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Supporting Information for

Enigmatic tsunami waves amplified by repetitive source events near Sofugan volcano, Japan

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Introduction

This Supporting Information contains supplementary figures and tables, to support our conclusions documented in Main Text.

Supplementary figures

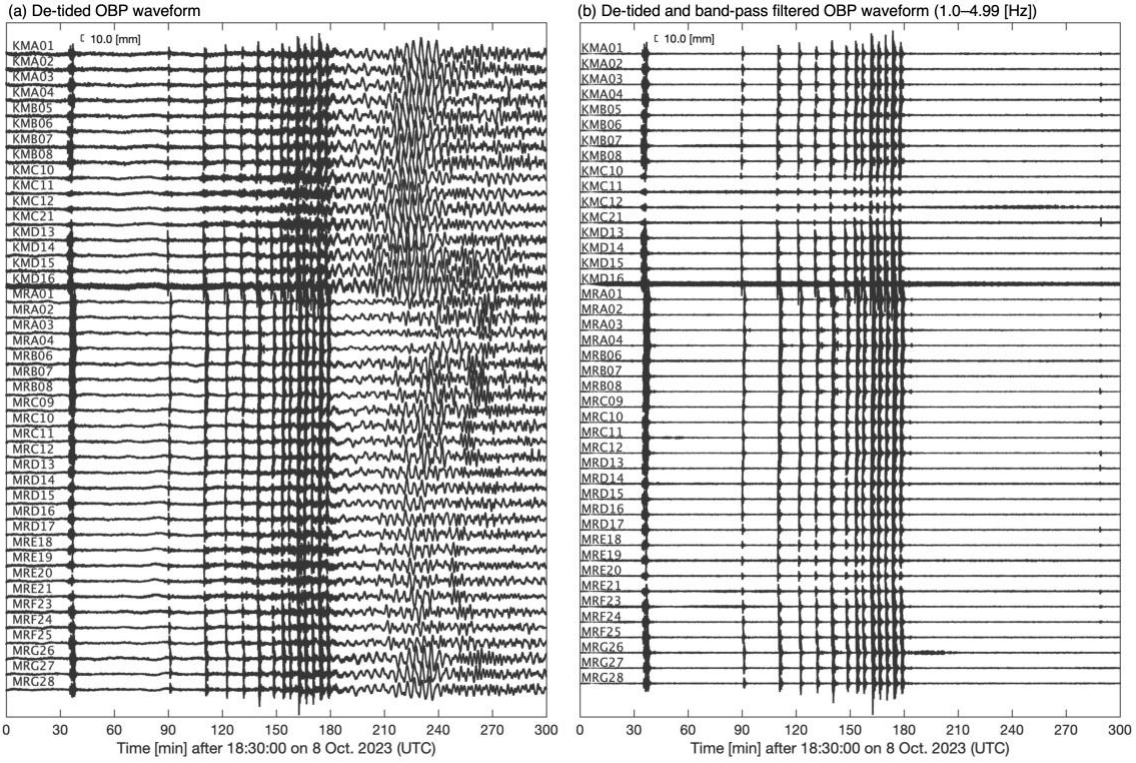

Figure S1. Data of OBP gauges of DONET after 18:30:00 on 8 October 2023 (UTC). (**a**) Data after removing the tidal component by polynomial approximation. (**b**) Data after the tidal-trend removal and the band-pass filtering (1.0–4.99 Hz), in the frequency range where T-phase is dominant.

