ASSESSMENT OF EARTHQUAKE DEPTH INDICATORS FROM HYDROACOUSTIC ANALYSIS OF T-PHASES

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INTRODUCTION AND MAIN RESULTS

In this study we show that spectral and arrival time properties of earthquake – generated T-phases can be used as depth indicators (DIs) of crustal vs. subcrustal events. The DIs are sensitive to hypocenter depth variations for a set of earthquakes occurred in Sumatra and Japan at depths up to 600 km.

In addition to confirmation of the T-phase spectral property and arrival time depth dependence, we discuss observations and characteristics of unexpected, unblocked T-phases from very deep earthquakes in and around the Sea of Japan. Our study suggests consideration of these events for the T-phase propagation mapping.

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SUMMARY

Depth assessment is one of the most difficult, however, most effective event screening methods and is usually achieved using seismic sensors.

Analysis of waveforms recorded at hydrophone arrays (HA01W, HA04, HA08 and HA11) from a small set of high Signal to Noise Ratio (SNR) events occurred between 2008 and 2024 at depths up to 600 km, located in Central Sumatra and near Honshu, Japan, indicates promising depth dependency of T-phase signal properties.

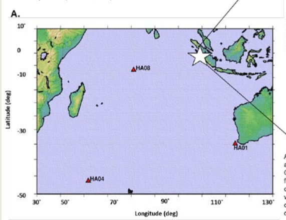
Beginning with results from decades of observations of *T*-phase spectrograms (*Okal and Talandier*, 1997), we designed and tested (Tibuleac et al., 2024) a set of T-phase depth-indicators (DI) in both the time and spectral domains. The most effective indicators are:

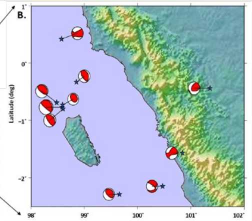
- **RT**, the rise time ,
- **DU**, the signal duration,
- **SV**, the spectral content and its variation with time,
- **BAZRES**, the signal's back azimuth residual and variation in time and
- **TTRES**, the travel time residual.

Observations of unblocked T-phases from events occurred on the opposite side of the Japanese Archipelago from HA11 hydrophone array appear to confirm the Okal, 2001 hypothesis of P/S phase propagation through a mechanically continuous slab followed by coupling at the slab-ocean intersection east of Japan. Our study suggests consideration of these events for the T-phase propagation mapping.

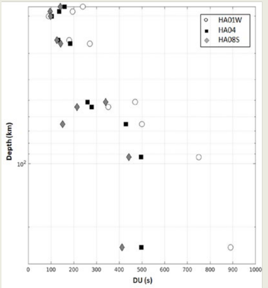
DEPTH INDICATORS: Sumatra

Here we use hydrophone arrays from the International Monitoring System (IMS), which include one or two triads of sensors deployed within the SOFAR channel (Okal, 2001). The IMS arrays were deployed by the Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO) to monitor the world for nuclear explosions (Gibbons, 2022).

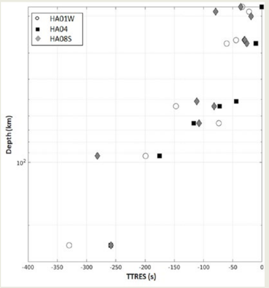




An initial investigation used analyzed waveforms with relatively high SNR recorded at hydrophone arrays from a small set of events with similar mechanisms located in Central Sumatra (except for the mechanisms of events deeper than 60 km) and found promising depth dependency of various T-phase signal properties. To avoid complexity in the DI that might be caused by mechanism or earthquake magnitude we used only large earthquakes within one magnitude unit (5.0 ≤ mb ≤ 5.8) that occurred in 2023 – 2024. with similar mechanism, as possible, located within one degree distance.

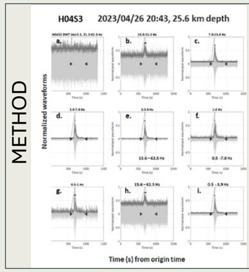


T-phase duration (DU) estimated by an analyst is shown as a function of depth at three hydroacoustic arrays: HA01W (open circles), HA04 (black squares), and HA08S (gray diamonds). The values shown in this figure are the median values estimated for each event at each hydrophone array.



The T-phase **TTRES** shown as a function of depth. Each data point in this figure is the median value of the T-phase residuals at all the available elements of each station. The absolute values of the T-phase travel time residuals increase as a function of depth, i.e the *T-phases* arrive earlier than estimated at all stations. Only one outlier is observed, from the 2024/06/05 11:16:14 earthquake with a depth of 65 km.

METHOD



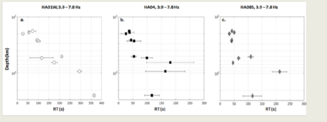
An example of T-phase Discrete Wavelet Transform filtering, using a 'bior3.3' wavelet for the shallow 2023/04/26 20:43 25.6 km depth Sumatra earthquake recorded at the HA04N3. Seven filters based on DWT Details (2-8) are shown in panels a-g and two waveform reconstructions from Details 2 and 3 and from Details 6,7 and 8 are shown in panels h and respectively i. The equivalent frequency bands of each filter are shown above each panel. The DWT filtered waveforms (gray) are normalized to the maximum value. The dark gray waveform envelopes were estimated in each panel as the absolute value of the waveform Hilbert transform. The open triangles show the analyst-picked start and end T-phase times. The maximum value of the amplitude is marked by a ramp starting at the time when the signal exceeds one standard deviation of the noise. The slope of the ramp equal to 1/RT is sometimes used instead of RT (for instance by Yun and Lee, 2022), however using RT was preferred in this study. In all panels the thick black horizontal lines are estimates of the T-phase envelope width.

The start and end time lags of the T-phase were picked by an analyst guided by the WT weight values (Eq. 1). The picks were validated by an analyst by comparison to the spectral representation of the T-phase energy. The WT was calculated as a product of weights attributed to the middle time lag of a six second moving window with a step of three seconds, as follows:

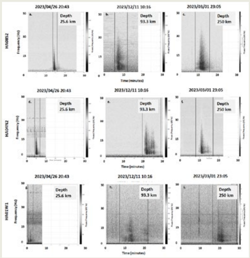
WT=WB*WF*WDWT (1)

WB was estimated using Fourier – filtered waveforms, with a Butterworth filter, 4-8 Hz, six poles, zero phase). Assuming the signal moves as a plane wave across each triad filtered waveforms were beamed after being time-delayed using a grid of possible horizontal velocity and back azimuth values. The maximum value of the chosen, highest energy beam was named MAXENB. In each six second moving window with three second overlap the values of horizontal velocity (TVEL) and back azimuth (TBAZ) corresponding to MAXENB were attributed to the center time lag as in the panels a of Figures A-C. Consistent TVEL between 1.4 and 1.7 km/s and estimated TBAZ within 20 deg of the USGS-estimated earthquake back azimuth were indicators of T-phases. To avoid including reflections from bathymetry scatterers in the T-phases the time gaps in acceptable TBAZ and TVEL values attributed to a T-phase do not exceed 45 s.

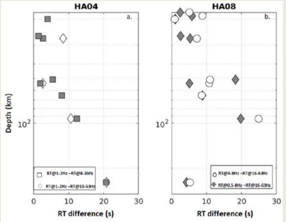
The WB is calculated as the total energy exceeding 90% of MAXENB. WF is the F-statistic value applied to the beam formed using TVEL and TBAZ and is estimated using the Blandford (1974) formula. WDWT is median of the normalized, smoothed (using a two second window) absolute value of the DWT filtered, normalized waveforms.



Example of the RT increase at each station as a function of depth in the frequency band 3.9 to 7.8 Hz. Each data point in this figure is the median value of the T-phase RT at all the available elements of HA01W (a), HA04 (b), and HA08S (c). The horizontal bars are half of the interquartile range (the difference between 75th and 25th percentile of the RT values) for each value. The interquartile range was estimated with the Matlab function iqr (https://www.mathworks.com/help/matlab/ref/iqr.html, last accessed on July 11 2025)



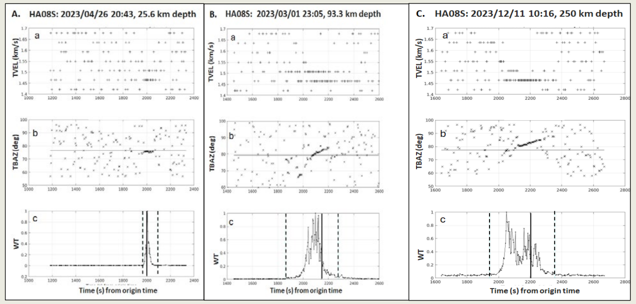
SV: Spectrograms of events at three different depths at each station show clear duration and frequency content differences of shallower and deeper events. The waveforms are decimated to 125 sps. The Matlab® function "spectrogram" was used for calculations, with a Hanning 512 samples window moved with 500 samples overlap. The final analyst-picked start and end times are shown as thin black vertical lines. Note an arrival outside the event window at HA08S2 in Panel a which was identified as another, smaller event from an earthquake series. The spectral representation is useful in identification of noisiest stations, such as HA01W (Panels g,h,i).



