Supplement to: Deep neural networks based denoising of regional seismic waveforms and impact on analysis of North Korean nuclear tests

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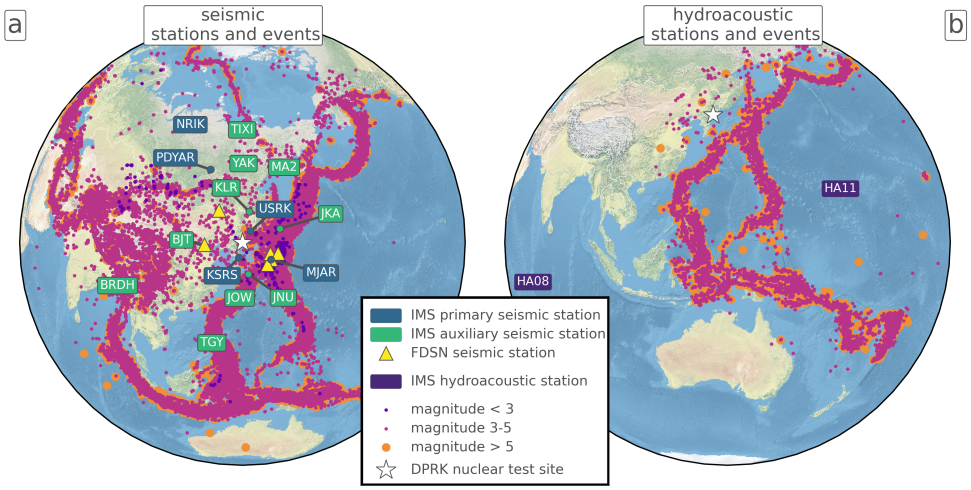

Fig. S1 Map of all events 50 degree around the North Korean test site in the REB catalog between 2006 and 2023, before selection based on SNR, for seismic data (a) and hydroacoustic data (b).

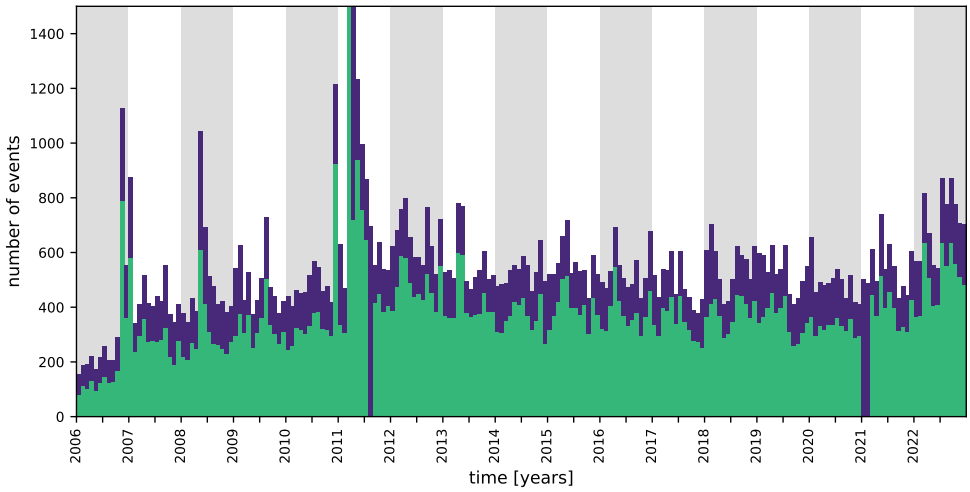

Fig. S2 Monthly number of events for the time 01/2006 to 12/2022. Blue bars in the background represent number of events included in the CTBTO REB catalog, green bars represent events remaining after applying a SNR event criteria (SNR > 10dB at 1-8 Hz). 77717 out of 114168 (68%) events remain after SNR screening.

