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**Reef disturbance archives in coral sclerochronological proxies
and the responses on skeletal calcification**

(サンゴ骨格中の古環境指標及び成長パラメータに記録された
生息環境の攪乱と石灰化応答)

伊藤 早織

北海道大学大学院理学院
自然史科学専攻

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Ph.D. Thesis

**Reef disturbance archives in coral sclerochronological proxies
and the responses on skeletal calcification**

Saori Ito

**Department of Natural History Sciences
Faculty of Science, Hokkaido University**

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Abstract

Coral reefs are currently facing numerous disturbances that have multiple and mixed components of natural and anthropogenic factors at a local and global scale (i.e., climate change, temporary meteorological phenomena, human activity, and land-use change). Annual mean precipitation in the high latitudes and the equatorial Pacific are likely to increase, and extreme precipitation events will likely become more intense and more frequent. There is also an expected area with the potential occurrence of a large earthquake ($M_w > 8$) and tsunami event. The intensity of human activities is also expected to increase. These factors would exacerbate the risk of reef disturbances. Despite this situation, there are many coastal areas in tropics and subtropics where periodic monitoring surveys and *in situ* environmental data are not available. While, a massive coral skeleton has the long-term archives of environmental change with a high temporal resolution, and they should be a useful tool for the quantitative evaluation for the impact of the reef disturbance and coral calcification response. It can be essential to the discussion of survival strategies for reef-building corals in which extreme rainfall occurrence, large earthquake-tsunami occurrence, and human activities will increase. Here we show the reef disturbance archives in coral sclerochronological proxies and the responses on skeletal calcification using the massive coral skeletons (e.g., *Porites* sp.). This study showed how natural (e.g., earthquake-related seafloor displacement, tsunami, heavy rainfall, river runoff, and mangrove systems) or anthropogenic (e.g., local industrial history and land use) factors lead to a reef disturbance, and how corals respond to these disturbances. The study sites and focuses were 1) Simeulue Island, Indonesia: Earthquake, seafloor displacement, and tsunami event, 2) Kikai Island, Japan: Tsunami event, 3) Amami-Oshima Island, Japan: Heavy rainfall, river flood event, and mangrove system, and 4) Amami-Oshima Island, Japan: Local industrial changes and land use, as summarized as below;

1) The remarkable signals of the 2004 and 2005 earthquake events (including coseismic seafloor displacement and tsunami) were observed on the surface of coral skeletons (the stress bands; the green band; incorporation of the small particles like clay materials), skeletal growth parameters (the significant decrease in the annual extension/calcification rate corresponding to the coseismic seafloor displacement; the significant mean difference between pre- and post-earthquake), and skeletal $\delta^{13}\text{C}$ (step change corresponding to the coseismic seafloor displacement). The earthquake events led to the coral growth disturbance and the change in the coral light availability. Coral paleo-earthquake archive will provide us with local information on crustal deformation at the decimeter scale.

2) The remarkable signals of the 1911 tsunami event were observed on skeletal Ba/Ca (a high peak) and skeletal growth parameters (a significant decrease in the annual extension/calcification rate). This study showed the evidence for a new possibility of the skeletal Ba/Ca as a past-tsunami proxy. The tsunami-related sediment load in the seawater could temporarily cause low water visibility (i.e., high turbidity). Though the tsunami event occurs in the very short-term, the tsunami-related sediments will harm coral calcification, and then the annual skeletal calcification rate reflected the tsunami effect.

3) The remarkable signals of heavy rainfalls and river floods were observed on the skeletal Ba/Ca (a high peak in the isolated < 2 years trend data) and temporary skeletal growth parameters (the stress bands; the increasing $\Delta\text{Sr}/\text{Ca}$). These results suggested the increase in the sediment load in the seawater due to river flood events. Especially when the extreme-heavy rainfall or devastating river flood occurred, skeletal Sr/Ca, skeletal Mg/Ca, and coral derived $\delta^{18}\text{O}_{\text{sw}}$ showed the temporal low-SST signal or low-SSS (due to the cold freshwater plume or the cold heavy

precipitation). Moreover, the skeletal Ba/Ca record in this study was mainly controlled by the amount of the desorbed Ba^{2+} (in the estuary) from the Ba-containing sediment transported by the rivers and mangrove forests. The skeletal Ba/Ca in the corals that inhabit near the mangrove area or estuarine reflects the mangrove system (affected by both tide level and precipitation) and SST variation on the seasonal scale.

4) The remarkable signals of local industrial history and land use were observed on the skeletal Ba/Ca (isolated > 2 years trend data) and annual skeletal growth parameters. These proxies would reflect the local industry (e.g., traditional silk fabric) and land use for 46 years. The sensitivity (response) of the reef-building coral to sediment load would reflect the change in the rhythm of sediment outflow into the bay, corresponding to the local industrial history.

These study cases suggested that the combined methodology, coral geochemical proxies with skeletal growth parameters, provides a quantitative scale of the impacts of natural and anthropogenic reef disturbance with a long time series. The skeletal geochemical proxies recorded natural/anthropogenic reef disturbance events, and coral calcification responded to these reef disturbances. The natural/anthropogenic disturbance event will be one of the controlling factors of coral calcification. Reef disturbance archives in the coral sclerochronological proxies will provide us the worthy key for understanding the skeletal calcification responses to the habitat environmental change and creating a sustainable healthy relationship in coral reefs and human society.

1. General introduction for reef disturbance archives in coral sclerochronological proxies and the responses on skeletal calcification

1.1 Coral reef disturbances (natural and anthropogenic factors)

Healthy coral reefs supply a wide range of benefits to local communities around the world (e.g., an attraction for tourism, stable livelihoods in coastal areas, and stable habitat for marine life). Coral reefs are currently facing multiple disturbances caused by natural/anthropogenic factors at a local and global scale (e.g., global warming, sea-level change, extreme meteorological phenomena, ocean acidification, land-/marine-based pollution, overfishing, and sediments). Approximately 75 % of the world's coral reefs are rated as threatened when local threats are combined with thermal stress (Burke et al., 2011; Hughes et al., 2018a; 2018b). These stressors will cause a change in coral assemblages and coral populations (Bauman et al., 2013a; 2013b; Hughes et al., 2018a; Riegl et al., 2018; Burt and Bauman 2019; Hughes et al., 2019), and coral reefs will expand their habitats to higher latitudes corresponding to global warming (Yamano et al., 2011). Annual mean precipitation in the high latitudes and the equatorial Pacific are likely to increase, and extreme precipitation events will very likely become more intense and more frequent, which would exacerbate sediment runoff to the coral reefs (Burke et al., 2011; Pachauri, 2014). Besides, the intensity of human activities is expected to increase, leading to sediment and nutrient runoff, which can affect corals and reef communities (Burke et al., 2011; Maina et al., 2013; Burt and Bartholomew, 2019).

Reef disturbances, especially natural forcing (e.g., river runoff, earthquake, and tsunami) and industry-related sediment input, have a negative impact on shallow reef ecosystems. Previous studies described that the calcification rates/growth rates in massive *Porites* sp. and *Diploastrea* sp. have declined of 14 ~ 30 % in Great Barrier Reef (Cooper et al., 2008; De'ath et al., 2009), Red Sea (Cantin et al., 2010), and Thailand (Tanzil et al., 2009), since the 1980s ~ 1990s, which might reflect the change in the habitat environment due to the synergistic effect of elevated seawater temperatures and $p\text{CO}_2$. Decreased coral calcification causes a reduction or cessation of reef growth and may trigger a reduction in biodiversity on reefs (Brown and Howard, 1985; Rogers, 1990; Fabricius, 2005; Mora and Sale, 2011; Jokiel et al., 2014). Corals are also sensitive to the impacts of sediments and turbidity, and a sustained high-sediments and high-nutrient will “switch off” reef growth (Van Woesik and Done, 1997; Van Woesik et al., 1999; Dikou and Van Woesik, 2006; Erftemeijer et al., 2012). It would cause the loss of resources with environmental, economic, and socio-cultural impacts (Bruke et al., 2011). Most of the recent reef assessments on the natural/anthropogenic reef disturbance were based on temporary and qualitative methods, for example, coral bleaching observations, reef cover monitoring, or modelling the variability of climate-related stressors in the future (e.g., Burke et al., 2011; De'ath et al., 2012; Hughes et al., 2017; 2018a; 2018b; Fisher et al., 2019). However, temporary and qualitative methods cannot precisely demonstrate long-term changes in the reef environment. It was difficult to precisely assess the effects of the reef disturbance and coral calcification responses in the area where *in situ* data on rivers and estuaries (e.g., water quality, river discharge, and water temperature) are limited. Moreover, there is no report directly comparing coral calcification with local industrial histories with multidecadal time series. While, a long-term quantitative assessment can simultaneously evaluate a reef

environment and coral calcification. It can be essential to the discussion of survival strategies for reef-building corals in which precipitation and human activities will increase. It is important to understand how natural/anthropogenic factors lead to a reef disturbance and how corals respond to these disturbances in order to create a sustainable human society that can benefit from healthy coral reefs.

1.2 Coral skeletons as a paleo-reef environmental proxy

1.2.1 Reef corals

Reef-building corals widely inhabit the tropical and subtropical regions (Fig. 1-1). They grow by adding calcium carbonate (CaCO_3) skeletons, simultaneously recording the chemical composition of the habitat marine environment. Especially in massive corals (e.g., *Porites* sp.), they have several hundred years of life span. Thus, massive coral skeletons provide archives of various proxies for environmental and climatic reconstructions with high temporal resolution in the several hundred years past (e.g., Quinn et al., 1998; Zinke et al., 2004; Hendy et al., 2002; Kawakubo et al., 2014; Tangri et al., 2018). Additionally, coral calcification could also provide a quantitative scale of the impacts of natural and anthropogenic reef disturbance with a long time series.

1.2.2 Skeletal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$

Oxygen has three stable isotopic species (^{16}O , ^{17}O , and ^{18}O). Carbon has two stable isotopic species (^{12}C and ^{13}C). Delta values of oxygen and carbon isotope ratios are defined as an equation, as follows:

$$\delta_{\text{VPDB}} (\text{‰VPDB}) = \left\{ \left(\frac{^{18}\text{O}/^{16}\text{O}}{^{18}\text{O}/^{16}\text{O}} \right)_{\text{sample}} / \left(\frac{^{18}\text{O}/^{16}\text{O}}{^{18}\text{O}/^{16}\text{O}} \right)_{\text{PDB}} - 1 \right\} \times 1000 \quad (1)$$

$$\delta_{\text{VPDB}} (\text{‰VPDB}) = \left\{ \left(\frac{^{13}\text{C}/^{12}\text{C}}{^{13}\text{C}/^{12}\text{C}} \right)_{\text{sample}} / \left(\frac{^{13}\text{C}/^{12}\text{C}}{^{13}\text{C}/^{12}\text{C}} \right)_{\text{PDB}} - 1 \right\} \times 1000 \quad (2)$$

The reference standard for oxygen and carbon stable isotope ratios was established as the Pee Dee Belemnite (PDB). The Pee Dee Belemnite was carbonate made from a Cretaceous marine fossil, *Belemnitella americana*, which was from the Peedee Formation in South Carolina, USA. Since the original PDB specimen is no longer available, it replaced PDB with NBS-18 and NBS-19. These standards calibrated to the same ratio, such as Vienna PDB (VPDB).

Coral skeletal oxygen isotope ratios ($\delta^{18}\text{O}$) 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). By combination with skeletal Sr/Ca (see below), the oxygen isotope in seawater ($\delta^{18}\text{O}_{\text{SW}}$) is also available (e.g., Gagan et al., 1998; Ren et al., 2003; Cahyarini et al., 2008; Juillet-Leclerc and Schmidt, 2001).

Many researchers have discussed the controlling factors of coral skeletal carbon isotope ratios ($\delta^{13}\text{C}$). 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 $\delta^{13}\text{C}$ 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

$\delta^{13}\text{C}$.

1.2.3 Skeletal Sr/Ca, Mg/Ca, and Ba/Ca

Skeletal strontium/calcium ratios (Sr/Ca) is the most useful proxy for paleo-SST variations (e.g., Beck et al., 1992; McCulloch et al., 1994; Corrège, 2006; Cahyarini et al., 2014). The skeletal Sr/Ca is controlled by only SST variation, and it negatively correlated with SST variations (Smith et al., 1987; Shen et al., 1996; Inoue et al., 2007; Delong et al., 2013). While, several previous studies had 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; 2019; Alpert et al., 2016).

Skeletal magnesium/calcium ratios (Mg/Ca) is also known as a proxy for paleo-SST variations (e.g., Mitsuguchi et al., 1996; Wei et al., 2000; Watanabe et al., 2001a). While, 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. (2001b) 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).

Skeletal barium/calcium ratio (Ba/Ca) provides a long-term record of sediment load in seawater associated with precipitation (heavy rainfall events), river discharge (flood events), coastal development, and coastal land use (Alibert et al., 2003; McCulloch et al., 2003; Prouty et al., 2010; Grove et al., 2012; Sowa et al., 2014; Saha et al., 2018). The coral skeletal Ba/Ca reflects seawater Ba concentration ($\text{Ba/Ca}_{\text{coral}}/\text{Ba/Ca}_{\text{seawater}} \approx 1$; Saha et al., 2016), and the desorbed Ba^{2+} from the particulate matter is readily substituted for Ca^{2+} in the coral aragonite lattice in proportion to the aqueous Ba/Ca ratio (Lea et al., 1989; LaVigne et al., 2016; Saha et al., 2016). Lea et al. (1989) has reported the convention of skeletal Ba/Ca to seawater Ba concentration (distribution coefficient D), using *Pavona clavus* and *Diploria labyrinthiformis*, which were from Galapagos Islands and Bermuda Island. LaVigne et al. (2016) has also reported the multi-colony (*Porites lobata*, *Pavona clavus*, and *Pavona gigantea*) calibrations of skeletal Ba/Ca with a contemporaneous *in situ* seawater Ba record. While, Ba incorporation was observed to have a temperature dependency (e.g., Lea et al., 1989; Gaetani et al., 2011) and Ba uptake in sea surface due to upwelling (e.g., Lea et al., 1989; Shen et al., 1992; Tudhope et al., 1996). It may complicate paleo-environmental reconstructions based on coral Ba/Ca records; however, the temperature dependency of Ba is negligible relative to the pollution-induced Ba/Ca anomalies (McCulloch et al., 2003; Saha et al., 2016).

1.2.4 Skeletal growth parameters and the responses on skeletal calcification

Coral skeletons have annual density bands (high- and low-density band pairs), which provide precise skeletal growth data. Lough and Cooper (2011) reviewed previous studies on skeletal growth. Two materials: linear extension rate (linear growth rate) and average skeletal density are obtained from the density bands. The mass of CaCO_3 deposited per unit time or “calcification rate” (e.g., annual calcification rate, $\text{g}\times\text{cm}^{-2}/\text{year}$) is obtained from

these parameters. Many previous studies have reported a spatial gradient of skeletal growth in various species. Depth gradients (e.g., Huston, 1985; Buddemeier et al., 1974; Highsmith, 1979; Rosenfeld et al., 2003; Runnalls and Coleman, 2003; Grigg, 2006; Watanabe et al., 2019) suggest that light availability is a primary control on the coral growth. 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). According to the previous studies, inshore to offshore gradients (e.g., Aller and Dodge, 1974; Dodge et al., 1974; Hudson, 1981; Done, 1982; Isdale, 1983; Wilkinson and Cheshire, 1988; Lough et al., 1999) suggest that skeletal growth associates with the gradients of terrigenous influences such as wave energy, turbidity, nutrient, and salinity. Lough and Barnes (1992) and Lough et al. (1999) indicated that skeletal density was the highest and linear extension lowest at offshore sites compared to inshore. Temperature gradients (Weber and White, 1974; 1977; Grigg, 1981; Scoffin et al., 1992; Lough and Barnes, 2000; Lough, 2008; Goodkin et al., 2011) suggest that habitat seawater temperature is also a major factor of skeletal growth pattern.

Coral skeletal growth and calcification should be a useful proxy for assessing the impacts of reef disturbances. Hiatuses in coral growth often show as the unusual banding patterns such as anomalous high- or low-density bands, it called “stress bands,” which can be observed on X-rays of coral skeletal slabs (e.g., Hudson et al., 1976; Mendes and Woodley, 2002; Lough and Cooper, 2011). Besides, irregularly green color bands have also been observed on the coral skeletal slabs under habitat environmental stress, for example, a bleaching event and or terrestrial runoff (Fine and Loya, 2002; Carilli et al., 2010). It is also well-known that sediments 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). Coral growth parameters (extension rate, density, calcification rate) also have a potential for long-term quantitative assessment of the growth response to the environmental stressors (i.e., natural and anthropogenic factors).

Figure

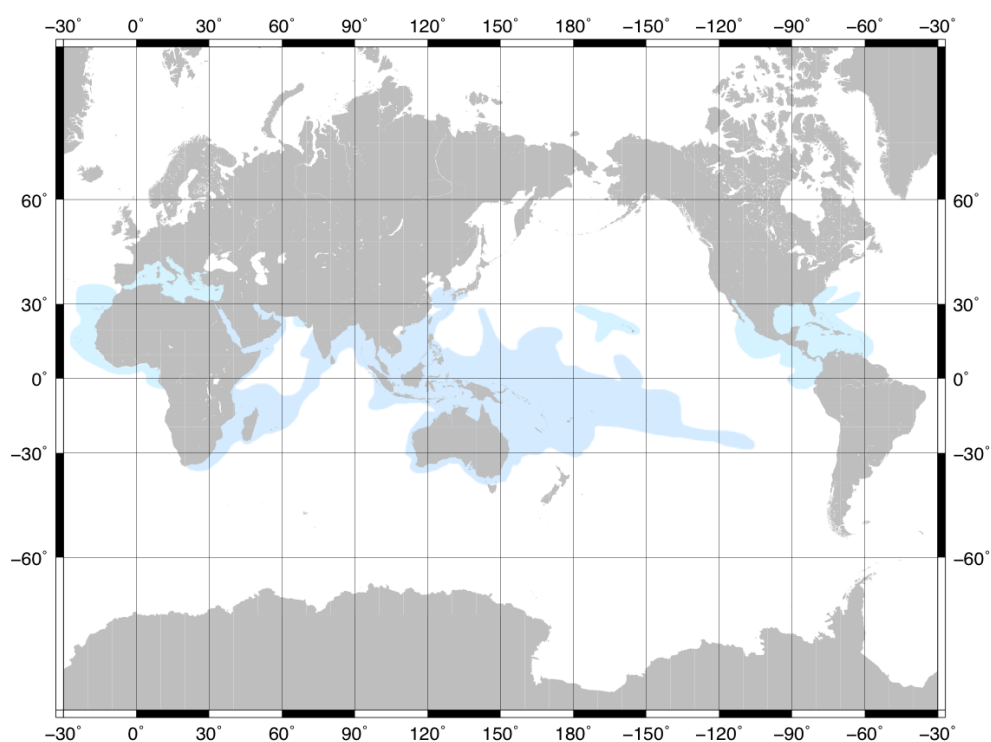


Fig. 1-1 Distribution map of reef corals

The blue hatched areas indicate the predicted distribution of reef corals (Veron, 2000). The map figure was generated using Generic Mapping Tools (GMT v. 5.3.3, Wessel et al., 2013).

2. Study objectives

The objectives of this study were to understand how natural/anthropogenic factors lead to a reef disturbance, how corals make an archive of reef disturbance in their skeleton, and how corals respond to these disturbances. This study inferred that natural (e.g., heavy rainfall, river runoff, mangrove systems, earthquake-related seafloor displacement, and tsunami) and anthropogenic factors (e.g., local industrial history and land use) of coral reef disturbances would be one of the controlling factors of coral calcification.

2.1. Reef disturbances caused by natural factors

2.1.1. Simeulue Island, Indonesia: Earthquake, seafloor displacement, and tsunami event (Case-1)

This study assessed the impact of natural reef disturbances: earthquake-related seafloor displacement and tsunami events using five living coral cores of *Porites* sp. from Simeulue Island, Indonesia (Ito et al., 2020a).

Great ($> M_w 7$) subduction zone earthquakes have occurred in the last several hundred years along the Sunda trench. 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). Our sample site, Simeulue Island, is part of the Mentawai Islands, which are located between the epicenters of the 2004 and 2005 earthquakes. The 2004 Sumatra-Andaman earthquake triggered a giant tsunami, which devastated coasts around the Indian Ocean. Previous studies on paleo-earthquake and tsunami events using coral skeletons were based on tsunami boulders and microatolls without skeletal geochemical proxy. Unfortunately, tsunami boulders could not record the coral habitat-environmental changes caused by the earthquake event (seismic shaking and coseismic uplift/subsidence) because they disintegrate while drifting ashore during a tsunami. By contrast, massive living corals have the proxy potential for recording habitat-environmental changes that are attributable to paleo-earthquake events; for example, coseismic vertical seafloor deformation. This study focused on the response (signal) of the coral skeletal $\delta^{13}C$ to the coseismic vertical seafloor deformation (coseismic uplift). Besides, 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 a negative control factor in skeletal growth. 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. Several articles have reported that the significant coral damage for several months after the 2004 earthquake and tsunami; however, the skeletal growth responses to earthquake events and tsunami disturbances are still unknown. This study assessed the effects of the coseismic uplift and tsunami on the skeletal growth.

2.1.2. Kikai Island, Japan: Tsunami event (Case-2)

This study assessed the impact of tsunami event (excluding seismic seafloor displacement event) as one of the natural reef disturbances using three living coral cores of *Porites* sp. from Kikai Island, Japan (Ito et al., *in prep*).

Kikai Island is located in the Amami Islands, near the Ryukyu Trench, which has a potential occurrence of a large earthquake ($M_w > 8$). It is well known as coral reef terraces, which have been uplifted seismotectonically ~1-4 m every 1500 ~ 2000 years during the past 6000 years; thus, it suggests that the surrounding area has high seismic activity in this area. The 1911 Kikai Island earthquake (M_w 8.1) occurred on 15th June triggered a large tsunami. Huge tsunami waves associated with megathrust earthquakes would lead to the amount of terrestrial input or resuspension of seafloor sediments, and it wreaks devastating damage on shallow marine ecosystems, especially coral reefs. The 1911 Kikai tsunami archives were very limited in the Amami Islands, and most of the records were the interviewed records or ancient documents. The 1911 tsunami-related impact on the coral reefs was still unknown because any geological or geochemical evidence was found in Kikai Island. There is a possibility that massive corals (*Porites* sp.) may record the tsunami-generated sediment load in their skeleton (i.e., geochemical evidence); however, there has not been reported. Besides, the coral specimens that inhabited in Shumichi (Shiomichi) Bay, the eastern part of Kikai Island, would not be affected by freshwater because there is no river in Kikai Island. The coseismic deformation (uplift/subsidence, i.e., coseismic seafloor displacement) around Kikai Island regarding the 1911 earthquake has not been reported. Therefore, it could be able to discuss the impact of only the tsunami event on the corals.

2.1.3. Amami-Oshima Island, Japan: Heavy rainfall, river flood event, and mangrove system (Case-3)

This study assessed the impact of heavy rainfall and river flood event, and mangrove system effect as one of the natural reef disturbances using one living coral core of *Porites* sp. from Amami-Oshima Island, Japan (Ito et al. 2020b).

Sumiyo Bay is located in the eastern part of Amami-Oshima Island. The Sumiyo River and Yakugachi River run to the bay, and a mangrove forest covers the estuary. These rivers have caused river flooding four times (June 1977, September 1990, August 1991, and October 2010) over the past 46 years. Despite such a situation, *in situ* data on rivers, estuaries, and bay (e.g., water quality, turbidity, salinity, river discharge, and water temperature) has not been monitored. Especially in the 2010 river flood event, it caused a mangrove collapse and sediment flow into Sumiyo Bay. It also triggered a coral breaching. A coral cover or coral breaching monitoring is a good approach for assessing the damage on corals (i.e., coral health); however, it is difficult to understand the quantitative response of coral calcification to natural reef disturbances such as heavy rainfall, typhoon, and river flood. There are many coastal areas in tropics and subtropics where periodic monitoring surveys and *in situ* environmental data are not available. Coral skeletal geochemistry has potential as a quantitative proxy of natural reef disturbance in the past. This study focused on the signals in the coral skeletal Ba/Ca and the temporary hiatus of the skeletal growth due to the heavy rainfall and river flood events. Besides, the coral calcification inside bay may also be influenced by the natural estuarine systems (e.g., the mangrove function, tidal variation, and river discharge), which have a seasonal pattern. Thus, it is necessary to focus on the seasonal effect for a precise understanding of coral calcification inside the bay.

2.2. Reef disturbances caused by anthropogenic factors

2.2.1 Amami-Oshima Island, Japan: Local industrial changes and land use (Case-3)

This study assessed the impact of local industrial changes and land use as one of the anthropogenic reef disturbances using one living coral core of *Porites* sp. from Amami-Oshima Island, Japan (Ito et al. 2020b).

Anthropogenic sediment load is one of the local stressors on coral calcification. Numerous previous studies were focused on the anthropogenic sediment load, and they have shown the signals on the coral skeletal geochemical record. Human activities or coastal developments have a multidecadal history; however, there is no report directly comparing coral calcification with local industrial histories with multidecadal time series. In the study site, Sumiyo Bay, traditional silk fabric (*Oshima tsumugi*), farming, forestry, construction, and quarries have prospered in the past 46 years. The industries would be a source of the sediment load in Sumiyo Bay. The Sumiyo corals may record the sediment load corresponding to the coastal industrial history. Besides, anthropogenic reef disturbance (i.e., sediment load) on the multidecadal scale may have an impact on the coral calcification. It is important to understand how anthropogenic sediment loads lead to a reef disturbance and how corals respond to them to create a sustainable human society that can benefit from coral reefs. The qualitative visual census, such as monitoring surveys and temporary comparison with human activity, can assess the temporary damage in the reefs. While, the quantitative calcification records also provide us an essential key for understanding the coral response and adapt strategy. This study assessed the relationship between the coral calcification response (skeletal Ba/Ca and skeletal calcification rate) and local industrial developments.

3. Methodology for paleo-reef environmental reconstruction using coral skeletons and water samples

3.1 Coral skeleton samples

3.1.1 Coral core drilling, cutting, and sample preparation

Living and fossil coral cores of *Porites* sp. were collected by an air drill with a 7.6 cm diameter core barrel. All cores were cut into 5 mm thick slabs. The slab edges formed into a ledge shape, 1.5 mm thick and 1.0 ~ 2.0 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 (Study Case-1) or 50 kV and 1.0 mA (Study Case-2 and -3) using TATSCAN-X (at JAMSTEC, Study Case-1) or a digital X-ray scanner NAOMI (at Hokkaido University, Study Case-2 and -3) to observe the annual density bands.

For the fossil coral specimens, the secondary-calcite contents on coral skeletons were checked by X-ray diffraction and scanning electron microscope (at Hokkaido University). The secondary-calcite parts of coral skeletons were avoided from the geochemical analytical lines.

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 as follows;

(1) Milling method

This method has described in Watanabe et al. (2019). I used a micro drill (1.8 mm diameter), and a PC controlled XY stage. The microsampling intervals were 0.2 ~ 1.0 mm. The milled area was cleaned using high-pressure air after each microsampling in order to avoid cross-contamination. This method was carried out in Study Case-1, Case-2 for skeletal Ba/Ca analysis with the high temporal resolution, and Case-3.