Increasing differences were observed between the RT for lower (1 -2 Hz) and higher frequency (16 - 63 Hz) filtered waveforms as a function of depth. Figure 8b shows lower (4-8 Hz or 0.5-8 Hz) and higher frequency (16 - 63 Hz) filtered waveform RT increasing as a function of depth. Note one outlier at HA08, ie the deepest earthquake

The hypocentral location of the events used in this study was estimated by the USA National Earthquake Information Center and obtained via the NSF SAGE facility https://ds.iris.edu/wilber3/find_event (Last accessed in August 2025). The moment tensors of the events was published by the Global Centroid-Moment-Tensor (CMT) Project (Ekstrom et al., 2012, located at https://www.globalcmt.org/ (last accessed on 30 August 2024). Locations are from the NEIC PDE catalog (https://earthquake.usgs.gov/data/comcat/catalog/us/, last accessed on 2025/01/23)

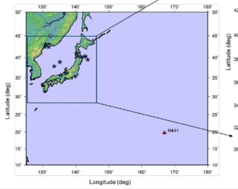
Nr	Origin time	Epicenter location	Event depth (km)	Magnitude
1	2023/03/01 23:05:23	-1.57 100.84	93.3	5.0 (Mww)
2	2023/04/22 17:09:45	-2.77 98.58	26.7	5.8 (Mww)
3	2023/04/22 23:33:52	-0.80 98.8	18.4	5.2 (Mww)
4	2023/04/26 20:43:02	-0.73 98.56	25.6	5.1 (mb)
5	2023/12/11 10:16:39	-0.44 101.36	250	5.0 (mb)
6	2023/12/16 06:45:06	-0.33 98.81	53.9	5.0 (Mww)
7	2024/01/06 09:51:30	-2.29 99.66	18.7	5.2 (mb)
8	2024/02/05 00:52:22	-2.15 100.47	31.2	5.0 (Mww)
9	2024/02/23 07:46:26	-0.69 98.48	20.0	5.3 (Mww)
10	2024/06/05 11:16:14	0.42 98.57	65	5.1 (Mww)

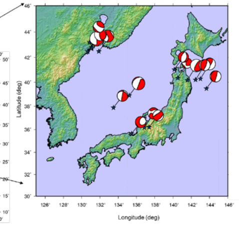


BAZRES A-C: Example of the delay and sum analysis and the total weights used by an analyst to estimate the T-phase duration for three representative earthquakes recorded at HA08S. The values in panels a and b show T-phase horizontal velocity (TVEL) and back azimuth (TBAZ). A horizontal line in panels b shows the expected TBAZ. Panels c show the normalized total weight WT. The vertical continuous black line shows the time lag corresponding to a horizontal velocity of 1.5 km/s. Vertical dotted lines show the analyst picks of the start and end of the T-phase.

DEPTH INDICATORS: Japan

Preliminary analysis of waveforms with relatively high SNR recorded at the HA11 hydrophone array from two sets of events located in or around the Sea of Japan and in Honshu found promising depth dependency of various T-phase signal properties.

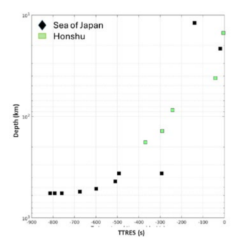




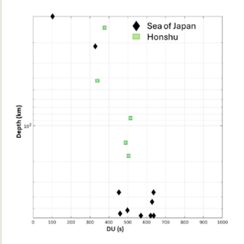
The hypocentral location of the Japan events used in this preliminary analysis. The earthquakes encircled in green occurred near Honshu, Japan. The remaining earthquakes occurred in or near the Sea of Japan.

Nr.	Origin time	Epicenter location** Lat. Lon.	Event depth (km)	Magnitude
1	2008/05/19 10:08:36	42.49 131.88	515.6	5.7 (Mw)
2	*2010/02/18 01:13:18	42.6 130.70	573.7	6.7 (Mw)
3	2010/08/26 15:08:05	36.15 136.83	281	5.4 (Mw)
4	2011/02/26 20:38:06	36.13 137.48	12	5.1 (Mw)
5	2012/03/16 18:37:56	37.83 133.62	438	5.2 (Mw)
6	2013/04/06 00:29:55	42.74 131.05	572	5.8 (Mw)
7	2013/10/29 20:17:50	43.21 131.0	551.2	5.2 (mb)
8	2014/12/05 16:01:56	35.51 135.71	355	5.3 (Mw)
9	2021-09-29 08:37:05	38.89 135.44	364	6.1 (Mw)
10	2023-03-22 07:36:58	40.29 142.95	343	5.6 (Mw)
11	2023-08-01 13:07:20	40.27 140.56	128	4.9 (mb)
12	2023-10-13 09:59:51	41.07 140.14	168	5.0 (Mw)
13	2024-04-01 19:24:36	40.14 141.70	73	5.9 (Mw)
14	2024-07-28 10:13:22	39.52 143.66	10	5.3
15	2024-10-18 04:38:07	40.24 142.28	60	5.2 (Mw)

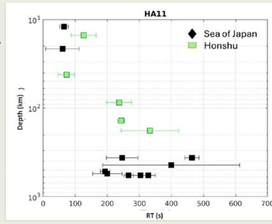
The T-phase **TTRES** shown as a function of depth. Each data point in this figure is the median value of the T-phase residuals at all the available elements of HA11. The absolute values of the T-phase travel time residuals increase as a function of depth, i.e the *T-phases* arrive earlier than estimated at all stations.

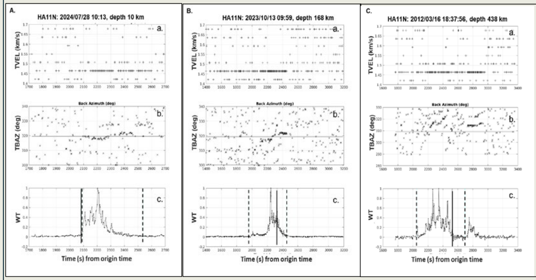


DU: T-phase duration (DU) estimated by an analyst is shown as a function of depth at HA11. The values shown in this figure are the median values estimated for each earthquake.



Example of the RT increase at HA11 as a function of depth in the frequency band 3.9 to 7.8 Hz. Each data point in this figure is the median value of the T-phase RT at all the available elements. The horizontal bars are half of the interquartile range (the difference between 75th and 25th percentile of the RT values) for each value. The interquartile range was estimated with the Matlab function iqr (https://www.mathworks.com/help/matlab/ref/iqr.html, last accessed on July 11 2025)





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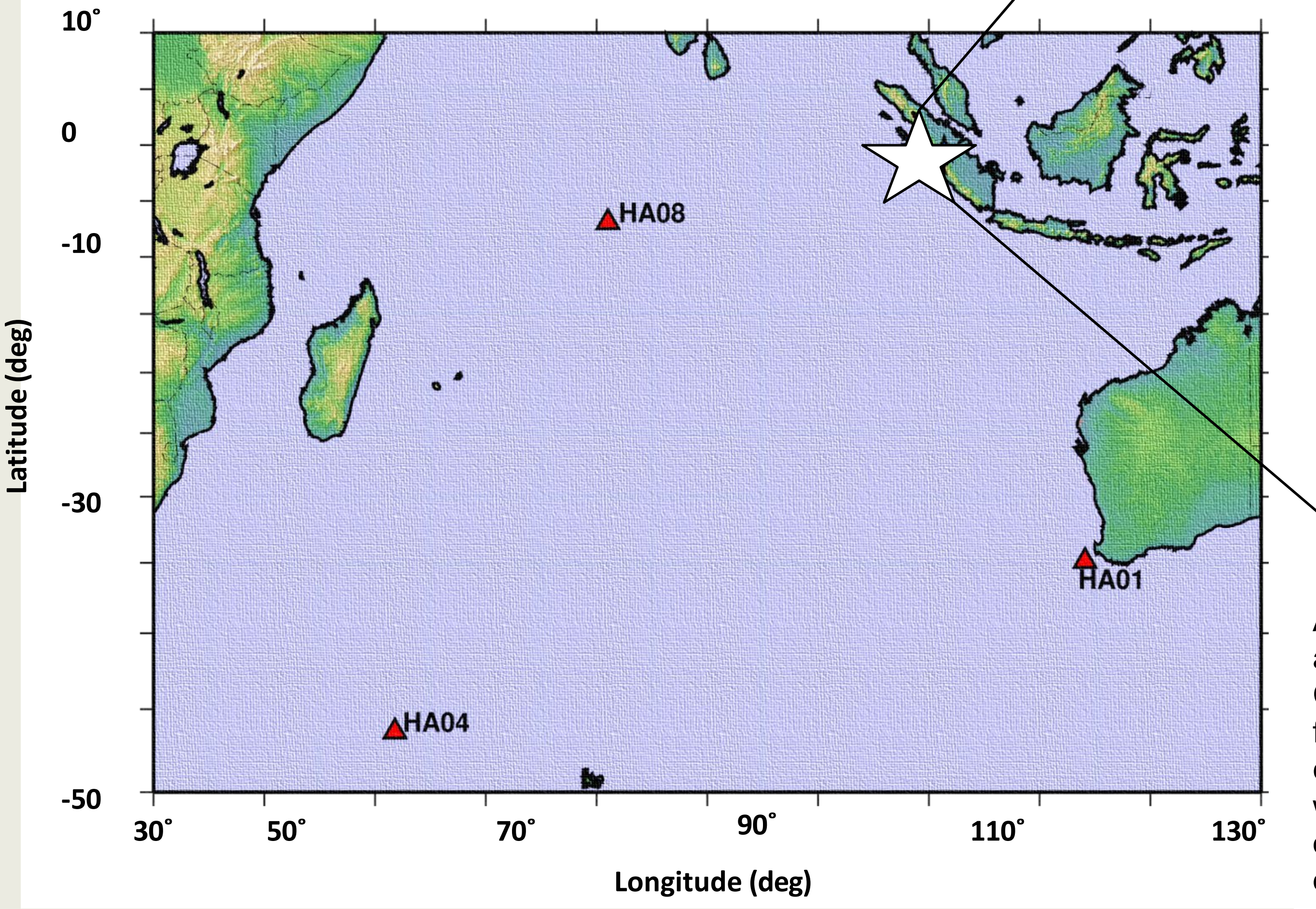
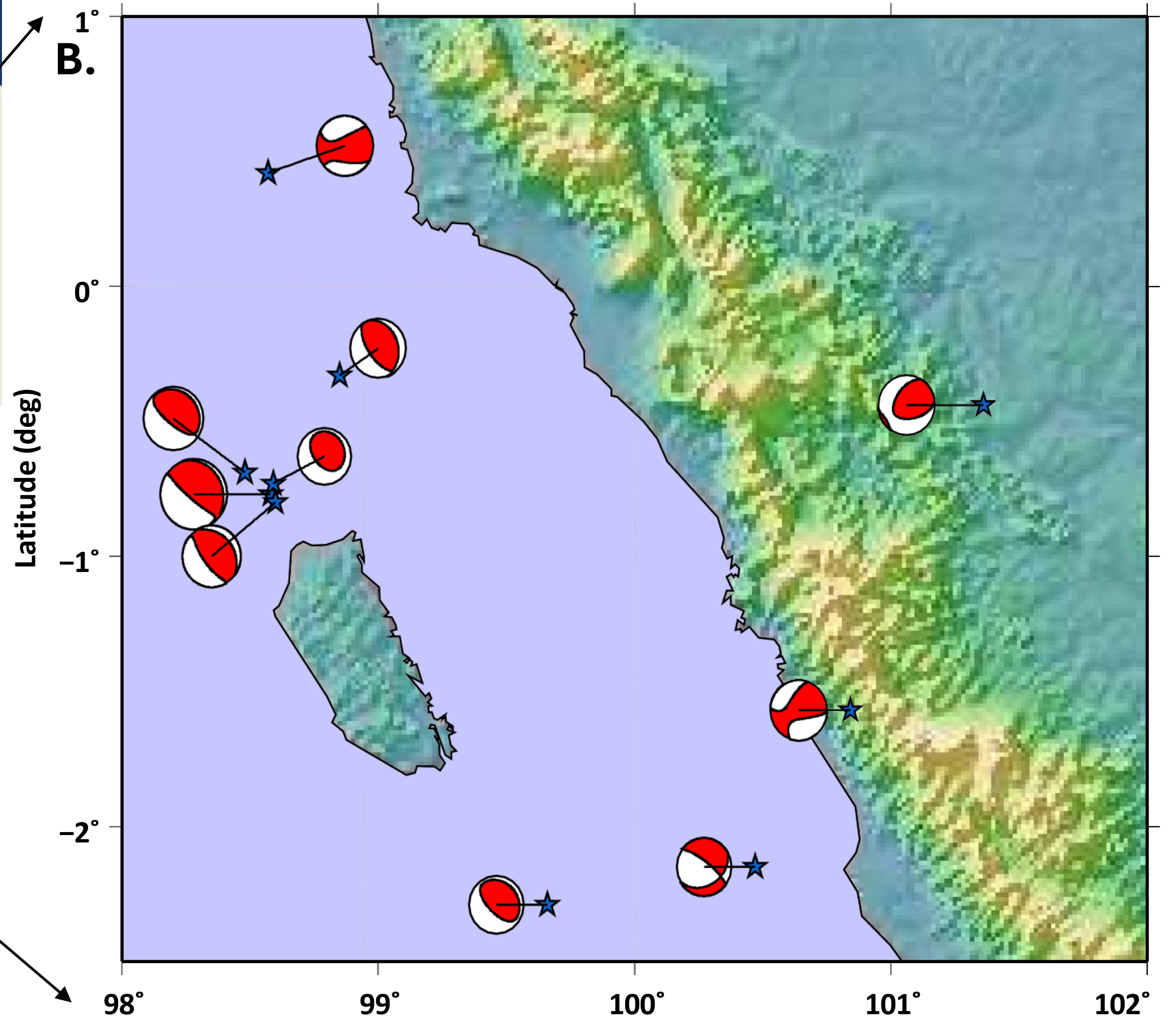
A.