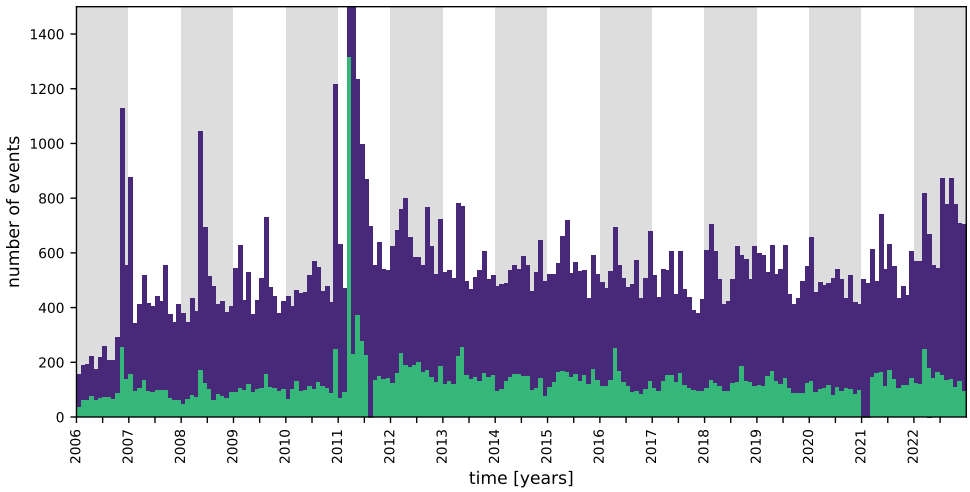

Fig. S3 Same as figure S2, but for SNR > 20dB at 1-8 Hz). 26214 out of 114168 events (23%) remain after SNR screening.

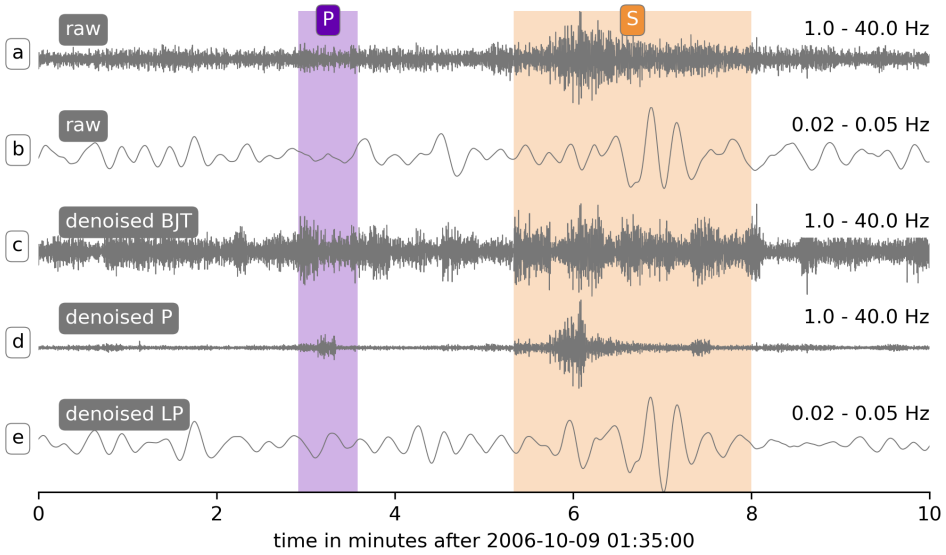

Fig. S4 Plot of waveforms at station BJT at a distance of 1100 km from the 2006 test which are a) raw and filtered between 1 and 40 Hz, b) raw and filtered between 20-50s, c) denoised with the BJT specific DAE filtered between 1 and 40 Hz, d) denoised with the general P-phase model filtered between 1 and 40 Hz, e) denoised with the LP model and filtered between 1 and 40 Hz. The waveform amplitudes are maximum normalized.

