



Title	Coral geochemical signals and growth responses to coseismic uplift during the great Sumatran megathrust earthquakes of 2004 and 2005
Author(s)	Ito, Saori; Yamazaki, Atsuko; Nishimura, Yuichi et al.
Citation	Geochimica et cosmochimica acta, 273, 257-274 https://doi.org/10.1016/j.gca.2020.01.037
Issue Date	2020-03-15
Doc URL	https://hdl.handle.net/2115/84393
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Rights(URL)	https://creativecommons.org/licenses/by-nc-nd/4.0/
Type	journal article
File Information	Geochim. cosmochim. acta 273_257-274.pdf



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

3
4 Saori Ito ^a, Atsuko Yamazaki ^{a, b, c}, Yuichi Nishimura ^d, Eko Yulianto ^e, Tsuyoshi Watanabe ^{a, b, *}

5
6 ^aDepartment of Natural History Sciences, Faculty of Science, Hokkaido University, Sapporo, 060-0810, Japan

7 ^bKIKAI institute for coral reef sciences, Kikai town, 891-6151, Japan

8 ^cDepartment of Earth and Planetary Sciences, Faculty of Science, Kyushu University, 819-0395, Japan

9 ^dInstitute of Seismology and Volcanology, Faculty of Science, Hokkaido University, Sapporo, 060-0810, Japan

10 ^eResearch Center for Geotechnology, Indonesian Institute of Science, Java Island, 40132, Indonesia

11 *Corresponding author: nabe@sci.hokudai.ac.jp (T. Watanabe)

12
13 ABSTRACT

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

22
23 1. INTRODUCTION

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

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

47 paleo-earthquake events; for example, coseismic vertical seafloor deformation and tsunami-induced sediment
48 load (terrestrial input by the backwash and sediment resuspension).

49 Massive coral skeletons (e.g., *Porites* sp.) provide archives of various proxies for environmental and
50 climatic reconstructions with high temporal resolution. Coral skeletal oxygen isotope ratios ($\delta^{18}\text{O}$) reflect the
51 sea surface temperature (SST) and the oxygen isotope ratios in seawater related to the sea surface salinity (e.g.,
52 Dunbar and Wellington, 1981; McConnaughey, 1989a; Gagan et al., 1994). Skeletal strontium/calcium ratios
53 (Sr/Ca, e.g., Beck et al., 1992; McCulloch et al., 1994; Cahyarini et al., 2014) and magnesium/calcium ratios
54 (Mg/Ca, e.g., Mitsuguchi et al., 1996; Wei et al., 2000; Watanabe et al., 2001) are also useful proxies for paleo-
55 SST variations. Many researchers have discussed the controlling factors of coral skeletal carbon isotope ratios
56 ($\delta^{13}\text{C}$). Photosynthesis by symbiotic algae (zooxanthellae) is a major factor, and it has a strong relationship to
57 the coral light availability and coral habitat water depth (e.g., Weber et al., 1976; Fairbanks and Dodge, 1979;
58 McConnaughey, 1989a; Grottoli and Wellington, 1999; Heikoop et al., 2000; Rosenfeld et al., 2003; Dassié et
59 al., 2013). The $\delta^{13}\text{C}$ of dissolved inorganic carbon in seawater (e.g., Nozaki et al., 1978; Grottoli and Wellington,
60 1999; Swart et al., 2010), coral mass spawning (e.g., Gagan et al., 1994), heterotrophic feeding (e.g., Felis et al.,
61 1998; Grottoli and Wellington, 1999) and respiration (e.g., Swart, 1983; McConnaughey, 1989b; Carriquiry et
62 al., 1994; McConnaughey et al., 1997; Grottoli and Wellington, 1999) are also known as controlling factors of
63 coral skeletal $\delta^{13}\text{C}$. The hypothesis on the topic of using the geochemical proxy to detect paleo-earthquake in
64 this study is as follows: The seismic uplift event does not change the environmental proxy such as SST. Coral
65 skeletal Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$ would not be much influenced by seismic uplift. The seismic uplift means the
66 persistent change in the coral habitat depth. When the habitat depth becomes shallower, coral light availability
67 will increase, and then the photosynthesis by zooxanthellae will activate. Skeletal $\delta^{13}\text{C}$ will show a significant
68 positive “step change” corresponding to vertical seafloor displacement (seismic uplift). The uplift-related step
69 change in the skeletal $\delta^{13}\text{C}$ is distinguished from other controlling factors (e.g., the $\delta^{13}\text{C}$ of dissolved inorganic

70 carbon in seawater, changes corresponding to mass-spawning would not show “step change”). The respiration
71 and heterotrophic feeding components are also negligible because the variable range and the skeletal carbon
72 derived from these components are smaller than the seafloor displacement-related changes in the skeletal $\delta^{13}\text{C}$.
73 The geochemical proxy of annually banded coral skeletons potentially will record past seismic events, especially
74 in the skeletal $\delta^{13}\text{C}$. Gagan et al. (2015) demonstrated that the skeletal $\delta^{13}\text{C}$ of massive *Porites* corals recorded
75 abrupt changes in light availability by coseismic seafloor displacements during the M_w 8.6 Nias-Simeulue
76 earthquake in 2005. The step change in the coral skeletal $\delta^{13}\text{C}$ was 0.6 ± 0.1 ‰/m for vertical seismic
77 displacements of +1.8 m (n=6) and -0.4 m (n=3) at Nias Island, Mentawai Islands, Indonesia.

78 Coral skeletal growth should also be a useful proxy for assessing the earthquake impact in a reef. A
79 coseismic uplift event may be a positive control factor in skeletal growth because coral skeletal calcification is
80 enhanced by active photosynthesis. While a tsunami event may be negative control factor in skeletal growth. It
81 is well-known that sedimentation caused by coastal runoff will lead to disturbances in coral growth (e.g., Hudson,
82 1981; Hudson and Robbin, 1981; Dodge and Lang, 1983; Crabbe and Smith, 2005). Tsunami events could also
83 temporarily cause low water visibility due to the resuspension of the seafloor sediments and coastal runoff.
84 Huge tsunami waves associated with megathrust earthquakes wreak devastating damage on shallow marine
85 ecosystems, especially coral reefs. Significant coral damage associated with the 2004 Indian Ocean tsunami at
86 Mu Ko Similan Marine National Park in Thailand was reported by Chavanich et al. (2008). It showed that the
87 percent of damaged corals ranged from 7.2 % to 39.7 % of the total live coral cover, and the intensity of the
88 coral damage was high at depths deeper than 10 m at most of its study sites. Besides, the previous study
89 mentioned that massive and tabulate coral forms were the most susceptible to tsunami damage. Moreover,
90 several articles have reported that the damaged corals were observed over several months after the earthquake
91 and tsunami (e.g., Chavanich et al., 2008; Kumaraguru et al., 2005; Foster et al., 2006); however, the skeletal
92 growth responses to earthquake events and tsunami disturbances are still unknown.

