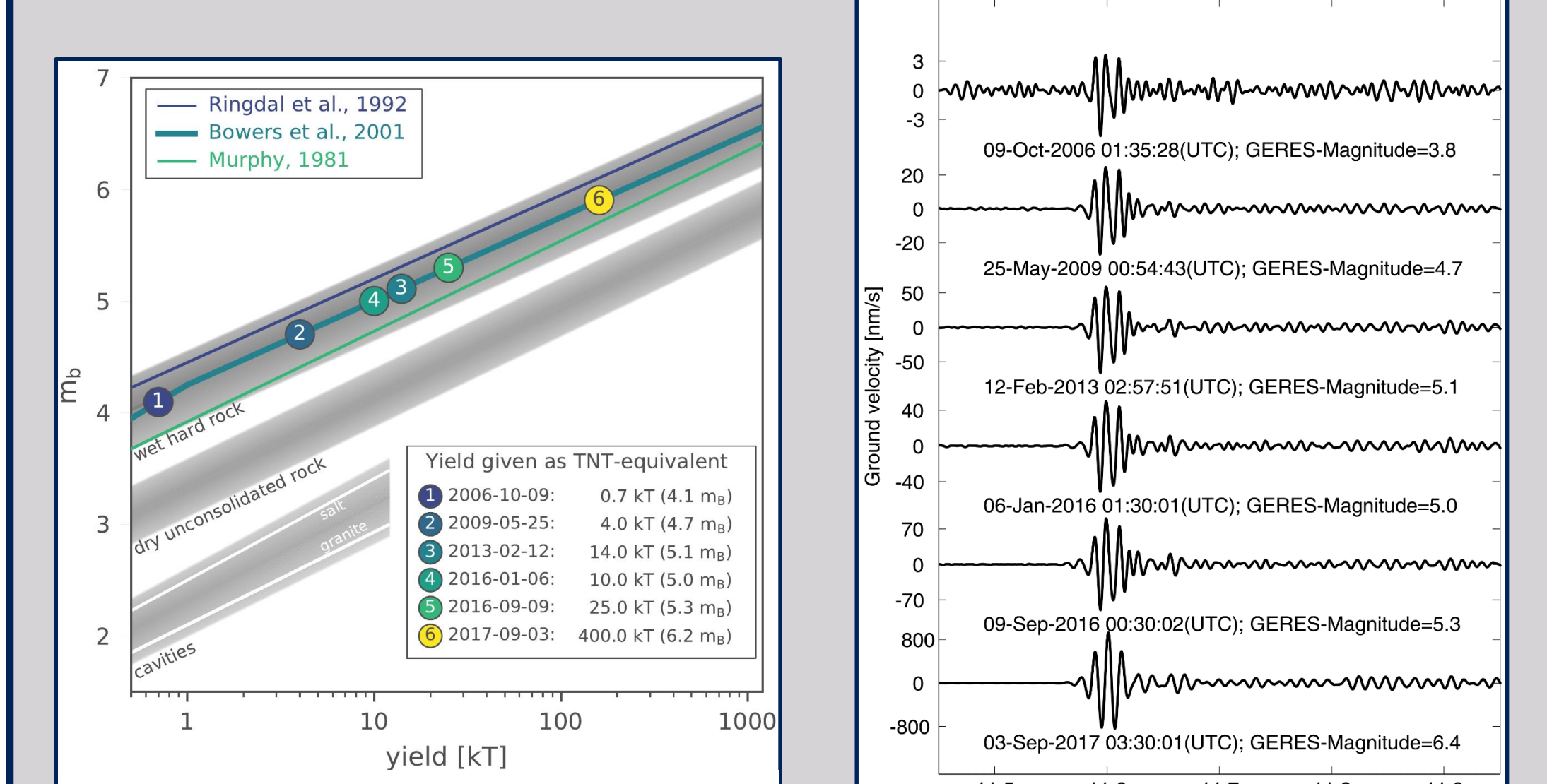


Figure 4: Magnitude-yield relation curves for different geological settings. Numbered circles indicate the six North Korean nuclear tests. Gray background shading represents lower and upper boundary literature values for the different environments.

Figure 5: Beam seismograms calculated from the vertical components of the GERES array showing the P wave of the six North Korean nuclear explosions. The seismograms are normalized to the individual maximum amplitudes, for which the station magnitude is estimated.