B.



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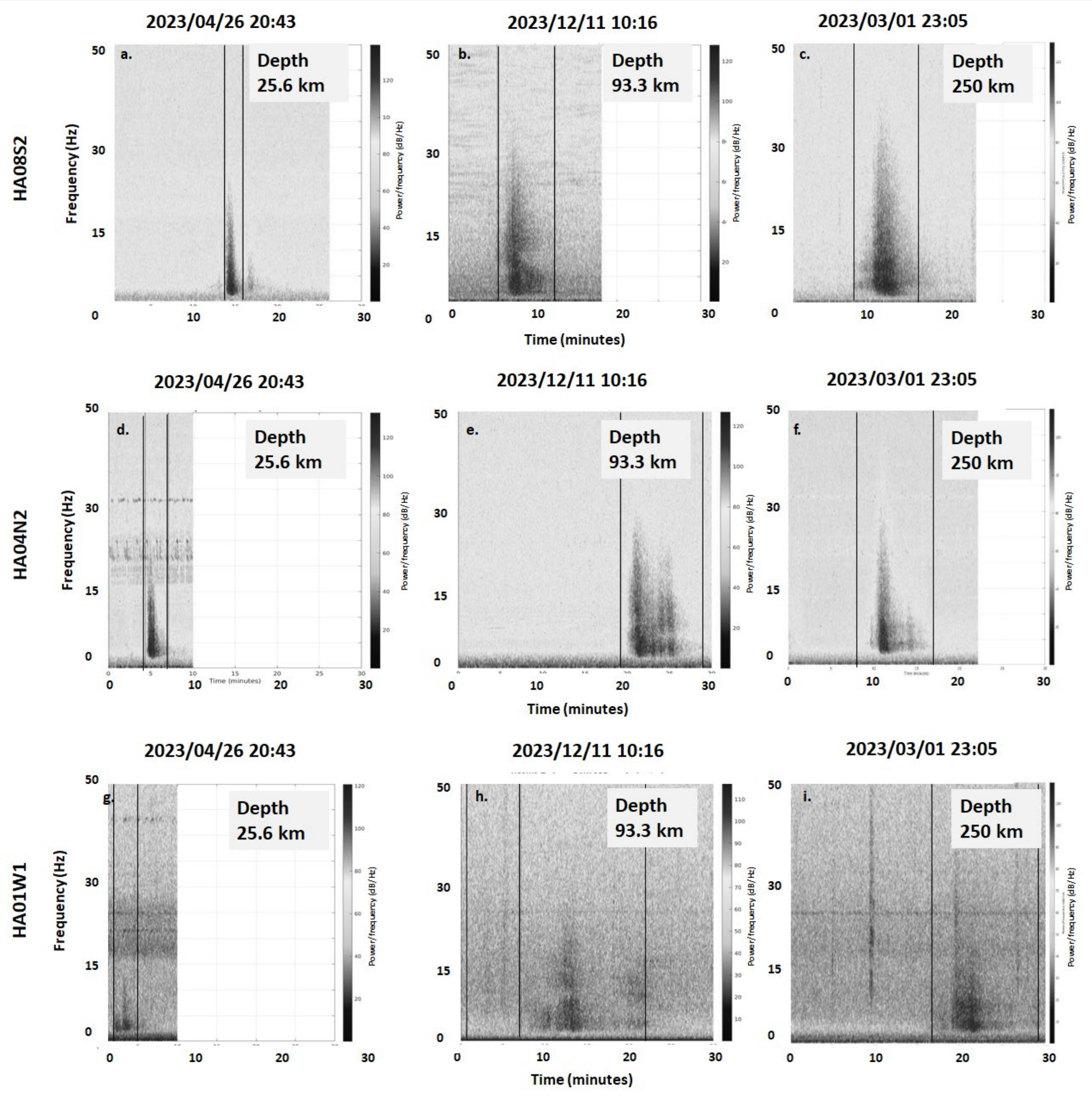

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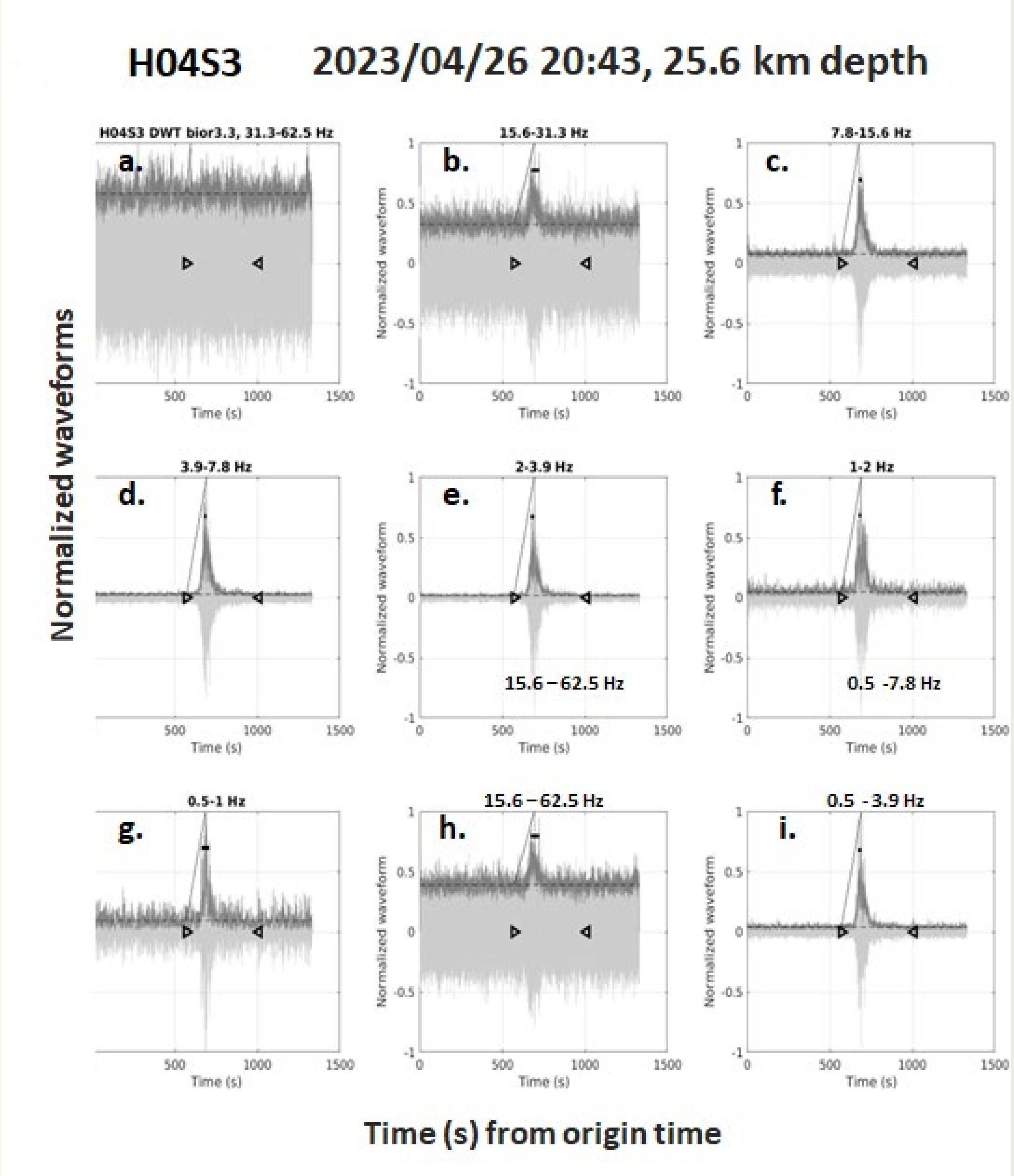