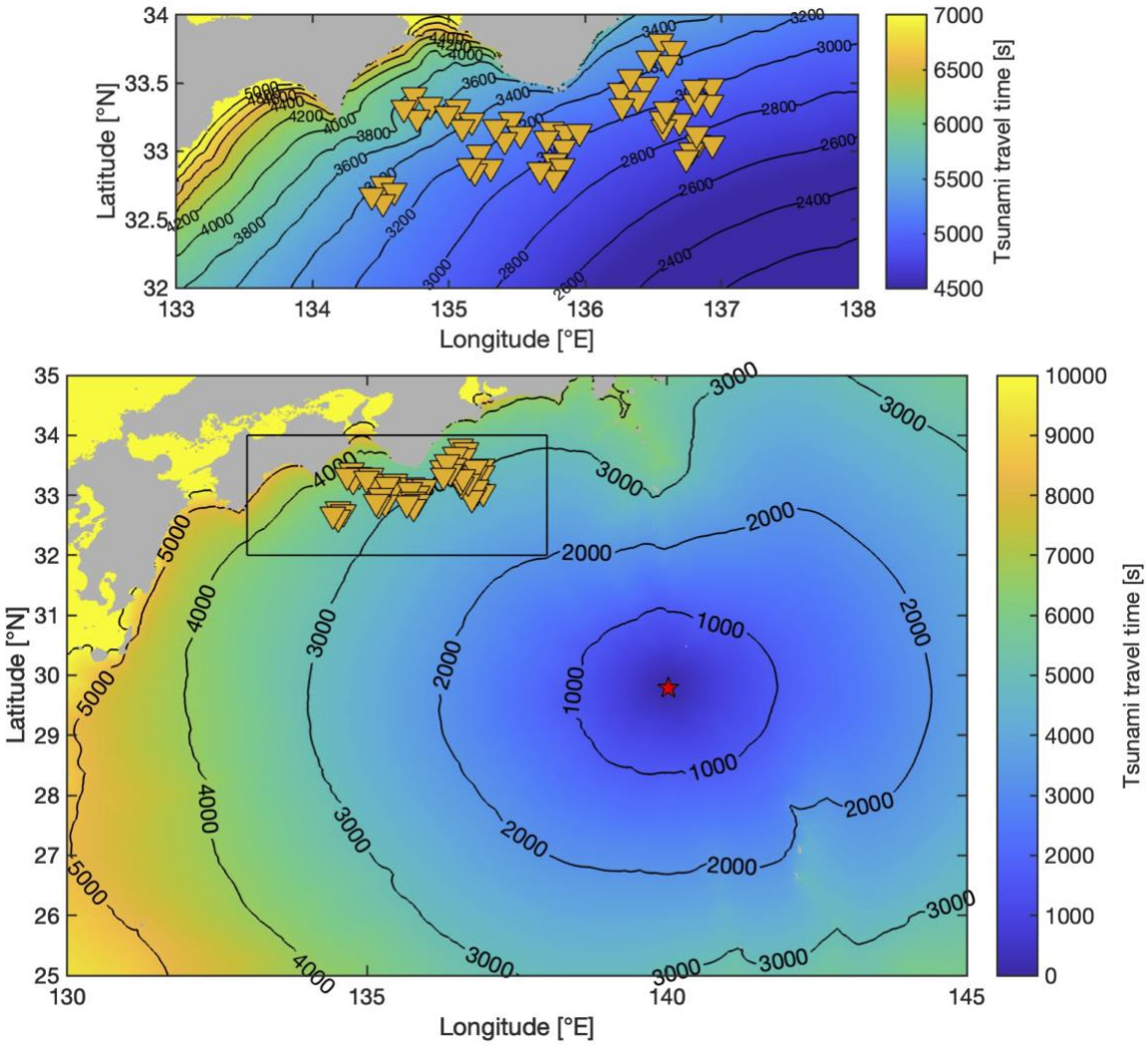

Figure S2. Tsunami travel time from a point source near the source region of the seismic event swarm on 8 October 2023 (140.026°E, 29.787°N), computed by the Geoware TTT (Tsunami Travel Time) software. A red star and orange inverted triangles represent the locations of the point source and DONET stations, respectively. The bathymetry data of JTOPO30 is used for the computation. See Table S2 for the travel time information.

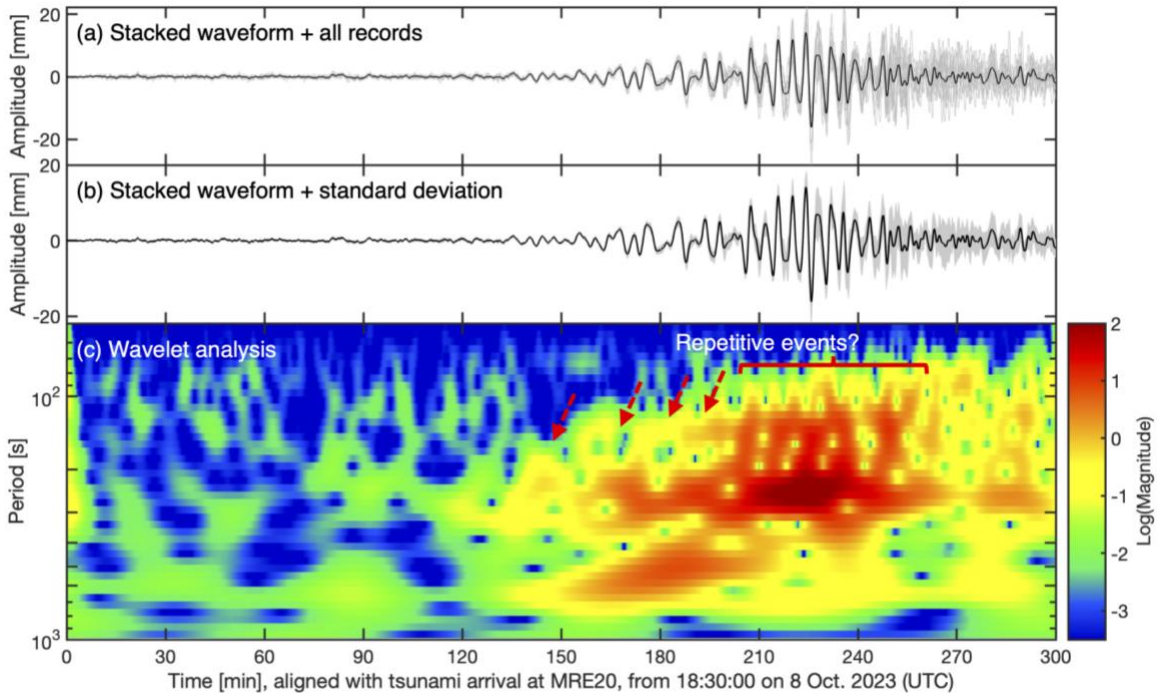

Figure S3. Same as Figure 2c–e in Main Text, but for the stacked tsunami waveform obtained from 13 records of DONET2 (MRC, MRD, and MRE; Table S2). These 13 records are chosen here, because the stations are close to each other, exhibiting similar tsunami waveforms. The time is aligned with the tsunami arrival at MRE20 (see Figure 1b).