Moment tensor inversion

- MT solution 2017 test: +60% ISO, 16% CLVD, 24% DC
 - explosive source character
- MT solution aftershock: -65% ISO, 29% CLVD, 6% DC
 - cavity collapse

For the 2017 test the seismic moment tensor is inverted by fitting the low-frequency amplitude spectra (epicentral distances up to 1200 km) and full displacement waveforms (epicentral distances up to 600 km) in the frequency range from 0.02 to 0.04 Hz. The moment tensor solution for the 2017 test shows a dominant positive isotropic part of 60 %, 16 % positive CLVD, and 24 % of DC. The best solution, found at a depth of around 2 km, has a scalar moment of 2.33×10^{17} Nm, equivalent to a M_w of 5.55. Examples of full waveform displacement and amplitude spectra fits are shown in Figure 6. The moment tensor optimization resolves a broad ensemble of well-fitting moment tensor solutions (Figure 7).

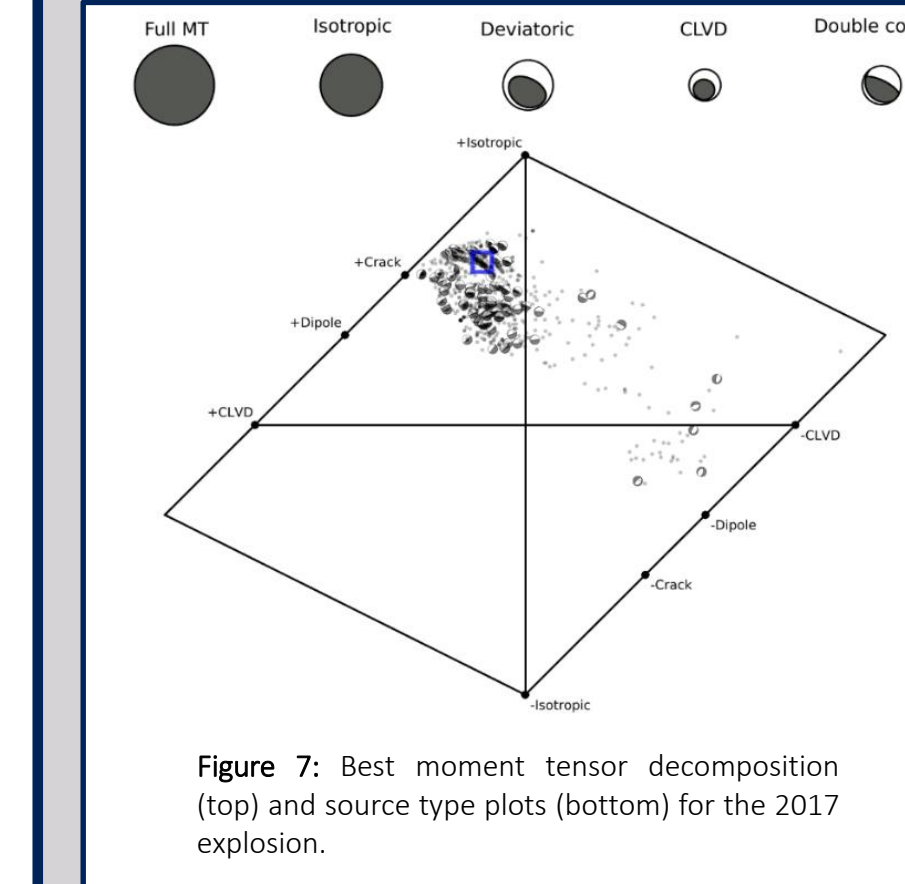


Figure 7: Best moment tensor decomposition (top) and source type plots (bottom) for the 2017 explosion.