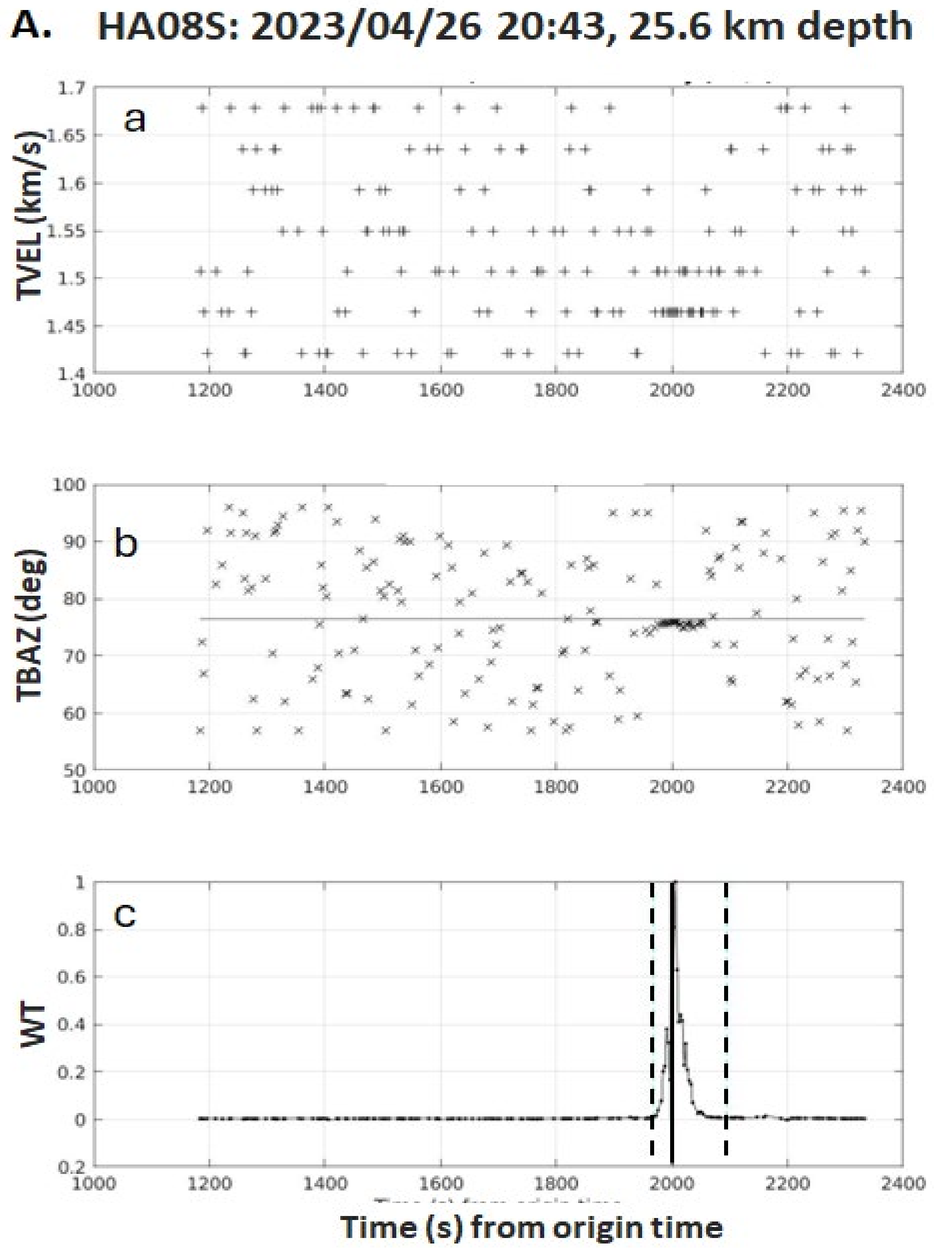
An example of T-phase Discrete Wavelet Transform filtering, using a ‘bior3.3’ wavelet for the shallow 2023/04/26 20:43 25.6 km depth Sumatra earthquake recorded at the HA04N3. Seven filters based on DWT Details (2-8) are shown in panels a-g and two waveform reconstructions from Details 2 and 3 and from Details 6,7 and 8 are shown in panels h and respectively i. The equivalent frequency bands of each filter are shown above each panel. The DWT filtered waveforms (gray) are normalized to the maximum value. The dark gray waveform envelopes were estimated in each panel as the absolute value of the waveform Hilbert transform. The open triangles show the analyst-picked start and end T-phase times. The maximum value of the amplitude is marked by a ramp starting at the time when the signal exceeds one standard deviation of the noise. The slope of the ramp equal to 1/RT is sometimes used instead of RT (for instance by Yun and Lee, 2022), however using RT was preferred in this study. In all panels the thick black horizontal lines are estimates of the T-phase envelope width.

The start and end time lags of the T-phase were picked by an analyst guided by the **WT** weight values (Eq. 1). The picks were validated by an analyst by comparison to the spectral representation of the T-phase energy . The **WT** was calculated as a product of weights attributed to the middle time lag of a six second moving window with a step of three seconds, as follows:

WT=WB*WF*WDWT (1)

WB was estimated using Fourier – filtered waveforms, with a Butterworth filter, 4-8 Hz, six poles, zero phase). Assuming the signal moves as a plane wave across each triad filtered waveforms were beamed after being time-delayed using a grid of possible horizontal velocity and back azimuth values. The maxim value of the chosen, highest energy beam was named MAXENB. In each six second moving window with three second overlap the values of horizontal velocity (**TVEL**) and back azimuth (**TBAZ**) corresponding to MAXENB were attributed to the center time lag as in the panels a of Figures A-C. Consistent **TVEL** between 1.4 and 1.7 km/s and estimated **TBAZ** within 20 deg of the USGS-estimated earthquake back azimuth were indicators of *T-phases*. To avoid including reflections from bathymetry scatterers in the *T-phases* the time gaps in acceptable TBAZ and TVEL values attributed to a T-phase do not exceed 45 s.

The **WB** is calculated as the total energy exceeding 90% of MAXENB. **WF** is the F-statistic value applied to the beam formed using **TVEL** and **TBAZ** and is estimated using the Blandford (1974) formula. **WDWT** is median of the normalized, smoothed (using a two second window) absolute value of the DWT filtered, normalized waveforms.



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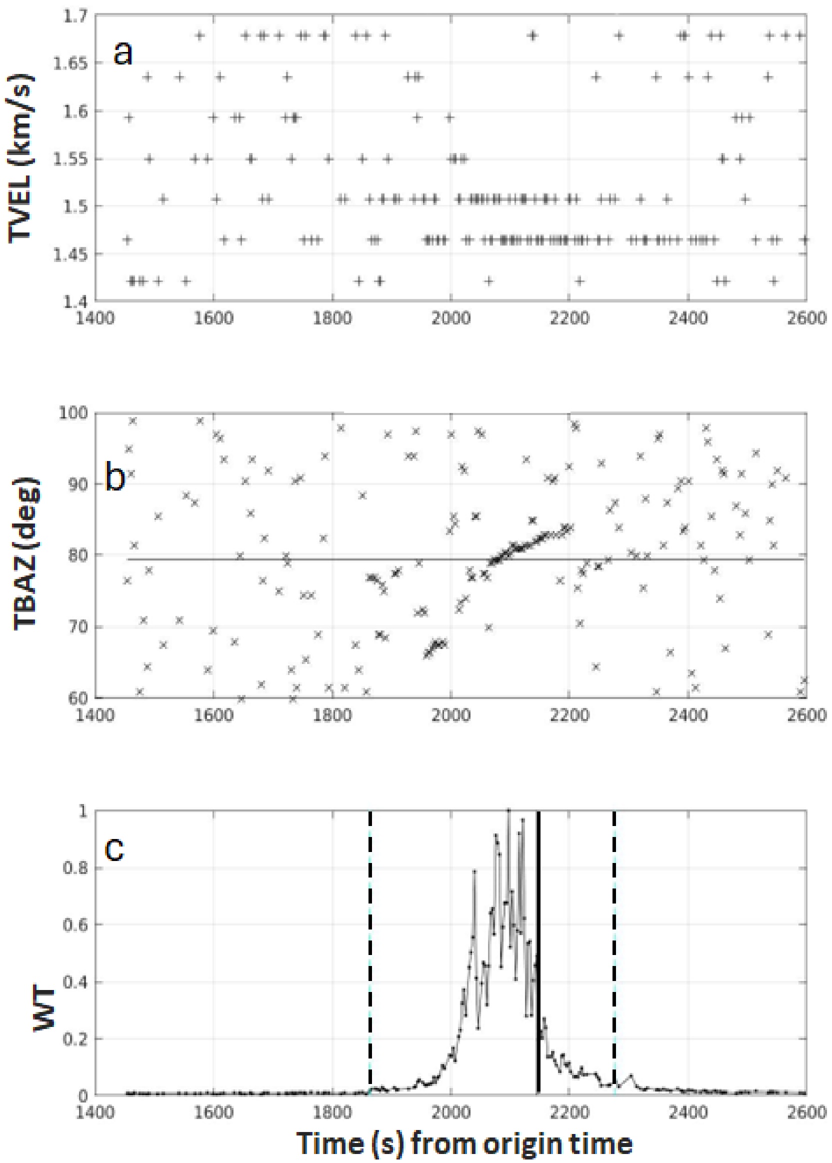
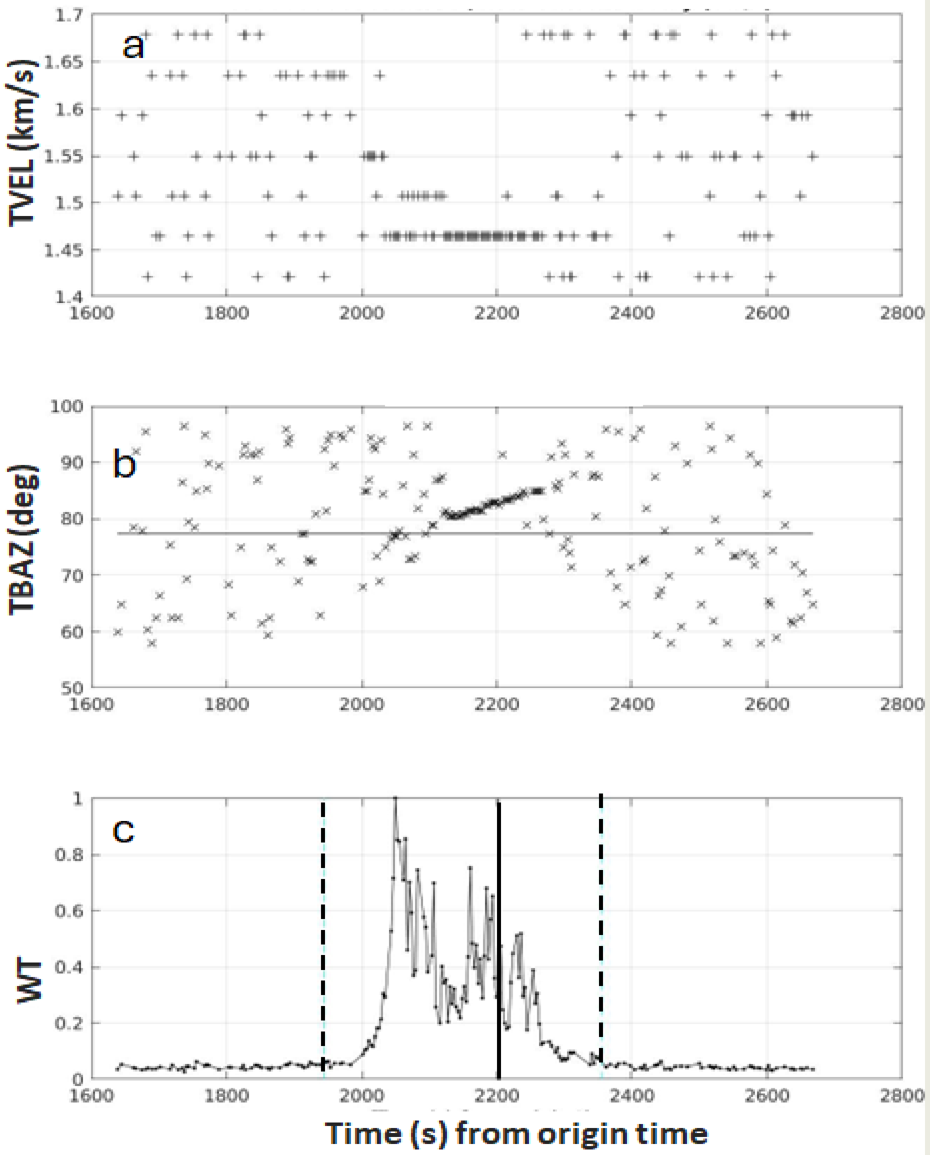
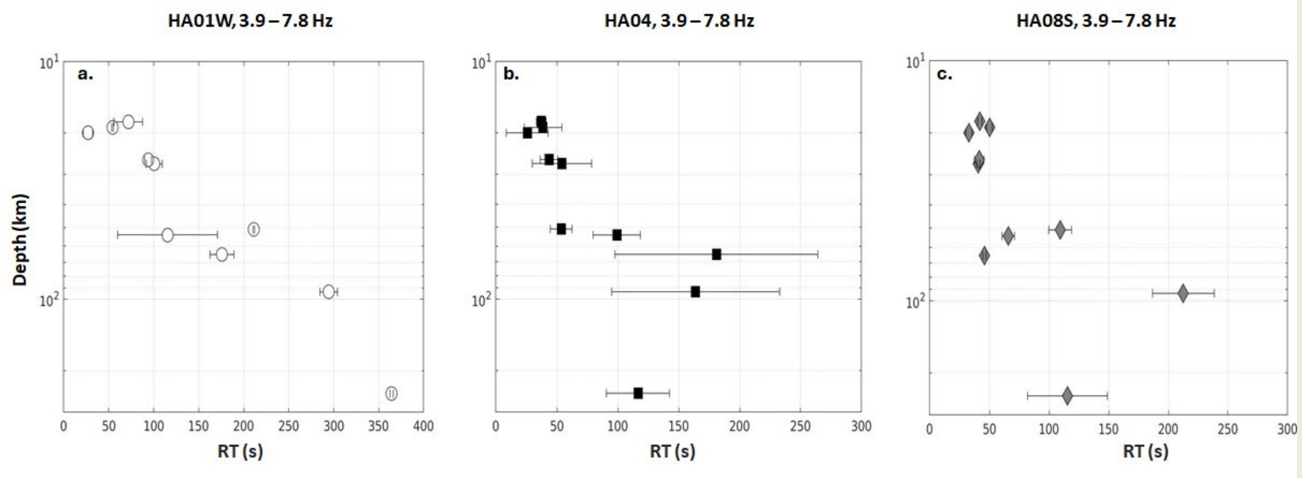
B. HA08S: 2023/03/01 23:05, 93.3 km depth



