

Supplementary Materials for
Delayed submarine caldera subsidence creates extreme tsunami hazard

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This PDF file includes:

Figs. S1 to S8
Tables S1 and S2

Supplementary Figures

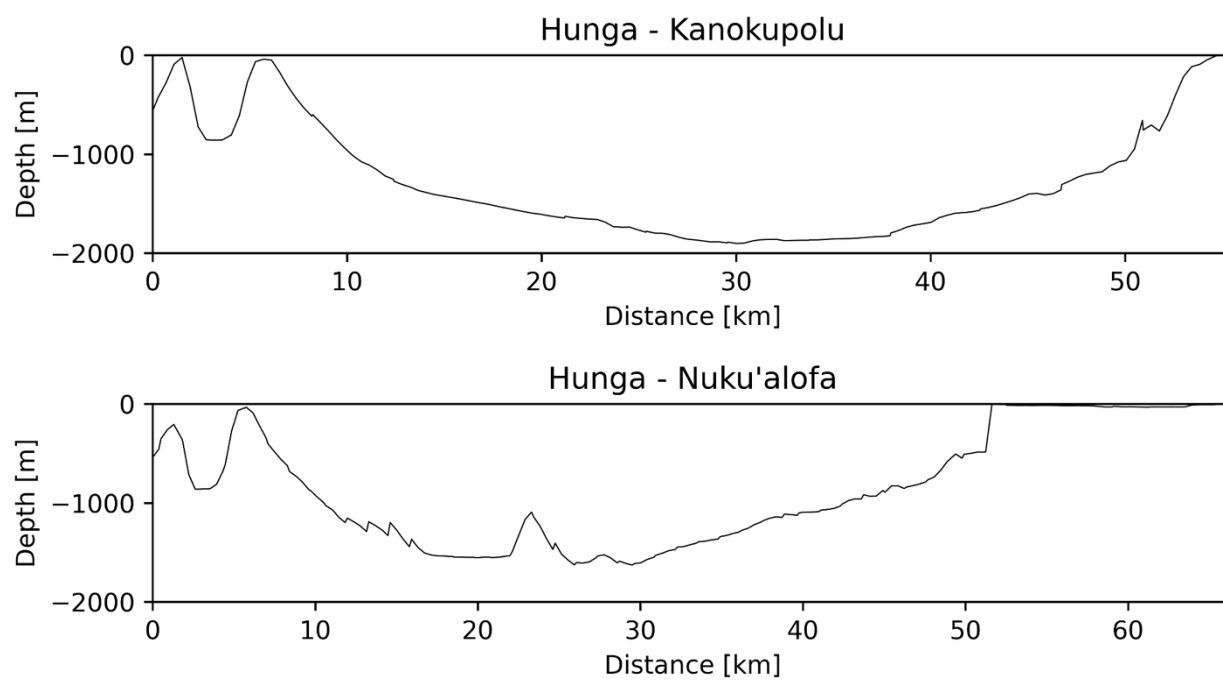


Fig. S1.

Bathymetric profiles from Hunga volcano (post-eruption caldera morphology seen at left of plot) to the Kanokupolu Peninsula (West Tongatapu) and the Nuku'alofa Harbor (Northern Tongatapu, Fig. 1).

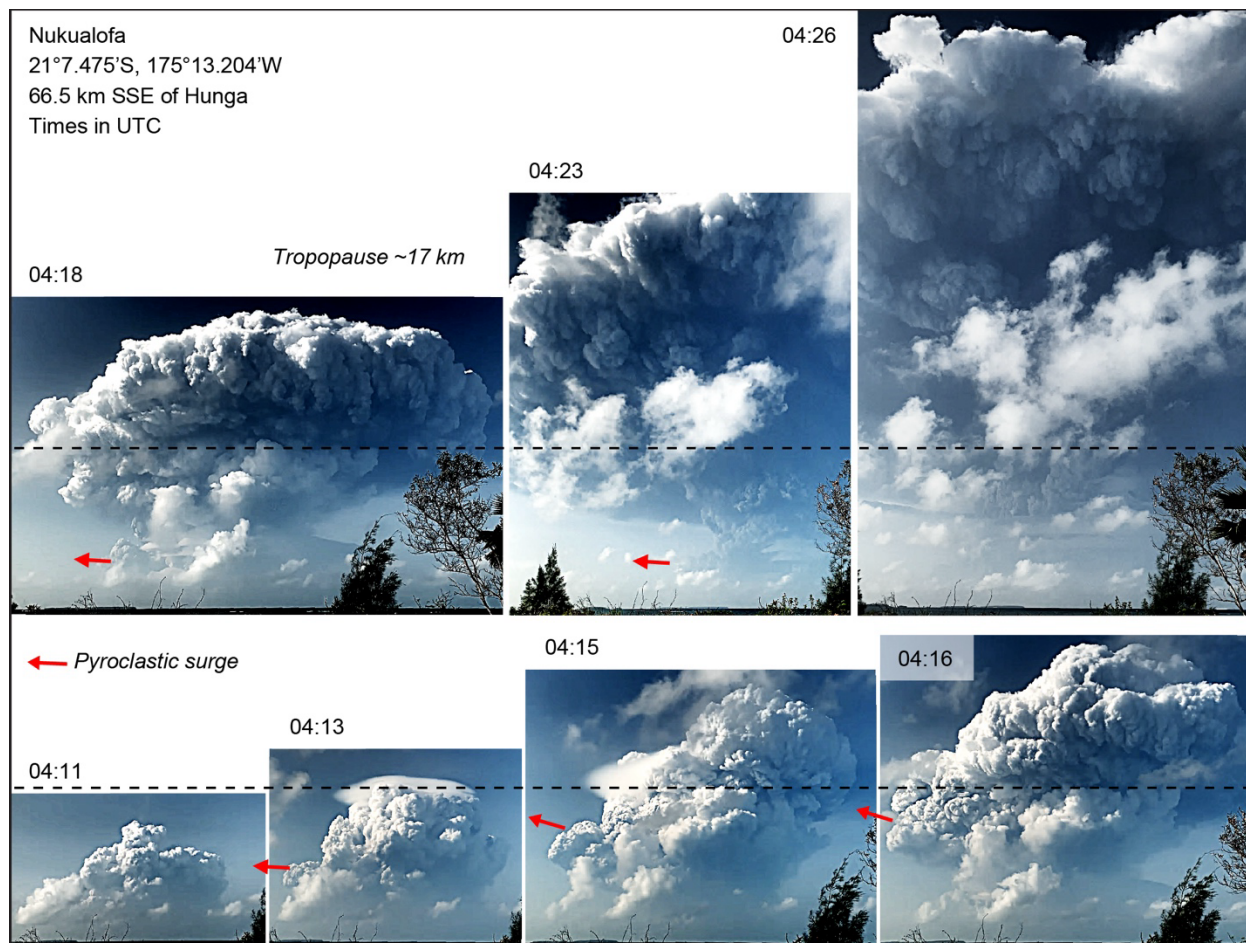


Fig. S2.

Photographs during the main growth phase of the eruption plume on 15 January 2022 taken from the Nuku'alofa waterfront, Tongatapu. The elevation of the tropopause is indicated by the black dashed line (~17 km elevation) and estimated from ice formation height and comparison to Van Eaton et al. (3) The red arrows indicate steam/ash clouds lofting above laterally moving pyroclastic surges over the water surface (pyroclastic density currents), these expanding at least 6 km from the eruption plume center. Original images by Connor Campbell.

