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Large tsunamis reset growth of massive corals

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Abstract

Corals at Ishigaki Island, Japan, are characterized by their high species diversity. Not only are they struck by storm waves generated annually by typhoons, the corals, especially the massive ones, in the fringing reef were buffeted by huge tsunami waves with a run-up height of ca. 30 m in 1771 Meiwa tsunami and its predecessors at few hundred-year intervals. We present field survey and numerical results demonstrating that such near-field large tsunamis could have reset the growth of massive corals, a phenomenon which large typhoons have not caused. Our field survey revealed that the massive corals in the lagoon are not attached to the bedrock but are instead located on the sandy sea bottom. Therefore, those are movable of sufficiently large wave inundated in the lagoon. Our numerical results further showed that the maximum velocity of the tsunami at the reef edge, calculable as < 21.2 m/s at the study area, is still high in the shallow lagoon, perhaps generating sufficiently strong hydrodynamic force to devastate the massive corals in the shallow lagoon entirely, as well as some presumed damages on tabular and branching corals on the reef crest and reef slope. This numerical result is consistent with the observed fact that even a 9-m long *Porites* boulder (about 220 t) was cast ashore by the 1771 tsunami. The sizes of the presently living massive corals of *Porites* spp. are consistent with our hypothesis that they started to grow after the latest 1771 tsunami event. At the coral reefs of high tsunami-risk countries, severe destruction of corals by large tsunami waves should be considered for their growth history because, depending on the bathymetry, coral characteristics, and tsunami hydrodynamic features, tsunamis can radically alter coral habitats.

Keywords: Boulder, Coral, Disaster, Hazard, Ishigaki Island, Tsunami, Tsunami effects on coral, Coral boulder, Numerical modeling

Introduction

Physical perturbation of corals by extreme waves can generate a remarkably strong influence on marine ecosystems (Madin and Connolly 2006; Puotinen et al. 2016). Tsunami waves are extremely powerful, affecting coral communities. In fact, coral damage by tsunami waves, which includes whole or partial damage of corals by destruction, rotation, sedimentation of sands on corals, and local slides of reef slopes, has been reported in the case of the 2004 Indian Ocean tsunami (IOT) (e.g., Phuket Marine Biological Center (PMBC) 2005; Chavanich et al. 2008) and the 2009 South Pacific tsunami (McAdoo et al. 2011; Witt et al. 2011; Dilmen et al. 2015).

Coral damage is generally related to the place where the tsunami hydrodynamic forces strengthen (Goto and Imamura 2009; Kawamata et al. 2009), although the relation is unclear. For example, coral damage by the 2004IOT at the islands in Thailand was high in straits among the islands and at the northern and southern headlands of the respective islands (PMBC 2005), where the tsunami hydrodynamic forces are stronger (Kawamata et al. 2009). However, coral damage by the 2004IOT was generally low. Therefore, researchers who conducted studies after 2004IOT have tended to conclude that the tsunami impact effects on coral communities are limited (Baird et al. 2005; Morri et al. 2015).

However, because few case studies have been reported, one must not underestimate the tsunami effects on corals' ability to inhabit an area. Huge tsunami waves are likely to have the capability of devastating coral communities depending on the nearby bathymetric features,

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coral characteristics, and related hydrodynamic forces. This possibility must be explored because tsunami waves might be able to change the coral habitability radically: they present a high risk to reef environments. In fact, huge coral boulders are well known to be cast ashore by tsunami waves (so-called tsunami boulders) and storm waves (e.g., Goto et al. 2010a, 2013; Atwater et al. 2017; Ramos et al. 2017; Hongo et al. 2018; Rixhon et al. 2018). These phenomena in turn indicate that large corals can be damaged by extreme wave events.

As one example, based on field observations and tsunami numerical modeling, we describe the possible catastrophic destruction of massive corals by the 1771 Meiwa tsunami, which struck the east coast of Ishigaki Island, Japan (Fig. 1a) (Goto et al. 2010a). Moreover, we discuss the effects of catastrophic but infrequent tsunami wave strikes on coral communities.

Study area

Ishigaki Island is encircled by a < 1.5 km wide fringing reef (Hongo and Kayanne 2009). Our study area, Ibaruma reef, has a fringing reef 500–900 m offshore (Fig. 1b, c, Goto et al. 2010b). The coral reef is divisible into a reef flat and reef slope (Fig. 1c): the former is further classified into a shallow lagoon that is up to 5 m deep and a reef crest (Hongo and Kayanne 2009). During low tide, the reef crest lies exposed above the ocean surface. The reef slope is steep, with approx. 1/10 inclination (Fig. 1c). The reef is well-developed along the Pacific windward coast rather than leeward areas (Ministry of the Environment and the Japanese Coral Reef Society 2004). Few typhoons annually pass close to the Ishigaki Island, and the coral reef in the study area is frequently affected by the storm waves (e.g., Hongo et al. 2012).

Forty-four coral species are found between the shoreline and 1580 m from the shoreline, characterized by a

