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Coral geochemical signals and growth responses to coseismic uplift during the great Sumatran megathrust earthquakes of 2004 and 2005

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ABSTRACT

The annual banded skeletons of reef corals potentially record past earthquakes events. We examined cores of five living *Porites* coral heads in Simeulue Island, Indonesia, near the epicenter of the 2004 Sumatra-Andaman and the 2005 Nias-Simeulue earthquakes. These sites showed 0.4-1.4 m of uplift. We measured skeletal strontium, magnesium, and calcium; carbon and oxygen isotopic ratios; and skeletal density, extension, and calcification rates, from 1994 to 2010. Coral geochemistry fluctuates more than are expected from strictly environmental causes; however, stress bands, reduced growth rates, and changed skeletal $\delta^{13}C$ appear to reflect the tsunami and seismic uplift (the step-change in skeletal $\delta^{13}C$ results equated to 0.31 ± 0.10 ‰/m in response to the 2004 uplift and 0.23 ± 0.03 ‰/m to the 2005 uplift).

1. INTRODUCTION

The distribution of great earthquake epicenters (> M_w 5.0) since 1900 overlaps with that of reef corals along the convergent plate boundaries, especially around the Indian and Pacific Oceans (Fig. 1-a). Reef coral skeletons may record these paleo-earthquakes. Previous studies on paleo-earthquake and tsunami events using coral skeletons were based on tsunami boulders and microatolls without skeletal geochemical proxy. Tsunami boulders are recognized as geological evidence of tsunami event occurrences of the past (e.g., Nott et al., 1997; Suzuki et al., 2008; Araoka et al., 2010; 2013). Massive coral (e.g., *Porites* sp.) that grows into a large cylinder or atoll with a flat top is called a “microatoll.” Microatolls are limited in their upward growth due to the exposure of their heads during low tide (Stoddart and Scoffin, 1979). Thus, microatolls were useful for reconstructing sea level changes and uplift/subsidence-related vertical seafloor displacement (e.g., Taylor et al., 1987; Woodroffe and McLean, 1990; Smithers and Woodroffe, 2001; Natawidjaja et al., 2006; Sieh et al., 2008).

Great (> M_w 7) subduction zone earthquakes have occurred in the last several hundred years along the Sunda trench, the boundary of the Indian-Australian plates and the Eurasian plate (Fig. 1-b). Two remarkable earthquakes occurred on December 26th, 2004 (Sumatra-Andaman earthquake; M_w 9.2) and March 28th, 2005 (Nias-Simeulue earthquake; M_w 8.6). The 2004 Sumatra-Andaman earthquake triggered a giant tsunami, which devastated coasts around the Indian Ocean. A large number of tsunami boulders were found at Thailand (e.g., Goto et al., 2007; Feldens et al., 2009; Scheucher and Vortisch, 2011) and western Banda Ache in Indonesia (e.g., Paris et al., 2009; Nandasena et al., 2011). Moreover, the crustal deformations (uplift and subsidence) that accompanied the 2004 and 2005 earthquakes have been reported by satellite-based observations and coral microatoll elevations along the Sunda trench (Andaman and Nicobar Islands, Simeulue Island, and Nias Island, e.g., Jade et al., 2005; Briggs et al., 2006; Meltzner et al., 2012). Unfortunately, tsunami boulders could not record the coral habitat-environmental changes caused by the earthquake event (seismic shaking, tsunami, and coseismic uplift/subsidence) because they disintegrated while drifting ashore during a tsunami. By contrast, massive living corals have proxy potential for recording habitat-environmental changes that are attributable to paleo-earthquake events; for example, coseismic vertical seafloor deformation and tsunami-induced sediment load (terrestrial input by the backwash and sediment resuspension).

Massive coral skeletons (e.g., *Porites* sp.) provide archives of various proxies for environmental and climatic reconstructions with high temporal resolution. Coral skeletal oxygen isotope ratios ($\delta^{18}O$) reflect the sea surface temperature (SST) and the oxygen isotope ratios in seawater related to the sea surface salinity (e.g., Dunbar and Wellington, 1981; McConnaughey, 1989a; Gagan et al., 1994). Skeletal strontium/calcium ratios (Sr/Ca, e.g., Beck et al., 1992; McCulloch et al., 1994; Cahyarini et al., 2014) and magnesium/calcium ratios (Mg/Ca, e.g., Mitsuguchi et al., 1996; Wei et al., 2000; Watanabe et al., 2001) are also useful proxies for paleo-SST variations. Many researchers have discussed the controlling factors of coral skeletal carbon isotope ratios ($\delta^{13}C$). Photosynthesis by symbiotic algae (zooxanthellae) is a major factor, and it has a strong relationship to the coral light availability and coral habitat water depth (e.g., Weber et al., 1976; Fairbanks and Dodge, 1979; McConnaughey, 1989a; Grottoli and Wellington, 1999; Heikoop et al., 2000; Rosenfeld et al., 2003; Dassié et al., 2013). The $\delta^{13}C$ of dissolved inorganic carbon in seawater (e.g., Nozaki et al., 1978; Grottoli and Wellington, 1999; Swart et al., 2010), coral mass spawning (e.g., Gagan et al., 1994), heterotrophic feeding (e.g., Felis et al., 1998; Grottoli and Wellington, 1999) and respiration (e.g., Swart, 1983; McConnaughey, 1989b; Carriquiry et al., 1994; McConnaughey et al., 1997; Grottoli and Wellington, 1999) are also known as controlling factors of coral skeletal $\delta^{13}C$. The hypothesis on the topic of using the geochemical proxy to detect paleo-earthquake in this study is as follows: The seismic uplift event does not change the environmental proxy such as SST. Coral skeletal Sr/Ca, Mg/Ca, and $\delta^{18}O$ would not be much influenced by seismic uplift. The seismic uplift means the persistent change in the coral habitat depth. When the habitat depth becomes shallower, coral light availability will increase, and then the photosynthesis by zooxanthellae will activate. Skeletal $\delta^{13}C$ will show a significant positive "step change" corresponding to vertical seafloor displacement (seismic uplift). The uplift-related step change in the skeletal $\delta^{13}C$ is distinguished from other controlling factors (e.g., the $\delta^{13}C$ of dissolved inorganic carbon in seawater, changes corresponding to mass-spawning would not show “step change”). The respiration and heterotrophic feeding components are also negligible because the variable range and the skeletal carbon derived from these components are smaller than the seafloor displacement-related changes in the skeletal $\delta^{13}C$. The geochemical proxy of annually banded coral skeletons potentially will record past seismic events, especially in the skeletal $\delta^{13}C$. Gagan et al. (2015) demonstrated that the skeletal $\delta^{13}C$ of massive *Porites* corals recorded abrupt changes in light availability by coseismic seafloor displacements during the M_w 8.6 Nias-Simeulue earthquake in 2005. The step change in the coral skeletal $\delta^{13}C$ was 0.6 ± 0.1 ‰/m for vertical seismic displacements of +1.8 m (n=6) and −0.4 m (n=3) at Nias Island, Mentawai Islands, Indonesia.

Coral skeletal growth should also be a useful proxy for assessing the earthquake impact in a reef. A coseismic uplift event may be a positive control factor in skeletal growth because coral skeletal calcification is enhanced by active photosynthesis. While a tsunami event may be negative control factor in skeletal growth. It is well-known that sedimentation caused by coastal runoff will lead to disturbances in coral growth (e.g., Hudson, 1981; Hudson and Robbin, 1981; Dodge and Lang, 1983; Crabbe and Smith, 2005). Tsunami events could also temporarily cause low water visibility due to the resuspension of the seafloor sediments and coastal runoff. Huge tsunami waves associated with megathrust earthquakes wreak devastating damage on shallow marine ecosystems, especially coral reefs. Significant coral damage associated with the 2004 Indian Ocean tsunami at Mu Ko Similan Marine National Park in Thailand was reported by Chavanich et al. (2008). It showed that the percent of damaged corals ranged from 7.2 % to 39.7 % of the total live coral cover, and the intensity of the coral damage was high at depths deeper than 10 m at most of its study sites. Besides, the previous study mentioned that massive and tabulate coral forms were the most susceptible to tsunami damage. Moreover, several articles have reported that the damaged corals were observed over several months after the earthquake and tsunami (e.g., Chavanich et al., 2008; Kumaraguru et al., 2005; Foster et al., 2006); however, the skeletal growth responses to earthquake events and tsunami disturbances are still unknown.

