

Supplementary Material: Performance of the 2021-2022 UPFLOW large ocean bottom seismometer array in the Azores-Madeira-Canary Islands region, Atlantic Ocean

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This document provides additional information supporting the main text.

Section S 1 Data Products

Additional online materials, including comprehensive data products, are available at Zenodo. Below is a list of the available resources along with their link:

1. PPSD Channels 1 and 2

- This resource contains Power Spectral Density (PSD) plots for channels 1 and 2.
- <https://doi.org/10.5281/zenodo.14288145>

2. PPSD Channels Z and H

- This resource provides Probability Power Spectral Density (PPSD) plots for the vertical (Z) and hydrophone (H) channels.
- <https://doi.org/10.5281/zenodo.14288127>

3. Spectrograms Channels Z

- This resource contains time-frequency representations (spectrograms) for the vertical (Z) channel.
- <https://doi.org/10.5281/zenodo.14288155>

4. State of Health Files (All Stations)

- This resource includes metadata files detailing the operational status and performance metrics of all working stations.
- <https://doi.org/10.5281/zenodo.13144839>

Section S 2 Instrument response

Instrument corrections are applied to seismic data by using a transfer function for seismometers and hydrophones that removes the instruments' specific response from recorded signals. Fig. S1 shows an example of removing the instrument response from a recorded earthquake by using *ObsPy* (class *read_inventory*, function *remove_response*). It visualises the separate steps of response removal in the frequency and time domain. For all figures in this study, we used the same response removal settings. One important user setting is the pre-filtering, which involves applying a taper in the frequency domain using four specified frequencies ($f_1 < f_2 < f_3 < f_4$). The taper consists of a passband in the interval $[f_2, f_3]$ where the value is set to one, and a cosine function tapering from one to zero on both sides in the intervals $[f_1, f_2]$ and $[f_3, f_4]$ (Fig. S1).

Water levelling, on the other hand, involves not amplifying values below a certain amplitude threshold during the deconvolution process. The threshold is typically given in dB and is based on the maximum amplitude response function of the instrument as a reference. When applying the instrument response with *ObsPy* (*remove_response*), it by default uses water levelling as a way to suppress high-frequency and low-frequency noise during the deconvolution of the instrument response. The water level in *ObsPy* is set to 60 dB by default (60 dB is equal to a factor 10^6 in power and 10^3 in amplitude) with respect to the peak amplitude in the instrument response. After experimenting with various parameters, we found that using a water level of 300 led to optimal results, and so we use this value in our analysis.

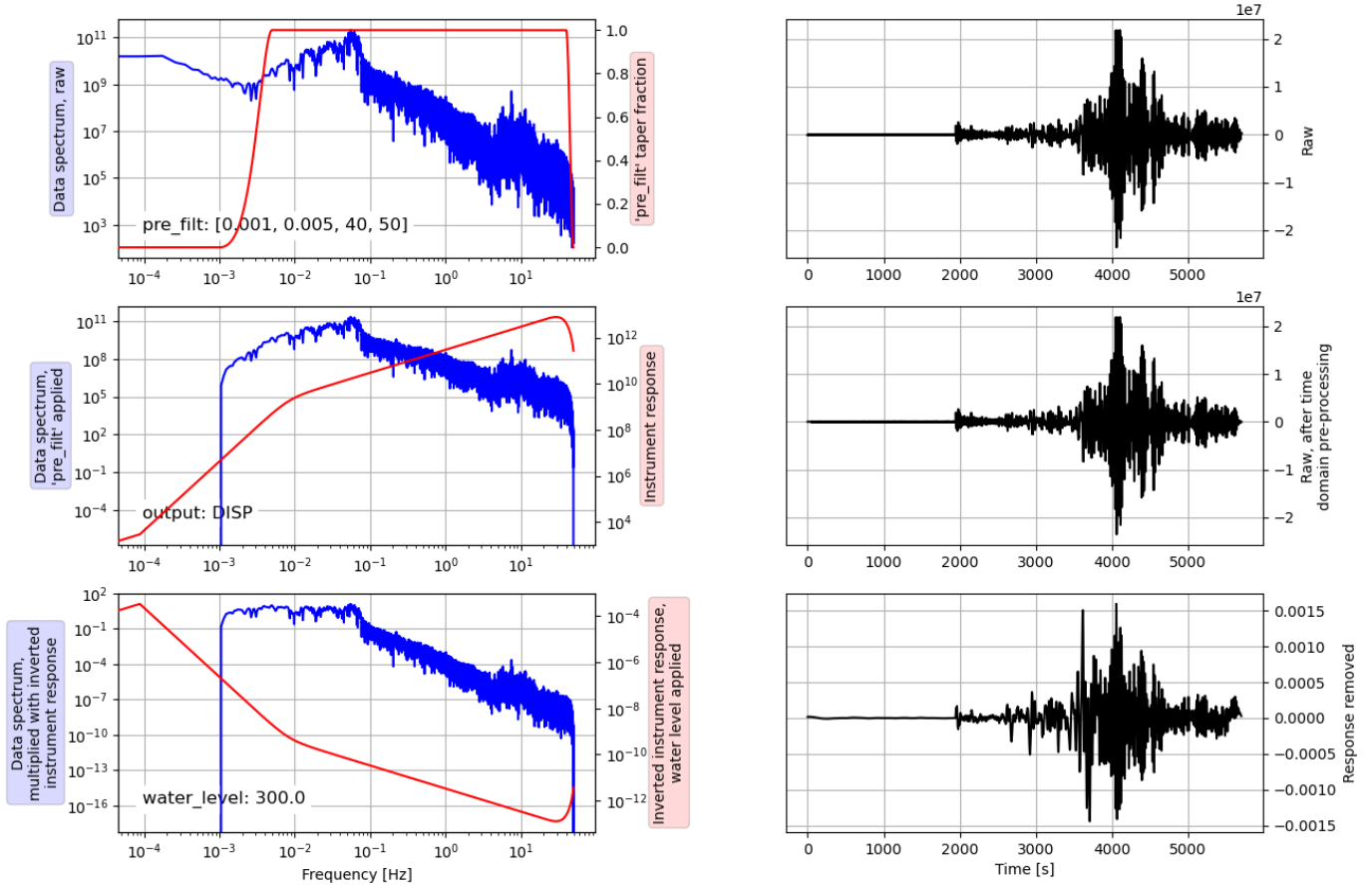


Figure S1 Key steps in seismometer's response removal from raw vertical component seismic data (BHZ). We use vertical component waveforms from the 2021-07-29 Alaska earthquake recorded by UP29 (see Fig. 1 in the main paper). The steps are the same for all UPFLOW stations and channels. The left panels show the spectrum, and on the right side, the corresponding time series. The top panels show raw data along with the pre-filter setting (red line on the left). In the second row, the pre-filter has been applied to the data, and this time the red line corresponds to the instrument response. The third row shows the restituted displacement trace; the red line corresponds to the inverted instrument response. Please note the different y-axis scales.

Section S 3 State-of-Health



Figure S 2 Illustrative example of state-of-health data for station UP06. The top panel shows battery voltage, the second panel shows temperatures measured from the 6d6 recorder and the seismometer, the third panel shows mass, and the lowest panel shows static sensor acceleration. Note the different scales for each coloured graph. Most variations are small (check the actual values on the y-axis), and in the case of the third and fourth panels, scales plotted between -1 and 1 would not show apparent changes. For more examples of SOH plots, please refer to the additional [online materials](#).



Figure S3 Same as in Fig. S2 but for station OBS12. In this case, the two bottom diagrams indicate the tilting of the instrument.



Figure S4 Same as in Fig. S2 but for station UP19. The mass voltage (2nd panel) and seismometer temperature (3rd panel) show significant variations, while the temperature of the data logger remained relatively constant. The OBS might have moved or tilted during deployment, leading to the battery being depleted earlier than expected (top panel). See the main text for further details.



Figure S 5 Same as Fig. S2 but for station UP26. As explained in the main text, the temperature, mass position and static sensor acceleration show normal behaviour, but the battery was depleted earlier than expected, which suggests the insufficient capacity of the battery packs at the experiment's outset.



Figure S 6 Same as in Fig. S5 but for station UP28 (see also main text for further details).

Section S 4 Station recording period

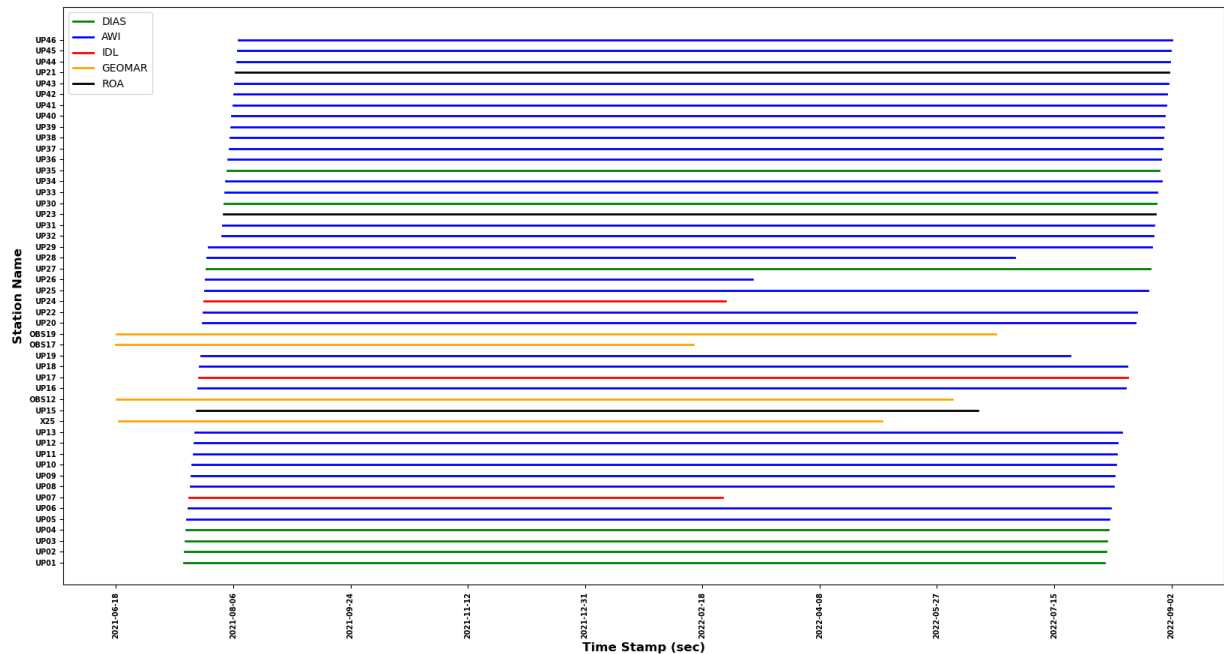


Figure S 7 Overview of the station recording period. Stations are coloured by OBS pools. The figure shows at a glance when stations were deployed and when they stopped recording. The early stops of some stations are clearly seen. The recording span does not correspond to data quality.

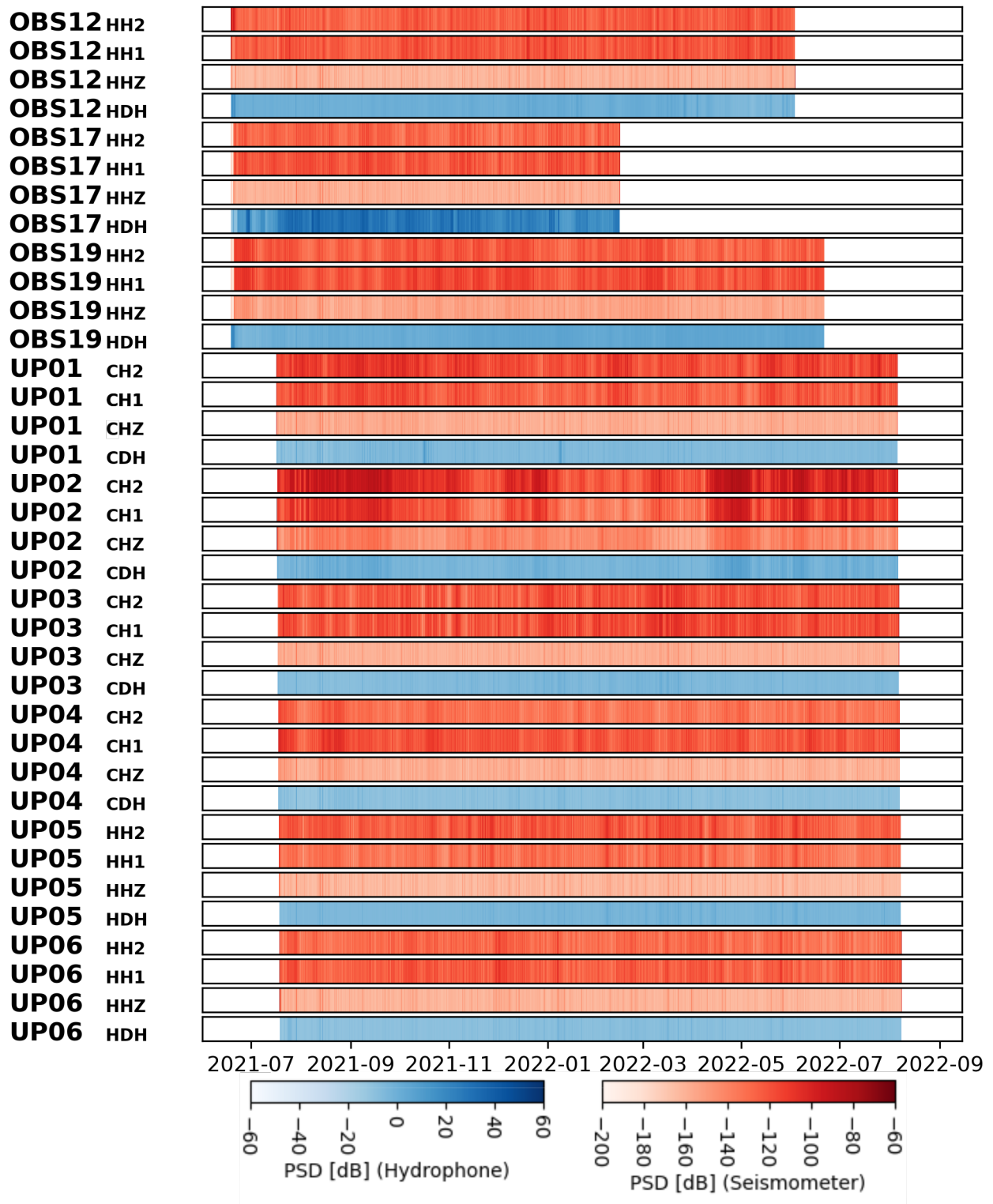


Figure S 8 Recording span for stations OBS12, OBS17, OBS19 and UP01 to UP06. Each panel shows a different channel, and the colour corresponds to noise levels extracted from PPSD in a 30-second period. Seismometers are shaded in red, hydrophones are shaded in blue for clarity. OBS12, OBS17 and OBS19 stopped early, whereas the rest of the stations recorded continuously until their recovery day. Higher noise levels correspond to darker shaded colours and can be tracked across neighbouring stations.