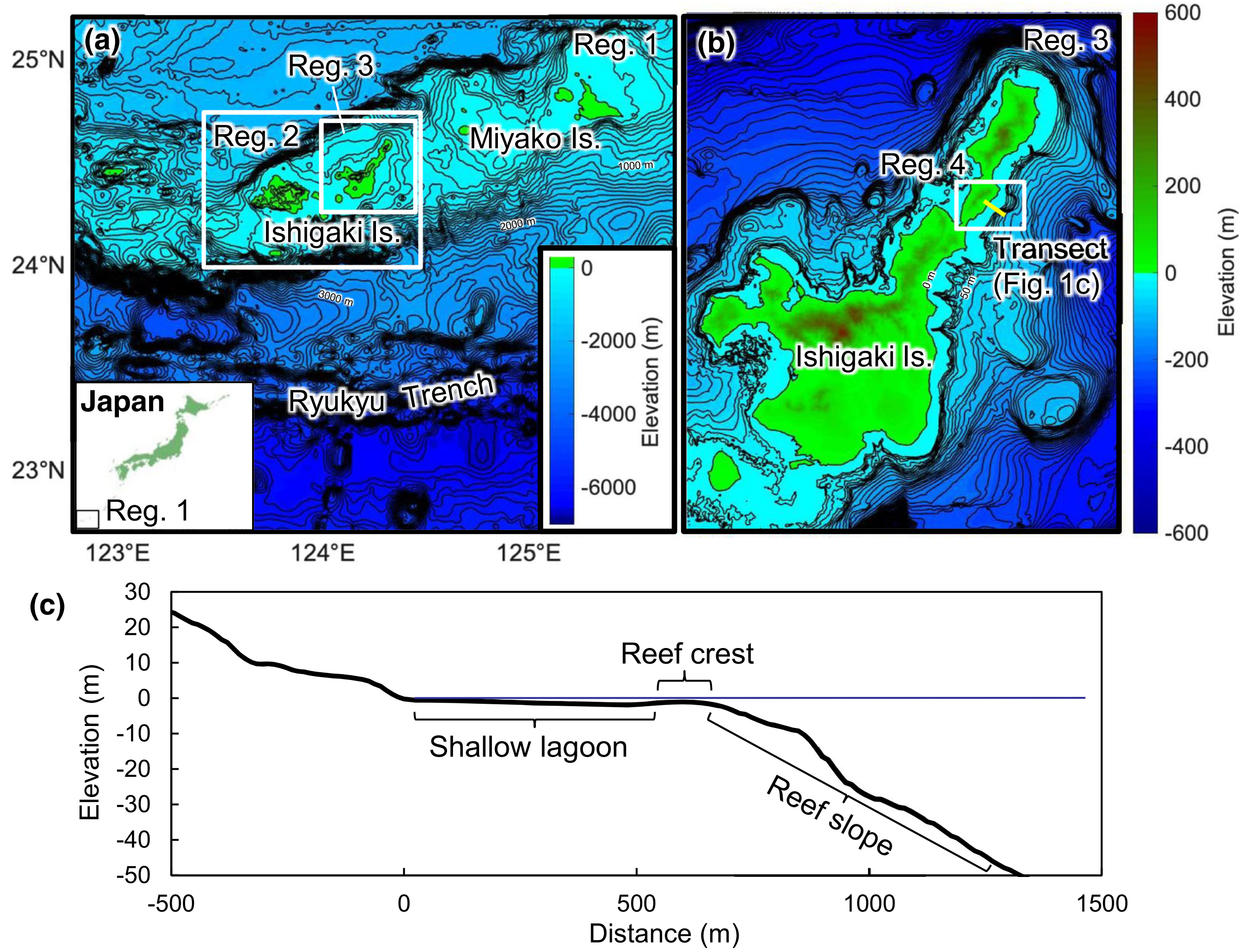

Fig. 1 **a** A map showing bathymetry and computational domains for this study from regions 1 to 4. A bathymetry contour line is 100-m interval. **b** A map showing Ishigaki Island and our survey area. A bathymetry contour line is 10-m interval. **c** A representative cross-sectional profile of elevation (m) at the Ibaruma reef reproduced from grid data

water depth of 20 m, at Ibaruma reef (Hongo and Kayanne 2010). Massive corals, tabular corals, and branching corals represent 33%, 10%, and 6% of the total coverage, respectively. Other growth forms of coral (e.g., encrusting and sub-massive) are also observed in the reef. The shallow lagoon is dominated by massive corals (e.g., *Porites* spp.). Tabular corals (e.g., *Acropora* spp.) are mainly found from the reef crest to the upper reef slope. Branching corals (e.g., *Montipora* spp. and *Acropora* spp.) are widely distributed from the shallow lagoon to the reef crest. Encrusting corals (e.g., *Pachyseris* spp.) occupy the lower reef slope.

The 1771 Meiwa tsunami struck Ishigaki Island although the epicenter causing this tsunami has not been revealed. Historical documents revealed that the run-up heights were estimated as up to about 30 m at the southeast coast of Ishigaki Island (Goto et al. 2010a). Displacement of *Porites* boulders by the tsunami, which were originally located in the shallow lagoon, was reported along the shoreline of the east coast including the Ibaruma reef (Kawana and Nakata 1994; Suzuki et al. 2008; Goto et al. 2010a, 2010b, 2013; Araoka et al. 2013). Despite their mass, the exceedingly heavy boulders are scattered well beyond the transport limit for storm waves estimated by Goto et al. (2010b, 2013). Watanabe et al. (2016) further supported the reports of their tsunami origin using numerical modeling results, demonstrating that their size and spatial distributions are not explainable by typhoon-generated storm waves. Moreover, according to the ^{14}C age results, most of them were deposited by the 1771 Meiwa tsunami although some of the boulders might have been deposited by earlier tsunamis (Suzuki et al. 2008; Araoka et al. 2013). Recent studies estimated tsunami recurrence intervals of about 150–400 years based on tsunami boulders (Araoka et al. 2013) and about 600 years based on fine-grained tsunami deposits (Ando et al. 2018; Kitamura et al. 2018a, 2018b). The largest *Porites* boulder of the 1771 Meiwa tsunami origin, locally called a *Bari-ishi* boulder (Fig. 2a, *Bari-ishi* means a stone split into pieces in Japanese), is 129 m^3 (9.0 × 7.0 × 3.9 m), weighing an estimated 216 t (Goto et al. 2010b; Araoka et al. 2013).

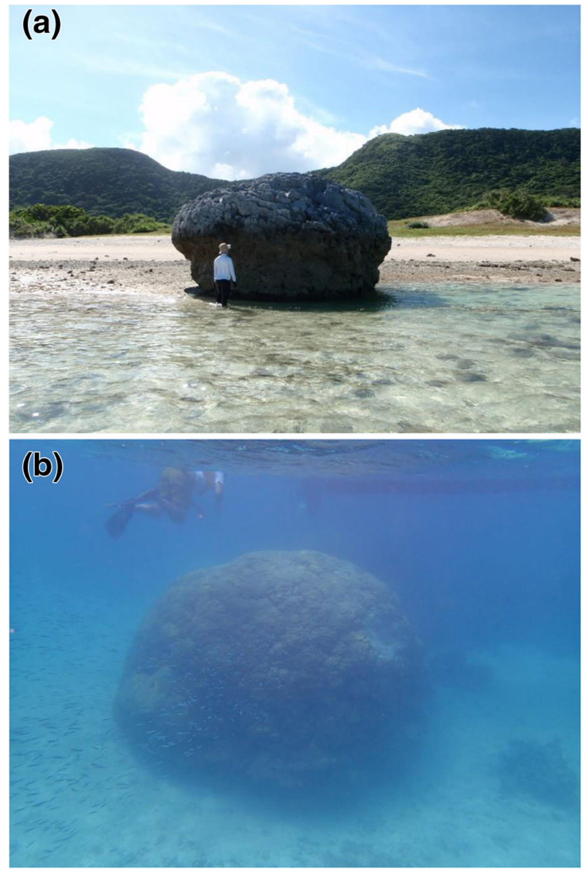

Fig. 2 a The largest *Bari-ishi* boulder that was deposited by the 1771 Meiwa tsunami at the Ibaruma reef (Goto et al. 2010b). **b** An image of typical massive living coral in the lagoon

Methods/Experimental

Since the massive corals grow annually with a nearly constant rate (e.g., Araoka et al. 2010), their size distribution allows us to test whether these massive corals started to grow after the 1771 Meiwa tsunami. We therefore took non-destructive underwater measurements of the size and spatial distributions of 85 massive corals of *Porites* spp. using a scale and handy global positioning system (GPS) in the Ibaruma reef mainly in August 2011. We measured massive corals having a long axis greater than approx. 2 m (Table 1).