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

101

102 2. MATERIALS AND METHODS

103 2.1. Geological setting in Simeulue Island, Indonesia

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

113

114 2.2. Coral core drilling

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

116 Five living coral cores of *Porites* sp. were collected by SCUBA and an air drill with a 7.6 cm diameter core
117 barrel. In order to evaluate the effects of habitat-environmental factors, our core collection was performed at
118 four sites on Simeulue Island where the scale of seismic vertical displacement (coseismic uplift), habitat water
119 depth, and location (inshore/offshore) was different (Fig. 1-c). Table 1 shows the details of our coral cores. The
120 Av-NW (vertical-drilled core) and Ah-NW (horizontal-drilled core) are from a single microatoll colony (Fig.
121 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
122 the sea surface at the lowest tide. The water depth of all the specimens was calibrated to the depth during lowest
123 tide using tide data (derived from the IOC Sea Level Monitoring Facility at the Mealaboh station, from April
124 20th to May 20th, 2010, <http://www.ioc-sealevelmonitoring.org/>).

125

126 2.3. Sample preparation

127 All the cores were cut into 5 mm-thick slabs. The slab edges formed into a ledge shape, 1.5 mm thick and
128 1.0 mm width using a micro drill. The slabs were rinsed with distilled water in an ultrasonic bath several times
129 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
130 observe the annual density bands (Fig. 2). The analytical lines were determined along the major growth axis.
131 Following the annual density band observation, skeletal powder samples for geochemical analysis were obtained
132 by a precise microsampling method using a micro drill (1.8 mm diameter) and a PC controlled XY stage, as the
133 method described in Watanabe et al (2019). The microsampling intervals were 0.2 mm for the Av-NW, Ah-NW,
134 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
135 mm). The milled area was cleaned using high-pressure air after each microsampling in order to avoid cross-
136 contamination.

137

138 2.4. Geochemical analysis

139 2.4.1. Trace element analysis (Sr/Ca, Mg/Ca)

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

148

149 2.4.2. Isotope analysis ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$)

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

156

157 2.5. Environmental data and age determination

158 The age determination of each coral was based on the relationship between skeletal Sr/Ca and monthly
159 SST. The monthly IGOSS-SST time series from June 1994 to May 2010 at $1^\circ \times 1^\circ$ (2.5 N, 95.5 E) was derived
160 from the Integrated Global Ocean Services System Products Bulletin
161 (https://iridl.ldeo.columbia.edu/SOURCES/IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst/). We used tie points

162 to connect the highest (lowest) Sr/Ca values to the coolest (warmest) SST record to establish each year. The
163 growth rate was assumed to be constant during each of the tied points. In a part of Sr/Ca records of B-NW, C-
164 SE, and D-SE, it was difficult to confirm that the maximum (minimum) peak corresponding to the minimum
165 (maximum) SST. In this case, the chronologies were inserted by combining skeletal Sr/Ca with annual density
166 band patterns (Fig. 2). As a result, shown in Fig. S2, skeletal Sr/Ca in Av-NW and Ah-NW indicated a clear
167 annual cycle. Skeletal Sr/Ca in B-NW and C-SE also showed annual cycle; however, the summer or winter peak
168 had one-month time-lag compared with SST record. The annual cycle in the skeletal Sr/Ca of D-SE was not
169 clear while the annual bands are very clear. There were significant correlations between monthly skeletal Sr/Ca
170 in all the corals and monthly SST (Table S1). The 1997 Indian Ocean Dipole (IOD) signal was found in the
171 skeletal Sr/Ca records, excluding D-SE (no data), and the signal was used as a guide for the age models.
172 Furthermore, an anomalous high-density band (or area) on the X-radiographs (Fig. 2) and a green band that was
173 observed on the D-SE slab surface (Fig. S3) was marked as a signal of earthquake occurrence. The age model
174 of the dead Av-NW core was established by comparison with Ah-NW (horizontal-drilled core). As shown in Fig.
175 S4, small particles like clay minerals were observed in Ah-NW skeleton. The Av-NW skeleton incorporated the
176 small particles, too. At first, we made the age model of Ah-NW based on the relationship between SST and
177 skeletal Sr/Ca. The small particles showed coincident with the 2004 earthquake. The Av-NW and Ah-NW
178 skeleton should incorporate the small particles simultaneously because both of cores were collected from a
179 single colony. The age model of Av-NW was established with a premise that the small particles started to
180 incorporate at the same time with Ah-NW. Age determination was based on the relationship between SST and
181 skeletal Sr/Ca as with the other specimens. Annual cycles of skeletal Sr/Ca in Av-NW and Ah-NW were shown
182 in Fig. S2. The age models of all coral cores were cross-checked through the characteristics of the geochemical
183 records, the relationships between skeletal Sr/Ca and IGOSS-SST data, the 2004 earthquake and tsunami signals
184 on the coral skeleton, and the skeletal growth parameters (see Table S2 and Supplementary Text S1).

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

190 The precipitation data and cloud fraction data were used in order to compare with the seasonal trend of
191 geochemical data (see Discussion 4.1). The monthly precipitation time series from June 1994 to May 2010 at
192 $1^\circ \times 1^\circ$ (2.5 N, 95.5 E) was derived from WCRP GCOS GPCC Monitoring
193 (<http://iridl.ldeo.columbia.edu/SOURCES/.WCRP/.GCOS/.GPCC/.Monitoring/.MONTHLY/.version1/>). The
194 monthly cloud fraction time series from June 1994 to May 2010 at $2^\circ \times 2^\circ$ (2.5 N, 95.5 E) was derived from
195 FRESCO+ SCIAMACHY (https://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=fresco_cloud).

196

197 2.6. Skeletal growth parameters analysis

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

202

203 3. RESULTS

204 3.1. Geochemical signals of seismic vertical displacement

205 The geochemical records were shown in Fig. 3. We identified the post-earthquake period (from the 2004
206 or 2005 earthquake to the date of core drilling) by the age model. The difference in the mean values between
207 the pre- and post-earthquake periods is shown as $\Delta Proxy$ (Post – Pre). Pre-earthquake periods of each coral

208 specimens were defined as the date of 2004 or 2005 coseismic uplift events (from the oldest age to December
209 26th, 2004 for NW corals, and to March 28th, 2005 for SE corals; see Method 2.1). Any significant difference in
210 $\Delta Proxy$ values was not detected between both earthquake periods, excluding the skeletal Mg/Ca in Av-NW
211 (Table S3). It is noted that there was no significant correlation between skeletal growth parameters and
212 geochemical records, excluding in B-NW (Sr/Ca vs. density and Mg/Ca vs. density) and in C-SE ($\delta^{13}C$ vs.
213 extension rate; Table S4). The data deviation for the skeletal density in B-NW and skeletal extension rate in C-
214 SE were relatively large (“SD” in Table S5). The large deviation of skeletal growth parameters might affect the
215 significant relationships.