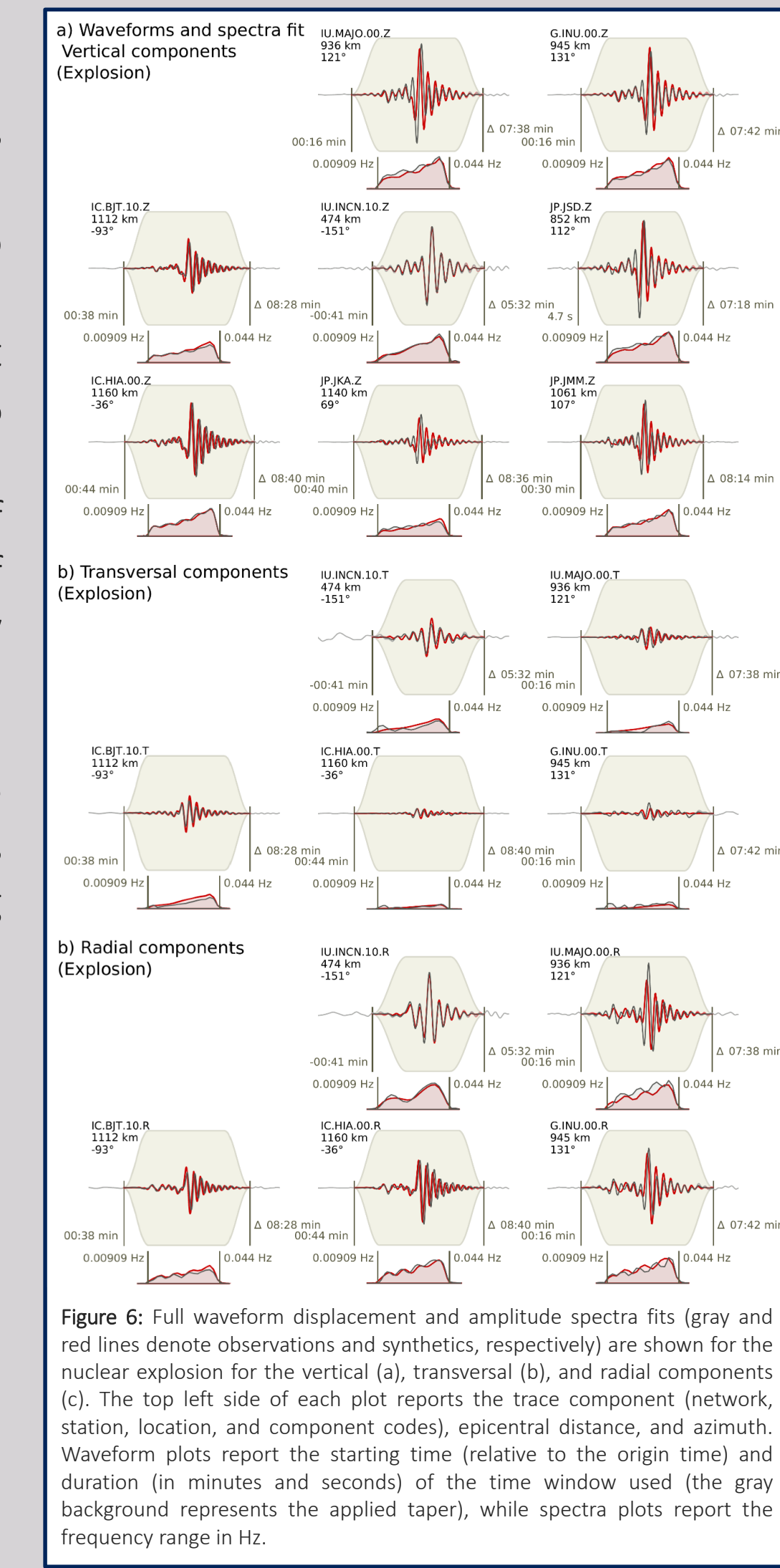


Figure 6: Full waveform displacement and amplitude spectra fits (gray and red lines denote observations and synthetics, respectively) are shown for the nuclear explosion for the vertical (a), transversal (b), and radial components (c). The top left side of each plot reports the trace component (network, station, location, and component codes), epicentral distance, and azimuth. Waveform plots report the starting time (relative to the origin time) and duration (in minutes and seconds) of the time window used (the gray background represents the applied taper), while spectra plots report the frequency range in Hz.

In the aftermath of the nuclear test, a seismic event took place in its direct vicinity around 8 min later. The estimated scalar moment and M_w are 1.88×10^{16} Nm and 4.81, respectively. Waveform displacement and amplitude spectra fits of the MTI are shown in Figure 8. The best MTI solution suggests a dominant implosive source component (65 %), negative CLVD (29 %), and a DC component of 6 %. This source mechanism is compatible with a shallow collapse source or might hint at some kind of break-in process (Figure 9).