Results reported by Miyazawa et al. (2012) provide the basis of our numerical modeling of the tsunami inundation. A linear equation is adopted to calculate propagation of the 1771 Meiwa tsunami in the wider regions. A nonlinear equation in a rectangular coordinate system is used to calculate the tsunami propagation in the reef and the surrounding regions (Goto et al. 1997), and the bottom friction is allowed (Kotani et al. 1998). For the calculation, a nested grid system is created across four regions (Figs. 1 and 3a). Spatial grid sizes of the respective regions are 300 m, 100 m, 50 m, and 10 m for regions 1, 2, 3, and 4, respectively (after Miyazawa et al. 2012). Manning's friction coefficient is based on the land use map. The calculation time is 45 min after tsunami generation, which is a sufficient time to evaluate the tsunami effects on the reef (Miyazawa et al. 2012). It should be noted that bathymetric data in the lagoon are not well reproduced because taking such measurements is difficult inside the lagoon and future update of the bathymetric data in the lagoon is required.

Some source models are proposed for the 1771 Meiwa tsunami. Imamura et al. (2008) and Miyazawa et al. (2012) proposed an intraplate fault plus landslide model.

Table 1 Locations and three dimensions of measured living massive corals

No.	Latitude (°N)	Longitude (°E)	Long axis (cm)	Short axis (cm)	Height (cm)
1	24.51656	124.29756	340	330	130
2	24.51655	124.29747	240	140	115
3	24.51655	124.29743	380	270	165
4	24.51599	124.29714	315	265	135
5	24.51557	124.29736	345	325	140
6	24.51574	124.2974	230	220	120
7	24.51589	124.29751	195	150	130
8	24.51493	124.29794	330	330	250
9	24.51469	124.29806	410	390	200
10	24.51466	124.29796	370	310	170
11	24.51466	124.29802	340	265	197
12	24.51458	124.29829	455	395	280
13	24.5146	124.29834	330	230	245
14	24.51459	124.29828	250	200	90
15	24.51457	124.29825	210	190	175
16	24.51483	124.29823	340	220	80
17	24.51464	124.29819	260	220	75
18	24.5145	124.29846	390	350	285
19	24.51479	124.29908	315	290	210
20	24.51483	124.29903	440	430	242
21	24.51501	124.299	300	300	196
22	24.51501	124.299	370	340	187
23	24.51501	124.299	250	245	185
24	24.51517	124.29877	235	200	129
25	24.51518	124.29884	300	285	232
26	24.51463	124.29982	430	365	228
27	24.51465	124.29977	340	320	278
28	24.51459	124.29979	490	410	265
29	24.51462	124.29961	455	425	250
30	24.51463	124.29958	550	410	248
31	24.51464	124.29947	480	445	260
32	24.5146	124.29935	440	385	250
33	24.51452	124.29928	490	410	312
34	24.51471	124.29922	430	360	198
35	24.51394	124.29768	435	410	310
36	24.5131	124.29748	310	250	175
37	24.5131	124.29748	350	305	150
38	24.51322	124.29745	305	300	185
39	24.51318	124.29765	415	300	172
40	24.51315	124.29773	290	265	213
41	24.51012	124.29201	650	615	190
42	24.51287	124.29357	340	240	130
43	24.51266	124.29351	455	330	172
44	24.51253	124.29349	225	180	155

Table 1 Locations and three dimensions of measured living massive corals *(Continued)*

No.	Latitude (°N)	Longitude (°E)	Long axis (cm)	Short axis (cm)	Height (cm)
45	24.51262	124.29381	210	145	120
46	24.51247	124.294	340	270	192
47	24.51243	124.29408	350	280	190
48	24.51231	124.29415	390	380	207
49	24.51228	124.29416	280	240	185
50	24.51223	124.29438	270	190	142
51	24.51212	124.29429	445	400	102
52	24.5122	124.29443	315	240	145
53	24.51245	124.29459	380	375	135
54	24.51261	124.29461	365	345	160
55	24.51252	124.29506	425	415	118
56	24.51238	124.2949	360	270	190
57	24.51227	124.29513	490	460	210
58	24.51225	124.29521	285	150	180
59	24.51176	124.29476	360	340	172
60	24.51189	124.29476	350	200	178
61	24.51187	124.29477	265	190	145
62	24.51244	124.29581	465	420	224
63	24.51242	124.29587	450	370	160
64	24.51242	124.29587	350	310	125
65	24.51242	124.29595	330	295	143
66	24.51227	124.29598	300	260	132
67	24.5122	124.29593	345	300	115
68	24.51062	124.29468	525	400	195
69	24.51067	124.29466	355	335	190
70	24.51097	124.29337	270	200	150
71	24.51109	124.29347	235	220	195
72	24.51106	124.29348	425	375	190
73	24.51091	124.29326	235	190	135
74	24.51088	124.29315	320	265	225
75	24.51085	124.29319	180	170	135
76	24.51078	124.29317	400	380	173
77	24.51053	124.29333	350	310	170
78	24.51078	124.29328	210	165	125
79	24.51078	124.29328	250	175	135
80	24.51078	124.29328	200	190	133
81	24.51083	124.29299	420	385	165
82	24.51088	124.29292	340	280	160
83	24.51087	124.29251	275	225	160
84	24.511	124.29203	330	265	175
85	24.51107	124.29218	320	210	120