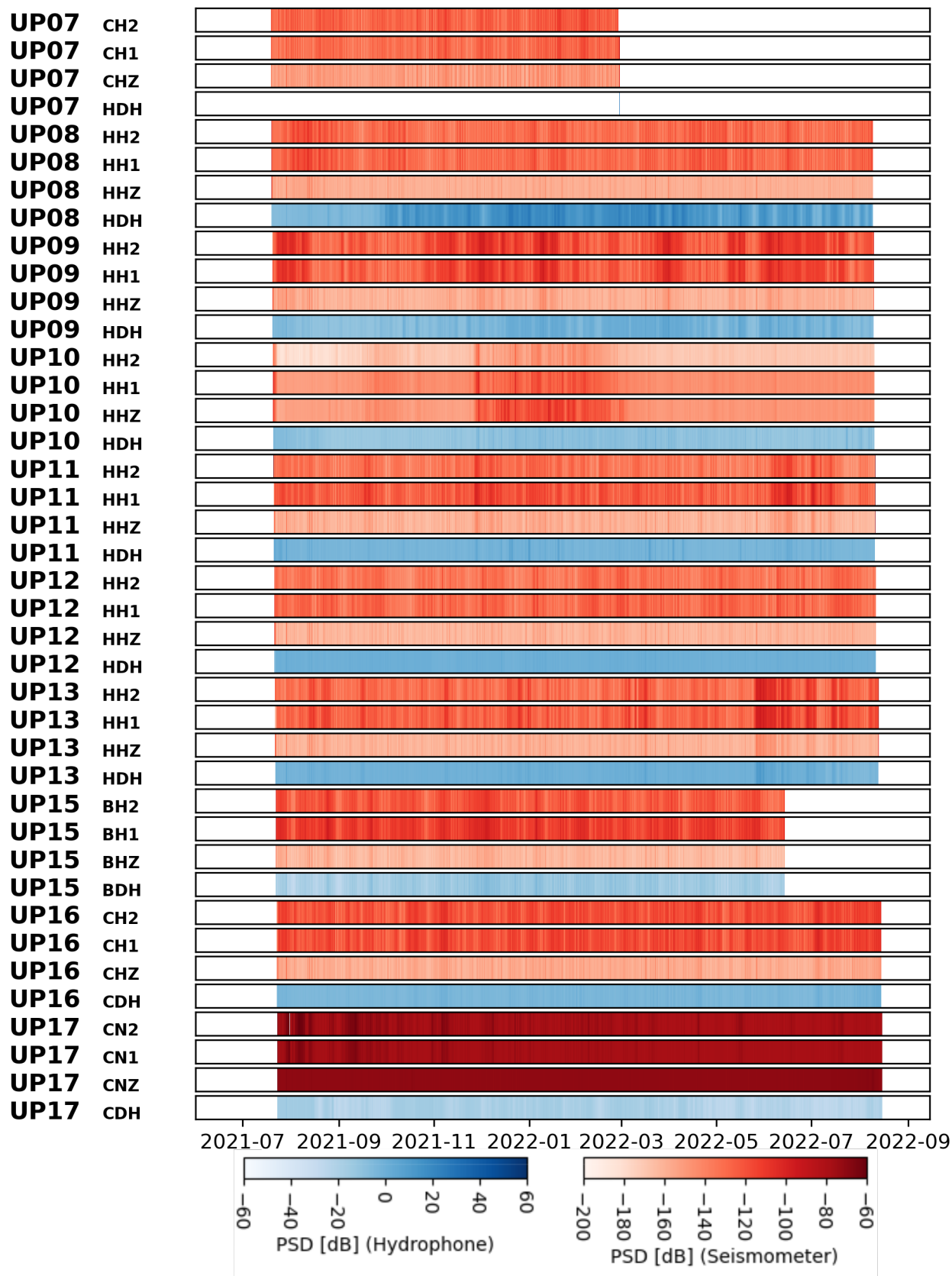


Figure S9 Same as in Fig. S8 but for stations UP07 to UP17.

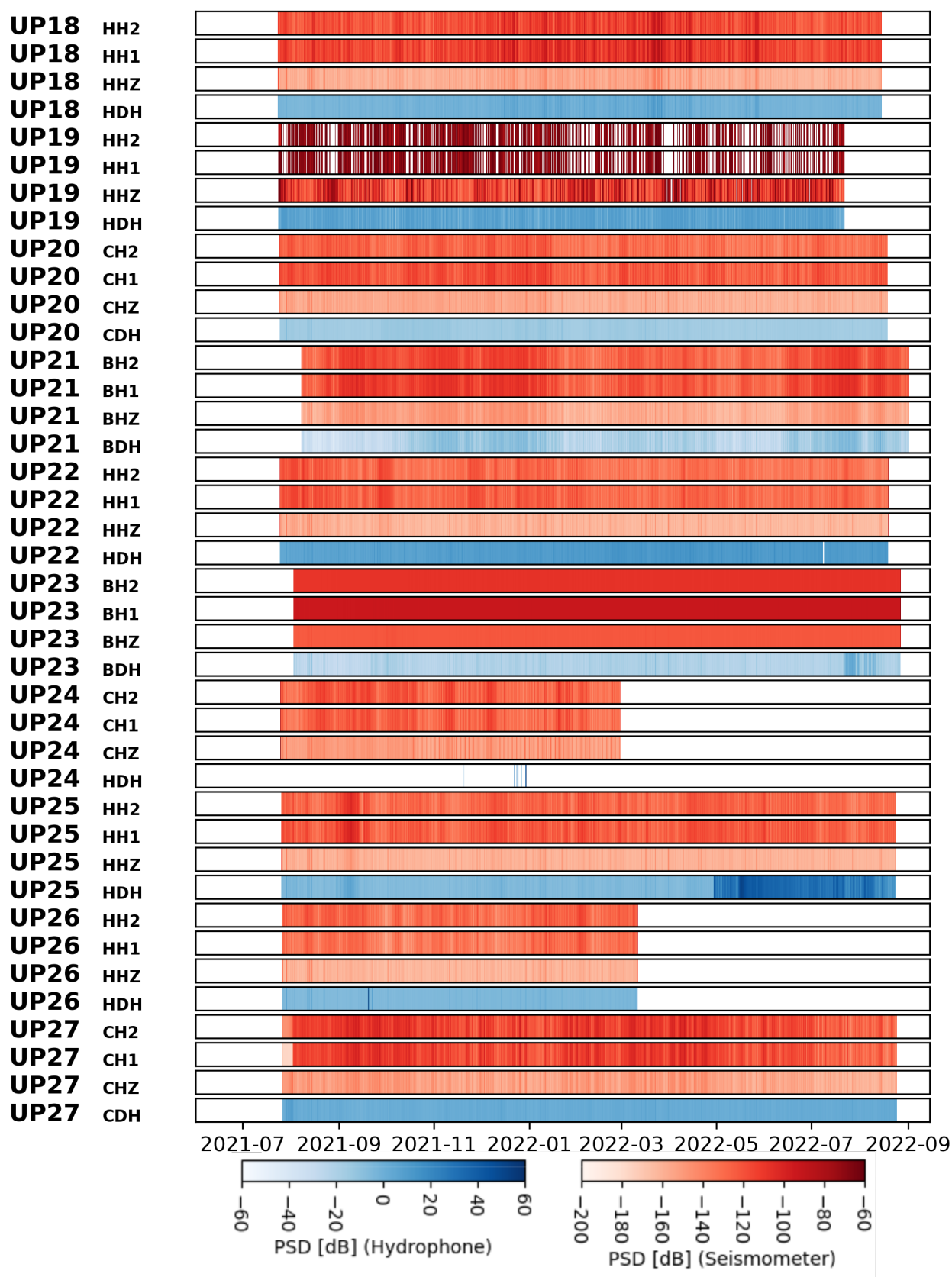


Figure S 10 Same as in Fig. S8 but for stations UP18 to UP27. UP19, as stated in the main document did not record correctly, and several stations stopped early, e.g. UP24.

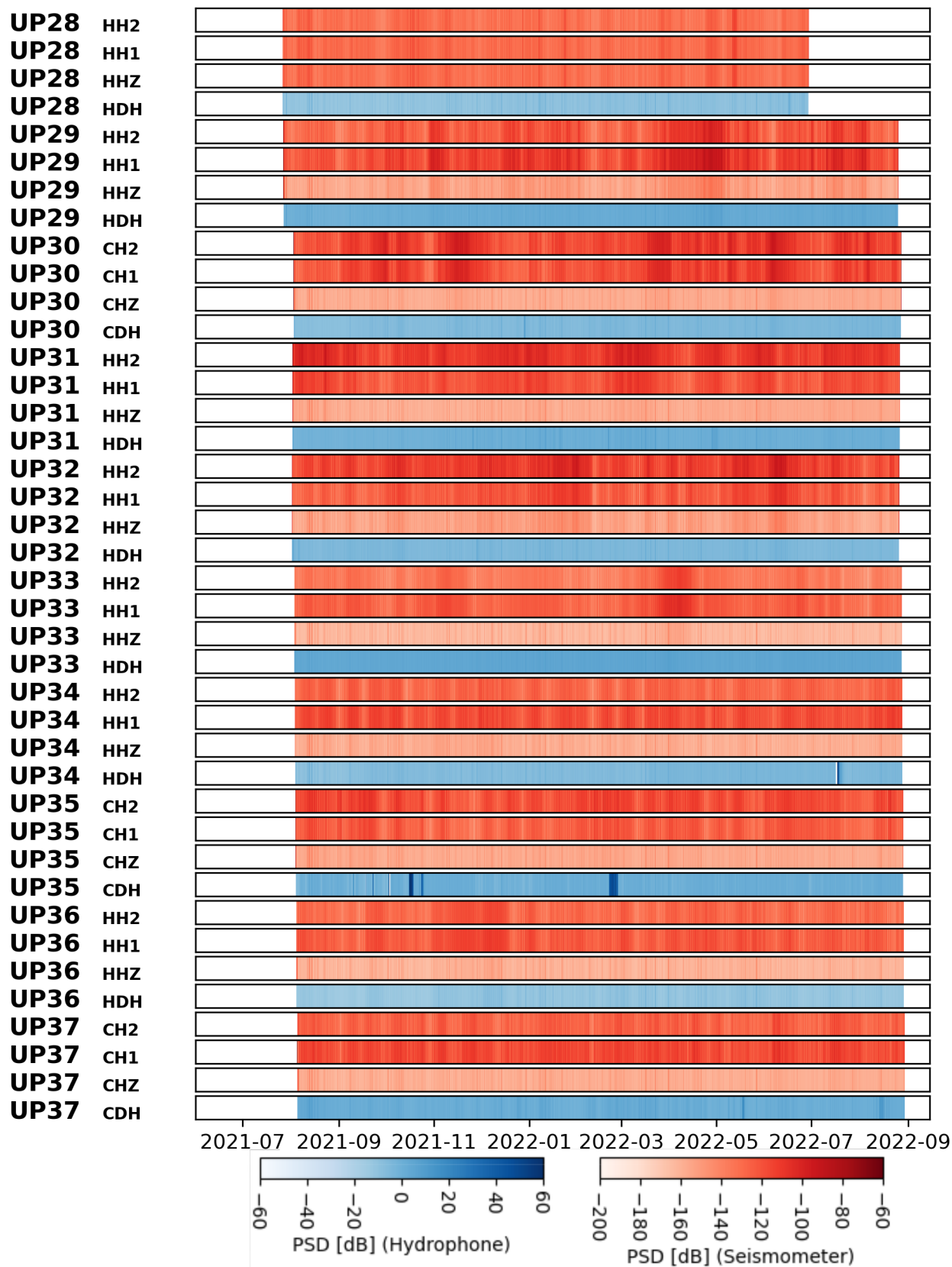


Figure S 11 Same as in Fig. S8 but for stations UP28 to UP37.

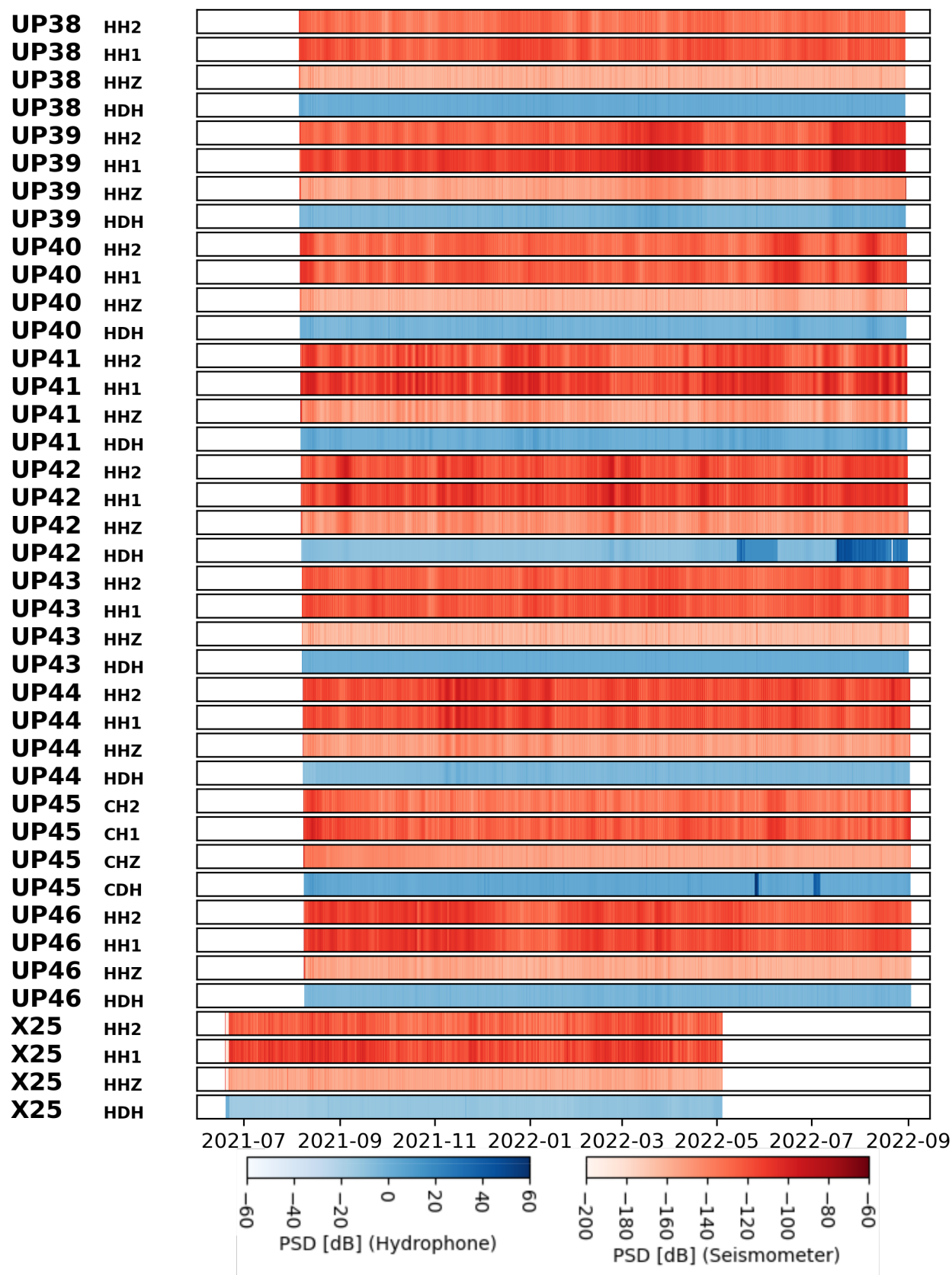


Figure S12 Same as in Fig. S8 but for stations UP38 to UP46 and X25.

Section S 5 Earthquake Catalogue

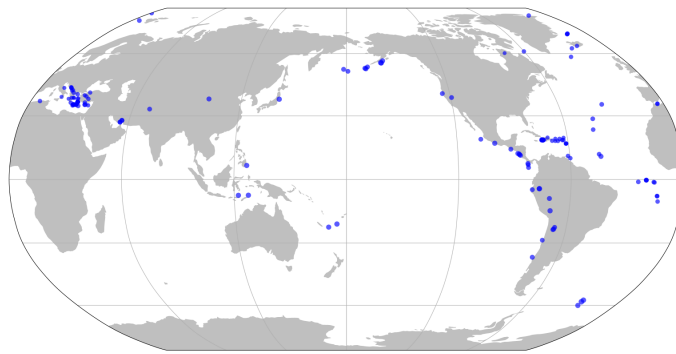


Figure S 13 Map of the 149 events used for initial analysis (e.g., quality of recorded earthquakes, Fig. 13 in the main text) and orientation analysis (see [Section S 6](#)). A combination of global and regional events was selected based on their magnitude and their distance to the UPFLOW experiment. Small magnitude events (e.g., M4.0) were selected up to an epicentral distance of 50° . Earthquake Tables [S1](#) to [S3](#) show the time, location, and magnitude of all used events. Earthquakes from the USGS Earthquake Catalogue ([U.S. Geological Survey, 2023](#)).

Table S 1 Earthquake catalogue as described in Fig. S13. Mwr refers to the moment magnitude derived from radiated energy, Mww is the moment magnitude calculated from the W-phase (commonly used for larger earthquakes), and Mwb represents the moment magnitude obtained from moment tensor inversion of long-period body waves (P and SH). MI denotes local magnitude, and Md refers to duration magnitude.