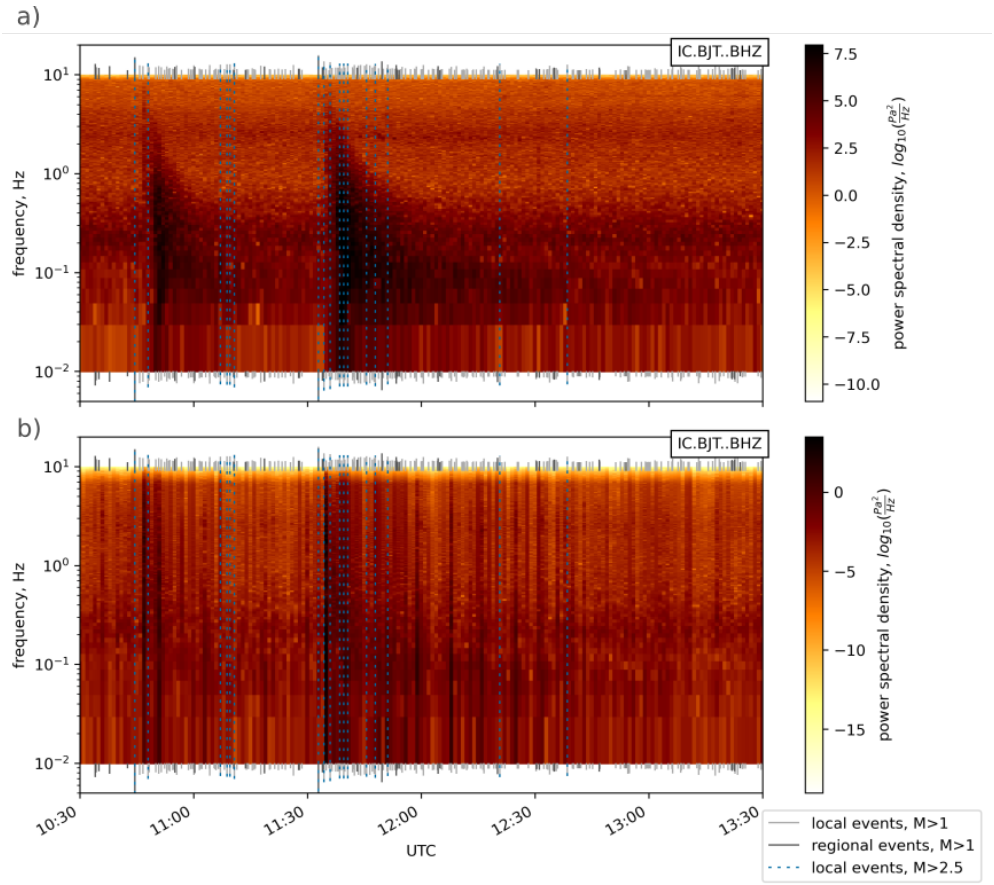

Fig. S5 Plot of spectra of vertical components at station BJT on 2016-09-12 between 10:30 and 13:30, at distance of 1100 km from the 2016-09-12 11:32 Mw 5.4 earthquake and its aftershocks from a) raw and b) P-model denoised waveforms.