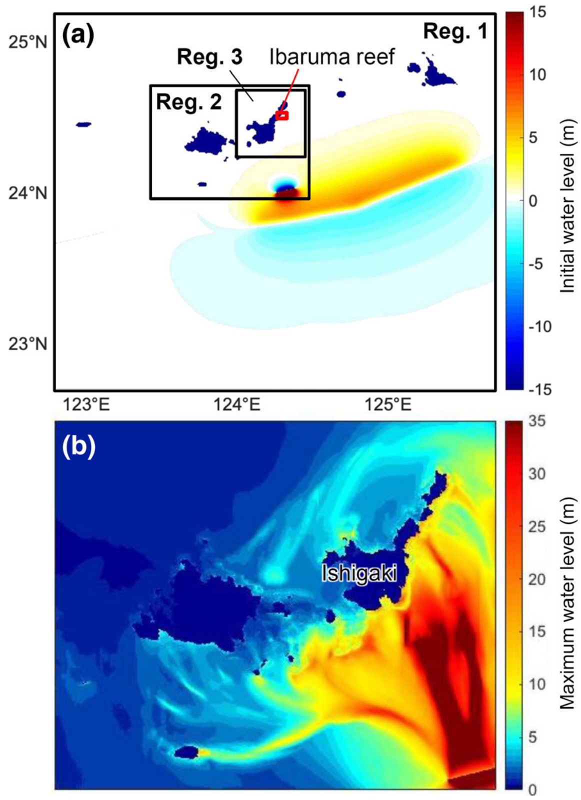

Fig. 3 **a** Computational domains for this study from region 1 to region 3. The initial water level of the 1771 Meiwa tsunami is also shown after Miyazawa et al. (2012) and Hisamatsu et al. (2014). **b** Maximum water level at 45 min after the tsunami in region 2 calculated in this study

Nakamura (2009) suggested a tsunami earthquake model that is set along the Ryukyu Trench. Arai et al. (2016) and Ando et al. (2018) supported this model. Hsu et al. (2013) proposed a mega-splay fault as the tsunami source. Okamura et al. (2018) proposed tsunami was generated by a large collapse of the accretionary prism along the oblique subduction zone. All these models are tuned parameters to fit the historical description of tsunami run-up heights (e.g., Goto et al. 2012). Consequently, no significant difference is found during the propagation and run-up processes. For that reason, the difference of source models is not crucially important for our research. Therefore, this study applied the source model proposed by Hisamatsu et al. (2014) (Table 2), which is the updated version of the model described by Miyazawa et al. (2012), for the main discussion. Results obtained using the models of Imamura et al. (2008) and Nakamura (2009) are attached in the supplement file. As described above, the results are fundamentally the same in terms of local inundation and run-up at Ibaruma reef (Additional file 1: Figures S1–S6). Therefore, we do not advance our discussion using these models.

To evaluate the damage to corals from the tsunami, it is important to estimate the hydrodynamic force, which is expressed as the sum of the drag, inertia, and lift forces, acting on the corals (Massel and Done 1993; Madin and Connolly 2006; Imamura et al. 2008). We assumed living massive corals as ellipsoidal boulders and adopted numerical models for boulder transport by tsunami waves as proposed by Imamura et al. (2008). The model validity was well evaluated by subsequent studies (e.g., Goto et al. 2010c). For the calculation of the massive coral movement by the tsunami, we assumed average ($2.5 \times 1.9 \times 1.2$ m) and maximum ($9.0 \times 7.0 \times 3.9$ m) sizes of measured tsunami boulders (after Watanabe et al. 2016) to investigate the difference of tsunami impact against the coral size. The wet density of the boulders is assumed as 1.68 g/cm^3 (Goto et al. 2010b; Watanabe et al. 2016). The coefficients of static friction, dynamic friction, drag, and mass are respectively 0.68, 0.65, 1.05, and 1.67.

Results

Field observation

Living colonies of meter-long *Porites* spp. are observed in the shallow lagoon (Figs. 2b and 4). Some of them have a microatoll shape. Tabular and branching corals are distributed mainly on the reef crest and the reef slope, although they are observed in rare cases in the shallow lagoon (Hongo and Kayanne 2009).

Whereas many massive corals exist in the Ibaruma reef, the distribution of meter-size living corals occurs only to a limited degree in the shallow lagoon (Fig. 4).

Table 2 A fault model used for this study

Tsunami source	Latitude (deg)	Longitude (deg)	Depth (km)	Length (km)	Width (km)	Dislocation (m)	Strike (deg)	Dip (deg)	Rake (deg)
Fault 1	24.2018	125.5184	5	41	35	14	245	70	90
Fault 2	24.0526	125.1497	5	40	35	14	246	70	90
Fault 3	23.9100	124.8000	5	35	35	13	259	70	90
Fault 4	23.8421	124.4576	5	36	35	14	261	70	90
Landslide	24.0036	124.2640	0.1	12	8	90	76	70	90

The model was proposed by Miyazawa et al. (2012) and modified by Hisamatsu et al. (2014). The model is composed of four sub-faults with another fault that imitate the submarine landslide. Latitude and longitude of the fault model denote upper left corner of the rectangular fault

The lagoon became deep from the beach toward the landward edge of the reef crest. Therefore, massive corals also tend to be large toward the deeper zone. The sea floor in the lagoon is covered by sand and coral rubble, with no exposure of the hard ground. Therefore, the massive corals in the lagoon are not attached to the bedrock but are instead located on the sandy sea bottom. This is an extremely important finding when considering the initial condition of corals for the tsunami numerical simulation.

The lengths of long and short axes of living massive corals show a positive correlation (Fig. 5), although their heights are weakly correlated with the long axis length: the heights are also constrained by the water depth because they cannot grow higher than the low tide level. The largest living massive coral observed in the Ibaruma reef is 6.5 × 6.2 × 1.9 m (no. 41 in Table 1). No coral is observed larger than this one in the studied region.

Goto et al. (2010b) studied the tsunami boulders deposited inside the lagoon and along the coast at the Ibaruma reef. According to their results, some of these boulders are also composed of massive *Porites* corals with the maximum of the *Bari-ishi* boulder (Fig. 2a, 9.0 × 7.0 × 3.9 m). Similar to the living corals, some tsunami boulders show microatoll shape (Goto et al. 2010b). Not only are there coral boulders, but there are also some reef boulders. Different from the distribution of living corals, coral tsunami boulders tend to be observed in the landward half of the lagoon (shallower zone) and are mostly deposited along the shoreline (Fig. 4). Some large boulders are still deposited in the lagoon, but they had died. Part of them emerges during the low tide, indicating that they had certainly been moved landward from their original location.

Numerical modeling

Figure 3 shows the initial water level and the modeled maximum water level at 45 min after tsunami generation. The water level, which is high at the south to east coast of Ishigaki Island (ca. 28.2 m), is consistent with estimated run-up heights from historical documents (ca.