In our study, we examined the giant 2004 and 2005 earthquake events by using a combination of skeletal geochemical analysis (stable isotope and trace element ratios) with high temporal resolution and a coral growth parameter analysis on *Porites* corals collected from Simeulue Island, Indonesia. Our coral cores were collected from four sites of the island with different scale of seismic vertical displacement (coseismic uplift) and environmental conditions (depth and inshore/offshore). Our study objectives were to detect the uplift-related persistent step change (significant difference in the mean values between pre- and post-earthquake periods) in the coral geochemical proxies, especially in the skeletal $\delta^{13}C$. Moreover, we discussed the skeletal growth responses to the earthquake events by coral growth analysis.

2. MATERIALS AND METHODS

2.1. Geological setting in Simeulue Island, Indonesia

Our sample site, Simeulue Island (Fig. 1-c), is part of the Mentawai Islands, which are located between the epicenters of the 2004 and 2005 earthquakes. Crustal deformation around Simeulue Island has been reported by Briggs et al. (2006), and this formation was based on measurements of the highest level of survival (HLS) in coral microatolls and a continuous global positioning station (CGPS). Seismic vertical displacements around our sampling sites were deduced by Briggs et al. (2006) as follows: 1.1 m and 0.4 m during the 2004 earthquake for northwest corals (NW corals from shallow to deep depth; Av-NW, Ah-NW, and B-NW), and 1.4 m and 0.6 m during the 2005 earthquake for southeast corals (SE corals from shallow to deep depth; C-SE and D-SE). Besides, the tsunami elevation in 2004 was as high as 13 m in the northern island, and it decreased to 4 m in the southern one. The tsunami elevation in 2005 was 5 m in the southern island (Jaffe et al., 2006).

2.2. Coral core drilling

Field survey with research vessel at Simeulue Island was conducted from May 15th to May 20th, 2010.

Five living coral cores of *Porites* sp. were collected by SCUBA and an air drill with a 7.6 cm diameter core barrel. In order to evaluate the effects of habitat-environmental factors, our core collection was performed at four sites on Simeulue Island where the scale of seismic vertical displacement (coseismic uplift), habitat water depth, and location (inshore/offshore) was different (Fig. 1-c). Table 1 shows the details of our coral cores. The Av-NW (vertical-drilled core) and Ah-NW (horizontal-drilled core) are from a single microatoll colony (Fig. S1). Av-NW was a dead core (the top of the core was covered in algae). The Av-NW core top was 1.0 m over the sea surface at the lowest tide. The water depth of all the specimens was calibrated to the depth during lowest tide using tide data (derived from the IOC Sea Level Monitoring Facility at the Mealaboh station, from April 20th to May 20th, 2010, http://www.ioc-sealevelmonitoring.org/).

2.3. Sample preparation

All the cores were cut into 5 mm-thick slabs. The slab edges formed into a ledge shape, 1.5 mm thick and 1.0 mm width using a micro drill. The slabs were rinsed with distilled water in an ultrasonic bath several times and dried at 50 °C for 24 h. X-ray photographs were taken at 28.6 kV and 2.02 mA using TATSCAN-X to observe the annual density bands (Fig. 2). The analytical lines were determined along the major growth axis. Following the annual density band observation, skeletal powder samples for geochemical analysis were obtained by a precise microsampling method using a micro drill (1.8 mm diameter) and a PC controlled XY stage, as the method described in Watanabe et al (2019). The microsampling intervals were 0.2 mm for the Av-NW, Ah-NW, B-NW, and C-SE. In the D-SE, the microsampling intervals were 0.4 mm (0-72.6 mm) and 1.0 mm (73-115 mm). The milled area was cleaned using high-pressure air after each microsampling in order to avoid cross-contamination.

2.4. Geochemical analysis

2.4.1. Trace element analysis (Sr/Ca, Mg/Ca)

Skeletal Sr/Ca and Mg/Ca analyses were performed by inductively coupled plasma-atomic emission spectrometry (ICP-AES; iCAP 6200 ICP Spectrometer; Thermo Scientific) with an autosampler (CETAC; ASX-260). Powdered samples (150 ± 10 μg) were dissolved in 250 μL of 25 % high-purity HNO_3 and then diluted with ultrapure water (Milli-Q). We ultimately prepared sample solutions in which the Ca concentration was 15 ppm. Calibrations of the five gravimetric standard solutions yielded high correlation coefficients (r^2), all of which were 0.9999 for Sr, Mg and Ca. To correct the instrumental drift, we measured reference solution JCp-1 (Okai et al., 2002) at 5-sample intervals. The analytical uncertainties were 0.33 % (relative standard deviations) or 0.03 mmol/mol (1σ) for Sr/Ca, and 0.55 % or 0.02 mmol/mol for Mg/Ca.

2.4.2. Isotope analysis ($\delta^{18}O$, $\delta^{13}C$)

The powdered samples (100 ± 10 μg) were reacted with phosphoric acid at 70 °C in a carbonate reaction device (Kiel device II and IV). The CO_2 gas produced in the reaction was then introduced into a coupled mass spectrometer (Finnigan MAT 251 and Thermo MAT 253). The skeletal $\delta^{18}O$ and $\delta^{13}C$ values are expressed in conventional delta notation in ‰ units relative to Vienna Peedee Belemnite (V-PDB) using measurements of the isotopic ratio for CO_2 gas derived from Standards NBS-19 ($\delta^{18}O = -2.20$ ‰; $\delta^{13}C = 1.95$ ‰). The standard deviations (2σ; 95 % confidence) were 0.04 ‰ and 0.05 ‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively.

2.5. Environmental data and age determination

The age determination of each coral was based on the relationship between skeletal Sr/Ca and monthly SST. The monthly IGOSS-SST time series from June 1994 to May 2010 at 1° × 1° (2.5 N, 95.5 E) was derived from the Integrated Global Ocean Services System Products Bulletin (https://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst/). We used tie points to connect the highest (lowest) Sr/Ca values to the coolest (warmest) SST record to establish each year. The growth rate was assumed to be constant during each of the tied points. In a part of Sr/Ca records of B-NW, C-SE, and D-SE, it was difficult to confirm that the maximum (minimum) peak corresponding to the minimum (maximum) SST. In this case, the chronologies were inserted by combining skeletal Sr/Ca with annual density band patterns (Fig. 2). As a result, shown in Fig. S2, skeletal Sr/Ca in Av-NW and Ah-NW indicated a clear annual cycle. Skeletal Sr/Ca in B-NW and C-SE also showed annual cycle; however, the summer or winter peak had one-month time-lag compared with SST record. The annual cycle in the skeletal Sr/Ca of D-SE was not clear while the annual bands are very clear. There were significant correlations between monthly skeletal Sr/Ca in all the corals and monthly SST (Table S1). The 1997 Indian Ocean Dipole (IOD) signal was found in the skeletal Sr/Ca records, excluding D-SE (no data), and the signal was used as a guide for the age models. Furthermore, an anomalous high-density band (or area) on the X-radiographs (Fig. 2) and a green band that was observed on the D-SE slab surface (Fig. S3) was marked as a signal of earthquake occurrence. The age model of the dead Av-NW core was established by comparison with Ah-NW (horizontal-drilled core). As shown in Fig. S4, small particles like clay minerals were observed in Ah-NW skeleton. The Av-NW skeleton incorporated the small particles, too. At first, we made the age model of Ah-NW based on the relationship between SST and skeletal Sr/Ca. The small particles showed coincident with the 2004 earthquake. The Av-NW and Ah-NW skeleton should incorporate the small particles simultaneously because both of cores were collected from a single colony. The age model of Av-NW was established with a premise that the small particles started to incorporate at the same time with Ah-NW. Age determination was based on the relationship between SST and skeletal Sr/Ca as with the other specimens. Annual cycles of skeletal Sr/Ca in Av-NW and Ah-NW were shown in Fig. S2. The age models of all coral cores were cross-checked through the characteristics of the geochemical records, the relationships between skeletal Sr/Ca and IGOSS-SST data, the 2004 earthquake and tsunami signals on the coral skeleton, and the skeletal growth parameters (see Table S2 and Supplementary Text S1).