216

217 3.1.1. Av-NW and Ah-NW (–1.0 and 0.5 m depth, uplifted 1.1 m during the 2004 earthquake)

218 The Av-NW record is presented in Fig. 3-a. There was no significant difference between the pre- and
219 post-earthquake periods in the skeletal $\delta^{13}C$ and Sr/Ca. The skeletal Mg/Ca and $\delta^{18}O$ during the post-earthquake
220 period significantly decreased significantly ($\Delta Mg/Ca = -0.14$ mmol/mol, $P < 0.05$ and $\Delta \delta^{18}O = -0.10$ ‰, $P <$
221 0.01).

222 The Ah-NW record is presented in Fig. 3-b. All the geochemical records in the Ah-NW were
223 characterized by the large amplitude found over one year in the aftermath of the 2004 earthquake. The skeletal
224 $\delta^{13}C$ showed a significant increase from August 2004 to the earthquake occurrence, and it revealed a large
225 amplitude with three high peaks in the aftermath of the earthquake (until the summer of 2006). In addition, a
226 significant step change between the pre- and post-earthquake periods was also shown in the skeletal $\delta^{13}C$ ($\Delta \delta^{13}C$
227 $= 0.34$ ‰; $P < 0.01$). During the same period, one year into the aftermath of the 2004 earthquake, there were
228 positive peaks in the skeletal Sr/Ca and $\delta^{18}O$. Simultaneously, the skeletal Mg/Ca showed a negative peak. There
229 was a significant difference between the pre- and post-earthquake results for the skeletal Sr/Ca ($\Delta Sr/Ca = 0.04$
230 mmol/mol; $P < .0001$). Skeletal Mg/Ca showed no significant difference. The skeletal $\delta^{18}O$ for the post-

231 earthquake period increased significantly ($\Delta\delta^{18}\text{O} = 0.21 \text{ ‰}$; $P < .0001$).

232

233 3.1.2. B-NW (5.0 m depth and 0.4 m uplift during the 2004 earthquake)

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

239

240 3.1.3. C-SE (2.1 m depth and uplifted 1.4 m during the 2005 earthquake)

241 The C-SE record is presented in Fig. 3-d. In the aftermath of the 2004 earthquake, the skeletal $\delta^{13}\text{C}$
242 displayed a positive peak (1.48 ‰), and it showed a significant step change ($\Delta\delta^{13}\text{C} = 0.32 \text{ ‰}$; $P < .0001$). During
243 the same period, there were positive peaks in the skeletal Sr/Ca and $\delta^{18}\text{O}$. Simultaneously, the skeletal Mg/Ca
244 showed a negative peak. These characteristic peaks were similar to those in the Ah-NW record. There were
245 significant differences between the pre- and post-earthquake skeletal Sr/Ca ($\Delta\text{Sr/Ca} = -0.04$ mmol/mol; P
246 $< .0001$), Mg/Ca ($\Delta\text{Mg/Ca} = -0.15$ mmol/mol; $P < .0001$) and $\delta^{18}\text{O}$ ($\Delta\delta^{18}\text{O} = -0.09 \text{ ‰}$; $P < .0001$).

247

248 3.1.4. D-SE (6.8 m depth and uplifted 0.6 m during the 2005 earthquake)

249 The D-SE record is presented in Fig. 3-e. Similar to B-NW, no signal of earthquake occurrence and no
250 remarkable variation was found in the aftermath of the earthquakes. A significant step change was not obtained
251 in the skeletal $\delta^{13}\text{C}$. There were significant differences between the pre- and post-earthquake in the skeletal
252 Sr/Ca ($\Delta\text{Sr/Ca} = -0.03$ mmol/mol; $P < .0001$; within the measurement error range) and Mg/Ca ($\Delta\text{Mg/Ca} = -$
253 0.47 mmol/mol; $P < .0001$). However, the skeletal $\delta^{18}\text{O}$ did not show a significant difference. Furthermore, there

254 was no marked variation in a part of the green band.

255

256 3.2. Skeletal growth record

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

263 The mean values for the annual extension rates during the post-earthquake period for inshore corals were
264 significantly higher than they were pre-earthquake (Ah-NW: +2.86 mm/yr, $P < 0.01$; and C-SE: +6.64 mm/yr,
265 $P < 0.05$); however, the Av-NW showed the opposite result (-5.44 mm/yr, $P < .0001$). There was no
266 significant difference in the offshore corals (B-NW and D-SE). The annual mean density showed no
267 significant difference in all the corals. Furthermore, the D-SE displayed a particular green band (Fig. S3). The
268 green band was coincident with the 2004 earthquake occurrence. The X-radiograph showed the green band as
269 a high-density band, with an 8 mm length equivalent to approximately 8 months of the post-earthquake
270 period. The small particles incorporated in the Av-NW and Ah-NW were coincident with the 2004 earthquake
271 (Fig. S4). The X-radiograph of these skeletal areas did not show a significant difference.

272

273 4. DISCUSSION

274 4.1. Impact of the earthquake on coral calcification

275 The 2004 earthquake and tsunami damage to the coral reefs has been reported by several articles (e.g.,
276 Chavanich et al., 2008; Kumaraguru et al., 2005; Foster et al., 2006). According to these previous studies, the

277 damaged corals were observed over several months after the earthquake and tsunami. Our coral skeleton showed
278 the four signals of tsunami damage: (1) a stress band (inshore corals; Fig. 2), (2) a significant decrease in the
279 annual extension/calcification rate in 2005 (NW corals; Fig. 4), (3) a green band (D-SE; Fig. S3), and (4) an
280 incorporation of the small particles like clay materials (Av-NW and Ah-NW; Fig. S4).

281 Anomalous high-density bands are skeletal growth responses to environmental stressors, for example,
282 thermal stress (Mendes and Woodley, 2002; Lough and Cooper, 2011). In our study site, the monthly IGOSS-
283 SST and the weekly AVHRR-SST did not show unusually cooler/warmer variations during three months before
284 and after the earthquakes. The monthly precipitation and the monthly cloud fraction also did not show unusually
285 variations. The annual mean of precipitation was 296.3 mm from 1994 to 2010, and that of 2004 and 2005 was
286 301.3 mm. Besides, our sampling sites were not close to the river. Thus, the thermal effect and the influence of
287 the sedimentation due to much precipitation or river runoff would not significantly. The stress band in the Ah-
288 NW and C-SE was caused by other stress factors such as sedimentation, which was created by the tsunami event.
289 The difference in the coral habitat location (inshore or offshore, i.e., the distance from the nearest shore) should
290 produce a discrepant growth disturbance. Sedimentation-related disturbances associated with tsunami events
291 (e.g., terrestrial runoff by the backwash and sediment resuspension) should stagnate in the water mass inshore
292 rather than offshore. In this study, the sampling site of Ah-NW and C-SE was inshore (the distance from the
293 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
294 m and 800 m for B-NW and D-SE). Each skeletal growth response showed a slight difference due to these
295 characteristics of the habitat condition. As a result, the inshore corals for Ah-NW and C-SE recorded the signal
296 from the earthquake event as a prominent stress band. The significant decrease in the annual growth record in
297 NW corals (especially in B-NW) would reflect the tsunami event which leads to a growth disturbance with over
298 months. In addition to the habitat condition (inshore/offshore), the distribution of the tsunami elevation could
299 also have produced a significant coral growth response. The tsunami elevation in 2004 was as high as 13 m in