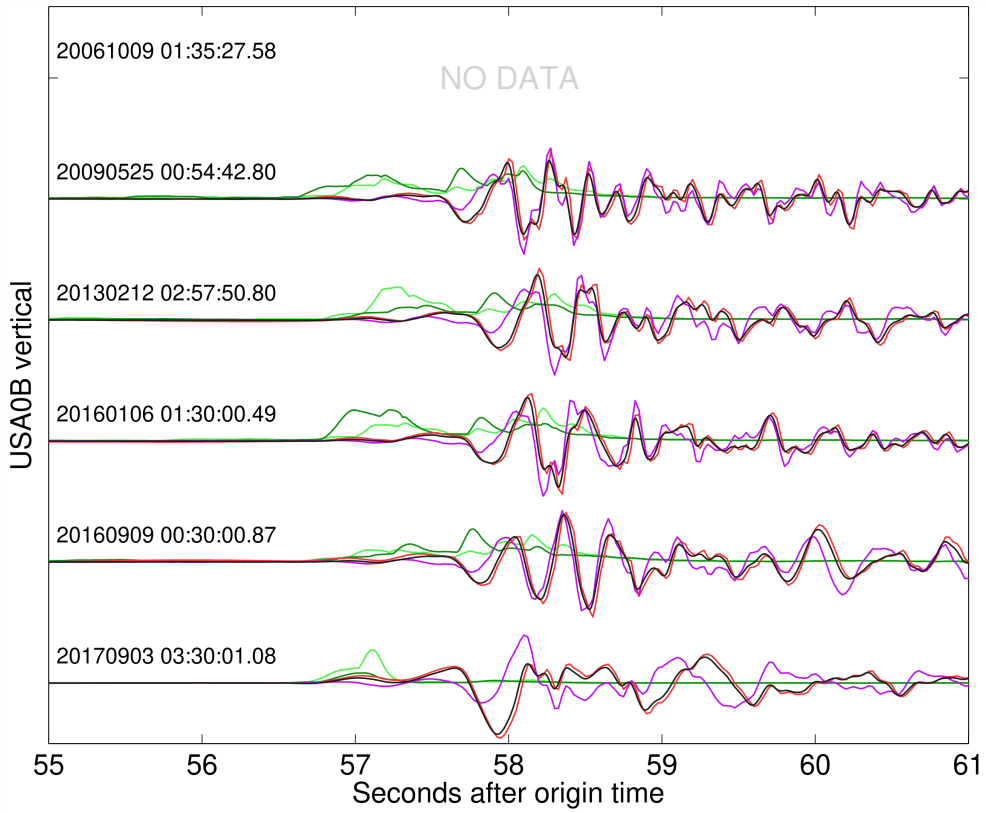

Fig. S6 Plot of waveforms for all six North Korean nuclear explosions at the vertical component of station USA0B zoomed in for the P wave. The traces for original data (red), high pass filtered data (purple) and denoised data (black) are overlayed. The continuously estimated SNR is included for the high pass filtered data (light green) and the denoised data (dark green). The waveform traces as well as the SNR traces are normalized for each event individually. Each event is marked by its origin time, as given in the Reviewed Event Bulletin (REB) of CTBTO.

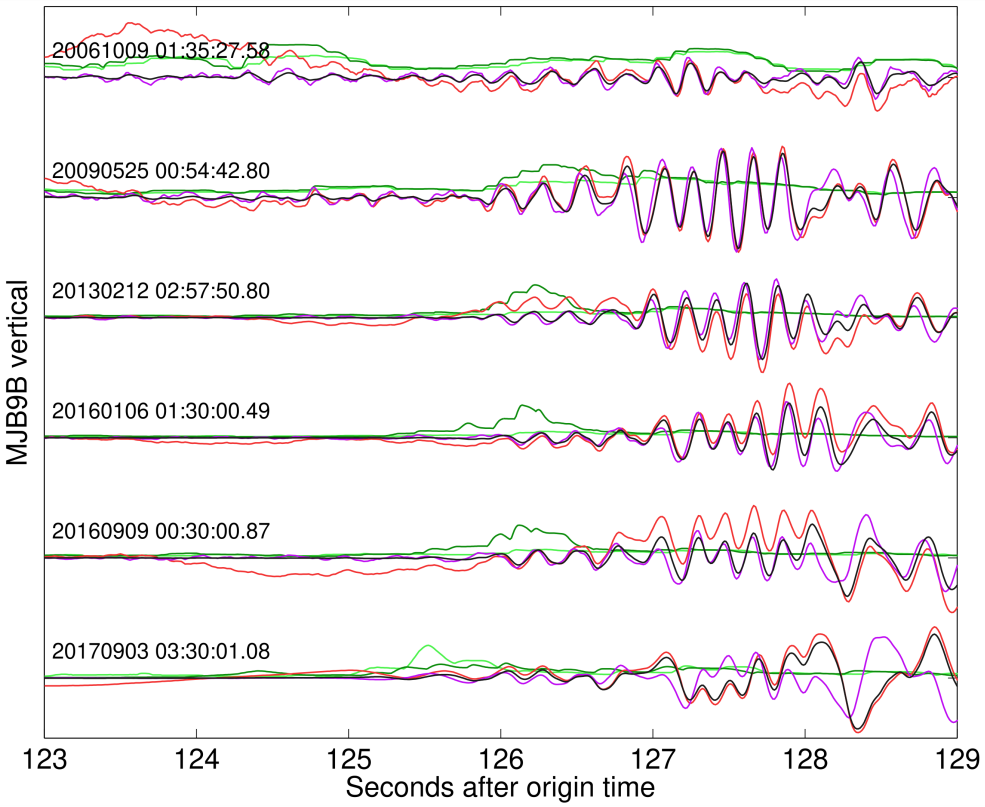

Fig. S7 Plot of waveforms for all six North Korean nuclear explosions at the vertical component of station MJB9B zoomed in for the P wave. The traces for original data (red), high pass filtered data (purple) and denoised data (black) are overlayed. The continuously estimated SNR is included for the high pass filtered data (light green) and the denoised data (dark green). The waveform traces as well as the SNR traces are normalized for each event individually. Each event is marked by its origin time, as given in the Reviewed Event Bulletin (REB) of CTBTO.