Moreover, we collected daily AVHRR-SST time series at 0.125° × 0.125° (northern part: 3.125 N, 95.875 E; southern part: 2.375 N, 96.375 E) from an Advanced Very High Resolution Radiometer (https://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.AVHRR/). The daily AVHRR-SST record was used to verify the difference in the SST between the northern and southern parts of Simeulue Island (see Discussion 4.1 and 4.4). The daily SST time series were converted to a weekly resolution.

The precipitation data and cloud fraction data were used in order to compare with the seasonal trend of geochemical data (see Discussion 4.1). The monthly precipitation time series from June 1994 to May 2010 at 1° × 1° (2.5 N, 95.5 E) was derived from WCRP GCOS GPCC Monitoring (http://iridl.ldeo.columbia.edu/SOURCES/.WCRP/.GCOS/.GPCC/.Monitoring/.MONTHLY/.version1/). The monthly cloud fraction time series from June 1994 to May 2010 at 2° × 2° (2.5 N, 95.5 E) was derived from FRESCO+ SCIAMACHY (https://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=fresco_cloud).

2.6. Skeletal growth parameters analysis

The annual skeletal extension rate (mm/yr) was assumed to be constant between adjacent dates of skeletal Sr/Ca, which are equivalent to the monthly IGOSS-SST minima (winter). The skeletal density (g/cm^3) was calculated using a CoreCal 2 program method as described by Sowa et al. (2013). The annual skeletal calcification rate (g*cm^{-2}/yr) was obtained from both parameters.

3. RESULTS

3.1. Geochemical signals of seismic vertical displacement

The geochemical records were shown in Fig. 3. We identified the post-earthquake period (from the 2004 or 2005 earthquake to the date of core drilling) by the age model. The difference in the mean values between the pre- and post-earthquake periods is shown as Δ*Proxy* (Post − Pre). Pre-earthquake periods of each coral specimens were defined as the date of 2004 or 2005 coseismic uplift events (from the oldest age to December 26th, 2004 for NW corals, and to March 28th, 2005 for SE corals; see Method 2.1). Any significant difference in Δ*Proxy* values was not detected between both earthquake periods, excluding the skeletal Mg/Ca in Av-NW (Table S3). It is noted that there was no significant correlation between skeletal growth parameters and geochemical records, excluding in B-NW (Sr/Ca vs. density and Mg/Ca vs. density) and in C-SE ($\delta^{13}C$ vs. extension rate; Table S4). The data deviation for the skeletal density in B-NW and skeletal extension rate in C-SE were relatively large ("SD" in Table S5). The large deviation of skeletal growth parameters might affect the significant relationships.

3.1.1. Av-NW and Ah-NW (–1.0 and 0.5 m depth, uplifted 1.1 m during the 2004 earthquake)

The Av-NW record is presented in Fig. 3-a. There was no significant difference between the pre- and post-earthquake periods in the skeletal $\delta^{13}C$ and Sr/Ca. The skeletal Mg/Ca and $\delta^{18}O$ during the post-earthquake period significantly decreased significantly (ΔMg/Ca = –0.14 mmol/mol, $P < 0.05$ and $\Delta\delta^{18}O = -0.10$ ‰, $P < 0.01$).

The Ah-NW record is presented in Fig. 3-b. All the geochemical records in the Ah-NW were characterized by the large amplitude found over one year in the aftermath of the 2004 earthquake. The skeletal $\delta^{13}C$ showed a significant increase from August 2004 to the earthquake occurrence, and it revealed a large amplitude with three high peaks in the aftermath of the earthquake (until the summer of 2006). In addition, a significant step change between the pre- and post-earthquake periods was also shown in the skeletal $\delta^{13}C$ ($\Delta\delta^{13}C = 0.34$ ‰; $P < 0.01$). During the same period, one year into the aftermath of the 2004 earthquake, there were positive peaks in the skeletal Sr/Ca and $\delta^{18}O$. Simultaneously, the skeletal Mg/Ca showed a negative peak. There was a significant difference between the pre- and post-earthquake results for the skeletal Sr/Ca (ΔSr/Ca = 0.04 mmol/mol; $P < .0001$). Skeletal Mg/Ca showed no significant difference. The skeletal $\delta^{18}O$ for the post-earthquake period increased significantly ($\Delta\delta^{18}$O = 0.21 ‰; $P < .0001$).

3.1.2. B-NW (5.0 m depth and 0.4 m uplift during the 2004 earthquake)

The B-NW record is presented in Fig. 3-c. No signal of earthquake occurrence and no remarkable variation was found in the aftermath of the earthquakes. A significant step change was not obtained in the skeletal δ^{13}C. The skeletal Sr/Ca during the post-earthquake period significantly increased (ΔSr/Ca = 0.05 mmol/mol; $P < 0.001$). Skeletal Mg/Ca showed no significant difference. The skeletal δ^{18}O during the post-earthquake significantly decreased ($\Delta\delta^{18}$O = –0.34 ‰; $P < .0001$).

3.1.3. C-SE (2.1 m depth and uplifted 1.4 m during the 2005 earthquake)

The C-SE record is presented in Fig. 3-d. In the aftermath of the 2004 earthquake, the skeletal δ^{13}C displayed a positive peak (1.48 ‰), and it showed a significant step change ($\Delta\delta^{13}$C = 0.32 ‰; $P < .0001$). During the same period, there were positive peaks in the skeletal Sr/Ca and δ^{18}O. Simultaneously, the skeletal Mg/Ca showed a negative peak. These characteristic peaks were similar to those in the Ah-NW record. There were significant differences between the pre- and post-earthquake skeletal Sr/Ca (ΔSr/Ca = –0.04 mmol/mol; $P < .0001$), Mg/Ca (ΔMg/Ca = –0.15 mmol/mol; $P < .0001$) and δ^{18}O ($\Delta\delta^{18}$O = –0.09 ‰; $P < .0001$).

3.1.4. D-SE (6.8 m depth and uplifted 0.6 m during the 2005 earthquake)

The D-SE record is presented in Fig. 3-e. Similar to B-NW, no signal of earthquake occurrence and no remarkable variation was found in the aftermath of the earthquakes. A significant step change was not obtained in the skeletal δ^{13}C. There were significant differences between the pre- and post-earthquake in the skeletal Sr/Ca (ΔSr/Ca = –0.03 mmol/mol; $P < .0001$; within the measurement error range) and Mg/Ca (ΔMg/Ca = –0.47 mmol/mol; $P < .0001$). However, the skeletal δ^{18}O did not show a significant difference. Furthermore, there was no marked variation in a part of the green band.

3.2. Skeletal growth record

As shown in Fig. 2, a prominent high-density band coincident with the 2004 earthquake was observed in Ah-NW and C-SE. Our results for the skeletal growth parameters are shown in Fig. 4. The annual extension rates and annual calcification rates in 2005 decreased sharply in the NW corals, excluding the Av-NW. The SE corals did not show a sharp decrease in 2005. Table 2 shows the differences in the mean growth parameters (annual extension rate, annual mean density, and annual calcification rate) between the pre- and post-earthquake periods (see also Table S5 which shows the mean and SD values in all period).