300 the northern island, and it decreased to 4 m in the southern island (Jaffe et al., 2006). A higher tsunami elevation
301 will lead to a more extensive growth disturbance. Therefore, the annual extension/calcification rate in 2005 for
302 NW corals showed a significant decrease; and that of the SE corals showed no significant difference. The 8 mm
303 green band on the D-SE skeletal surface (Fig. S3) would represent the remnant concentration of the endolithic
304 algae, *Ostreobium* spp., as reported in several previous studies (e.g., Highsmith, 1981; Le Campion-Alsumard
305 et al., 1995). *Ostreobium* spp. are capable of CaCO₃-dissolving activity when they drill into the coral skeleton.
306 Endolithic algae bloom into the coral skeleton suggests an environmental stress response, for example, a
307 bleaching event and or terrestrial runoff (Fine and Loya, 2002; Carilli et al., 2010). The algae bloom is caused
308 by an increase in the amount of coastal nutrients or an enhanced upwelling or vertical mixing, which may
309 enhance the marine phytoplankton growth. Following the Indian Ocean tsunami in 2004, satellite-derived
310 chlorophyll-a surveys have been reported (e.g., Tang et al., 2006; 2009; Singh et al., 2007; Yan and Tang, 2009).
311 These previous studies showed a chlorophyll-a (algae) bloom following the tsunami event in the Indian Ocean.
312 Besides, Dipole Mode Index (derived from JAMSTEC,
313 http://www.jamstec.go.jp/aplinfo/sintexf/iod/dipole_mode_index.html) and IGOSS-SST did not show any
314 upwelling occurrence (e.g., the significant positive IOD signal and low-SST signal) during one year in the pre-
315 and post-earthquake. Thus, the upwelling effect was not strong in the period, and the green band was the
316 evidence of tsunami-related algae bloom. The nutrient pulse might stimulate photosynthesis by the
317 zooxanthellae and biomass; however, it would inhibit coral calcification (McConnaughey, 2012). The D-SE did
318 not show the significant change in the annual extension/calcification rate in 2005; while, the tsunami-related
319 algae bloom may cause the stress bands or the significant growth extension/calcification decrease. The small
320 particles in the coral skeleton (Av-NW and Ah-NW, Fig. S4) were coincident with the 2004 earthquake. The
321 coral skeletons sometimes incorporate noncarbonate detrital material such as sediment suspended in waters in
322 which the corals lived (Barnard et al., 1974). We did not make sure the small particles in Av-NW and Ah-NW

323 by mineralogical analysis in this study; however, there is a possibility that the brown and lustrous particles (Fig.
324 S4-B and -D) was incorporated with the coral skeleton by tsunami-induced sediment load (terrestrial input by
325 the backwash and sediment resuspension). Thus, these four signals would be short-term evidence of earthquake
326 and tsunami event.

327 The Ah-NW and C-SE (inshore corals) geochemical record in the aftermath of the 2004 earthquake
328 showed significant simultaneous increase or decrease (Figs. 3-f and 3-g). The fluctuating duration in C-SE was
329 shorter than that of Ah-NW. The skeletal geochemical signals are smoothed during skeletogenesis within the
330 living tissue layer (Barnes et al., 1995; Gagan et al., 2012). The analysis time resolution of C-SE (biweekly)
331 was higher than Ah-NW (monthly). The annual mean of skeletal extension rate and the tissue layer depth were
332 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
333 within the living tissue layer would be smooth the geochemical signals over a period equivalent to 3 months for
334 C-SE and 16 months for Ah-NW. Because of the higher resolution, faster growth, and the smoothing in a shorter
335 period, the C-SE recorded the earthquake and tsunami events more sharply than the Ah-NW. Besides, the age
336 model was established so that the skeletal growth rate (mm/yr) was assumed to be constant during one year.
337 The wrapped time series of Ah-NW might be extended earthquake-tsunami signals because of the lower
338 resolution and slower growth. The SST proxies (skeletal Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$) showed the lower-SST signal
339 in the aftermath of the 2004 earthquake. It seemed to fluctuate more than would be expected from (satellite-
340 derived) SST causes. There may be a difference between the in situ and satellite data, and these geochemical
341 proxies may reflect the local SST variation in the aftermath of the 2004 earthquake. Besides, seismic shaking
342 and tsunami would temporarily suspend sediments and reduce light availability in seawater, and these effects
343 might cause skeletal growth disturbance (intra-annual growth decrease). The skeletal $\delta^{13}\text{C}$ record signal might
344 be influenced by the growth stress or the abrupt increasing light availability due to the uplift event.

345

346 4.2. Influences of past seismic vertical displacement on coral calcification

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

349
$$I_D = I_0 \exp [-kD] \quad (1)$$

350 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
351 surface ($D = 0$), and k is the extinction coefficient (Fig. 5-a). The differences in the collection water depth and
352 the amount of seismic vertical displacements should be considered in order to assess the skeletal growth
353 responses precisely. Our coral specimens are categorized into two patterns (Category-1 and -2) by a relative
354 difference in light availability (RLA). The RLA (i.e., $I_{D_{\text{post}}} - I_{D_{\text{pre}}}$) is obtained by taking the difference in the
355 water depth between the pre- and post-earthquake values (the amount of vertical displacement) as follows:

356
$$RLA = \exp [-k (D_{\text{post}} - D_{\text{pre}})] \quad (D = 0, RLA = 1; k = 1) \quad (2)$$

357 where the extinction coefficient k is constant ($k = 1$) in this study because the k varies spatiotemporally due to
358 depending on the quantity and quality of various substances (undissolved organic matter and suspended
359 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.,
360 sea surface). The category-1 specimens, Ah-NW and C-SE, have shallow depth (1.6~3.5 m) and large
361 displacement (+1.1~1.4 m) characteristics. Conversely, the category-2 specimens, B-NW and D-SE, have deep
362 depth (5.4~7.4 m) and small displacement (+0.4~0.6 m) characteristics. The RLA of category-1 is larger than
363 that of category-2.

