Auxiliary Material

The Character of Seafloor Ambient Noise Recorded Offshore New Zealand: Results from the MOANA Ocean Bottom Seismic Experiment

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Keywords: Noise, OBS, infragravity wave, continental shelf, New Zealand

Auxiliary Material A. Collection of PDFs, Plots of Maximum Double-Frequency Peak Amplitudes, and the Station List.

Figure S1. Power Density Functions (PDFs) of PSDs of 26 stations (not including station NZ01, NZ04 (Fig. 2b), NZ17, and NZ18 (Fig. 2a)) deployed during MOANA seismic experiment. The unit on the Y axis is $10\log(m^2/s^4/Hz)$, referred as dB. Each row is for one station with three components BH1, BH2, and BHZ. Plots are sorted in ascending order of station numbers.

Figure S2. Maximum amplitudes of the double-frequency peak vs. station depths of west stations (a) and east stations (b).

Table S1. List of station locations.

Staname	Lat.(^{o})	Long.(^{o})	Depth (m)
NZ01	-44.4981	165.0016	-4682
NZ02	-43.9980	166.5011	-3816
NZ03	-43.0018	165.9995	-4225
NZ04	-41.9993	165.5024	-4470
NZ05	-40.6493	167.2510	-1188
NZ06	-39.7498	168.0011	-859
NZ07	-40.2501	169.0003	-852
NZ08	-40.9998	168.5011	-995
NZ09	-41.6507	167.8998	-1335
NZ10	-43.2007	168.0004	-1193
NZ11	-43.3000	168.8502	-911
NZ12	-43.0017	169.5986	-625
NZ13	-42.4997	169.0000	-1165
NZ14	-42.6506	169.9500	-633
NZ16	-41.7499	169.2491	-1063
NZ18	-41.0002	170.0000	-805
NZ19	-40.7502	170.9004	-549
NZ20	-40.1995	170.7503	-714
NZ21	-39.5005	170.0001	-676
NZ22	-44.5006	173.9987	-776
NZ23	-45.1494	174.8520	-1091
NZ24	-45.4984	176.0026	-1507
NZ25	-45.9978	174.7504	-1727
NZ26	-46.9979	174.4984	-1316
NZ27	-46.5007	173.2497	-1544
NZ28	-45.9639	171.7514	-1328
NZ29	-45.2474	172.2535	-1383
NZ30	-45.4980	173.5010	-1416

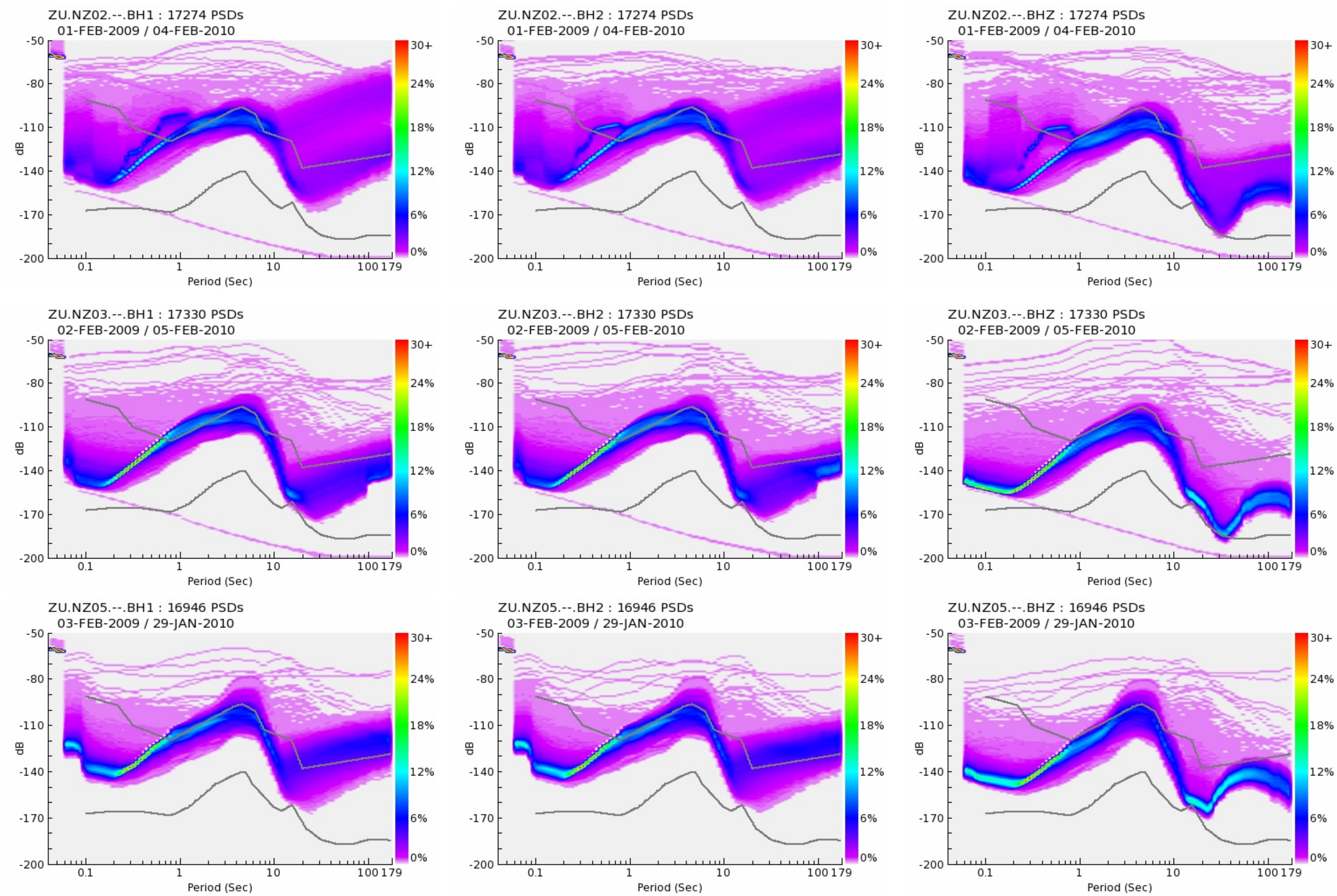


Figure S1 (NZ02, Nz03, and NZ05)