# Nr.	Latitude [°]	Longitude [°]	Depth [km]	Datetime [UTC]	Magnitude
1	58.29	-32.18	10.0	2021-06-05 01:31:45	Mww 5.2
2	60.19	-74.03	10.0	2021-06-10 11:20:15	Mwr 4.0
3	18.12	-68.50	87.0	2021-06-14 10:15:43	MI 5.0
4	36.44	27.04	9.0	2021-06-21 22:14:13	Mww 5.5
5	37.92	20.79	15.0	2021-06-25 11:02:32	Mwr 4.2
6	11.81	-44.23	10.0	2021-06-26 18:01:22	Mww 5.6
7	-28.74	-71.48	22.0	2021-07-04 01:29:15	Mww 6.0
8	38.51	-119.50	7.0	2021-07-08 22:49:48	Mw 6.0
9	38.41	23.32	10.0	2021-07-11 00:00:17	Mwr 4.3
10	6.83	-82.68	4.0	2021-07-17 20:56:10	Mww 6.1
11	7.39	-82.78	10.0	2021-07-21 21:15:12	Mww 6.7
12	35.19	25.23	10.0	2021-07-24 02:07:38	Mwr 4.7
13	55.36	-157.89	35.0	2021-07-29 06:15:49	Mww 8.2
14	-4.92	-80.62	34.0	2021-07-30 17:10:19	Mww 6.2
15	36.41	27.06	11.0	2021-07-31 19:57:55	Mwr 4.7
16	36.40	27.01	10.0	2021-08-01 04:31:26	Mww 5.6
17	36.37	27.04	6.0	2021-08-01 09:14:27	Mwr 4.5
18	62.69	-25.26	10.0	2021-08-01 10:40:27	Mww 5.2
19	36.39	27.04	10.0	2021-08-03 12:38:17	Mww 5.2
20	36.37	27.00	8.0	2021-08-03 19:53:13	Mwr 4.6
21	36.27	27.04	18.0	2021-08-07 01:39:45	Mww 5.0
22	6.48	126.72	55.0	2021-08-11 17:46:13	Mww 7.1
23	-57.57	-25.03	47.0	2021-08-12 18:32:52	Mww 7.5
24	-58.38	-25.26	23.0	2021-08-12 18:35:17	Mww 8.1
25	55.18	-157.64	21.0	2021-08-14 11:57:43	Mww 6.9
26	18.43	-73.48	10.0	2021-08-14 12:29:08	Mww 7.2
27	18.50	-73.71	10.0	2021-08-14 16:08:03	Mwr 4.7
28	18.43	-73.60	10.0	2021-08-14 17:05:19	Mwr 4.9
29	18.59	-73.62	9.0	2021-08-14 18:11:10	Mwr 5.2
30	18.53	-74.03	16.0	2021-08-14 22:14:08	Mwr 4.5
31	18.61	-73.57	14.0	2021-08-15 02:37:53	Mww 5.1
32	18.40	-74.09	8.0	2021-08-15 03:20:45	Mww 5.8
33	18.54	-73.72	10.0	2021-08-15 12:05:43	Mwr 4.8
34	18.36	-73.51	6.0	2021-08-18 16:47:53	Mwr 4.7
35	18.42	-73.60	13.0	2021-08-19 03:57:36	Mwr 4.2
36	36.34	27.12	10.0	2021-08-19 11:26:33	Mwr 4.7
37	-60.29	-24.87	6.0	2021-08-22 21:33:18	Mww 7.1
38	39.04	30.19	10.0	2021-08-31 11:04:26	Mww 5.1
39	-1.24	-24.15	10.0	2021-09-01 13:50:10	Mww 5.7
40	-1.51	-15.51	10.0	2021-09-01 22:51:36	Mww 5.4
41	36.48	27.17	10.0	2021-09-08 01:40:02	Mwr 4.5
42	16.95	-99.75	20.0	2021-09-08 01:47:47	Mww 7.0
43	16.81	-61.14	41.0	2021-09-10 00:43:18	Mwr 4.8
44	-23.76	-67.01	205.0	2021-09-13 05:18:14	Mww 6.2
45	-1.35	-15.93	10.0	2021-09-15 09:36:45	Mww 5.2
46	-36.78	-73.93	19.0	2021-09-21 13:14:32	Mww 6.4
47	12.14	-87.87	21.0	2021-09-22 09:57:07	Mww 6.5
48	51.08	-179.02	18.0	2021-09-24 11:52:28	Mww 6.1
49	16.83	-61.16	27.0	2021-09-25 03:12:13	Mwr 4.8
50	35.24	25.27	6.0	2021-09-27 06:17:21	Mww 6.0

Table S 2 Continuation of Table S1.

# Nr.	Latitude [°]	Longitude [°]	Depth [km]	Datetime [UTC]	Magnitude
51	35.33	25.27	10.0	2021-09-27 07:30:46	Mwr 4.5
52	35.20	25.37	10.0	2021-09-27 08:21:58	Mwr 4.4
53	35.23	25.32	10.0	2021-09-27 21:37:11	Mwr 4.3
54	35.08	25.20	10.0	2021-09-28 04:48:08	Mww 5.3
55	-21.13	174.90	527.0	2021-10-02 06:29:17	Mww 7.3
56	18.01	-65.39	11.0	2021-10-08 18:28:23	MI 4.8
57	56.30	-156.58	52.0	2021-10-11 09:10:25	Mww 6.9
58	35.17	26.22	20.0	2021-10-12 09:24:05	Mww 6.4
59	41.79	19.66	30.0	2021-10-17 20:13:31	Mwr 4.4
60	34.58	28.40	44.0	2021-10-19 05:32:32	Mww 5.9
61	18.43	-62.34	31.0	2021-11-01 22:08:17	Mww 5.0
62	37.84	32.17	10.0	2021-11-08 17:43:21	Mww 5.1
63	11.22	-86.53	20.0	2021-11-09 06:25:14	Mww 6.3
64	63.97	-19.71	10.0	2021-11-11 13:21:41	Mww 5.0
65	18.38	-74.29	8.0	2021-11-12 07:42:47	Mwr 4.6
66	27.72	56.07	9.0	2021-11-14 12:07:03	Mwb 6.0
67	27.73	56.07	10.0	2021-11-14 12:08:38	Mwb 6.4
68	40.86	31.00	7.0	2021-11-17 12:40:16	Mwr 4.8
69	19.63	-70.75	10.0	2021-11-22 07:42:47	Mwr 4.5
70	82.13	-17.66	10.0	2021-11-23 12:04:19	Mww 5.4
71	-4.47	-76.81	126.0	2021-11-28 10:52:14	Mww 7.5
72	37.74	26.08	10.0	2021-11-30 04:00:40	Mww 5.1
73	38.37	22.25	10.0	2021-11-30 14:20:22	Mwr 4.4
74	17.99	-66.83	16.0	2021-12-10 01:25:34	MI 4.2
75	-7.60	122.23	14.0	2021-12-14 03:20:23	Mww 7.3
76	36.09	23.24	64.0	2021-12-18 05:16:39	Mww 5.0
77	40.39	-124.30	27.0	2021-12-20 20:10:31	Mw 6.2
78	18.84	-107.07	10.0	2021-12-22 23:22:58	Mww 6.0
79	35.15	26.89	10.0	2021-12-26 15:15:11	Mww 5.1
80	35.19	26.97	10.0	2021-12-26 18:59:02	Mww 5.6
81	34.83	25.14	65.0	2021-12-29 05:08:09	Mww 5.7
82	-7.55	127.58	165.0	2021-12-29 18:25:51	Mww 7.3
83	35.28	-35.25	10.0	2022-01-04 03:18:37	Mww 5.9
84	36.15	31.29	43.0	2022-01-05 03:21:16	Mww 5.1
85	11.94	-87.14	17.0	2022-01-06 16:25:05	Mww 6.1
86	37.83	101.29	13.0	2022-01-07 17:45:30	Mww 6.6
87	40.83	21.39	13.0	2022-01-09 21:43:47	Mww 5.5
88	28.48	-43.64	10.0	2022-01-10 23:26:44	Mww 5.8
89	35.23	31.94	21.0	2022-01-11 01:07:48	Mww 6.6
90	18.43	-73.54	16.0	2022-01-11 06:07:45	Mwr 4.6
91	18.49	-73.56	13.0	2022-01-11 06:18:12	Mwr 4.2
92	52.34	-167.76	20.0	2022-01-11 11:35:43	Mww 6.8
93	52.58	-168.33	19.0	2022-01-11 12:39:32	Mww 6.6
94	42.04	20.06	10.0	2022-01-14 21:37:56	Mwr 4.3
95	40.04	24.36	7.0	2022-01-16 11:48:05	Mww 5.5
96	38.81	16.06	10.0	2022-01-20 09:19:58	Mwr 4.4
97	53.24	-166.68	29.0	2022-01-22 05:17:04	Mww 6.2
98	39.58	28.82	3.0	2022-01-22 19:31:42	Mwr 4.6
99	18.46	-73.34	10.0	2022-01-24 13:16:23	Mww 5.3
100	18.49	-73.30	10.0	2022-01-24 14:06:43	Mww 5.1

Table S 3 Continuation of Table S2.

# Nr.	Latitude [°]	Longitude [°]	Depth [km]	Datetime [UTC]	Magnitude
101	9.92	-59.89	10.0	2022-01-25 02:14:31	Mww 5.2
102	18.54	-72.68	5.0	2022-01-25 18:50:57	Mwr 4.2
103	5.50	-82.58	8.0	2022-01-28 11:14:09	Mww 6.0
104	10.98	-61.06	26.0	2022-01-29 13:40:09	Mww 5.1
105	35.06	31.82	26.0	2022-02-02 21:03:48	Mww 5.3
106	-4.47	-76.93	110.0	2022-02-03 15:58:57	Mww 6.5
107	-0.42	-19.89	10.0	2022-02-08 11:59:25	Mww 6.2
108	-10.52	-13.04	10.0	2022-02-11 06:24:13	Mww 5.3
109	-0.49	-19.99	10.0	2022-02-12 20:48:54	Mww 5.5
110	70.71	-14.39	10.0	2022-02-14 20:28:21	Mww 5.7
111	16.77	-61.34	47.0	2022-02-15 08:03:00	Mww 5.0
112	14.15	-91.40	60.0	2022-02-16 07:12:22	Mww 6.2
113	-22.67	-66.27	251.0	2022-02-22 06:12:50	Mww 6.0
114	-0.47	-19.79	10.0	2022-03-02 04:41:08	Mww 5.4
115	19.12	-66.63	23.0	2022-03-02 09:11:27	Md 4.1
116	37.71	141.58	41.0	2022-03-16 14:36:30	Mww 7.3
117	36.85	5.19	10.0	2022-03-19 09:59:30	Mww 5.2
118	10.75	-43.38	10.0	2022-03-22 16:35:08	Mww 6.7
119	18.80	-74.11	10.0	2022-03-23 19:40:41	Mww 5.1
120	-22.59	170.37	10.0	2022-03-31 05:44:01	Mww 7.0
121	38.35	23.58	5.0	2022-04-07 07:38:56	Mwr 4.0
122	11.55	-86.96	27.0	2022-04-21 07:42:46	Mww 6.6
123	43.07	18.18	10.0	2022-04-22 21:07:48	Mww 5.7
124	43.05	18.14	10.0	2022-04-24 04:27:53	Mww 4.8
125	18.98	-64.36	25.0	2022-05-08 13:32:58	MI 5.5
126	70.50	-14.85	10.0	2022-05-08 21:14:01	Mww 5.1
127	70.43	-15.19	10.0	2022-05-08 23:33:15	Mww 5.4
128	-23.50	-66.65	220.0	2022-05-10 23:06:32	Mww 6.8
129	38.17	26.15	5.0	2022-05-13 22:08:49	Mwr 4.3
130	35.52	-3.48	10.0	2022-05-20 12:35:49	Mww 5.5
131	84.24	0.59	10.0	2022-05-21 07:01:22	Mww 5.8
132	-14.87	-70.19	252.0	2022-05-26 12:02:23	Mww 7.2
133	23.38	-45.06	10.0	2022-05-28 14:19:04	Mww 5.5
134	35.63	-3.48	10.0	2022-06-02 12:55:15	Mwr 4.5
135	52.07	178.30	105.0	2022-06-04 23:38:12	Mww 6.3
136	-9.09	-71.21	609.0	2022-06-08 00:55:46	Mww 6.5
137	19.54	-62.07	10.0	2022-06-09 01:11:28	Mwr 4.4
138	43.07	13.98	10.0	2022-06-09 11:18:00	Mwr 4.3
139	34.84	33.87	47.0	2022-06-10 01:40:21	Mww 5.0
140	-7.92	-13.67	10.0	2022-06-11 06:35:29	Mww 5.2
141	-7.99	-13.62	10.0	2022-06-11 07:29:54	Mww 5.6
142	18.45	-62.99	39.0	2022-06-17 10:48:12	Mww 5.1
143	35.32	27.16	41.0	2022-06-19 23:24:33	Mww 4.9
144	33.05	69.48	10.0	2022-06-21 20:54:36	Mww 6.0
145	43.49	17.61	51.0	2022-06-30 06:07:14	Mwr 4.3
146	26.94	55.25	16.0	2022-07-01 21:32:08	Mww 6.0
147	26.88	55.32	10.0	2022-07-01 23:25:14	Mwb 6.0
148	61.09	-60.08	10.0	2022-07-12 16:58:05	Mww 5.2
149	78.62	6.25	10.0	2022-07-18 18:40:33	Mww 5.9

Section S 6 Station Orientation

Waveforms for all earthquakes with $M \geq 6.0$ were extracted from the continuous data. At preprocessing, all traces were instrument-corrected and converted to velocity seismograms. The timing was corrected based on the preliminary skew estimate obtained by assuming linear drift between the synchronization points just before deployment and just after recovery; we note that the exact timing is not critical for the orientation estimation algorithm and is only used to cut out the analysis window for the P polarisation measurements; remnant timing errors of a few seconds could be tolerated due to the window sizes used.

Section S 6.1 P polarisation

For a laterally homogeneous Earth model and in the absence of noise, the particle motion of an incoming P wave is expected to be aligned with the backazimuth and point towards the source. The estimated orientation ϕ is therefore simply given by the difference between back azimuth (BAZ) and apparent azimuth θ (with respect to the '1' component), $\phi = BAZ - \theta$. The azimuth is measured by calculating the covariance matrix of the three components, and then carrying out an eigenvalue decomposition (Flinn, 1965; Jurkevics, 1988). The azimuth θ and incidence angle ι of the eigenvector corresponding to the largest eigenvalue λ_1 then describe the dominant polarisation. We carry out this analysis in three frequency bands, with the length of the analysis window adopted to the frequency content according to the following table, where the reference time for the analysis window is the theoretically predicted P arrival time.

Bandpass	Signal window (s)
Unfiltered	-5 – 20
2–15 s	-4 – 12
8–33 s	-5 – 25

The intermediate filter and window length follow the parameters suggested in Braunmiller et al. (2020)

We analyse all previously extracted events, and in a fully automatic workflow, select for further analysis those fulfilling the following criteria:

Horizontal (Amplitude) SNR > 5 (Signal-to-Noise Ratio). First, a time series of the absolute horizontal amplitude is constructed as $x_h(t) = \sqrt{x_1(t)^2 + x_2(t)^2}$.

We define the SNR as the ratio between the peak absolute amplitude of this time series in the signal window and its root-mean-square in the noise window. The noise window is taken from the waveform ahead of the P arrival time, with a buffer to allow for early arrivals and filter side effects; its length was set to two times the low pass corner period of the filter band or the length of the signal window, whichever is longer.

Rectilinearity $r \geq 0.5$. The rectilinearity (1: linear motion; 0: motion in a plane or volume) is calculated from the ratio of the two largest eigenvalues $\lambda_{1,2}$ by $r = 1 - \lambda_2/\lambda_1$. We note that even for the ideal assumption of no lateral heterogeneity and noise, the particle motion in three dimensions would not be expected to be perfectly linear due to conversions and reverberations in the sub-surface as well as water multiples. In practice, a low linearity of the P wave arrival typically indicates a noisy trace, though.

Incidence angle $\iota \leq 50^\circ$. The incidence angle is measured relative to the vertical down direction. For P arrivals, a relatively steep incidence is expected. Large values of ι (i.e. close to horizontal polarisation) indicate problems with a component or dominant horizontal noise.

The results of the analysis are summarised in Fig. S14 for an exemplary station. The majority of events failed the SNR criterion; measurements above the SNR threshold generally returned consistent estimates for the orientation, while the estimates below it tended to scatter widely. When the SNR criterion was fulfilled, usually the other two criteria passed as well, but they were useful to catch a few pathological cases, e.g. when a disturbing transient signal (e.g. a spike) appeared coincidentally in the signal window. The thresholds for the three criteria were set after visual inspection of plots, as in Fig. S14 for a few stations. As a counter example, we present UP40, Fig. S15.