(2) Spot sampling method

This method is suitable for the samples which have complicated or curved growth direction with > 10 mm/ year of skeletal extension rate. I used a micro drill (0.8 mm diameter) and a semi-manually controlled XY stage. Each microsampling interval (x-direction) was 1.2 mm, and the sampling depth was 1.0 mm. The milled area was cleaned using high-pressure air after each microsampling in order to avoid cross-contamination. This method was carried out in Study Case-2 for skeletal Sr/Ca analysis.

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

The powdered samples ($100 \pm 10 \mu\text{g}$) were reacted with 100 % 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 (Study Case-1) and Thermo MAT 253 (Study Case-1, -2, and -3) installed at Hokkaido University). The skeletal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ 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 ($\delta^{18}\text{O} = -2.20 \text{ ‰}$; $\delta^{13}\text{C} = 1.95 \text{ ‰}$). The standard deviations (2σ ; 95 % confidence) for all study were in 0.02 ~ 0.04 ‰ and 0.03 ~ 0.05 ‰ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, respectively.

3.1.3 Trace element analysis (Sr/Ca, Mg/Ca, Ba/Ca)

In Study Case-1, the skeletal Sr/Ca and Mg/Ca analyses were performed by inductively coupled plasma-atomic emission spectrometry (ICP-OES; iCAP 6200 ICP Spectrometer; Thermo Scientific) with an autosampler (ASX-260, Teledyne CETAC Technologies) installed at Hokkaido University. Powdered samples ($150 \pm 10 \mu\text{g}$) were dissolved in 250 μL of 25 % high-purity HNO_3 and then diluted with ultrapure water (Milli-Q). I 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, I measured reference solution JCp-1 (Okai et al., 2002) at 5-sample intervals. The analytical uncertainties (1σ) were 0.33 % (relative standard deviations) or 0.03 mmol/mol for Sr/Ca, and 0.55 % or 0.02 mmol/mol for Mg/Ca.

In Study Case-2, the skeletal Sr/Ca analyses for the age determination were performed by inductively coupled plasma-atomic emission spectrometry (ICP-OES; iCAP 6200 ICP Spectrometer; Thermo Scientific) with an autosampler (ASX-260, Teledyne CETAC Technologies) installed at Hokkaido University. Powdered samples ($150 \pm 10 \mu\text{g}$) were dissolved in 250 μL of 25 % high-purity HNO_3 and then diluted with ultrapure water (Milli-Q), as described by Watanabe et al. (2020). I 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, I measured reference solution JCp-1 (Okai et al., 2002) at 5-sample intervals. The analytical uncertainties (1σ) were 0.33 % (relative standard deviations) or 0.03 mmol/mol for Sr/Ca. Following the age model establishing (1798 ~ 2011), the analytical line for the skeletal Ba/Ca was determined by the age model (1907 ~ 1917). The skeletal Ba/Ca analyses were performed by inductively coupled plasma-atomic emission spectrometry (ICP-OES; iCAP 6200 ICP Spectrometer; Thermo Scientific) with an autosampler (ASX-260, Teledyne CETAC Technologies) and an ultrasonic nebulizer (U-5000AT, Teledyne CETAC Technologies) installed at Hokkaido University. Powdered samples ($115 \sim 128 \mu\text{g}$) were dissolved in 0.57 ml of 25 % high-purity HNO_3 and then diluted with ultrapure water (Milli-Q). I ultimately prepared sample solutions in which the Ca concentration was 9 ppm. Calibrations of the five gravimetric standard solutions yielded high correlation coefficients (r^2) of 0.9999 for Ba and Ca. To correct the instrumental drift, I measured the reference solution JCp-1 (Okai et al., 2002) at 5 sample intervals. The analytical uncertainties (1σ) were 2.239 % (relative standard deviations) or 0.18 mmol/mol for Ba/Ca.

In Study Case-3, the skeletal Ba/Ca, Sr/Ca, and Mg/Ca analyses were performed by inductively coupled plasma-atomic emission spectrometry (ICP-OES; iCAP 6200 ICP Spectrometer; Thermo Scientific) with an autosampler (ASX-260, Teledyne CETAC Technologies) and an ultrasonic nebulizer (U-5000AT, Teledyne CETAC Technologies) installed at Hokkaido University. Powdered samples ($115 \sim 128 \mu\text{g}$) were dissolved in 0.57 ml of 25 % high-purity HNO_3 and then diluted with ultrapure water (Milli-Q). I ultimately prepared sample solutions in which the Ca concentration was 9 ppm. Calibrations of the five gravimetric standard solutions yielded high correlation coefficients (r^2) of 0.9999 for Ba, Sr, Mg, and Ca. To correct the instrumental drift, I measured the reference solution JCp-1 (Okai et al., 2002) at 5 sample intervals. The analytical uncertainties (1σ ; relative standard deviations) were 2.239 % or 0.18 $\mu\text{mol/mol}$ for Ba/Ca, 0.167 % or 0.01 mmol/mol for Sr/Ca, and 0.729 % or 0.03 mmol/mol for Mg/Ca.

3.1.4 Age determination

The age determination of the coral core was based on the relationship between skeletal Sr/Ca and monthly SST. The monthly IGOSS-SST time series at $1^{\circ} \times 1^{\circ}$ was derived from the Integrated Global Ocean Services System Products Bulletin (https://iridl.ldeo.columbia.edu/SOURCES/IGOSS/.nmc/.Reyn_SmithOlv2/.monthly/.sst/; Reynolds et al., 2002). I 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.

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 skeletal growth parameters, and the reef disturbance signals on the coral skeleton.

For the fossil coral specimens (Study Case-2), the ages model was established by the skeletal Sr/Ca, the annual density bands, and the high precision U-Th dating technique (Shen et al., 2012). Skeletal U and Th isotopic compositions were measured by Dr. Takaaki. K. Watanabe, using a multi-collector inductively coupled plasma mass spectrometer MC-ICP-MS (Thermo Fisher NEPTUNE) installed at National Taiwan University.

3.1.5 Calculation for skeletal growth parameters

The extension rates of the corals were determined by measuring the distance between Sr/Ca maxima (SST minima). The skeletal density (g/cm^3) was calculated using the CoreCal 2 program method (Sowa et al. (2013)). The annual skeletal calcification rate ($\text{g} \times \text{cm}^{-2}/\text{year}$) was obtained from pairs of extension rates and annual skeletal density.

3.2 Water samples (river- and sea-water)

3.2.1 Sampling and chemical treatment

In Study Case-3, the 14 water samples (river- and sea-water) were collected. Water samples were filtered using a $0.45 \mu\text{m}$ Membrane filter (Merck Millipore), and it stored in PP bottles with 0.16 mL of stored in PP bottles with 70 % HNO_3 (Trace Sure grade, FUJIFILM Wako Pure Chemical Corporation; $\text{pH} = 2$) to inhibit the change in trace elements caused by microorganisms. The bottles were stored refrigerated at 5°C immediately upon collection. Additionally, I measured in situ salinity when I collected the water samples.

3.2.2 Trace element analysis (Ba)

The Ba contents in the water samples (both river-water and seawater) were analyzed using ICP-OES (iCAP 6200, Thermo Scientific) with a cyclonic spray chamber with a baffle installed at Hokkaido University. An analytical method for Ba in the river-water and seawater was modified from Dehairs et al. (1989) by Dr. Takaaki. K. Watanabe. For the preparation, four external standards in which the Ba and Sr solution standards (FUJIFILM Wako Pure Chemical Corporation) and $35 \mu\text{g}/\text{L}$ NaCl (Trace Sure grade, FUJIFILM Wako Pure Chemical Corporation) were mixed. The concentrations of Ba and Sr ranged from 3.0 to 30.0 ppb and 0.98 to 7.80 ppm, respectively. After the analysis of four external standards, the water samples were analyzed. In order to correct the instrumental drift, a running standard (artificial seawater) was measured at 5 sample intervals. The analytical

precision of Ba in seawater was 1.185 (nmol/kg) based on a standard deviation of the running standard (1σ).

4. Case-1 (Natural disturbance): Coral geochemical signals and growth responses to coseismic uplift during the great Sumatran megathrust earthquakes of 2004 and 2005

4.1 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. 4-1-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. 4-1-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 Aceh 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 (e.g., *Porites* sp.) have the proxy potential for recording the reef disturbances 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). Besides, since the 2004 Sumatra-Andaman earthquake (M_w 9.2), $M_w \geq 8.0$ earthquake repeatedly occurred with a short-term rate increase of $> 200\%$, compared with the occurrence time from 1900 to 2004 (e.g., Lay, 2015). Developing disaster risk management and an assessment of coral reefs are highly required.

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 $\delta^{18}\text{O}$ 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 $\delta^{13}\text{C}$ will show a significant positive “step change”

corresponding to vertical seafloor displacement (seismic uplift). The uplift-related step change in the skeletal $\delta^{13}\text{C}$ is distinguished from other controlling factors (e.g., the $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$. The geochemical proxy of annually banded coral skeletons potentially will record past seismic events, especially in the skeletal $\delta^{13}\text{C}$. Gagan et al. (2015) demonstrated that the skeletal $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ 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 a negative control factor in skeletal growth. It is well-known that sediments 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). Natural reef disturbance, the 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; Campbell et al., 2007; Bahuguna et al., 2008); however, the skeletal growth responses to earthquake events and tsunami disturbances are still unknown.

4.2 Study area

Our sample site, Simeulue Island (Fig. 4-1-c), is a 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; SLG100516 [SLG], SLGH100516 [SLGH] and SPI100515 [SPI]), and 1.4 m and 0.6 m during the 2005 earthquake for southeast corals (SE corals from shallow to deep depth; SBB100520 [SBB] and SLB100518 [SLB]). 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).

4.3 Materials

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. 4-1-c).

Table 4-1 shows the details of our coral cores. The SLG (vertical-drilled core) and SLGH (horizontal-drilled core) are from a single microatoll colony (Fig. 4-2). SLG was a dead core (the top of the core was covered in algae). The SLG 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 the lowest tide using tide data (see below).

4.4 Environmental data

In this study, I collected monthly and daily SST time series, monthly precipitation, monthly fraction, and tide data (in minutes). 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 from the Integrated Global Ocean Services System Products Bulletin (Reynolds et al., 2002; https://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst/). I collected daily AVHRR-SST time series at $0.125^{\circ} \times 0.125^{\circ}$ (northern part: 3.125 N, 95.875 E; southern part: 2.375 N, 96.375 E) from an Advanced Very High Resolution Radiometer (Reynolds et al., 2007; <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. 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. The monthly precipitation time series from June 1994 to May 2010 at $1^{\circ} \times 1^{\circ}$ (2.5 N, 95.5 E) was derived from WCRP GCOS GPCC Monitoring (Rudolf et al., 2010; <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 $2^{\circ} \times 2^{\circ}$ (2.5 N, 95.5 E) was derived from FRESCO+ SCIAMACHY (Wang et al., 2008; https://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=fresco_cloud). The tide data derived from the IOC Sea Level Monitoring Facility (<http://www.ioc-sealevelmonitoring.org/>) at the Mealaboh station, from April 20th to May 20th, 2010. This tidal data was used for the re-evaluation of coral habitat depth (see Table 4-1).

4.5 Age model

The age determination of each coral was based on the relationship between skeletal Sr/Ca and monthly SST. I 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, SBB, and SLB, 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. 4-3). As a result, shown in Fig. 4-4, skeletal Sr/Ca in SLG and SLGH indicated a clear

annual cycle. Skeletal Sr/Ca in SPI and SBB also showed an annual cycle; however, the summer or winter peak had a one-month time-lag compared with the SST record. The annual cycle in the skeletal Sr/Ca of SLB 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 4-2). The 1997 Indian Ocean Dipole (IOD) signal was found in the skeletal Sr/Ca records, excluding SLB (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. 4-3) and a green band that was observed on the SLB slab surface (Fig. 4-5) was marked as a signal of earthquake occurrence. The age model of the dead SLG core was established by comparison with SLGH (horizontal-drilled core). As shown in Fig. 4-6, small particles like clay minerals were observed in the SLGH skeleton. The SLG skeleton incorporated the small particles, too. At first, I made the age model of SLGH based on the relationship between SST and skeletal Sr/Ca. The small particles showed coincident with the 2004 earthquake. The SLG and SLGH skeleton should incorporate the small particles simultaneously because both of cores were collected from a single colony. The age model of SLG was established with a premise that the small particles started to incorporate at the same time with SLGH. 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 SLG and SLGH were shown in Fig. 4-4.

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 (Table 4-3). There are multiple “proof points” for the accuracy of age model, for example, a clear annual cycle with the valid range in skeletal Sr/Ca (SLG, SLGH, and SPI, Fig. 4-4), the strong positive correlation between skeletal Sr/Ca and monthly IGOSS-SST (all coral cores, Table 4-3), the IOD signal in skeletal Sr/Ca record (all coral cores, SLB is no data, Fig. 4-7), the 2004 earthquake and tsunami occurrence signals on the coral skeleton (a stress band for SLGH and SBB, Fig. 4-3; a green band for SLB, Fig. 4-5; and small particles like clay materials for SLG and SLGH, Fig. 4-6), the annual extension rate consistent with previous studies (all coral cores, Figs. 4-8 and 4-9), and the clear density bands (SLB, Fig. 4-3). This evidence certifies that the age models are correct.

(1) Skeletal Sr/Ca

Skeletal Sr/Ca significantly correlated with monthly SST in all coral cores (Table 4-2). In our study site, an annual amplitude of SST observed on IGOSS-SST (1.5 °C on average) should be equal to 0.09 mmol/mol range in an annual cycle, based on skeletal Sr/Ca-SST dependency (Abram et al., 2007). As shown in Fig. 4-4 and Table 4-3, skeletal Sr/Ca in SLG and SLGH indicated a clear annual cycle with the range of 0.09 and 0.08 mmol/mol. Skeletal Sr/Ca in SPI and SBB also showed an annual cycle with the range of 0.07 and 0.05 mmol/mol. The annual cycle in skeletal Sr/Ca of SLB was not clear (with the range of 0.13 mmol/mol), while the annual bands were clearly visible on the X-ray image (Fig. 4-3). Thus, the results of Table 4-2, Fig. 4-4, the IOD signal in skeletal Sr/Ca record, clear density bands (SLB), and the skeletal signal of earthquake occurrence provides strong evidence that the age models are correct. Moreover, the extreme Indian Ocean Dipole (IOD) signal in 1997 was found in the skeletal Sr/Ca records, excluding SLB (no data), and the signal was used as a guide to making the age models. The IOD is an interannual, aperiodic oscillation of sea-surface temperatures in the equatorial Indian Ocean. Therefore, the IOD signal in skeletal

Sr/Ca record was one of the evidence of the precision of the age model.

(2) Skeletal “pin-point” signals of the 2004 earthquake and tsunami occurrence

A stress band (inshore corals, SLGH and SBB, Fig. 4-3), a green band (SLB, Fig. 4-5), and an incorporation of the small particles like clay materials (SLG and SLGH, Fig. 4-6) were confirmed as the skeletal “pin-point” signals of the 2004 earthquake and tsunami occurrence. These signals are the guides for the precise age models.

(3) Skeletal extension rate

Our results of skeletal growth parameters were also cross-checked by comparison with previous studies (Scoffin et al., 1992; Lough and Barnes, 2000; Goodkin et al., 2011). Figs. 4-8 and 4-9 indicate that all of our records agree with the previous studies. Especially in Fig. 4-8-a *Density vs. Extension rate*, it suggests that the chronologies and extension rates for our coral cores must be correct because these growth parameters are independent variables. The annual skeletal extension rate (mm/yr) was assumed to be constant between dates of the adjacent highest Sr/Ca (i.e., age model). The skeletal density (g/cm³) was calculated based on the X-ray photographs of coral cores. Therefore, Fig. 4-8-a provides good evidence that the chronologies and skeletal extension rates for our coral cores are correct. Besides, the SBB has a relatively fast extension rate (Fig. 4-10 and Table 4-5, the mean value: 25.3 mm/yr, the range: 18.4 ~ 34.4 mm/yr). The skeletal extension rate in SBB was cross-checked by comparison with annual SST, based on Goodkin et al. (2011). Our *Porites* coral core SBB agrees with the relationship between the skeletal extension rate and annual SST (Fig. 4-9). It suggests that the extension rate for SBB must be correct. Moreover, Watanabe et al. (2017) reported that the Oman coral grew very quickly, the 25.1 mm/year on the average with a range between 19 to 31.5 mm/year. Thus, our skeletal extension rates agreed with the previous studies, and these results provide strong evidence of the precision of the age model.

4.6 Results and Discussions

Geochemical signals of seismic vertical displacement

The geochemical records were shown in Fig. 4-7. The post-earthquake period (from the 2004 or 2005 earthquake to the date of core drilling) was identified by the age model. The difference in the mean values between the pre- and post-earthquake periods is shown as $\Delta Proxy$ (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 4.2 *Study area*). Any significant difference in $\Delta Proxy$ values was not detected between both earthquake periods, excluding the skeletal Mg/Ca in SLG (Table 4-4). It is noted that there was no significant correlation between skeletal growth parameters and geochemical records, excluding in SPI (Sr/Ca vs. density and Mg/Ca vs. density) and in SBB ($\delta^{13}C$ vs. extension rate; Table 4-5). The data deviation for the skeletal density in SPI and skeletal extension rate in SBB were relatively large (“SD” in Table 4-6). The large deviation of skeletal growth parameters might affect the significant relationships.

SLG and SLGH (–1.0 and 0.5 m depth, uplifted 1.1 m during the 2004 earthquake)

The SLG record is presented in Fig. 4-7-a. There was no significant difference between the pre- and post-earthquake periods in the skeletal $\delta^{13}\text{C}$ and Sr/Ca. The skeletal Mg/Ca and $\delta^{18}\text{O}$ during the post-earthquake period significantly decreased significantly ($\Delta\text{Mg/Ca} = -0.14$ mmol/mol, $p < 0.05$ and $\Delta\delta^{18}\text{O} = -0.10$ ‰, $p < 0.01$).

The SLGH record is presented in Fig. 4-7-b. All the geochemical records in the SLGH were characterized by the large amplitude found over one year in the aftermath of the 2004 earthquake. The skeletal $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ ($\Delta\delta^{13}\text{C} = 0.34$ ‰; $p < 0.01$). During the same period, one year into the aftermath of the 2004 earthquake, there were positive peaks in the skeletal Sr/Ca and $\delta^{18}\text{O}$. 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 ($\Delta\text{Sr/Ca} = 0.04$ mmol/mol; $p < .0001$). Skeletal Mg/Ca showed no significant difference. The skeletal $\delta^{18}\text{O}$ for the post-earthquake period increased significantly ($\Delta\delta^{18}\text{O} = 0.21$ ‰; $p < .0001$).

SPI (5.0 m depth and 0.4 m uplift during the 2004 earthquake)

The SPI record is presented in Fig. 4-7-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 $\delta^{13}\text{C}$. The skeletal Sr/Ca during the post-earthquake period significantly increased ($\Delta\text{Sr/Ca} = 0.05$ mmol/mol; $p < 0.001$). Skeletal Mg/Ca showed no significant difference. The skeletal $\delta^{18}\text{O}$ during the post-earthquake significantly decreased ($\Delta\delta^{18}\text{O} = -0.34$ ‰; $p < .0001$).

SBB (2.1 m depth and uplifted 1.4 m during the 2005 earthquake)

The SBB record is presented in Fig. 4-7-d. In the aftermath of the 2004 earthquake, the skeletal $\delta^{13}\text{C}$ displayed a positive peak (1.48 ‰), and it showed a significant step change ($\Delta\delta^{13}\text{C} = 0.32$ ‰; $p < .0001$). During the same period, there were positive peaks in the skeletal Sr/Ca and $\delta^{18}\text{O}$. Simultaneously, the skeletal Mg/Ca showed a negative peak. These characteristic peaks were similar to those in the SLGH record. There were significant differences between the pre- and post-earthquake skeletal Sr/Ca ($\Delta\text{Sr/Ca} = -0.04$ mmol/mol; $p < .0001$), Mg/Ca ($\Delta\text{Mg/Ca} = -0.15$ mmol/mol; $p < .0001$) and $\delta^{18}\text{O}$ ($\Delta\delta^{18}\text{O} = -0.09$ ‰; $p < .0001$).

SLB (6.8 m depth and uplifted 0.6 m during the 2005 earthquake)

The SLB record is presented in Fig. 4-7-e. Similar to SPI, 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 $\delta^{13}\text{C}$. There were significant differences between the pre- and post-earthquake in the skeletal Sr/Ca ($\Delta\text{Sr/Ca} = -0.03$ mmol/mol; $p < .0001$; within the measurement error range) and Mg/Ca ($\Delta\text{Mg/Ca} = -0.47$ mmol/mol; $p < .0001$). However, the skeletal $\delta^{18}\text{O}$ did not show a significant difference. Furthermore, there was no marked variation in a part of the green band.

Skeletal growth record

As shown in Fig. 4-3, a prominent high-density band coincident with the 2004 earthquake was observed in SLGH and SBB. Our results for the skeletal growth parameters are shown in Fig. 4-10. The annual extension rates and annual calcification rates in 2005 decreased sharply in the NW corals, excluding the SLG. The SE corals did not show a sharp decrease in 2005. Table 4-7 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 4-6, 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 (SLGH: +2.86 mm/yr, $p < 0.01$; and SBB: +6.64 mm/yr, $p < 0.05$); however, the SLG showed the opposite result (−5.44 mm/yr, $p < .0001$). There was no significant difference in the offshore corals (SPI and SLB). The annual mean density showed no significant difference in all the corals. Furthermore, the SLB displayed a particular green band (Fig. 4-5). 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 SLG and SLGH were coincident with the 2004 earthquake (Fig. 4-6). The X-radiograph of these skeletal areas did not show a significant difference.

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. 4-3), (2) a significant decrease in the annual extension/calcification rate in 2005 (NW corals; Fig. 4-10), (3) a green band (SLB; Fig. 4-5), and (4) incorporation of the small particles like clay materials (SLG and SLGH; Fig. 4-6).

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 unusual 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 sediments due to much precipitation or river runoff would not significantly. The stress band in the SLGH and SBB was caused by other stress factors such as sediments, 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. Sediments-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 SLGH and SBB was inshore (the distance from the nearest shore was 165 m and 50 m for SLGH and SBB), while that of SPI and SLB was offshore (1720 m and 800 m for SPI and SLB). Each skeletal growth response showed a slight difference due to these characteristics of the habitat condition. As a result, the inshore corals for SLGH and SBB 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 SPI) would reflect the tsunami event, which leads to a growth disturbance 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 SLB skeletal surface (Fig. 4-5) 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 SLB did not show a significant change in the annual extension/calcification rate in 2005; while, the tsunami-related algae bloom may cause the stress bands or the significant decrease in growth extension/calcification. The small particles in the coral skeleton (SLG and SLGH, Fig. 4-6) 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). This study did not make sure the small particles in SLG and SLGH by mineralogical analysis in this study; however, there is a possibility that the brown and lustrous particles (Fig. 4-6-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 events.

The SLGH and SBB (inshore corals) geochemical record in the aftermath of the 2004 earthquake showed significant simultaneous increase or decrease (Figs. 4-7-f and -g). The fluctuating duration in SBB was shorter than that of SLGH. The skeletal geochemical signals are smoothed during skeletogenesis within the living tissue layer (Barnes et al., 1995; Gagan et al., 2015). The analysis time resolution of SBB (biweekly) was higher than SLGH (monthly). The annual mean of skeletal extension rate and the tissue layer depth were 25.6 mm/yr and 7 mm for SBB, and 6.1 mm/yr and 8 mm for SLGH. Therefore, the effect of skeletogenesis within the living tissue layer would be smooth the geochemical signals over a period equivalent to 3 months for SBB and 16 months for SLGH. Because of the higher resolution, faster growth, and the smoothing in a shorter period, the SBB recorded the earthquake and tsunami events more sharply than the SLGH. Besides, the age model was established so that the skeletal growth rate (mm/yr) was assumed to be constant for one year. The wrapped time series of SLGH might be extended earthquake-

tsunami signals because of the lower resolution and slower growth. The SST proxies (skeletal Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$) 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 $\delta^{13}\text{C}$ record signal might be influenced by the growth stress or the abrupt increasing light availability due to the uplift event.

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:

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

where I_D is the light intensity (i.e., relative light availability) at water depth D (m), I_0 is the light intensity at the sea surface ($D = 0$), and k is the extinction coefficient (Fig. 4-11-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., $I_{D \text{ post}} - I_{D \text{ pre}}$) is obtained by taking the difference in the water depth between the pre- and post-earthquake values (the amount of vertical displacement) as follows:

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

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, SLGH and SBB, have shallow depth (1.6 ~ 3.5 m) and large displacement (+1.1 ~ 1.4 m) characteristics. Conversely, the category-2 specimens, SPI and SLB, 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 4-7 and Fig. 4-11-b). There was a strong positive correlation between the skeletal calcification rate and the extension rate ($r = 0.85 \sim 0.97$; $p < 0.05$; $n = 9 \sim 16$), 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. 4-11-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 SLG, the annual extension rate and the calcification rate decreased by 44 % post-earthquake. I concluded that the SLG survived for approximately 5 years following the earthquake event, according to the density bands observation and skeletal geochemical records. The SLG 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. The estimated depth in pre-earthquakes of SLG was 0.1 m, and the depth during the lowest tide in the post-earthquake was -1.0 m (Table 4-1). SLG 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 SLG has a possible inclusion of non-continuous data). Therefore, the SLG did not reflect the RLA, although it experienced a large seismic displacement (+1.1 m). The significant $\Delta\text{Mg}/\text{Ca}$ and $\Delta\delta^{18}\text{O}$ might be influenced by the irregular growing situation or organic matters (described by Watanabe et al., 2001b).

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

It is a bit difficult to show the coral skeletal $\delta^{13}\text{C}$ and light model because the relationship is quite complicated. Photosynthesis by symbiotic algae (zooxanthellae) is one of the major factors of skeletal $\delta^{13}\text{C}$, 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; Rosenfeld et al., 2003; 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 $\delta^{13}\text{C}$ might be lost. In our study, the warm season at Simeulue Island is less cloudy than the cooler season. As shown in Fig. 4-12, there was a significant correlation between skeletal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in the post-earthquake, only in SLG (-1.0 m depth) and SPI (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 SLGH, SBB, and SLB).

Gagan et al. (2015) indicated the coral skeletal $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ paleogeodetic model was constructed by finding the step changes in the skeletal $\delta^{13}\text{C}$ produced by decimeter-scale seafloor displacements. The step change in the skeletal $\delta^{13}\text{C}$ was distinguished from other controlling factors such as the $\delta^{13}\text{C}$ of dissolved inorganic carbon in seawater (e.g., Nozaki et al., 1978; Grottooli 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; Grottooli and Wellington, 1999) and heterotrophic feeding components (e.g., Felis et al., 1998; Grottooli 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 $\delta^{13}\text{C}$. Our skeletal $\delta^{13}\text{C}$ records showed the significant step changes in category-1 ($\Delta\delta^{13}\text{C}$ in SLGH and SBB were 0.34 ‰ and 0.32 ‰; Fig. 4-7-b and Fig. 4-7-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 the 2004 earthquake and +1.4 m during the 2005 earthquake for SLGH and SBB, respectively. Thus, our $\Delta\delta^{13}\text{C}$ results 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 uplift for SLGH and SBB, respectively. Our result was consistent with Gagan et al. (2015), who showed the abrupt increase in the skeletal $\delta^{13}\text{C}$ 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 SLGH and SBB, respectively (Table 4-2).