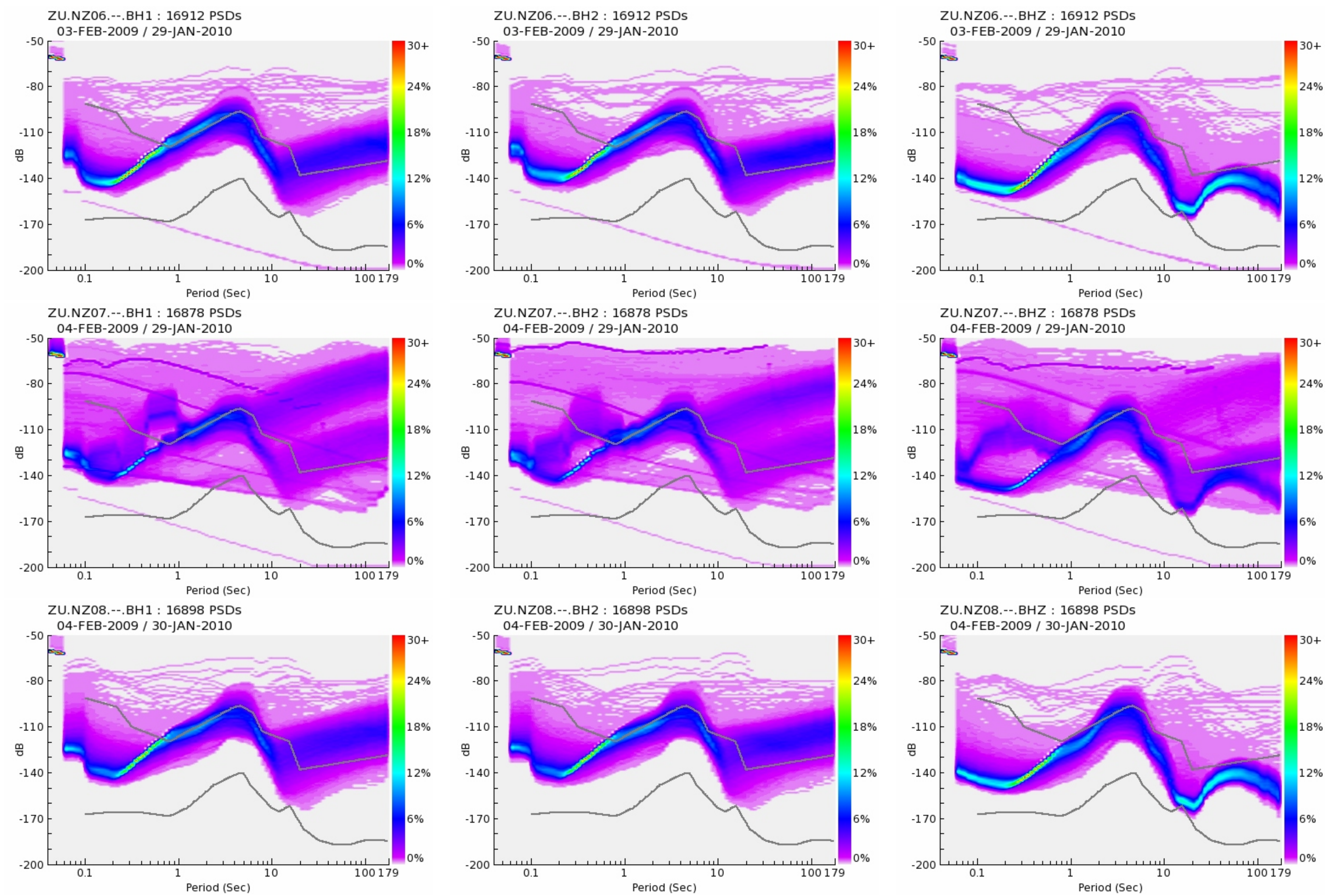


Figure S1 (NZ06, NZ07, and NZ08)

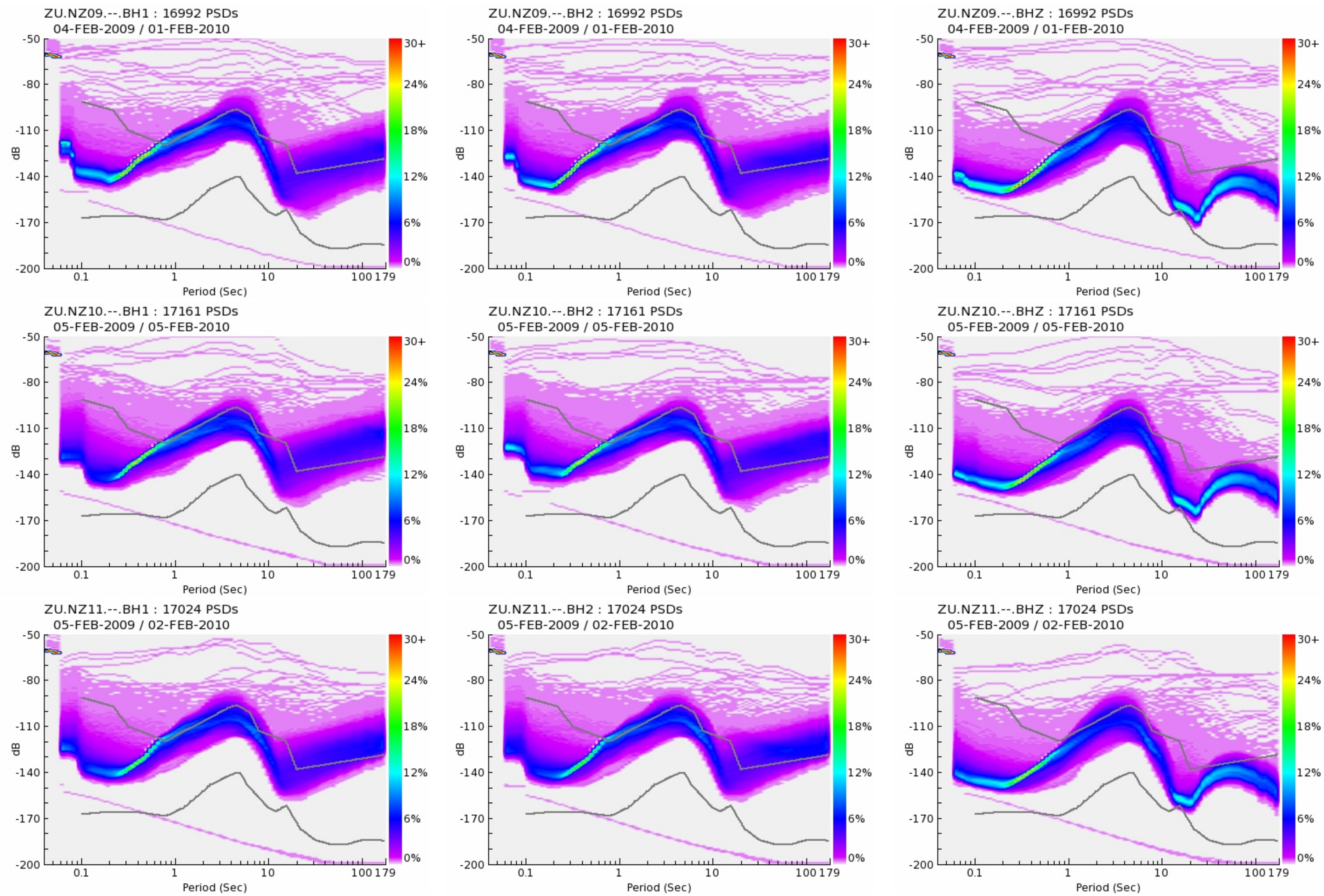


Figure S1 (NZ09, NZ10, and NZ11)