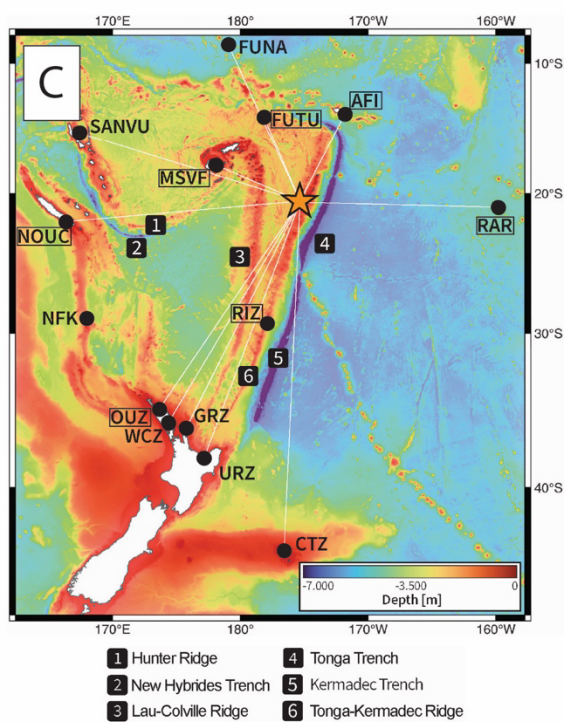
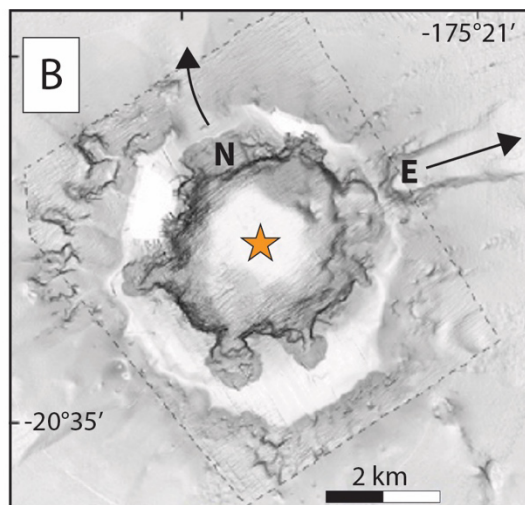
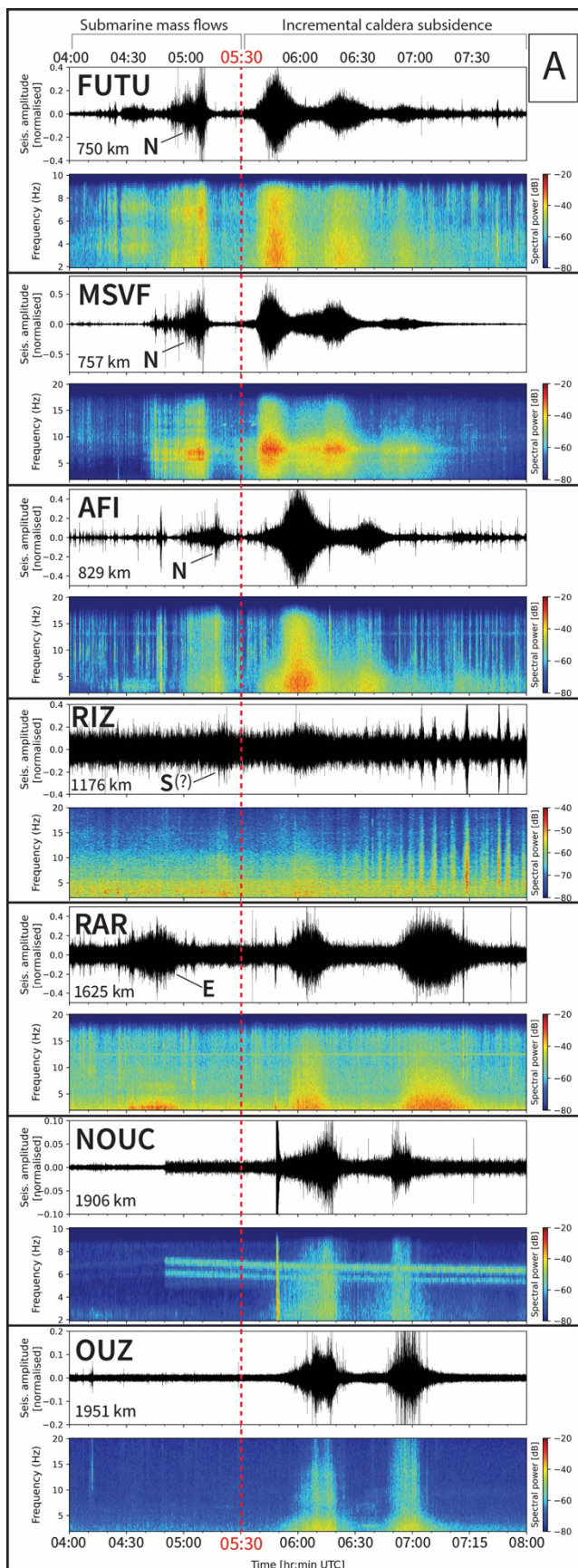
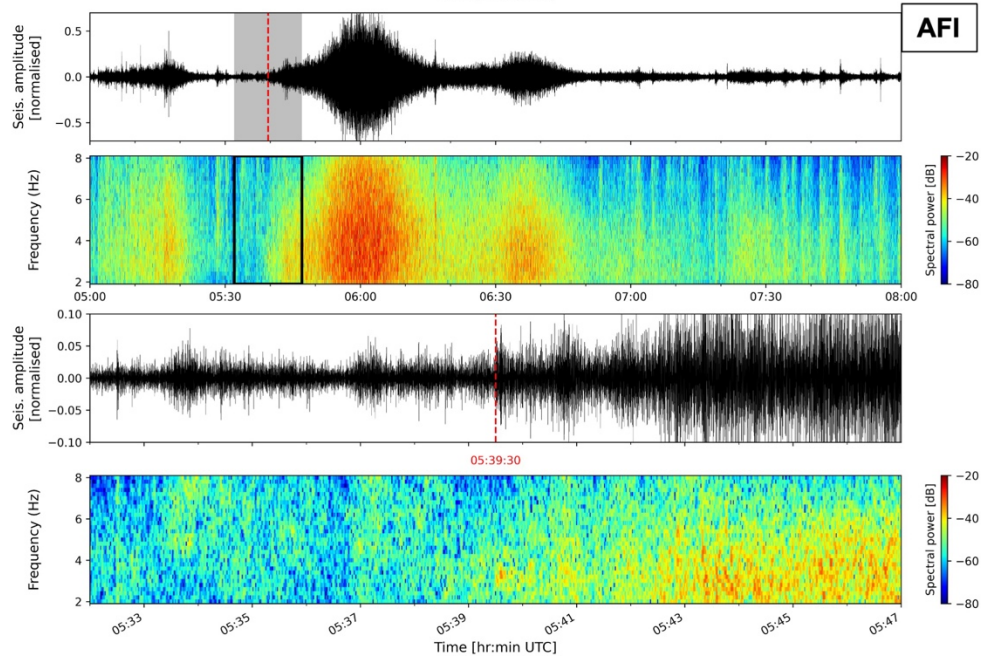
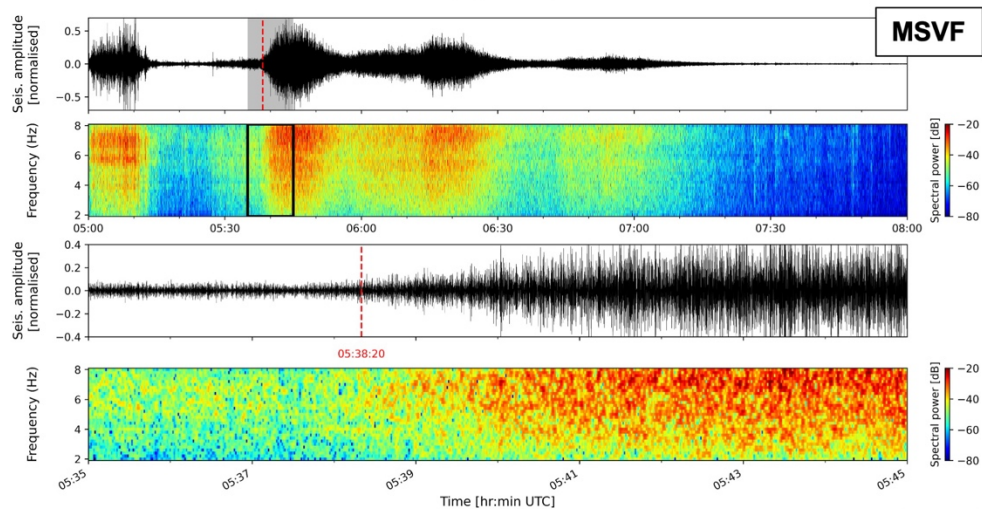
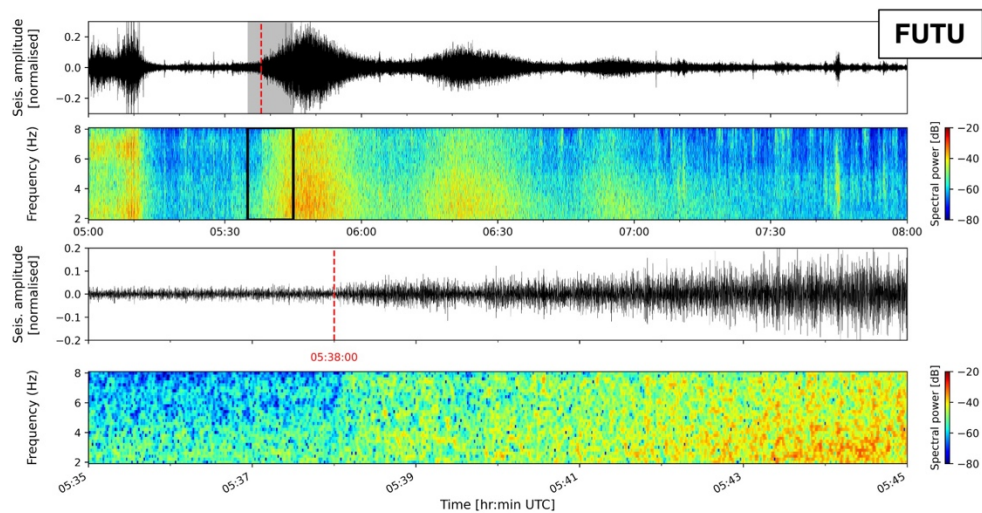