For each band, the mean and median values were calculated after removing outliers in an iterative procedure; most stations did not have any outliers (see Table S4). No azimuthal weighting was applied; the relatively small number of total observations, which are fairly well distributed in back azimuth, made it seem advisable to let each of them contribute equally. For a larger number of observations with back azimuthal clustering, down-weighting of observations from oversampled back azimuthal directions can help to reduce biasing effects due to lateral heterogeneity. Generally, the long-period band (8-33 s) worked best in having the highest SNR values, and with the largest number of events passing the selection criteria. As also the longest periods are expected to be least influenced by lateral heterogeneity, the final P wave estimate of orientation, ϕ_P was taken from the circular mean (von Mises average) of the long period measurements, with the other two bands used for validation.

The circular standard deviation of the measurements σ_ϕ is calculated based on the implementation in `scipy.stats` function `circstd`, which follows Mardia (1972, p 18-24). The expected error of the final estimate is then calculated, assuming the independence of single event measurements, as $\Delta\phi_P = \frac{\sigma_\phi}{\sqrt{n-1}}$, where n is the number of single-event measurements.

A final coarse classification into the following categories was made for guidance:

Good: (i) Based on at least 5 non-outlier measurements, (ii) less than 30% of (accepted) measurements classed as outliers, (iii) a consistent result (i.e. within the error expectation) is obtained in at least one additional band, and (iv) the difference between the mean and median is less than 10° .

Poor: All station averages failing at least one of the four criteria above, but based on a minimum of 3 single-event measurements. For stations failing criterion (iv), the median is reported as the best orientation estimate, and no error is returned (P-err=NaN). For stations where a minimum of 3 long-period measurements could not be made, the mean value of either the short-period or the unfiltered band was taken as the final estimate.

Invalid: All stations not having at least three accepted measurements in at least one period band. No orientation estimate is reported.

Figure S14 and S16 illustrate the P wave analysis and quality control for an exemplary station returning a ‘good’ result. Equivalent plots were produced for all stations and visually inspected. A counterexample for poor results is shown in Fig. S15 and S17 for UP40.

Table S 4 Horizontal component estimates. For further details about the method used to obtain these estimates, see the text in [Section S 6](#).

Station	Preferred Orientation	Type	P arrival Orientation	Quality	#OK #Outlier	Rayleigh Orientation	Quality	#OK #Outlier
OBS12	3± 3°	joint	0± 5°	good	6/ 0	5± 4°	good	12/ 1
OBS17	188± 2°	surf	196± 7°	poor	6/ 0	188± 2°	good	9/ 1
OBS19	196± 5°	surf	193± 3°	poor	6/ 0	196± 5°	good	11/ 0
UP01	44± 5°	surf	42± 6°	poor	4/ 0	44± 5°	good	7/ 0
UP02	148± 7°	surf	149± 3°	poor	3/ 1	148± 7°	good	7/ 0
UP03	159± 3°	joint	156± 5°	good	10/ 0	160± 3°	good	7/ 0
UP04	71± 6°	surf	60± 7°	poor	4/ 0	71± 6°	good	12/ 1
UP05	173± 2°	joint	173± 2°	good	7/ 1	175± 4°	good	15/ 1
UP06	194± 4°	surf	196± 2°	poor	8/ 0	194± 4°	good	15/ 0
UP07	344± 1°	joint-poor	342± 3°	poor	4/ 0	345± 2°	poor	4/ 2
UP08	206± 3°	joint	205± 5°	good	11/ 0	207± 4°	good	14/ 0
UP09	325± 4°	joint	328± 6°	good	7/ 0	322± 5°	good	7/ 0
UP10	153± nan°	P-poor	153± nan°	poor	0/ 2	nan± nan°	invalid	0/ 0
UP11	277± 4°	surf	276± 6°	poor	6/ 0	277± 4°	good	10/ 0
UP12	197± 5°	surf	203± 2°	poor	6/ 3	197± 5°	good	13/ 3
UP13	232± 3°	joint	232± 4°	good	9/ 0	231± 4°	good	11/ 2
UP15	180± 2°	joint-poor	180± 3°	poor	3/ 0	181± 7°	poor	3/ 2
UP16	29± 4°	joint	29± 5°	good	6/ 0	30± 5°	good	9/ 2
UP18	304± 3°	joint-poor	304± 3°	poor	3/ 0	301± 8°	poor	3/ 2
UP19	nan± nan°	invalid	nan± nan°	invalid	0/ 0	nan± nan°	invalid	0/ 0
UP20	145± 5°	surf	145± 6°	poor	6/ 0	145± 5°	good	10/ 1
UP21	116± 7°	surf-poor	nan± nan°	invalid	0/ 2	116± 7°	poor	3/ 1
UP22	127± 3°	surf	124± 4°	poor	5/ 0	127± 3°	good	11/ 0
UP23	nan± nan°	invalid	nan± nan°	invalid	0/ 0	nan± nan°	invalid	0/ 0
UP24	163± 4°	joint-poor	163± 4°	poor	4/ 0	166± 12°	poor	3/ 2
UP25	278± 5°	surf	272± 5°	poor	3/ 0	278± 5°	good	8/ 0
UP26	57± 3°	surf	71± nan°	poor	4/ 0	57± 3°	good	9/ 0
UP27	136± 7°	surf	135± 7°	poor	4/ 0	136± 7°	good	5/ 1
UP28	275± 12°	P-poor	275± 12°	poor	7/ 1	nan± nan°	invalid	0/ 0
UP29	180± 3°	joint	182± 5°	good	7/ 0	179± 5°	good	10/ 0
UP30	238± 8°	surf	238± 3°	poor	3/ 0	238± 8°	good	6/ 2
UP31	301± 2°	surf-poor	nan± nan°	invalid	0/ 1	301± 2°	poor	4/ 1
UP32	128± 5°	surf	129± 3°	poor	4/ 0	128± 5°	good	6/ 0
UP33	13± 2°	surf	11± 2°	poor	9/ 1	13± 2°	good	12/ 0
UP34	46± 7°	surf	41± 4°	poor	7/ 0	46± 7°	good	7/ 3
UP35	240± 5°	surf	246± 12°	poor	5/ 0	240± 5°	good	7/ 2
UP36	183± 3°	surf	185± 4°	poor	4/ 0	183± 3°	good	11/ 1
UP37	84± 6°	surf	nan± nan°	invalid	0/ 2	84± 6°	good	11/ 0
UP38	168± 3°	surf	165± 5°	poor	4/ 0	168± 3°	good	9/ 0
UP39	332± 4°	surf-poor	nan± nan°	invalid	0/ 0	332± 4°	poor	4/ 0
UP40	345± 3°	surf	nan± nan°	invalid	0/ 0	345± 3°	good	13/ 0
UP41	91± 6°	surf	nan± nan°	invalid	0/ 1	91± 6°	good	5/ 2
UP42	72± 6°	surf	nan± nan°	invalid	0/ 1	72± 6°	good	7/ 3
UP43	81± 4°	surf	76± 3°	poor	7/ 0	81± 4°	good	10/ 0
UP44	319± 8°	surf	319± 2°	poor	6/ 1	319± 8°	good	7/ 0
UP45	115± 4°	surf	115± 4°	poor	6/ 0	115± 4°	good	12/ 0
UP46	195± 5°	surf	nan± nan°	invalid	0/ 2	195± 5°	good	9/ 0
X25	173± 7°	surf	168± 2°	poor	3/ 0	173± 7°	good	10/ 0

An extended version of this table is made available as a supplementary CSV file (polanalysis_summary-mod.csv). In addition to the information shown in the table, the CSV file contains information on which events contributed to each estimate, and which ones resulted in outlier measurements, provides more significant digits, and reports the standard deviation of single-event orientations for the P wave method.

Section S 6.2 Rayleigh wave method

This method (Stachnik et al., 2012; Petersen et al., 2019) is based on the retrograde elliptical particle motion of the fundamental mode Rayleigh wave. This motion implies that the radial component leads the vertical component by a quarter period, or in other words, the Hilbert-transformed radial component should be highly correlated with the vertical component. To obtain unbiased results, it is critical that the time window for the analysis only contains the fundamental mode Rayleigh wave on the vertical component and is free from either higher modes or later obviously multi-pathed arrivals, which are likely to arrive from directions potentially far from the back azimuth. An overlap with the Love wave is expected and not a problem, as for the optimal orientation, the Love wave fully separates

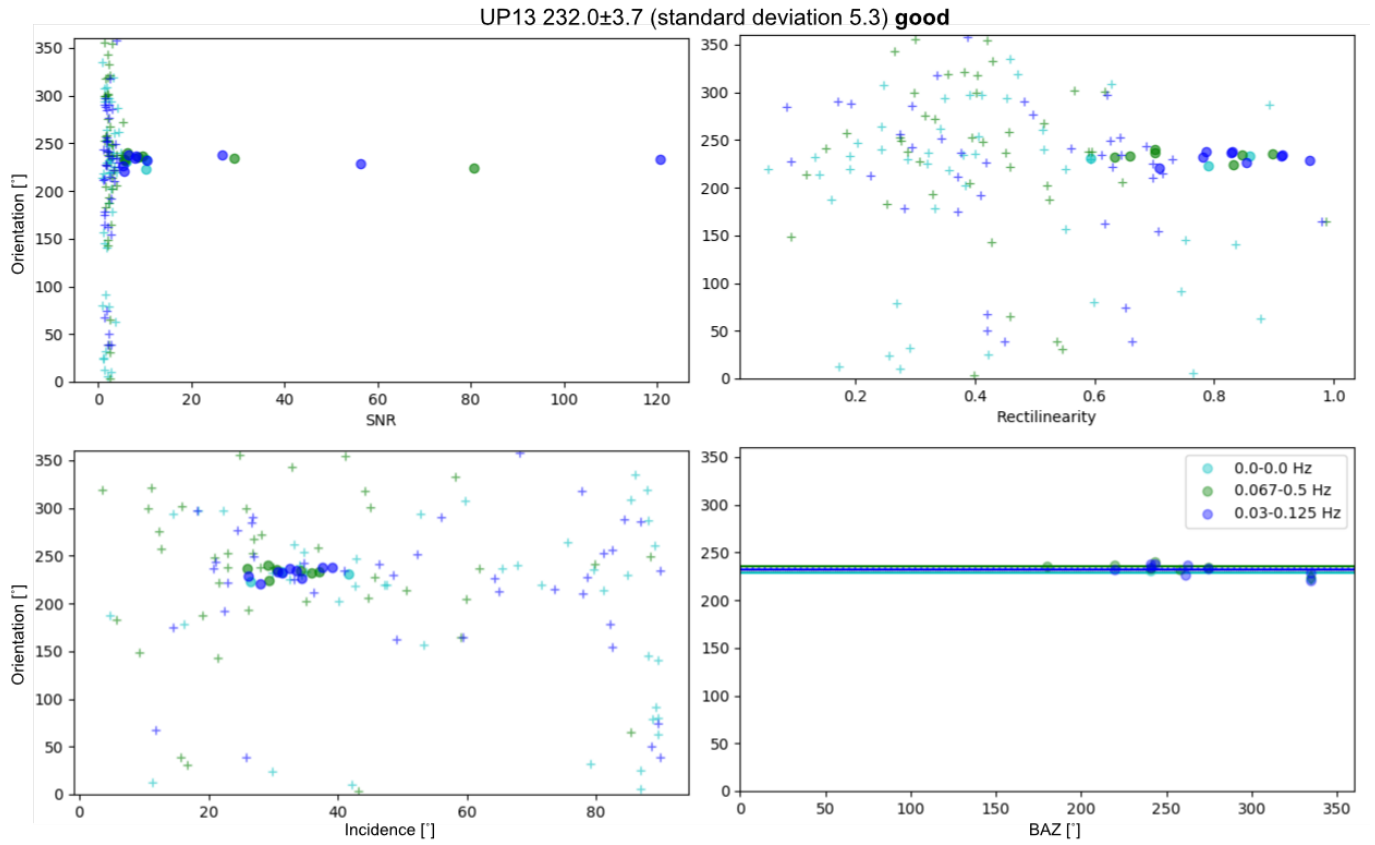


Figure S 14 Summary of all P wave polarisation measurements for a station with good quality measurements (UP13). The different colours designate the different bandpass filters applied (Cyan – Unfiltered, Green – 2-15 s, Blue – 8-33 s). The y-axis in each case shows the station orientations estimated from single events, plotted as a function of signal noise ratio, rectilinearity and incidence angle, and back azimuth. Circles indicate measurements fulfilling all quality criteria, and crosses designate measurements failing at least one quality criterion. In the bottom right figure, poor quality measurements (crosses) are not shown to put the focus on judging the consistency of accepted orientation estimates. Continuous horizontal lines indicate mean values of the accepted estimates in the three bands (nearly overlapping for this station); dotted lines indicate the median, but are fully overlapped in this case. The final estimate is taken from the longest period band (blue line). The title gives estimated 95% error bounds for the mean value; their standard deviation is also quoted.

from the Rayleigh wave. We inspected all events which were band-pass filtered from 20–70 s, and 40–80 s. Given that many of the selected events cross the ocean-continent boundary and cover a wide range of distances, average group velocities can be quite variable. Therefore, the analysis windows were all picked manually, separately for the two bands. About twice as many windows could be picked for the 20–70 s band due to more favourable signal-to-noise ratios at the shorter periods. The event selection also aimed to achieve a well-balanced azimuthal distribution.

Initially, each filterband is analysed separately. For the analysis, the bandpass-filtered and windowed time series are decimated to a 2 Hz sampling rate. A grid search is performed with 1° increments, where the horizontal components are rotated according to the trial orientation and the backazimuth of the event, and the trial radial component is Hilbert transformed. The normalised zero lag correlation for event i is then calculated from the vertical time series z_t and the Hilbert-transformed trial radial component $\tilde{r}_t(\phi)$ (assuming trial orientation ϕ).

$$C_i(\phi) = \frac{\sum_t z_t \tilde{r}_t(\phi)}{\sum_t z_t^2}$$

where the summation is over the samples of the selected time window. Note that this is not a cross-correlation coefficient as we normalise with the vertical component power rather than the geometric mean of radial and vertical

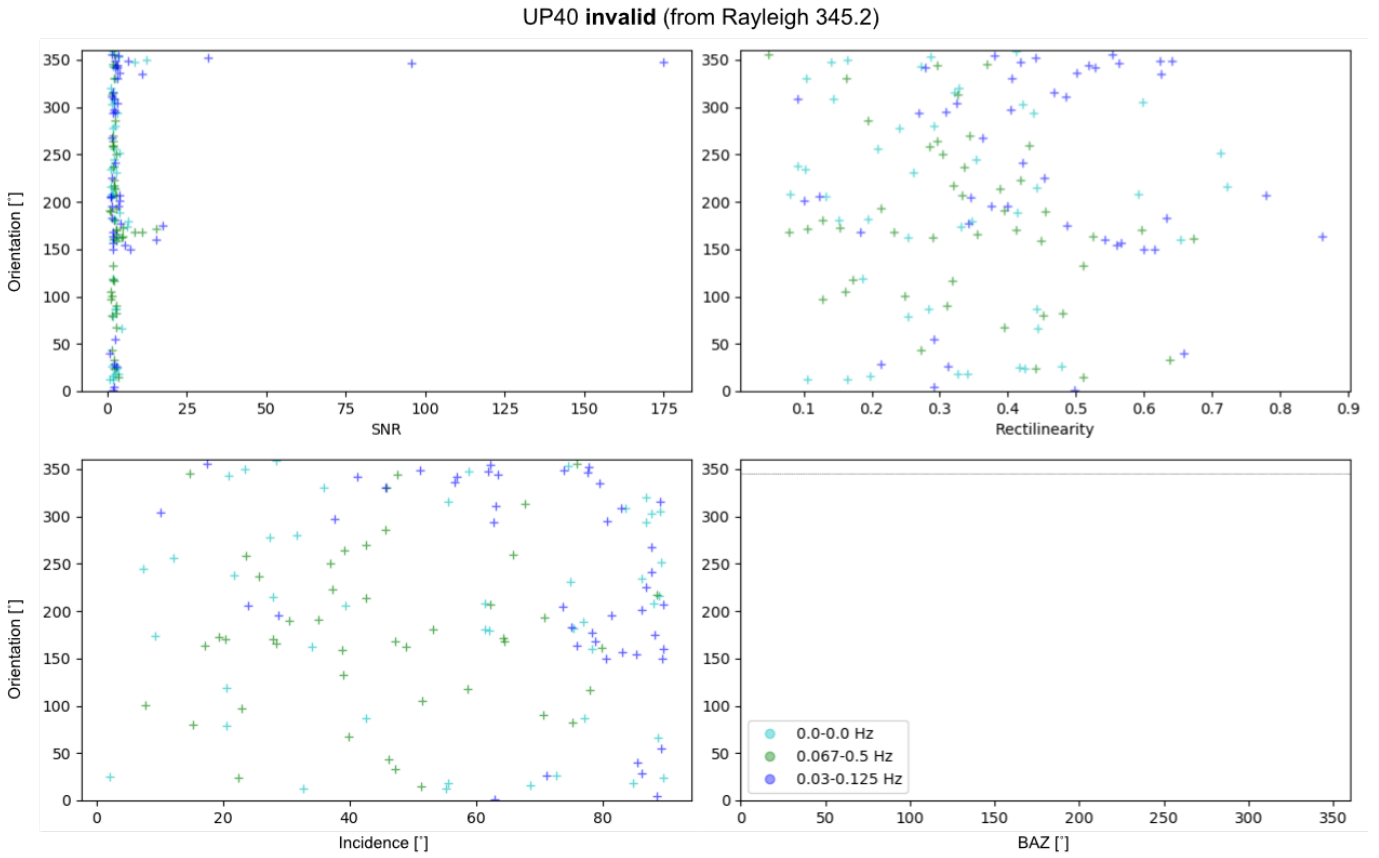


Figure S15 Summary of all P wave polarisation measurements for a station with poor quality P wave measurements (UP40). The format is identical to Fig. S14. In the plot on the bottom right, no circles or mean/median estimates are shown because no single-event measurements for this station passed the rectilinearity or incidence angle threshold acceptance criteria. The thin grey line provides the orientation estimate derived from the Rayleigh wave method for comparison. Even though none of the measurements got accepted, it is worth noting that the high signal-to-noise-ratio (SNR) measurements are still consistent with the orientation estimate from the surface waves, which adds confidence to this station's orientation estimates. Due to the particle motion being more planar than linear, there is a 180° ambiguity visible in the orientation vs SNR plot for measurements at moderate SNR of ~ 10 – 20 .

component powers. This has the advantage of the denominator being independent of the trial rotation angle, which results in clearer maxima (Stachnik et al., 2012).