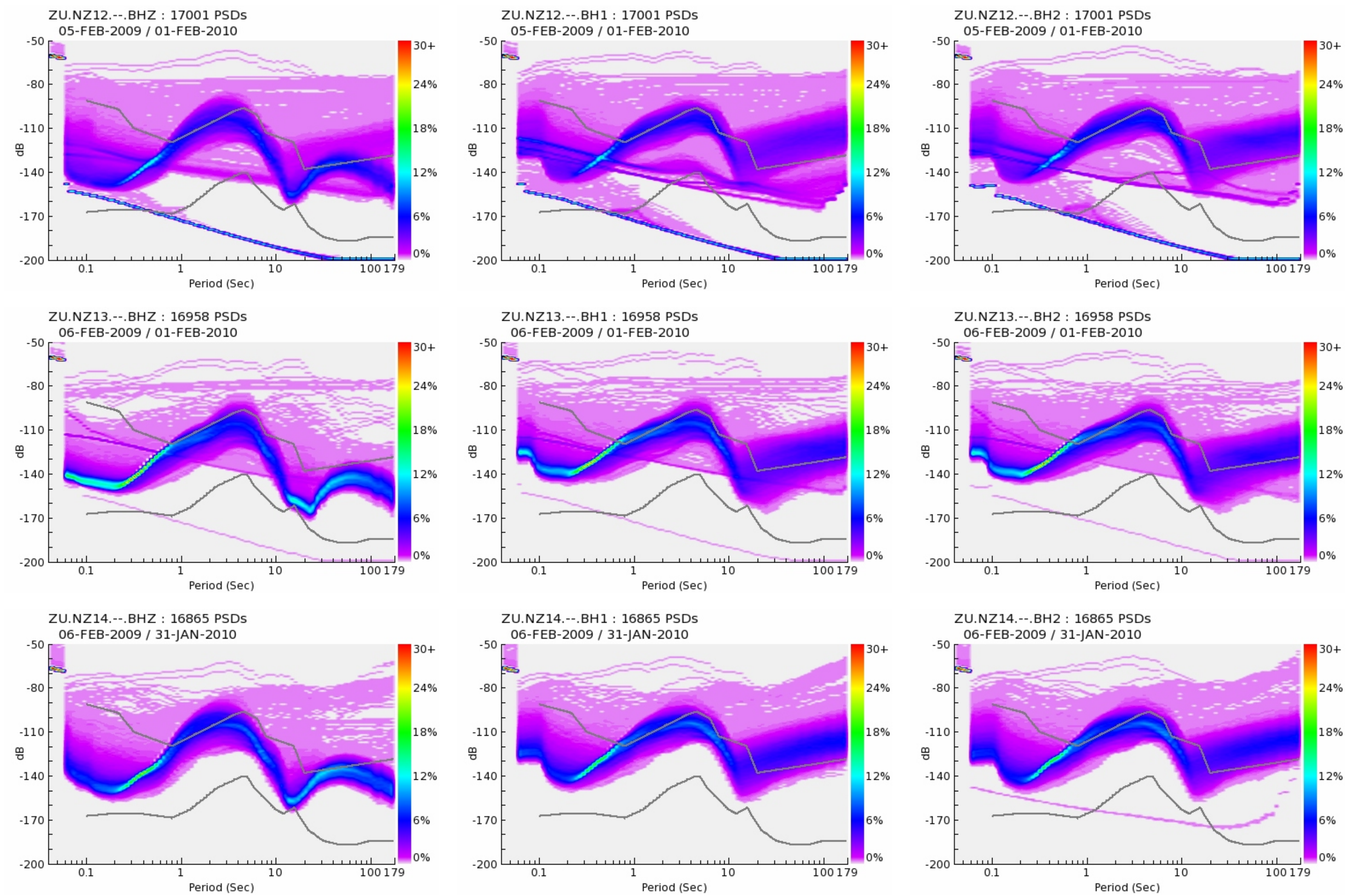


Figure S1 (NZ12, NZ13, and NZ14)