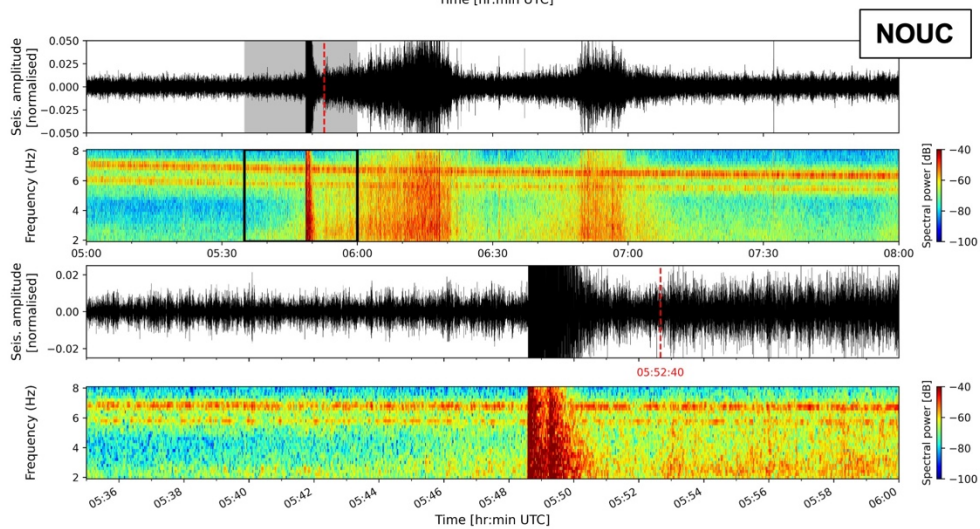
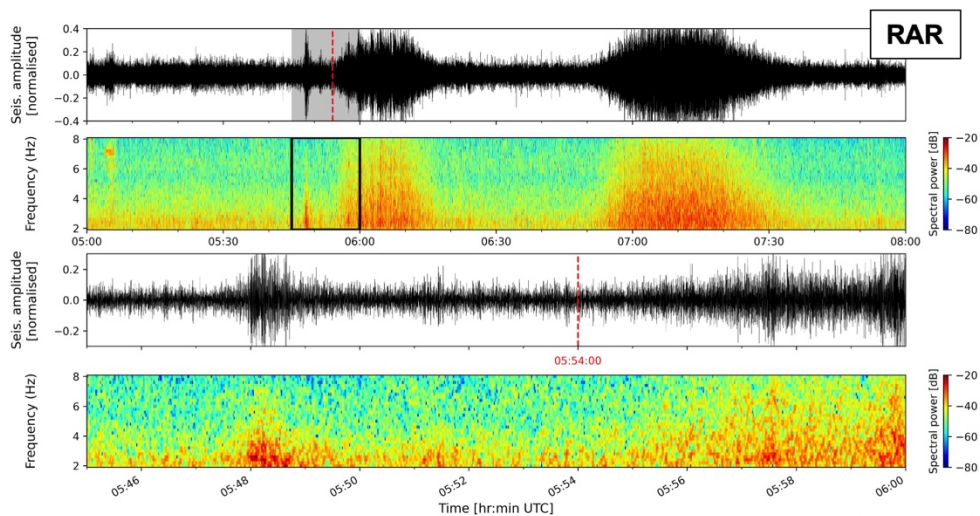
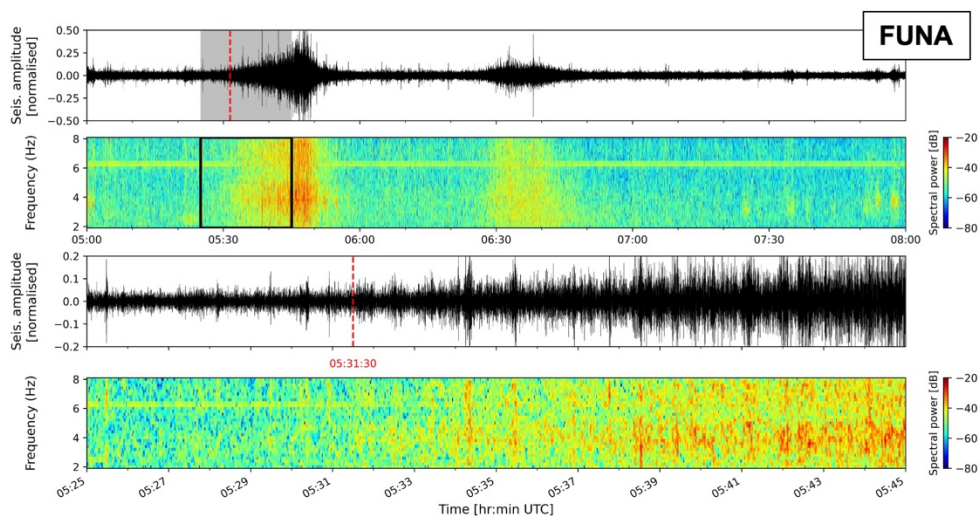
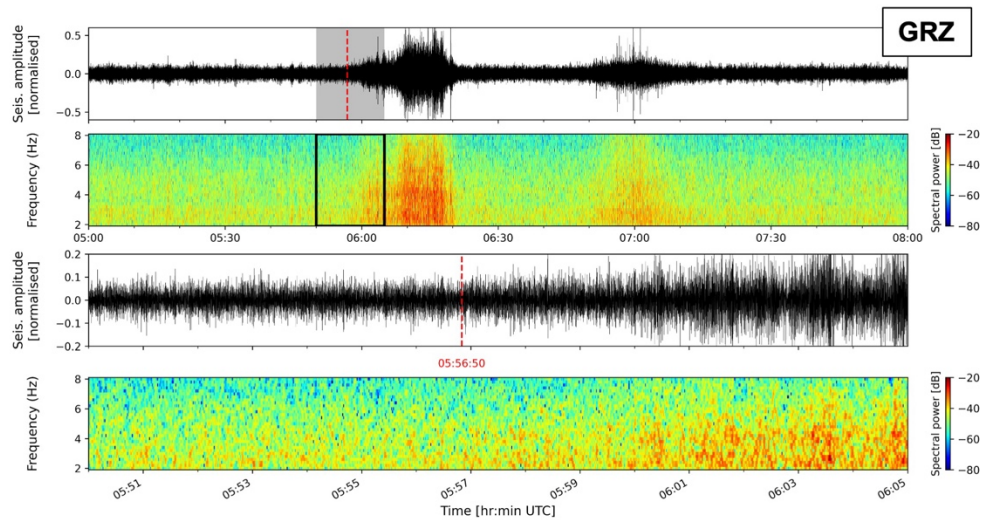
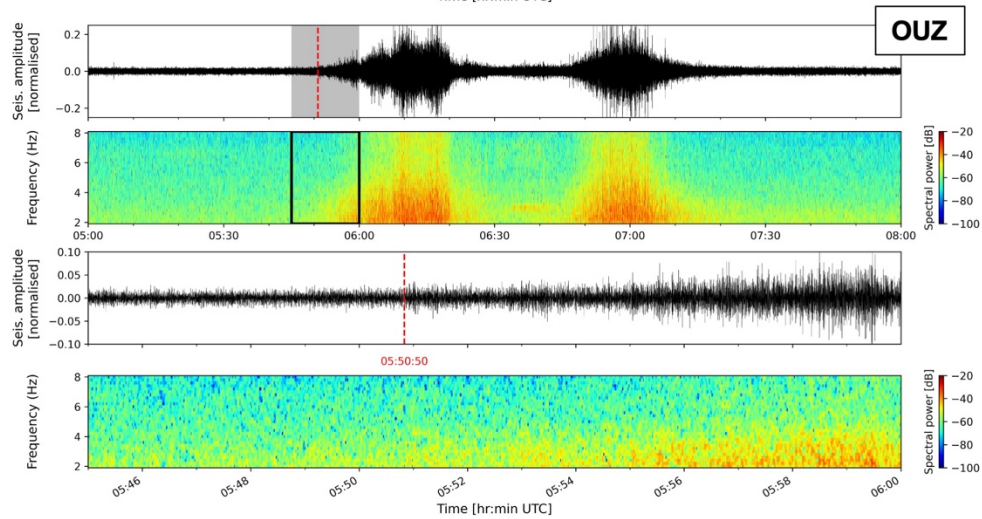
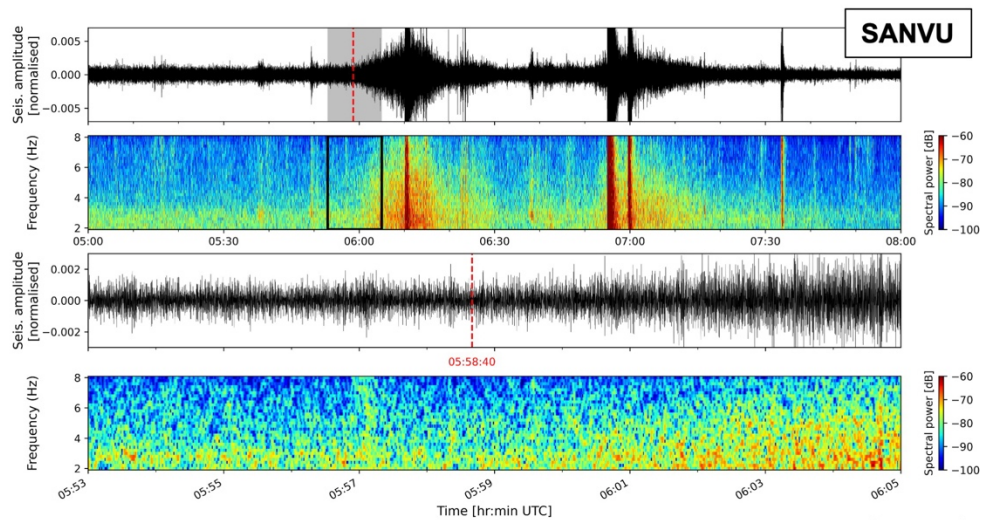