364 In category-1, the skeletal growth response to RLA was shown as a significant increase in the annual
365 extension rate (Table 2 and Fig. 5-b). There was a strong positive correlation between the skeletal calcification
366 rate and the extension rate ($R = 0.85-0.97$; $P < 0.05$), and it was consistent with Lough and Barnes (2000).
367 Skeletal calcification is controlled by the activity of Ca^{2+} -ATPase (Kingsley and Watabe, 1985; McConnaughey,
368 1998), which is enhanced by light availability (Barnes and Chalker, 1990). Therefore, our result for category-1

369 would reflect the skeletal calcification activity owing to the increasing light availability caused by seismic
370 vertical displacement. By contrast, the growth response to the RLA was relatively small in category-2 (Fig. 5-
371 b). The RLAs of category-2 would be too small to affect the coral skeletal growth. The skeletal growth in
372 category-2 would reflect not only the uplift-related RLA but also the other environmental factors. Our results
373 suggest that the corals that experienced high RLA are suitable for accessing the growth response to seismic
374 vertical displacement.

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

385 386 4.3. Step change in the coral skeletal $\delta^{13}\text{C}$ with seismic vertical displacement

387 It is a bit difficult to show the coral skeletal $\delta^{13}\text{C}$ and light model because the relationship is quite
388 complicated. Photosynthesis by symbiotic algae (zooxanthellae) is one of the major factors of skeletal $\delta^{13}\text{C}$, and
389 it has a strong relationship to the coral light availability and coral habitat water depth (e.g., Weber et al., 1976;
390 Fairbanks and Dodge, 1979; Heikoop et al., 2000; Dassié et al., 2013). While McConnaughey (1989a) reported
391 that shallow corals (it grew at approximately the low tide line) might be light saturated, and the positive

392 correlation among light, photosynthesis, and skeletal $\delta^{13}\text{C}$ might be lost. In our study, the warm season at
393 Simeulue Island is less cloudy than the cooler season. As shown in Fig. S5, there was a significant correlation
394 between skeletal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in the post-earthquake, only in Ah-NW (-1.0 m depth) and B-NW (5.0 m depth).
395 Any significant relationship was not detected in the other corals, which did not agree with the previous study
396 (McConnaughey 1989a, Figure 7, *Porites* in Academy Bay). There is the possibility of the influence of light
397 saturation; however, our result suggests that the influence was not significant in this study (especially in Ah-
398 NW, C-SE, and D-SE).

399 Gagan et al. (2015) indicated the coral skeletal $\delta^{13}\text{C}$ paleogeodesy technique for studying the specimens
400 that experienced seismic vertical displacements of +1.6 m (n=6) and -0.4 m (n=4), which were collected at a
401 ~ 1.0 m depth. A coral skeletal $\delta^{13}\text{C}$ paleogeodetic model was constructed by finding the step changes in the
402 skeletal $\delta^{13}\text{C}$ produced by decimeter-scale seafloor displacements. The step change in the skeletal $\delta^{13}\text{C}$ was
403 distinguished from other controlling factors such as the $\delta^{13}\text{C}$ of dissolved inorganic carbon in seawater (e.g.,
404 Nozaki et al., 1978; Grottoli and Wellington, 1999; Swart et al., 2010) and during mass-spawning (e.g., Gagan
405 et al., 1994). In addition, the respiration (e.g., Swart, 1983; McConnaughey, 1989b; Carriquiry et al., 1994;
406 McConnaughey et al., 1997; Grottoli and Wellington, 1999) and heterotrophic feeding components (e.g., Felis
407 et al., 1998; Grottoli and Wellington, 1999) are negligible because the variable range and the skeletal carbon
408 derived from these components are smaller than the seafloor displacement-related changes in the skeletal $\delta^{13}\text{C}$.
409 Our skeletal $\delta^{13}\text{C}$ records showed the significant step changes in category-1 ($\Delta\delta^{13}\text{C}$ in Ah-NW and C-SE were
410 0.34 ‰ and 0.32 ‰; Fig. 3-b and Fig. 3-d). These significant step changes reflect the uplift-related RLAs
411 leading to activating photosynthesis by zooxanthellae. The seismic uplift values were +1.1 m during 2004
412 earthquake and +1.4 m during 2005 earthquake for Ah-NW and C-SE, respectively. Thus, our $\Delta\delta^{13}\text{C}$ results
413 equated to a skeletal $\delta^{13}\text{C}$ response of 0.31 ‰/m in response to the 2004 uplift and 0.23 ‰/m to the 2005
414 uplift for Ah-NW and C-SE, respectively. Our result was consistent with Gagan et al. (2015), who showed the

415 abrupt increase in the skeletal $\delta^{13}\text{C}$ associated with the coseismic uplift in the aftermath of the Nias-Simeulue
416 earthquake. Importantly, the annual extension rate during the post-earthquake period was 8.1 mm/yr and 30.0
417 mm/yr for the Ah-NW and C-SE, respectively (Table 2). Therefore, the kinetic isotope effect would be
418 negligible during that period. Moreover, there was no significant mean difference in the cloud fraction
419 between pre- and post-earthquake. The significant step change in the skeletal $\delta^{13}\text{C}$ would reflect the uplift-
420 related RLAs, not the change of cloud fraction. In category-2, a significant step change in the skeletal $\delta^{13}\text{C}$
421 was not obtained. McConnaughey (1989a) mentioned that the deeper corals did not show the significant
422 trends in the skeletal $\delta^{13}\text{C}$ because the reduction in depth caused by coral growth was insignificant compared
423 to total depth. Our result (Fig. 5) in D-SE and B-NW (deeper coral, smaller seafloor displacement, and smaller
424 RLA) generally agreed with the previous study. The RLAs of category-2 seem to be too small to record the
425 significant step change produced by seismic vertical displacement. The skeletal $\delta^{13}\text{C}$ in category-2 would
426 reflect not only the uplift-related RLA but also the other controlling factors (e.g., respiration, heterotrophic
427 feeding, or the $\delta^{13}\text{C}$ of dissolved inorganic carbon in seawater).