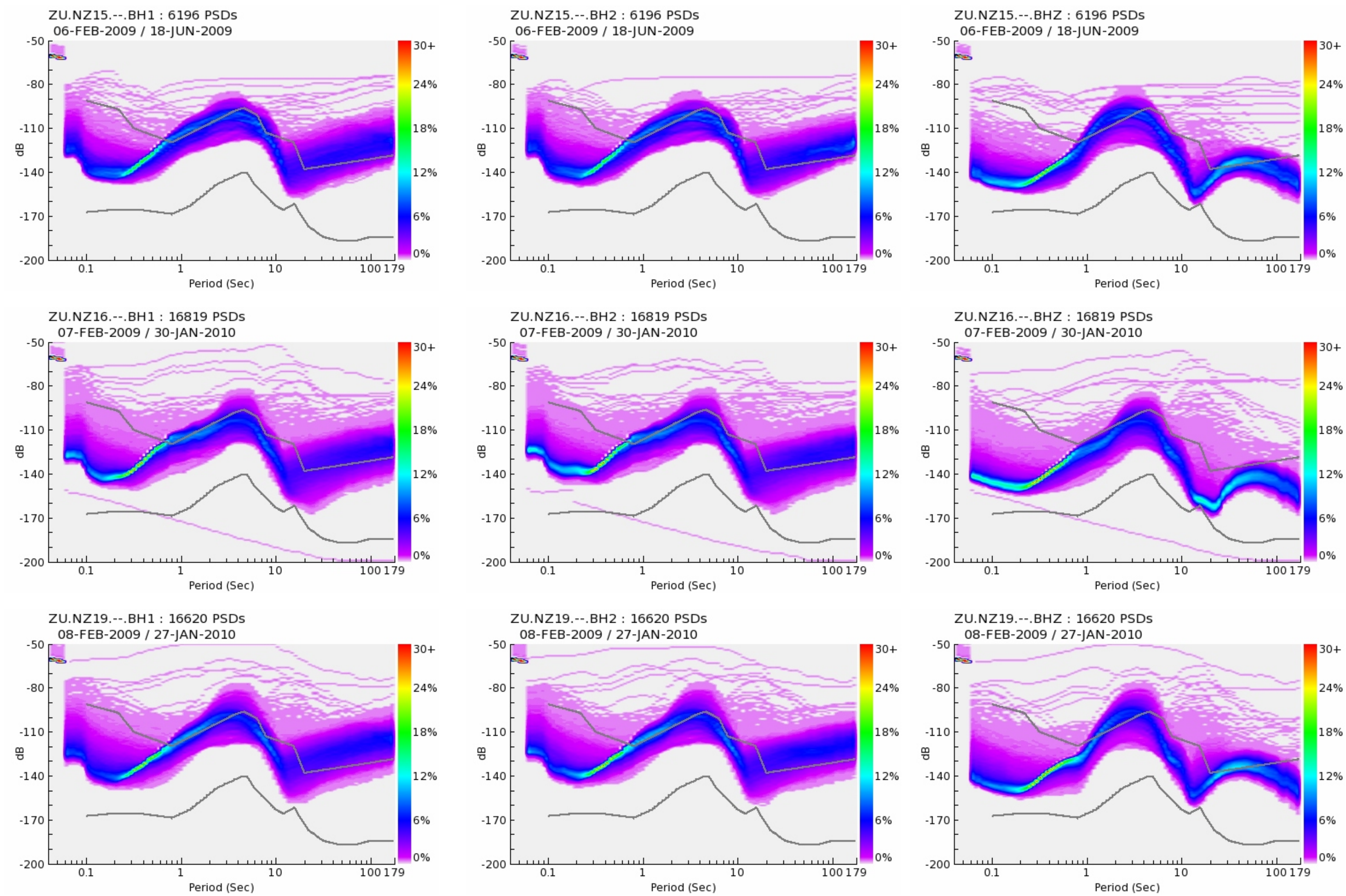


Figure S1 (NZ15, NZ16, and NZ19)

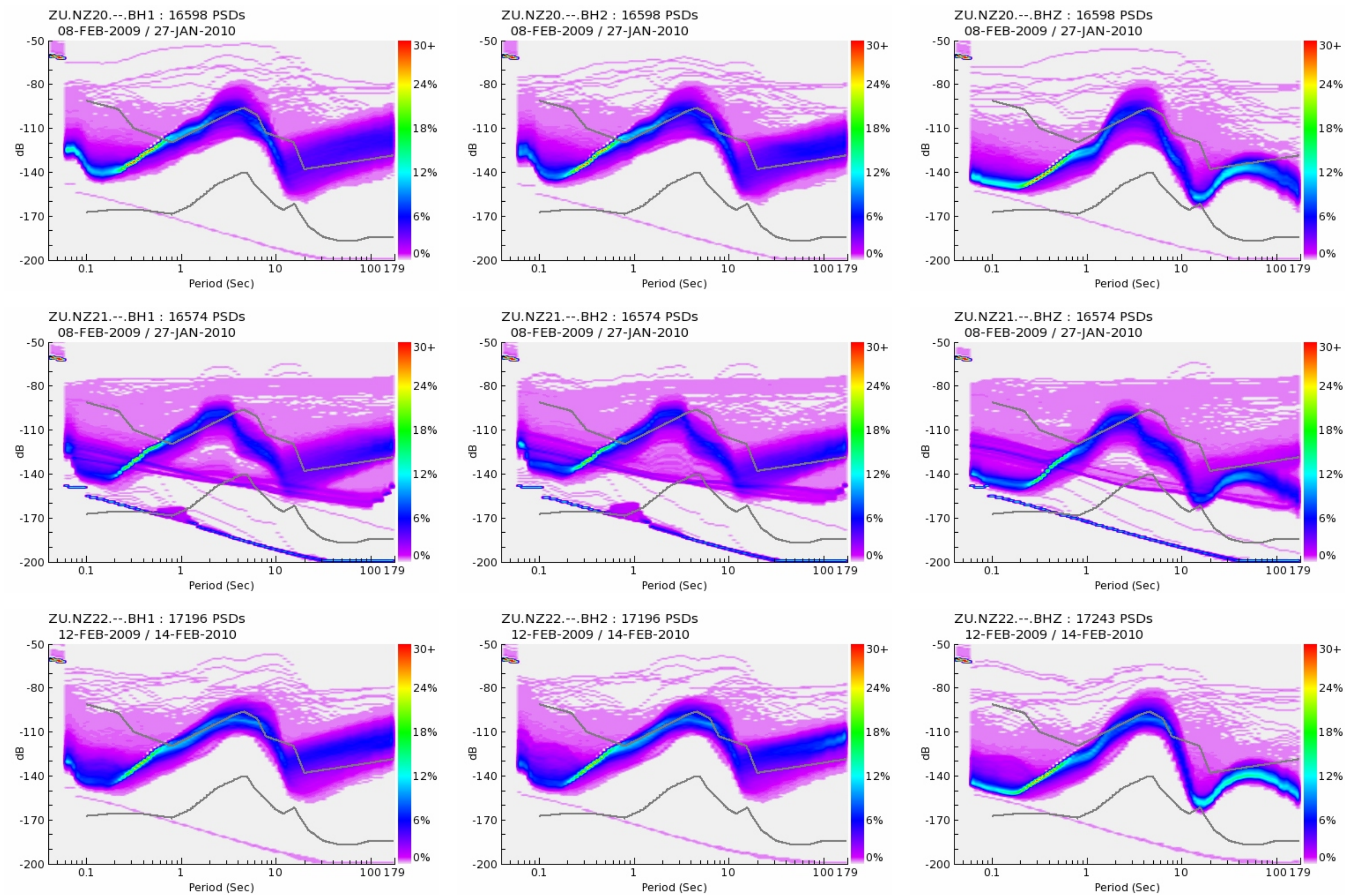


Figure S1 (NZ20, NZ21, and NZ22)