Fig. S3.

A. Waveforms and spectra of seismic sensors located in the SW Pacific from 15 January 2022. **B.** Post-eruption morphology of the Hunga edifice with main submarine mass flow channels (N and E) indicated by arrows. **C.** Location map of analyzed seismic stations and main bathymetric features of the region. Hunga volcano is indicated by the orange star. In (**A**), high-amplitude events before 05:30 UTC recorded at FUTU, MSVF and AFI are not visible on other stations, unlike the signal post-05:30. We interpret this as signals originating from two different source processes: (1) Predominantly northwards directed submarine mass flows (pre-05:30), and (2) incremental caldera subsidence (post-05:30). Some of the recorded landslide events from this phase were likely directed southwards also, as indicated by the very weak pattern at RIZ at ~05:15. While this occurrence may represent a residual T-phase of mass flows directed in other directions, a S-directed flow at this time corresponds with the failure of the international submarine data cable located 60 km south of Hunga around 30 minutes later. Note also the emergent signal at RAR between ~ 04:30 and 05:00, which (considering travel time) was barely recorded by northern sensors. We suggest that this signal indicates an eastwards-directed mass flow event, which coincides with the failure of the domestic submarine communications cable located 20 km east of the volcano, with flow directed down the deeply eroded gorge on the Eastern volcano flanks (**B**). Station AFI may show a weak trace of this event, as hydroacoustic energy crossed the Kermadec Trench and then also travelled north towards AFI. The remaining stations located south of Hunga volcano display patterns similar to OUZ and thus are not shown here. NFK's record is incomplete and was omitted from this figure.







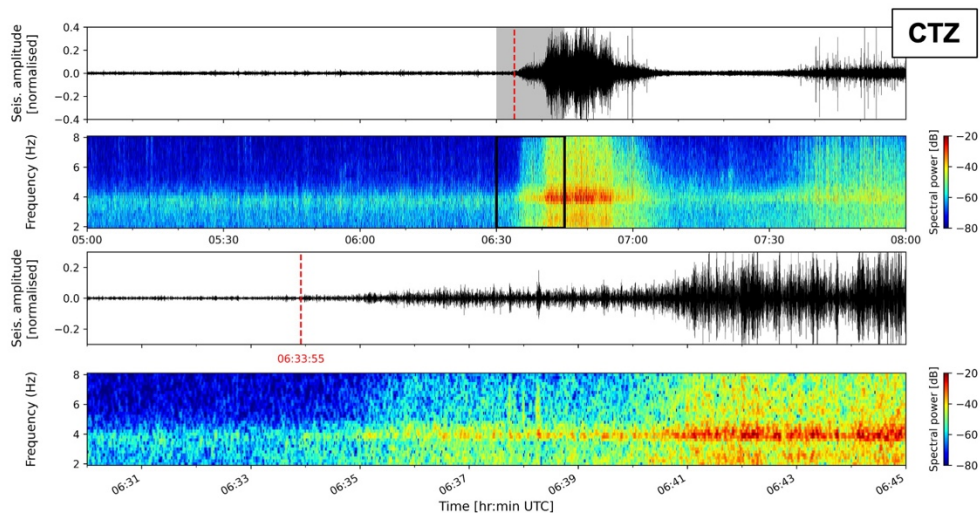
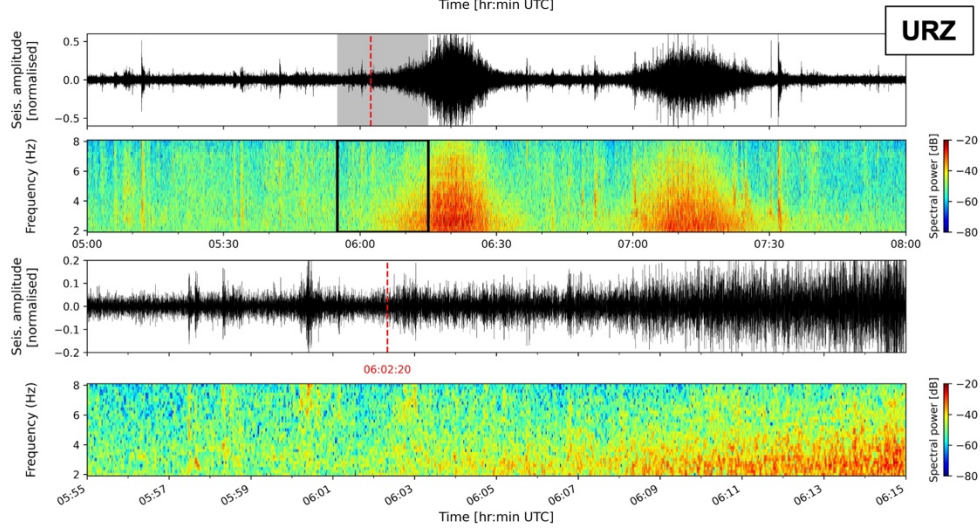
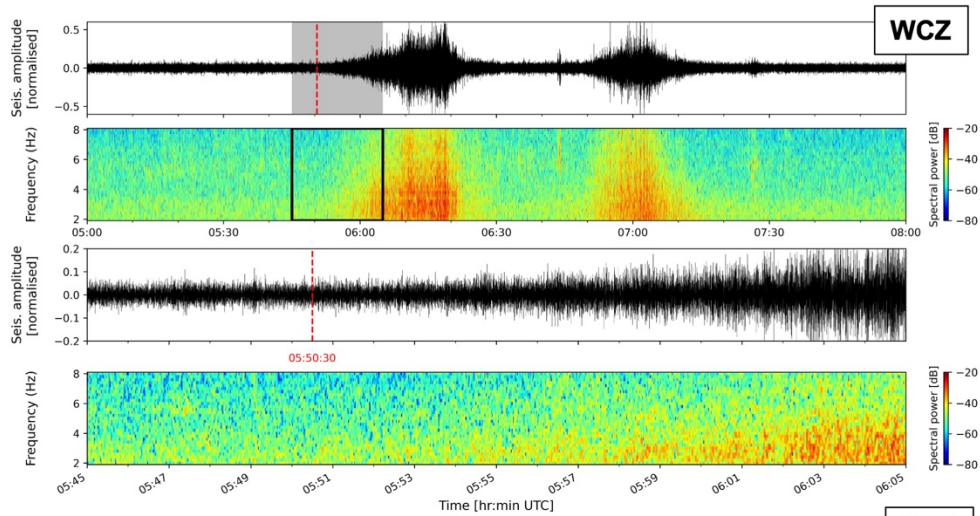


Fig. S4 (four panels)

Waveforms and spectra from records of all 12 stations considered for T-phase arrival picking (05:00-08:00 UTC on 12 January 2022; signal processing as explained in the main text). For each station the amplitude and spectrogram are shown for a 3-hour window and the onset area in a window between 10 to 20 min-long, depending on the site. Picking of the suspected arrival times assumed that signal contamination by seismic body and surface waves of the same event is minimal (higher dispersion velocity than hydro acoustic waves). An exception is NOUC, which recorded an earthquake event around the time of suspected T-phase arrival - a possible alternative for signal onset at NOUC could be 05:45, shifting the theoretical origin event time of the main T-phase to 05:24. An alternative signal onset for AFI is 05:37, shifting the origin time to 05:26/27. Thus, considering uncertainty in arrival times, the time of the main collapse stage likely lies between 05:24-05:29 UTC, although earlier onset times would imply longer delay at other stations. FUNA remains an exceptional signal whose onset time we cannot explain considering signal arrival at station FUTU, which lies on the same ray path.