428 In order to strongly ensure the accuracy of the coral skeletal $\delta^{13}\text{C}$ paleogeodesy technique, it is necessary
429 to understand the relationships among the coral habitat depth, the step change in the skeletal $\delta^{13}\text{C}$ derived from
430 vertical displacement, and the RLA. Because our specimens had different RLAs, we obtained the significant
431 relationships. The skeletal $\delta^{13}\text{C}$ of the uplifts ($\text{‰}/\text{m}$) in our and previous study exponentially decreased with the
432 decreasing RLA ($R = 0.99$; $P < 0.05$; Fig. 5-c; excluding Av-NW). This significant relationship seems to reflect
433 an exponential available light attenuation. Importantly, the skeletal $\delta^{13}\text{C}$ of the uplift was significantly correlated
434 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
435 excluded because it showed a slight decrease in post-earthquakes ($\Delta\delta^{13}\text{C} = -0.17 \text{ ‰}$; *n.s.*). There were two
436 categories of skeletal $\delta^{13}\text{C}$ response against the vertical displacements within the RLAs. One is Ah-NW and
437 Gagan et al. (2015), these corals strongly reflected its large RLAs produced by shallow habitat depth (0.6~1.0

438 m) and large displacement (+1.1~1.6 m). The other is C-SE and D-SE, its habitat water depths were deeper
439 and the RLAs were smaller than the Ah-NW and the value in Gagan et al. (2015). The step changes in the
440 skeletal $\delta^{13}\text{C}$ in Ah-NW and Gagan et al. (2015) would be dependent on the changes in coral light availability
441 produced by seismic vertical displacement rather than the changes by the other environmental cause. While the
442 skeletal $\delta^{13}\text{C}$ records for the C-SE and D-SE seemed to reflect not only the uplift-related changes in light
443 availability but also other environmental factors or vital effects. This result suggests that the corals that lived at
444 shallow depths and experienced large RLA values are suitable for the coral skeletal $\delta^{13}\text{C}$ paleogeodetic tool.
445 Besides, there is a possibility of including the responses to earthquake precursors and post-seismic activity. In
446 this study, we could not precisely distinguish the earthquake precursors (e.g., foreshock), co-seismic shaking,
447 and post-seismic activity (e.g., aftershock) from the proxy signals. There are still issues with precise detecting
448 the uplift or tsunami signals because these events might lead to a severe disturbance in coral skeleton. Especially
449 in a shallow depth, the uplift-related exposure or tsunami-related sediment suspension may cause a gap in
450 skeletal growth. The skeletal growth gap smooths the earthquake signal in the geochemical record, or it might
451 not record the earthquake events. However, our result is important evidence because a significant coral skeletal
452 $\delta^{13}\text{C}$ -RLA relationship will ensure good coral skeletal $\delta^{13}\text{C}$ paleogeodesy. Additionally, Gagan et al. (2015)
453 mentioned the detection limits of dome-shaped coral skeletal $\delta^{13}\text{C}$ paleogeodesy; the lower detection limit for
454 vertical displacement appears to be ~0.3 m for short coral $\delta^{13}\text{C}$ records limited to ~5 years of growth before or
455 after an earthquake. Our results were mostly consistent with these detection limits. In addition to the detection
456 limits, we propose that the coral RLA related to the habitat water depth and scale of vertical displacement are
457 also noteworthy keys for coral skeletal $\delta^{13}\text{C}$ paleogeodesy. These characteristics would allow us to use the coral
458 skeleton as a paleo-earthquake proxy with much more precise detection qualities than those of the current
459 methods.

460

461 4.4. Changes in other skeletal geochemical proxies with seismic vertical displacement

462 4.4.1. Skeletal Sr/Ca

463 The coral skeletal Sr/Ca is widely used in paleo-thermometry (e.g., Beck et al., 1992; McCulloch et al.,
464 1994; Cahyarini et al., 2014). Several previous studies have reported the difference in the skeletal Sr/Ca
465 sensitivity to temperatures among neighboring coral colonies even when they were collected on the same reef
466 (Goodkin et al., 2005; Linsley et al., 2006; Cahyarini et al., 2009; Pfeiffer et al., 2009; Alpert et al., 2016).
467 Although the sites where we collected coral specimens are not far from one another, five of the coral skeletal
468 Sr/Ca records have each had different variations (mean value, and seasonal variation; Table 3-a). The difference
469 in the mean values among the five profiles was 0.198 mmol/mol at maximum (the minimum value was 8.831
470 mmol/mol in D-SE, and the maximum value was 9.029 mmol/mol in B-NW). The predicted difference in the
471 mean Sr/Ca-derived temperature was 3.24 °C (Abram et al., 2007), and it was larger than that of the mean
472 AVHRR-SST between the northern and southern parts of Simeulue Island (difference in mean values: 0.03 °C).
473 In Av-NW, the mean value for the seasonal variation (MSV; difference between the maximum/minimum value
474 during one year) was 0.151 mmol/mol. The Av-NW record from the pre-earthquake period revealed clear annual
475 cycles with 0.172 mmol/mol of mean seasonal variation, and this cycle became unclear with the significant
476 small mean seasonal variation of the post-earthquake period ($\Delta\text{MSV} = 0.059$ mmol/mol, $P < 0.01$). By contrast,
477 the Ah-NW, which is a horizontal-drilled core from the same colony as Av-NW, the MSV was 0.160 mmol/mol.
478 The seasonal variation of Ah-NW in the post-earthquake period was slightly smaller than the variation pre-
479 earthquake ($\Delta\text{MSV} = 0.003$ mmol/mol; *n.s.*; within the measurement error range). In B-NW, the MSV was 0.172
480 mmol/mol. The seasonal variation of B-NW in the post-earthquake was smaller than that of the pre-earthquake
481 period ($\Delta\text{MSV} = 0.081$ mmol/mol; $P < 0.05$). In C-SE, the MSV was 0.213 mmol/mol. The seasonal variation
482 of C-SE in the post-earthquake was slightly smaller than it was pre-earthquake ($\Delta\text{MSV} = 0.006$ mmol/mol; *n.s.*).
483 In D-SE, the MSV was 0.350 mmol/mol. The seasonal variation of D-SE in the post-earthquakes was larger

484 than it was pre-earthquakes ($\Delta\text{MSV} = 0.079$ mmol/mol; $P < 0.01$). The seasonal variation of the AVHRR-SST
485 in the post-earthquakes was smaller than it was pre-earthquakes (ΔMSV of northern AVHRR-SST: 0.333 °C;
486 *n.s.*; ΔMSV of southern AVHRR-SST: 0.523 °C; $P < 0.05$). Therefore, the skeletal Sr/Ca record in Av-NW, Ah-
487 NW, B-NW, and C-SE could have the potential to indicate the long-term SST trend, although there was a
488 difference in the mean seasonal variability. However, the skeletal Sr/Ca record in D-SE might be explained by
489 other factors. Moreover, there is no significant difference in the mean AVHRR-SST and IGOSS-SST between
490 the pre- and post-earthquake periods. The earthquake events did not affect SST and skeletal Sr/Ca. Thus, the
491 significant $\Delta\text{Sr/Ca}$ in the Ah-NW, B-NW and C-SE were attributable to the skeletal Sr/Ca sensitivity to
492 temperature or another factor.