The mean values for the annual extension rates during the post-earthquake period for inshore corals were significantly higher than they were pre-earthquake (Ah-NW: +2.86 mm/yr, $P < 0.01$; and C-SE: +6.64 mm/yr, $P < 0.05$); however, the Av-NW showed the opposite result (–5.44 mm/yr, $P < .0001$). There was no significant difference in the offshore corals (B-NW and D-SE). The annual mean density showed no significant difference in all the corals. Furthermore, the D-SE displayed a particular green band (Fig. S3). The green band was coincident with the 2004 earthquake occurrence. The X-radiograph showed the green band as a high-density band, with an 8 mm length equivalent to approximately 8 months of the post-earthquake period. The small particles incorporated in the Av-NW and Ah-NW were coincident with the 2004 earthquake (Fig. S4). The X-radiograph of these skeletal areas did not show a significant difference.

4. DISCUSSION

4.1. Impact of the earthquake on coral calcification

The 2004 earthquake and tsunami damage to the coral reefs has been reported by several articles (e.g., Chavanich et al., 2008; Kumaraguru et al., 2005; Foster et al., 2006). According to these previous studies, the damaged corals were observed over several months after the earthquake and tsunami. Our coral skeleton showed the four signals of tsunami damage: (1) a stress band (inshore corals; Fig. 2), (2) a significant decrease in the annual extension/calcification rate in 2005 (NW corals; Fig. 4), (3) a green band (D-SE; Fig. S3), and (4) an incorporation of the small particles like clay materials (Av-NW and Ah-NW; Fig. S4).

Anomalous high-density bands are skeletal growth responses to environmental stressors, for example, thermal stress (Mendes and Woodley, 2002; Lough and Cooper, 2011). In our study site, the monthly IGOSS-SST and the weekly AVHRR-SST did not show unusually cooler/warmer variations during three months before and after the earthquakes. The monthly precipitation and the monthly cloud fraction also did not show unusually variations. The annual mean of precipitation was 296.3 mm from 1994 to 2010, and that of 2004 and 2005 was 301.3 mm. Besides, our sampling sites were not close to the river. Thus, the thermal effect and the influence of the sedimentation due to much precipitation or river runoff would not significantly. The stress band in the Ah-NW and C-SE was caused by other stress factors such as sedimentation, which was created by the tsunami event. The difference in the coral habitat location (inshore or offshore, i.e., the distance from the nearest shore) should produce a discrepant growth disturbance. Sedimentation-related disturbances associated with tsunami events (e.g., terrestrial runoff by the backwash and sediment resuspension) should stagnate in the water mass inshore rather than offshore. In this study, the sampling site of Ah-NW and C-SE was inshore (the distance from the nearest shore was 165 m and 50 m for Ah-NW and C-SE), while that of B-NW and D-SE was offshore (1720 m and 800 m for B-NW and D-SE). Each skeletal growth response showed a slight difference due to these characteristics of the habitat condition. As a result, the inshore corals for Ah-NW and C-SE recorded the signal from the earthquake event as a prominent stress band. The significant decrease in the annual growth record in NW corals (especially in B-NW) would reflect the tsunami event which leads to a growth disturbance with over months. In addition to the habitat condition (inshore/offshore), the distribution of the tsunami elevation could also have produced a significant coral growth response. The tsunami elevation in 2004 was as high as 13 m in the northern island, and it decreased to 4 m in the southern island (Jaffe et al., 2006). A higher tsunami elevation will lead to a more extensive growth disturbance. Therefore, the annual extension/calcification rate in 2005 for NW corals showed a significant decrease; and that of the SE corals showed no significant difference. The 8 mm green band on the D-SE skeletal surface (Fig. S3) would represent the remnant concentration of the endolithic algae, *Ostreobium* spp., as reported in several previous studies (e.g., Highsmith, 1981; Le Campion-Alsumard et al., 1995). *Ostreobium* spp. are capable of $CaCO_3$-dissolving activity when they drill into the coral skeleton. Endolithic algae bloom into the coral skeleton suggests an environmental stress response, for example, a bleaching event and or terrestrial runoff (Fine and Loya, 2002; Carilli et al., 2010). The algae bloom is caused by an increase in the amount of coastal nutrients or an enhanced upwelling or vertical mixing, which may enhance the marine phytoplankton growth. Following the Indian Ocean tsunami in 2004, satellite-derived chlorophyll-a surveys have been reported (e.g., Tang et al., 2006; 2009; Singh et al., 2007; Yan and Tang, 2009). These previous studies showed a chlorophyll-a (algae) bloom following the tsunami event in the Indian Ocean. Besides, Dipole Mode Index (derived from JAMSTEC, http://www.jamstec.go.jp/aplinfo/sintexf/iod/dipole_mode_index.html) and IGOSS-SST did not show any upwelling occurrence (e.g., the significant positive IOD signal and low-SST signal) during one year in the pre- and post-earthquake. Thus, the upwelling effect was not strong in the period, and the green band was the evidence of tsunami-related algae bloom. The nutrient pulse might stimulate photosynthesis by the zooxanthellae and biomass; however, it would inhibit coral calcification (McConnaughey, 2012). The D-SE did not show the significant change in the annual extension/calcification rate in 2005; while, the tsunami-related algae bloom may cause the stress bands or the significant growth extension/calcification decrease. The small particles in the coral skeleton (Av-NW and Ah-NW, Fig. S4) were coincident with the 2004 earthquake. The coral skeletons sometimes incorporate noncarbonate detrital material such as sediment suspended in waters in which the corals lived (Barnard et al., 1974). We did not make sure the small particles in Av-NW and Ah-NW by mineralogical analysis in this study; however, there is a possibility that the brown and lustrous particles (Fig. S4-B and -D) was incorporated with the coral skeleton by tsunami-induced sediment load (terrestrial input by the backwash and sediment resuspension). Thus, these four signals would be short-term evidence of earthquake and tsunami event.

The Ah-NW and C-SE (inshore corals) geochemical record in the aftermath of the 2004 earthquake showed significant simultaneous increase or decrease (Figs. 3-f and 3-g). The fluctuating duration in C-SE was shorter than that of Ah-NW. The skeletal geochemical signals are smoothed during skeletogenesis within the living tissue layer (Barnes et al., 1995; Gagan et al., 2012). The analysis time resolution of C-SE (biweekly) was higher than Ah-NW (monthly). The annual mean of skeletal extension rate and the tissue layer depth were 25.6 mm/yr and 7 mm for C-SE, and 6.1 mm/yr and 8 mm for Ah-NW. Therefore, the effect of skeletogenesis within the living tissue layer would be smooth the geochemical signals over a period equivalent to 3 months for C-SE and 16 months for Ah-NW. Because of the higher resolution, faster growth, and the smoothing in a shorter period, the C-SE recorded the earthquake and tsunami events more sharply than the Ah-NW. Besides, the age model was established so that the skeletal growth rate (mm/yr) was assumed to be constant during one year. The wrapped time series of Ah-NW might be extended earthquake-tsunami signals because of the lower resolution and slower growth. The SST proxies (skeletal Sr/Ca, Mg/Ca, and $\delta^{18}O$) showed the lower-SST signal in the aftermath of the 2004 earthquake. It seemed to fluctuate more than would be expected from (satellite-derived) SST causes. There may be a difference between the in situ and satellite data, and these geochemical proxies may reflect the local SST variation in the aftermath of the 2004 earthquake. Besides, seismic shaking and tsunami would temporarily suspend sediments and reduce light availability in seawater, and these effects might cause skeletal growth disturbance (intra-annual growth decrease). The skeletal $\delta^{13}C$ record signal might be influenced by the growth stress or the abrupt increasing light availability due to the uplift event.