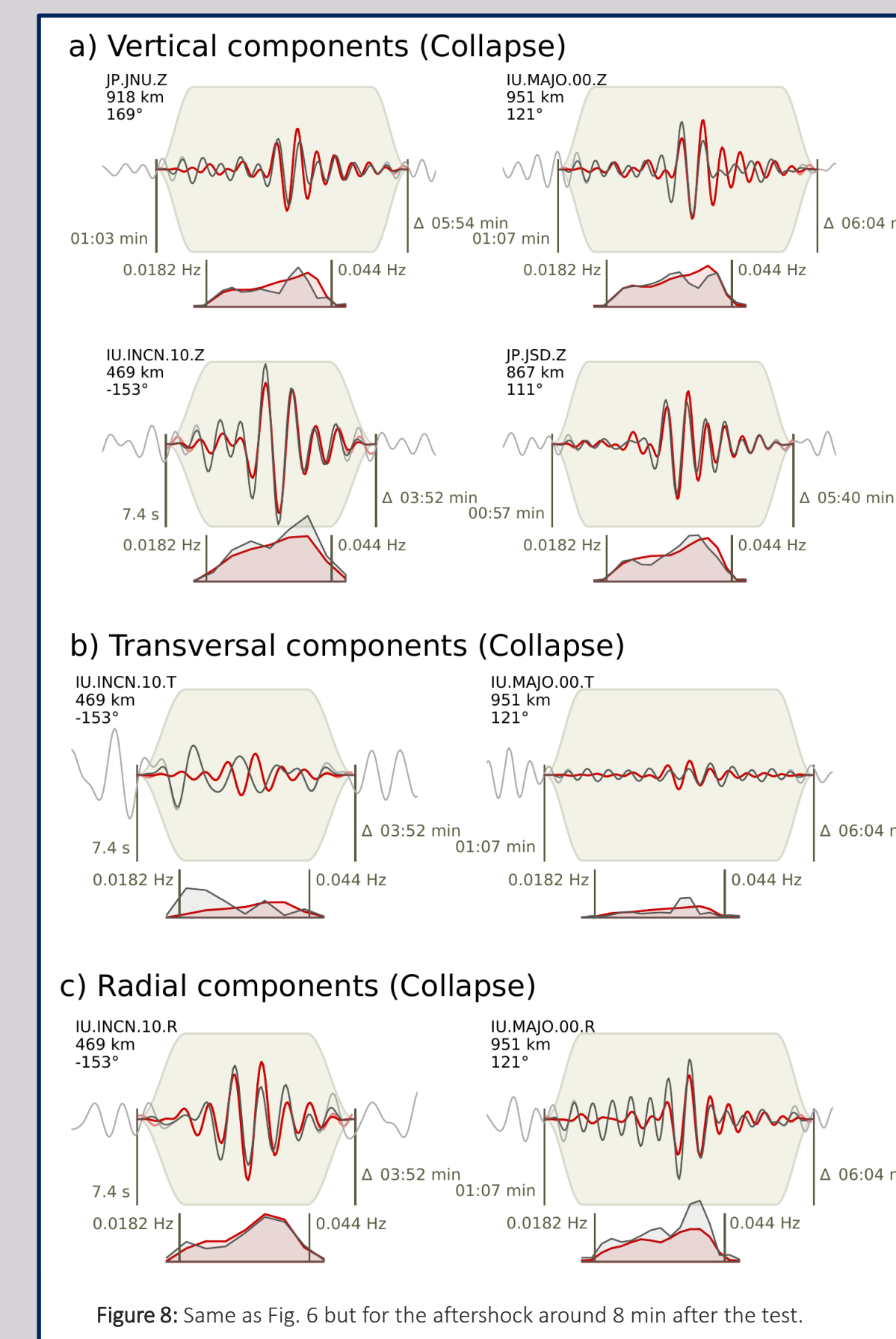


Figure 8: Same as Fig. 6 but for the aftershock around 8 min after the test.