493

494 4.4.2. Skeletal Mg/Ca

495 Several previous studies have shown that the coral skeletal Mg/Ca could be used in paleo-thermometry
496 (Mitsuguchi et al., 1996; Wei et al., 2000; Watanabe et al., 2001). In skeletal Sr/Ca vs. Mg/Ca through both pre-
497 and post-earthquake periods, there was a significant correlation in Av-NW, Ah-NW, and B-NW (Fig. S5). This
498 result suggests that skeletal Mg/Ca reflected SST variation as with skeletal Sr/Ca. Similar to skeletal Sr/Ca
499 records, five coral skeletal Mg/Ca records each showed different variations (mean value and seasonal variation;
500 Table 3-b). The difference in the mean values among the five profiles was 0.574 mmol/mol at a maximum (the
501 minimum value was 4.408 mmol/mol in the Ah-NW, and the maximum value was 4.982 mmol/mol in the D-
502 SE). The predicted difference in the mean Mg/Ca-derived temperature was 4.45 °C (Mitsuguchi et al., 1996),
503 and it was larger than that of the mean AVHRR-SST between the northern and southern parts of Simeulue Island
504 (difference in mean values: 0.03 °C). In Av-NW, the MSV was 0.911 mmol/mol. The seasonal variation of Av-
505 NW in the post-earthquake was slightly smaller than it was pre-earthquake ($\Delta\text{MSV} = 0.047$ mmol/mol; *n.s.*). In
506 Ah-NW, the MSV was 0.484 mmol/mol. The seasonal variation of Av-NW in the post-earthquake was slightly

507 smaller than the variation pre-earthquake ($\Delta\text{MSV} = 0.012$ mmol/mol, *n.s.*). In B-NW, the MSV was 0.604
508 mmol/mol. The seasonal variation of B-NW in the post-earthquake was significantly smaller than the variation
509 in the pre-earthquake ($\Delta\text{MSV} = 0.416$ mmol/mol, $P < 0.05$). In C-SE, the MSV was 0.717 mmol/mol. The
510 seasonal variation of C-SE in the post-earthquake was slightly larger than it was pre-earthquake ($\Delta\text{MSV} = 0.149$
511 mmol/mol; *n.s.*). In Ah-NW, the MSV was 0.689 mmol/mol. The seasonal variation of D-SE in the post-
512 earthquake was also slightly larger than it was pre-earthquakes ($\Delta\text{MSV} = 0.214$ mmol/mol; *n.s.*). Similar to the
513 discussion of Sr/Ca, the earthquake event did not affect SST and skeletal Mg/Ca. Thus, the $\Delta\text{Mg/Ca}$ in the C-
514 SE and D-SE were attributable to the skeletal Mg/Ca sensitivity to temperature or another factor (e.g., organic
515 matters, described by Watanabe et al., 2001; Nagtegaal et al., 2012).

516 A significant fraction of the organic compound-related Mg in the coral skeleton was recognized in many
517 previous studies (e.g. Amiel et al., 1973). Watanabe et al. (2001) suggested that 60 % of the Mg in the coral
518 aragonite substitutes for calcium but more than 40 % of the Mg in the coral is associated with organic matter or
519 absorbed onto the surfaces of the crystal. Moreover, Nagtegaal et al. (2012) noted that there is a possibility that
520 the Mg in the coral skeleton may remain as extra crystalline precipitates from sea salts and or as organic matter
521 since Mg is a structural element in the chlorophyll of the symbiotic zooxanthellae (Mg-rich chlorophyll
522 derivatives). A chlorophyll-a (algae) bloom occurrence following the 2004 tsunami event in the Indian Ocean
523 has been reported by several previous studies (e.g., Tang et al., 2006; 2009; Singh et al., 2007; Yan and Tang,
524 2009; see Discussion 4.1). The presence of this bloom implies that a tsunami-related chlorophyll bloom leads
525 to high-Mg concentrations in the coral skeleton. Thus, skeletal Mg/Ca could have potential as a proxy for
526 detecting a tsunami event. In fact, the skeletal Mg/Ca in Ah-NW and C-SE showed a positive peak after the
527 tsunami events (Figs. 3-f and 3-g). A positive peak in the C-SE seemed to reflect the 2005 tsunami (5 m at
528 southern Simeulue Island) rather than the 2004 tsunami. The coral habitat location either inshore or offshore
529 must be considered to ensure the skeletal Mg/Ca paleo-tsunami proxy. Similar to sedimentation (see Discussion

530 4.1), the coastal nutrients and phytoplankton bloom from a tsunami event should stagnate in the water mass
531 inshore rather than offshore. Thus, further experiments to assess the difference in the habitat location (inshore
532 or offshore) would be required to ensure the possibility of coral skeletal paleo-tsunami detection. Moreover, the
533 effect of *Ostreobium* spp. (which creates a green band) on the geochemical proxy has been discussed by
534 Highsmith (1981) and Tribollet (2008). According to these previous studies, the *Ostreobium* spp. filaments
535 facilitate CaCO₃ precipitation and aragonite precipitation lowers Ca²⁺ activity, thereby increasing the local
536 Mg/Ca ratio in the coral skeleton. Unfortunately, our skeletal Mg/Ca in D-SE did not show the significant
537 variation caused by the green band. It might be required to measure the skeletal Mg/Ca with higher-resolution
538 or to measure the Mg/Ca in the microstructures.

539

540 4.4.3. Skeletal $\delta^{18}\text{O}$

541 The coral skeletal $\delta^{18}\text{O}$ reflects the SST and the oxygen isotope ratios in seawater (i.e., sea surface
542 salinity, e.g., Dunbar and Wellington, 1981; McConnaughey, 1989a; Gagan et al., 1994). In tropical and
543 subtropical areas, variations in the seawater salinity caused by evaporation, rainfall, or freshwater input from
544 the river affect the skeletal $\delta^{18}\text{O}$, and then the influence of these components should be considered when
545 establishing a skeletal $\delta^{18}\text{O}$ -SST relationship (Cole and Fairbanks, 1990; Carriquiry et al., 1994; Al-Rousan et
546 al., 2007). According to Abram et al. (2007), it is difficult to reliably determine the coral $\delta^{18}\text{O}$ -SST dependence
547 using coral skeletons from the Mentawai Islands because this area experiences high and variable amounts of
548 rainfall/evaporation, which produce non-SST-related changes in the $\delta^{18}\text{O}$ of seawater (and coral). In this study,
549 The $\delta^{18}\text{O}_{\text{sw}}$ correlated with SST (Fig. S2; $R = 0.60\text{-}0.91$; $P < 0.05$; excluding D-SE), not precipitation. It
550 suggested that the $\delta^{18}\text{O}_{\text{sw}}$ would reflect evaporation rather than precipitation. In the cooler season (November),
551 $\delta^{18}\text{O}_{\text{sw}}$ might reflect the high precipitation. In skeletal Sr/Ca vs. $\delta^{18}\text{O}$ through both pre- and post-earthquake periods,
552 there was a significant correlation in Ah-NW, B-NW, and C-SE (Fig. S5). This result suggests that skeletal $\delta^{18}\text{O}$