4.2. Influences of past seismic vertical displacement on coral calcification

The coral light availability will be changed exponentially by the habitat water depth. Underwater light decreases exponentially in the depth direction according to Lambert-beer Law as follows:

$$I_D = I_0 \exp[-kD] \qquad (1)$$

where I_D is the light intensity (i.e., relative light availability) at water depth D (m), I_0 is the light intensity at sea surface ($D = 0$), and k is the extinction coefficient (Fig. 5-a). The differences in the collection water depth and the amount of seismic vertical displacements should be considered in order to assess the skeletal growth responses precisely. Our coral specimens are categorized into two patterns (Category-1 and -2) by a relative difference in light availability (RLA). The RLA (i.e., $I_{D\ post} - I_{D\ pre}$) is obtained by taking the difference in the water depth between the pre- and post-earthquake values (the amount of vertical displacement) as follows:

$$RLA = \exp[-k\,(D_{post} - D_{pre})] \quad (D = 0, RLA = 1; k = 1) \qquad (2)$$

where the extinction coefficient k is constant ($k = 1$) in this study because the k varies spatiotemporally due to depending on the quantity and quality of various substances (undissolved organic matter and suspended particles) in seawater and the wavelength of light in seawater. It is noted that the RLA is 1 when the D is 0 (i.e., sea surface). The category-1 specimens, Ah-NW and C-SE, have shallow depth (1.6~3.5 m) and large displacement (+1.1~1.4 m) characteristics. Conversely, the category-2 specimens, B-NW and D-SE, have deep depth (5.4~7.4 m) and small displacement (+0.4~0.6 m) characteristics. The RLA of category-1 is larger than that of category-2.

In category-1, the skeletal growth response to RLA was shown as a significant increase in the annual extension rate (Table 2 and Fig. 5-b). There was a strong positive correlation between the skeletal calcification rate and the extension rate ($R = 0.85$-0.97; $P < 0.05$), and it was consistent with Lough and Barnes (2000). Skeletal calcification is controlled by the activity of Ca^{2+}-ATPase (Kingsley and Watabe, 1985; McConnaughey, 1998), which is enhanced by light availability (Barnes and Chalker, 1990). Therefore, our result for category-1 would reflect the skeletal calcification activity owing to the increasing light availability caused by seismic vertical displacement. By contrast, the growth response to the RLA was relatively small in category-2 (Fig. 5-b). The RLAs of category-2 would be too small to affect the coral skeletal growth. The skeletal growth in category-2 would reflect not only the uplift-related RLA but also the other environmental factors. Our results suggest that the corals that experienced high RLA are suitable for accessing the growth response to seismic vertical displacement.

Additionally, in the Av-NW, the annual extension rate and the calcification rate decreased by 44 % post-earthquake. We concluded that the Av-NW survived for approximately 5 years following the earthquake event, according to the density bands observation and skeletal geochemical records. The Av-NW core top was 0.5 m over the sea surface at core drilling. The tidal range was 1.2 m at maximum for one month. Estimated depth in pre-earthquakes of Av-NW was 0.1 m, and the depth during the lowest tide in the post-earthquake was –1.0 m (Table 1). Av-NW coral continued growing at the intertidal zone after the 2004 uplift (+1.1m); however, there is a possibility that skeletal growth was not continuous (the skeletal geochemical record of Av-NW has a possible inclusion of non-continuous data). Therefore, the Av-NW did not reflect the RLA, although it experienced a large seismic displacement (+1.1 m). The significant ΔMg/Ca and $\Delta\delta^{18}O$ might be influenced by the irregular growing situation or organic matters (described by Watanabe et al., 2001).

4.3. Step change in the coral skeletal $\delta^{13}C$ with seismic vertical displacement

It is a bit difficult to show the coral skeletal $\delta^{13}C$ and light model because the relationship is quite complicated. Photosynthesis by symbiotic algae (zooxanthellae) is one of the major factors of skeletal $\delta^{13}C$, and it has a strong relationship to the coral light availability and coral habitat water depth (e.g., Weber et al., 1976; Fairbanks and Dodge, 1979; Heikoop et al., 2000; Dassié et al., 2013). While McConnaughey (1989a) reported that shallow corals (it grew at approximately the low tide line) might be light saturated, and the positive correlation among light, photosynthesis, and skeletal δ^{13}C might be lost. In our study, the warm season at Simeulue Island is less cloudy than the cooler season. As shown in Fig. S5, there was a significant correlation between skeletal δ^{18}O and δ^{13}C in the post-earthquake, only in Av-NW (–1.0 m depth) and B-NW (5.0 m depth). Any significant relationship was not detected in the other corals, which did not agree with the previous study (McConnaughey 1989a, Figure 7, *Porites* in Academy Bay). There is the possibility of the influence of light saturation; however, our result suggests that the influence was not significant in this study (especially in Ah-NW, C-SE, and D-SE).

Gagan et al. (2015) indicated the coral skeletal δ^{13}C paleogeodesy technique for studying the specimens that experienced seismic vertical displacements of +1.6 m (n=6) and –0.4 m (n=4), which were collected at a ～1.0 m depth. A coral skeletal δ^{13}C paleogeodetic model was constructed by finding the step changes in the skeletal δ^{13}C produced by decimeter-scale seafloor displacements. The step change in the skeletal δ^{13}C was distinguished from other controlling factors such as the δ^{13}C of dissolved inorganic carbon in seawater (e.g., Nozaki et al., 1978; Grottoli and Wellington, 1999; Swart et al., 2010) and during mass-spawning (e.g., Gagan et al., 1994). In addition, the respiration (e.g., Swart, 1983; McConnaughey, 1989b; Carriquiry et al., 1994; McConnaughey et al., 1997; Grottoli and Wellington, 1999) and heterotrophic feeding components (e.g., Felis et al., 1998; Grottoli and Wellington, 1999) are negligible because the variable range and the skeletal carbon derived from these components are smaller than the seafloor displacement-related changes in the skeletal δ^{13}C. Our skeletal δ^{13}C records showed the significant step changes in category-1 ($\Delta\delta^{13}$C in Ah-NW and C-SE were 0.34 ‰ and 0.32 ‰; Fig. 3-b and Fig. 3-d). These significant step changes reflect the uplift-related RLAs leading to activating photosynthesis by zooxanthellae. The seismic uplift values were +1.1 m during 2004 earthquake and +1.4 m during 2005 earthquake for Ah-NW and C-SE, respectively. Thus, our $\Delta\delta^{13}$C results equated to a skeletal δ^{13}C response of 0.31 ‰/m in response to the 2004 uplift and 0.23 ‰/m to the 2005 uplift for Ah-NW and C-SE, respectively. Our result was consistent with Gagan et al. (2015), who showed the abrupt increase in the skeletal δ^{13}C associated with the coseismic uplift in the aftermath of the Nias-Simeulue earthquake. Importantly, the annual extension rate during the post-earthquake period was 8.1 mm/yr and 30.0 mm/yr for the Ah-NW and C-SE, respectively (Table 2). Therefore, the kinetic isotope effect would be negligible during that period. Moreover, there was no significant mean difference in the cloud fraction between pre- and post-earthquake. The significant step change in the skeletal δ^{13}C would reflect the uplift-related RLAs, not the change of cloud fraction. In category-2, a significant step change in the skeletal δ^{13}C was not obtained. McConnaughey (1989a) mentioned that the deeper corals did not show the significant trends in the skeletal δ^{13}C because the reduction in depth caused by coral growth was insignificant compared to total depth. Our result (Fig. 5) in D-SE and B-NW (deeper coral, smaller seafloor displacement, and smaller RLA) generally agreed with the previous study. The RLAs of category-2 seem to be too small to record the significant step change produced by seismic vertical displacement. The skeletal δ^{13}C in category-2 would reflect not only the uplift-related RLA but also the other controlling factors (e.g., respiration, heterotrophic feeding, or the δ^{13}C of dissolved inorganic carbon in seawater).