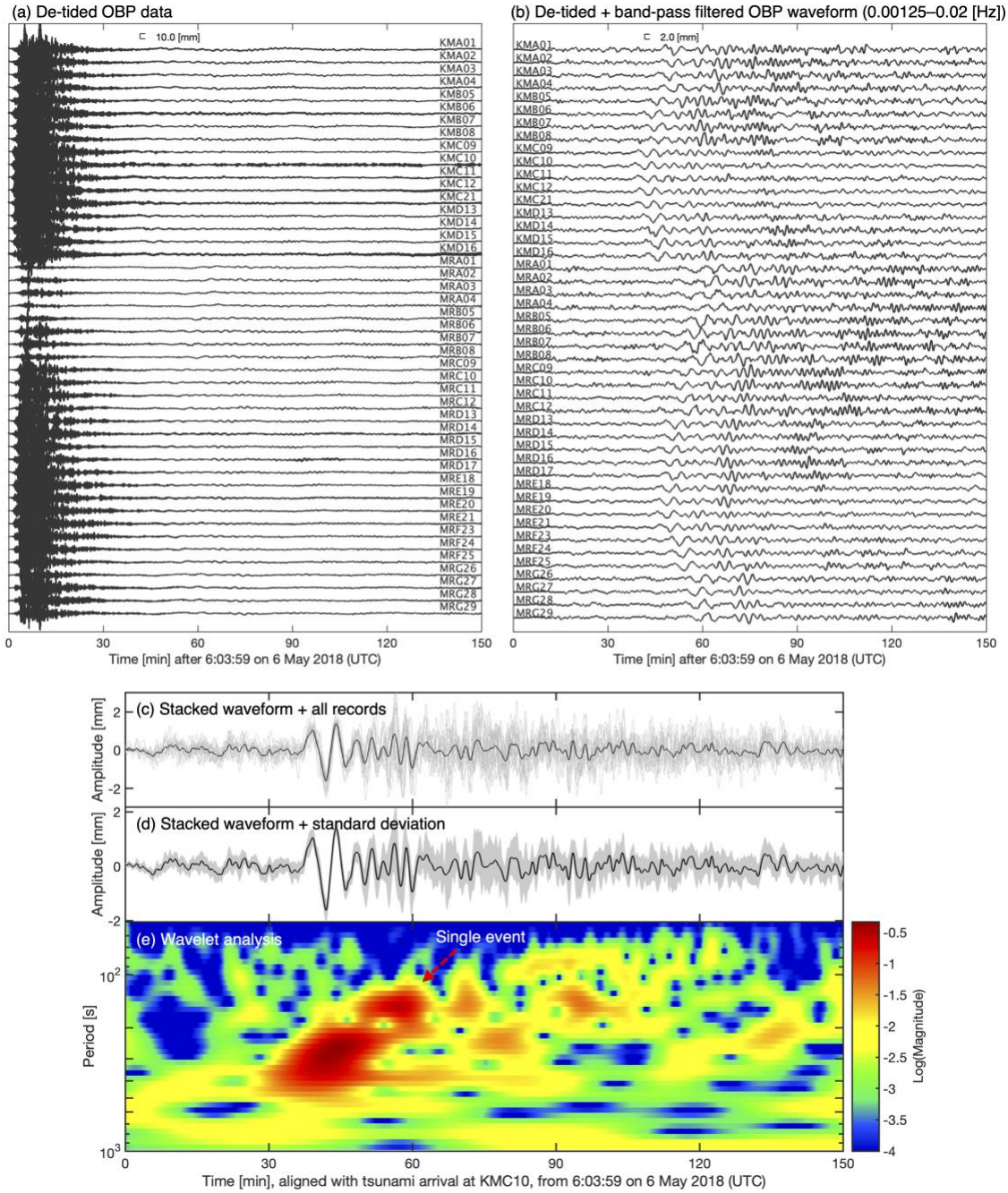

Figure S4. Same as Figure 2 in Main Text, but for the Sumisu Caldera earthquake (M_w 5.4) at 6:03:59 on 6 May 2018 (UTC). For the waveform stacking, we compute the tsunami travel time from the source location at the center of Sumisu Caldera (140.05°E, 31.48°E). Compared to those of the data on 8 October 2023, the tsunami duration is shorter (note the difference in time length scale). Only a single wave train is found in the wavelet analysis result; waves in later phases after ~60 min with smaller amplitudes may be due to reflected or refracted waves.