553 reflected SST variation as with skeletal Sr/Ca. The lack of correlation in Sr/Ca vs. $\delta^{18}\text{O}$ (Av-NW and D-SE)
554 suggests that our skeletal $\delta^{18}\text{O}$ records would be influenced by not only SST but also $\delta^{18}\text{O}$ seawater. Similar to the
555 skeletal Sr/Ca and Mg/Ca records, five of the coral skeletal $\delta^{18}\text{O}$ records have each shown different variations
556 (mean value and seasonal variation; Table 3-c). The difference in the mean values among the five profiles was
557 0.320 ‰ at a maximum (the minimum value was -5.821 ‰ in the D-SE, and the maximum value was -5.501 ‰
558 in the Ah-NW). The difference seems to be too large against that of the mean AVHRR-SST between the northern
559 and southern parts of Simeulue Island (difference of mean values: 0.03 °C), even if the component of $\delta^{18}\text{O}$ in
560 sea water is considered. In Av-NW, the MSV was 0.468 ‰. The ΔMSV was 0.003 ‰ (*n.s.*), which is within the
561 measurement error range (0.04 ‰). In Ah-NW, the MSV was 0.496 ‰. The seasonal variation of Av-NW in the
562 post-earthquake period was significantly larger than it was pre-earthquake ($\Delta\text{MSV} = 0.216$ ‰, $P < 0.05$). In B-
563 NW, the MSV was 0.584 ‰. The seasonal variation of B-NW in the post-earthquake was significantly smaller
564 it was pre-earthquake ($\Delta\text{MSV} = 0.265$ ‰, $P < 0.01$), in contrast to the result for the Ah-NW. In C-SE, the MSV
565 was 0.562 ‰. The seasonal variation of C-SE in the post-earthquake was slightly larger than it was pre-
566 earthquake ($\Delta\text{MSV} = 0.045$ ‰, *n.s.*). In D-SE, the MSV was 0.560 ‰. The seasonal variation of D-SE in the
567 post-earthquake was slightly smaller than it was pre-earthquake ($\Delta\text{MSV} = 0.094$ ‰, *n.s.*). Gagan et al. (2015)
568 showed no significant change in the skeletal $\delta^{18}\text{O}$ when using two fossil *Porites* that experienced an abrupt
569 change in the light exposure or 0.7 m of uplift in 1797. However, in this study, there was a significant difference
570 between the pre- and post-earthquake in the skeletal $\delta^{18}\text{O}$ in the Ah-NW, B-NW and C-SE. There is no
571 significant difference in the mean SST and precipitation between the pre- and post-earthquake periods. The
572 earthquake events did not affect SST, precipitation, and skeletal $\delta^{18}\text{O}$. The $\Delta\delta^{18}\text{O}$ in the Ah-NW may reflect the
573 temporal lower-SST signal in the aftermath of the earthquakes (see Discussion 4.1). Unfortunately, we could
574 not find the exact variable factors for the $\Delta\delta^{18}\text{O}$ in the B-NW and C-SE. These records fluctuated more than are
575 expected from environmental causes.

576

577 5. CONCLUSIONS

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

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

596

597 6. ACKNOWLEDGMENTS

598 This work was supported by JSPS KAKENHI [grant number: JP21684031, 17H04708]. The field

599 survey was a part of the Science and Technology Research Partnership for Sustainable Development
600 (SATREPS) project “Multi-disciplinary natural hazard reduction from earthquakes and volcanoes in Indonesia”
601 supported by JST and JICA of Japan and RISTEK and LIPI of Indonesia. SATREPS is a Japanese government
602 program that promotes international joint research, and our coral collection and research were performed under
603 an international agreement between two countries. Foreign Research Permit was also included into the
604 agreement. We acknowledge M. Ikeda, K. Sowa, T. E. Putra, Y. Sato, and T. K. Watanabe for their support
605 during the cutting of the coral core specimens, the collection of X-radiographs, and the microsampling.
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607 7. REFERENCE

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829 8. TABLE AND FIGURE CAPTIONS

830 [Tables]

831 **Table 1 Sample information**

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

837

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

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

844

845 **Table 3 Mean values and seasonal mean variations in the skeletal Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$ records**

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

850

851 [Figures]

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

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

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

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

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

860 **(c) Sample sites on Simeulue Island.**

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

865

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

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

874

875 **Fig. 3 Skeletal geochemical records ($\delta^{13}\text{C}$, Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$)**

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

885

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

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

892

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

894 (a) Relative light availability during pre- (●) and post-earthquakes (○) in all corals (Av-NW in post-
895 earthquakes was excepted because the top of colony was over the sea surface after the uplift event; see in the
896 text and Fig. S1). Underwater light decreases exponentially in the depth direction according to Lambert-beer
897 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

898 (i.e., relative light availability) at sea surface ($D = 0$), and the extinction (attenuation) coefficient k is constant
899 ($k = 1$) in this study because the k varies spatiotemporally due to depending on the quantity and quality of various
900 substances (undissolved organic matter and suspended particles) in seawater and the wavelength of light in
901 seawater. It is noted when the D is 0, I is 1 (\times). “Water depth D ” is the estimated depth in pre-earthquakes (Pre)
902 and the depth during lowest tide (Post), which is shown in Table 2. (b) Relationship between the RLA and
903 skeletal growth. The y-axis shows the difference (post- – pre-earthquakes) in the annual skeletal extension
904 rates (see Table 2, “Difference”). The x-axis shows the RLA which is obtained by taking the difference in the
905 water depth between the pre- and post-earthquake values (i.e., $I_{D_{\text{post}}} - I_{D_{\text{pre}}}$) as follows: $RLA = \exp [-k (D_{\text{post}} -$
906 $D_{\text{pre}})]$ where D is 0, $RLA = 1$, and the extinction coefficient k is 1. Our coral specimens are categorized into two
907 patterns (Category-1: \bullet and -2: \circ) by a relative difference in light availability (RLA, see in the text). The
908 category-1 specimens have shallow depth (1.6~3.5 m) and large displacement (+1.1~1.4 m) characteristics. The
909 category-2 specimens (\circ) have deep depth (5.4~7.4 m) and small displacement (+0.4~0.6 m) characteristics.
910 Av-NW (the gray circle) was excluded from these categories because there is a possibility that skeletal growth
911 was not continuous due to the uplift event. (c) Relationship between the RLA and the skeletal $\Delta\delta^{13}\text{C}$. The skeletal
912 $\delta^{13}\text{C}$ shows the ‰/m of uplift. Circle plots indicate the results of this study. The category-1 (\bullet) and -2 (\circ)
913 characteristics were as described above. Triangle plots indicate the results in the supplemental data from Gagan
914 et al. (2015); ~1.0 m depth; and the skeletal $\delta^{13}\text{C}$ increased 0.26 ‰/m; n=6; in Nias Island. Larger RLA, and
915 larger skeletal growth or larger skeletal $\Delta\delta^{13}\text{C}$ indicates uplift-related change.

916