In order to strongly ensure the accuracy of the coral skeletal δ^{13}C paleogeodesy technique, it is necessary to understand the relationships among the coral habitat depth, the step change in the skeletal δ^{13}C derived from vertical displacement, and the RLA. Because our specimens had different RLAs, we obtained the significant relationships. The skeletal δ^{13}C of the uplifts (‰/m) in our and previous study exponentially decreased with the decreasing RLA ($R = 0.99$; $P < 0.05$; Fig. 5-c; excluding Av-NW). This significant relationship seems to reflect an exponential available light attenuation. Importantly, the skeletal δ^{13}C of the uplift was significantly correlated with the RLA ($R = 0.94$; $P < 0.05$; Fig. 5-c; excluding Av-NW and B-NW). It is notable that the B-NW was excluded because it showed a slight decrease in post-earthquakes ($\Delta\delta^{13}$C = –0.17 ‰; *n.s.*). There were two categories of skeletal δ^{13}C response against the vertical displacements within the RLAs. One is Ah-NW and Gagan et al. (2015), these corals strongly reflected its large RLAs produced by shallow habitat depth (0.6～1.0

m) and large displacement (+1.1～1.6 m). The other is C-SE and D-SE, its habitat water depths were deeper and the RLAs were smaller than the Ah-NW and the value in Gagan et al. (2015). The step changes in the skeletal $\delta^{13}C$ in Ah-NW and Gagan et al. (2015) would be dependent on the changes in coral light availability produced by seismic vertical displacement rather than the changes by the other environmental cause. While the skeletal $\delta^{13}C$ records for the C-SE and D-SE seemed to reflect not only the uplift-related changes in light availability but also other environmental factors or vital effects. This result suggests that the corals that lived at shallow depths and experienced large RLA values are suitable for the coral skeletal $\delta^{13}C$ paleogeodetic tool. Besides, there is a possibility of including the responses to earthquake precursors and post-seismic activity. In this study, we could not precisely distinguish the earthquake precursors (e.g., foreshock), co-seismic shaking, and post-seismic activity (e.g., aftershock) from the proxy signals. There are still issues with precise detecting the uplift or tsunami signals because these events might lead to a severe disturbance in coral skeleton. Especially in a shallow depth, the uplift-related exposure or tsunami-related sediment suspension may cause a gap in skeletal growth. The skeletal growth gap smooths the earthquake signal in the geochemical record, or it might not record the earthquake events. However, our result is important evidence because a significant coral skeletal $\delta^{13}C$-RLA relationship will ensure good coral skeletal $\delta^{13}C$ paleogeodesy. Additionally, Gagan et al. (2015) mentioned the detection limits of dome-shaped coral skeletal $\delta^{13}C$ paleogeodesy; the lower detection limit for vertical displacement appears to be ~0.3 m for short coral $\delta^{13}C$ records limited to ~5 years of growth before or after an earthquake. Our results were mostly consistent with these detection limits. In addition to the detection limits, we propose that the coral RLA related to the habitat water depth and scale of vertical displacement are also noteworthy keys for coral skeletal $\delta^{13}C$ paleogeodesy. These characteristics would allow us to use the coral skeleton as a paleo-earthquake proxy with much more precise detection qualities than those of the current methods.

4.4. Changes in other skeletal geochemical proxies with seismic vertical displacement

4.4.1. Skeletal Sr/Ca

The coral skeletal Sr/Ca is widely used in paleo-thermometry (e.g., Beck et al., 1992; McCulloch et al., 1994; Cahyarini et al., 2014). Several previous studies have reported the difference in the skeletal Sr/Ca sensitivity to temperatures among neighboring coral colonies even when they were collected on the same reef (Goodkin et al., 2005; Linsley et al., 2006; Cahyarini et al., 2009; Pfeiffer et al., 2009; Alpert et al., 2016). Although the sites where we collected coral specimens are not far from one another, five of the coral skeletal Sr/Ca records have each had different variations (mean value, and seasonal variation; Table 3-a). The difference in the mean values among the five profiles was 0.198 mmol/mol at maximum (the minimum value was 8.831 mmol/mol in D-SE, and the maximum value was 9.029 mmol/mol in B-NW). The predicted difference in the mean Sr/Ca-derived temperature was 3.24 °C (Abram et al., 2007), and it was larger than that of the mean AVHRR-SST between the northern and southern parts of Simeulue Island (difference in mean values: 0.03 °C). In Av-NW, the mean value for the seasonal variation (MSV; difference between the maximum/minimum value during one year) was 0.151 mmol/mol. The Av-NW record from the pre-earthquake period revealed clear annual cycles with 0.172 mmol/mol of mean seasonal variation, and this cycle became unclear with the significant small mean seasonal variation of the post-earthquake period (ΔMSV = 0.059 mmol/mol, $P < 0.01$). By contrast, the Ah-NW, which is a horizontal-drilled core from the same colony as Av-NW, the MSV was 0.160 mmol/mol. The seasonal variation of Ah-NW in the post-earthquake period was slightly smaller than the variation pre-earthquake (ΔMSV = 0.003 mmol/mol; *n.s.*; within the measurement error range). In B-NW, the MSV was 0.172 mmol/mol. The seasonal variation of B-NW in the post-earthquake was smaller than that of the pre-earthquake period (ΔMSV = 0.081 mmol/mol; $P < 0.05$). In C-SE, the MSV was 0.213 mmol/mol. The seasonal variation of C-SE in the post-earthquake was slightly smaller than it was pre-earthquake (ΔMSV = 0.006 mmol/mol; *n.s.*). In D-SE, the MSV was 0.350 mmol/mol. The seasonal variation of D-SE in the post-earthquakes was larger than it was pre-earthquakes (ΔMSV = 0.079 mmol/mol; $P < 0.01$). The seasonal variation of the AVHRR-SST in the post-earthquakes was smaller than it was pre-earthquakes (ΔMSV of northern AVHRR-SST: 0.333 °C; *n.s.*; ΔMSV of southern AVHRR-SST: 0.523 °C; $P < 0.05$). Therefore, the skeletal Sr/Ca record in Av-NW, Ah-NW, B-NW, and C-SE could have the potential to indicate the long-term SST trend, although there was a difference in the mean seasonal variability. However, the skeletal Sr/Ca record in D-SE might be explained by other factors. Moreover, there is no significant difference in the mean AVHRR-SST and IGOSS-SST between the pre- and post-earthquake periods. The earthquake events did not affect SST and skeletal Sr/Ca. Thus, the significant ΔSr/Ca in the Ah-NW, B-NW and C-SE were attributable to the skeletal Sr/Ca sensitivity to temperature or another factor.

4.4.2. Skeletal Mg/Ca

Several previous studies have shown that the coral skeletal Mg/Ca could be used in paleo-thermometry (Mitsuguchi et al., 1996; Wei et al., 2000; Watanabe et al., 2001). In skeletal Sr/Ca vs. Mg/Ca through both pre- and post-earthquake periods, there was a significant correlation in Av-NW, Ah-NW, and B-NW (Fig. S5). This result suggests that skeletal Mg/Ca reflected SST variation as with skeletal Sr/Ca. Similar to skeletal Sr/Ca records, five coral skeletal Mg/Ca records each showed different variations (mean value and seasonal variation; Table 3-b). The difference in the mean values among the five profiles was 0.574 mmol/mol at a maximum (the minimum value was 4.408 mmol/mol in the Ah-NW, and the maximum value was 4.982 mmol/mol in the D-SE). The predicted difference in the mean Mg/Ca-derived temperature was 4.45 °C (Mitsuguchi et al., 1996), and it was larger than that of the mean AVHRR-SST between the northern and southern parts of Simeulue Island (difference in mean values: 0.03 °C). In Av-NW, the MSV was 0.911 mmol/mol. The seasonal variation of Av-NW in the post-earthquake was slightly smaller than it was pre-earthquake (ΔMSV = 0.047 mmol/mol; *n.s.*). In Ah-NW, the MSV was 0.484 mmol/mol. The seasonal variation of Av-NW in the post-earthquake was slightly smaller than the variation pre-earthquake (ΔMSV = 0.012 mmol/mol, *n.s.*). In B-NW, the MSV was 0.604 mmol/mol. The seasonal variation of B-NW in the post-earthquake was significantly smaller than the variation in the pre-earthquake (ΔMSV = 0.416 mmol/mol, $P < 0.05$). In C-SE, the MSV was 0.717 mmol/mol. The seasonal variation of C-SE in the post-earthquake was slightly larger than it was pre-earthquake (ΔMSV = 0.149 mmol/mol; *n.s.*). In Ah-NW, the MSV was 0.689 mmol/mol. The seasonal variation of D-SE in the post-earthquake was also slightly larger than it was pre-earthquakes (ΔMSV = 0.214 mmol/mol; *n.s.*). Similar to the discussion of Sr/Ca, the earthquake event did not affect SST and skeletal Mg/Ca. Thus, the ΔMg/Ca in the C-SE and D-SE were attributable to the skeletal Mg/Ca sensitivity to temperature or another factor (e.g., organic matters, described by Watanabe et al., 2001; Nagtegaal et al., 2012).