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 $\delta^{13}\text{C}$ would reflect the uplift-related RLAs, not the change of cloud fraction. In category-2, a significant step change in the skeletal $\delta^{13}\text{C}$ was not obtained. McConnaughey (1989a) mentioned that the deeper corals did not show the significant trends in the skeletal $\delta^{13}\text{C}$ because the reduction in depth caused by coral growth was insignificant compared to total depth. Our result (Fig. 4-11) in SLB and SPI (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 $\delta^{13}\text{C}$ in category-2 would reflect not only the uplift-related RLA but also the other controlling factors (e.g., respiration, heterotrophic feeding, or the $\delta^{13}\text{C}$ of dissolved inorganic carbon in seawater).

In order to strongly ensure the accuracy of the coral skeletal $\delta^{13}\text{C}$ paleogeodesy technique, it is necessary to understand the relationships among the coral habitat depth, the step change in the skeletal $\delta^{13}\text{C}$ derived from vertical displacement, and the RLA. Because our specimens had different RLAs, the significant relationship was obtained. The skeletal $\delta^{13}\text{C}$ of the uplifts ($\text{‰}/\text{m}$) in our and previous study exponentially decreased with the decreasing RLA ($r = 0.99$; $p < 0.05$; $n = 5$; Fig. 4-11-c; excluding SLG). This significant relationship seems to reflect an exponential available light attenuation. Importantly, the skeletal $\delta^{13}\text{C}$ of the uplift was significantly correlated with the RLA ($r = 0.94$; $p < 0.05$; $n = 4$; Fig. 4-11-c; excluding SLG and SPI). It is notable that the SPI was excluded because it showed a slight decrease in post-earthquakes ($\Delta\delta^{13}\text{C} = -0.17 \text{ ‰}$; *n.s.*). There were two categories of skeletal $\delta^{13}\text{C}$ response against the vertical displacements within the RLAs. One is SLGH 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 SBB and SLB, its habitat water depths were deeper and the RLAs were smaller than the SLGH and the value in Gagan et al. (2015). The step changes in the skeletal $\delta^{13}\text{C}$ in SLGH 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 $\delta^{13}\text{C}$ records for the SBB and SLB 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 $\delta^{13}\text{C}$ paleogeodetic tool. Besides, 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 $\delta^{13}\text{C}$ -RLA relationship will ensure good coral skeletal $\delta^{13}\text{C}$ paleogeodesy. Additionally, Gagan et al. (2015) mentioned the detection limits of dome-shaped coral skeletal $\delta^{13}\text{C}$ paleogeodesy; the lower detection limit for vertical displacement appears to be $\sim 0.3 \text{ m}$ for short coral $\delta^{13}\text{C}$ 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, I propose that the coral RLA related to the habitat water depth and scale of vertical displacement are also noteworthy keys for coral skeletal $\delta^{13}\text{C}$ 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.

Changes in other skeletal geochemical proxies with seismic vertical displacement

As described in *Chapter 1*, the coral Sr/Ca (e.g., Beck et al., 1992; McCulloch et al., 1994; Cahyarini et al., 2014) and Mg/Ca (Mitsuguchi et al., 1996; Wei et al., 2000; Watanabe et al., 2001a) are widely used in paleothermometry. Besides, the coral skeletal $\delta^{18}\text{O}$ 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). There is no significant difference in the mean AVHRR-SST and IGOSS-SST between the pre- and post-earthquake periods. The earthquake events would not affect SST. Thus, the coral skeletal SST proxies (Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$) should not show the irregular fluctuation due to the SST components. Besides, the satellite AVHRR-SST in the northern and southern parts of Simeulue Island showed the 0.03 °C of the difference in the mean value. The significant $\Delta\text{Sr/Ca}$, $\Delta\text{Mg/Ca}$, and $\Delta\delta^{18}\text{O}$ were explained by the sensitivity to SST or another controlling factor.

(1) Skeletal Sr/Ca

Several previous studies had 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 sampling sites of each coral specimen 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 4-3-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 SLB, and the maximum value was 9.029 mmol/mol in SPI). 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 SLG, the mean value for the seasonal variation (MSV; the difference between the maximum/minimum value during one year) was 0.151 mmol/mol. The SLG 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 ($\Delta\text{MSV} = 0.059$ mmol/mol, $p < 0.01$). By contrast, the SLGH, which is a horizontal-drilled core from the same colony as SLG, the MSV was 0.160 mmol/mol. The seasonal variation of SLGH in the post-earthquake period was slightly smaller than the variation pre-earthquake ($\Delta\text{MSV} = 0.003$ mmol/mol; *n.s.*; within the measurement error range). In SPI, the MSV was 0.172 mmol/mol. The seasonal variation of SPI in the post-earthquake was smaller than that of the pre-earthquake period ($\Delta\text{MSV} = 0.081$ mmol/mol; $p < 0.05$). In SBB, the MSV was 0.213 mmol/mol. The seasonal variation of SBB in the post-earthquake was slightly smaller than it was pre-earthquake ($\Delta\text{MSV} = 0.006$ mmol/mol; *n.s.*). In SLB, the MSV was 0.350 mmol/mol. The seasonal variation of SLB in the post-earthquakes was larger than it was pre-earthquakes ($\Delta\text{MSV} = 0.079$ 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 SLG, SLGH, SPI, and SBB 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 SLB 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 $\Delta\text{Sr/Ca}$ in the SLGH, SPI, and SBB were attributable to the skeletal Sr/Ca sensitivity to temperature or another factor.

(2) Skeletal Mg/Ca

In skeletal Sr/Ca vs. Mg/Ca through both pre- and post-earthquake periods, there was a significant correlation in SLG, SLGH, and SPI (Fig. 4-11). 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 4-8-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 SLGH, and the maximum value was 4.982 mmol/mol in the SLB). 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 SLG, the MSV was 0.911 mmol/mol. The seasonal variation of SLG in the post-earthquake was slightly smaller than it was pre-earthquake ($\Delta\text{MSV} = 0.047$ mmol/mol; *n.s.*). In SLGH, the MSV was 0.484 mmol/mol. The seasonal variation of SLG in the post-earthquake was slightly smaller than the variation pre-earthquake ($\Delta\text{MSV} = 0.012$ mmol/mol, *n.s.*). In SPI, the MSV was 0.604 mmol/mol. The seasonal variation of SPI in the post-earthquake was significantly smaller than the variation in the pre-earthquake ($\Delta\text{MSV} = 0.416$ mmol/mol, $p < 0.05$). In SBB, the MSV was 0.717 mmol/mol. The seasonal variation of SBB in the post-earthquake was slightly larger than it was pre-earthquake ($\Delta\text{MSV} = 0.149$ mmol/mol; *n.s.*). In SLGH, the MSV was 0.689 mmol/mol. The seasonal variation of SLB in the post-earthquake was also slightly larger than it was pre-earthquakes ($\Delta\text{MSV} = 0.214$ mmol/mol; *n.s.*). Similar to the discussion of Sr/Ca, the earthquake event did not affect SST and skeletal Mg/Ca. Thus, the $\Delta\text{Mg/Ca}$ in the SBB and SLB were attributable to the skeletal Mg/Ca sensitivity to temperature or another factor (e.g., organic matters, described by Watanabe et al., 2001b; 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. (2001b) 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). 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 SLGH and SBB showed a positive peak after the tsunami events (Figs. 4-7-f and -g). A positive peak in the SBB 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 sediments, 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 SLB 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.

(3) Skeletal $\delta^{18}\text{O}$

In tropical and subtropical areas, variations in the seawater salinity caused by evaporation, rainfall, or freshwater input from the river affect the skeletal $\delta^{18}\text{O}$, and then the influence of these components should be considered when establishing a skeletal $\delta^{18}\text{O}$ -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 $\delta^{18}\text{O}$ -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 $\delta^{18}\text{O}$ of seawater (and coral). In this study, the $\delta^{18}\text{O}_{\text{sw}}$ correlated with SST (Fig. 4-4; $r = 0.60 \sim 0.91$; $p < 0.05$; $n = 12$; excluding SLB), not precipitation. It suggested that the $\delta^{18}\text{O}_{\text{sw}}$ would reflect evaporation rather than precipitation. In the cooler season (November), $\delta^{18}\text{O}_{\text{sw}}$ might reflect the high precipitation. In skeletal Sr/Ca vs. $\delta^{18}\text{O}$ through both pre- and post-earthquake periods, there was a significant correlation in SLGH, SPI, and SBB (Fig. 4-11). This result suggests that skeletal $\delta^{18}\text{O}$ reflected SST variation as with skeletal Sr/Ca. The lack of correlation in Sr/Ca vs. $\delta^{18}\text{O}$ (SLG and SLB) 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 skeletal Sr/Ca and Mg/Ca records, five of the coral skeletal $\delta^{18}\text{O}$ records have each shown different variations (mean value and seasonal variation; Table 4-3-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 SLB, and the maximum value was -5.501 ‰ in the SLGH). 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 $\delta^{18}\text{O}$ in sea water is considered. In SLG, the MSV was 0.468 ‰. The ΔMSV was 0.003 ‰ (*n.s.*), which is within the measurement error range (0.04 ‰). In SLGH, the MSV was 0.496 ‰. The seasonal variation of SLG in the post-earthquake period was significantly larger than it was pre-earthquake ($\Delta\text{MSV} = 0.216$ ‰, $p < 0.05$). In SPI, the MSV was 0.584 ‰. The seasonal variation of SPI in the post-earthquake was significantly smaller than it was pre-earthquake ($\Delta\text{MSV} = 0.265$ ‰, $p < 0.01$), in contrast to the result for the SLGH. In SBB, the MSV was 0.562 ‰. The seasonal variation of SBB in the post-earthquake was slightly larger than it was pre-earthquake ($\Delta\text{MSV} = 0.045$ ‰, *n.s.*). In SLB, the MSV was 0.560 ‰. The seasonal variation of SLB in the post-earthquake was slightly smaller than it was pre-earthquake ($\Delta\text{MSV} = 0.094$ ‰, *n.s.*). Gagan et al. (2015) showed no significant change in the skeletal $\delta^{18}\text{O}$ when using two fossil *Porites* that experienced an abrupt change in 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 $\delta^{18}\text{O}$ in the SLGH, SPI and SBB. 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 $\delta^{18}\text{O}$. The $\Delta\delta^{18}\text{O}$ in the SLGH may reflect the temporal lower-SST signal in the aftermath of the earthquakes (see Discussion 4.1). Unfortunately, this study could not find the exact variable factors for the $\Delta\delta^{18}\text{O}$ in the SPI and SBB. These records fluctuated more than are expected from environmental causes.

4.7 Conclusion

Annual banding skeletons in reef corals have potential uses in the detection of natural reef disturbance due to paleo-earthquakes. There was the first evidence for skeletal growth responses to the seismic uplift and tsunami 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. Besides, a green band on the skeleton slab due to an endolithic algae bloom (*Ostreobium* spp.) and incorporation of the small particles like clay materials were also the remarkable signals of natural reef disturbance associated with the earthquake and tsunami occurrence.

The seismic uplift event did not affect environmental conditions such as SST and precipitation. While, several geochemical records (Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$) showed significant differences. Skeletal Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$ 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 $\delta^{13}\text{C}$ would reflect the uplift-related RLAs, not the cloud fraction. In conclusion, the coral RLA associated with the habitat water depth and the scale of vertical displacement would be a noteworthy key in coral skeletal $\delta^{13}\text{C}$ paleogeodesy. Coral skeletal $\delta^{13}\text{C}$, skeletal growth parameters, and the remarkable signals on the skeletons will be useful for detecting and reconstructing the effect of the reef disturbances.

Figures and Tables

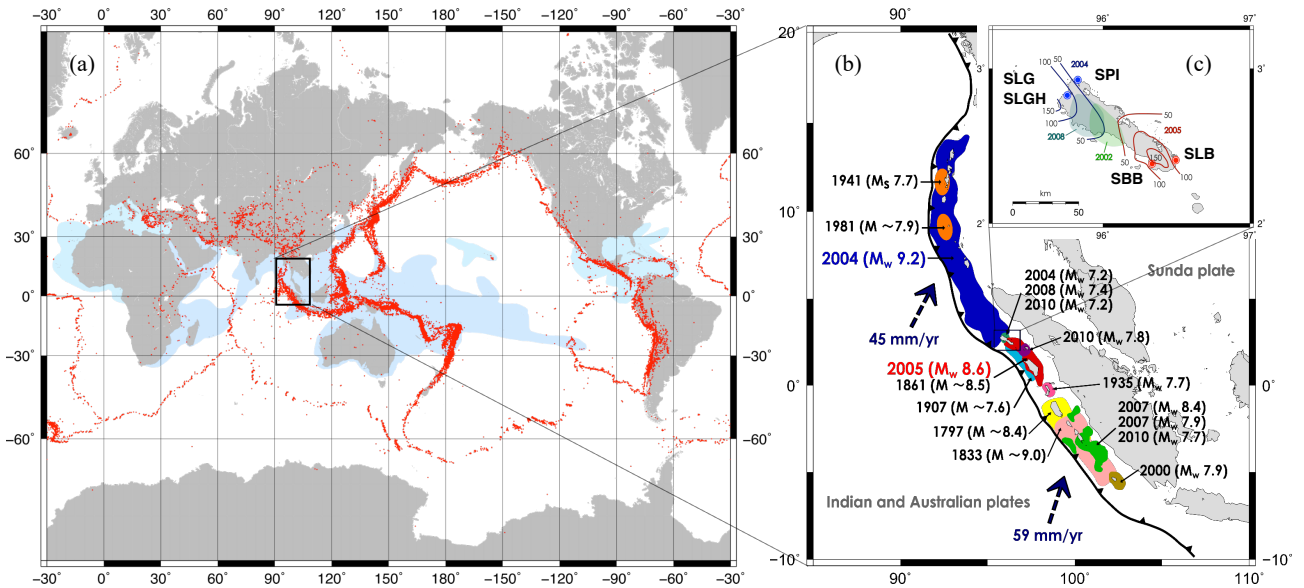


Fig. 4-1 Distribution map of paleo-earthquakes and reef corals and a regional map of sample sites

(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, Engdahl et al., 1998; Engdahl and Villaseñor, 2002). 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).

All map figures were generated using Generic Mapping Tools (GMT v. 5.3.3, Wessel et al., 2013).

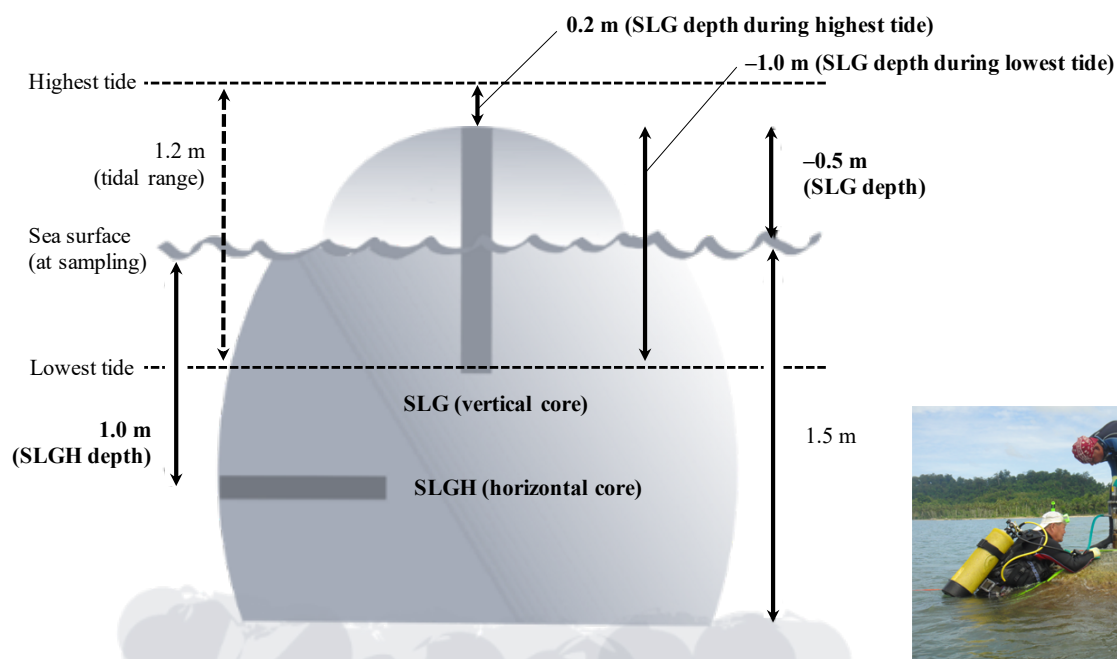


Fig. 4-2 Sample positions of SLG and SLGH

SLG (vertical core) and SLGH (horizontal core) are from a single colony. The values (in m) with bold character mean water depth of each core top at core drilling. The dashed lines show the highest or lowest tide (1.2 m tidal range). “Depth during highest/lowest tide” was estimated on the basis of water depth and the tidal range (see also Table 4-1). The photo was taken during the SLG core drilling.

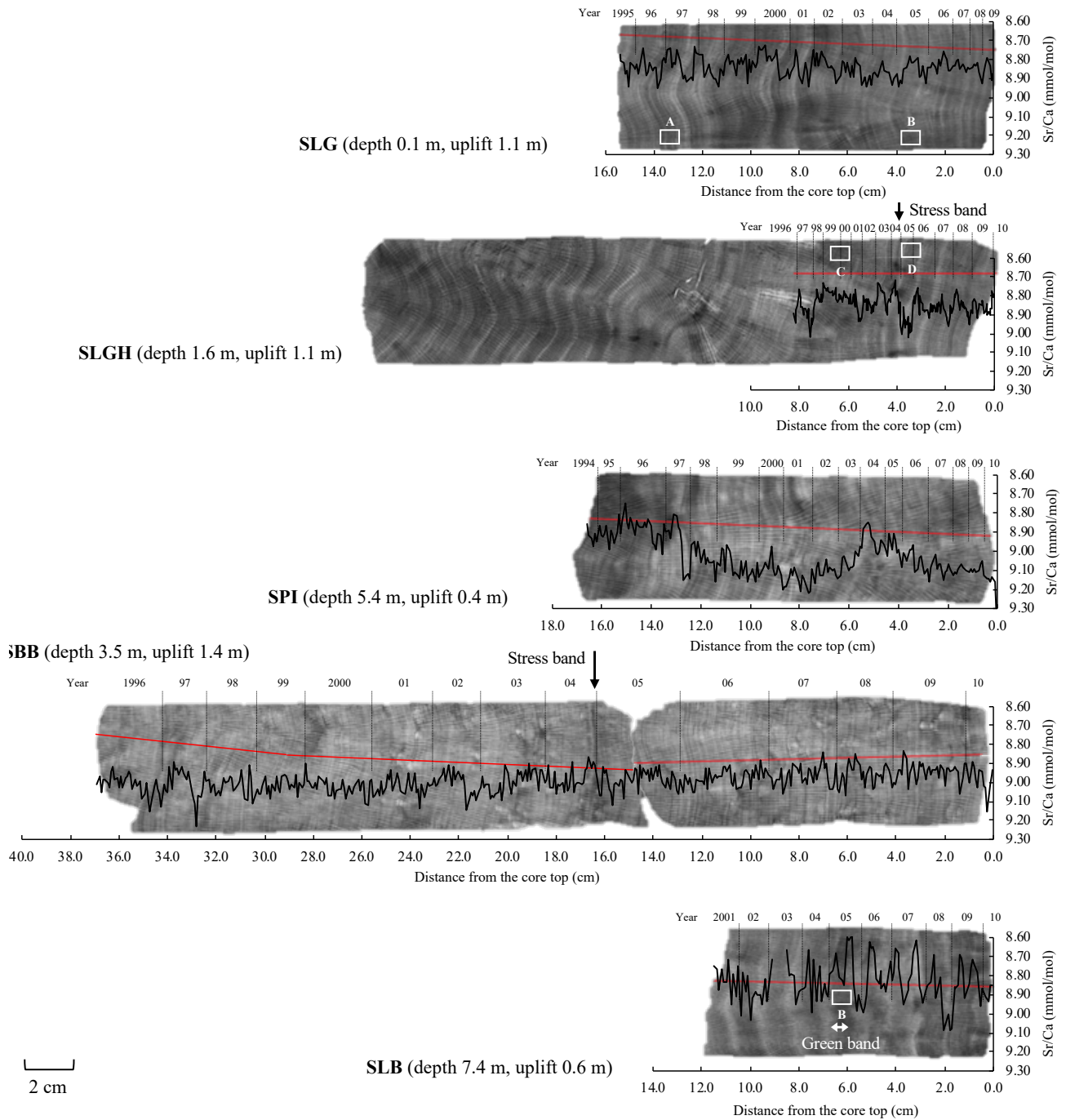


Fig. 4-3 Images of X-radiographs (positive) and skeletal Sr/Ca records

“Depth” is the value of “Estimated depth in pre-earthquakes” shown in Table 4-1. “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 of the relationship between skeletal Sr/Ca and monthly SST. The areas “A, B, C, D” on the SLG and SLGH indicate the positions of the microscopic picture shown in Fig. 4-6. The arrows above SLGH and SBB show the positions of stress bands. The white arrow on the SLB X-ray shows the position of the green band and the area “B” (on the SLB X-ray) indicates the position of the microscopic picture shown in Fig. 4-5.

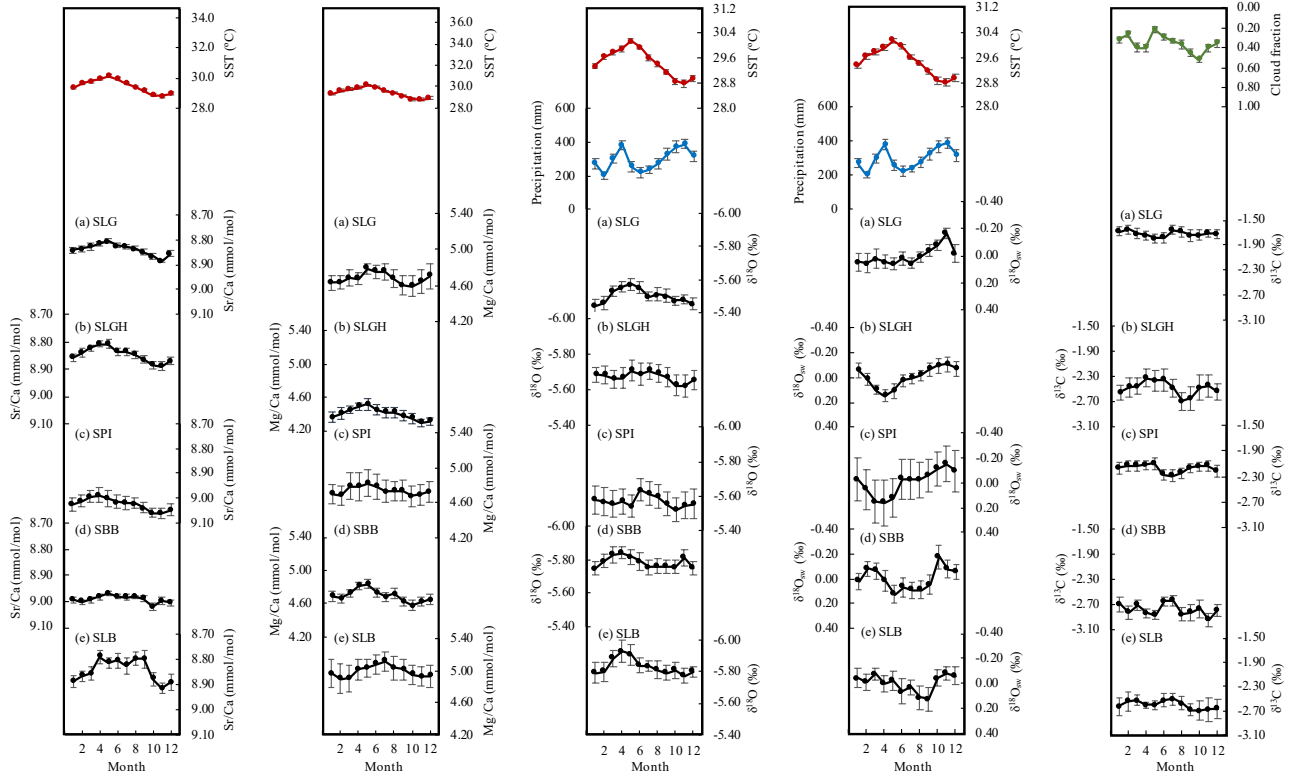


Fig. 4-4 Seasonal trends of environmental data (SST, precipitation, and cloud fraction) and geochemical data

The red lines show the monthly IGOSS-SST, which was derived from the Integrated Global Ocean Services System Products Bulletin. The blue lines show the monthly precipitation data, which was derived from WCRP GCOS GPCC Monitoring. The green line shows the cloud fraction data (1 = covered with cloud completely), which was derived from FRESCO+ SCIAMACHY. All the geochemical records were resampled monthly resolution. Each y-axis range in SST was determined by the variable range in the geochemical proxy as follows: Sr/Ca was 0.4 mmol/mol which is equivalent to 6.6 °C (Abram et al., 2007), Mg/Ca was 1.2 mmol/mol which is equivalent to 9.3 °C (Mitsuguchi et al., 1996), and $\delta^{18}\text{O}$ was 0.6 ‰, which is equivalent to 3.2 °C (Abram et al., 2007). The error bars show standard errors. Estimated $\delta^{18}\text{O}_{\text{sw}}$ was calculated from skeletal Sr/Ca and $\delta^{18}\text{O}$ (Juillet-Leclerc and Schmidt, 2001; Cahyarini et al., 2008).