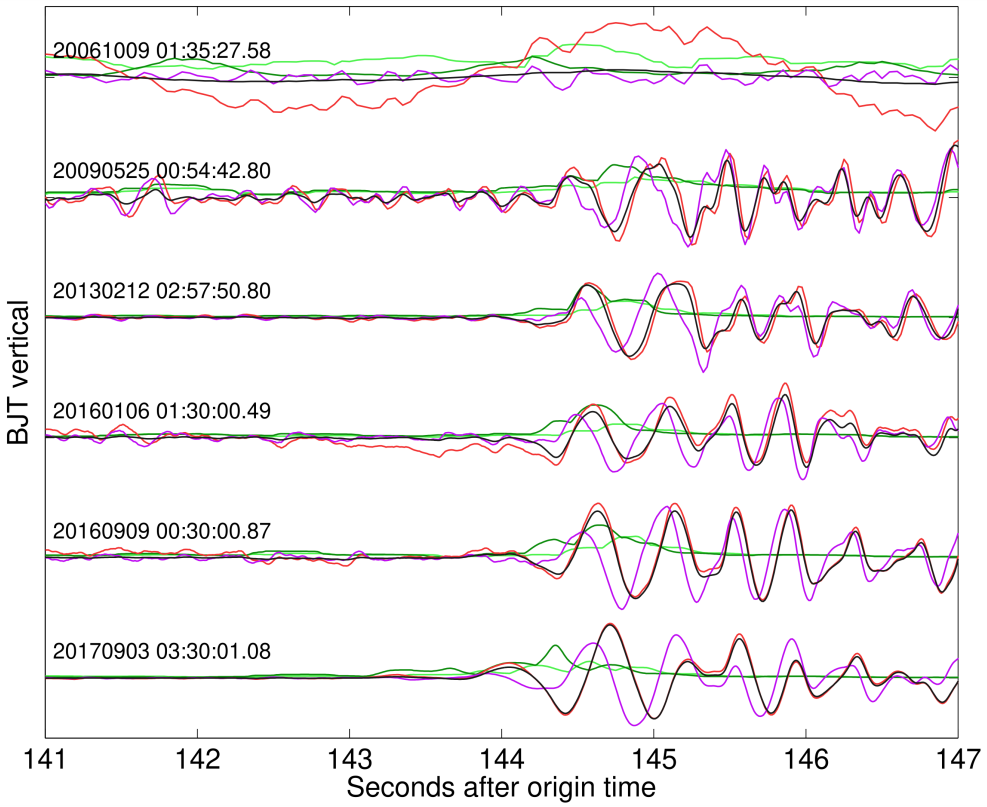

Fig. S8 Plot of waveforms for all six North Korean nuclear explosions at the vertical component of station BJT zoomed in for the P wave. The traces for original data (red), high pass filtered data (purple) and denoised data (black) are overlayed. The continuously estimated SNR is included for the high pass filtered data (light green) and the denoised data (dark green). The waveform traces as well as the SNR traces are normalized for each event individually. Each event is marked by its origin time, as given in the Reviewed Event Bulletin (REB) of CTBTO.