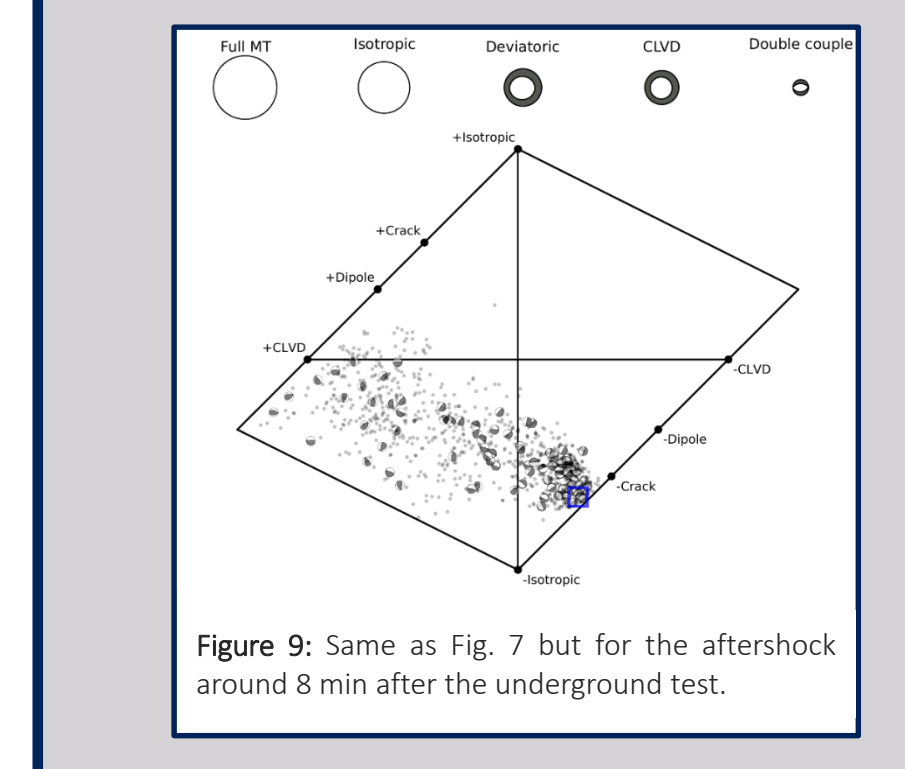


Figure 9: Same as Fig. 7 but for the aftershock around 8 min after the underground test.

Influence of topography

- Strong influence of Mt. Mantap topography on
 - generation/radiation of seismic energy
 - generation of infrasound signals
 - explosive yield estimation

Two-dimensional synthetic wave-field simulations are used to study the influence of topography of the Mt. Mantap complex on the propagation of P- and S-wave energy emitted by a point-like explosion source. Wave energy is focused due to the shape of the mountain, especially from the easterly flank with a change in altitude of approximately 600 m (see Figure 1). In general, this numerical modeling gives indications of (1) the generation of clear infrasonic signals because topography increases the amount of radiated acoustic energy in the subhorizontal direction; (2) a reduced value of the isotropic part obtained by MTI because a larger amount of S-wave energy is generated in the source region due to topography effects above the source; (3) an overestimation of the yield of the explosion because P and pP phases are considered as a single onset in teleseismic distances and in the investigated frequency range for shallow sources, leading to an increase in maximum P-wave amplitude of approximately 1.3 and hence in m_b of around 0.1.