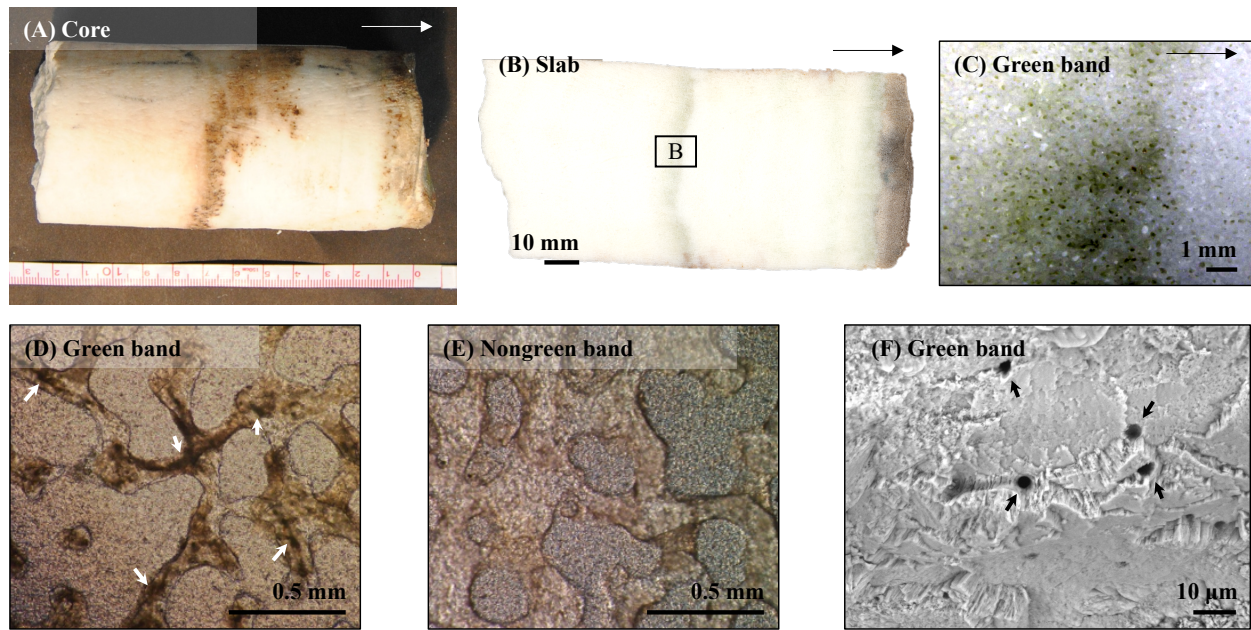


Fig. 4-5 Green band created by endolithic algae on the SLB slab surface

(A) The photo of the SLB core. The rightwards arrow shows the growth direction. (B) 8 mm green band on the SLB slab surface. (C) The microscopic picture of the green band area “B” on figure (B). (D) (E) A part of the green band and nongreen band shown under a microscope (thin sections). The skeletal structure of the nongreen band area was clear (E), while the skeletal structure of the green band area would contain the endolithic algae (D; white arrows; e.g., *Ostreobium* spp.). (F) Trace of microbioerosion due to microboring by endolithic algae (black arrows), shown under an electron microscope (cross section of the green band). *Ostreobium* spp. left the 3 ~ 5 μm microborings, which conform to the shape of their thallic (filament).

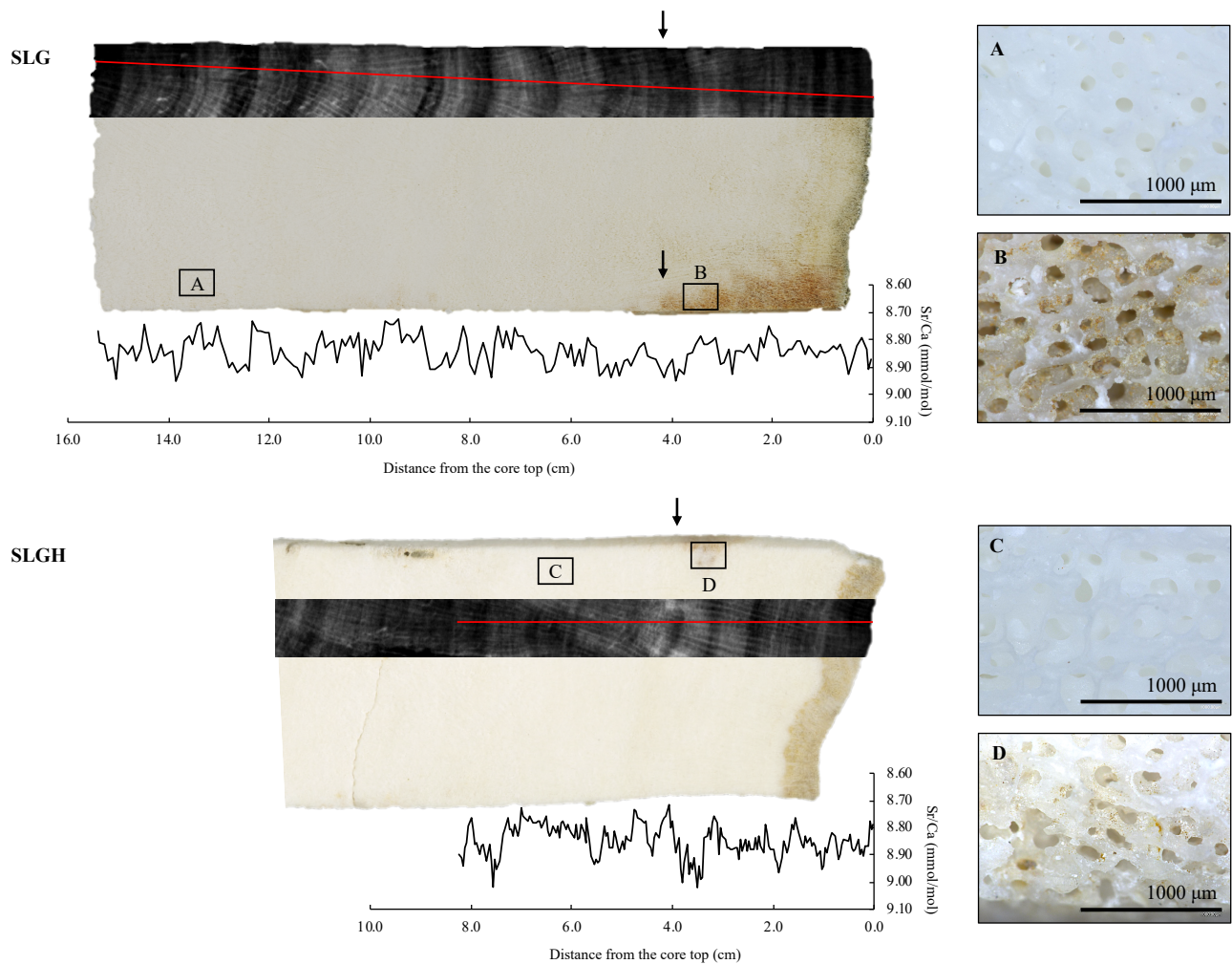


Fig. 4-6 Incorporation of suspended small particles on the SLG and SLGH skeleton

The X-ray images (negative) are combined with the slab images. The slab images were taken after microsampling (SLGH slab has cracked during microsampling). The black arrows show the occurrence of the 2004 earthquake (and tsunami). (A) and (C) are parts of the pre-earthquake shown under a microscope, which indicates a normal slab surface. (B) and (D) are parts of the post-earthquake shown under a microscope, which indicates the incorporation of small particles like clay minerals in the skeleton. X-radiographs did not show the anomalous high or low density on the (B) and (C) area (compared by Fig. 4-3).

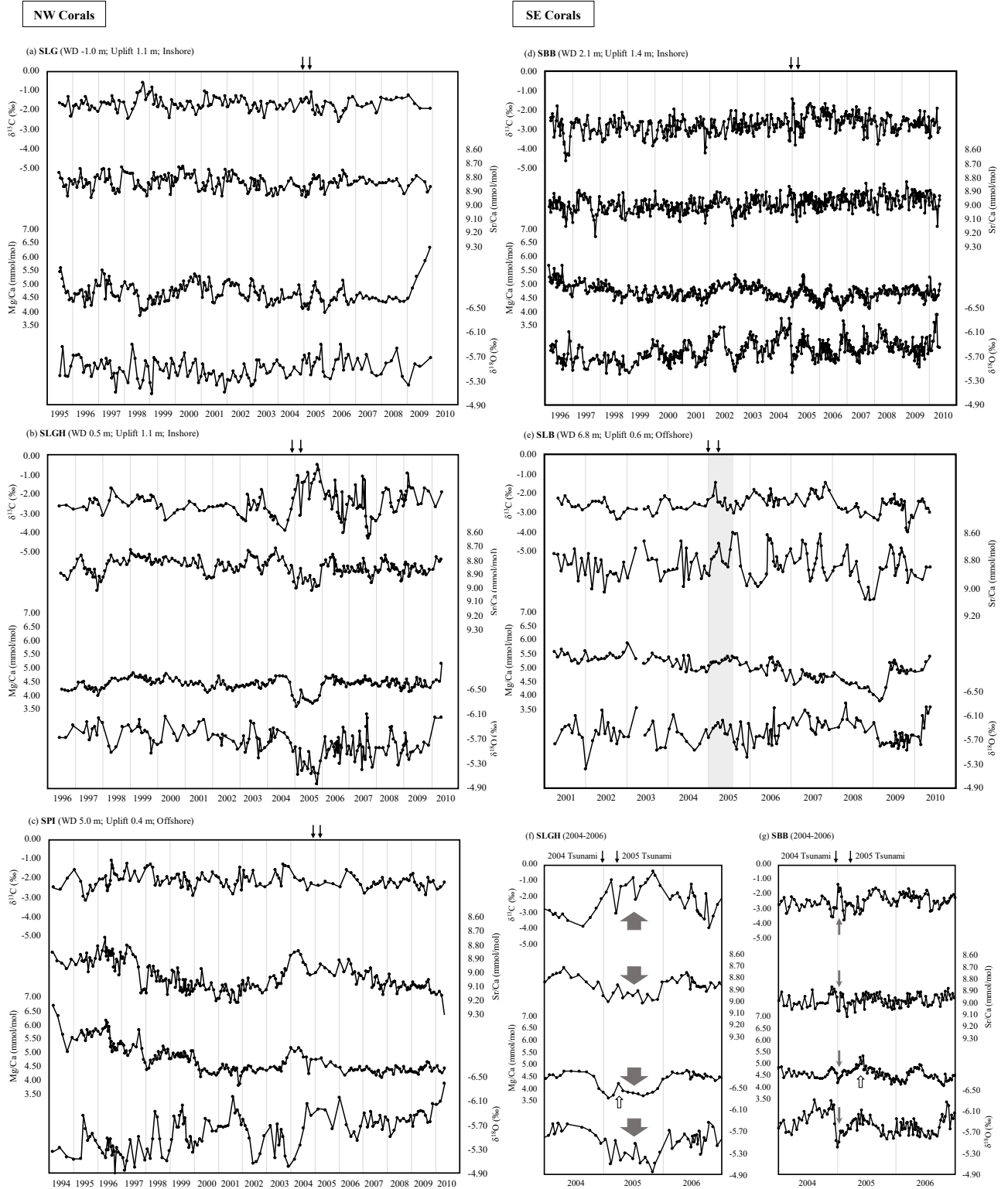
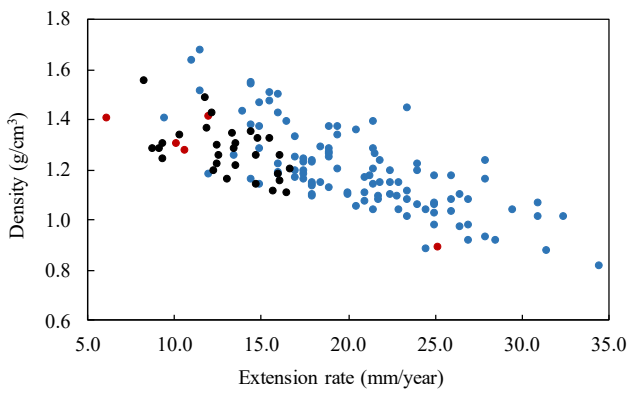


Fig. 4-7 Skeletal geochemical records ($\delta^{13}\text{C}$, Sr/Ca , Mg/Ca , and $\delta^{18}\text{O}$)

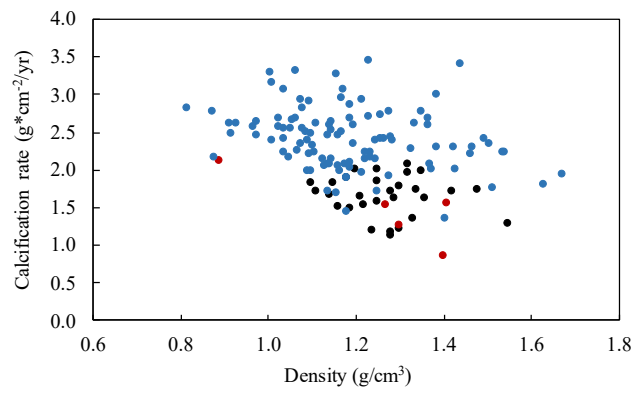
The mean difference between the pre- and post-earthquake data (dashed lines) is shown as $\Delta Proxy$ in the text. Pre-earthquake periods of each coral specimens were defined as the date of 2004 or 2005 coseismic uplift events (from the oldest age to December 26th 2004 for NW corals, and to March 28th 2005 for SE corals; see 4.2 Study area).

The black arrows show the occurrence of the 2004 or 2005 earthquake. The gray hatching in the SLB record shows the period of the green band was observed on the SLB slab surface. “WD” means water depth value (“Depth during lowest tide” in Table 4-1). 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 after the tsunami events.

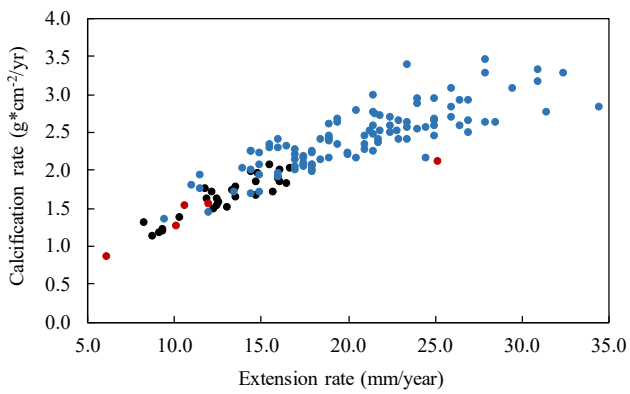
(a) Density vs. Extension rate



(b) Calcification rate vs. Density



(c) Calcification rate vs. Extension rate



● Lough & Barnes (2000) Great Barrier Reef
● Scoffin et al. (1992) South Thailand
● This Study Simeulue Island, Indonesia

Fig. 4-8 Scatter diagrams of average skeletal growth data (*Porites* sp.) for the previous studies and this study.

Data is from the Great Barrier Reef (the black circles, Lough and Barnes, 2000), South Thailand (the blue circles, Scoffin et al., 1992), and Simeulue Island (the red circles, this study, mean value of each core).

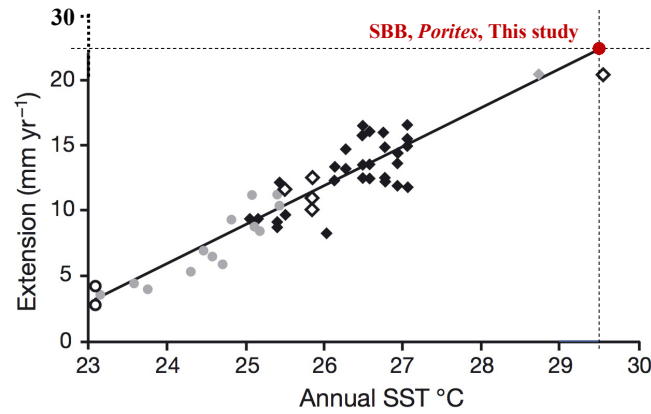


Fig. 4-9 Colony extension rate vs. annual SST for *Porites* corals (Goodkin et al., 2012, Fig. 6, modified).

Data is from the Hawaiian archipelago (the gray circles, Grigg 1981), Phuket, Thailand (the gray diamonds, Scoffin et al., 1992), the Great Barrier Reef (the black diamonds, Lough and Barnes 2000), the Arabian Gulf and Lihir Island (the white diamonds, Lough, 2008), and Hong Kong (the white circles, Goodkin et al., 2012). The red circle shows the SBB *Porites* core in this study (x: 29.5 °C, y: 25.26 mm/year). The regression line excepts Goodkin et al. (2012) and this study.

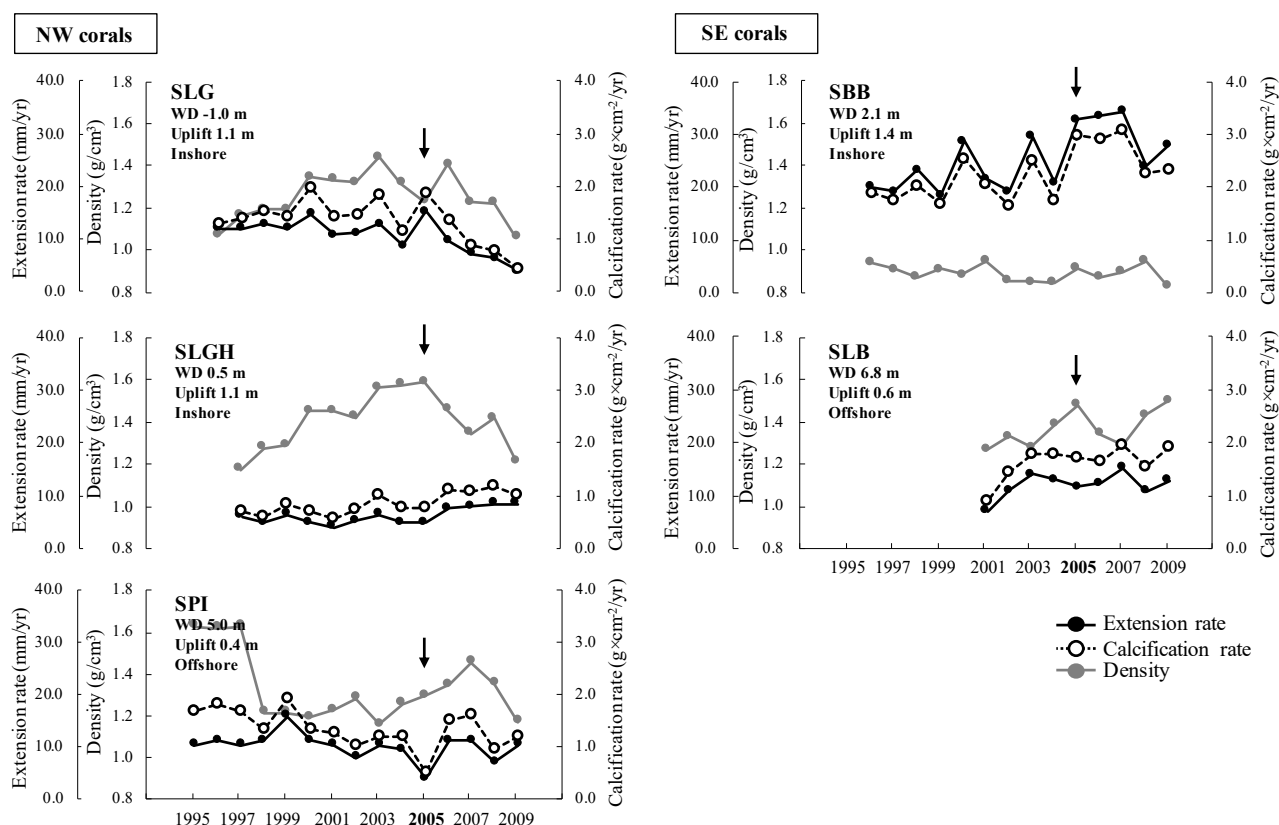


Fig. 4-10 Annual skeletal growth parameters (skeletal extension rate, calcification rate, and density)

The closed circles with a solid line indicate the annual extension rate (mm/yr); open circles with dashed lines indicate the annual calcification rate ($\text{g} \times \text{cm}^{-2}/\text{yr}$); 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 4-1.

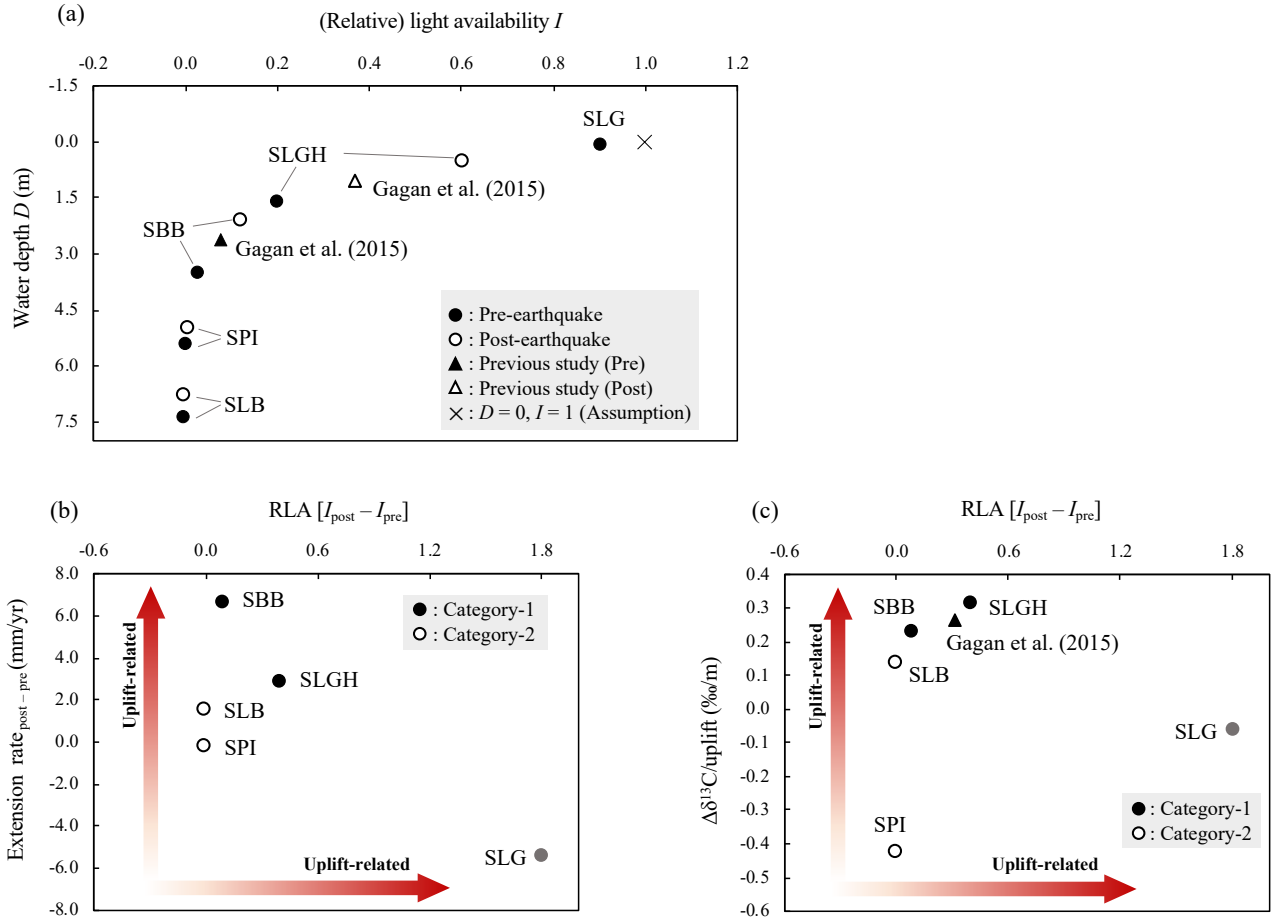


Fig. 4-11 Relationships among uplift-related RLA, skeletal growth, and skeletal $\Delta\delta^{13}\text{C}$

(a) Relative light availability during pre- (●) and post-earthquakes (○) in all corals (SLG in post-earthquakes was excepted because the top of the colony was over the sea surface after the uplift event; see in the text and Fig. 4-2). 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 the 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 4-1. (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 4-7, “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., $I_{D_{\text{post}}} - I_{D_{\text{pre}}}$) as follows: $RLA = \exp[-k(D_{\text{post}} - D_{\text{pre}})]$ 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. SLG (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 $\Delta\delta^{13}\text{C}$. The skeletal $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ increased 0.26 ‰/m; $n = 6$; in Nias Island. Larger RLA, and larger skeletal growth or larger skeletal $\Delta\delta^{13}\text{C}$ indicates uplift-related change.

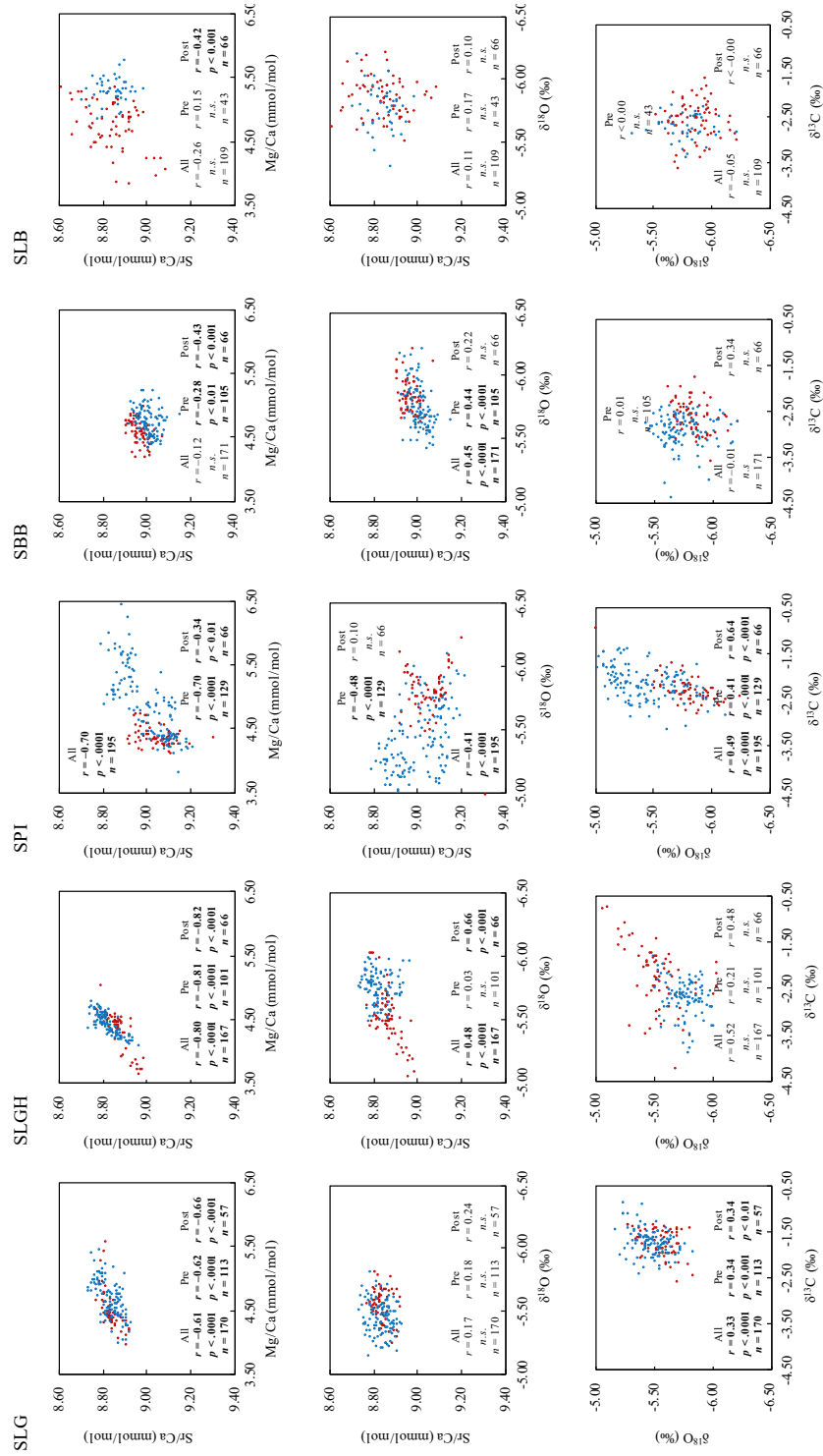


Fig. 4-12 Plots of skeletal geochemical proxies (Sr/Ca vs. Mg/Ca, Sr/Ca vs. $\delta^{18}\text{O}$, and $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$)

Plots were resampled monthly resolution (the last 4 data points of the Mg/Ca record in SLG were excluded because these 4 data showed anomalous change due to air-exposed stress). The blue plots show the data in pre-earthquakes (“Pre”, from the oldest date to November 2004), and the red plots show the data in post-earthquakes (“Post”, from December 2004 to the date of core drilling). “All” means the data through both pre- and post-earthquakes periods.