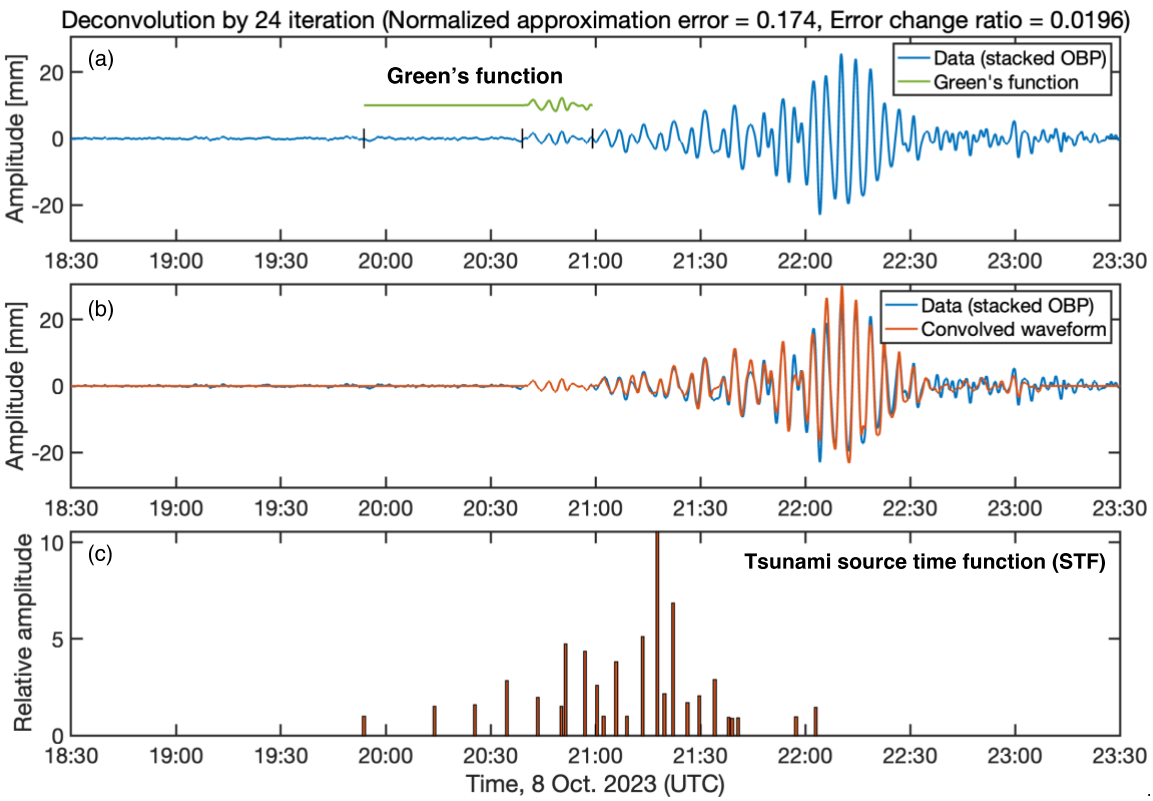

Figure S5. Estimation of the tsunami source time function by the iterative deconvolution (24 times) only, without the least-squares method. (**a**) The Green's function (green line) obtained from the stacked OBP tsunami waveform (blue line). (**b**) The convolved tsunami waveform (red line) compared with the stacked waveform. The normalized approximation error is 0.174. (**c**) Tsunami STF, without the least-squares method.