The value of ϕ maximising this function represents the single event estimate:

$$\phi_i = \arg \max_{\phi} C_i(\phi) .$$

We also calculate the correlation coefficient at this maximum and verified that the correlation coefficient is at least 0.7. In fact, all time windows passed this check because they had been manually pre-selected. The individual station estimates are then analysed to eliminate outliers; most stations did not have outliers, though (Table S4). The final estimation is made from a stack of the event correlation functions $C_i(\phi)$ not belonging to outlier stations:

$$\phi_R = \arg \max_{\phi} \sum_{i \notin \{Outliers\}} C_i(\phi) .$$

Figure S18 illustrates this analysis for an exemplary station and Fig. S19 for a poor result.

The error for each filterband is estimated by bootstrap resampling across events before outlier removal, then repeating the estimation procedure, i.e., first identifying and removing outliers and then repeating the stacking. We

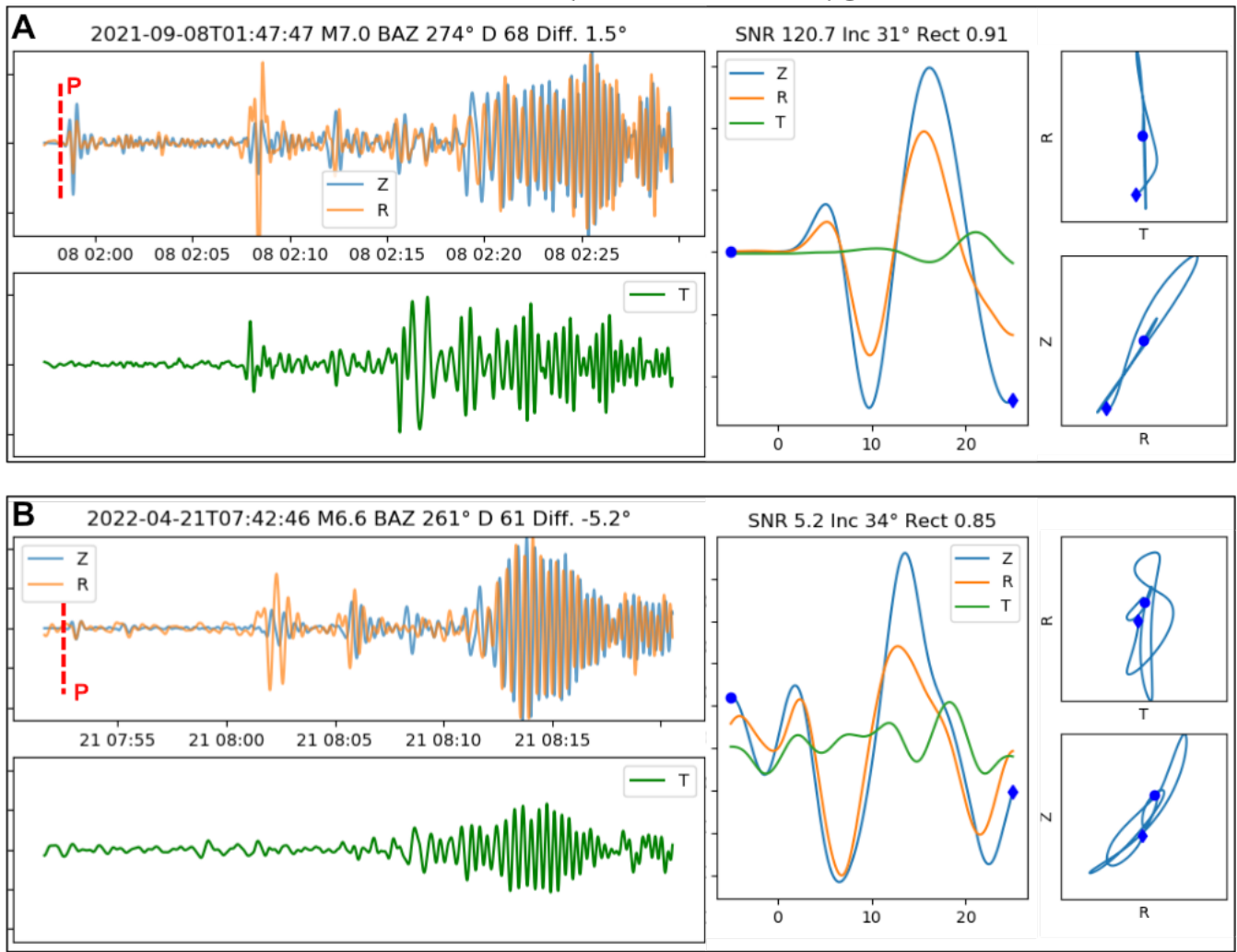
UP13 232.0±3.7 (standard deviation 5.3) good

Figure S 16 Velocity waveform plots for station UP13 after rotation into radial and transverse components according to the best estimate from P wave particle motion. Plots in A show the full waveform from P arrival to the fundamental mode Rayleigh (cut off at group velocity 3 km/s), bandpass filtered 20-80 s. The plot title provides information on the origin time, magnitude, back azimuth, epicentral distance of the earthquake, and the difference in the estimated orientation between the single-event measurement, and the mean value for all accepted events. Waveform plots in the central panel of A zoom in on the P arrival analysis window in the long period band, bandpass filtered 8-33 s, with the plot title stating SNR, incidence angle and rectilinearity measured from the covariance analysis of this waveform. The same data are visualised as R-T and Z-T particle motion plots on the right. The upper earthquake example in A shows the waveforms with the highest P wave horizontal SNR in the 8-33 s band, and the example in B shows the waveforms with the lowest but still just accepted SNR.

determined the 95% confidence interval from the 2.5th and 97.5th percentile of 200 bootstrap samples.

Finally, the estimates of both filter bands are combined in a weighted average, with the final error estimated based on error propagation. The error calculation is somewhat simplified here, as the possible asymmetry of the error bounds resulting from the bootstrap sampling and the presumed partial correlation of the errors of the measurements in the two (overlapping) frequency bands are ignored.

The categorisation into 'Good', 'Poor' and 'Invalid' measurements follows exactly the criteria described in detail for the P polarisation analysis, except that no check of the difference between mean and median is made.

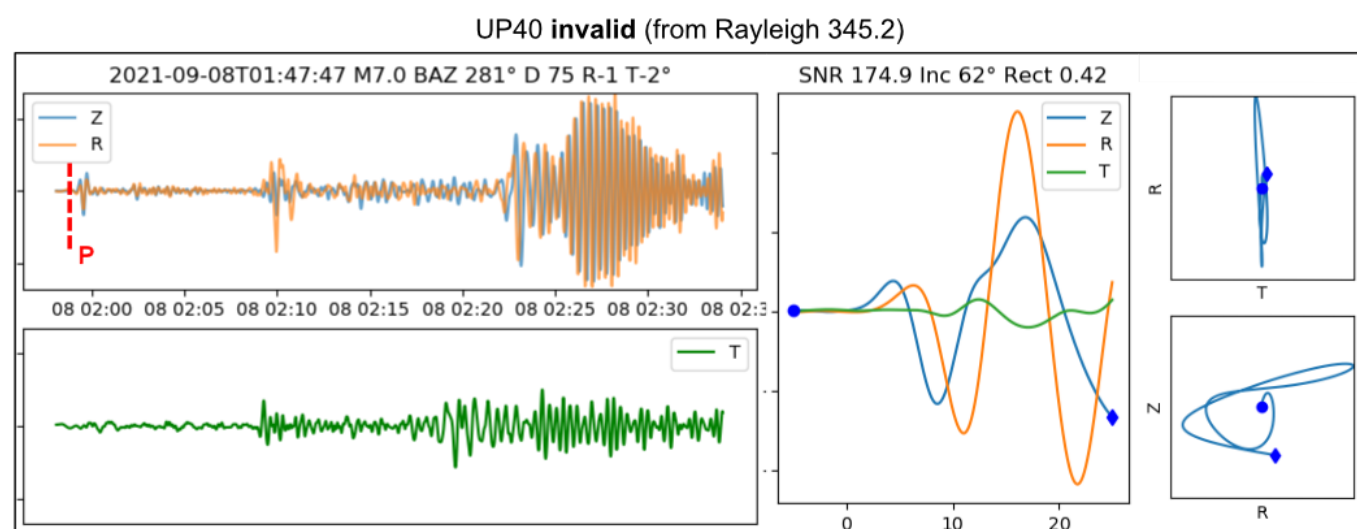


Figure S 17 Velocity waveform plots for station UP40 after rotation into radial and transverse components. As no estimate was available from the P wave method, the orientation from the Rayleigh method is used for rotation. Otherwise, the figure format is like Fig. S16, except that only the station with the highest SNR is shown. With this rotation, the particle motion is mostly constrained to the Z-R plane as expected, even though the rectilinearity is lower, and the incidence angle is higher than expected for a P wave arrival.

Section S 6.3 Joint Results

For stations where both methods were classed as reliable, the joint estimate is simply the circular mean of the two estimates, weighted by their estimated variances. The variance of the final estimate is calculated as half the harmonic mean of both estimates (from simple error propagation).

In other instances, where only one of the methods was classed as ‘good’, the associated estimate and its error were used as the final estimate. The classification of the joint estimate is inherited from the classification of the two methods.

An additional check was carried out for consistency, which required the difference between the two estimates to be smaller than the root-mean-square of their estimated errors. The consistency check was passed by all stations. Table S4 summarises the orientation estimations.

Although the errors presented in the table and figures nominally represent 95% error bounds, due to some not fully justified assumptions and the inherent uncertainty of small number statistics, the actual error bounds are probably somewhat wider. Nevertheless, they should represent the orientation uncertainty fairly well for practical purposes, as is confirmed by the general consistency of the independent P and Rayleigh method estimates even for most estimates classed as ‘poor’.

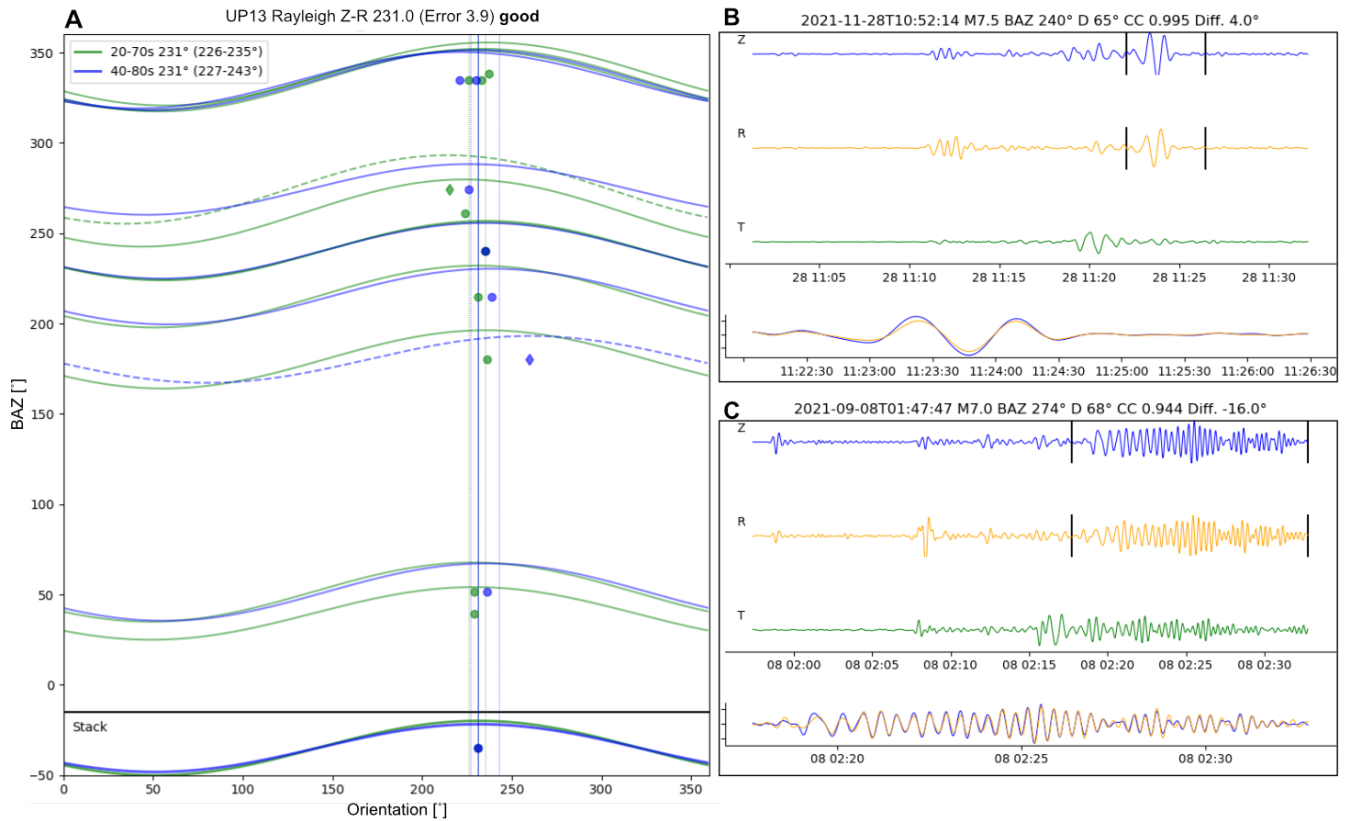


Figure S 18 A: Rayleigh wave analysis for UP13. The panel shows the correlation curves in the two analysed period bands, plotted with the zero correlation value and shifted vertically according to the back azimuth. Circles/diamonds mark the single-event-orientation estimates based on the maxima of the correlation curves. Continuous lines and circles designate events contributing to the stack; dashed lines and diamonds designate outlier results excluded from the stack. The legend shows the period band, the estimated orientation for this band based on the maximum of the stacks, and its 95% confidence interval estimated from bootstrap resampling. The plot title shows the overall Rayleigh-based estimate based on the weighted mean of the results from the two filter bands.

B: Seismic waveforms for the event with the highest cross-correlation bandpass filtered in the 20-70 s range and rotated using the overall Rayleigh wave method estimate. Vertical black lines mark the surface wave analysis window for the 20-70 s band. The subtitle shows the event parameters, the cross-correlation coefficient between Z and Hilbert-transformed R trace, and the difference between the single-event optimum orientation and the optimum orientation derived from all accepted waveforms. At the bottom, zoom of the analysis window shows the vertical component (Z) and the Hilbert-transformed R trace. C: Same as in B, but for the event with outlier measurements in the 20-70 s band. The title shows the same as in B.