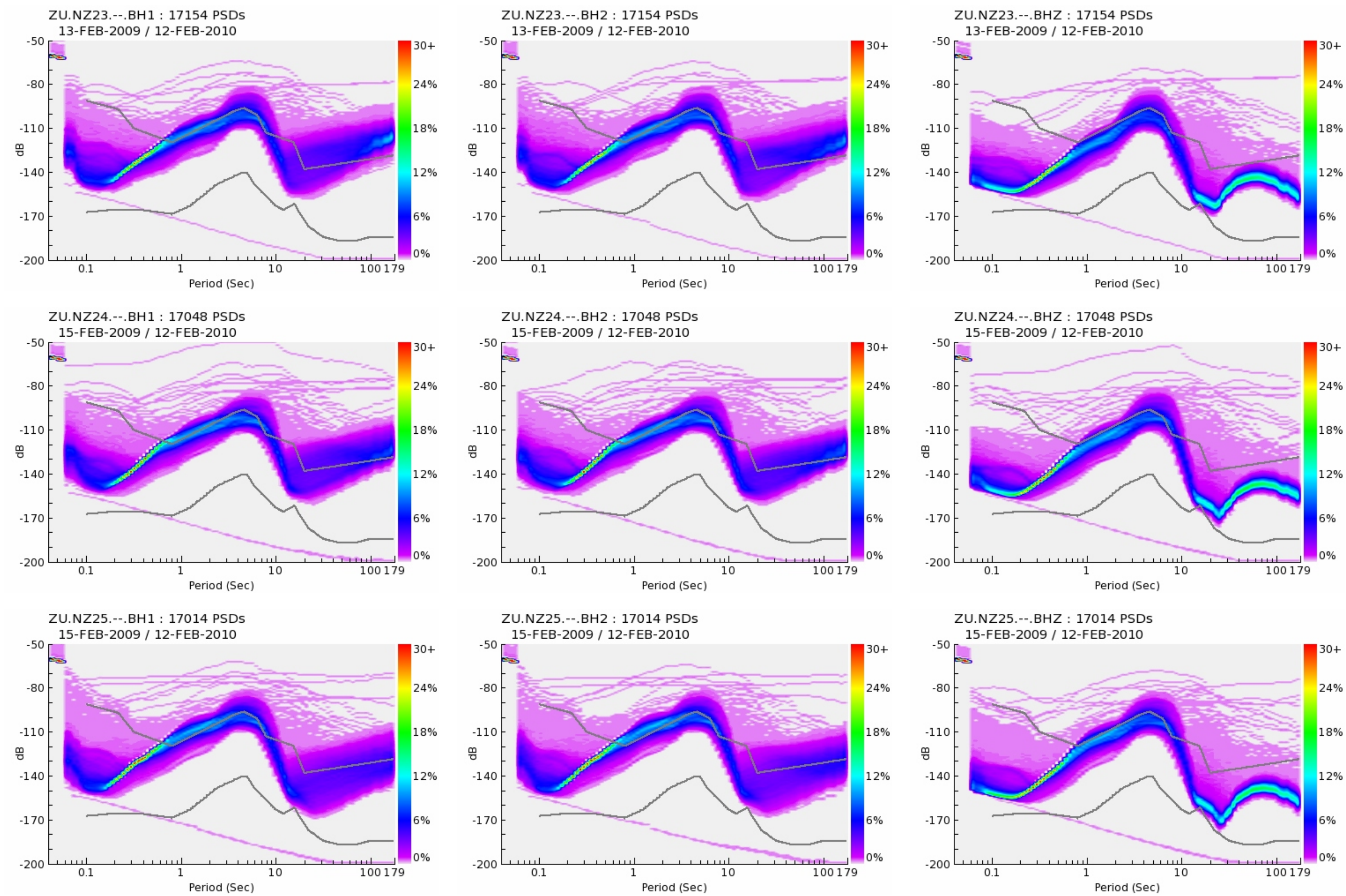


Figure S1 (NZ23, NZ24, and NZ25)