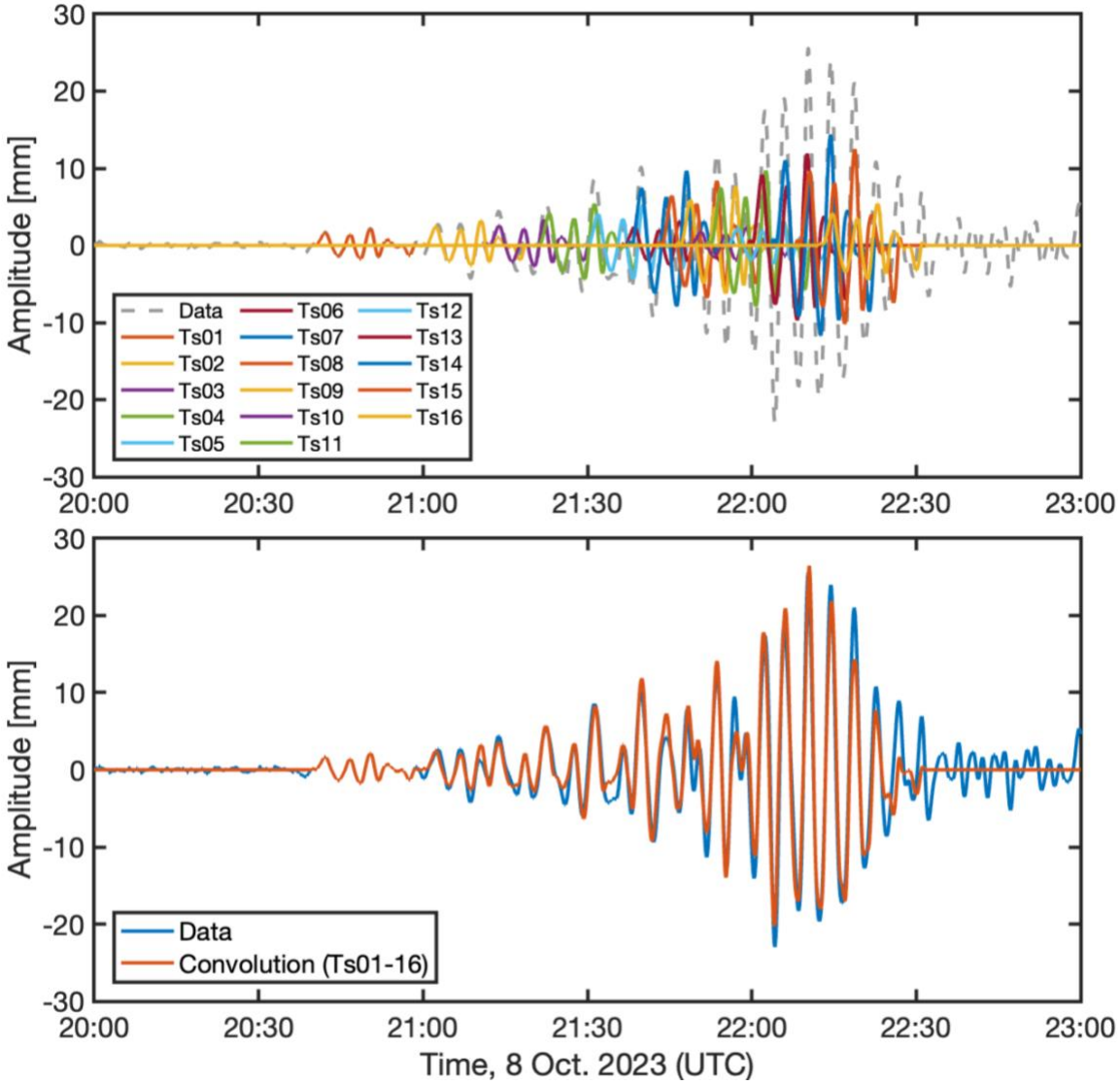

Figure S6. Tsunami waves of the major events, in the case of DONET1. (**a**) The waveforms due to each event of Ts01–16, shown in the inset panel. (**b**) The convolved waveform with Ts01–16 (orange line) and the stacked waveform (blue line). Note that it is not clear whether the worse fit after ~22:20 arises from the imperfect Green's function (with unmodelled later waves) or missing of later source events.