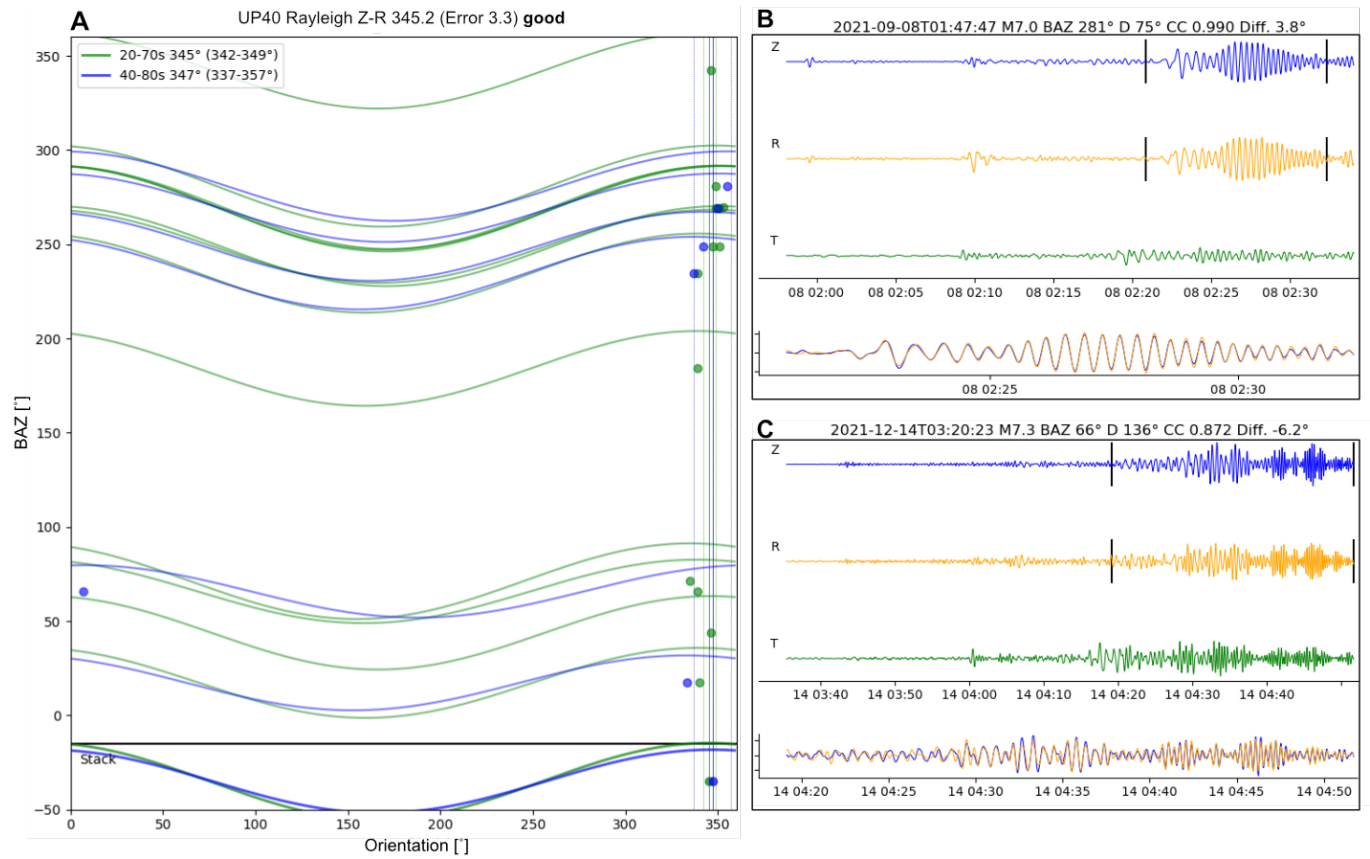


Figure S19 Rayleigh wave analysis for UP40. Figure format as described in Fig. S18 except that no outlier was identified for this station, such that the right bottom shows the seismograms corresponding to the lowest cross-correlation coefficient between vertical and Hilbert-transformed radial component. Although the P wave method did not give a clear result for the orientation of this station, the Rayleigh wave analysis is not anomalous and returns a robust result.

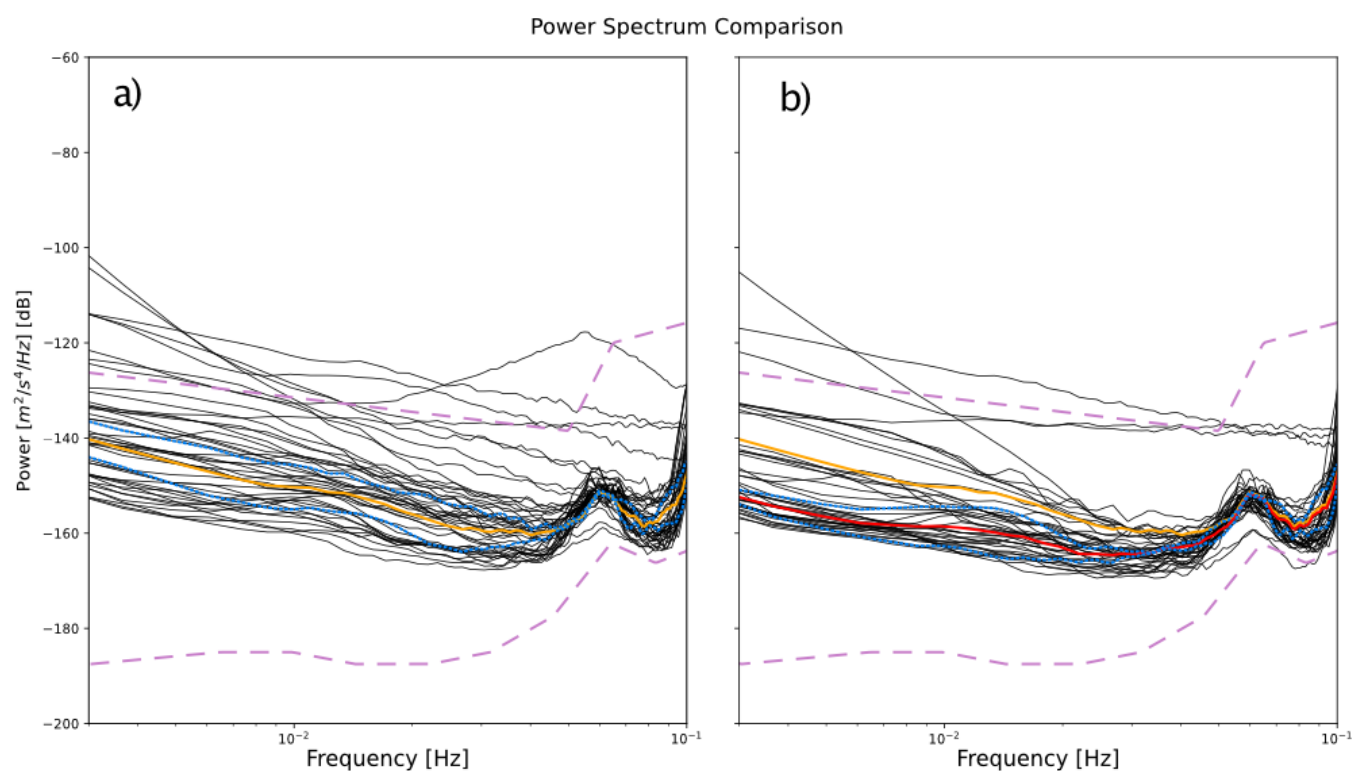
179 **Section S 7 Compliance and tilt corrections**

Figure S 20 Compliance and tilt removal comparison. a) Raw power spectra of the OBSs for a calm day (2021-08-19), b) Denoised vertical acceleration spectra, after application of tilt and compliance corrections, for the same day. Upper and Lower purple dashed lines correspond to the NHNM and NHLM (Peterson, 1993). The orange line shows the average raw vertical acceleration power, and the red line shows the power of the denoised vertical acceleration for the same frequency range. The blue lines above and below the orange (a) and red (b) lines show their associated standard deviation.

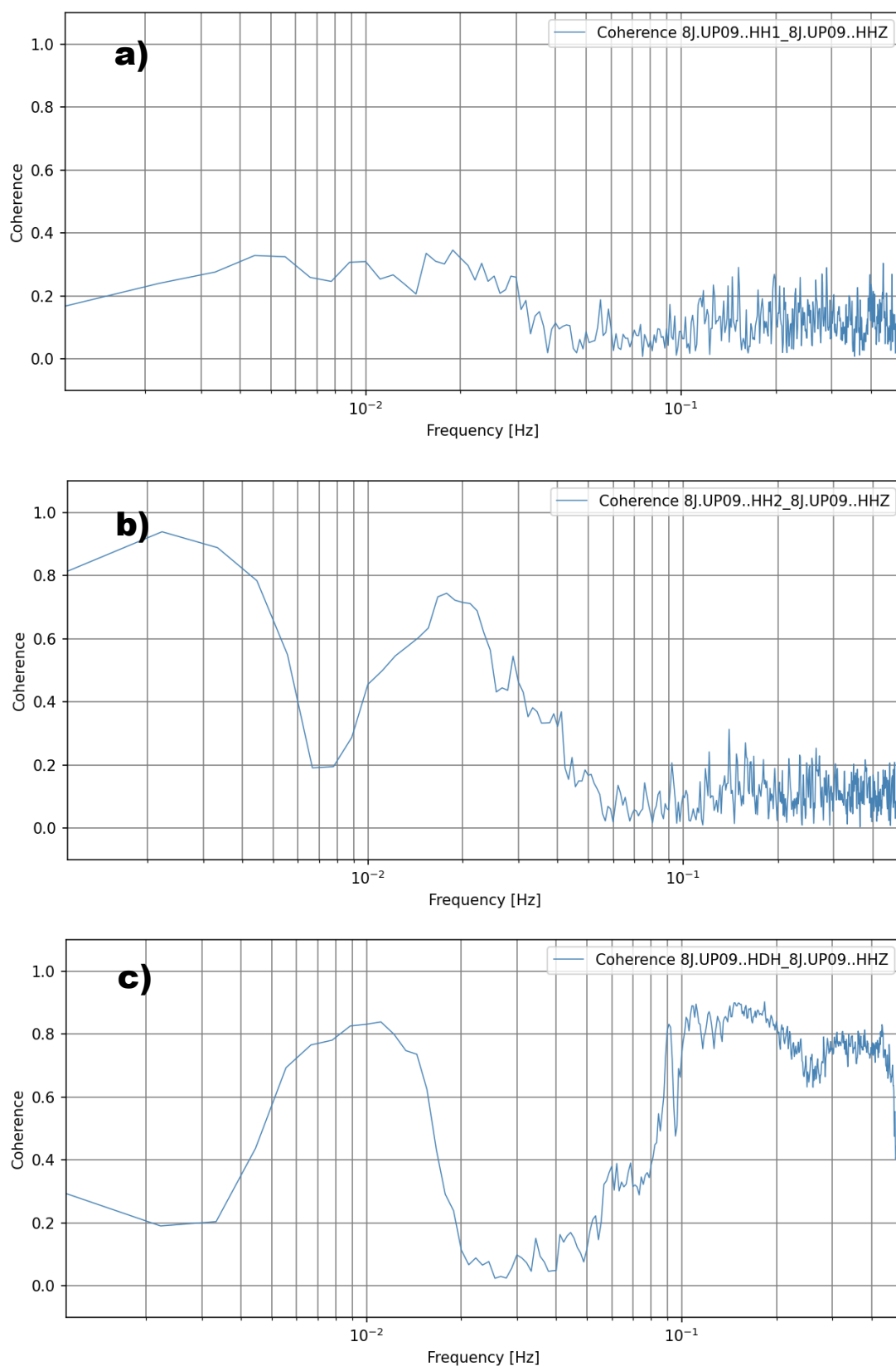


Figure S 21 Illustrative example of spectral coherence between OBS components for the same time period as in Fig. S20 for station UP09. a) Coherence between horizontal component 1 and vertical component. b) Coherence between horizontal component 2 and vertical component; and, c) coherence between vertical component and hydrophone.

Section S 8 Probability Power Spectral Density (PPSD)

Table S 5 Default parameters used in PPSD computation using ObsPy ([Krischer et al., 2015](#)).

Parameter	Default Value
ppsd_length	3600.0 seconds
overlap	0.5
special_handling	None
period_smoothing_width_octaves	1.0
period_step_octaves	0.125
period_limits	None

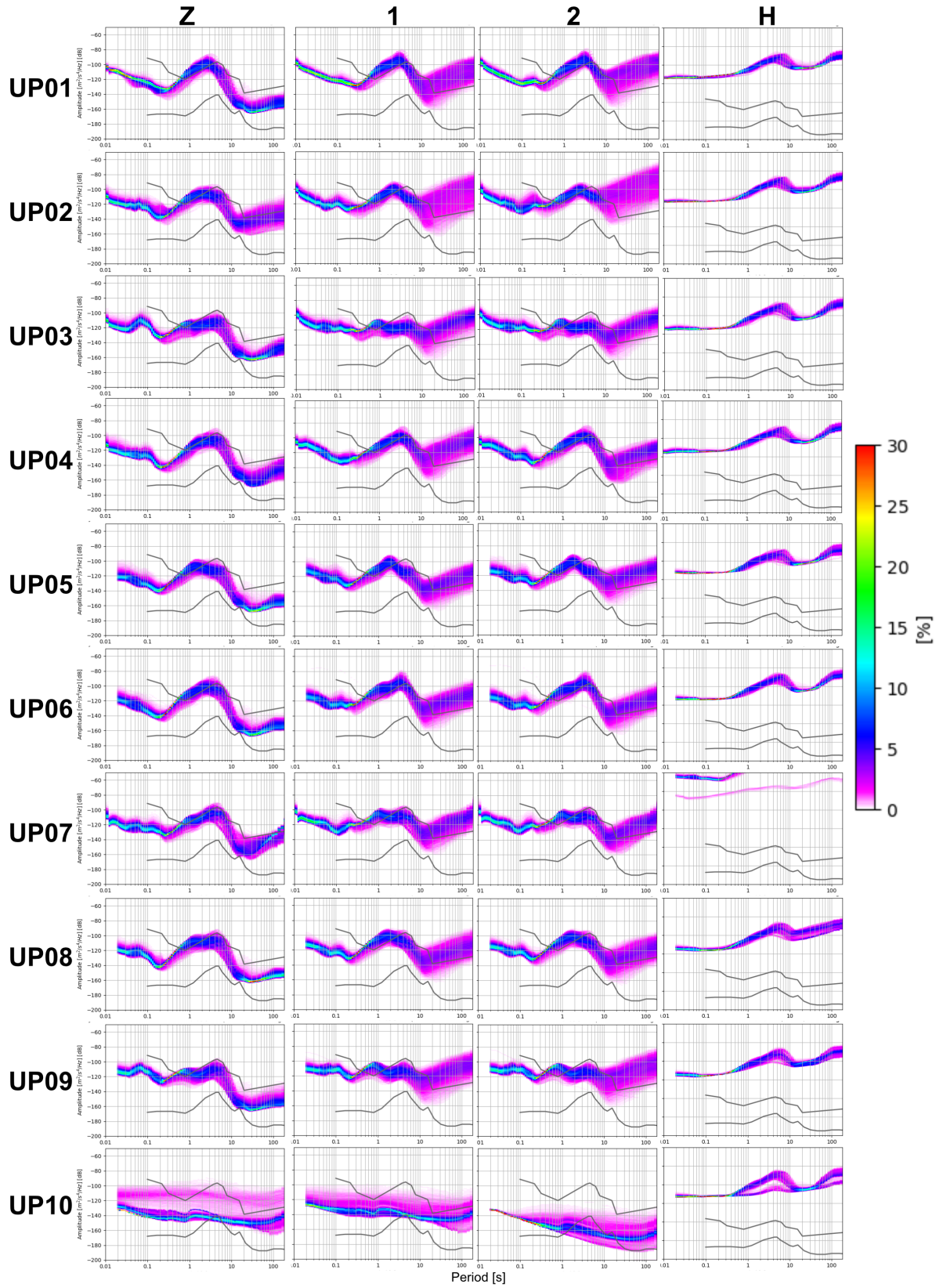


Figure S 22 PPSD of all components for stations UP01 to UP10. For single-component figures of the PPSD and more details, please refer to the online material (link in [Section S 1](#)). PPSDs were calculated using obspy ([Krischer et al., 2015](#)) using default values (window length 3600.0 s, window overlap 0.5% and PSD values on the frequency axis are measured every 1/8 of an octave), as explained in [Table S5](#). Original sampling rates were used during the processing.