C. HA08S: 2023/12/11 10:16, 250 km depth





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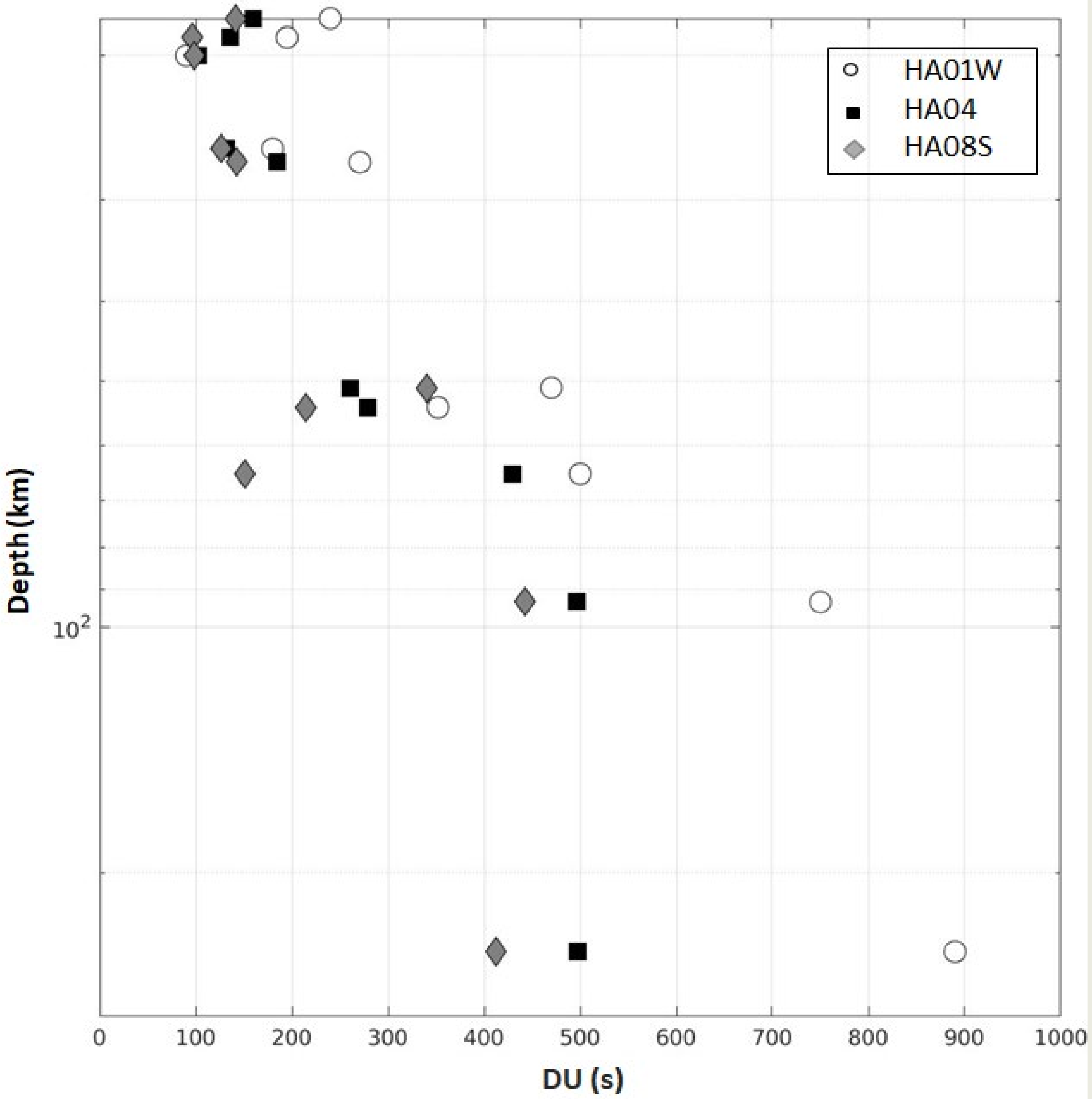
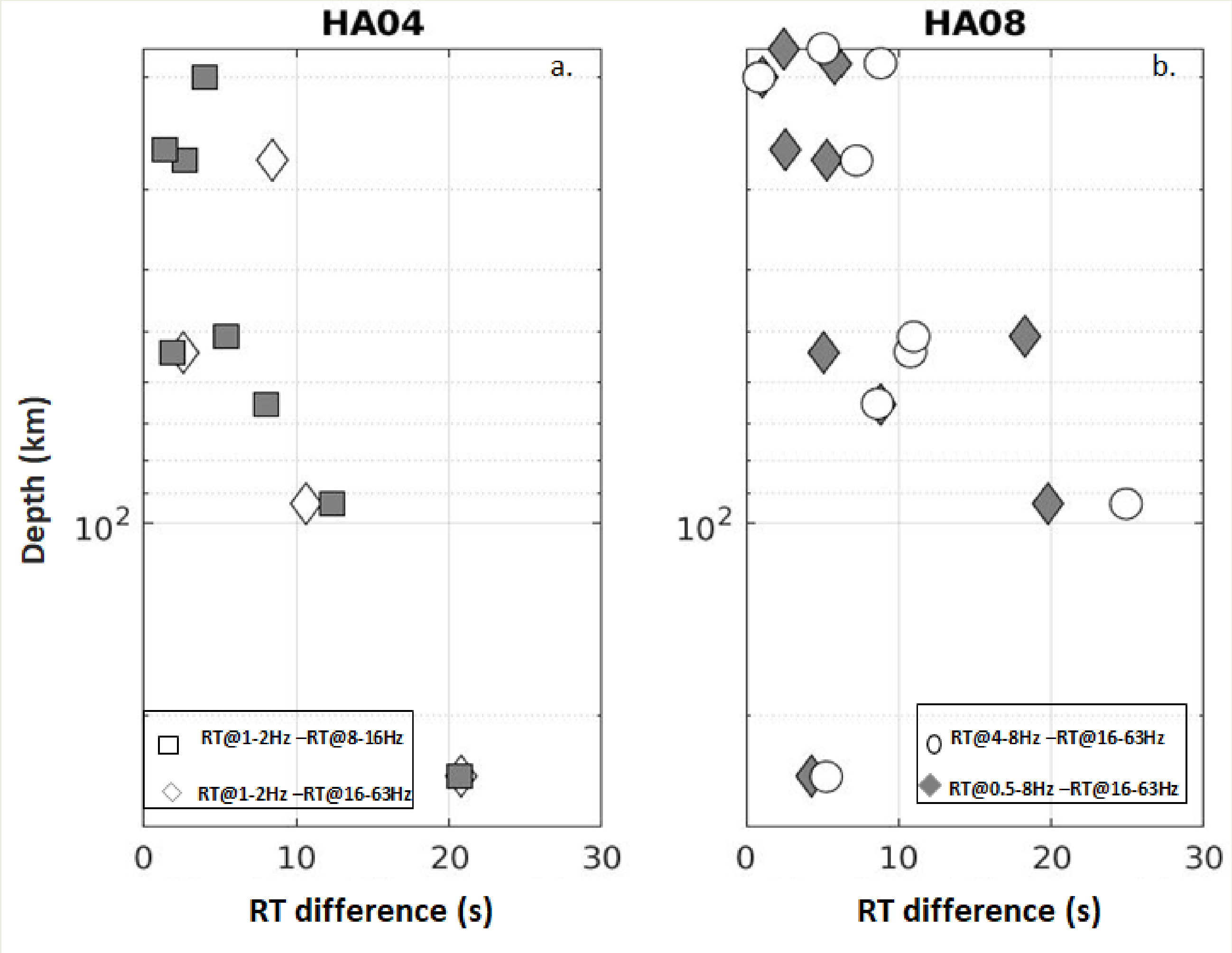
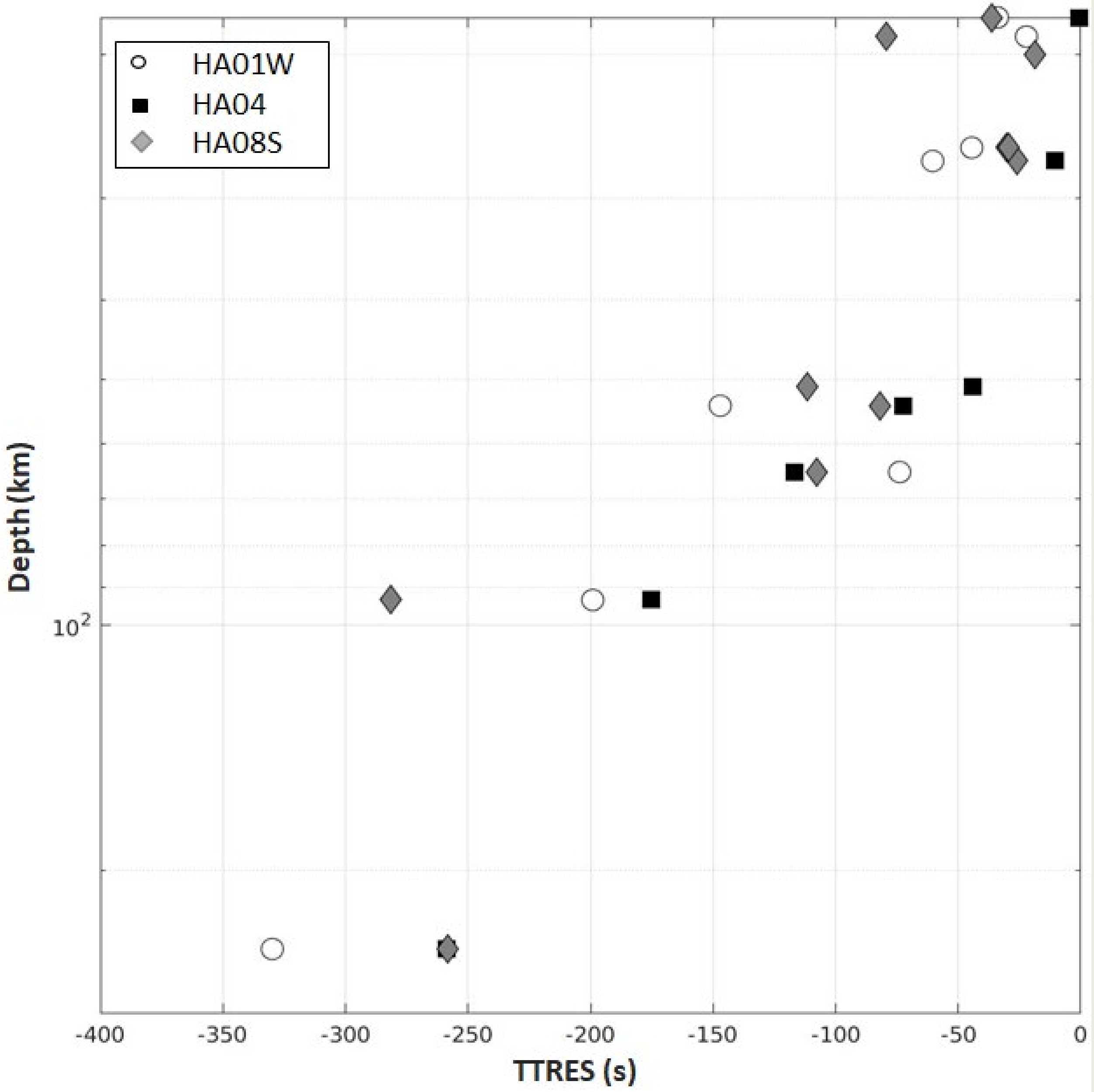