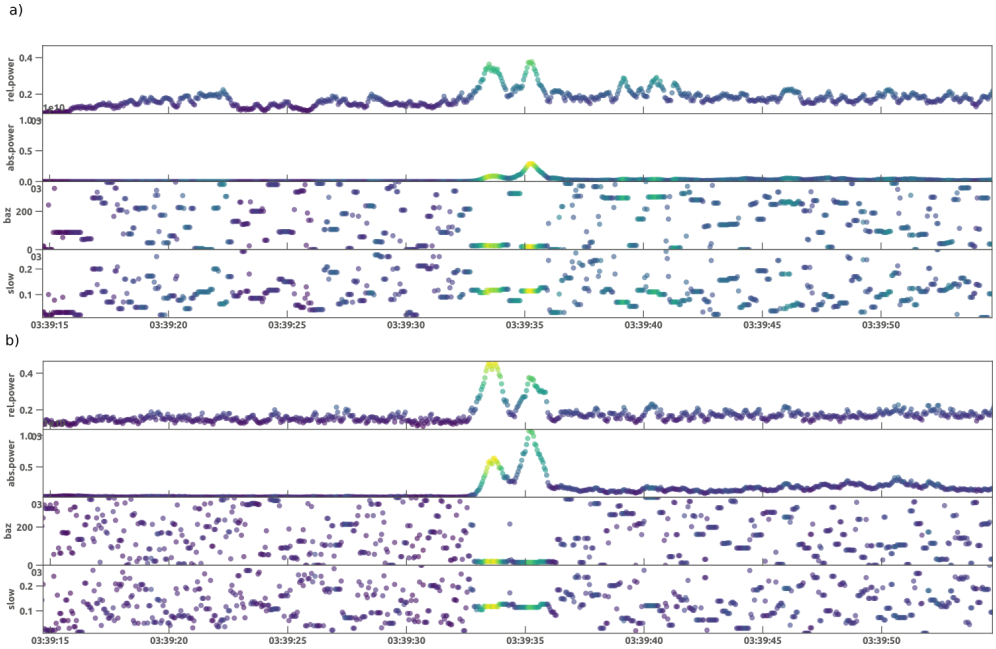

Fig. S9 FK processing results of the P-wave signal of the collapse after the 2017 test at the KSRS array in South Korea for a) raw and b) denoised data showing in each subplot from top to bottom: relative power (rel. power), absolute power (abs. power), backazimuth (baz) in degree and slowness (slow) in degree/s. The samples are coloured after the absolute power, with warmer colors indicating higher absolute power.

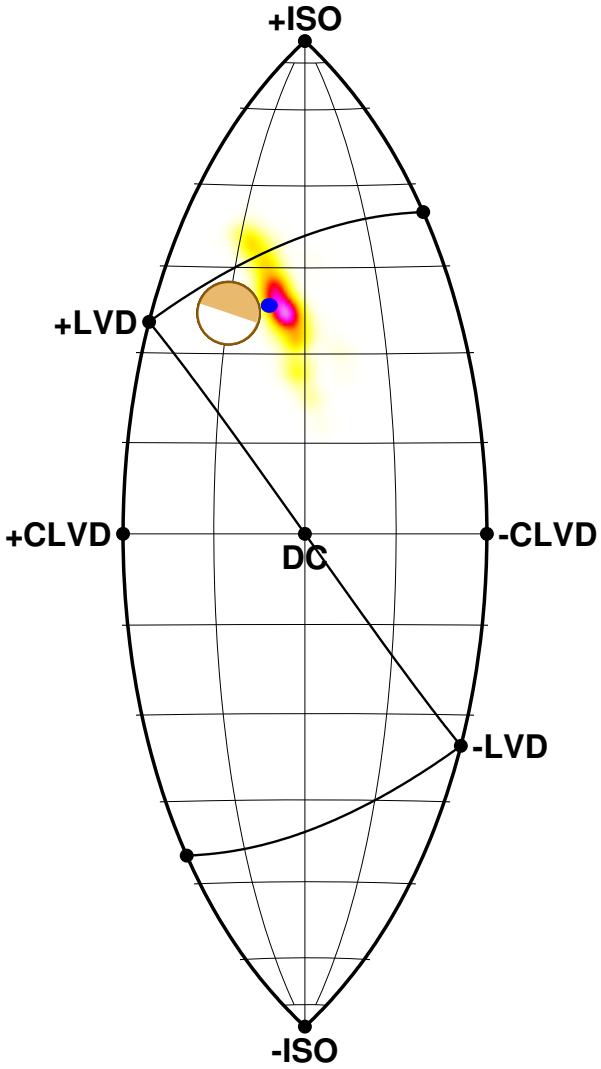

Fig. S10 Lune plot to test the recovery of a pre-defined MT (blue dot indicates location in the Lune, input MT is shown besides that) after denoising of synthetic signals with added real pre-event noise, from before the 2017 test. The color indicates the density of estimates, with warmer colors indicating higher densities.