Sample	Sampling date	Sampling time (UTC)	Water depth (m)	Depth during lowest tide (m)	Depth during highest tide (m)	Uplift (m) [yr] Briggs et al. (2006)	Estimated depth in pre-earthquakes (m)	Location	Distance from the nearest shore (m)
SLG	May 16 th , 2010	08:44-11:06	(-0.5)	(-1.0)	0.2	1.1 [2004]	(0.1)	Inshore	165
SLGH	May 16 th , 2010	08:44-11:06	1.0	0.5	1.7	1.1 [2004]	1.6	Inshore	165
SPI	May 15 th , 2010	09:22-11:04	5.5	5.0	6.2	0.4 [2004]	5.4	Offshore	1720
SBB	May 20 th , 2010	04:10-08:24	3.0	2.1	3.3	1.4 [2005]	3.5	Inshore	50
SLB	May 18 th , 2010	03:48-04:14	7.8	6.8	8.0	0.6 [2005]	7.4	Offshore	800

Table 4-1 Sample information

“Water depth (in m)” is the measurement value at core drilling. The SLG core top was 0.5 m over the sea surface (see also Fig. 4-2). “Depth during lowest/highest tide” was estimated on the basis of water depth and tidal range (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).

(a) SLG		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	SST	-0.95***	0.67*	-0.75**	-0.28
	Precipitation	0.55**	-0.49	0.05	-0.25
	Cloud fraction	0.59*	-0.68*	0.23	-0.02
(b) SLGH		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	SST	-0.96***	0.95***	-0.73**	0.53
	Precipitation	0.42	-0.38	0.80**	0.03
	Cloud fraction	0.55	-0.47*	0.74**	-0.30
(c) SPI		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	SST	-0.93***	0.79**	-0.42	0.02
	Precipitation	0.41	-0.17	0.60*	0.40
	Cloud fraction	0.49	-0.39	0.42	0.08
(d) SBB		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	SST	-0.75**	0.87**	-0.54	0.27
	Precipitation	0.36	-0.25	-0.21	-0.49
	Cloud fraction	0.58*	-0.59*	0.15	-0.10
(e) SLB		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	SST	-0.64*	0.42	-0.80**	0.74**
	Precipitation	0.25	-0.31	<-0.01	-0.73**
	Cloud fraction	0.15	-0.22	0.24	-0.56*

* $p < 0.05$; ** $p < 0.01$; *** $p < .0001$

Table 4-2 Correlation coefficient r value between environmental data and geochemical records

All environmental data and geochemical data were a monthly resolution (see also Fig. 4-4).

Evidence	SLG	SLGH	SPI	SBB	SLB
(a) Seasonal cycle range (mmol/mol)					
Skeletal Sr/Ca	0.09	0.08	0.07	0.05	0.13
Skeletal Mg/Ca	0.28	0.22	0.15	0.27	0.22
Skeletal $\delta^{18}\text{O}$	0.13	0.09	0.12	0.09	0.16
(b) Skeletal Sr/Ca vs IGOSS-SST (r -value; * $p < 0.05$; ** $p < 0.01$; *** $p < .0001$)					
	-0.95***	-0.96***	-0.93***	-0.75**	-0.64*
(c) The 1997 Indian Ocean Dipole Signal in the skeletal Sr/Ca record					
	○	○	○	○	No data
(d) The 2004 earthquake and tsunami occurrence signals on the coral skeleton					
Stress band	-	○	-	○	-
Green band	-	-	-	-	○
Small particles like clay materials	○	○	-	-	-
(e) Annual extension rate (mm/yr)					
	10.69	6.12	10.19	25.26	11.98

Table 4-3 Cross-checking and the evidence of age models

(a) The seasonal trend of each geochemical record is shown in Fig. 4-4. In our study site, an annual amplitude of SST observed on IGOSS-SST (1.5 °C on average) should be equal to 0.09 mmol/mol (Abram et al., 2007), 0.19 mmol/mol (Mitsuguchi et al., 1996), and 0.28 ‰ (Abram et al., 2007) range in an annual cycle for skeletal Sr/Ca, Mg/Ca, $\delta^{18}\text{O}$ based on each proxy-SST dependency, respectively. In skeletal Sr/Ca, the seasonal cycle in SLG, SLGH, and SPI showed a clear annual cycle with valid range, while the SBB and SLB record fluctuated more than are expected from SST cause. The annual cycle in skeletal Sr/Ca of SLB was not clear, while the annual bands were clearly visible on the X-ray image (Fig. 4-3). In skeletal Mg/Ca, the annual cycle range in our records did not agree with the skeletal Mg/Ca-SST dependency estimated by the previous study. Our skeletal Mg/Ca record fluctuated more than are expected from SST cause because of the complexity of the controlling factors (e.g., Watanabe et al. 2001b; Nagtegaal et al. 2012). In skeletal $\delta^{18}\text{O}$, the annual cycle range in our records did not agree with the skeletal $\delta^{18}\text{O}$ -SST dependency estimated by the previous study. These small seasonal amplitudes of skeletal $\delta^{18}\text{O}$ would be caused by salinity changes (Cole and Fairbanks, 1990; Carriquiry et al., 1994; Al-Rousan et al., 2007; McCulloch et al., 1999). Skeletal $\delta^{18}\text{O}$ reflects both SST and seawater oxygen isotopes ($\delta^{18}\text{O}_{\text{seawater}}$: positively correlated with salinity). In our sample sites, salinity variations (32.4 ~ 34.3 psu for CARTON-GIESE SODA data, from June 1994 to December 2008 at 2.25 N, 95.25 E with 5.01 m depth; and 33.0 ~ 34.9 for Aquarius IPRC/SOEST OISSS data, from September 2011 to May 2015 at 2.3 N, 95.3 E) are equal to 0.80 ‰ in $\delta^{18}\text{O}_{\text{seawater}}$, based on the salinity- $\delta^{18}\text{O}_{\text{seawater}}$ slope (0.42 ‰VSMOW/psu: Morimoto et al., 2002). Thus, the small seasonal amplitude of SST components

for skeletal $\delta^{18}\text{O}$ (0.28 ‰, equal to 1.5 °C) could be masked by $\delta^{18}\text{O}_{\text{seawater}}$ variations due to evaporation or freshwater input (i.e., precipitations, input from the river). (b) r - and p -values are shown in Table 4-2. Skeletal Sr/Ca significantly correlated with monthly SST in all coral cores. It suggests that skeletal Sr/Ca record reflects SST variation. (c) The skeletal Sr/Ca records are shown in Fig. 4-7. The extreme Indian Ocean Dipole (IOD) signal in 1997 was found in the skeletal Sr/Ca records in all cores (the SLB was excluded because of no data). The 1997 IOD signal in the skeletal Sr/Ca provides the precision of the age model. (d) The 2004 earthquake and tsunami signals: a stress band (inshore corals; Fig. 4-3), a green band (SLB; Fig. 4-5), and an incorporation of the small particles like clay materials (SLG and SLGH; Fig. 4-6) were observed on the coral skeleton. These signals are evidence of the precise age model. (e) The annual skeletal extension rate (mm/yr) was assumed to be constant between dates of the adjacent highest Sr/Ca (i.e., age model). The 6.12-25.26 mm/yr of annual extension rate for *Porites* coral agrees with previous studies (e.g., Lough and Barnes, 2000; Scoffin et al., 1992; Goodkin et al., 2012; Watanabe et al., 2017).

Post-earthquake period	$\Delta\delta^{13}\text{C}$ (‰)	$\Delta\text{Sr/Ca}$ (mmol/mol)	$\Delta\text{Mg/Ca}$ (mmol/mol)	$\Delta\delta^{18}\text{O}$ (‰)
(a) SLG				
from the 2004 earthquake	-0.08	0.05	-0.14*	-0.10**
from the 2005 earthquake	-0.11	<-0.01	-0.08	-0.08*
(b) SLGH				
from the 2004 earthquake	0.34**	0.04***	-0.05	0.21***
from the 2005 earthquake	0.30*	0.04***	-0.01	0.19***
(c) SPI				
from the 2004 earthquake	-0.17*	0.05***	-0.53***	-0.34***
from the 2005 earthquake	-0.16*	0.06***	-0.53***	-0.33***
(d) SBB				
from the 2004 earthquake	0.34***	-0.04***	-0.16***	-0.08***
from the 2005 earthquake	0.32***	-0.04***	-0.15***	-0.09***
(e) SLB				
from the 2004 earthquake	0.14	-0.02	-0.46***	-0.03
from the 2005 earthquake	0.08	-0.01	-0.47***	-0.01

* $p < 0.05$; ** $p < 0.01$; *** $p < .0001$

Table 4-4 Comparison of $\Delta Proxy$ in two post-earthquake periods

The post-earthquake period means from the 2004 or 2005 earthquake to the date of core drilling. The “ p ” is a statically significant p value for the Student’s t-test.

(a) SLG		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	Extension rate	-0.15	-0.25	0.07	-0.20
	Density	0.08	-0.28	0.26	-0.20
(b) SLGH		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	Extension rate	0.08	0.20	0.37	0.17
	Density	0.06	-0.28	0.34	-0.13
(c) SPI		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	Extension rate	0.07	0.19	0.25	0.18
	Density	-0.69**	0.69**	0.45	-0.02
(d) SBB		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	Extension rate	-0.46	-0.39	-0.15	0.80**
	Density	0.28	-0.23	0.19	-0.25
(e) SLB		Sr/Ca	Mg/Ca	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
	Extension rate	-0.57	-0.04	-0.21	0.42
	Density	0.02	-0.38	0.29	-0.36

* $p < 0.05$; ** $p < 0.01$

Table 4-5 Correlation coefficient r value between annual skeletal growth parameters (skeletal extension rate and skeletal density) and annual mean of geochemical records

The analyzed period was 1996 to 2009, 1997 to 2009, 1995 to 2009, 1997 to 2009, and 2002 to 2009 for SLG, SLGH, SPI, SBB, and SLB, respectively. There was no significant correlation between annual skeletal growth parameters and annual mean of geochemical records, excluding in SPI (Sr/Ca vs. density and Mg/Ca vs. density) and in SBB ($\delta^{13}\text{C}$ vs. extension rate). These significant correlations seem to be affected by the large deviation in skeletal extension rate and density (shown in Table 4-6, “SD”).

Sample	Extension rate (mm/yr)		Density (g/cm ³)		Calcification rate (g×cm ⁻² /yr)	
	Mean	SD	Mean	SD	Mean	SD
SLG	10.69	3.99	1.27	0.11	1.52	0.53
SLGH	6.12	1.54	1.40	0.13	0.85	0.20
SPI	10.19	2.56	1.30	0.17	1.25	0.37
SBB	25.26	5.79	0.89	0.04	2.10	0.50
SLB	11.98	2.34	1.41	0.09	1.54	0.32

Table 4-6 Mean and standard deviation value for skeletal growth parameters

Calculation methods for extension rate, density, and calcification rate were shown in the main text. “SD” means standard deviation value.

Sample	Extension rate (mm/yr)			Density (g/cm ³)			Calcification rate (g×cm ⁻² /yr)		
	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
SLG	12.24	6.80	-5.44***	1.26	1.23	-0.03	1.54	0.86	-0.68**
SLGH	5.24	8.10	2.86**	1.42	1.36	-0.06	0.74	1.10	0.36**
SPI	10.25	10.00	-0.25	1.37	1.33	-0.04	1.34	1.33	-0.01
SBB	23.36	30.00	6.64*	0.89	0.89	-0.01	2.08	2.65	0.57
SLB	11.32	12.80	1.48	1.35	1.39	0.04	1.53	1.42	-0.11

* $p < 0.05$; ** $p < 0.01$; *** $p < .0001$

Table 4-7 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).

Sample	Mean	Seasonal mean variation			
		Mean (MSV)	Pre	Post	Difference (ΔMSV)
(a) Skeletal Sr/Ca (mmol/mol)					
SLG	8.840	0.151	0.172	0.114	0.059**
SLGH	8.848	0.160	0.161	0.159	0.003
SPI	9.029	0.172	0.199	0.118	0.081*
SBB	8.990	0.213	0.215	0.209	0.006
SLB	8.831	0.350	0.300	0.379	0.079**
(b) Skeletal Mg/Ca (mmol/mol)					
SLG	4.667	0.911	0.928	0.881	0.047
SLGH	4.408	0.484	0.488	0.476	0.012
SPI	4.747	0.604	0.743	0.327	0.416*
SBB	4.694	0.717	0.663	0.813	0.149
SLB	4.982	0.689	0.555	0.769	0.214
(c) Skeletal δ ¹⁸ O (‰)					
SLG	−5.501	0.468	0.467	0.470	0.003
SLGH	−5.629	0.496	0.413	0.629	0.216*
SPI	−5.573	0.584	0.672	0.408	0.265**
SBB	−5.790	0.562	0.546	0.591	0.045
SLB	−5.821	0.560	0.619	0.525	0.094

* $p < 0.05$; ** $p < 0.01$

Table 4-8 Mean values and seasonal mean variations in the skeletal Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$ records

The seasonal variation was calculated by taking the difference between the maximum/minimum value for 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.

Notes

The parts of this chapter have been published as Ito et al. (2020a), by *Geochimica et Cosmochimica Acta*.
The samples' name and reference information are below;

<< Reference >>

Ito, S., Yamazaki, A., Nishimura, Y., Yulianto, E. and Watanabe, T. (2020a) Coral geochemical signals and growth responses to coseismic uplift during the great Sumatran megathrust earthquakes of 2004 and 2005. *Geochim. Cosmochim. Acta* **273**, 257–274.

<< Samples' name >>

In this chapter:

SLG100516 (SLG); SLGH100516 (SLGH); SPI100515 (SPI); SBB100520 (SBB); SLB100518 (SLB)

In the published article (Ito et al., 2020a):

Av-NW; Ah-NW; B-NW; C-SE; D-SE

5. Study Case-2 (Natural disturbance): Fossil coral geochemical signals and growth responses to the 1911 Kikai tsunami event

5.1 Introduction

At the Ryukyu Trench (Fig. 5-1), southwest Japan, the Philippine Sea Plate subducts toward the northwest. Ando et al. (2009) described the potential occurrence of a large earthquake ($M_w > 8$) around this area. Besides, Kikai Island (Fig. 5-2) is well known as coral reef terraces, which have been uplifted seismotectonically ~1-4 m every 1500 ~ 2000 years during the past 6000 years (e.g., Webster et al., 1998). It suggests that the surrounding area has high seismic activity. The 1911 Kikai Island earthquake (M_w 8.1) occurred on 15th June, and the epicenter located eastern Kikai Island. The 1911 earthquake triggered a large tsunami, which may cause devastating damage to Kikai Island and Amami-Oshima Island. The tsunami archives were very limited in the Amami Islands, and most of the records were the interviewed records or ancient documents (e.g., Imamura, 1913; Tsuji, 1997). According to the limited archives, the tsunami elevation was estimated as high as 10 m in Nakazato, 8 m in Agaren (Akaren), and 5.5 m in Araki, southwest part in Kikai Island (Fig. 5-2), and it was relatively small in the eastern one. Because any geological or geochemical evidence regarding the 1911 Kikai earthquake was found in Kikai Island, the tsunami-related impact on the coral reefs was still unknown.

Tsunami events could temporarily cause reef disturbance. Huge tsunami waves associated with megathrust earthquakes wreak devastating damage on shallow marine ecosystems, especially coral reefs. For the Ryukyu Islands, there have been numerous previous reports on the tsunami boulders (tsunami deposits), which were recognized clast size and spatial distributions (e.g., Kawana and Nakata, 1994; Goto et al., 2010a; 2010b; 2010c; 2013; Araoka et al., 2010; 2013). Massive coral-made tsunami boulders would give us the historical and geological information for the tsunami occurrence. However, they could not record the coral habitat-environmental changes caused by the earthquake event because they disintegrated while drifting ashore during a tsunami. Tsunami-related reef disturbance has reported by coral bleaching observations and reef monitoring (i.e., visual census), for example, after the 2004 Indian Ocean Tsunami (e.g., Chavanich et al., 2008; Kumaraguru et al., 2005; Foster et al., 2006; see also *Chapter 4*). Visual census survey is effective for assessing the coral cover and coral health; however, it is difficult to assess the coral calcification quantitatively. Besides, the quantitative earthquake signals on the coral skeleton (i.e., skeletal carbon isotope ratios geodesy: skeletal $\delta^{13}\text{C}$ geodesy) have been reported Gagan et al. (2015) and Ito et al. (2020a; see also *Chapter 4*). They showed a significant change in skeletal $\delta^{13}\text{C}$, which reflects the change in light availability due to coseismic seafloor displacement in the 2004 and 2005 Sumatra-Andaman and Nias-Simeulue earthquakes. Moreover, Ito et al. (2020a) described the earthquake and tsunami effect on skeletal growth (calcification). There are the opposite effects: the coseismic uplift event will lead to an increase in the coral light availability, while the tsunami event will lead to a decrease in the coral light availability due to the terrestrial input by the backwash and sediment resuspension. When both of the coseismic seafloor displacement and tsunami events occur simultaneously, it is difficult to isolate each event's effect on the skeletal $\delta^{13}\text{C}$ signal and the skeletal growth (calcification) response. Thus, verification and discussion with a new perspective are needed to detect the effects of only past tsunamis and to assess the coral skeletal response. Besides,

skeletal barium/calcium ratio (Ba/Ca) provides a long-term record of sediment load in seawater associated with precipitation (heavy rainfall events), river discharge (flood events or freshwater plume), coastal development, and coastal land use (e.g., Alibert et al., 2003; McCulloch et al., 2003; Prouty et al., 2010; Grove et al., 2012; Sowa et al., 2014; Saha et al., 2018; Ito et al., 2020b). Similar to these controlling factors, tsunami events also would lead to the amount of terrestrial input or resuspension of seafloor sediments. There is a possibility that massive corals (*Porites* sp.) may record the tsunami-generated sediment load in their skeleton (i.e., geochemical evidence); however, there has not been reported.

5.2 Study area

Shumichi (Shiomichi) Bay is located in the eastern Kikai Island, Kagoshima Prefecture, Japan (Fig. 5-2). The corals that inhabited in Shumichi Bay would not be affected by freshwater because there is no river in Kikai Island. Besides, in the 1911 Kikai earthquake, the coseismic deformation (uplift/subsidence, i.e., coseismic seafloor displacement) around Kikai Island has not been reported. Therefore, it could be able to discuss the impact of only the tsunami event on the corals.

5.3 Materials

Three *Porites* coral cores were drilled at Shumichi (inside a bay), Kikai Island, Kagoshima Prefecture, Japan in June 2015 (Fig. 5-2). One was a living (modern) *Porites* coral (a top slab of KISM150611 has published by Kajita et al., 2017), which the core top is 2 m depth, and the others were dead microatoll-shaped (fossil) *Porites* corals (KISM150612-1 and -2).

For the fossil coral specimens, the secondary-calcite contents on coral skeletons (along the geochemical analysis lines) were checked by X-ray diffraction and scanning electron microscope. As a result, the pristine aragonite was well preserved, as shown in Fig. 5-3.

5.4 Environmental data

In this study, I collected monthly SST time series from November 1981 to June 2015 at $1^{\circ} \times 1^{\circ}$ (28.5 N 129.5 E). It was derived from the Integrated Global Ocean Services System Products Bulletin (Reynolds et al., 2002; https://iridl.ldeo.columbia.edu/SOURCES/IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst/).

5.5 Age model

The age determination of each coral was based on the seasonal cycles in the skeletal Sr/Ca, monthly SST, annual density bands, and U/Th dating technique (see 3.1.4 *Age determination*). I 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. The age model before November 1981 was established using the tie points to connect the highest (lowest) Sr/Ca and March/August because the monthly SST dataset showed the warmest in August and the coolest in March, on average. The age model was cross-checked by comparing the results of U/Th dating (Fig. 5-4; Table 5-1).

5.6 Results and Discussions

U/Th dating and coral skeletal Sr/Ca record jointed three cores

The results of U/Th dating for each coral core were shown in Table 5-1. The ages of three samples were agreement with each other. Fig. 5-5 shows the skeletal Sr/Ca record of these coral cores. The record of three cores was from 1924 to 2015, from 1884 to 1926, and from 1796 to 1886 for KISM150611, KISM150612-1, and KISM150612-2, respectively. The skeletal Sr/Ca record revealed very clear annual cycles.

High temporal coral skeletal Sr/Ca and Ba/Ca records from 1907 to 1917

I measured skeletal Sr/Ca and Ba/Ca with high temporal resolution from 1907 to 1917 using KISM150612-1 (bi-weekly resolution; the analytical lines were shown in Fig. 5-6; see also 3.1.3 *Trace element analysis (Sr/Ca, Mg/Ca, and Ba/Ca)*) in order to reconstruct the 1911 Kikai tsunami event. As shown in Figs. 5-7 and 5-8, the high temporal skeletal Sr/Ca and Ba/Ca have a clear annual pattern. The skeletal Sr/Ca record showed the SST cycles (winter: low-SST, summer: high-SST; Fig. 5-7). The seasonal pattern of skeletal Ba/Ca showed high values in spring (March and April, Fig. 5-8). There is a significant relationship between the skeletal Sr/Ca and Ba/Ca (Fig. 5-9; $r = 0.24$, $p < 0.001$, $n = 206$). Previous studies have indicated the SST dependency in skeletal Ba/Ca (e.g., Lea et al., 1989; Gaetani et al., 2011); however, the result of the low correlation coefficient value ($r = 0.24$) suggested that Kikai coral Ba/Ca did not show the SST variation. Therefore, the SST component on the skeletal SST would be negligible in the Kikai coral. Besides, several previous studies have reported that the skeletal Ba/Ca record could be affected by nutrient-rich upwelling events (e.g., Lea et al., 1989; Shen et al., 1992; Tudhope et al., 1996). There has been no previous report that shows the evidence of the upwelling in the eastern Amami Islands, while, there is the Ryukyu Current System, which has a northeastward current in the southeast of the Ryukyu Islands (Yuan et al., 1998; Ichikawa et al., 2004; Thoppil et al., 2016). The seasonal cycle in the volume transport of the Ryukyu Current System across the Amami-Oshima Island showed the higher values from winter to spring (i.e., from November to April; Thoppil et al., 2016, data from 1993 to 2012). The Kikai corals might be affected by the Ryukyu Current System on the seasonal scale. This result is opposite to Kawakubo et al. (2017), which has explained that the upwelling effect on coral geochemical proxy collected in Kikai Island (near the Araki area, the southwest in the island) is negligible. The difference is probably caused by the sampling site. There is a possibility that the effect of the Ryukyu Current System is stronger in the eastern part in Kikai Island (our sampling site) than that in the southwest. Moreover, the seasonal effect of the Ba-containing sediments input into the bay associated with the freshwater/plume was negligible because there is no river in Kikai Island.

Coral geochemical signals of the 1911 Kikai earthquake and tsunami

The high temporal skeletal Ba/Ca record in 1911 showed a high peak during winter and summer (Fig. 5-7). The winter peak could be explained by the seasonal Ba uptake associated with the Ryukyu Current System, as described above. The summer peak did not agree with the seasonal pattern in the volume transport of the Ryukyu Current System (Thoppil et al., 2016). Because the SST effect and freshwater/plume were also negligible, there was another factor for the summer peak in 1911. Ito et al. (2020a, 2020b) and *Chapter 4* have mentioned a potential that coral skeletal geochemistry can detect a tsunami event. Murakami-Sugihara et al. (2019) also has indicated a high

Manganese/Calcium ratio (Mn/Ca) peak in the mussel shell skeleton due to a prolonged tsunami disturbance effect. Similar to these previous studies, the summer peak in 1911 in Kikai coral Ba/Ca indicates the signal of the 1911 Kikai earthquake and tsunami event occurred on 15th June. Tsunami event will cause the resuspension of bottom sediments and terrestrial input by the backwash. When the Ba-containing sediments flow into the ocean, the aqueous Ba/Ca or Ba concentration in the seawater will increase (Sinclair and McCulloh, 2004; Saha et al., 2016). The coral skeletal Ba/Ca reflects seawater Ba concentration ($Ba/Ca_{\text{coral}}/Ba/Ca_{\text{seawater}} \approx 1$; Saha et al., 2016), and the desorbed Ba^{2+} from the particulate matter is readily substituted for Ca^{2+} in the coral aragonite lattice in proportion to the aqueous Ba/Ca ratio (Lea et al., 1989; LaVigne et al., 2016; Saha et al., 2016). Therefore, the 1911 high peak of the Kikai coral Ba/Ca suggests that the aqueous Ba/Ca or Ba concentration in the seawater (Shumichi Bay) had increased due to the 1911 Kikai earthquake and tsunami event. Besides, the tsunami elevation and the damage for the 1911 Kikai earthquake and tsunami event has been estimated by previous reports (e.g., Imamura, 1913; Tsuji, 1997); however, there is no detail estimation on the eastern part in Kikai Island. The tsunami impact on reef environments is also unknown. The skeletal Ba/Ca record shows an increase with approximately 2 months after the 1911 Kikai earthquake and tsunami event, and it recorded the high peak (6.89 $\mu\text{mol/mol}$) in August 1911 (Fig. 5-7). Therefore, there is a possibility that the tsunami effect (i.e., terrestrial input by the backwash and sediment resuspension) on the Shumichi Bay had continued for approximately 2 months after the 1911 Kikai earthquake and tsunami event. The tsunami events could temporarily cause low water visibility due to the resuspension of the seafloor sediments and coastal runoff. Corals are sensitive to the impacts of sediments and turbidity (Erftemeijer et al., 2012). Huge tsunami waves associated with megathrust earthquakes wreak devastating damage on shallow marine ecosystems, especially coral reefs (Campbell et al., 2007; Bahuguna et al., 2008). Thus, approximately 2 months of tsunami effect may cause negative damage to the reef environments and ecosystems.

Impact of the 1911 Kikai tsunami event on coral growth and calcification

As described in *Chapter 1*, coral skeletal growth and calcification pattern mainly associates with the gradients of temperature (Weber and White, 1974; 1977; Grigg, 1981; Scoffin et al., 1992; Lough and Barnes, 2000; Lough, 2008; Goodkin et al., 2011). In the Kikai coral from 1907 to 1917, there is no significant relationship among the annual extension rate, the annual calcification rate, and the annual mean value of skeletal Sr/Ca (Fig. 5-10). It suggests that the annual extension rate and calcification rate did not show the similar gradients (pattern) of SST. Therefore, the skeletal growth and calcification pattern of the Kikai coral would not be affected by SST.