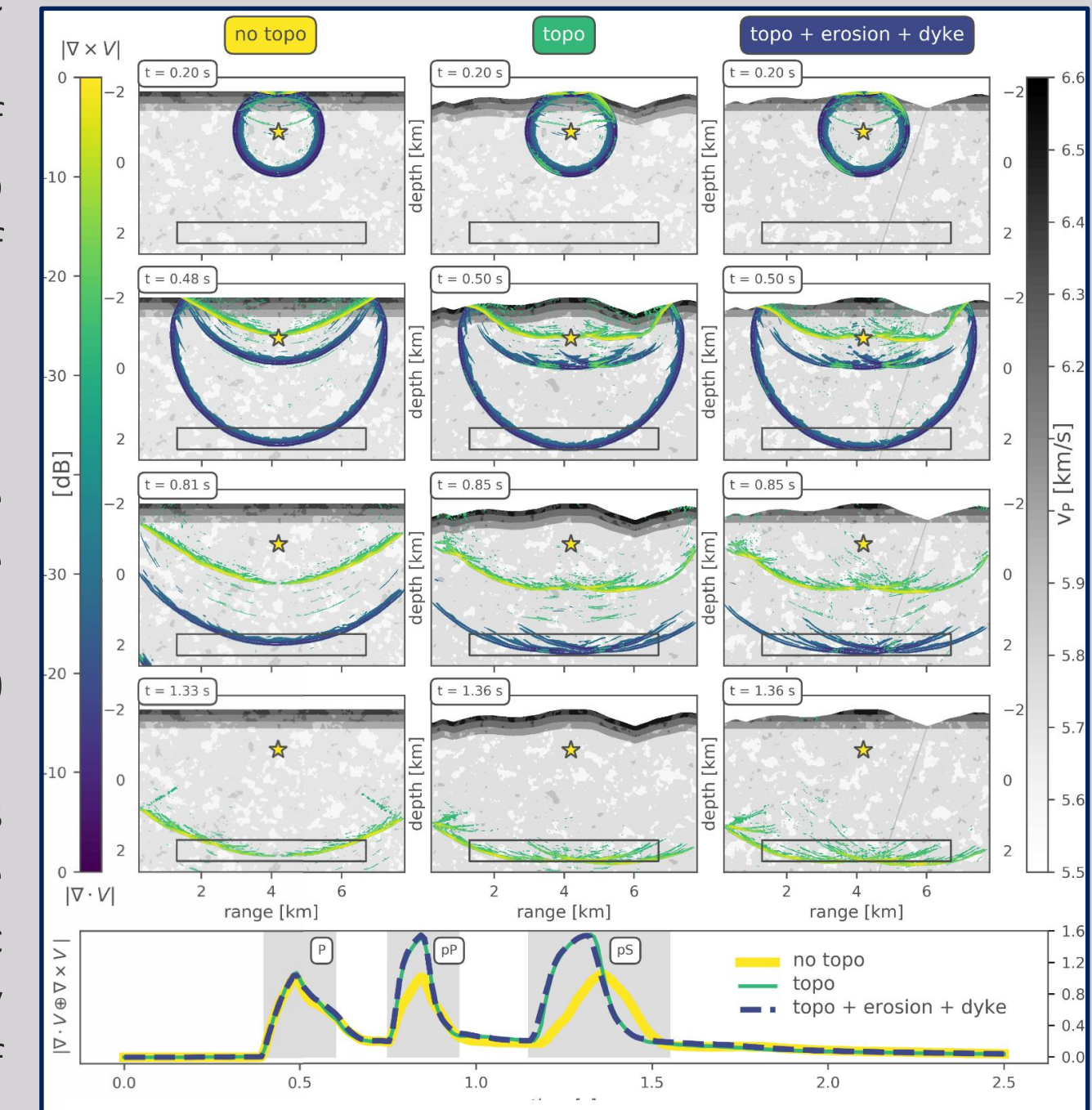


Figure 10: Snapshots obtained by and velocity model used for numerical simulations. P-wave velocities are indicated by shading according to the gray scale map (for S-wave velocities we assume a V_p/V_s ratio of 1.73), as well as logarithmically scaled divergence (P-wave energy) and curl (S-wave energy) by blue and green colors, respectively. The snapshots in (a) show the P- and S-wave separated propagation for an explosion source without topography, the middle panels with topography across the North Korean test site for a west-east profile along 41.3° N with Mt. Mantap in the middle. Panels in (c) are similar to those in (b) but with a more realistic geological setting, where erosion is accounted for. The time stamp of each snapshot is displayed in the upper left corner. The point source is beneath the center of Mt. Mantap at a depth of 0.6 km below the surface. The panel below the snapshots compares the summed average divergence and curl computed every 0.02 s in a rectangular box below the source for the case without (yellow) and the cases with (green and blue) topography. The downward-propagating wave field shows strongly increased amplitudes for pP and pS phases in both cases of topography.

Conclusions

- The explosive character of the 3 September 2017 North Korean event is confirmed by MTI analysis.
- The yield of the event is estimated to be around 400 kt TNT equivalent with indications that this value should be considered as an upper limit and might be as low as 160 kt TNT equivalent. This overestimation can be explained by the enhancement of peak amplitudes of tele-seismic P waves due to topography and depth phase effects.
- The estimated yield of the nuclear device is certainly smaller than the largest documented yield ever achieved by a boosted fission device and is therefore still compatible with a fission-only device.
- The aftershock directly following the nuclear explosion has a similar depth as the test and can be characterized as a collapse of the cavity created by the test.
- The test site might have been strongly stressed and shattered and thus rendered useless for further test activities.

References/Publication

For references and more details on the applied methods and results please be referred to the paper *A multi-technology analysis of the 2017 North Korean nuclear test* by Gaebler et al. (2019) in the EGU journal Solid Earth. The manuscript is open access and can be downloaded at <https://www.solid-earth.net/10/59/2019/> or using the adjacent QR-code.