DU: T-phase duration (DU) estimated by an analyst is shown as a function of depth at three hydroacoustic arrays: HA01W (open circles), HA04 (black squares), and HA08S (gray diamonds). The values shown in this figure are the median values estimated for each event at each hydrophone array.



Increasing differences were observed between the RT for lower (1 -2 Hz) and higher frequency (16 - 63 Hz) filtered waveforms as a function of depth. Figure 8b shows lower (4-8 Hz or 0.5-8 Hz) and higher frequency (16 - 63 Hz) filtered waveform RT increasing as a function of depth. Note one outlier at HA08, ie the deepest earthquake

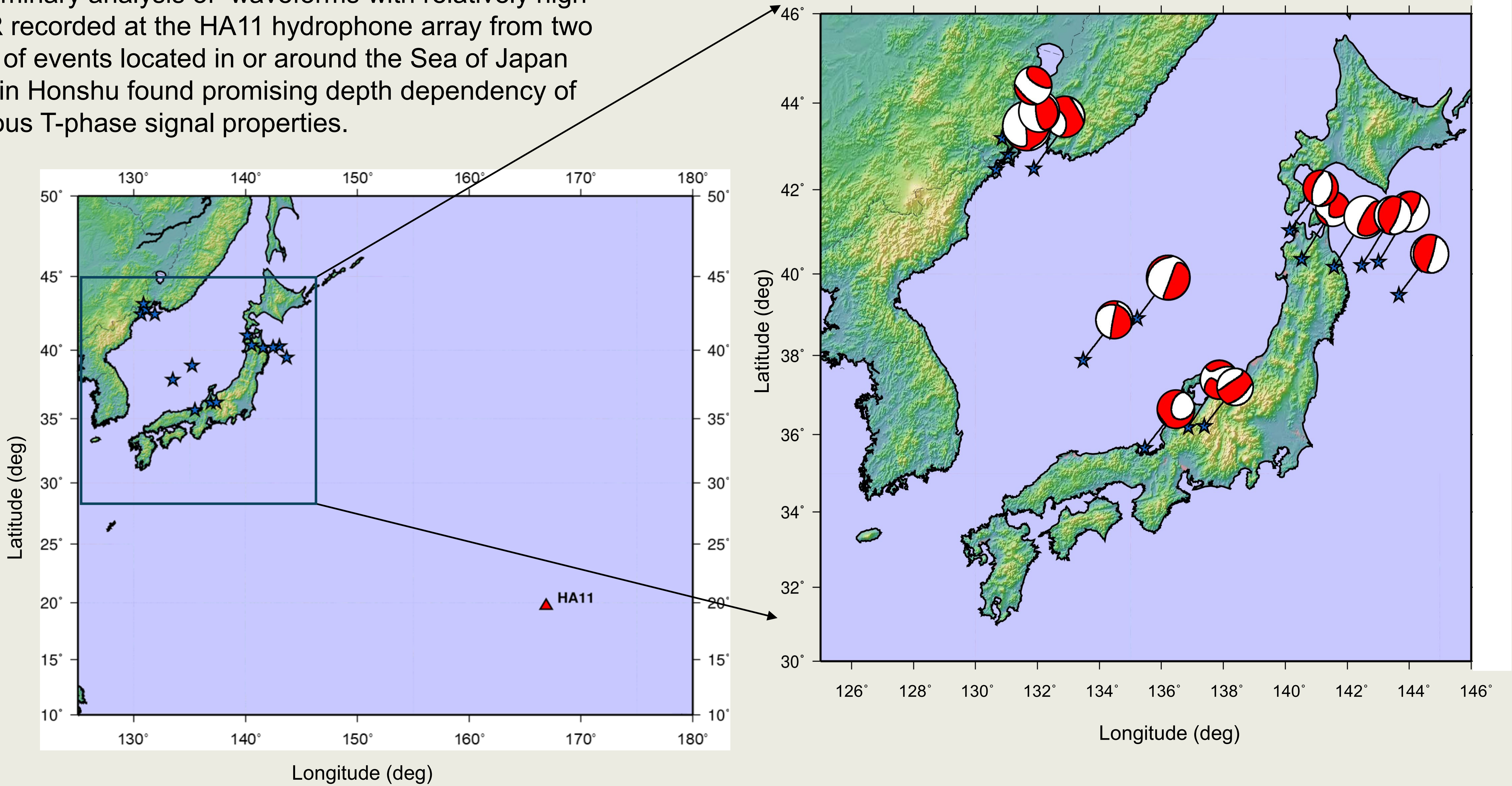


The T-phase **TTRES** shown as a function of depth. Each data point in this figure is the median value of the T-phase residuals at all the available elements of each station. The absolute values of the T-phase travel time residuals increase as a function of depth, i.e the *T-phases* arrive earlier than estimated at all stations. Only one outlier is observed, from the 2024/06/05 11:16:14 earthquake with a depth of 65 km.