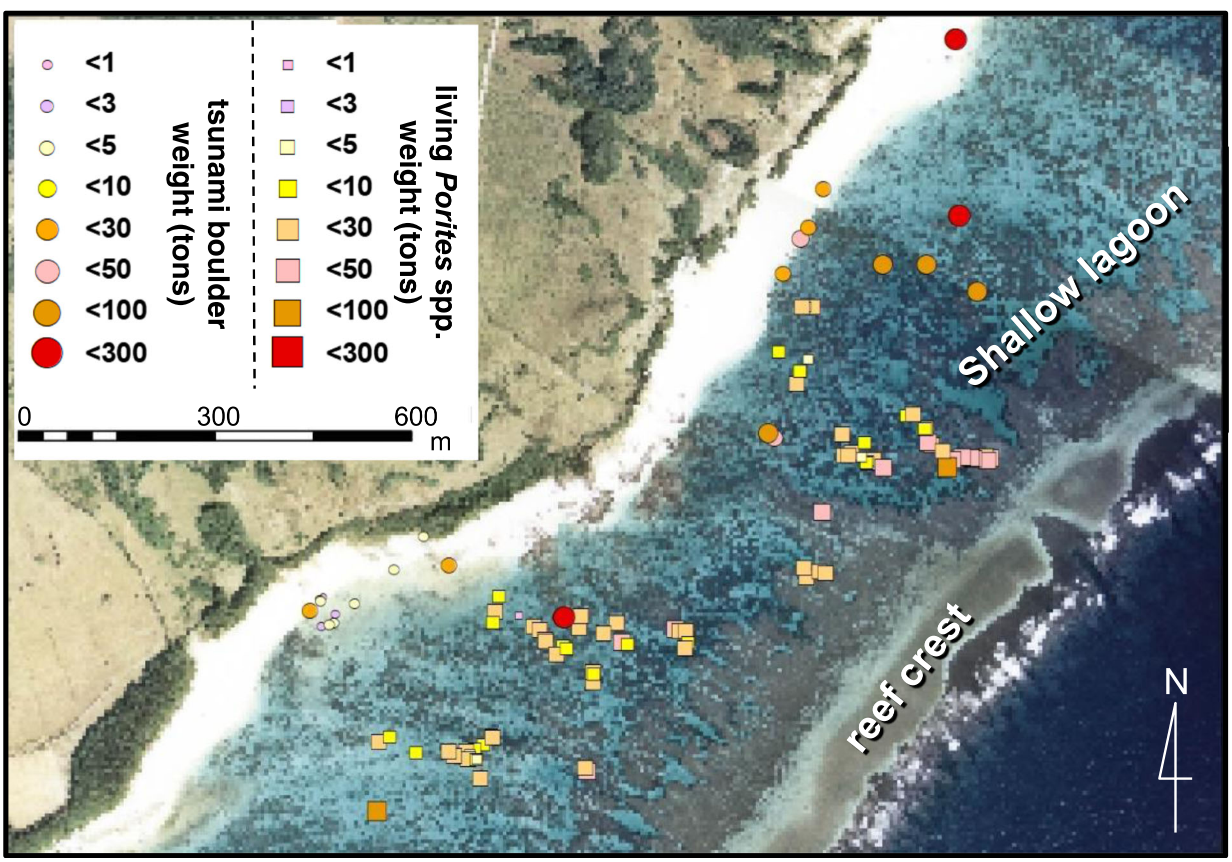

Fig. 4 A map showing the distribution and size of living massive corals of *Porites* sp. (see Table 1 for the list) and coral tsunami boulders at Ibaruma reef (after Goto et al. 2010b). Aerial photographs were provided by the Ministry of Land, Infrastructure, Transport and Tourism, Government of Japan (1977 photograph). The weight of living corals was estimated based on the assumption of ellipsoidal shape with a wet density of 1.68 g/cm^3

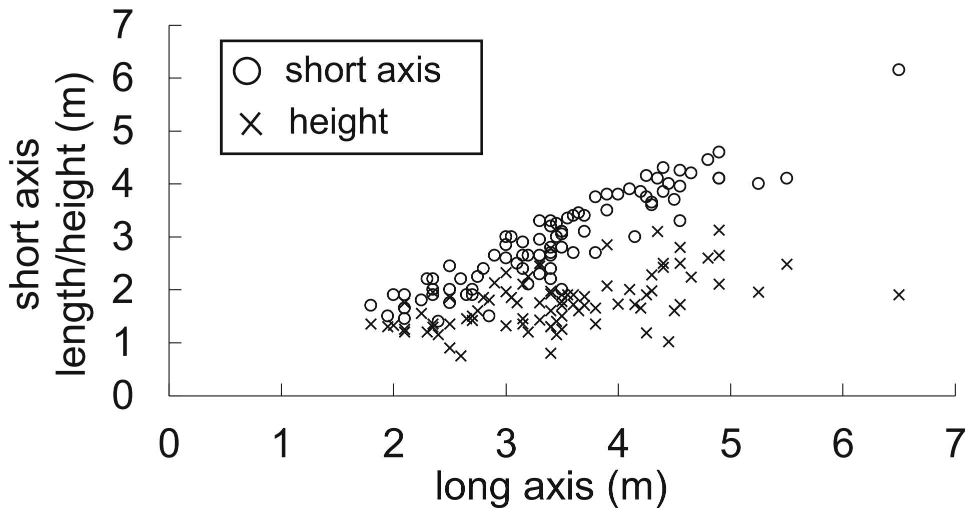

Fig. 5 A diagram showing the relation between long and short axes lengths and height of the living massive corals of *Porites* spp. See Table 1 for the list of original data

30 m, Goto et al. 2010a, 2012). The current velocity is higher at the reef slope rather than in the shallow lagoon (Fig. 6) because the very shallow fringing reef acts as a barrier and because the breaking point of the tsunami wave is far offshore of the reef edge. It is noteworthy that the maximum current velocity is reached at about 21.2 m/s around the reef near the Ibaruma reef (Fig. 6). Such an extremely high current velocity is marked at the reef edge and channel (Fig. 6b). The maximum velocity is still high, even in the shallow lagoon of the east coast (Fig. 6b, c). In contrast to the east coast, the velocities are generally lower at the west coast than at the east coast (Fig. 6b).