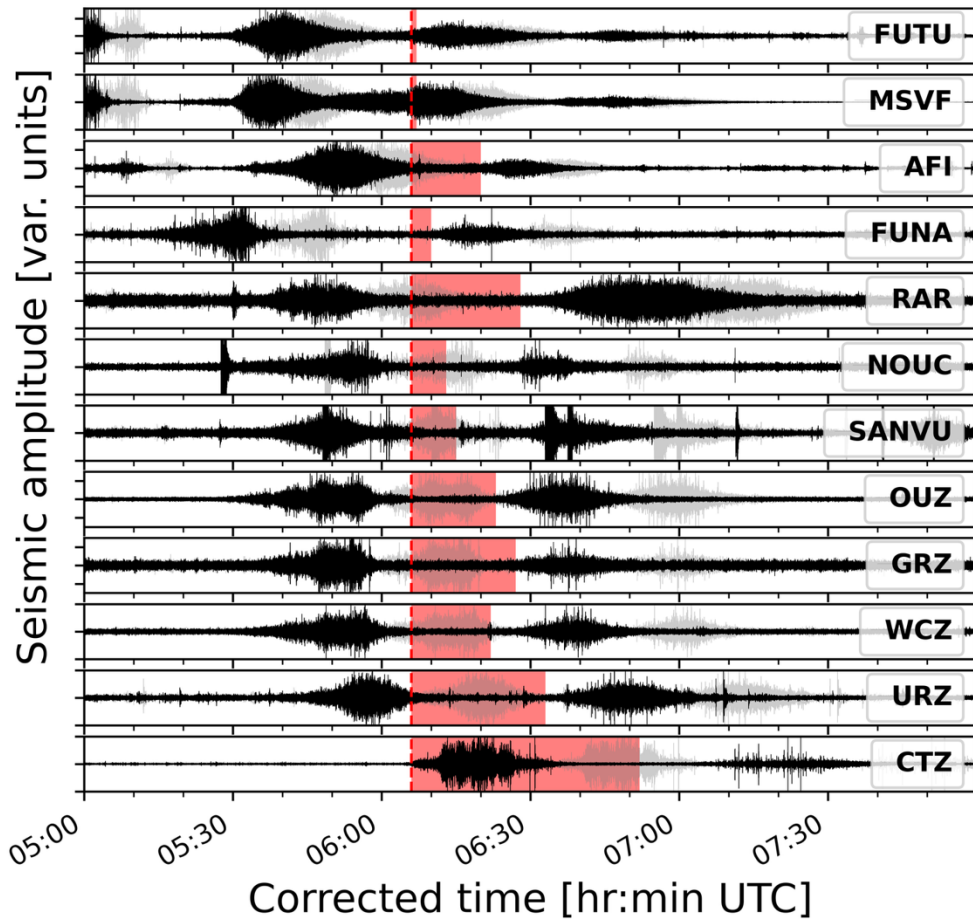
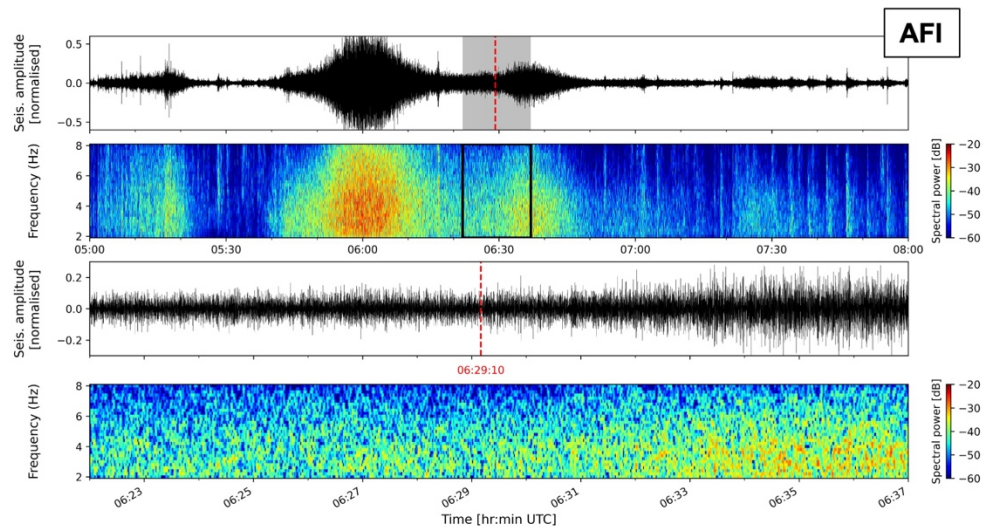
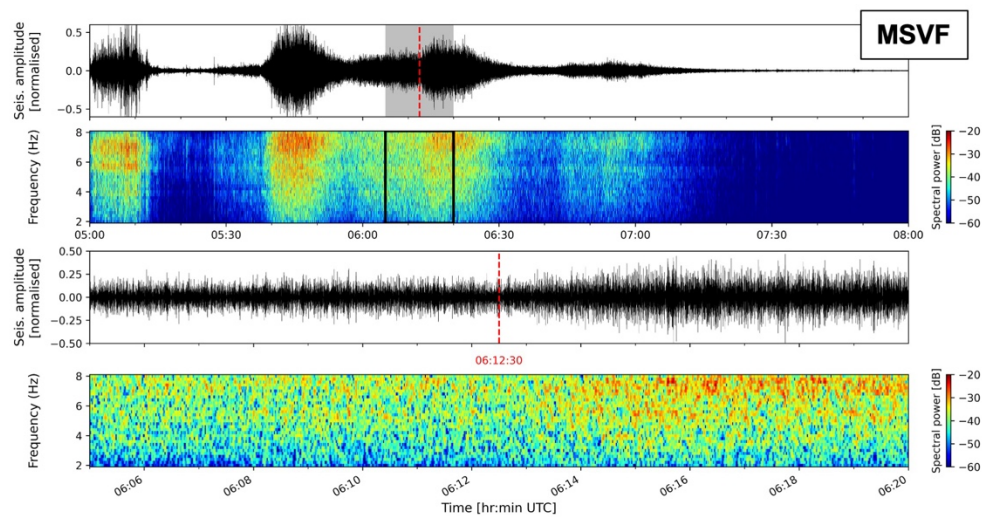
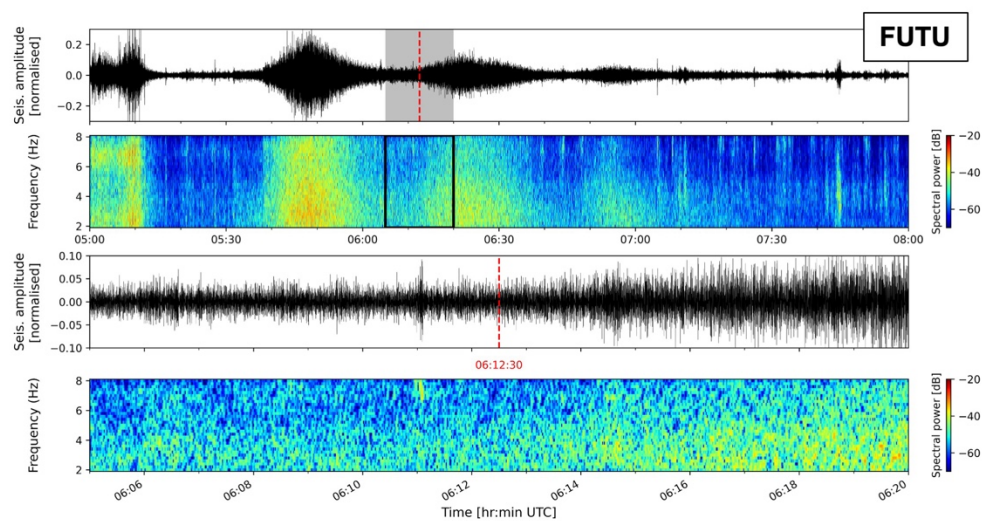
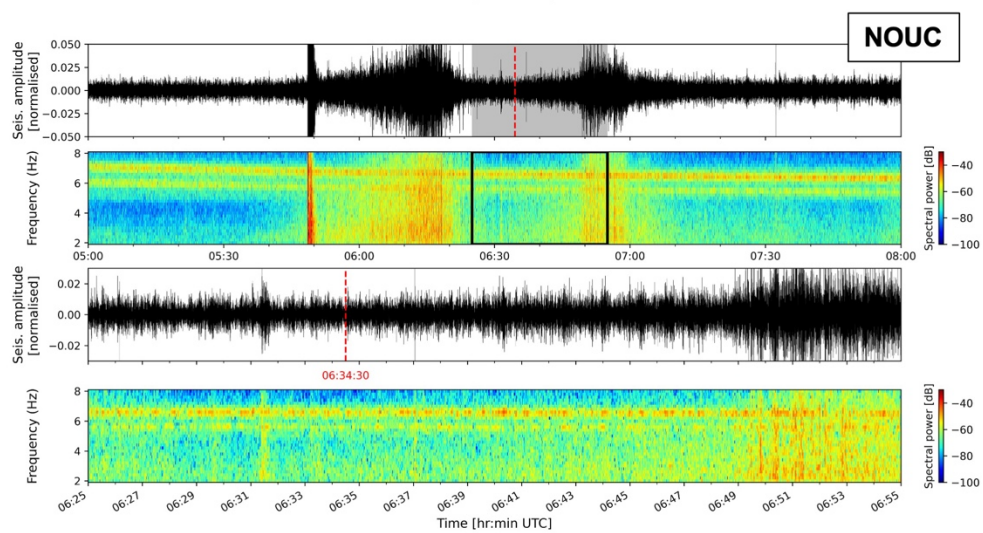