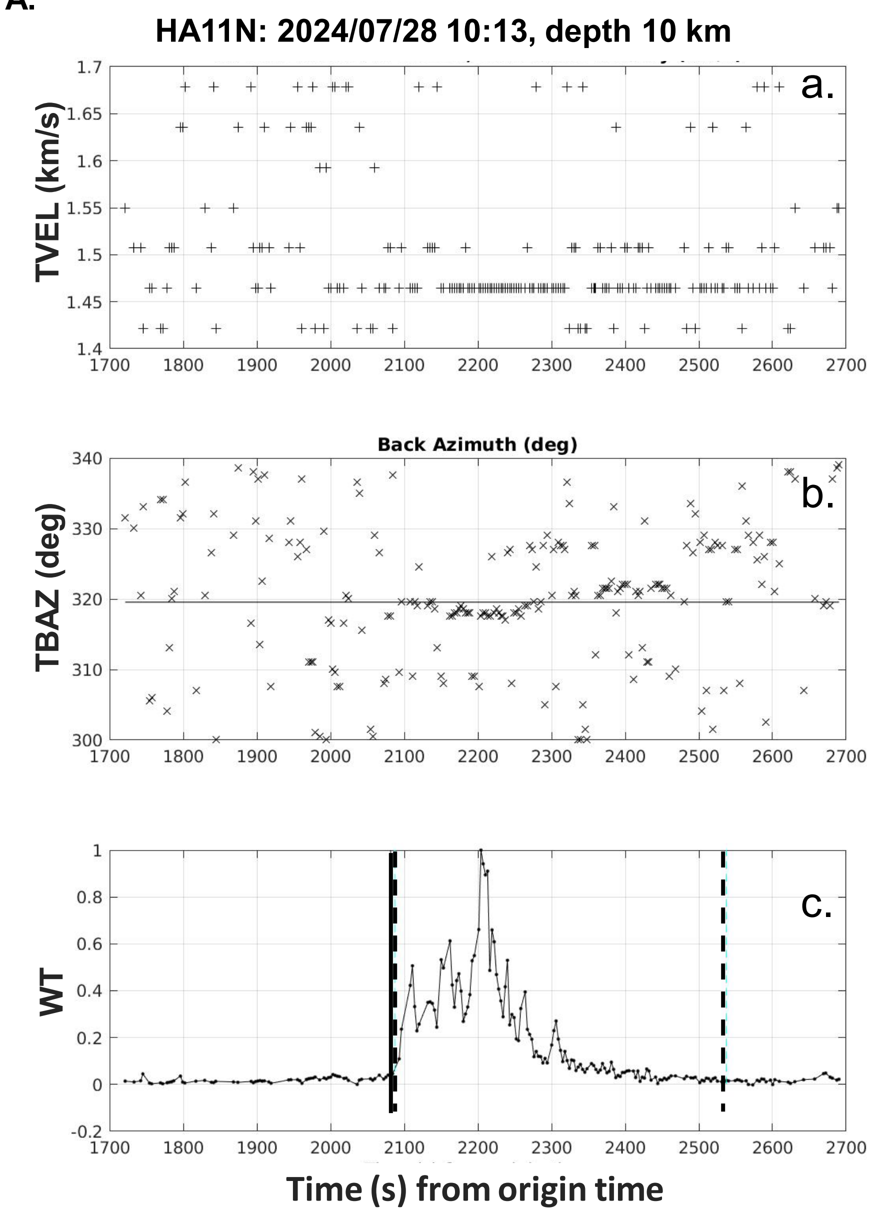
The hypocentral location of the Japan events used in this preliminary analysis.
The earthquakes encircled in green occurred near Honshu, Japan.
The remaining earthquakes occurred in or near the Sea of Japan.

Nr.	Origin time	Epicenter location** Lat. Lon.	Event depth (km)	Magnitude
1	2008/05/19 10:08:36	42.49 131.88	515.6	5.7 (Mw)
2	*2010/02/18 01:13:18	42.6 130.70	573.7	6.7 (Mw)
3	2010/08/26 15:08:05	36.15 136.83	281	5.4 (Mw)
4	2011/02/26 20:38:06	36.13 137.48	12	5.1 (Mw)
5	2012/03/16 18:37:56	37.83 133.62	438	5.2 (Mw)
6	2013/04/06 00:29:55	42.74 131.05	572	5.8 (Mw)
7	2013/10/29 20:17:50	43.21 131.0	551.2	5.2 (mb)
8	2014/12/05 16:01:56	35.51 135.71	355	5.3 (Mw)
9	2021-09-29 08:37:05	38.89 135.44	364	6.1 (Mw)
10	2023-03-22 07:36:58	40.29 142.95	343	5.6 (Mw)
11	2023-08-01 13:07:20	40.27 140.56	128	4.9 (mb)
12	2023-10-13 09:59:51	41.07 140.14	168	5.0 (Mw)
13	2024-04-01 19:24:36	40.14 141.70	73	5.9 (Mw)
14	2024-07-28 10:13:22	39.52 143.66	10	5.3
15	2024-10-18 04:38:07	40.24 142.28	60	5.2 (Mw)

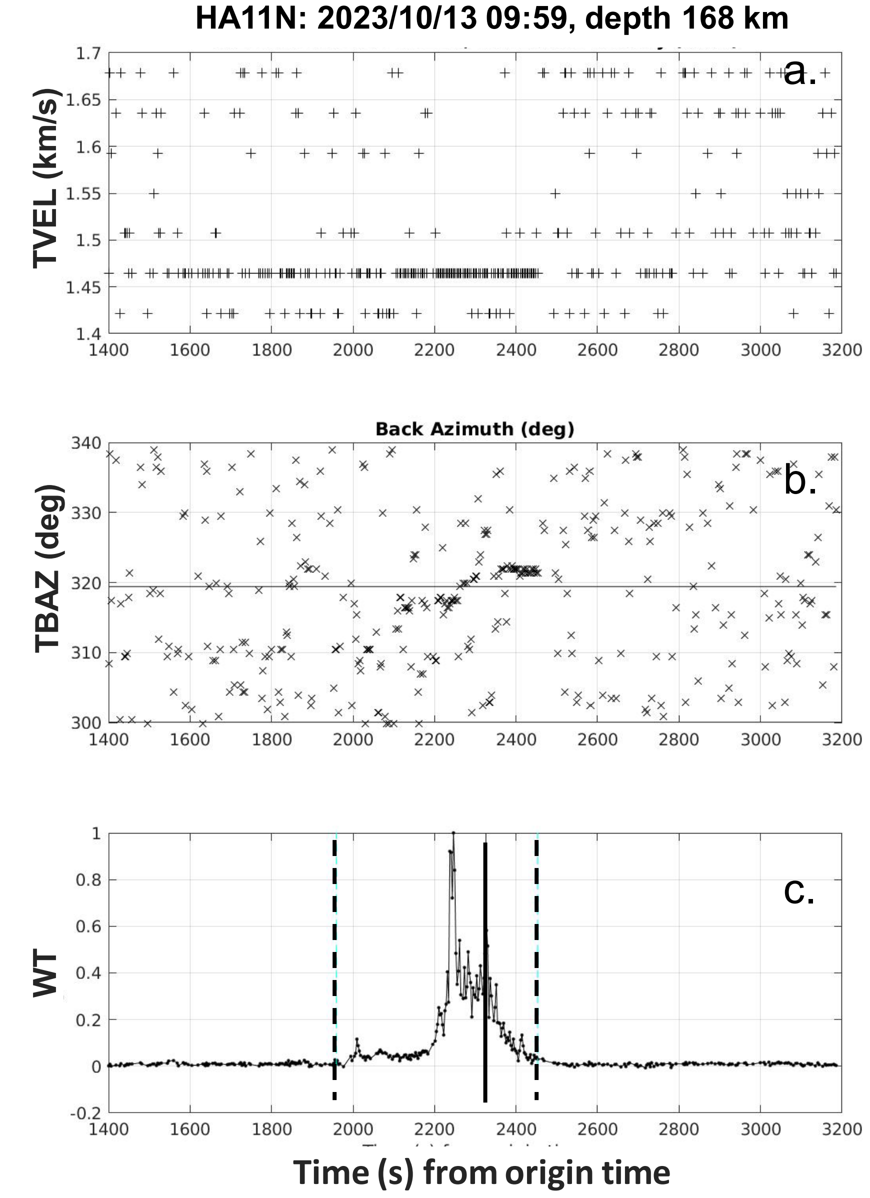
Preliminary analysis of waveforms with relatively high SNR recorded at the HA11 hydrophone array from two sets of events located in or around the Sea of Japan and in Honshu found promising depth dependency of various T-phase signal properties.

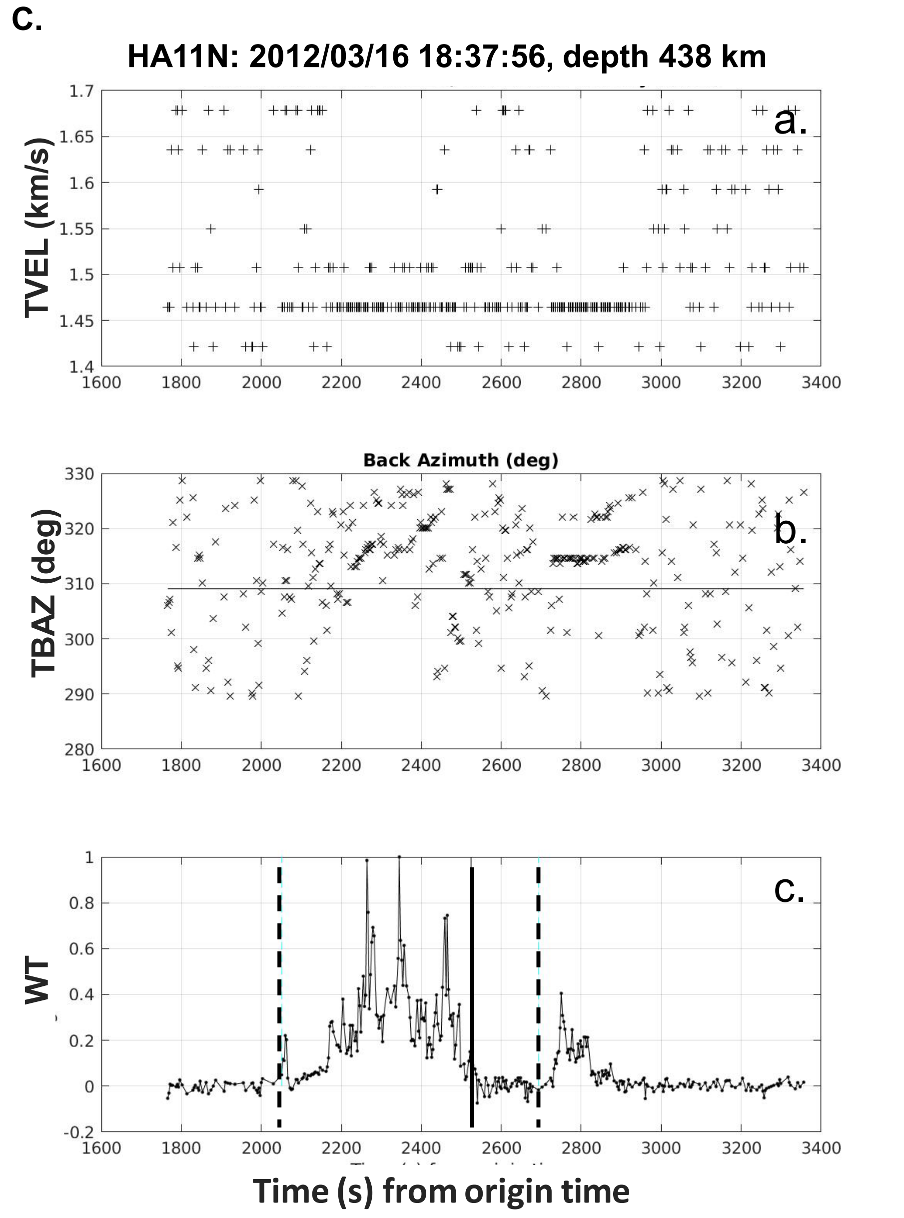


A.