Figure 7 shows the calculated initial and final stop positions of average and maximum sizes of corals moved by the 1771 Meiwa tsunami. The movement of average-size corals is well reproduced as they are cast ashore. However, the maximum boulder is moved a few hundred meters, although it is not shown to reach its present position. This underestimation by numerical results might be explained by two reasons. First, this region lacks a detailed description of tsunami run-up height: a study by Goto et al. (2012) estimated a wide range in run-up heights (9.4–29.3 m). Therefore, the constraint of the tsunami source model might have been insufficient locally, and tsunami hydrodynamic force could have been underestimated. Secondly, bathymetric data in the lagoon are not well reproduced because taking such measurements is difficult inside the lagoon. Therefore, a future update of the source model as well as bathymetry is required. Nevertheless, we infer that our results approximately reproduced the phenomena by which even a 9 m long huge massive coral could have been moved a few hundred meters. It could have emerged (dead) by the 1771 Meiwa tsunami.

Discussion

Tsunami impact on the massive corals

The lagoon in Ibaruma reef usually shows a calm condition, even during typhoon events, because the very shallow and wide reef crest protects the physical perturbation by the waves (Goto et al. 2010b; Hongo et al. 2012). In fact, massive corals could have grown to be very large (long axis of ca. 9 m) with no physical disturbance during the typhoon-generated storm waves even if the massive corals had not been fixed on the ground. Hongo et al. (2012) suggested that a large storm wave can break far offshore of the reef edge and attenuate well before it reaches the shallow lagoon because the reef crest at the east coast of Ishigaki Island is well developed. This developed reef crest would be the main reason why such vulnerable massive corals in the shallow lagoon can survive the yearly typhoon impact over such a long period.

The 1771 Meiwa tsunami is the notable exception during at least the last 240 years, showing physical disturbance inside the lagoon of Ibaruma reef because of its very high current velocities acting on the massive corals (< 21.2 m/s). In fact, the largest *Bari-ishi* boulder could have been displaced easily by the 1771 Meiwa tsunami (Araoka et al. 2013). Moreover, this velocity is a few times higher than the observed current velocity of the recent tsunami events (Goto et al. 2007; Matsutomi and Okamoto 2010) including the 2004IOT-devastated areas such as the west coast of Sumatra Island, Indonesia (Prasetya et al. 2011), where minor to moderate coral damage was reported (Baird et al. 2005), the 2009 South Pacific tsunami

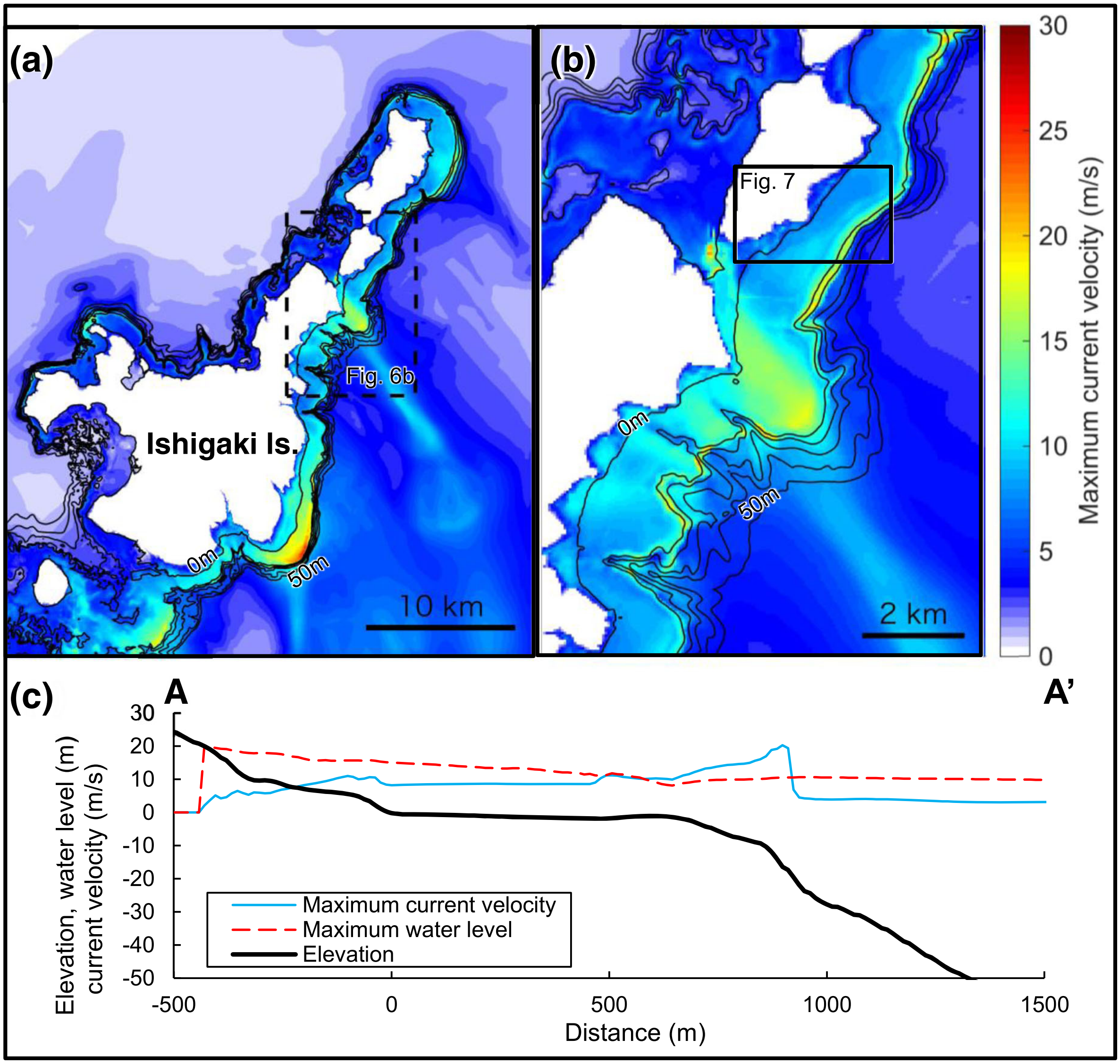

Fig. 6 **a** Numerical result for the absolute value of the maximum tsunami current velocity (m/s) around the Ishigaki Island and **b** around the Ibaruma reef. **c** Cross-sectional profiles of elevation (m), maximum water level (m), and maximum current velocity (m/s) at the Ibaruma reef. The transect location is depicted in Fig. 7a

(e.g., Dilmen et al. 2015) and the 2011 Tohoku-oki tsunami (Sugawara and Goto 2012).