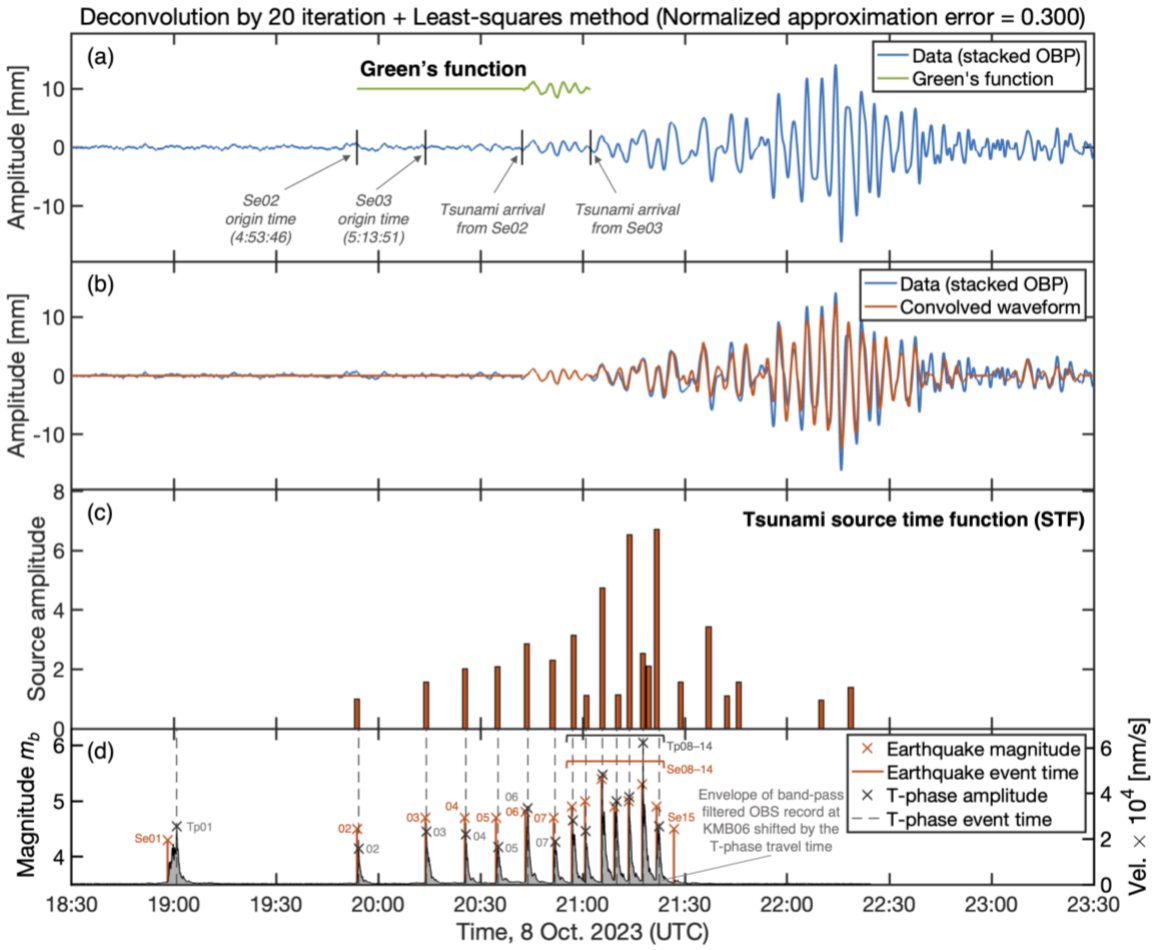

Figure S7. Same as Figure 3 in Main Text, but for the tsunami STF estimated from the stacked OBP tsunami waveform obtained from the 13 records of DONET2 (MRC, MRD, and MRE). The iterative deconvolution is performed 20 times, until the approximation error changes by less than 1.5 % by an iteration. The additional non-negative least-squares method is also applied. Note that the estimated tsunami STF is similar to that based on the OBP records of DONET1 (Figure 3).

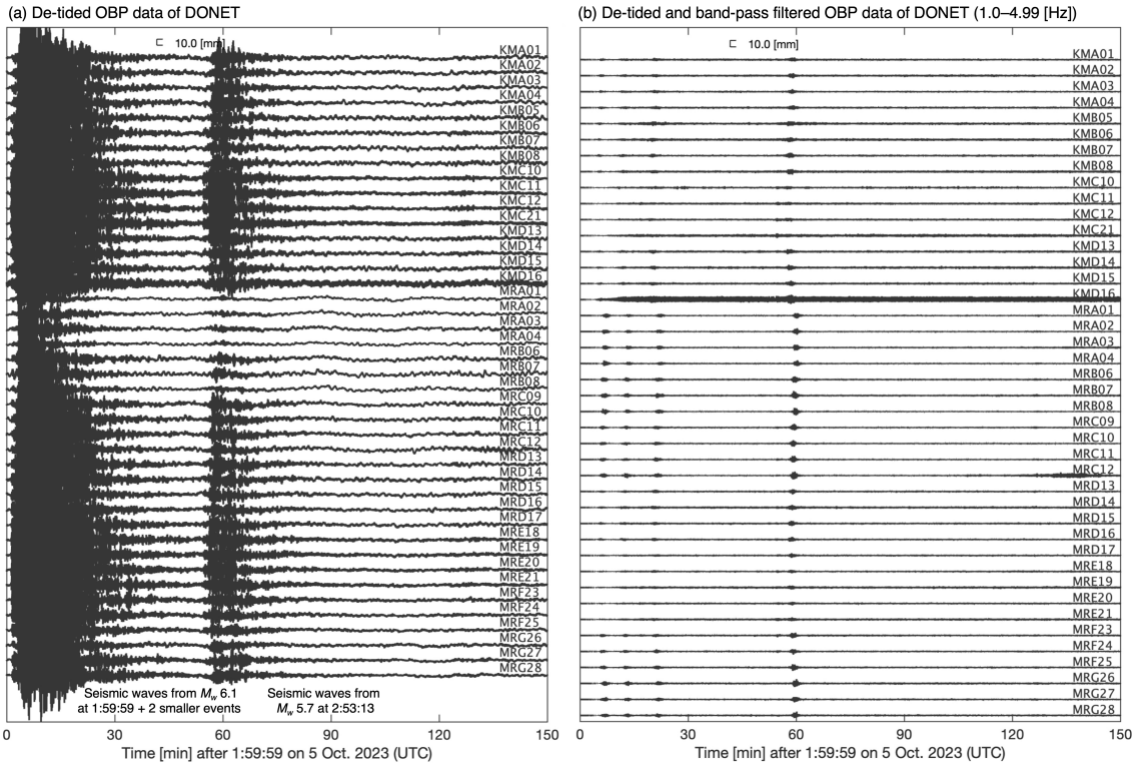

Figure S8. Same as Figure S1, but for the M_w 6.1 at 1:59:59 on 5 October 2023 (UTC). Note that, compared to the sequence on 8 October (Figure S1), the earthquakes on 5 October show stronger seismic signals in the non-filtered record (**a**), while signals in the frequency range of 1–4.99 Hz, where T-phase are dominant, are smaller (**b**).

Supplementary Tables

Table S1. Information of the seismic event swarm to the west of Sufugan volcano on 8 October 2023 (UTC), reported in the USGS catalog (accessed on 21 December 2023). Note that shallow source depths may not be determined accurately, which can be even shallower.