HA11N: 2024/07/28 10:13, depth 10 km
a.
TVEL (km/s)
Back Azimuth (deg)
b.
TBAZ (deg)
c.
WT
Time (s) from origin time

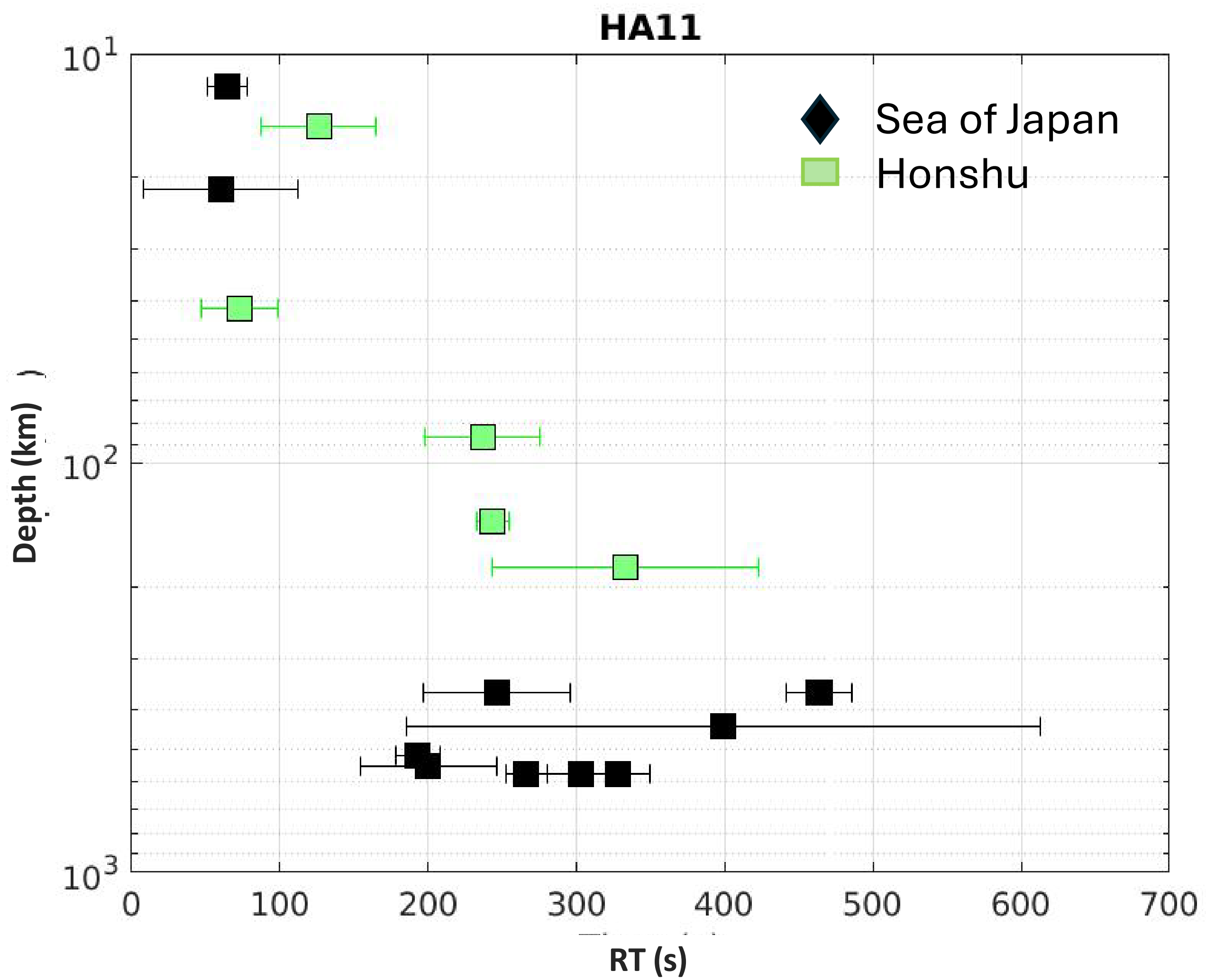
B.


HA11N: 2023/10/13 09:59, depth 168 km
a.
TVEL (km/s)
Back Azimuth (deg)
b.
TBAZ (deg)
c.
WT
Time (s) from origin time

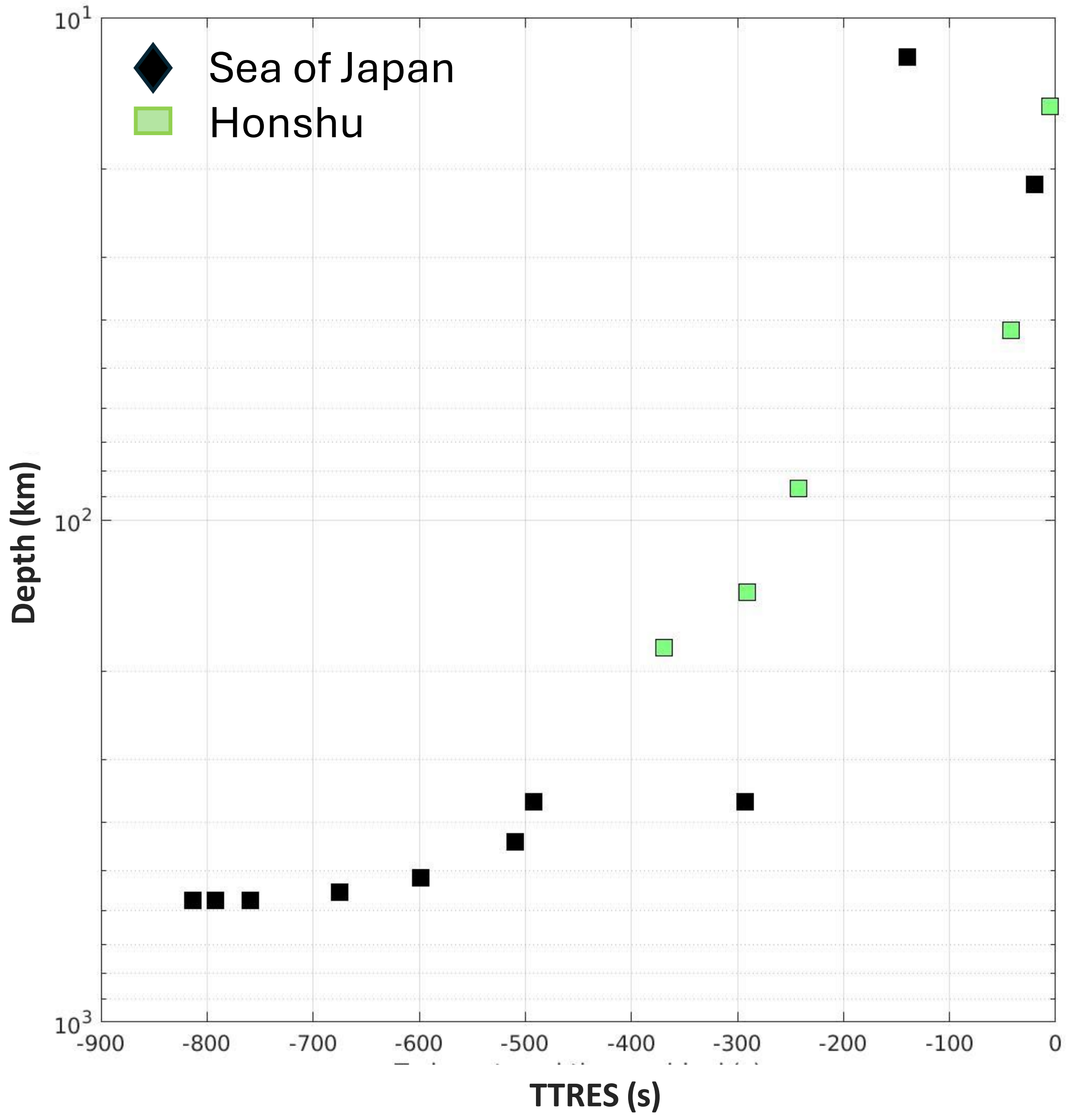


BAZRES A-C: Example of the delay and sum analysis and the total weights used by an analyst to estimate the T-phase duration for three representative earthquakes recorded at HA11N. The values in panels a and b show T-phase horizontal velocity (TVEL) and back azimuth (TBAZ). A horizontal line in panels b shows the expected TBAZ. Panels c show the normalized total weight WT. The vertical continuous black line shows the time lag corresponding to a horizontal velocity of 1.5 km/s. Vertical dotted lines show the analyst picks of the start and end of the T-phase.

Example of the **RT** increase at HA11 as a function of depth in the frequency band 3.9 to 7.8 Hz. Each data point in this figure is the median value of the T-phase RT at all the available elements. The horizontal bars are half of the interquartile range (the difference between 75th and 25th percentile of the RT values) for each value. The interquartile range was estimated with the Matlab function *iqr* (https://www.mathworks.com/help/matlab/ref/iqr.html, last accessed on July 11 2025)



The T-phase **TTRES** shown as a function of depth. Each data point in this figure is the median value of the T-phase residuals at all the available elements of HA11. The absolute values of the T-phase travel time residuals increase as a function of depth, i.e the *T-phases* arrive earlier than estimated at all stations.



DU: T-phase duration (DU) estimated by an analyst is shown as a function of depth at HA11. The values shown in this figure are the median values estimated for each earthquake.