Then, why is the tsunami velocity in the reef so high in case of the 1771 Meiwa tsunami? Recently, Kitamura et al. (2018b) examined the molluscan assemblages preserved within four ancient tsunami deposits, including 1771 Meiwa tsunami, in a trench located 4 km southwest of the study area. The authors concluded that the present-day shallow lagoon protected by reef crests has been present at least during the last 1200 years. Thus, high tsunami velocity is not explained by the absence of reef crests. First, this tsunami is exceedingly large locally, even if compared to recent large tsunami events. The maximum run-up height is estimated as approx. 30 m (Goto et al. 2010a) and is lower than the approx. ~ 40–50 m run-ups of the 2004IOT (Lavigne et al. 2009) and the 2011 Tohoku-oki tsunami (Mori et al. 2012). However, the maximum run-up height of the 1771 Meiwa tsunami was recorded at the flat coastal area with the protection of the coast by the approx. 1.5 km-wide reef (Goto et al. 2010a), whereas high run-up heights of the 2004IOT and the 2011 Tohoku-oki tsunami were recorded in narrow valleys and bays where tsunamis could have been focused and could have thereby reached so high. Therefore, the impact of the 1771 Meiwa tsunami on the reef could have been much stronger than the other recent large tsunamis. Secondly, the fault width, which affects the tsunami wave length, of the recent

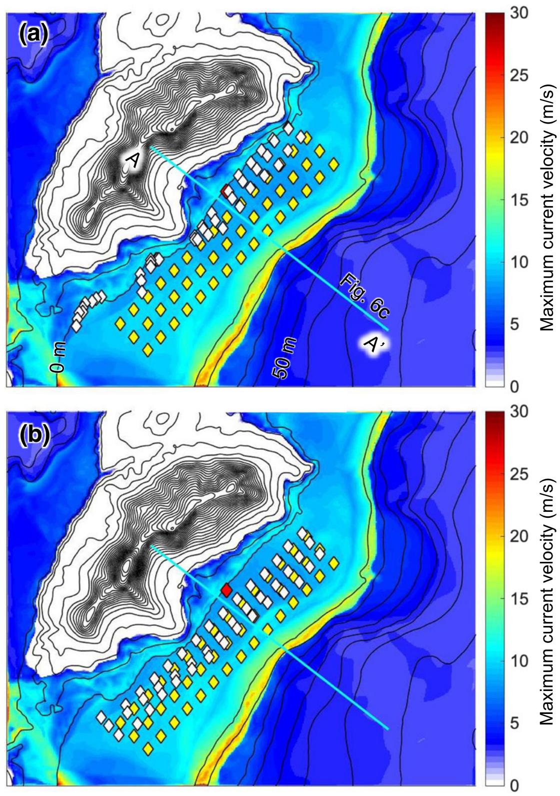

Fig. 7 Numerical results of coral transport by the 1771 Meiwa tsunami in region 4. **a** Average size boulder. **b** The largest boulder. Yellow, white, and red diamonds respectively denote original location, final stop position, and present location of *Bari-ishi* boulder. The line in **a** is the transect line in Fig. 6c

tsunami such as the 2011 Tohoku-oki tsunami is estimated as about 100 km (e.g., Imamura et al. 2012), whereas that of the 1771 Meiwa tsunami is estimated as less than 35 km (Table 2, Additional file 2, Imamura et al. 2008; Nakamura 2009; Miyazawa et al. 2012). If the wave length or period of the tsunami becomes short, the vertical variation of water level becomes faster; thus, horizontal current velocity also becomes faster. Indeed, some researchers stated that a tsunami with a shorter wave length usually generates a faster current for a given wave height (e.g., Gusman et al. 2012). Moreover, to explain a 30 m high run-up at the very flat and reef-protected coast, the initial maximum water levels must also be very high (Fig. 3a, Miyazawa et al. 2012). Therefore, the 1771 Meiwa tsunami can be characterized as having a short wave period with exceedingly large wave height, which indicates that the wave has a very steep shape. Such a wave can generate extremely high velocity at the reef after wave breaking.

No massive coral, living or dead, is larger than the *Bari-ishi* boulder in the shallow lagoon of the east coast of Ishigaki Island. Displacement of the largest *Bari-ishi* boulder by the 1771 Meiwa tsunami suggests that the massive corals of *Porites* spp. smaller than the boulder that was in the shallow lagoon before the 1771 Meiwa tsunami should have been displaced easily on land or resettled somewhere in the shallow lagoon by the tsunami. This supposition is well confirmed: small boulders are easily cast ashore by the tsunami (Fig. 7a). If this is the case, then massive corals of *Porites* spp. in the shallow lagoon of the Ishigaki Island were once fully devastated by the 1771 Meiwa tsunami: they subsequently restarted the growth after the tsunami. It is noteworthy that massive corals are not attached to the ground but merely located on the sandy ground. This would be very important evidence suggesting that many large massive corals were deposited by the 1771 Meiwa tsunami because they were movable.

This hypothesis is testable based on the size of the presently living massive corals. Massive corals of *Porites* spp. showed a high average growth rate of 7–20 mm/year at Ishigaki Island (Mitsuguchi et al. 1996; Tsunoda et al. 2006; Suzuki et al. 2008; Shimamura et al. 2008; Araoka et al. 2010). Among them, the study site by Araoka et al. (2010), where the average growth rate of *Porites* sp. is about 13.5 mm/year (about 10–20 mm/year, D. Araoka, personal communication), is the closest location to our site. In addition, Araoka et al. (2013)

estimated the creation of the *Bari-ishi* boulder as AD 1227–1317 (± 1σ) based on ^{14}C age measurements. The coral is dead by the time of the 1771 Meiwa tsunami. Therefore, this boulder grew up to 9 m in diameter during 454–544 years. Consequently, the growth rate can be estimated as about 8.3–9.9 mm/year (4.5 m in radius divided by 454–544), which is well consistent with the growth rate estimated from Araoka et al. (2010).

Today, some 240 years have passed since the tsunami for which we conducted the field survey in 2011. Therefore, the size of the massive corals can be expected to have reached up to about 4.0–6.5 m in diameter (8.3–13.5 (mm/year) × 240 (years) × 2 (to be diameter)). Considering the variation of the growth rate depending on the local factors, we infer that this estimated possible maximum size is well consistent with the observed maximum size of the living massive corals in the shallow lagoon of the Ibaruma reef, which is less than 6.5 m (Table 1, Fig. 5).