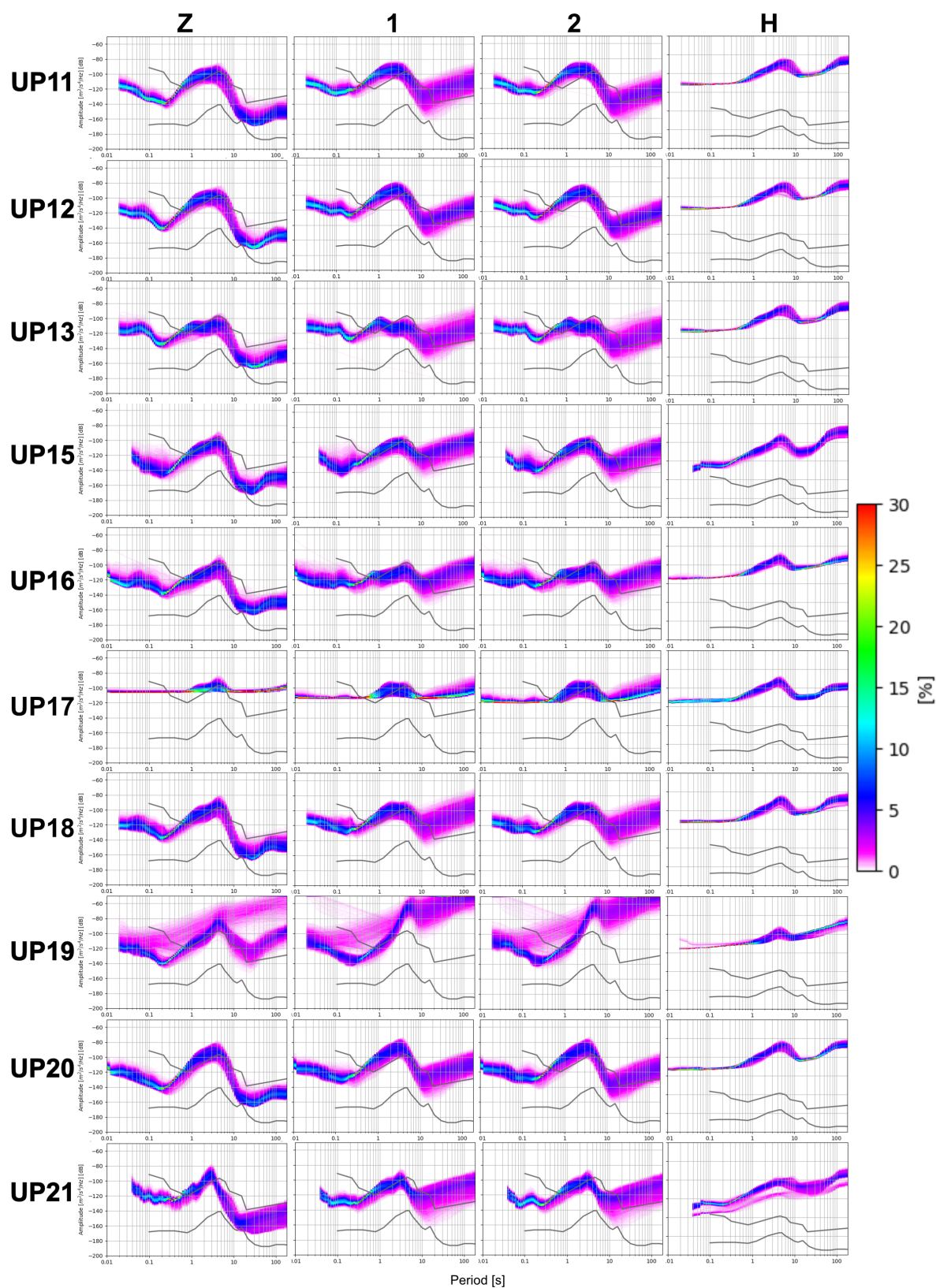


Figure S 23 Continuation of Fig. S 22.

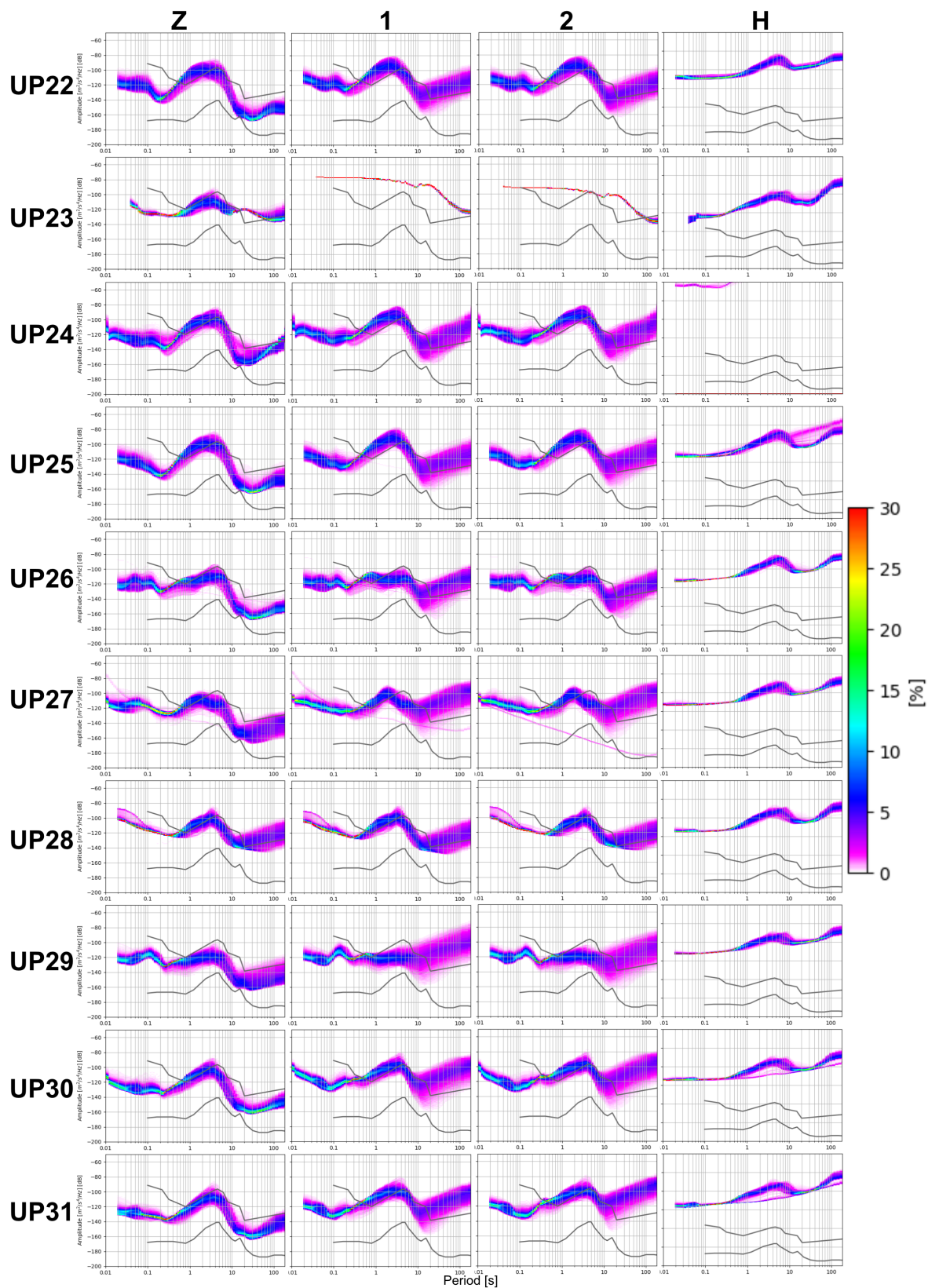


Figure S 24 Continuation of Fig. S 23.

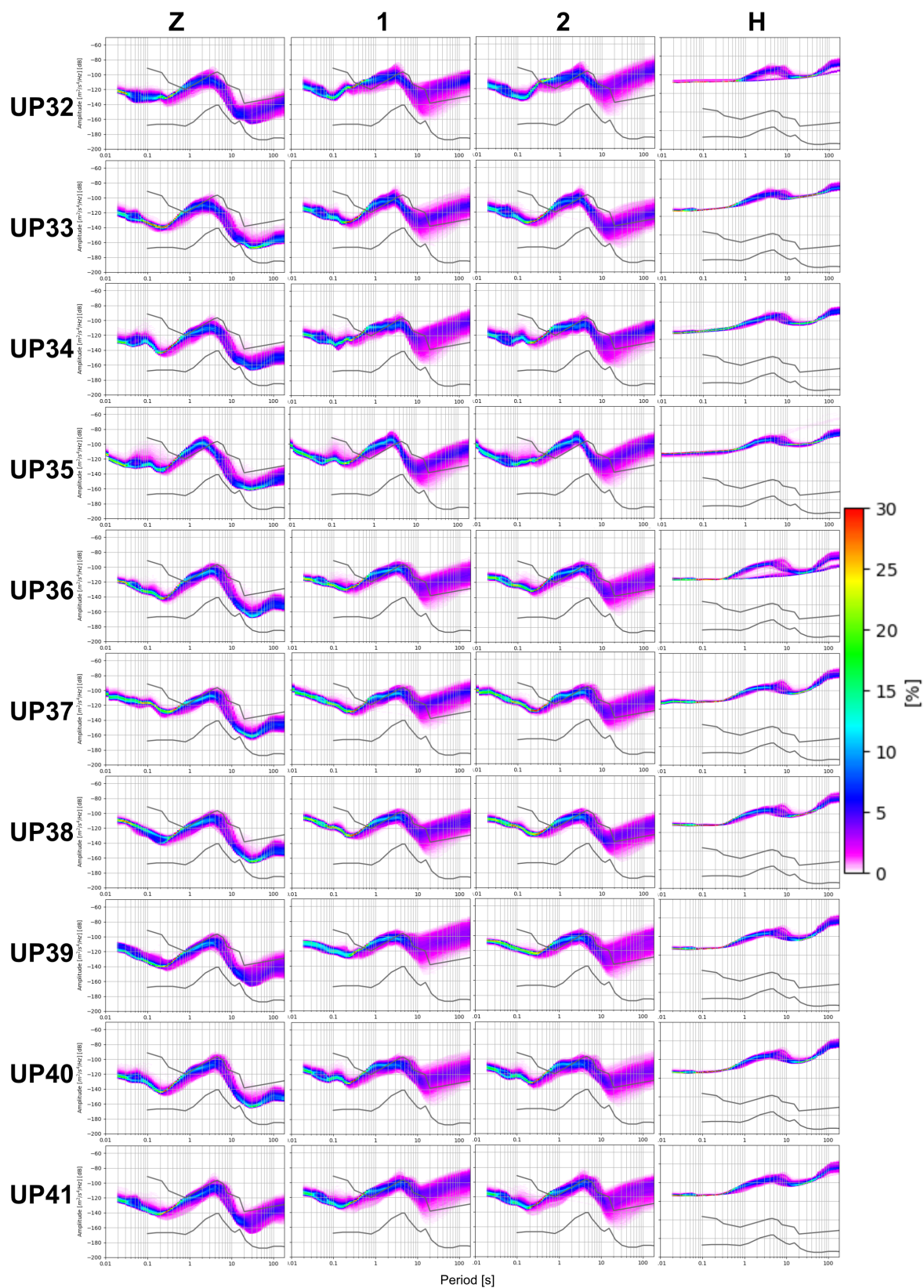


Figure S 25 Continuation of Fig. S 24.

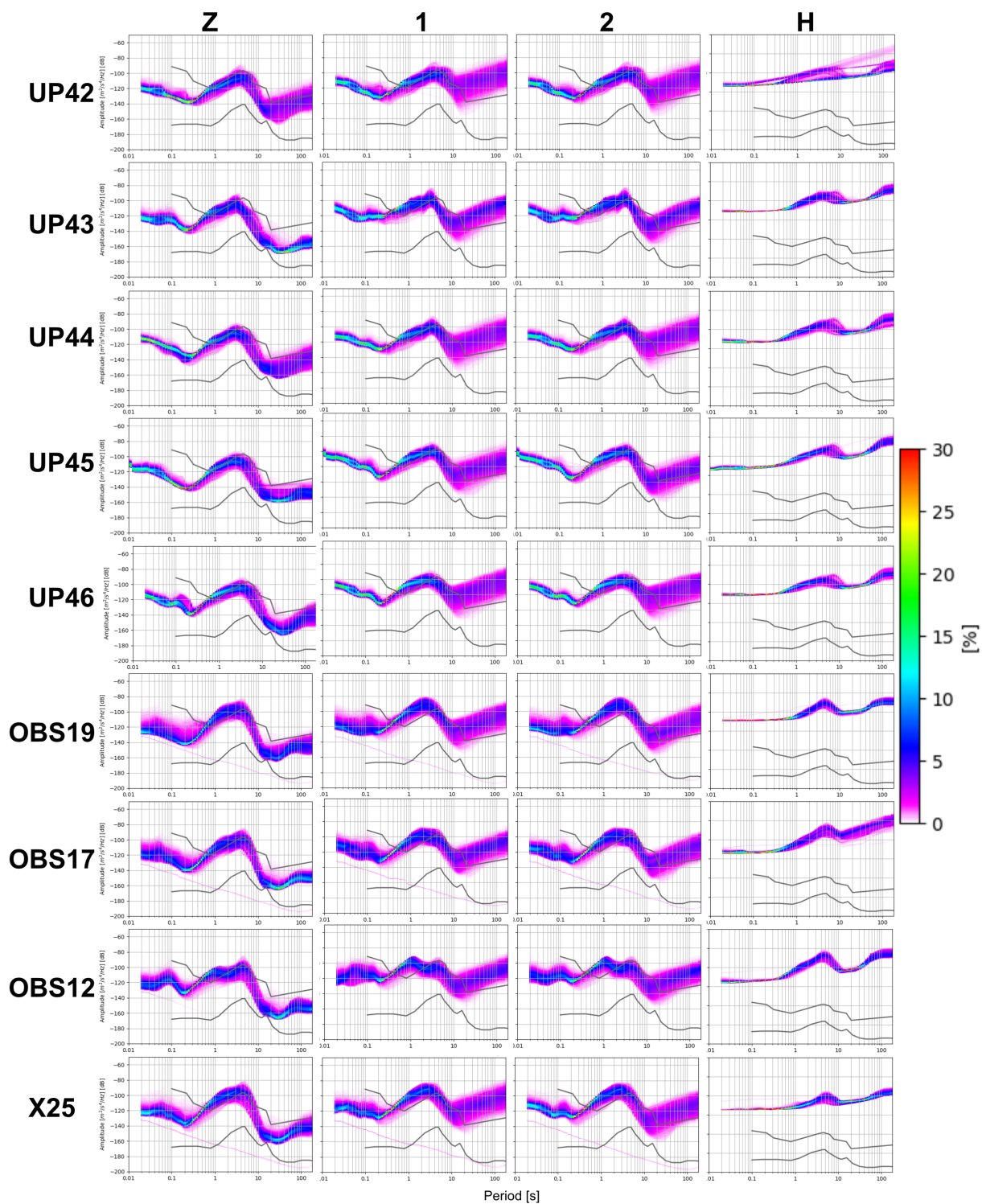


Figure S 26 Continuation of Fig. S 25.