There have been many previous reports on the impacts of reef disturbance on the coral growth and calcification (see *Chapter 1*, 1.2.4 *Skeletal growth parameters and the responses on skeletal calcification*). For the earthquake-related reef disturbance, Ito et al. (2020a) has described the skeletal growth response associated with the 2004 Indian Ocean tsunami, for example, a remarkable decrease in the annual extension/calcification rate. The time series of annual extension rate and annual calcification rate of the Kikai coral from 1907 to 1917 showed the minimum value in 1911 (Fig. 5-11). Skeletal calcification is controlled by the activity of Ca^{2+} -ATPase (Kingsley and Watabe, 1985; McConnaughey, 1998), which is enhanced by light availability (i.e., inhabitation of light-enhanced calcification, Barnes and Chalker, 1990). It is well-known that sediments (i.e., high water turbidity) caused by terrestrial runoff will lead to disturbances in coral growth and calcification (e.g., Hudson, 1981; Hudson

and Robbin, 1981; Dodge and Lang, 1983; Crabbe and Smith, 2005). Thus, the decrease of the annual calcification rate in 1911 could be the coral response to the 1911 Kikai earthquake and tsunami event. This result agrees with Ito et al. (2020a). There was a high peak in skeletal Ba/Ca (sediments proxy) for approximately 2 months (Fig. 5-7); however, the influence on the coral calcification would continue longer than be expected (> 2 months). Besides, coral light availability is also affected by insolation or cloudiness. There may also be the possibility of the insolation or cloudiness effect on the decadal scale. Because there was no river in Kikai Island, the freshwater plume effect (i.e., precipitation and salinity variation) on the decadal-scale was negligible.

Moreover, hiatuses in coral growth and unusual banding patterns such as anomalous high- or low-density bands (i.e., stress bands) would be caused by thermal stress (e.g., Mendes and Woodley, 2002; Lough and Cooper, 2011) or temporary sediment stress (e.g., Ito et al., 2020a). Besides, irregularly green color bands (i.e., stress bands) were also observed on the coral skeletal slabs under habitat environmental stress, for example, a bleaching event, terrestrial runoff, algae bloom (e.g., Fine and Loya, 2002; Carilli et al., 2010; Ito et al., 2020a). However, the Kikai coral skeleton showed neither stress band (Fig. 5-5) nor a green band. This result was not agreement with Ito et al. (2020a). The difference may be caused by the tsunami elevation or the damage scale between the 2004 Indian Ocean tsunami and the 1911 Kikai tsunami. It also indicates that there has not been temporary and strong stress and algae bloom due to the 1911 earthquake and tsunami event.

5.7 Conclusion

Three Kikai coral cores have the time series from 1796 to 2015. Both of the high temporal skeletal Sr/Ca and Ba/Ca records from 1907 to 1917 showed annual cycles. Skeletal Sr/Ca would reflect seasonal SST cycles. Skeletal Ba/Ca has the high peaks during winter, which would be affected by the Ryukyu Current System on the seasonal scale. The 1911 Kikai tsunami signal was observed in the skeletal Ba/Ca as a high peak during summer in 1911. It indicates that the aqueous Ba/Ca or Ba concentration in the seawater (Shumichi Bay) had increased for approximately 2 months after the 1911 Kikai earthquake and tsunami event. In general, increasing sediment load in the seawater could temporarily cause low water visibility (i.e., high turbidity), and the sediment-related disturbance will have a negative impact on shallow marine ecosystems, especially coral reefs. The approximately 2 months of the 1911 tsunami effect may cause negative damage to the reef environments and ecosystems in Shumichi (Shiomichi) Bay. Moreover, the coral skeletal response to the 1911 tsunami was shown as a decrease in the annual skeletal calcification. Decreased coral calcification causes a reduction or cessation of reef growth and may trigger a reduction in biodiversity on reefs (Brown and Howard, 1985; Rogers, 1990; Fabricius, 2005). Thus, the 1911 tsunami would be a damage to the coral calcification, and it probably influences the biodiversity in the reefs.

The skeletal Ba/Ca is a useful proxy for natural/anthropogenic sediment load in coral reefs (e.g., McCulloch et al., 2003; Grove et al., 2012; Sowa et al., 2014; Ito et al., 2020b). This study showed a new possibility of the skeletal Ba/Ca as a past-tsunami proxy. The tsunami signal detection using skeletal Ba/Ca combined with skeletal growth analysis will also provide us an essential key for understanding the coral response to the tsunami-generated reef disturbance. Moreover, the skeletal Ba/Ca-tsunami proxy will be useful to detect the unknown past-tsunami event. While, as mentioned in *Chapter 6* and *Chapter 7*, there are still unknown aspects of the skeletal Ba/Ca. The tsunami signal of the Kikai coral was not affected by freshwater plume, SST fluctuation,

and Ryukyu Current System (i.e., upwelling-like Ba uptake). Because these controlling factors might mask the tsunami signals in the skeletal Ba/Ca, it is necessary for isolating the effects to apply the skeletal Ba/Ca tsunami proxy to detecting the other past-tsunami event in the wide region.

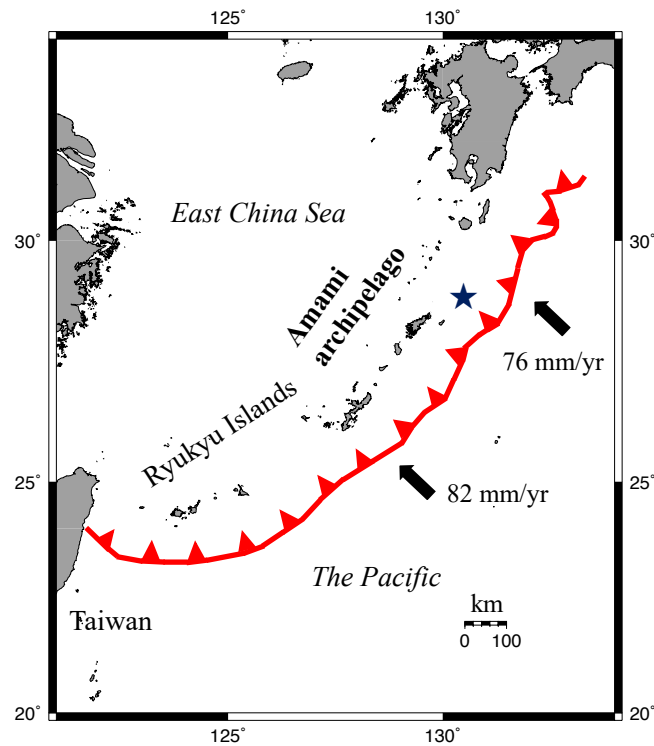


Fig. 5-1 Regional map and the hypocenter of the 1911 Kikai earthquake

The red line shows the Ryukyu Trench (Nishimura, 2014, modified) which located along the southeastern edge of Japan's Ryukyu Islands between northeastern Taiwan and southern Japan. The star shows the hypocenter of the 1911 Kikai earthquake (28.7 E, 130.6 N; M_w 8.1), which was reported by Goto (2013). The map figures (Japan, Amami-Oshima Island, and Kikai Island) were generated using Generic Mapping Tools (GMT v. 5.3.3, Wessel et al., 2013).



Fig. 5-2 Sampling site

Three coral cores (KISM150611, KISM150612-1, and KISM150612-2) were collected at Shumichi (Shiomichi) Bay, eastern Kikai Island. These coral colonies were located side by side. The figure was obtained by Google Maps (<https://www.google.co.jp/maps/>). Imagery Google ©2020.

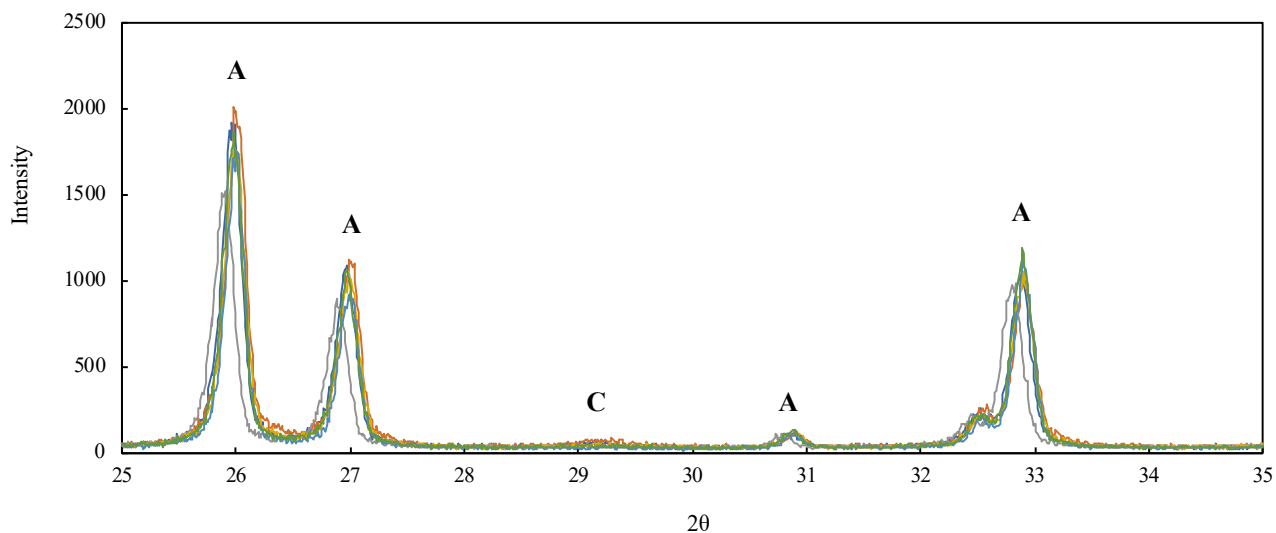


Fig. 5-3 XRD diagenesis screening (all analysis line of KISM150612-1 and -2)

The notes *A* shows the aragonite peak, and *C* shows the calcite peak. When the samples contain the aragonite (or calcite), the peaks would be shown. The pristine aragonite was well preserved in all analysis line.

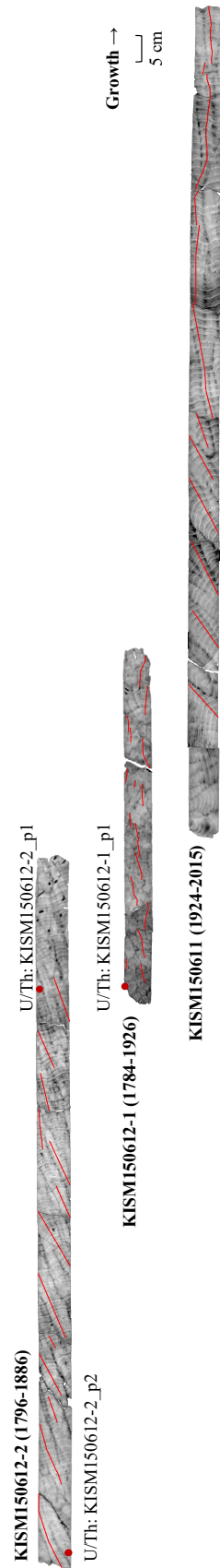


Fig. 5-4 X-radiographs (posi) and the position of measured U/Th dating

The red lines show the analytical lines. The red circles show the positions of measured U/Th dating.

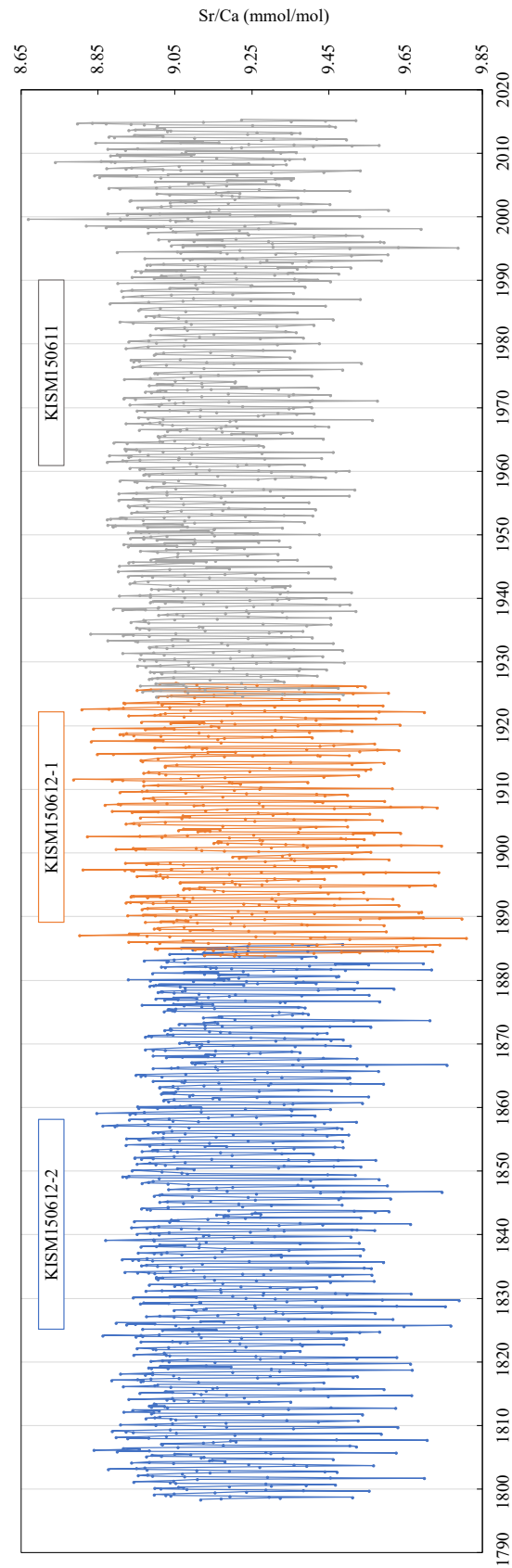


Fig. 5-5 Skeletal Sr/Ca record jointed three cores

The age models of three cores were connected by overlapped measurement.

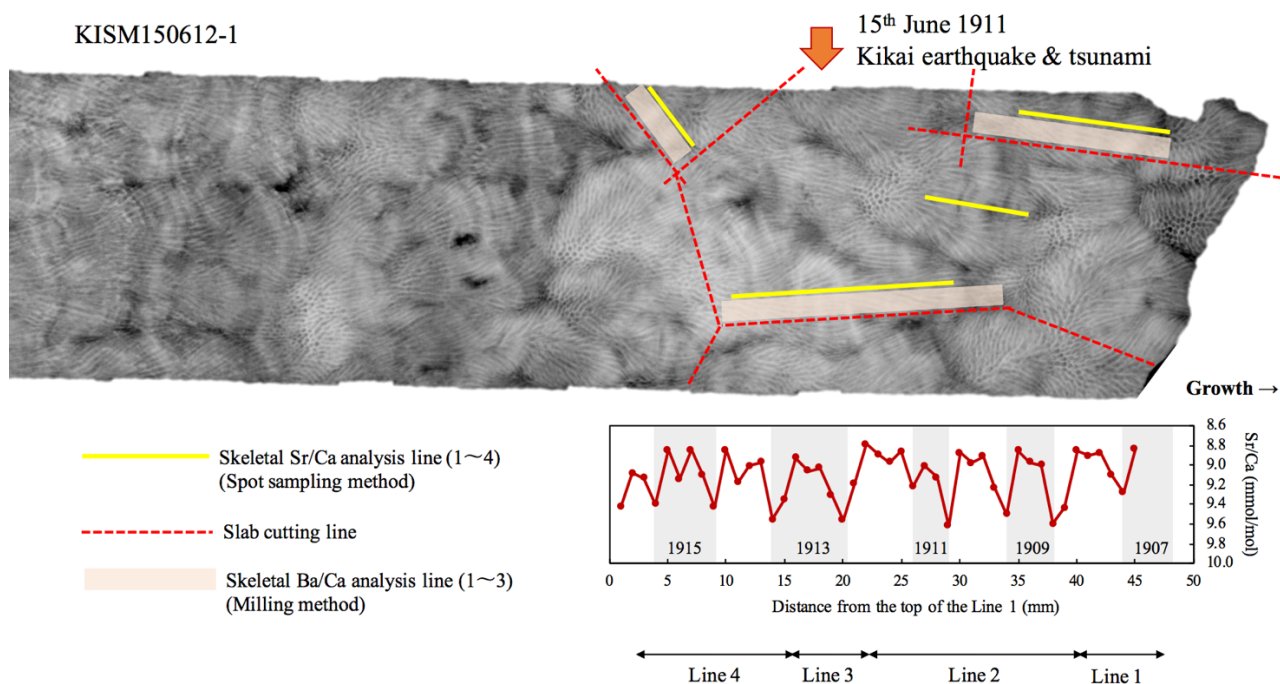


Fig. 5-6 Analysis lines of skeletal Ba/Ca with high temporal resolution

The X-radiograph is positive. The four yellow lines show skeletal Sr/Ca analysis line (low temporal resolution), and the record is shown right bottom in the figure. The red and dashed lines show the slab cutting lines. The red-hatched lines skeletal Ba/Ca analysis line (high temporal resolution). The orange arrow shows the timing of the 1911 Kikai earthquake and tsunami event which was estimated by the result of the skeletal Sr/Ca record.

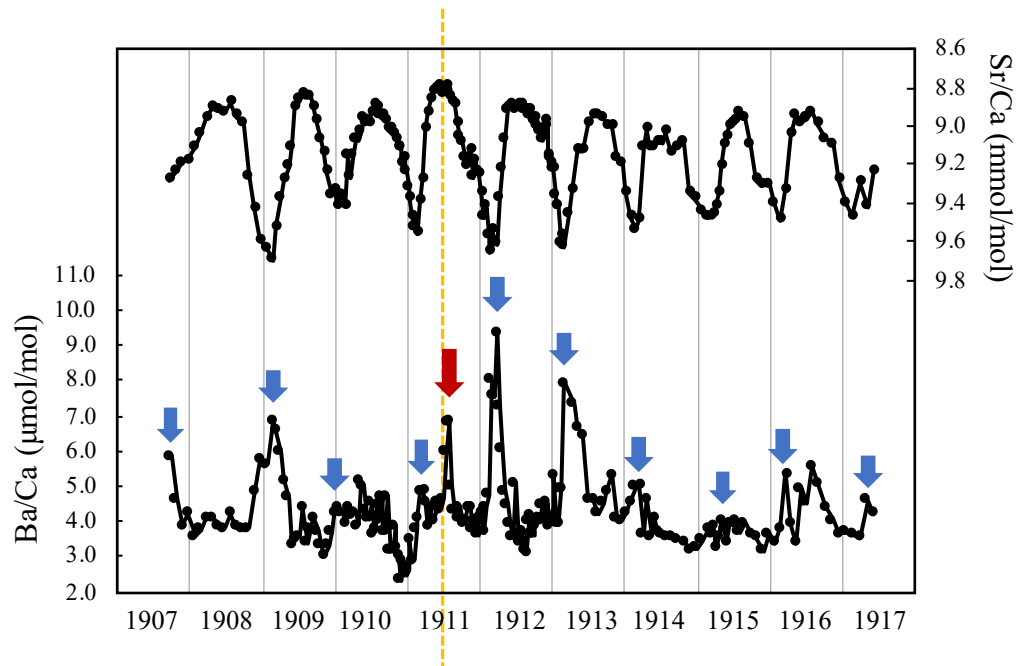


Fig. 5-7 Time series of high temporal skeletal Sr/Ca and Ba/Ca from 1907 to 1917

The yellow dashed line on the age shows the timing of the 1911 Kikai earthquake and tsunami event. The blue arrows show the winter peaks. The red arrow shows the tsunami signal.

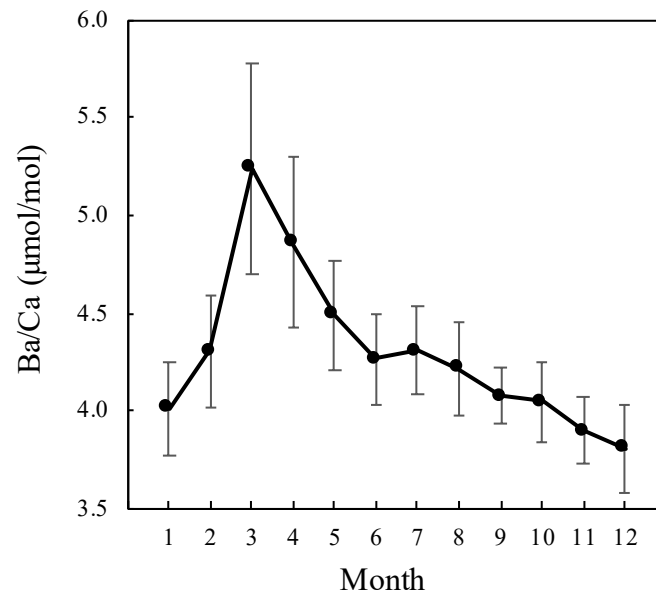


Fig. 5-8 Seasonal variation of high temporal skeletal Ba/Ca

The error bars show the standard error.

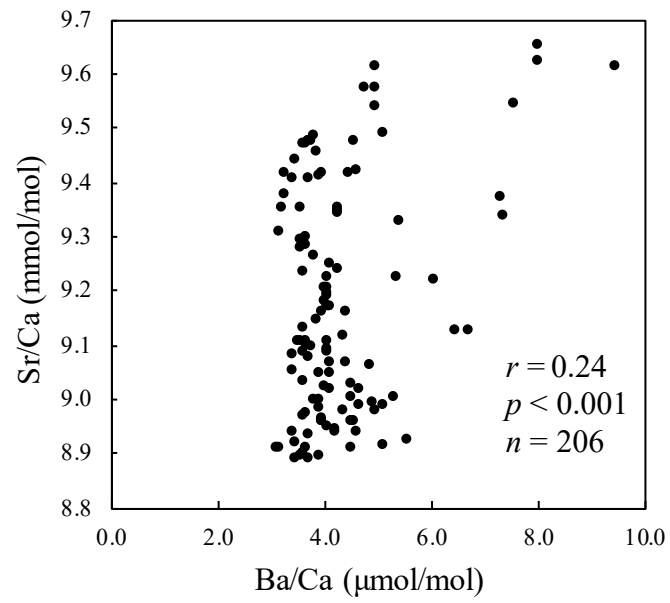


Fig. 5-9 Correlation between the high temporal skeletal Sr/Ca and Ba/Ca from 1907 to 1917

The raw time series of the skeletal Sr/Ca and Ba/Ca were shown in Fig. 5-7.

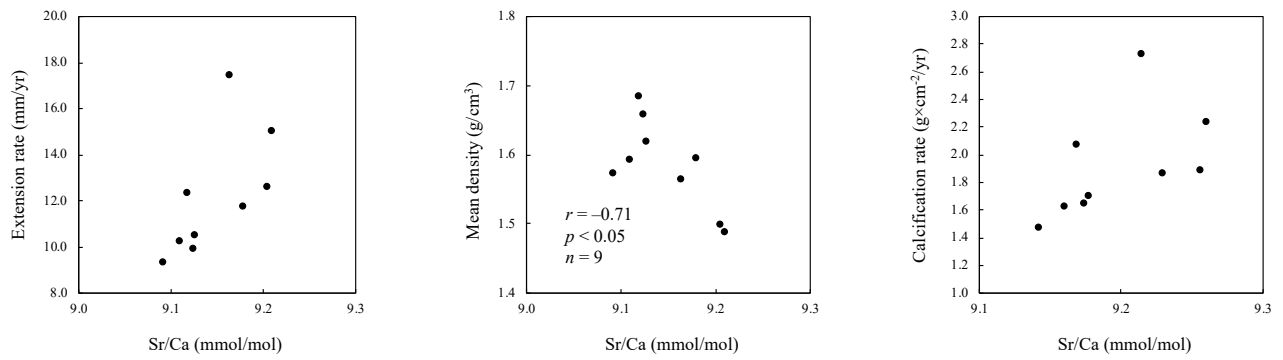


Fig. 5-10 Correlation between the skeletal growth parameters and annual mean of skeletal Sr/Ca

All of the skeletal parameters (extension rate, mean density, and calcification rate) were shown as the annual values. Skeletal Sr/Ca was shown as the annual mean value.

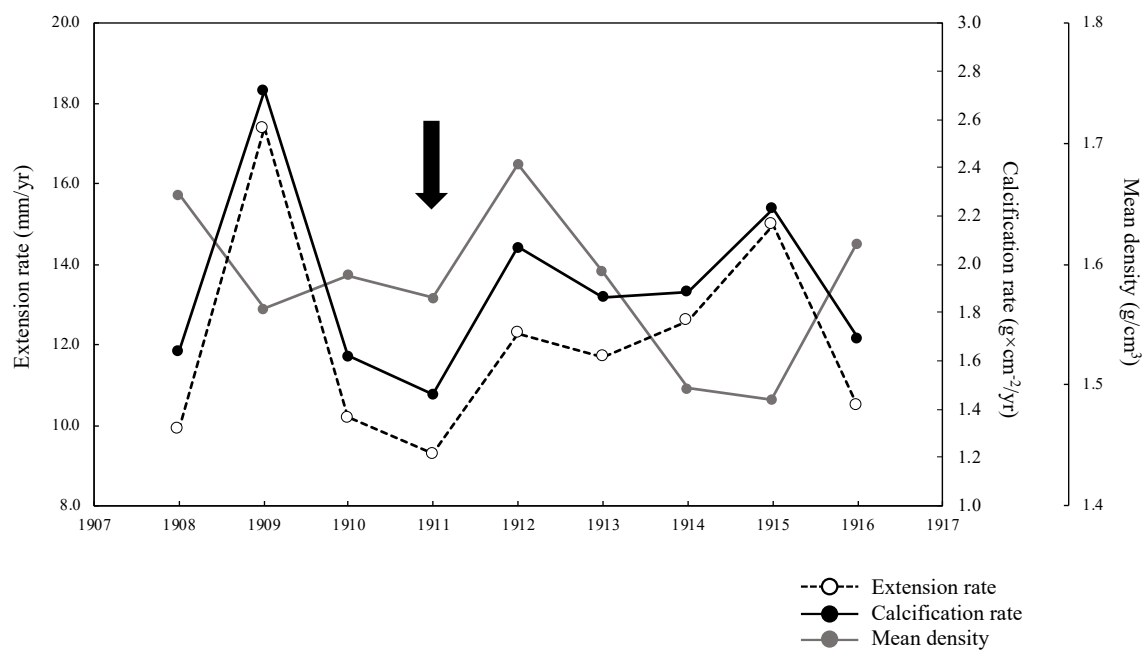


Fig. 5-11 Time series of the growth parameters

The opened circles with a dashed line indicate the annual extension rate (mm/yr); closed circles with solid lines indicate the annual calcification rate ($\text{g} \times \text{cm}^{-2}/\text{yr}$); 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 1911 Kikai earthquake and tsunami.

Sample ID	Weight g	²³⁸ U ppb ^a	²³² Th ppt	d ²³⁴ U measured ^a	[²³⁰ Th/ ²³⁸ U] activity ^b	[²³⁰ Th/ ²³² Th] ppm ^c	Age (yr ago) uncorrected	Age (yr ago) corrected ^{b,d}	Age (yr BP) relative to 1950 AD	d ²³⁴ U _{initial} corrected ^e	Age (common era)
KISM150612-1_p1	0.20635	3044.1 ± 4.15	274 ± 2	146.1 ± 1.6	0.0014 ± 0.00001	258 ± 3.01	134 ± 1	132 ± 1.52	66 ± 1.5	146 ± 1.6	1884 ± 1.5
KISM150612-2_p1	0.17400	2600.4 ± 2.73	397 ± 3	147.3 ± 1.6	0.00145 ± 0.00002	156 ± 2.24	138 ± 2	134 ± 2.48	67 ± 2.5	147.3 ± 1.6	1883 ± 2.5
KISM150612-2_p2	0.41340	2744.6 ± 2.49	320 ± 1	145.1 ± 1.5	0.00234 ± 0.00002	330 ± 3.46	223 ± 2	220 ± 2.59	153 ± 2.6	145.2 ± 1.5	1797 ± 2.6

^a $[^{238}\text{U}] = [^{235}\text{U}] \times 137.818 (\pm 0.65 \%)$ (Hess et al., 2012); $\delta^{234}\text{U} = ([^{234}\text{U}/^{238}\text{U}]_{\text{activity}} - 1) \times 1000$.