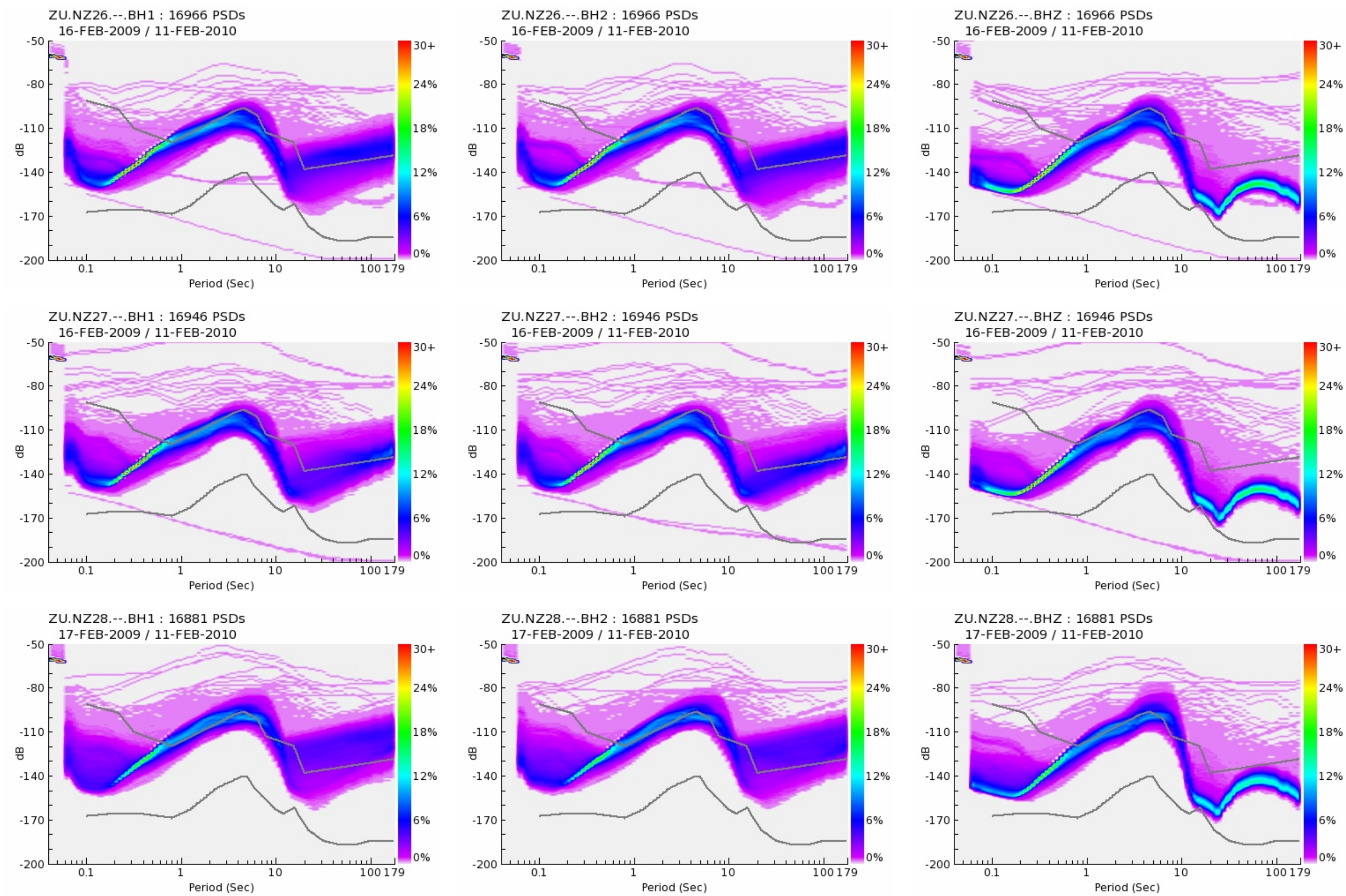


Figure S1 (NZ26, NZ27, and NZ28)

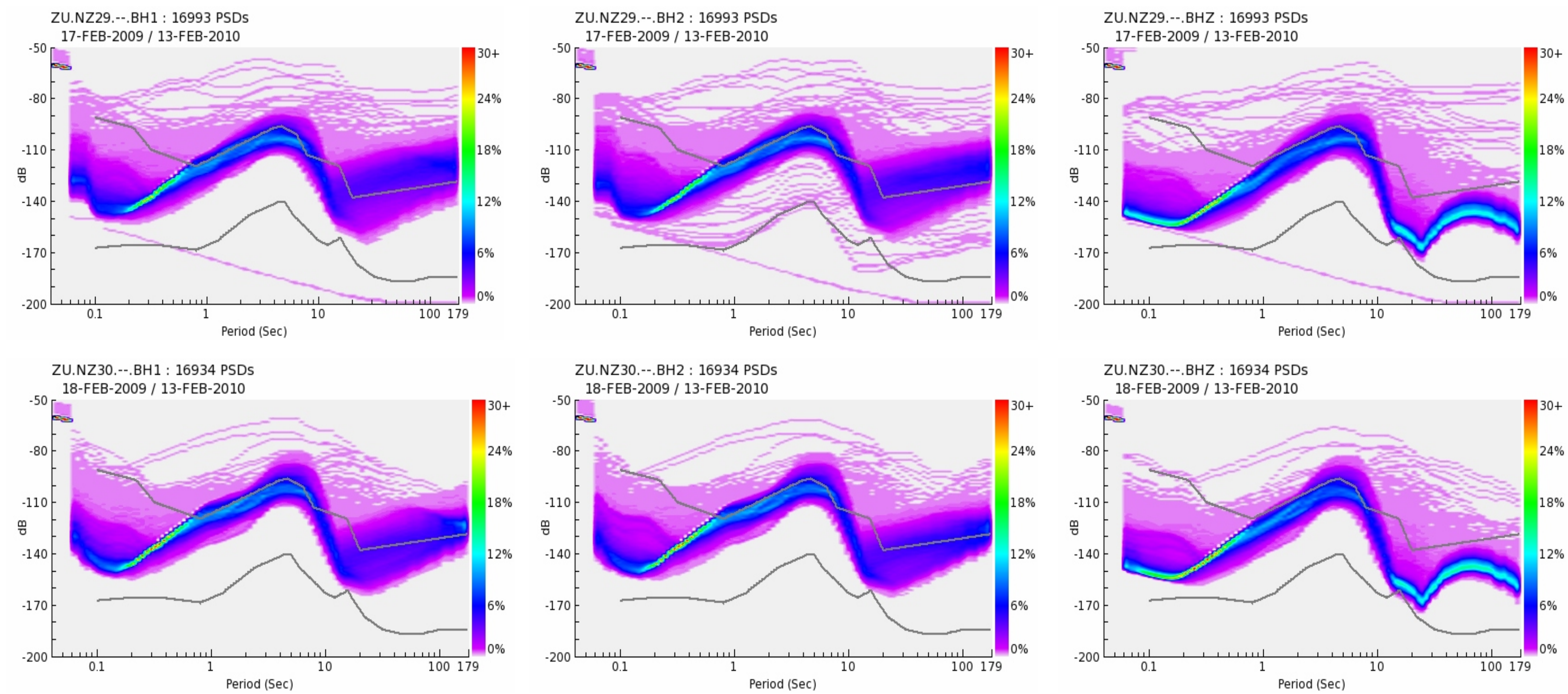
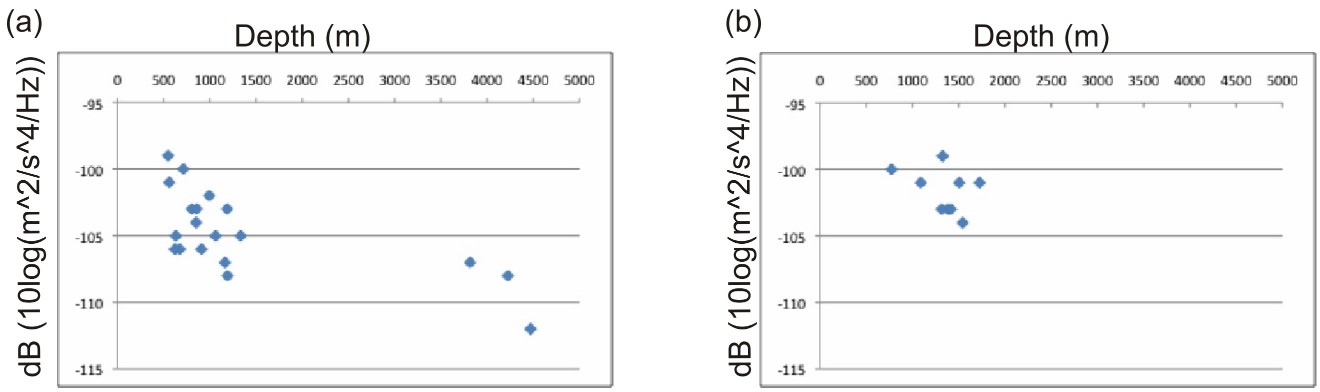


Figure S1 (NZ29 and NZ30)



(a)
Depth (m)
dB (10log(m^2/s^4/Hz))
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000
-95
-100
-105
-110
-115
(b)
Depth (m)
dB (10log(m^2/s^4/Hz))
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000
-95
-100
-105
-110
-115

Figure S2

Auxiliary Material B. Normal Mode Calibration of MOANA OBS

We calculated normal mode synthetic seismograms between 2 and 8 mHz to validate instrument response calibration issues that were raised during the review process.