Section S 9 Signal-to-Noise Analysis

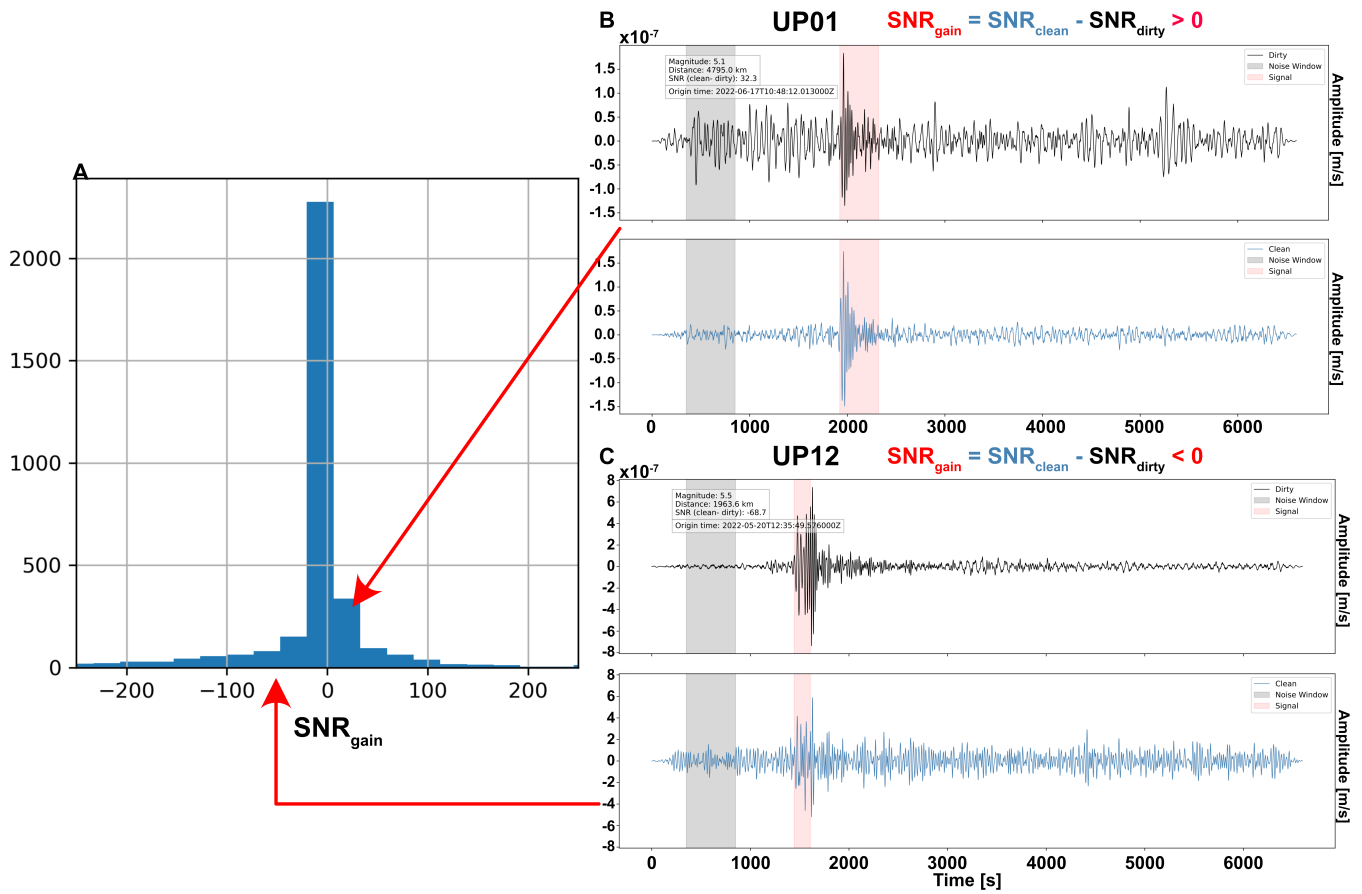


Figure S 27 A) Distribution of the Signal-to-Noise-Ratio (SNR) gain, which is the difference between the SNR of earthquake waveform signals with and without tilt and compliance corrections. The SNR is calculated by dividing the root-mean-square (RMS) of the Rayleigh wave window by the RMS of the preceding noise window, using exactly the same filtering as in our horizontal orientation analysis. SNR gain has been computed for over 3,700 vertical component recordings of the 149 earthquakes considered in this study (Tables S1-S3). B) Illustrative example of a case of improvement in SNR when using the tilt and compliance corrections (blue waveforms) versus waveforms without corrections (black waveforms). Pink areas correspond to the Rayleigh wave windows, while grey shows the noise windows. The top left key gives information about the earthquake as well as the SNR gain value for this event. The waveforms were recorded by station UP01 (vertical component) and were filtered using the same filtering parameters as in the surface wave analysis in Section 4.1 of the main manuscript. C) Same as in B) but for different earthquake waveforms recorded by UP12 (vertical component), whose SNR decreases when correcting them for tilt and compliance.

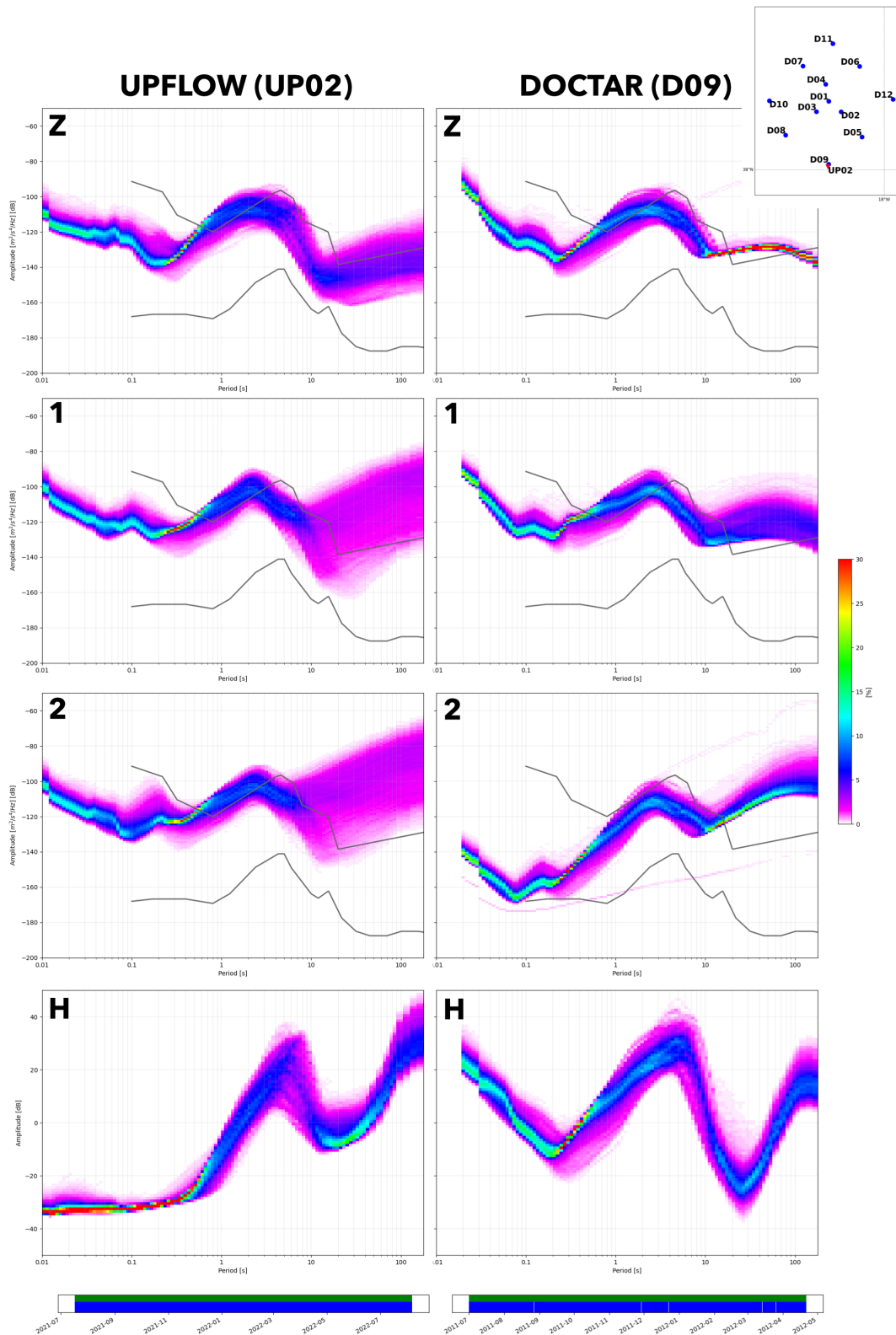
Section S 10 DOCTAR comparison

Figure S 28 Comparison between PPSDs for UP02 (left) and for DOCTAR station D09 (right), which was deployed as part of the DOCTAR experiment in the Atlantic from June 2011 until April 2012 (e.g., (Hannemann et al., 2017)). UP02 is the closest station to D09 (see the insert map in the upper right corner). The horizontal component PPSDs (1, 2) are overall similar for UP02 and D09, except for a marked decrease in the high-frequency noise of D09 in component 2. On the other hand, the vertical component (Z) of UP02 shows slightly decreased noise for $T > 10$ s. The hydrophone (H) PPSDs show lower high-frequency and higher low-frequency noise levels for UP02 than D09.

Section S 11 Station quality Distribution

To provide an overview of daily data availability and quality, we generated a station-day-component table following a similar concept to the supplementary material of Eilon et al. (2021). For each day of the deployment, we computed the power spectral density (PSD) for all channels and derived a root-mean-square (RMS) value summarising the total spectral energy. We then calculated the logarithm (base 10) of the ratio between each day's RMS and the average RMS over the full deployment for that station and component. This metric, $\log_{10}(RMS_{day}/RMS_{avg})$, provides a simple normalised measure of daily spectral behaviour. To flag potentially anomalous days, we applied a statistical threshold based on the distribution of this metric: days falling outside ± 3 standard deviations were marked as outliers. This approach allows us to systematically identify unusual spectral behaviour without relying on external noise models. The resulting table, provided in CSV format in the supplementary material (e.g. UPFLOW_Z_data_quality.csv), is intended as a guide for data users, who may apply their own quality criteria depending on the scientific application. The resulting CSV files are split by component (Z, 1, 2, H), with each column corresponding to one station and each row representing a calendar day during the deployment. Each entry can take one of three values: 1 (RMS within $\pm 3\sigma$ range), 0 (RMS outside $\pm 3\sigma$, indicating potentially poor data), or -1 (data missing). A visualisation of the CSV file structure is provided in Fig. S29, and Fig. S30 shows the overall distribution of data quality flags across all station-days in the UPFLOW dataset for the vertical component. While this metric provides a consistent, data-driven summary of spectral behaviour, it should not be used in isolation. For example, station UP10 appears to show generally “good” data quality in the CSV summary (Fig. S29), yet closer inspection of the corresponding PPSD (Fig. S22) and SOH records reveals that the data are unusable. This highlights that the RMS-based classification can miss certain issues and should therefore be used in combination with the other quality assessment tools described in this study.

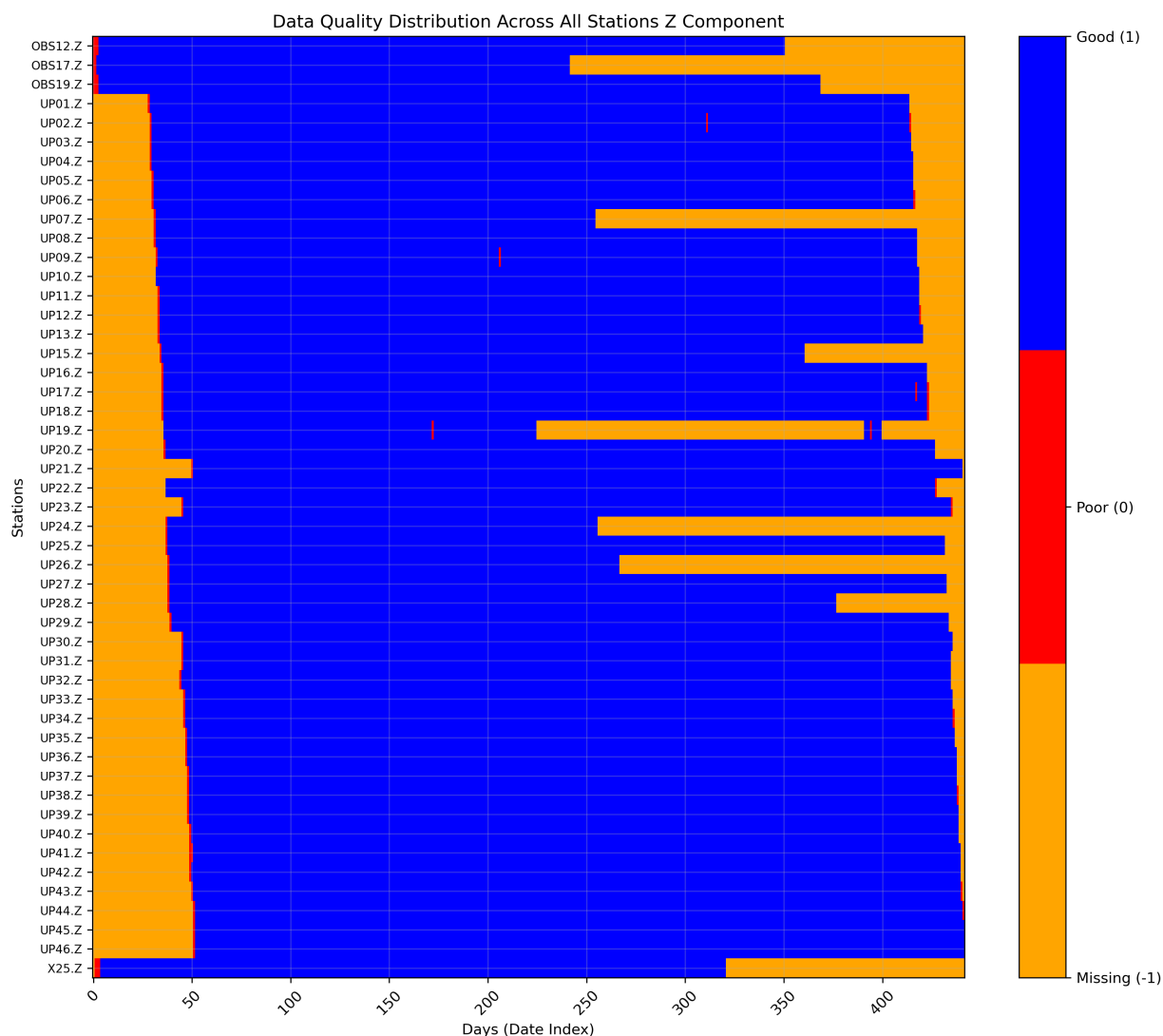


Figure S 29 Example of daily data quality assessment across the UPFLOW seismic network for vertical component data. The heatmap displays daily quality flags for each station over the deployment period, where blue indicates good quality data (within $\pm 3\sigma$ of station mean), red represents poor quality data (outside $\pm 3\sigma$), and orange shows missing data. Each row represents a different station, and each column represents a day. The quality classification is based on daily RMS amplitude deviations from each station's $\log_{10}$ -transformed mean, providing a comprehensive view of network performance and data availability throughout the experiment. Numbers in the colourbar correspond to numbers in the CSV file.

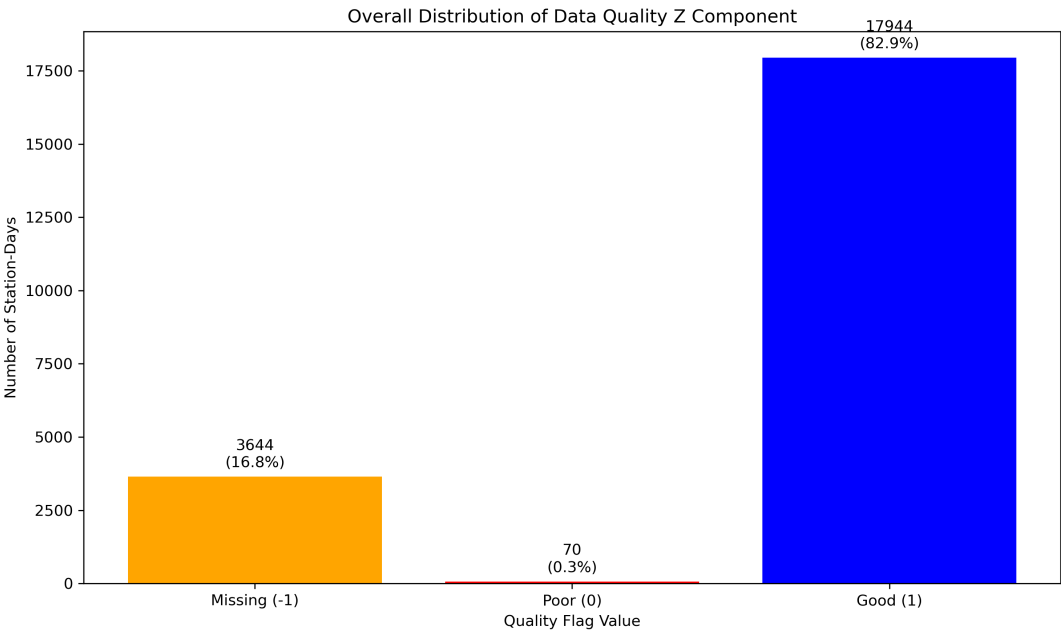


Figure S 30 Overall distribution of data quality flags across all station-days in the UPFLOW dataset for the vertical component. The bar chart shows the total count and percentage of good quality (blue), poor quality (orange), and missing (red) data across the entire network. Numbers above each bar indicate absolute counts and percentages of the total dataset.

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