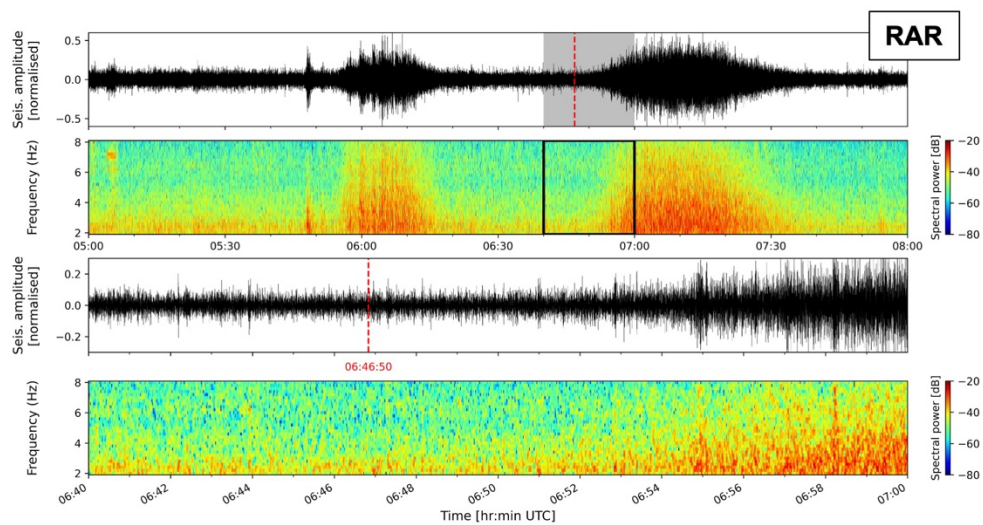
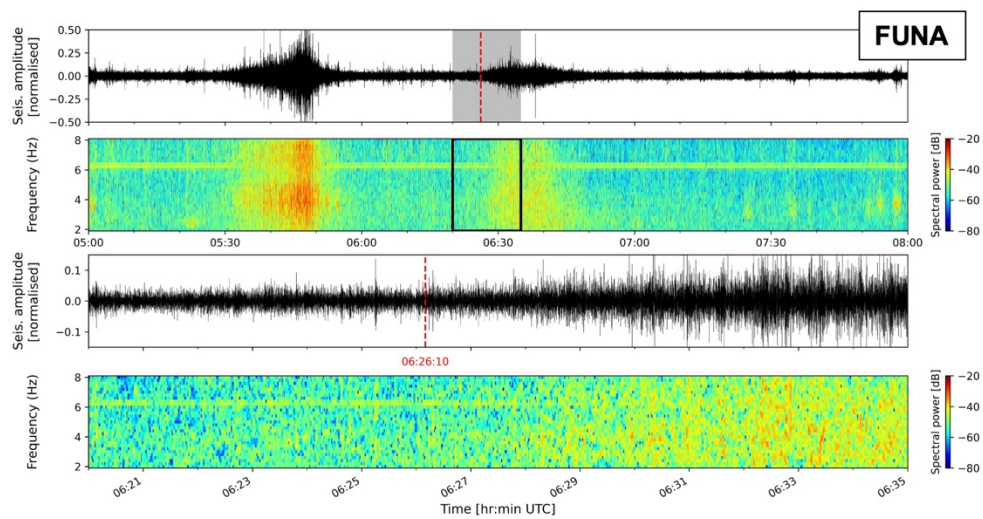
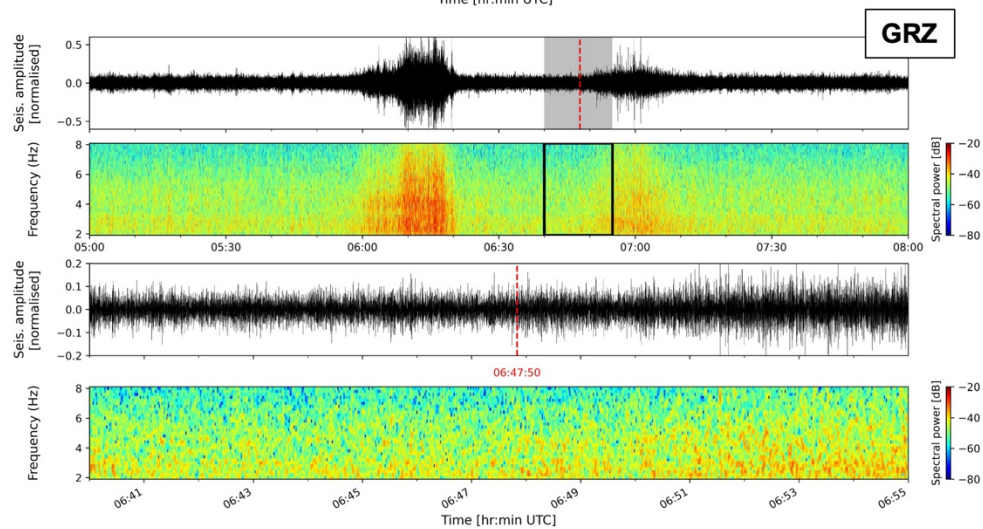
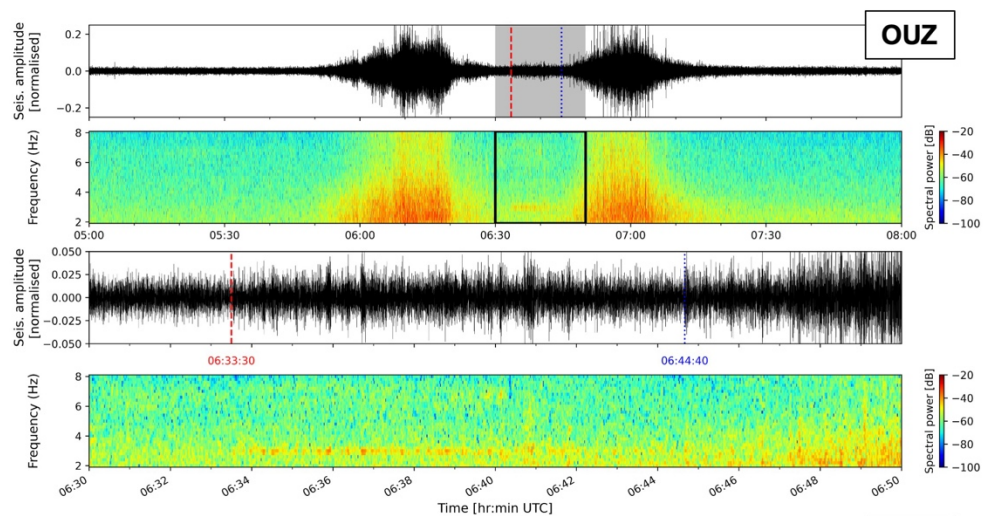
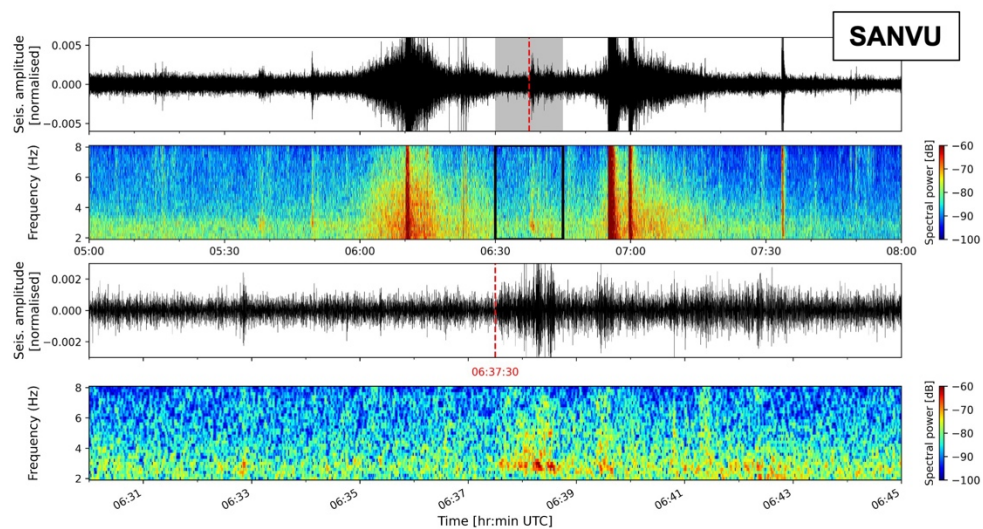