Data

The data used for normal mode calibration only includes the vertical-component BHZ channels where it is assumed that all three seismometer components have the same instrument response characteristics. The data were initially decimated from 50 sps to 1 sps using a non-zero phase-shift low-pass convolution filter with a 40-dB cutoff at 0.4 Hz. The data for 12-h long time series were then further decimated to 10 sps using a low-pass filter with a 40-dB cutoff at 0.04 Hz and a 20-dB high-pass at 0.001 Hz. The instrument response was removed to obtain both ground acceleration and ground velocity seismograms. To prepare the data specifically for normal mode comparisons, the data were once more band-pass filtered (with non-zero phase-shift convolution filters) with a 20-dB high-pass at 0.5 mHz and a 40-dB low-pass between 6 and 8.25 mHz.

Normal Mode Synthetics

Normal mode eigenfunctions and Green functions were calculated using the normal-mode summation code MINOS for all modes (fundamental modes and all overtones) between 2 and 8 mHz using the 1-D Earth reference model 1066a [Gilbert and Dziewonski, 1975]. The Greens functions were band-pass filtered using the same filters as for the real data. Synthetic seismograms were computed using the Lamont global CMTs (though the PDE locations published in that catalog were used for source coordinates). The comparisons between the synthetics and the data were performed for both acceleration and velocity seismograms using interactive computer screen tool. Relative scaling factors between the synthetic and the real waveforms were determined in the least-squares sense where we chose adequate windows around the first three major wave packets that roughly corresponded with the minor and major arc surface wave trains R1, R2 and R3.

Analysis

For a quick assessment, we extract general trends from analyzing the three events in Table S2. For virtually all wave trains analyzed, the synthetics are always larger than the real data by a factor of at least 2. Some individual wave trains have a factor as high as 5. Some wave packets appeared quite “noisy” and the analysis yielded factors with larger uncertainties. This applies particularly to some seismograms of event #3 where the following stations are affected: NZ02, NZ05, NZ10, NZ12, NZ14, NZ15, NZ21, NZ23, NZ24, NZ27, NZ28. There is no obvious correlation with the source radiation pattern nor water depth. Likely, this event was too small to excite the ultra-low frequency signals to a consistently high SNR level. We therefore included the measurements for this event but weighted them down by a factor of 2 when determining the final average scaling factors. In general, events #1 and #3 yielded relatively small factors, while event #2 yielded relatively large factors. This suggests: 1) the published scalar seismic moment may be slightly too high; 2) or the MOANA array is at an azimuth where the radiation pattern changes quickly with azimuth, i.e. a small rotation would adjust synthetics significantly. We should note that the influence from local site amplification effects and errors in the source parameters were not considered.

The final factors were determined using least squares averaging where the measurements from event #3 were assigned an error twice as large as the other measurements (which had an error of 1). Instrumental weighting was assumed, i.e. each datum was divided by the squared error. See case 2 in Table S3 for results of individual stations. For completeness of the analysis, the averages using equal weighting for all events are also shown (case 1). Results for individual stations may vary but most averages lie between 3.5 and 4.0. Assuming that all stations have the same calibration problem, the average factor is 3.6±0.4 in case 2 when event #3 was weighted down, and 3.5±0.4 when all three event received equal weight. The estimates at the following stations are uncertain because high noise levels prohibited the measurement of some individual wave trains: NZ02, NZ07, NZ15, NZ21. No seismic data are available at station NZ01. The estimates for high-noise stations are typically lower, thereby biasing the overall average low (more noise in the seismogram gives higher amplitudes, relative to the synthetic). **We therefore prefer the median of 3.7 as the best overall estimate, with 0.4 as uncertainty.** Discussions with the OBS lab engineers reveal that calibration errors caused by inconsistencies in the instrument assembly are most likely factors of 2, 4, 8 or 16. If we assume that the amplitude discrepancy between the data and the synthetic seismograms are all caused by such an inconsistency, **we recommend using a factor of 4**, i.e. the instrument response should be divided by a factor 4. It is conceivable but somewhat unlikely that station NZ14, which had a T-40 sensor has a slightly larger factor. The relatively high average results from consistently high values (≥ 5.5 as opposed to ≥ 4.3) for event #2, and no measurements were available for event #3 that would have resulted in a lower average, as is the case for the other stations.

Reference

Gilbert, F. and Dziewonski, A.M., 1975, An application of normal mode theory to the retrieval of structural parameters and source mechanisms from seismic spectra. Phil. Trans. R. Soc. A, 278, 187–269.

Table S2. Earthquakes used in the normal mode calibration.

Event Time	Source Region	Latitude	Longitude	M_0 [10^{20} Nm]	Azimuth from NZ14	Epicentral Distance [°]
2009-148 08:24:45.1	N. of Honduras	16.72	-86.23	1.28	86.5	111.2
2009-222 19:55:35.6	Andaman Islands	14.10	92.89	1.95	289.0	90.2
2009-297 14:40:43.7	Banda Sea	-6.13	130.38	0.30	304.7	50.4

Table S3. Averages over amplitude factors measures for all available Rayleigh-wave trains as discussed in the text. The three columns after the station names: case 1 - averages where all three events have equal weights; case 2 - number of measurements; averages where event #3 had a weight 1/4 (i.e. data had an error bar twice as large as the other two events).

events 09-148, 09-222 and 09-297 (equal weight;1,1,0.25)

NZ01	-		
NZ02	3.57	8	4.12
NZ03	3.66	14	3.81
NZ04	3.63	14	3.75
NZ05	3.50	13	3.65
NZ06	3.35	14	3.50
NZ07	2.88	6	2.83
NZ08	3.51	14	3.65
NZ09	3.52	13	3.70
NZ10	3.55	12	3.66
NZ11	3.63	14	3.77
NZ12	3.68	10	3.68
NZ13	3.67	14	3.80
NZ14	4.37	10	4.37
NZ15	2.07	6	2.07
NZ16	3.44	14	3.62
NZ18	3.41	14	3.61
NZ19	3.58	12	3.70
NZ20	3.41	14	3.56
NZ21	2.86	8	2.95
NZ22	3.49	14	3.70
NZ23	3.52	13	3.73
NZ24	3.30	12	3.45
NZ25	3.62	14	3.83
NZ26	3.78	14	4.01
NZ27	3.53	14	3.72
NZ28	3.81	11	3.88
NZ29	3.76	14	3.94
NZ30	3.74	14	3.92