Earthquake event #	Time, UTC	Longitude [°E]	Latitude [°N]	Depth [km]	Magnitude	Event interval [s]
Se01	18:58:10	139.8780	30.1221	10	4.3	–
Se02	19:53:46	140.0613	29.6904	10	4.5	3336
Se03	20:13:51	140.0888	29.6880	10	4.7	1205
Se04	20:25:23	139.9258	29.7121	10	4.7	692
Se05	20:34:33	139.9904	29.7181	10	4.7	550
Se06	20:43:09	140.2201	29.7256	10	4.8	517
Se07	20:51:26	139.9186	29.7700	10	4.7	496
Se08	20:56:48	139.9328	29.8249	10	4.9	323
Se09	21:00:41	140.0495	29.7418	10	5.0	232
Se10	21:05:32	139.9661	29.7638	10	5.4	292
Se11	21:09:16	140.1140	29.8308	10	4.9	224
Se12	21:13:28	140.0281	29.7985	10	5.0	252
Se13	21:17:28	140.0739	29.7700	10	5.3	240
Se14	21:21:42	139.8132	29.6373	10	4.9	253
Se15	21:26:45	140.3431	30.0050	10	4.5	303

Table S2. Station lists of DONET. In the 5th and 6th columns, tsunami travel times computed by the Geoware TTT software, and the data availability is shown, respectively. "Stacking" in the 6th column represents the available data that are used for the waveform stacking; those from DONET1 and DONET2 are used for the waveform stacking results shown in Figure 2c–e and Figure S3, respectively.

DONET1						DONET2					
#	Station code	Longitude [°E]	Latitude [°N]	Tsunami travel time [s]	Availability	#	Station code	Longitude [°E]	Latitude [°N]	Tsunami travel time [s]	Availability
1	M.KMA01	136.5570	33.8048	3323	Stacking	23	M.MRA01	134.7449	33.4085	3771	Available
2	M.KMA02	136.6488	33.7524	3260	Stacking	24	M.MRA02	134.8641	33.3393	3659	Available
3	M.KMA03	136.6037	33.6484	3199	Stacking	25	M.MRA03	134.7691	33.2490	3648	Available
4	M.KMA04	136.4674	33.6781	3262	Stacking	26	M.MRA04	134.6723	33.3205	3751	Available
5	M.KMB05	136.9264	33.4772	2991	Stacking	27	M.MRB05	135.0667	33.3222	3530	–
6	M.KMB06	136.9216	33.3584	2907	Stacking	28	M.MRB06	135.1698	33.2252	3407	Available
7	M.KMB07	136.8072	33.3613	2935	Stacking	29	M.MRB07	135.0964	33.1755	3401	Available
8	M.KMB08	136.8039	33.4664	3014	Stacking	30	M.MRB08	134.9869	33.2750	3542	Available
9	M.KMC09	136.8313	33.0584	2758	–	31	M.MRC09	135.4584	33.2280	3269	Stacking
10	M.KMC10	136.9335	33.0533	2732	Stacking	32	M.MRC10	135.5249	33.1251	3167	Stacking
11	M.KMC11	136.7790	33.0033	2739	Stacking	33	M.MRC11	135.4121	33.0837	3181	Stacking
12	M.KMC12	136.8188	33.1279	2797	Stacking	34	M.MRC12	135.3414	33.1752	3278	Stacking
13	M.KMC21	136.7417	32.9506	2719	Stacking	35	M.MRD13	135.7557	33.1594	3103	Stacking
14	M.KMD13	136.6903	33.2201	2880	Stacking	36	M.MRD14	135.8584	33.1359	3052	Stacking
15	M.KMD14	136.5770	33.1727	2875	Stacking	37	M.MRD15	135.9586	33.1420	3021	Stacking
16	M.KMD15	136.5631	33.2331	2923	Stacking	38	M.MRD16	135.8401	33.0299	3001	Stacking
17	M.KMD16	136.5958	33.3045	2964	Stacking	39	M.MRD17	135.7144	33.0915	3074	Stacking
18	M.KME17	136.4451	33.4850	3137	–	40	M.MRE18	135.7747	32.9270	2964	Stacking
19	M.KME18	136.3828	33.3860	3078	–	41	M.MRE19	135.8336	32.8920	2929	Stacking
20	M.KME19	136.2564	33.4459	3158	–	42	M.MRE20	135.7733	32.8017	2908	Stacking
21	M.KME20	136.3325	33.5444	3205	–	43	M.MRE21	135.6670	32.8603	2969	Stacking
22	M.KME22	136.2702	33.3303	3068	–	44	M.MRF22	135.2250	32.9879	3201	–
						45	M.MRF23	135.3082	32.8827	3108	Available
						46	M.MRF24	135.1916	32.8545	3133	Available
						47	M.MRF25	135.1538	32.8919	3169	Available
						48	M.MRG26	134.5167	32.7615	3366	Available
						49	M.MRG27	134.5996	32.7089	3301	Available
						50	M.MRG28	134.5164	32.6251	3312	Available
						51	M.MRG29	134.4334	32.6752	3373	–

Table S3. Tsunami source time function composed of repetitive tsunami source events, estimated by the iterative deconvolution (24 times) and the least-square method. Note that the iterative deconvolution initially determines an event at 21:19:44, but because the additional least-squares method re-determines the source amplitude as zero, we remove it from the event list.