A significant fraction of the organic compound-related Mg in the coral skeleton was recognized in many previous studies (e.g. Amiel et al., 1973). Watanabe et al. (2001) suggested that 60 % of the Mg in the coral aragonite substitutes for calcium but more than 40 % of the Mg in the coral is associated with organic matter or absorbed onto the surfaces of the crystal. Moreover, Nagtegaal et al. (2012) noted that there is a possibility that the Mg in the coral skeleton may remain as extra crystalline precipitates from sea salts and or as organic matter since Mg is a structural element in the chlorophyll of the symbiotic zooxanthellae (Mg-rich chlorophyll derivatives). A chlorophyll-a (algae) bloom occurrence following the 2004 tsunami event in the Indian Ocean has been reported by several previous studies (e.g., Tang et al., 2006; 2009; Singh et al., 2007; Yan and Tang, 2009; see Discussion 4.1). The presence of this bloom implies that a tsunami-related chlorophyll bloom leads to high-Mg concentrations in the coral skeleton. Thus, skeletal Mg/Ca could have potential as a proxy for detecting a tsunami event. In fact, the skeletal Mg/Ca in Ah-NW and C-SE showed a positive peak after the tsunami events (Figs. 3-f and 3-g). A positive peak in the C-SE seemed to reflect the 2005 tsunami (5 m at southern Simeulue Island) rather than the 2004 tsunami. The coral habitat location either inshore or offshore must be considered to ensure the skeletal Mg/Ca paleo-tsunami proxy. Similar to sedimentation (see Discussion

4.1), the coastal nutrients and phytoplankton bloom from a tsunami event should stagnate in the water mass inshore rather than offshore. Thus, further experiments to assess the difference in the habitat location (inshore or offshore) would be required to ensure the possibility of coral skeletal paleo-tsunami detection. Moreover, the effect of *Ostreobium* spp. (which creates a green band) on the geochemical proxy has been discussed by Highsmith (1981) and Tribollet (2008). According to these previous studies, the *Ostreobium* spp. filaments facilitate $CaCO_3$ precipitation and aragonite precipitation lowers Ca^{2+} activity, thereby increasing the local Mg/Ca ratio in the coral skeleton. Unfortunately, our skeletal Mg/Ca in D-SE did not show the significant variation caused by the green band. It might be required to measure the skeletal Mg/Ca with higher-resolution or to measure the Mg/Ca in the microstructures.

4.4.3. Skeletal $\delta^{18}O$

The coral skeletal $\delta^{18}O$ reflects the SST and the oxygen isotope ratios in seawater (i.e., sea surface salinity, e.g., Dunbar and Wellington, 1981; McConnaughey, 1989a; Gagan et al., 1994). In tropical and subtropical areas, variations in the seawater salinity caused by evaporation, rainfall, or freshwater input from the river affect the skeletal $\delta^{18}O$, and then the influence of these components should be considered when establishing a skeletal $\delta^{18}O$-SST relationship (Cole and Fairbanks, 1990; Carriquiry et al., 1994; Al-Rousan et al., 2007). According to Abram et al. (2007), it is difficult to reliably determine the coral $\delta^{18}O$-SST dependence using coral skeletons from the Mentawai Islands because this area experiences high and variable amounts of rainfall/evaporation, which produce non-SST-related changes in the $\delta^{18}O$ of seawater (and coral). In this study, The $\delta^{18}O_{sw}$ correlated with SST (Fig. S2; $R = 0.60$-0.91; $P < 0.05$; excluding D-SE), not precipitation. It suggested that the $\delta^{18}O_{sw}$ would reflect evaporation rather than precipitation. In the cooler season (November), $\delta^{18}O_{sw}$ might reflect the high precipitation. In skeletal Sr/Ca vs. $\delta^{18}O$ through both pre- and post-earthquake periods, there was a significant correlation in Ah-NW, B-NW, and C-SE (Fig. S5). This result suggests that skeletal $\delta^{18}O$

reflected SST variation as with skeletal Sr/Ca. The lack of correlation in Sr/Ca vs. δ^{18}O (Av-NW and D-SE) suggests that our skeletal δ^{18}O records would be influenced by not only SST but also δ^{18}O seawater. Similar to the skeletal Sr/Ca and Mg/Ca records, five of the coral skeletal δ^{18}O records have each shown different variations (mean value and seasonal variation; Table 3-c). The difference in the mean values among the five profiles was 0.320 % at a maximum (the minimum value was –5.821 ‰ in the D-SE, and the maximum value was –5.501 ‰ in the Ah-NW). The difference seems to be too large against that of the mean AVHRR-SST between the northern and southern parts of Simeulue Island (difference of mean values: 0.03 °C), even if the component of δ^{18}O in sea water is considered. In Av-NW, the MSV was 0.468 ‰. The ΔMSV was 0.003 ‰ (*n.s.*), which is within the measurement error range (0.04 %). In Ah-NW, the MSV was 0.496 %. The seasonal variation of Av-NW in the post-earthquake period was significantly larger than it was pre-earthquake (ΔMSV = 0.216 %, $P < 0.05$). In B-NW, the MSV was 0.584 %. The seasonal variation of B-NW in the post-earthquake was significantly smaller it was pre-earthquake (ΔMSV = 0.265 %, $P < 0.01$), in contrast to the result for the Ah-NW. In C-SE, the MSV was 0.562 %. The seasonal variation of C-SE in the post-earthquake was slightly larger than it was pre-earthquake (ΔMSV = 0.045 %, *n.s.*). In D-SE, the MSV was 0.560 %. The seasonal variation of D-SE in the post-earthquake was slightly smaller than it was pre-earthquake (ΔMSV = 0.094 %, *n.s.*). Gagan et al. (2015) showed no significant change in the skeletal δ^{18}O when using two fossil *Porites* that experienced an abrupt change in the light exposure or 0.7 m of uplift in 1797. However, in this study, there was a significant difference between the pre- and post-earthquake in the skeletal δ^{18}O in the Ah-NW, B-NW and C-SE. There is no significant difference in the mean SST and precipitation between the pre- and post-earthquake periods. The earthquake events did not affect SST, precipitation, and skeletal δ^{18}O. The $\Delta\delta^{18}$O in the Ah-NW may reflect the temporal lower-SST signal in the aftermath of the earthquakes (see Discussion 4.1). Unfortunately, we could not find the exact variable factors for the $\Delta\delta^{18}$O in the B-NW and C-SE. These records fluctuated more than are expected from environmental causes.

5. CONCLUSIONS

As shown, annual banding skeletons in reef corals have potential uses in the detection of paleo-earthquakes. We found the first evidence for skeletal growth responses during the subduction zone earthquake events. Severe reef disturbances caused by the 2004 Simeulue-Andaman earthquake, the 2005 Nias-Simeulue earthquake, and the 2004 Indian Ocean tsunami led to the coral growth disturbance shown as a stress band and a significant decrease in the annual extension/calcification rate. The annual extension rates for the uplifted corals significantly increased due to increasing light availability.