Figures

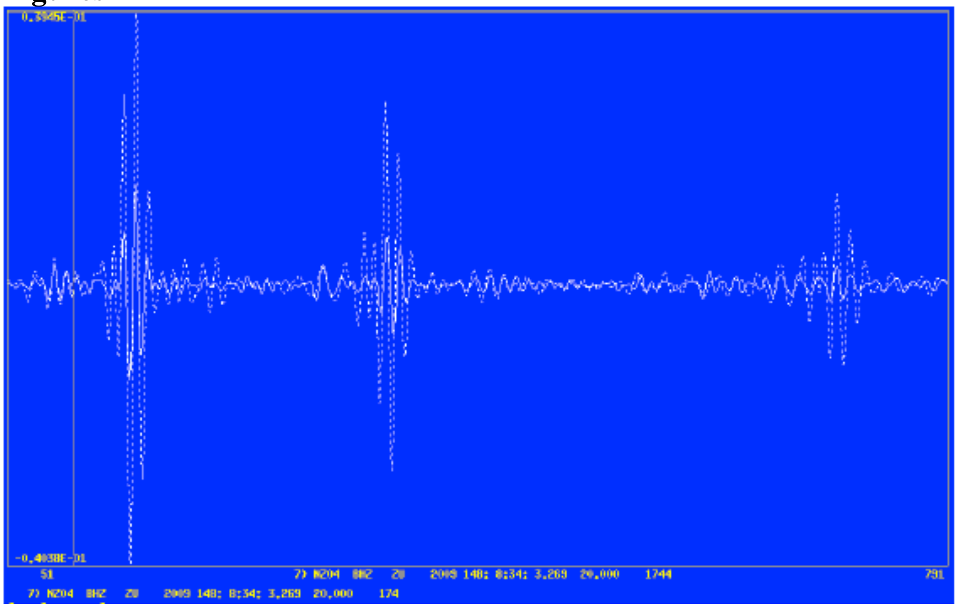


Figure S3. Ground acceleration seismogram (solid) and synthetic (dashed) for event #1 at station NZ04. Ground acceleration is in μm/s^2. The window shown here is 4.11 h long - (791-51)*20s, where 20s is the final sampling interval - and the figure shows the first three Rayleigh-wave trains. The synthetic is too large, for all three wave trains, implying that the instrument response is too large.

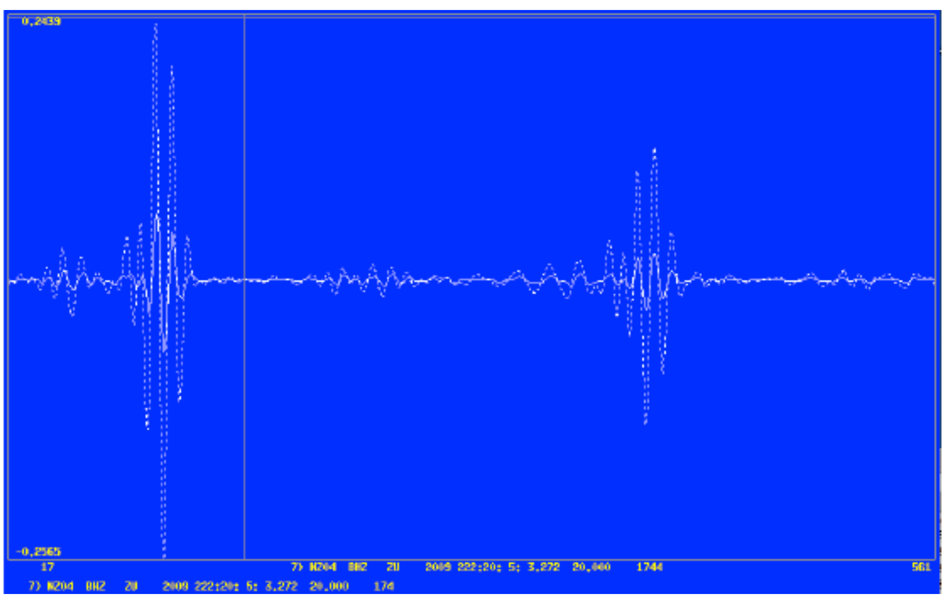


Figure S4. Ground acceleration seismogram (solid) and synthetic (dashed) for event #2 at station NZ04. The window shown here is 3.02 h long. See Figure S3 for details. Again, the synthetic is too large, for both wave trains.

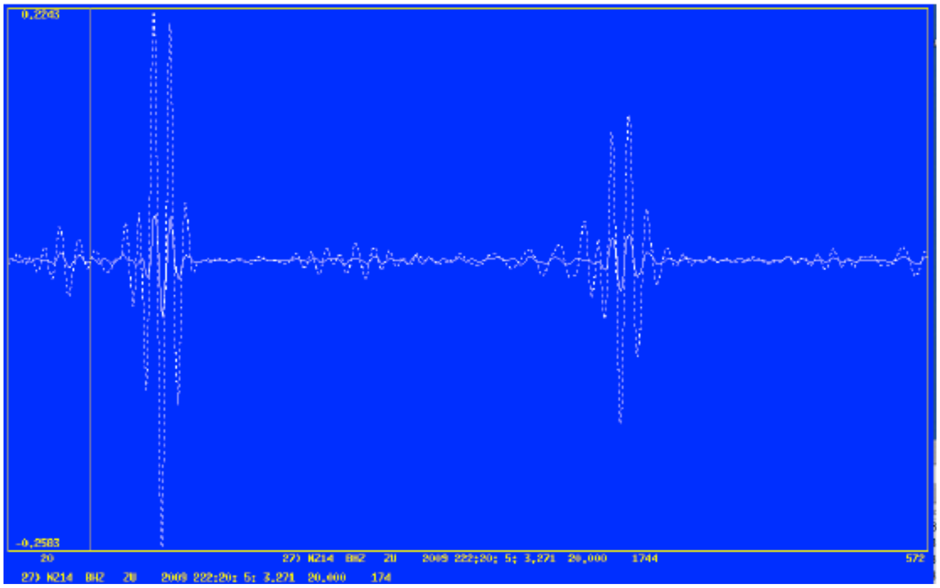


Figure S5. Ground acceleration seismogram (solid) and synthetic (dashed) for event #2 at station NZ14. The window shown here is 3.07 h long. See Figure S3 for details. The synthetic is too large, for both wave trains.