^b $[^{230}\text{Th}/^{238}\text{U}]_{\text{activity}} = 1 - e^{-\lambda^{230}T} + (\delta^{234}\text{U}_{\text{measured}}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda_{230} - \lambda_{234})T})$, where T is the age.

Decay constants are $9.1705 \times 10^6 \text{ yr}^{-1}$ for ²³⁰Th, $2.8221 \times 10^6 \text{ yr}^{-1}$ for ²³⁴U (Cheng et al., 2013), and $1.55125 \times 10^{10} \text{ yr}^{-1}$ for ²³⁸U (Jaffey et al., 1971).

^c The degree of detrital ²³⁰Th contamination is indicated by the [²³⁰Th/²³²Th] atomic ratio instead of the activity ratio.

^d Age corrections for samples were calculated using an estimated atomic ²³⁰Th/²³²Th ratio of 4 ± 2 ppm.

^e $\delta^{234}\text{U}_{\text{initial}}$ corrected was calculated based on ²³⁰Th age (T), i.e., $\delta^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{(\lambda^{234}T)}$, and T is corrected age.

Those are the values for a material at secular equilibrium, with the crustal ²³²Th/²³⁸U value of 3.8. The errors are arbitrarily assumed to be 50 %.

Table 5-1 Results of U/Th dating

Measurement was performed in March 2016 and July 2017 (Shen et al., 2008), and instrumental analysis on MC-ICP-MS (Shen et al., 2012). Analytical errors are 2σ of the mean.

6. Study Case-3 (Natural and anthropogenic disturbance): Impact of heavy rainfall and river flood event, and local industrial changes on reef coral calcification in Amami-Oshima Island

6.1 Introduction

Healthy coral reefs supply a wide range of benefits to local communities around the world; however, approximately 75 % of the world's coral reefs are rated as threatened when local threats are combined with thermal stress (Burke et al., 2011; Hughes et al., 2018b). Coral reefs will expand their habitats to higher latitudes corresponding to global warming (Yamano et al., 2011). Annual mean precipitation in the high latitudes and the equatorial Pacific are likely to increase, and extreme precipitation events will very likely become more intense and more frequent, which would exacerbate sediment runoff to the coral reefs (Burke et al., 2011; Pachauri, 2014). Besides, the intensity of human activities is expected to increase, leading to sediment and nutrient runoff, which can affect reef corals and reef communities (Burke et al., 2011; Maina et al., 2013; Burt and Bartholomew, 2019). Reef disturbances, especially natural forcing (e.g., river runoff, earthquake, and tsunami) and industrial-related sediment input, have a negative impact on shallow reef ecosystems. Corals are sensitive to the impacts of sediments and turbidity (Erftemeijer et al., 2012). Decreased coral calcification causes a reduction or cessation of reef growth and may trigger a reduction in biodiversity on reefs (Brown and Howard, 1985; Rogers, 1990; Fabricius, 2005).

Amami archipelago (Fig. 6-1) is located at the boundary between tropical and temperate regions. The total length of the reef edge was 420.3 km, and the total area of coral communities in the reef ponds was 5951.2 ha. Approximately 220 species of hermatypic corals (hereafter, corals) have been identified in the Amami sea area (Nishihira and Veron 1995). Well-developed communities dominated by *Acropora* sp. were found throughout the islands until the 1998 mass-bleaching event, after which the dominant corals of the lagoon and reef crest communities shifted to *Porites* sp. and *Favia* sp. (The Japanese Coral Reef Society and Ministry of the Environment, 2004). Amami-Oshima Island is the largest island (712.35 km²) in the Amami archipelago, and the coastal areas are designated as Amami Gunto National Park. Amami-Oshima Island has been developing rapidly since the 1950s, based on the promotion by the national and local governments. Besides, in Amami-Oshima Island, many localized heavy rainfalls, typhoon events repeatedly occurred in the last 50 years. These localized heavy rainfall events triggered the river flooding events, which caused a large amount of sediment and freshwater input into the coral reefs. Reef assessments based on coral bleaching observations and reef cover monitoring (visual census) has been conducted by the prefectural government and local authorities. However, it is not enough to assess the effects of the reef disturbance and coral calcification responses precisely because *in situ* data on the ocean, rivers, and estuaries (e.g., water quality, river discharge, and water temperature) are limited. Moreover, temporal and qualitative methods cannot precisely demonstrate long-term changes in sediment load. There is no report directly comparing coral calcification with local industrial histories with multidecadal time series.

6.2 Study area

Sumiyo Bay is located in the eastern part of Amami-Oshima Island, Kagoshima Prefecture, Japan (Fig. 6-2). The Sumiyo River (a 15.5 km flow path length and a 48.5 km² basin area) and Yakugachi River (a 15.1 km flow

path length and a 47.8 km² basin area) run to Sumiyo Bay, and a mangrove forest covers the estuary. These rivers have recently caused river flooding four times (June 1977, September 1990, August 1991, and October 2010) over the past 46 years. *In situ* data on rivers, estuaries, and bay (e.g., water quality, turbidity, salinity, river discharge, and water temperature) has not been monitored despite such a situation.

6.3 Materials

A living *Porites* coral core (AMI141001) was drilled at a depth of 5.1 m inside Sumiyo Bay, Amami-Oshima Island, Kagoshima Prefecture, Japan in October 2014. Geologically, this area consists of sandstone, mudstone, and shale. The distance between the mouths of the two rivers and the coral sampling site was 4.5 km, and the distance from the nearest shore was 80 m. The *Porites* coral specimen showed 46 clear annual density bands (Fig. 6-3).

The 14 water samples were collected in Sumiyo town (Fig. 6-2). Two of them were collected from the coral core drilling site (inside Sumiyo Bay) in October 2014. The other samples were collected from Sumiyo River, Yakugachi River, the mangrove forest, and Sumiyo Bay in July 2017.

6.4 Environmental data and local archived data

In this study, I collected the monthly SST time series, monthly precipitation. The monthly IGOSS-SST time series from January 1981 to October 2014 at 1° × 1° (28.5 N 129.5 E) was derived from the Integrated Global Ocean Services System Products Bulletin (Reynolds et al., 2002; https://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst/). Precipitation data were derived from the Japan Meteorological Agency with a monthly resolution (at Naze city, 28.380 N 129.496 E, from January 1968 to January 1998 and from December 1998 to December 1999) and Kagoshima Prefecture with a 10-minute resolution (at Sumiyo, 28.266 N 129.408 E, from February 1998 to November 1998 and from June 2000 to October 2014). The 10-minute time series were converted to a monthly resolution. In addition, monthly tide gauge data were derived from Permanent Service of Mean Sea Level (<https://www.psmsl.org/>) at the NASE station from 1968 to 2014.

Archived data on changes in land use and local industries, typhoon, heavy rainfall, landslide, and river flooding diseases in the past 46 years were based on literature surveys using “*Wakya shima nu ayumi*” (A history of Sumiyo, published in 2005, in Japanese), “*Amami Gunto no gaikyo*” (The overview of Amami Islands, an annual publication by Oshima Subprefecture in Kagoshima, Japan, in Japanese), national census data derived from Statistics Bureau of Japan (<https://www.e-stat.go.jp/>). Archived data on the 2010 heavy rainfall (river flooding) disaster was based on an official report published by Amami City and an academic research report published by Research and Education Center for Natural Hazards, Kagoshima University. Interviews in Sumiyo town and local newspapers (*The Amami Shimbun* and *The Nankai Nichi-nichi Shimbun*) also provide us the supporting data. Data on the production of *Oshima Tsumugi* were provided by Oshima Subprefecture, in Kagoshima Prefecture. The information of the Sumiyo River and Yakugachi River (path length and basin area) was derived by the fundamental river management policy and river improvement plans established by Kagoshima Prefecture.

6.5 Age model

The age determination of each coral was based on the relationship between skeletal Sr/Ca and monthly SST. I used tie points to connect the values of skeletal Sr/Ca and SST record to establish each year, as follows; highest Sr/Ca and coolest SST (i.e., winter tied point) and lowest Sr/Ca and warmest SST (i.e., summer tied point). Time series were inserted by assuming constant growth rates during each of the tied points. The seasonal variation of SST dataset from November 1981 to October 2014 indicates that February had the lowest SST and August had the highest SST. Therefore, the age model prior to November 1981 was also established using the tie points to connect the highest/lowest Sr/Ca and February/August.

6.6. Statistical analysis

The skeletal Ba/Ca record was filtered with a Gaussian bandpass filter (frequency = 0; bandwidth = 0.00137, i.e., isolating > 2 years or < 2 years trend) using Analyseries 2.0.8 (Paillard et al., 1996). The profiles of raw data and low-pass filtered data (i.e., isolating > 2 years trend) are shown in Fig. 6-4-f. The detrended data (i.e., isolating < 2 years trend; notch filtered data) are shown in Fig. 6-5-c. The core-top data that showed anomalously high values (i.e., tissue layer, 4.1 mm = 5.1 months) were excluded from the filtering analysis.

Moreover, the time series of the low-pass filtered skeletal Ba/Ca was divided into two periods using SiZer (SIGNificant ZERO crossings of derivatives) method (Chaudhuri and Marron, 1999). The analysis was performed using the statistical software R (v. 3.3.3; R Core Team, 2018) with Significant Zero Crossings for R package (v. 0.1-4; Sonderegger, 2012). The package was obtained from <https://CRAN.R-project.org/package=SiZer>. As a result, there is a significant trend shift point in 1995 ~ 1996 (Fig. 6-6). I divided the time series of the low-pass filtered skeletal Ba/Ca using the shift point (A-period: 1968 ~ 1995, B-period: 1996 ~ 2014). Because the increase and decrease trends were overlapped from 1975 to 1978 in a broad range of the filter width, we did not divide the time series of the low-pass filtered skeletal Ba/Ca. The high-peaks in the low-pass filtered skeletal Ba/Ca were determined the difference between the mean value of mean seasonal cycles (MSC) and the detrended data. When the peak points succeeded one another, the highest point was determined as a representative point (i.e., high-peak).

6.7 Results and Discussions

Ba/Ca profiles in the *Porites* coral and Ba concentration in river-waters and seawaters

The *Porites* coral specimen showed 46 clear annual density bands (Fig. 6-3). I analyzed skeletal Sr/Ca and skeletal Ba/Ca records for 46 years from 1968 to 2014 (Figs. 6-4-a and 6-4-f). The 46-year skeletal Ba/Ca record derived from the Sumiyo coral showed multidecadal fluctuations, which seemed to be larger than seasonal variability. Multidecadal fluctuation in the skeletal Ba/Ca record was isolated by Gaussian bandpass filter (i.e., low-pass filtered skeletal Ba/Ca; Fig. 6-5-b, see 6.6. *Statistical analysis*). The detrended skeletal Ba/Ca showed spike-like patterns (Fig. 6-5-c).

The coral skeletal Ba/Ca reflects seawater Ba concentration ($Ba/Ca_{\text{coral}}/Ba/Ca_{\text{seawater}} \cong 1$; Saha et al., 2016). Our data on the Ba concentration in seawater ranged from 32.1 to 45.1 nmol/kg (Fig. 6-7). The mean value of measured Ba concentration in seawater (39.0 nmol/kg) mostly agreed with the variable range of the coral-derived Ba

concentration in seawater in Sumiyo Bay (Fig. 6-8), and it was slightly higher than the reported values in previous studies (Table 6-1). There was a strong negative correlation between the Ba concentration in the water samples and the *in situ* salinity in the Sumiyo region (Fig. 6-7, $r = -0.89$; $p < .0001$; $n = 14$). Ba is released/desorbed from particulate matter by ion exchange with seawater Mg^{2+} and Ca^{2+} ions in a low-salinity estuary (Coffey et al., 1997; Hanor et al., 1977). The Ba concentration in seawater in Sumiyo Bay is controlled by the amount of the desorbed Ba^{2+} (in the estuary) from the Ba-containing sediment, which is transported from the two rivers through the mangrove forests with tides and precipitation effects. The primary source of Ba in the estuary is suspended fluvial sediment particles, which are transported by rivers towards the ocean with freshwater/flood plumes (Coffey et al., 1997; Hanor et al., 1977; Sinclair and McCulloch, 2004). The river flood event would lead to an increase in the river end-member Ba concentration (Sinclair and McCulloch, 2004). The desorbed Ba^{2+} from the particulate matter is readily substituted for Ca^{2+} in the coral aragonite lattice in proportion to the aqueous Ba/Ca ratio (Lea et al., 1989; LaVigne et al., 2016; Saha et al., 2016).

Multidecadal fluctuation in skeletal Ba/Ca

The trend of the low-pass filtered skeletal Ba/Ca was analyzed by SiZer trend analysis (Chaudhuri and Marron, 1999; see 6.6. *Statistical analysis*). A trend shift point in 1995 ~ 1996 was found, which is the significant increase trend changed into the significant decrease trend in < 25 years of filter width (Fig. 6-6). Thus, we divided the time series into two periods in this study: 1986 ~ 1995 (A-period) and 1996 ~ 2014 (B-period). Ba/Ca in corals might be controlled by following scenarios: (1) SST components of Ba/Ca (e.g., Lea et al., 1989; Gaetani et al., 2011), (2) Ba uptake in sea surface due to upwelling (e.g., Lea et al., 1989; Shen et al., 1992; Tudhope et al., 1996) and (3) Ba-containing sediments transported from river (i.e., freshwater/flood plumes, e.g., McCulloch et al., 2003; Alibert et al., 2003; Prouty et al., 2010; Grove et al., 2012; Sowa et al., 2014). The scenarios of (1) and (2) were denied by the reasons as follows;

In general, upwelling events will lead to cold and eutrophic seawater from deep-sea due to the vertical water mixing. Vertical distributions of Ba in seawater are similar to those of nutrients. In the surrounding area of our study site (eastern part of Amami-Oshima Island; 28.23 N 129.45 E), the upwelling is only known on the shelf off northeast Taiwan (25.68 N, 122.18 E, Chen et al., 2015). There has been no previous report that shows the evidence of the upwelling in the eastern Amami Islands and the upwelling effect on coral geochemical proxy collected in the Amami Islands (Kawakubo et al., 2017). Besides, there is the Ryukyu Current System, which has a northeastward current southeast of the Ryukyu Islands (Yuan et al., 1998; Ichikawa et al., 2004; Thoppil et al., 2016). According to Thoppil et al. (2016), the Ryukyu Current System in the southeast of Amami-Oshima Island (27-28.5 N, 129.5-131.5 E) shows the significant strong patterns in 1998, 1999, and 2011. IGOSS-SST time series and skeletal Sr/Ca and Mg/Ca record (SST proxy, Fig. 6-4-a) did not show the anomalous low-SST. There was no significant relationship between the low-pass filtered skeletal Ba/Ca and the low-pass filtered skeletal Sr/Ca (Fig. 6-9-a, $r = -0.17$; $p = 0.26$; $n = 47$). It suggested that the skeletal Ba/Ca did not show similar variations with SST. Therefore, the skeletal Ba/Ca has not been affected by SST on the multidecadal scale. The Ryukyu Current System is weaker, deeper, and relatively unstable than the Kuroshio Current (Thoppil et al., 2016). Therefore, the influence of the Ryukyu Current System to the coral proxies collected from Sumiyo Bay would be negligible. Moreover, a publishing data of seawater salinity

variation showed a declining pattern with water depth, measured at 28 N 135.9 E (the nearest station of this study area, Horibe and Ogura, 1968). The correlation coefficient value (r) between the low-pass filtered skeletal Ba/Ca and coral derived $\delta^{18}\text{O}_{\text{seawater}}$ was low (Fig. 6-9-b, $r = 0.29$; $p < 0.05$; $n = 47$). Thus, I concluded that the upwelling effect in our skeletal Ba/Ca record would be very small.

Thus, there was the other control factor of the annual mean of low-pass filtered skeletal Ba/Ca in Sumiyo Bay, for example, natural/anthropogenic sediment load.

Response of skeletal Ba/Ca to anthropogenic sediment load in Sumiyo Bay

Ba/Ca in corals reflects anthropogenic sediment load in the coastal area (e.g., land-use, coastal development: McCulloh et al., 2003; Prouty et al., 2010; Sowa et al., 2014). The industrial development around Sumiyo Bay in the past 46 years (see 6.4 *Environmental data and local archived data*) can also be divided into two periods (A-period and B-period, Fig. 6-5-a), and it was agreed with the significant trends shift in the low-pass filtered skeletal Ba/Ca. In the A-period, from the 1960s to 1995, the production of “*Oshima tsumugi*” and forestry prospered. *Oshima tsumugi* is a traditional silk fabric on Amami-Oshima Island. It is made by “mud dyeing” with plant-derived tannic acid pigments and iron oxide contained in mud fields. In the A-period, there were many mud fields for dyeing along rivers, and the process of mud washing-off was carried out in the rivers. Forestry in the A-period produced a substantial amount of pulp and chips (a timber factory in Sumiyo village closed in 1995). In the B-period, from 1996 to the present, the quarry and the construction industries (e.g., public works such as construction and maintenance work on roads, rivers, and the bay) prospered. In addition, the farming (e.g., citrus cultivation) also prospered during both periods. These local industries might have influenced the reef environment in Sumiyo Bay. It is necessary to compare the local archives on the change in the thriving industries with coral calcification responses to understand the anthropogenic reef disturbance.

The low-pass filtered skeletal Ba/Ca record and the annual production of *Oshima tsumugi* showed similar patterns (Fig. 6-5-b, see also 6.4 *Environmental data and local archived data*). There was a significant positive relationship between the low-pass filtered skeletal Ba/Ca and the production volume of *Oshima tsumugi* (Fig. 6-10, $r = 0.86$; $p < .0001$; $n = 26$). This result suggests that the multidecadal fluctuation in the skeletal Ba/Ca in the A-period reflected the mud or sediment load in Sumiyo Bay due to “mud dyeing” (including the silk thread dyeing at the muddy fields, the mud washing-off process carried out in the rivers, and then the mud was transported to the ocean by the rivers). In addition, deforestation in the A-period also could have affected the low-pass filtered skeletal Ba/Ca. In the A-period, the sediment or mud may have constantly been flowing out into Sumiyo Bay due to forestry and *Oshima tsumugi* production. On the other hand, in the B-period, the low-pass filtered skeletal Ba/Ca had an upward pattern (Fig. 6-5-b). The multidecadal fluctuation in the skeletal Ba/Ca in the B-period might have reflected an increase in sediment load due to rapid industrial development. In the B-period, a large amount of sediment flowed into Sumiyo Bay, which would be caused by the construction industry and quarries. In addition, the quarry collapse events (October 2011; November 2011; March 2014) would cause sediment input sporadically into Sumiyo Bay (Fig. 6-5-e).

Detrended skeletal Ba/Ca

The detrended skeletal Ba/Ca record was characterized by spike-like patterns (i.e., high-peaks). Skeletal Ba/Ca high-peaks were recorded 43 times in the A-period and 33 times in the B-period (Fig. 6-5-c). For the river flooding disasters associated with typhoons or heavy rainfall events (see 6.4 *Environmental data and local archived data*), the skeletal Ba/Ca high-peaks were recorded in September 1977 (with a 3-month time lag from the event), September 1990 (without a time lag), October 1991 (with a 2-month time lag), and February 2011 (with a 4-month time lag). The high-peak values in response to these events in the B-period were larger than those in the A-period (Figs. 6-5-d and 6-5-e). It is possible that the response of the coral skeleton to these events has changed due to local industrial development, throughout the two periods.

There are two possible reasons for the time lag of several months that occurred between the river flooding events associated with heavy rainfall events and the peaks of the skeletal Ba/Ca: (1) a delay in the desorption of Ba^{2+} in the mangroves and estuary and (2) a decrease in or cessation of skeletal growth (for the 2010 event).

(1) The estuarine Ba^{2+} desorption processes that affect the Ba concentration in seawater are known to be complex. Moyer et al. (2012) noted a time lag of several months between the peak of skeletal Ba/Ca and the peak of the river discharge, which was explained by the sporadic release of Ba from estuarine or floodplain-stored sediments. However, a large amount of sediment and freshwater will flow into the bay rapidly and suddenly when the limit of the mangrove trapping mechanism is exceeded due to heavy rainfall, river floods, and mangrove collapses. A large amount of sediment that flows out without being trapped by mangroves will be stored in the floodplains and estuaries, and then, the desorption of Ba^{2+} becomes sporadic and slow due to tidal mixing. As a result, the increase in the Ba concentration in Sumiyo Bay will be delayed.

(2) For the heavy rainfall disaster that occurred in October 2010, the daily precipitation of that day (622.0 mm) was highest in the 46 years past. The 2010 heavy rainfall specifically triggered a river flood and the collapse of mangrove forests, which caused a large amount of sediment and freshwater input into Sumiyo Bay (Amami City Report; Kagoshima University Report). The skeletal Ba/Ca record tracked the changes in sediment load due to the 2010 disaster showing an increasing trend for 4 months, and a maximum value of skeletal Ba/Ca was $5.32 \mu\text{mol/mol}$ (1.4 times the mean value over all periods). Similarly, the skeletal Ba/Ca record showed a time-lag signal that rose over several months during the heavy rainfall event that occurred in September and November 2011. Clear low-density bands were observed in the X-radiographs from 2010 to 2012 when the coral experienced heavy rainfall, river floods, and landslide events (Fig. 6-3). Anomalous high-/low-density bands are skeletal growth responses to environmental stressors, for example, thermal stress, sediments, or substantial precipitation (Lough and Cooper, 2011). In addition, the skeletal growth disturbance proxy, $\Delta\text{Sr/Ca}$ in the Sumiyo coral, showed high-peaks after the 2010 event (Fig. 6-4-g). The skeletal Sr/Ca and Mg/Ca in the Sumiyo coral recorded a low sea surface temperature (SST, $17.6 \sim 18.6^\circ\text{C}$ derived by SST-Sr/Ca and SST-Mg/Ca regression; Figs. 6-4-a, 6-4-b, and Fig. 11) after the 2010 river flood event. This scenario suggests that cold freshwater flowed into Sumiyo Bay from the Sumiyo and Yakugachi Rivers in the aftermath of the heavy rainfall event. The temporary heavy rainfall also probably influenced on corals. Fallon et al. (1999) explained that the time lag of the skeletal trace element record was caused by the temporary decrease in or cessation of skeletal growth during cold winters ($\text{SST} < 18^\circ\text{C}$). Thus, skeletal growth was temporarily inhibited by the 2010 river flood event, which might have created a time lag.

Seasonal pattern in skeletal Ba/Ca

Fig. 6-12 shows the annual detrended skeletal Ba/Ca record and the seasonal pattern in the two periods (A- and B-periods). The seasonal pattern in both periods was similar, while the variable ranges were different (A-period: 3.74 ~ 4.01 $\mu\text{mol/mol}$; B-period: 3.54 ~ 4.31 $\mu\text{mol/mol}$). The detrended skeletal Ba/Ca was significantly inversely correlated with precipitation and SST in both periods (A-period: Ba/Ca vs. precipitation: $r = -0.59$; $p < 0.05$; $n = 12$, Ba/Ca vs. SST: $r = -0.87$; $p < 0.001$; $n = 12$, B-period: Ba/Ca vs. precipitation: $r = -0.64$; $p < 0.05$; $n = 12$, Ba/Ca vs. SST: $r = -0.88$; $p < 0.001$; $n = 12$). There was no significant difference between the two periods for monthly precipitation and SST.

Only during the typhoon and heavy rainfall season (August to October) was the monthly mean of skeletal Ba/Ca showed a similar pattern with precipitation (A-period: $r = 0.99$; $p < 0.05$; $n = 3$, B-period: $r = 0.96$; $p = 0.19$; $n = 3$, Fig. 6-12). This result conflicts with the simple hypothesis that Ba-rich sediment particles are transported towards Sumiyo Bay by rivers with freshwater plumes associated with precipitation throughout the year. The estuaries serve as storage reservoirs for Ba-rich sediments (e.g., Edmond et al., 1978; Li and Chan, 1979; Dorval et al., 2005). The mangrove forest is one of the storage reservoirs. The mangrove can trap suspended sediments that are caused by river runoff or resuspension of bottom sediments (Wolanski et al., 1992; Wolanski, 1995; Furukawa et al., 1997). The trapping mechanism has a limitation in which too much sediments can lead to mangrove mortality as the sediments asphyxiate the respiratory structures (Sidik et al., 2016). In addition, the mangroves are affected by both river (river runoff related to precipitation) and ocean effects (seawater inflow and outflow due to tide levels). Increased river flow due to precipitation makes sediment transport more active and leads to sediment inflow into mangroves (Sidik et al., 2016). Heavy rainfall and strong winds associated with typhoons or storms sometimes trigger river floods and landslides, which can cause the outflow of large amounts of sediments into the ocean with mangrove collapse (Gilman et al., 2008). Seawater flows into the mangroves during the springtide and flows out during the ebb tide (Ellison, 1993; Furukawa et al., 1997; Mazda et al., 1990; 2005). Therefore, sediment transport is most active during springtide. The tide level in our study area was higher in summer and autumn (June to November) than in winter and spring (December to May). From August to October, typhoons and heavy rainfall events and river floods frequently occurred (Fig. 6-5-c). Therefore, Ba-containing sediments might slowly flow into Sumiyo Bay from mangroves during winter to early summer (November to June, when there might be no influence of typhoons or heavy rainfall). On the other hand, the sediments exceeding the limit of the mangrove trapping mechanism might suddenly flow into Sumiyo Bay during summer to autumn (July to October, when typhoons, heavy rainfalls, and river floods occur frequently). From May to June, the sediment input to Sumiyo Bay is controlled by the mangrove trapping mechanism, although there is substantial precipitation. In addition, the low-pass filtered skeletal Ba/Ca (i.e., multidecadal fluctuation) did not show the SST effect; however, our skeletal Ba/Ca may have been influenced by SST on the seasonal scale. This finding is consistent with that of previous studies (e.g., Lea et al., 1989; Gaetani et al., 2011). In particular, during winter to spring (December to May), the skeletal Ba/Ca may reflect the change in SST because the tide level is low and sediment transport from mangrove forests is considered to be less active. Thus, the skeletal Ba/Ca in the Sumiyo coral may reflect the mangrove system (affected by both tide level and precipitation) and SST variation on the seasonal scale. Moreover, the sensitivity (response) of the reef-building coral to sediment load has changed with the change in the rhythm of sediment outflow into Sumiyo Bay throughout the two periods. The results of the difference

in the variable range of the seasonal trend between the two periods and the increase in spike-like signals in the B-period can be explained by the histories of the local industries.

Response of the other skeletal proxies (Sr/Ca, Mg/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$) and coral derived $\delta^{18}\text{O}_{\text{seawater}}$ to the heavy rainfall, typhoon, and river flooding events

As described in *Chapter 1*, coral skeletal geochemistry is a useful proxy for reconstructing the environmental change in the past, for example, (1) SST (Sr/Ca, Mg/Ca, and $\delta^{18}\text{O}$), (2) salinity ($\delta^{18}\text{O}_{\text{seawater}}$: $\delta^{18}\text{O}_{\text{sw}}$), and (3) coral light availability ($\delta^{13}\text{C}$).