The seismic uplift event did not affect environmental condition such as SST and precipitation. While, several geochemical records (Sr/Ca, Mg/Ca, and δ^{18}O) showed significant differences. Skeletal Sr/Ca, Mg/Ca, and δ^{18}O fluctuated more than are expected from environmental causes. Besides, there was no significant mean difference in cloud fraction between the pre- and post-earthquake periods. The significant step change in the skeletal δ^{13}C would reflect the uplift-related RLAs, not the change of cloud fraction. We concluded that the coral RLA associated with the habitat water depth and the scale of vertical displacement is a noteworthy key in coral skeletal δ^{13}C paleogeodesy. Additionally, applying our method to the other coral species is important because it will provide a detail discussion of the proxy signal and the earthquake (and tsunami) effect on the reef system. A coral paleo-earthquake archive will provide us with local information on crustal deformation at the decimeter scale, and it will support assessments of the influence of reef disturbances and disaster risk management in the coastal area where the earthquake occurrence cycles are still unknown or natural/historical archives are rarely available.

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8. TABLE AND FIGURE CAPTIONS

[Tables]

Table 1 Sample information

"Water depth (in m)" is the measurement value at core drilling. The Av-NW core top was 0.5 m over the sea surface (see also Fig. S1). "Depth during lowest/highest tide" was estimated in the basis on water depth and tidal range (tide data derived from the IOC Sea Level Monitoring Facility at the Mealaboh station, from April 20th to May 20th, 2010, the tidal range was 1.2 m at maximum). "Estimated depth in pre-earthquake" was calculated by "Depth during lowest tide" and reporting "Uplift" value (Briggs et al., 2006).

Table 2 Difference in the annual skeletal growth parameters pre- and post-earthquakes

All the values are the means pre-/post-earthquake. "*P*" means statically significant *P* values for the Student's t-test. "Pre" means the pre-earthquake period (NW corals: from the oldest age to the 2004 earthquake; SE corals: from the oldest age to the 2005 earthquake) and "Post" means the post-earthquake period (NW corals: from the 2004 earthquake to the date of core drilling; SE corals: from the 2005 earthquake to the date of core drilling).

Table 3 Mean values and seasonal mean variations in the skeletal Sr/Ca, Mg/Ca, and δ^{18}O records

The seasonal variation was calculated by taking the difference between the maximum/minimum value during one year. The "*P*" is a statically significant *P* value for the Student's t-test. The mean value of the seasonal variation is shown as "MSV" in the text. Different values for seasonal mean variations are shown as "ΔMSV" in the text. "Pre" means the pre-earthquake period and "Post" means the post-earthquake period.

[Figures]

Fig. 1 Distribution map of paleo-earthquakes and reef corals and a regional map of sample sites

(a) Distribution of paleo-earthquakes and reef corals.

The red plots show the epicenters of large earthquakes (> M_w 5.0) since 1900 (a dataset derived from the United States Geological Survey). The blue hatched areas indicate the predicted distribution of reef corals (Veron, 2000).

(b) Regional map of the magnitude and rupture areas for previous earthquakes along the Sunda trench.

The rupture areas of previous large earthquakes are shown as each color. The rupture locations and magnitudes are from Briggs et al. (2006); Konca et al. (2008); Meltzner et al. (2010; 2012); Hill et al. (2012).

(c) Sample sites on Simeulue Island.

The map of Simeulue Island shows the sites where *Porites* corals were drilled (blue plots: NW corals; red plots: SE corals) in this study and the cumulative uplift value (in cm) for the earthquakes on December 2004 (blue lines) and March 2005 (red lines) from Briggs et al. (2006). Each color shows the rupture area of previous large earthquakes from Meltzner et al. (2010; 2012).

Fig. 2 Images of X-radiographs (positive) and skeletal Sr/Ca records

“Depth” is the value of “Estimated depth in pre-earthquakes” shown in Table 1. “Uplift” is the reported value by Briggs et al. (2006). The red lines show analytical lines. The black lines on the annual bands show age model which were established with the basis on the relationship between skeletal Sr/Ca and monthly SST. The areas “A, B, C, D” on the Av-NW and Ah-NW indicate the positions of the microscopic picture shown in Fig. S4. The arrows above Ah-NW and C-SE show the positions of stress bands. The white arrow on the D-SE X-ray shows the position of the green band and the area “B” (on the D-SE X-ray) indicates the position of the microscopic picture shown in Fig. S3.

Fig. 3 Skeletal geochemical records (δ^{13}C, Sr/Ca, Mg/Ca, and δ^{18}O)

The mean difference between the pre- and post-earthquake data (dashed lines) is shown as Δ*Proxy* in the text. Pre-earthquake periods of each coral specimens were defined as the date of 2004 or 2005 coseismic uplift events (from the oldest age to December 26th 2004 for NW corals, and to March 28th 2005 for SE corals; see Method 2.1). The black arrows show the occurrence of the 2004 or 2005 earthquake. The gray hatching in the D-SE record shows the period of the green band was observed on the D-SE slab surface. "WD" means water depth value ("Depth during lowest tide" in Table 1). The gray arrows in the enlarged-view figures (f) and (g) indicate the simultaneous variation in the skeletal geochemical record in the aftermath of the 2004 earthquake. The white arrows on the skeletal Mg/Ca record indicate the positive peak after the tsunami events (see Discussion 4.4.2).

Fig. 4 Annual skeletal growth parameters (skeletal extension rate, calcification rate, and density)

The closed circles with a solid line indicate the annual extension rate (mm/yr); open circles with dashed lines indicate the annual calcification rate (g*cm^{-2}/yr); and gray closed circles with a solid line indicate an annual density (g/cm^{-3}). The black arrows on the age (yrs) show the year when the coral skeletal growth responded to the 2004 and 2005 earthquakes. "WD" is the value of "Depth during lowest/highest tide" shown in Table 1.

Fig. 5 Relationships among uplift-related RLA, skeletal growth, and skeletal $\Delta\delta^{13}$C

(a) Relative light availability during pre- (●) and post-earthquakes (○) in all corals (Av-NW in post-earthquakes was excepted because the top of colony was over the sea surface after the uplift event; see in the text and Fig. S1). Underwater light decreases exponentially in the depth direction according to Lambert-beer Law as follows: $I_D = I_0 \exp[-kD]$ where I_D is the light intensity at water depth D (m), I_0 is the light intensity (i.e., relative light availability) at sea surface ($D = 0$), and the extinction (attenuation) coefficient k is constant ($k = 1$) in this study because the k varies spatiotemporally due to depending on the quantity and quality of various substances (undissolved organic matter and suspended particles) in seawater and the wavelength of light in seawater. It is noted when the D is 0, I is 1 (×). "Water depth D" is the estimated depth in pre-earthquakes (Pre) and the depth during lowest tide (Post), which is shown in Table 2. (b) Relationship between the RLA and skeletal growth. The y-axis shows the difference (post- − pre-earthquakes) in the annual skeletal extension rates (see Table 2, "Difference"). The x-axis shows the RLA which is obtained by taking the difference in the water depth between the pre- and post-earthquake values (i.e., $I_{\mathrm{D\ post}} - I_{\mathrm{D\ pre}}$) as follows: $RLA = \exp\,[-k\ (D_{\mathrm{post}} - D_{\mathrm{pre}})]$ where D is 0, $RLA = 1$, and the extinction coefficient k is 1. Our coral specimens are categorized into two patterns (Category-1: ● and -2: ○) by a relative difference in light availability (RLA, see in the text). The category-1 specimens have shallow depth (1.6~3.5 m) and large displacement (+1.1~1.4 m) characteristics. The category-2 specimens (○) have deep depth (5.4~7.4 m) and small displacement (+0.4~0.6 m) characteristics. Av-NW (the gray circle) was excluded from these categories because there is a possibility that skeletal growth was not continuous due to the uplift event. (c) Relationship between the RLA and the skeletal $\Delta\delta^{13}$C. The skeletal δ^{13}C shows the ‰/m of uplift. Circle plots indicate the results of this study. The category-1 (●) and -2 (○) characteristics were as described above. Triangle plots indicate the results in the supplemental data from Gagan et al. (2015); ~1.0 m depth; and the skeletal δ^{13}C increased 0.26 ‰/m; n=6; in Nias Island. Larger RLA, and larger skeletal growth or larger skeletal $\Delta\delta^{13}$C indicates uplift-related change.