Time	ML	SNR	Ref. Location	Location ori.	Location deno.	diff. ori./deno. [km]	EQT ori. (P/S)	EQT deno. (P/S)
2016-09-12 23:53:42.000	3.2	6.7	35.77,129.19,22.4	35.72,129.21,19.3	35.76,129.13,18.2	5.8/5.5	4/4	5/5
2016-09-12 23:27:22.000	2.6	3.4	35.76,129.18,28.8	35.73,129.22,22.3	35.73,129.22,22.3	4.9/4.9	3/4	4/4
2016-09-12 23:42:42.000	0.9	1.4	35.75,129.18,25.1	35.65,129.23,33.1	35.63,129.24,24.1	11.9/15.4	3/3	3/5

Table 1 Table of event parameters of selected aftershocks of the 2016-09-12 11:32 Mw 5.4 earthquake. The location is determined from 1-8 Hz bandpass filtered original and denoised waveforms using a 1D velocity model [1, 2] and the Lassie software (https://github.com/pyrocko/lassie-v2). Data used are from the center station of the KSRS array as well as stations KS.BUS2, KS.NAWB, KG.TJN, KS.CHJ2, so in total 5 stations. The reference location given is from the Korean Meterological Agency [3]. Mean SNR is determined from the unweighted mean of SNR of the first P-wave arrival. Locations are given as Lat,Lon,Depth(km). We also give the hypocentral difference in km between the reference and the original and denoised data. Furthermore the number of picks retrieved using Earthquake Transformer [4] is indicated for both filtered original and denoised waveforms, with the maximum possible number being 5 picks.

Time	ML	SNR	Ref. Loc.	Loc. ori. (bearing KSRS/USRK)	Location deno. (bearing KSRS/USRK)	diff. ori./deno. [km]
2017-09-03 03:30:01.934	6.1	1281	41.3007,129.0728	41.2488, 129.139 (14.48/216.23)	41.2488, 129.139 (14.48/216.23)	7.9/7.9
2023-06-10 16:46:45.68	2.4	1.6	41.2374,129.0594	41.01,129.245 (16.54, 213.4)	41.243,129.501 (16.55, 216.6)	29.6/37
2023-09-26 15:48:43.27	3.4	3.3	41.2923,129.1602	41.312,129.365 (16.54, 214.7)	41.219,129.273 (16.09, 214.54)	17.2/ 12.4

Table 2 Table of event parameters of selected events of different sizes around the North Korean Test site. The location is determined from 1-8 Hz bandpass filtered original and denoised waveforms using cross bearing from the KSRS and USRK arrays. The reference location given is from REB. Locations are given as Lat,Lon. The bearings determined from FK-analysis of the KSRS and USRK arrays is given in degrees in brackets behind the location. Mean SNR is determined from the unweighted mean of SNR of the first P-wave arrival at KSRS and USRK. We also give the hypocentral difference in km between the reference and the original and denoised data.

References

[1] Kennett, B.L.N., Engdahl, E.R., Buland, R.: Constraints on seismic velocities in the Earth from traveltimes. Geophys. J. Int. **122**, 108–124 (1995)

[2] Montagner, J.-P., Kennett, B.L.N.: How to reconcile body-wave and normalmode reference Earth models? Geophys. J. Int. **125**, 229–248 (1996)

[3] Korean Meteorological Administration, K.: Korean Meteorological Administration Earthquake Catalog. https://www.weather.go.kr/w/eqk-vol/search/

[4] Mousavi, S.M., Ellsworth, W.L., Zhu, W., Chuang, L.Y., Beroza, G.C.: Earthquake transformer—an attentive deep-learning model for simultaneous earthquake detection and phase picking. Nature communications **11**(1), 3952 (2020)