Some *Porites* boulders that had been transported by the tsunami have also been redeposited in the shallow lagoon (Fig. 4, Suzuki et al. 2008; Goto et al. 2010a). They could have survived the tsunami if the conditions of the shallow lagoon soon after the tsunami were suitable for coral growth. However, the absence of living corals larger than 6.5 m suggests that no such corals exist. Consequently, even massive corals that were transported by the tsunami but which were still located in the shallow lagoon might have died soon after the tsunami. This fact is probably explained by the indirect effect of the tsunami on the corals. For example, sand or coral fragments might have covered the massive corals. Impact of the sand and coral fragments flowing in the tsunami current on the living corals would have been another damaging influence on the living corals. Terrestrial reddish soil, which usually affects the coral habitability (Fortes 2001), might have been deposited by the backwash in great amounts in the shallow lagoon.

Tsunami impact on tabular and branching corals

Damage to tabular and branching corals by the tsunami is far more difficult to evaluate than that to the massive corals because of the corals' complex structures and their habitability. According to numerical modeling conducted by Kawamata et al. (2009), the coral damage is generally proportional to the tsunami current velocity: approx. 50% coral damage was generated at Similan Island in Thailand by the 2004IOT when the maximum current velocity of the tsunami exceeded about 5 m/s. Hongo et al. (2012) also suggested that tabular corals might be damaged by typhoon-generated storm waves with approx. 6 m/s current velocity. It is particularly important to note that our estimated maximum current velocity generated by the 1771 Meiwa tsunami at the Ibaruma reef is a few times higher than these estimates. Therefore, it is conservative to estimate that many tabular or branching corals at the east coast of Ishigaki Island were physically damaged by the 1771 Meiwa tsunami.

Hongo et al. (2012) revealed that larger tabular corals are more vulnerable to wave impact because they can be affected by larger wave force attributable to their shapes. This result in turn suggests that smaller tabular corals might have some chance of surviving the tsunami impact. In fact, Reyes et al. (2015) reported limited damage to corals after super typhoon Haiyan on 2013.

Tabular and branching corals are far smaller than the massive corals. Moreover, these corals are selectively distributed mainly on the reef crest and the reef slope, where the storm wave impact is strong (Hongo et al. 2012). Therefore, they might have been damaged repeatedly and restarted growth in a short return period by large typhoons every few to a few tens of years (Hongo et al. 2012). Therefore, the tsunami impact might have been one such destructive events for them and might not have been remarkable, as in the case of massive corals.

Conclusions

It is usually considered that local conditions (e.g., salinity, water temperature, frequency, and magnitude of storm wave impact) should have affected the growth history of corals and coral reefs (Montaggioni and Braithwaite 2009). However, catastrophic destruction of coral by the tsunami would also have been one important factor affecting the coral growth at Ishigaki Island because historical and geological evidence indicates that small and large tsunamis in the past frequently struck eastward of the island at 150 to 400 or 600-year intervals (e.g., Araoka et al. 2013; Ando et al. 2018). If this is the case, then coral habitability at the east coast of Ishigaki Island might have been repeatedly reset and restarted to grow every few hundred years. This idea can be tested further in future work to compare the differences of the coral characteristics, size, and diversity at the west coast of Ishigaki Island, where damage from the paleotsunamis is expected to have been minor (Goto et al. 2010a).

Our results further suggest that similar catastrophic damage of corals by tsunamis can be expected at locations where remarkably large near-field tsunamis might have been generated, such as tropical islands in the Pacific Ocean (e.g., Frohlich et al. 2009). Not only the tsunami energy and local bathymetry but also coral characteristics (e.g., whether massive corals attached to the ground or not) would be very important factors of coral damage. At the coral reefs of high tsunami-risk countries, the catastrophic destruction of corals by large tsunamis should be considered when assessing their growth history because tsunamis can radically change the coral habitability, reef geomorphology, and the environment. Living massive corals in the Ibaruma reef are not attached to the ground. Therefore, they are very vulnerable to large tsunami waves. The risk can be very high because 248 years have passed since the 1771 Meiwa tsunami. It is almost "on time" if we consider the tsunami recurrence of 150–400 years (Araoka et al. 2013). If the size of an incident tsunami is equivalent to the 1771 Meiwa tsunami, then presently living massive corals would be entirely devastated because they are still small (< 6.5 m). Therefore, environmental risk assessment of coral reefs should be performed, beyond considerations of damage to humanity and infrastructure.

Importantly, corals on the east coast of Ishigaki Island are now characterized by high species diversity (Veron 1992). Although it is uncertain how long environmental stress continued for corals after the tsunami, we infer that its effects are not permanent. Potentially, large tsunamis can act as important agents to alter coral diversity in the lagoon because all corals have a chance to occupy the niche of the barren reef as they contemporaneously start to grow after a large tsunami.

Additional files

Additional file 1: Figure S1. (a) Initial water level of the tsunami source model proposed by Imamura et al. (2008). (b) Maximum water level at 45 min after the tsunami in region 2. **Figure S2.** (a) Initial water level of the tsunami source model proposed by Nakamura (2009). (b) Maximum water level at 60 min after the tsunami in region 2. **Figure S3.** (a) Numerical result for the absolute value of the maximum tsunami current velocity (m/s) around the Ishigaki Island and (b) around the Ibaruma reef using the model proposed by Imamura et al. (2008). **Figure S4.** Numerical results of coral transport by the 1771 Meiwa tsunami using the model proposed by Imamura et al. (2008): (a) average size boulder and (b) the largest boulder. Yellow, green, and red diamonds respectively denote the original location, final stop position, and present location of *Bari-ishi* boulder. **Figure S5.** (a) Numerical result for the absolute value of the maximum tsunami current velocity (m/s) around the Ishigaki Island and (b) around the Ibaruma reef using the model proposed by Nakamura (2009). **Figure S6.** Numerical results of coral transport by the 1771 Meiwa tsunami using the model proposed by Nakamura (2009): (a) average size boulder and (b) the largest boulder. Yellow, green, and red diamonds respectively denote the original location, final stop position, and present location of *Bari-ishi* boulder. (PDF 1163 kb)

Additional file 2: Table S1. Fault models proposed by Nakamura (2009) and Imamura et al. (2001). (XLSX 9 kb)

Abbreviations
2004IOT: 2004 Indian Ocean tsunami; PMBC: Phuket Marine Biological Center

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Authors' contributions
KG proposed the topic and conceived and designed the study. KG and CH conducted the field survey. MW, KM, and AH conducted the numerical modeling of tsunami and boulder transport. CH collaborated with the corresponding author in the construction of the manuscript. All authors read and approved the final manuscript.

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KM and AH are, respectively, now at Tokyo Gas Co., Ltd. and Penta Ocean Construction Co., Ltd.

Competing interests
The authors declare that they have no competing interests.

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