Fig. S5

Seismic spectra of the second post-05:30 *T* wave of the Hunga eruption over twelve of the 14 SW Pacific stations at distances between ~750 and 2600 km (Station details and arrival times in table S2, and full spectra in fig. S6). Note RIZ is too noisy to isolate the signal onset and NFK has an incomplete record. The signals are time-corrected and stacked with respect to the theoretical arrival time of the first detectable signal onset (*T*-wave arrival). Back-projected travel times from the closest stations indicate an origin event starting at 06:06 at Hunga volcano. The arrival times to southern stations are notably longer than for the 05:30 generated *T* wave. Arrivals are more difficult to pick due to overlap of signals.







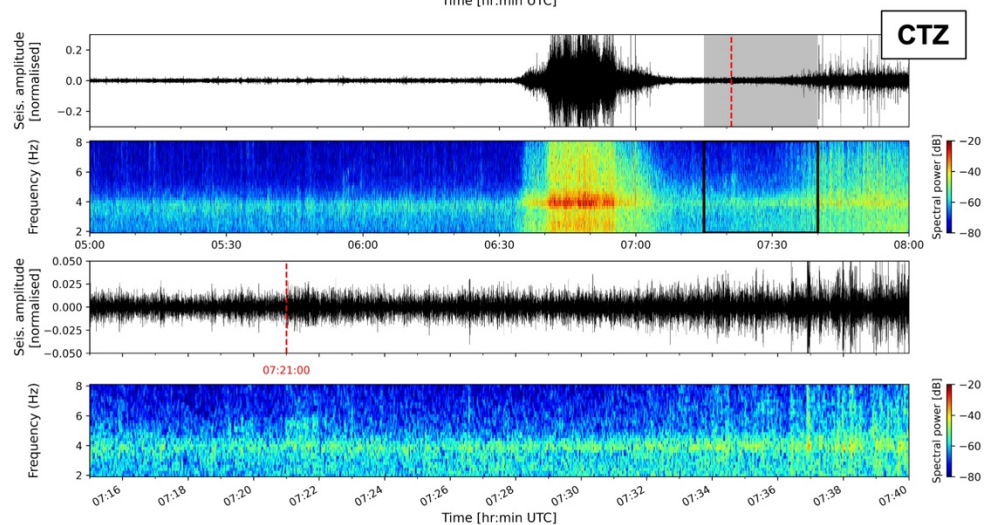
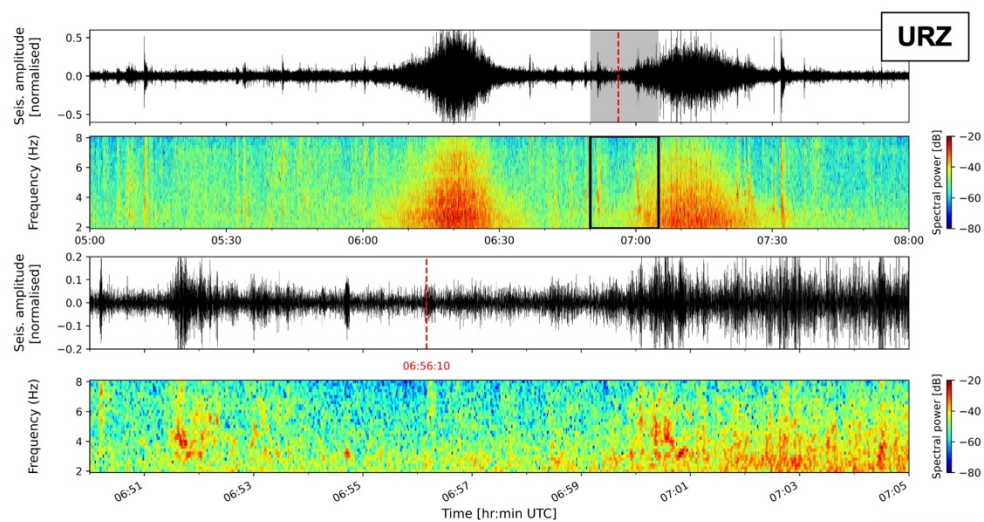
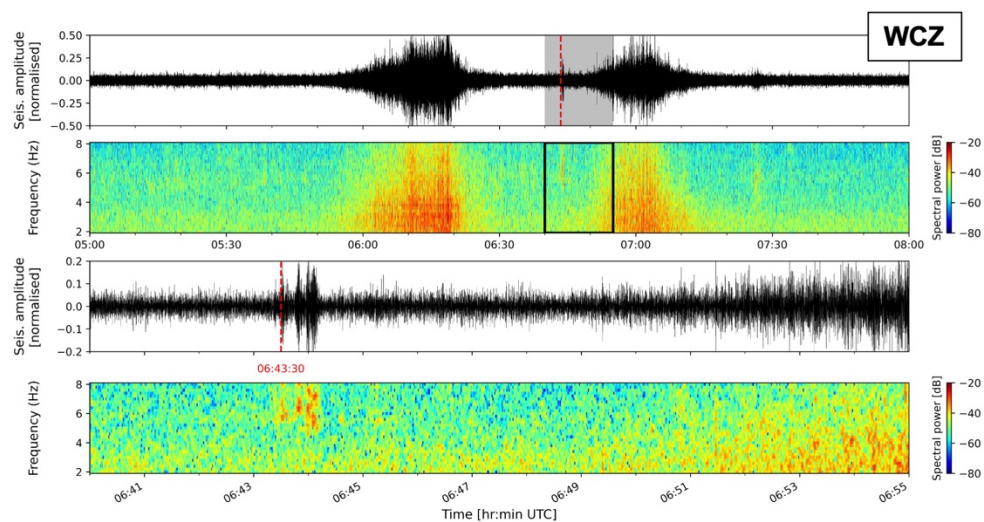
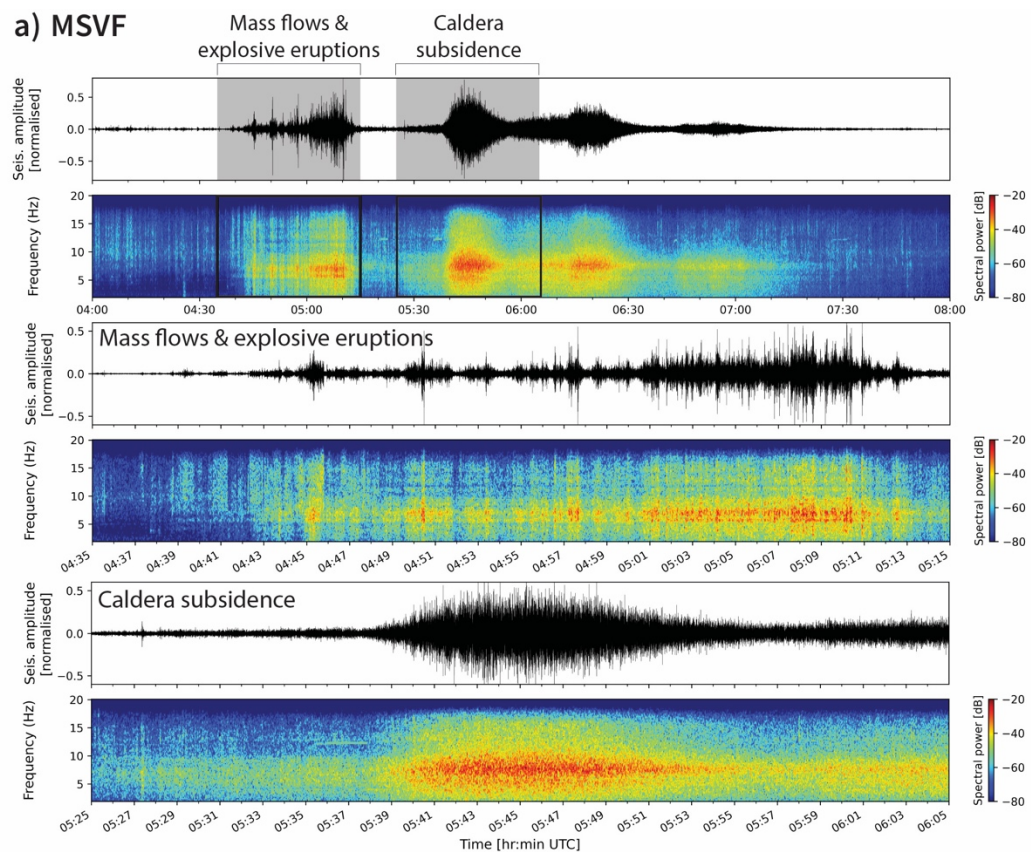


Fig. S6 (four panels)

Waveforms and spectra from records of all 12 stations considered for T-phase arrival picking (05:00-08:00 UTC on 12 January 2022; signal processing as explained in the main text). T-phase arrivals for the second collapse event were less obvious than for the first stage at 05:28 (fig. S4), mainly due to overlap of the coda from the first event with the onset of the second. An interesting observation is a transient T-pulse visible in some stations (e.g., SANVU, CTZ, WCZ), which may have influence arrival time picks. At OUZ, two possible signal arrival times are indicated, one before and another after the onset a ~10-min long 3 Hz signal. Given the delay observed at nearby station GRZ and WCZ in New Zealand, we selected the late arrival as T-phase onset to match arrival times amongst these stations (16-21 mins), while we interpret the prior 3 Hz signal as external noise. The significant delay at S and E stations is remarkable, and while we could not find earlier onset times for the second T-phase, the discrepancy between S/E and N/W stations may indicate a second source. Further work would be needed to investigate this.