Tsunami event #	Time, UTC	Ampllitude relative to Ts01	Event interval [s]
Ts01	19:53:45	1.00	–
Ts02	20:13:57	1.50	1211.8
Ts03	20:25:30	1.56	692.4
Ts04	20:34:38	2.50	548.0
Ts05	20:43:32	2.45	534.5
Ts06	20:50:11	1.47	399.2
Ts07	20:51:27	4.46	75.9
Ts08	20:56:59	3.86	331.4
Ts09	21:00:23	3.54	204.8
Ts10	21:02:18	1.09	115.0
Ts11	21:05:56	4.47	217.2
Ts12	21:09:02	1.39	186.8
Ts13	21:13:27	5.48	264.7
Ts14	21:17:44	6.60	256.7
Ts15	21:22:08	5.74	264.0
Ts16	21:26:19	2.50	251.4
Ts17	21:29:44	1.63	205.2
Ts18	21:34:07	1.87	262.6
Ts19	21:38:06	1.56	238.9
Ts20	21:39:04	1.09	58.4
Ts21	21:40:45	1.53	101.1
Ts22	21:57:21	1.08	995.9
Ts23	22:02:58	1.74	337.1

Table S4. T-phase events detected from the envelope of the vertical component record of the OBS of KMB06 station. The event times (2nd column) are calculated by shifting backward the maximum amplitude times at the station (4th column) by the travel time for the source-station distance between Se02 and KMB06 at a typical T-phase speed of 1.5 km/s.

T-phase event #	T-phase event time, UTC	Max. amplitude [nm/s] at KMB06	Time of max. amplitude at KMB06, UTC	Starting time at KMB06, UTC	Ending time at KMB06, UTC	Duration [s] at KMB06	Event interval [s]
Tp01	19:00:49	2.18.E+03	19:06:18	19:03:48	19:08:48	299.85	–
Tp02	19:54:14	1.58.E+04	19:59:43	19:59:20	20:00:58	98.00	3205.2
Tp03	20:14:06	2.34.E+04	20:19:35	20:19:23	20:22:04	161.35	1191.5
Tp04	20:25:41	2.20.E+04	20:31:10	20:30:55	20:32:39	104.05	695.4
Tp05	20:35:09	1.65.E+04	20:40:38	20:40:07	20:42:00	112.55	568.0
Tp06	20:43:53	3.35.E+04	20:49:22	20:48:45	20:52:09	204.60	524.0
Tp07	20:51:53	1.88.E+04	20:57:22	20:56:59	20:59:55	176.15	479.8
Tp08	20:57:05	2.82.E+04	21:02:34	21:02:22	21:05:22	180.25	311.7
Tp09	21:00:55	2.36.E+04	21:06:24	21:06:14	21:08:53	159.20	230.1
Tp10	21:05:47	4.83.E+04	21:11:16	21:11:05	21:14:22	197.40	292.0
Tp11	21:09:56	3.66.E+04	21:15:25	21:14:47	21:17:55	187.25	249.7
Tp12	21:13:43	3.85.E+04	21:19:12	21:18:53	21:21:59	186.25	226.2
Tp13	21:17:43	6.23.E+04	21:23:12	21:23:00	21:26:29	209.00	240.1
Tp14	21:22:28	2.55.E+04	21:27:57	21:26:58	21:30:19	201.50	285.1

Table S5. Source events on 8 October 2023 to the west of Sofugan volcano, detected commonly based on analyses of data of T-phases, seismic waves (the USGS catalog), and tsunami waves. The time is in JST. We exclude tsunami events Ts06 and Ts10, which are very close in time to a larger event.

Event #	Seismic event		Tsunami event		T-phase event	
EV01	Se01	18:58:10	–	–	Tp01	19:00:49
EV02	Se02	19:53:46	Ts01	19:53:45	Tp02	19:54:14
EV03	Se03	20:13:51	Ts02	20:13:57	Tp03	20:14:06
EV04	Se04	20:25:23	Ts03	20:25:30	Tp04	20:25:41
EV05	Se05	20:34:33	Ts04	20:34:38	Tp05	20:35:09
EV06	Se06	20:43:09	Ts05	20:43:32	Tp06	20:43:53
EV07	Se07	20:51:26	Ts07	20:51:27	Tp07	20:51:53
EV08	Se08	20:56:48	Ts08	20:56:59	Tp08	20:57:05
EV09	Se09	21:00:41	Ts09	21:00:23	Tp09	21:00:55
EV10	Se10	21:05:32	Ts11	21:05:56	Tp10	21:05:47
EV11	Se11	21:09:16	Ts12	21:09:02	Tp11	21:09:56
EV12	Se12	21:13:28	Ts13	21:13:27	Tp12	21:13:43
EV13	Se13	21:17:28	Ts14	21:17:44	Tp13	21:17:43
EV14	Se14	21:21:42	Ts15	21:22:08	Tp14	21:22:28
EV15	Se15	21:26:45	Ts16	21:26:19	–	–