a) MSVF



b) FUTU

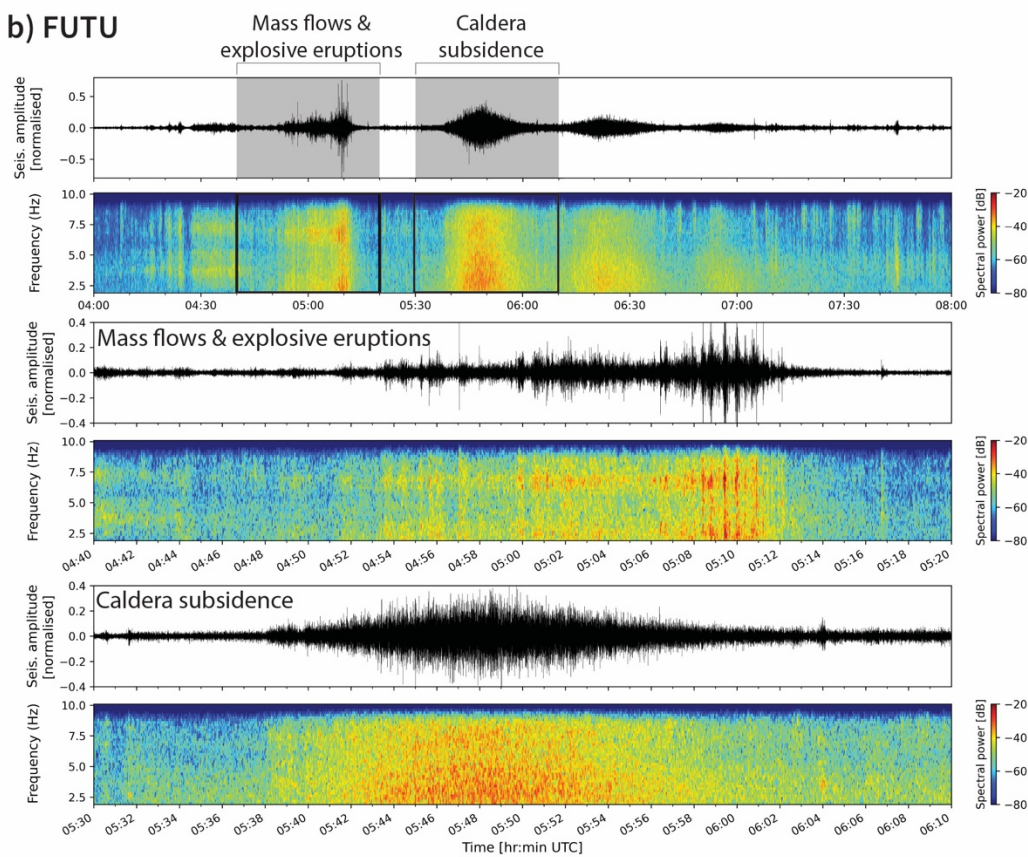


Fig. S7

Comparison of the T waves produced by submarine explosions and mass flows with the first and main tsunamigenic caldera floor collapse event using stations MSVF (top) and FUTU (bottom). We selected these two stations as they best illustrate the different dynamics and waveforms of both types of T wave source. The caldera collapse signal is smooth and emergent, while signals generated by explosions and mass flows are shorter and impulsive or pulsatory, reflecting the different source durations. While we cannot directly assign specific parts of the pre-collapse sequence to their respective sources, a gradually growing energy trend is apparent (~05:00-05:15 UTC on both stations), which can be attributed to increased material loading on the upper volcanic slopes and the resulting growth in magnitude and frequency of submarine mass flows generated at the volcano. By contrast, individual signals within the T-phase sequence attributed to caldera floor subsidence after 05:28 UTC are all similar in shape and duration, but show a decrease in amplitude – possibly reflecting an incremental caldera collapse in two to three main stages with decreasing subsidence amounts or decreasing slip-velocities.

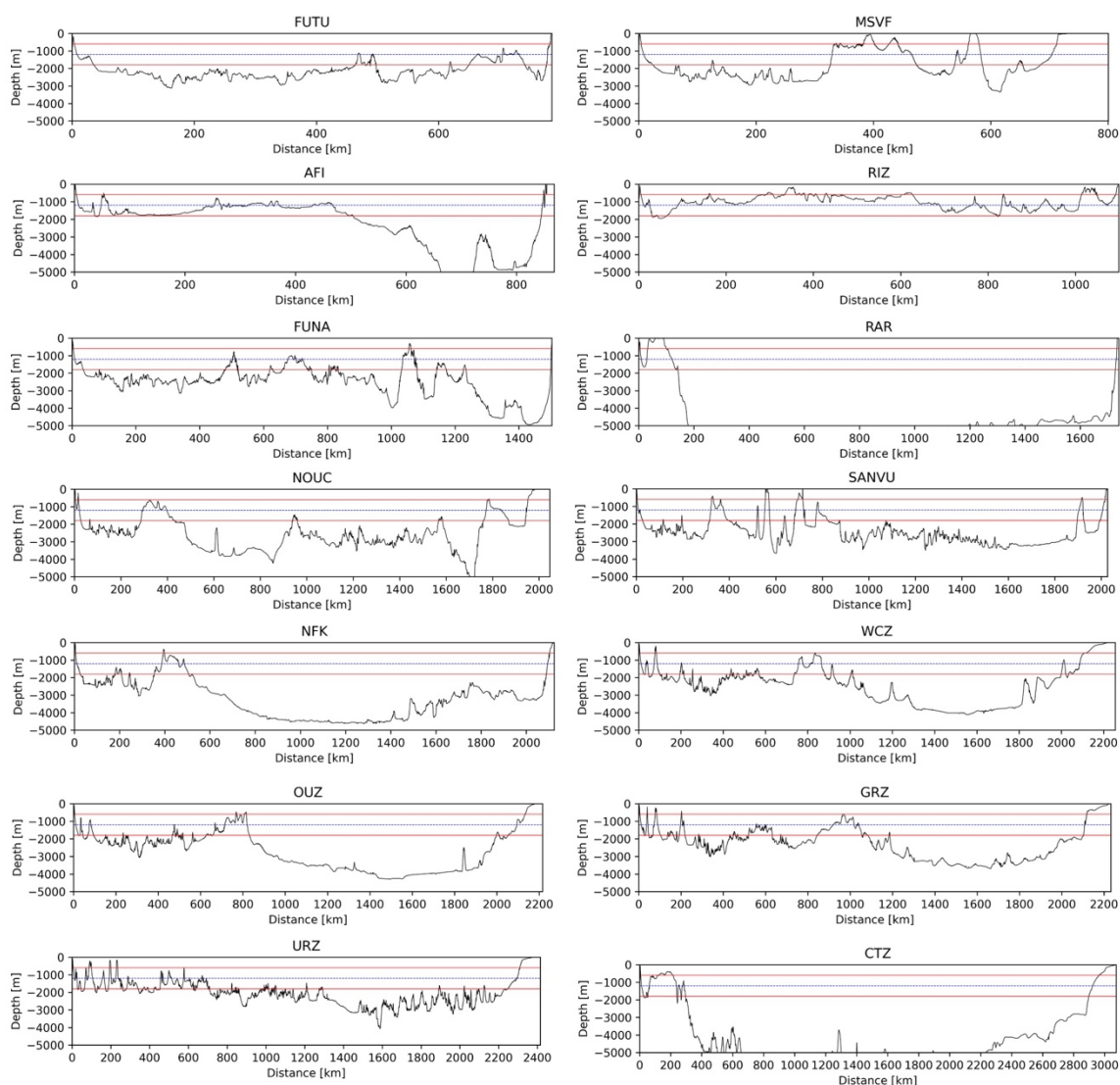


Fig. S8.

Bathymetric profiles between Hunga (0) and the 14 seismic stations used in this analysis (Figs. 1 and 3 and table S1). Red lines show SOFAR Channel limits, the blue line the approximate channel center. Major bathymetric features intersecting the SOFAR channel likely cause attenuation of signal by *T*-wave reflection, diversion and conversion (to seismic waves).

Table S1.

Details of seismic stations used in this analysis with travel time estimates for T waves from Hunga to each station, estimated arrival time of the major post 05:30 T wave (fig. S4), projected origin time and delay from ideal onset (05:28 UTC).

Station	Distance [km]	Latitude	Longitude	Country	Network	Travel time [min]	Arrival [UTC]	Origin time [UTC]	Delay from 05:28 event [min]
FUTU	749.8	-14.3077	-178.1211	Wallis and Futuna	G GEOSCOPE	8	05:38:00	05:30:00	2
MSVF	757	-17.7448	178.0528	Fiji	II IRIS-IDA	8	05:38:20	05:30:20	2
AFI	829	-13.9085	-171.7827	Samoa	IU IRIS- USGS	9	05:39:30	05:30:30	2
FUNA	1452	-8.5259	179.1966	Tuvalu	IU IRIS- USGS	16	<i>05:31:30</i>	<i>05:15:30</i>	
RAR	1625	-21.2125	-159.7733	Cook Islands	IU IRIS- USGS	18	05:54:00	05:36:00	8
NOUC	1906	-22.0986	166.3067	New Caledonia	G GEOSCOPE	21	05:52:40	05:31:40	4
SANVU	1927	-15.4471	167.2032	Vanuatu	G GEOSCOPE	22	05:58:40	05:36:40	9
OUZ	1951	-35.2197	173.5961	New Zealand	NZ GEONET	22	05:50:50	05:28:50	1
GRZ	1955	-36.2502	175.4578	New Zealand	NZ GEONET	22	05:56:50	05:34:50	7
WCZ	1978	-35.9411	174.3444	New Zealand	NZ GEONET	22	05:50:30	05:28:30	1
URZ	2091	-38.2592	177.1109	New Zealand	NZ GEONET	23	06:02:20	05:39:20	11
CTZ	2573	-43.7355	-176.6172	New Zealand	NZ GEONET	29	06:33:55	06:04:55	37

Table S2.

Details of seismic stations used in this analysis with travel time estimates for T waves from Hunga to each station, estimated arrival time of the major post 05:30 T wave (fig. S4), projected origin time and delay from ideal onset (05:28 UTC).

Station	Distance [km]	Travel time [min]	Arrival [UTC]	Origin time [UTC]	Delay from 06:06 event [min]	05:28 event delay[min]	Station direction
FUTU	749.8	8	06:12:30	06:06:30	1	2	NW
MSVF	757.1	8	06:12:30	06:06:30	1	2	W
AFI	829.0	9	06:29:10	06:20:10	14	2	NE
FUNA	1452.8	16	06:26:10	06:10:10	4		NW
RAR	1625.3	18	06:46:50	06:28:50	22	8	E
NOUC	1906.0	21	06:34:30	06:13:30	7	4	W
SANVU	1927.3	22	06:37:30	06:15:30	9	9	W
OUZ	1951.0	22	06:44:40	06:22:40	17	1	S
GRZ	1955.0	22	06:47:50	06:26:50	21	7	S
WCZ	1978.0	22	06:43:30	06:21:30	16	1	S
URZ	2091.4	23	06:56:10	06:33:10	27	11	S
CTZ	2573.4	29	07:21:00	06:52:00	46	37	S