(1) 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., 2001a) are useful proxies for paleo-sea surface temperature (SST) variations. The skeletal Sr/Ca and Mg/Ca records showed a low-SST peak after the 2010 river flooding disaster (Figs. 6-4-a and 6-4-b, as described above). It suggests that cold freshwater flowed into Sumiyo Bay from the two rivers (Sumiyo River and Yakugachi River) during the 2010 river flooding disaster. In the other events, the skeletal Sr/Ca and Mg/Ca did not show anomalous signals. Besides, Coral skeletal oxygen isotope ratios ($\delta^{18}\text{O}$) reflect the SST and the oxygen isotope ratios in seawater related to the sea surface salinity (e.g., Dunbar and Wellington, 1981; McConnaughey, 1989b; Gagan et al., 1994). The skeletal $\delta^{18}\text{O}$ record did not show the change in the habitat environments during the heavy rainfall, typhoon, and river flooding events (Fig. 6-4-c). It may be caused by the complexity of controlling factors. The component of sea surface salinity would be masked by the component of SST in the skeletal $\delta^{18}\text{O}$ record.

(2) $\delta^{18}\text{O}_{\text{sw}}$ is available by combination skeletal Sr/Ca with skeletal $\delta^{18}\text{O}$, and it reflects sea surface salinity and evaporation (e.g., Juillet-Leclerc and Schmidt, 2001; Cahyarini et al., 2008; Gagan et al., 1998; Ren et al., 2003). The coral derived $\delta^{18}\text{O}_{\text{sw}}$ records showed a negative peak after the 2010 river flooding disaster (Fig. 6-4-e). Similar to the low-SST signals in the skeletal Sr/Ca and Mg/Ca, it suggests that freshwater flowed into Sumiyo Bay from the two rivers (Sumiyo River and Yakugachi River) during the 2010 river flooding disaster. In addition, the temporary heavy rainfall would also affect the coral derived $\delta^{18}\text{O}_{\text{sw}}$. On the other hand, in the other events, the coral derived $\delta^{18}\text{O}_{\text{sw}}$ did not show anomalous signals. The difference might be caused by the daily precipitation during the event (the 1977 event: 281.0 mm; the 1990 event: 424.0 mm; the 1991 event: 325.5 mm; the 2010 event: 622.0 mm) or the impact of the river flooding (the 2010 river flooding event caused the most devastating damage in the Sumiyo area in 46 years; Sumiyo Village History Editorial Committee, 2005; Kagoshima University Report, 2012; Amami City Report, 2013). The negative peak in coral derived $\delta^{18}\text{O}_{\text{sw}}$ may be related to the magnitude (impact) of the river flooding and the amount of precipitation.

(3) Coral skeletal carbon isotope ratios ($\delta^{13}\text{C}$) is mainly controlled by photosynthesis by symbiotic algae (zooxanthellae) which has a strong relationship to changes in water quality (coral light availability) and water depth (e.g., McConnaughey, 1989a; Weber et al., 1976; Grottoli and Wellington, 1999; Heikoop et al., 2000; Rosenfeld et al., 2003). It is a possibility that the skeletal $\delta^{13}\text{C}$ could reflect lower light availability (i.e., high turbidity) due to the increased sediment load corresponding to the heavy rainfall, typhoon, and river flooding events; however, the skeletal $\delta^{13}\text{C}$ record did not show any signal during these events (Fig. 6-4-d). The complex in controlling factors of coral skeletal $\delta^{13}\text{C}$ has been reported by numerous previous studies, for example, the $\delta^{13}\text{C}$ 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 (Swart et al., 1983; McConnaughey et al., 1997; Grottoli and Wellington, 1999). These factors might affect the skeletal $\delta^{13}\text{C}$ record in the Sumiyo coral, and they would mask the influence of temporary high turbidity due to the events.

Coral calcification response to natural/anthropogenic sediment load

Coral skeletal growth parameters (skeletal extension rate, skeletal density, and skeletal calcification rate) are obtained from annual bands and age models (see 3.1.5 *Calculation for skeletal growth parameters*). As shown in Fig. 6-13, there were the significant relationships between the annual mean of the low-pass filtered skeletal Ba/Ca and the annual extension rate in both periods (A-period: $r = -0.53$; $p < 0.01$; $n = 27$, B-period: $r = -0.63$; $p < 0.01$; $n = 18$). Besides, there were also the significant relationships between the low-pass filtered skeletal Ba/Ca and the annual calcification rate in both periods (A-period: $r = -0.57$; $p < 0.01$; $n = 27$, B-period: $r = -0.72$; $p < 0.001$; $n = 18$). Therefore, natural/anthropogenic sediment load was likely one of the controlling factors of coral calcification in Sumiyo Bay. Skeletal calcification is enhanced by light availability (i.e., inhabitation of light-enhanced calcification: Barnes and Chalker, 1990). Numerous previous studies have reported that increasing the sediment load in seawater (i.e., high water turbidity) due to coastal runoff cause would reduce the coral light availability, and it will lead to disturbances in coral calcification (Hudson, 1981; Dodge and Lang, 1983; Crabbe and Smith, 2005). Besides, the correlation coefficient r -value of skeletal Ba/Ca vs. annual calcification rate in the B-period ($r = -0.76$; slope: -0.36 ± 0.08) was larger than that in the A-period ($r = -0.55$; slope: -0.29 ± 0.09). There is a possibility that coral calcification in the B-period could more strongly respond to natural/anthropogenic sediment load than in the A-period.

The notification of the skeletal Ba/Ca for detecting the sediment load

Skeletal Ba/Ca records the signals of heavy rainfall, river flooding, and sediment outflow into the ocean, as shown in this study and in previous studies. However, there are still unknown aspects of using skeletal Ba/Ca as a proxy. For example, our skeletal Ba/Ca record showed some peaks that did not coincide with the typhoons, heavy rainfall events, storms, landslides, or river flood events (e.g., January 1996, May 2005, and September 2008; see Fig. 6-5-c). The peak in January 1996 may reflect the October 1995 tsunami events corresponding to the M_w 6.9 and 6.7 earthquakes. Irregular skeletal Ba/Ca peaks in coastal corals have been reported by previous studies (e.g., Sinclair, 2005; Lewis et al., 2007; Chen et al., 2011; Nagtegaal et al., 2012). A few previous studies have proposed various mechanisms for the Ba biogeochemistry that could explain the irregular skeletal Ba/Ca peaks (Alibert et al., 2003; Esslemont et al., 2004; Sinclair, 2005; Gillikin et al., 2006; Nagtegaal et al., 2012; Moyer et al., 2012); however, these studies could not explain the whole biogeochemistry mechanisms in the skeletal Ba/Ca. Additional research is needed to understand in detail the biogeochemistry mechanisms in skeletal Ba/Ca, and this information will allow us to reconstruct reef disturbances and to assess skeletal calcification responses more precisely.

6.8 Conclusion

Massive reef-building coral skeleton collected from the Sumiyo Bay quantitatively reconstructed natural/anthropogenic reef disturbances with a high temporal resolution, and the skeletal calcification responses. The skeletal Ba/Ca of the Sumiyo Bay coral was mainly controlled by the amount of the desorbed Ba^{2+} (in the estuary) from the Ba-containing sediment transported by the two rivers and mangrove forests. The Smiyo coral Ba/Ca showed a response of natural reef disturbances (river flood events) as a high-peak. Besides, the skeletal Sr/Ca, Mg/Ca, and coral derived $\delta^{18}\text{O}_{\text{sw}}$ record showed the temporal low-SST signal or low-SSS corresponding to the natural reef disturbance (the cold freshwater plume or the cold heavy precipitation). The other coral skeletal proxies ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) did not show any significant signal of natural reef disturbance due to the complexity of controlling factors. When the extreme-heavy rainfall or devastating river flood occurred, these proxies will show the remarkable signals.

The tides and precipitation effects are shown as the seasonal pattern in skeletal Ba/Ca. The Sumiyo coral Ba/Ca records were characterized by two distinct periods: (A) the multidecadal change with smaller seasonal variation during the 1960s to 1995 corresponding to the change in the traditional silk fabric industry and (B) the increase pattern with a large seasonal variability during 1996 to the present corresponding to the development of quarries and the construction industry. Thus, the sensitivity (response) of the reef-building coral to sediment load has changed with the change in the rhythm of sediment outflow into Sumiyo Bay throughout the two periods. I concluded that natural (the sediment-trapping mechanism in the mangroves, precipitation effects, and river flooding effects) and anthropogenic sediment loads (industrial development and land-use effect) were two of the controlling factors of coral calcification. This study will be essential to the discussion of survival strategies for reef-building corals in which precipitation and human activities will increase, especially in the area where the *in situ* data or monitoring surveys are limited.

Figures and Tables

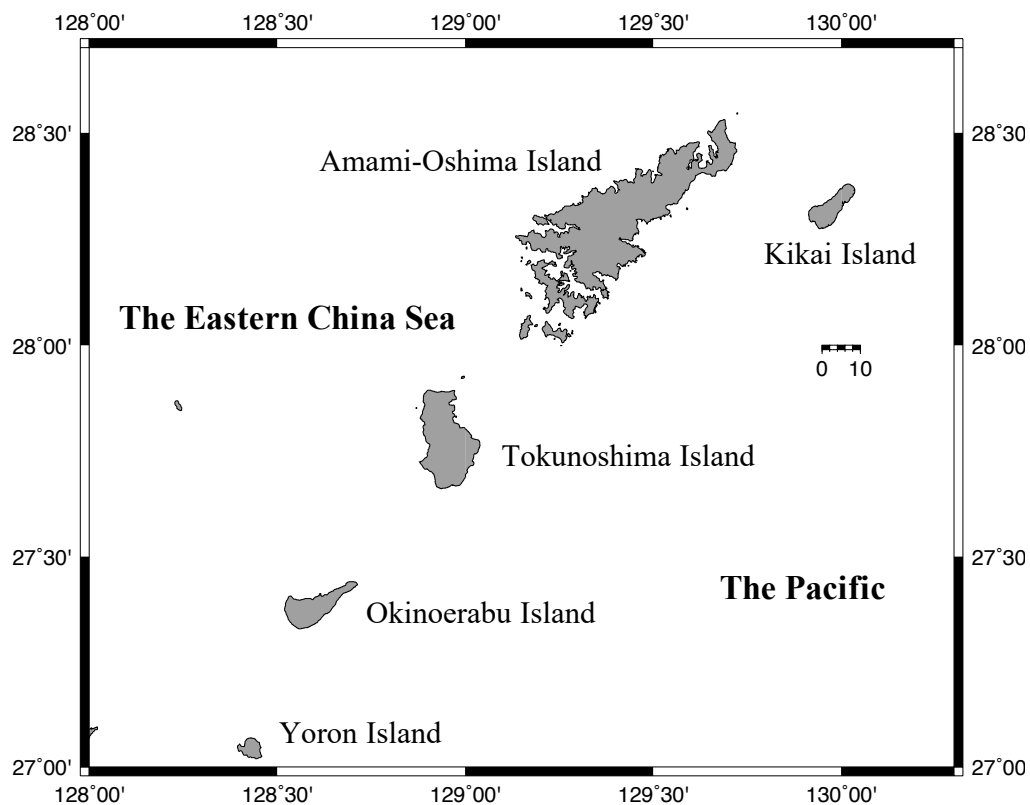


Fig. 6-1 Amami archipelago

Amami archipelago is located between the Eastern China Sea and the Pacific. Amami archipelago consists of Amami-Oshima Island, Tokunoshima Island, Okinoerabu Island, Kikai Island, and Yoron Island. The scale bar shows a 10 km length. The map figure was generated using Generic Mapping Tools (GMT v. 5.3.3, Wessel et al., 2013).

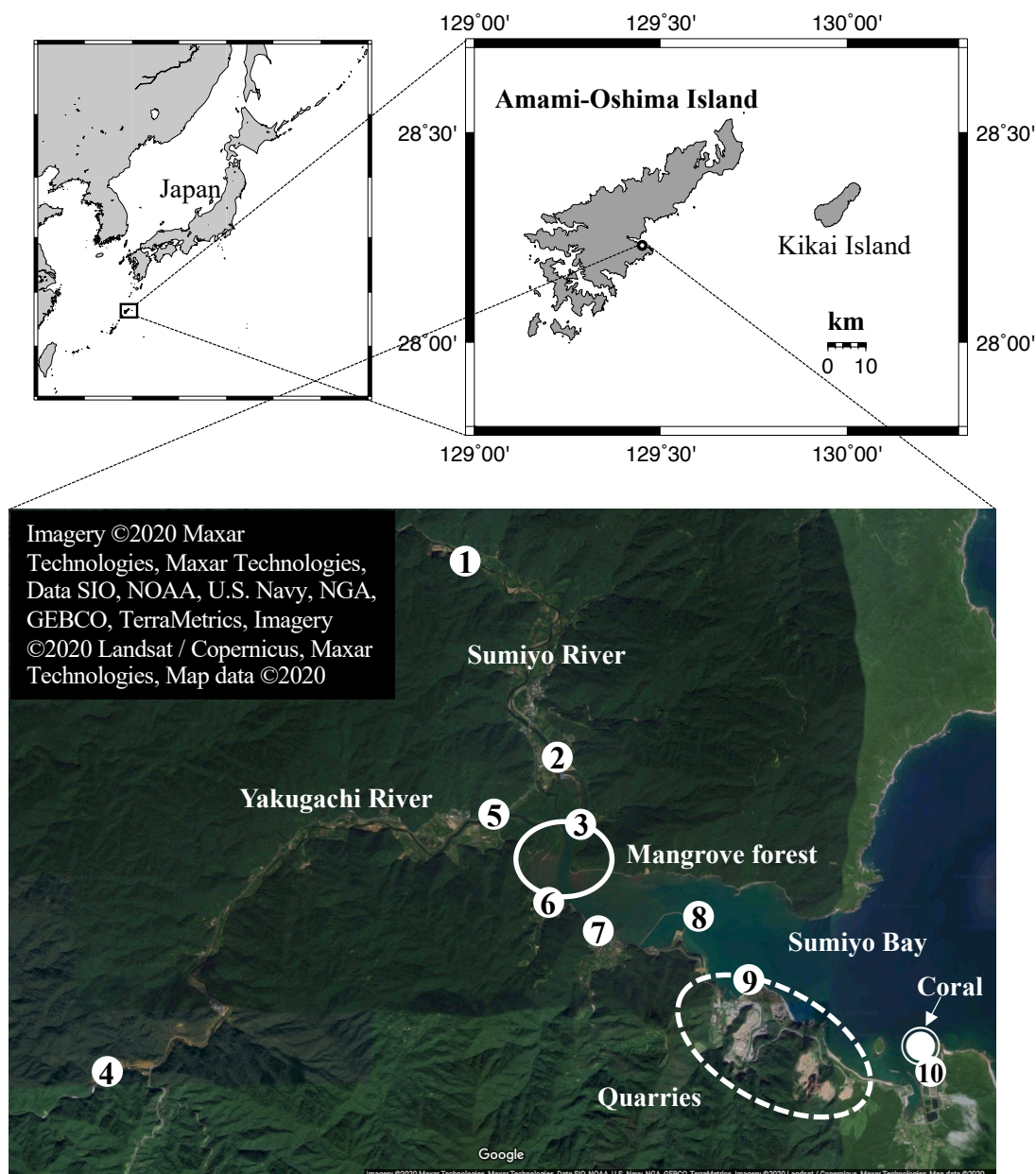


Fig. 6-2 Regional map around the sample site (Sumiyo Bay, Amami-Oshima Island)

Sumiyo River and Yakugachi River flow into Sumiyo Bay. The solid line area indicates a mangrove forest located at the rivers' mouth, and the broken line area shows quarries in the southern coastal area of Sumiyo Bay. The white double-circle shows the site where *Porites* coral was drilled in this study. The distance between the rivers' mouth and the sampling site was 4.5 km. The white single circles with a number show the site where the water samples were collected (No. 1, 2: Sumiyo River; No. 3: mangrove forest; No. 4, 5: Yakugachi River; No. 6, 7: Sumiyo Bay (brackish water); and No. 8, 9, 10: Sumiyo Bay (seawater)). The map figures (Japan, Amami-Oshima Island, and Kikai Island) were generated using Generic Mapping Tools (GMT v. 5.3.3, Wessel et al., 2013). Satellite image (the Sumiyo area) was obtained by Google Maps (<https://www.google.co.jp/maps/>); Imagery ©2020 Maxar Technologies, Maxar Technologies, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, TerraMetrics, Imagery ©2020

Landsat / Copernicus, Maxar Technologies, Map data ©2020. These figures were modified using Microsoft® PowerPoint for Mac (v. 16.35).

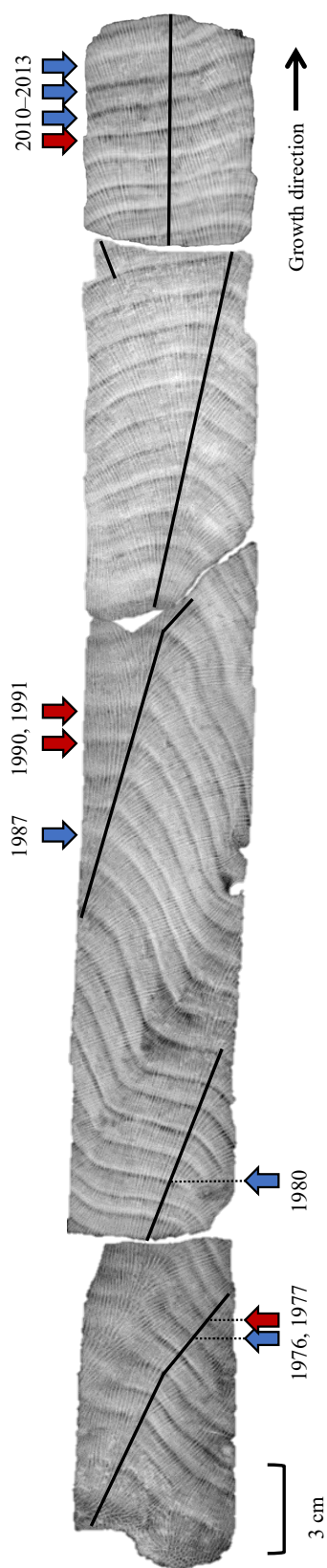


Fig. 6-3 Images of X-radiographs (positive)

The black lines show analytical lines. The color arrows indicate the annual bands when the typhoon (blue; 1976, 1980, 1987, 2011, 2012, 2013) and river flood disasters (red; 1977, 1990, 1991, 2010) occurred.

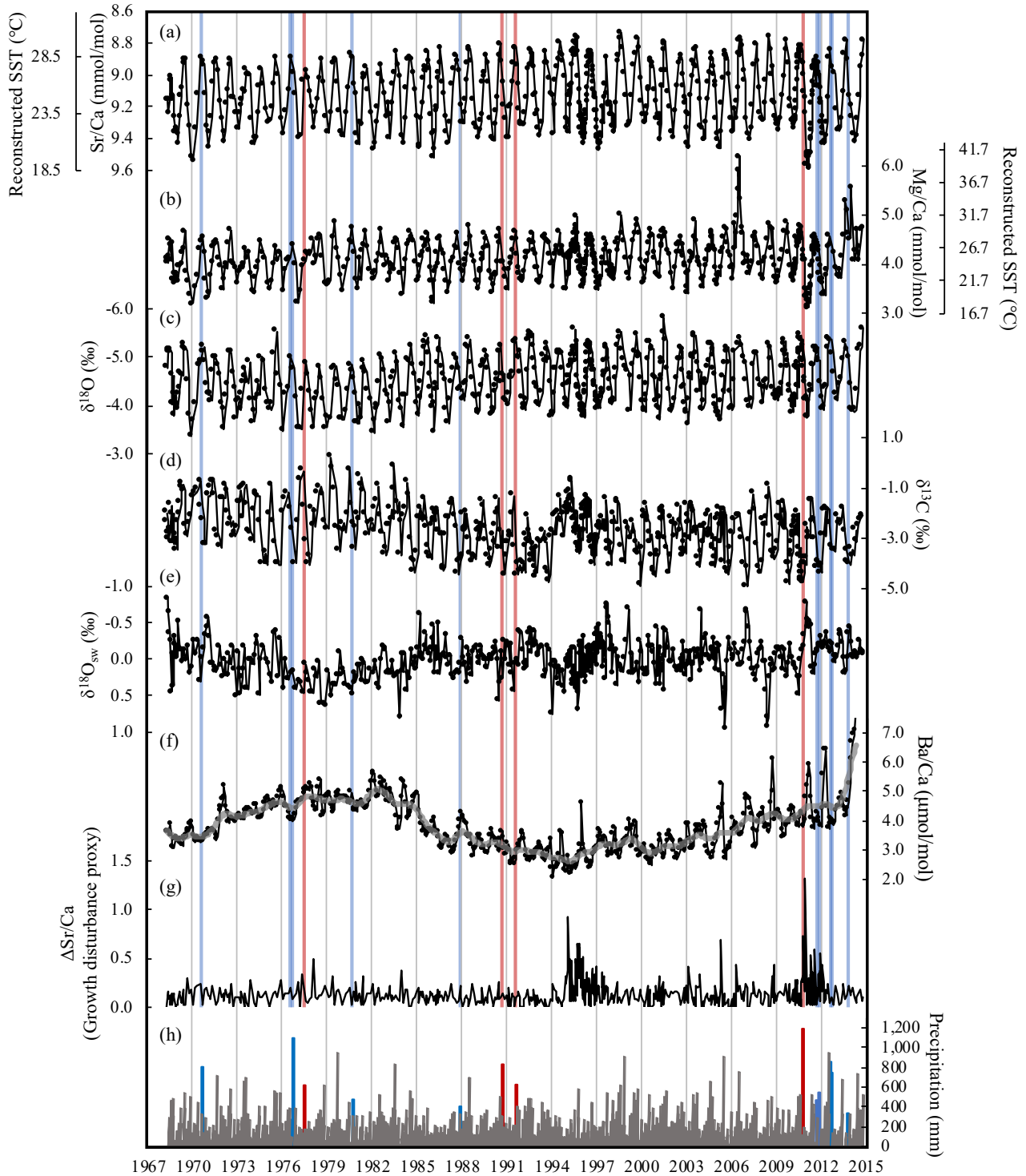


Fig. 6-4 Coral-derived geochemical records and precipitation data back to 1968.

(a) Sr/Ca, (b) Mg/Ca, (c) $\delta^{18}\text{O}$, (d) $\delta^{13}\text{C}$, and (f) Ba/Ca are skeletal geochemical records. The y-axis on the skeletal Sr/Ca and Mg/Ca indicates measured data (mmol/mol) and reconstructed SST ($^{\circ}\text{C}$). Both Sr/Ca-SST and Mg/Ca-SST regression are shown in Fig. 6-11. The gray line on the skeletal Ba/Ca indicates low-pass filtered data. (e) $\delta^{18}\text{O}$ of seawater ($\delta^{18}\text{O}_{\text{sw}}$) was calculated by skeletal Sr/Ca and $\delta^{18}\text{O}$ (Juillet-Leclerc and Schmidt, 2001; Cahyarini et al., 2008). The data was resampled with monthly resolution. (g) $\Delta\text{Sr/Ca}$ shows the difference in the neighboring values in the skeletal Sr/Ca record. The coral skeleton could not record SST when skeletal growth was

disturbed; therefore, a high value in $\Delta\text{Sr}/\text{Ca}$ indicates a temporary growth disturbance. (h) The resolution of the precipitation is monthly. The blue and red areas of precipitation show typhoons or heavy rainfall (blue) and river flooding disasters, corresponding to typhoons or heavy rainfall events (red).

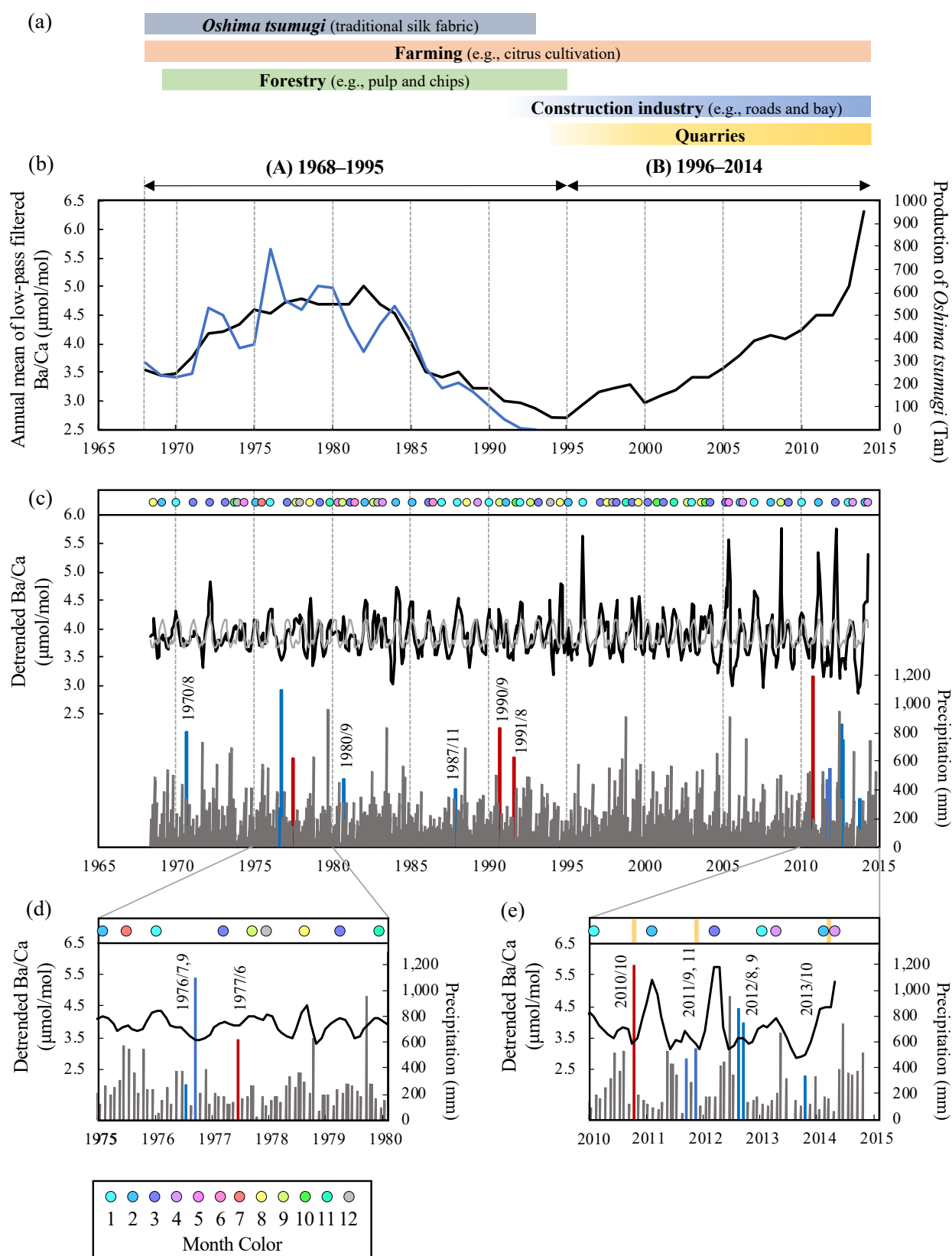


Fig. 6-5 Time series of the skeletal Ba/Ca and land-use history (industrial development).

(a) Land-use history (industrial development) in Sumiyo town from 1968 to 2014. In the A-period (1968 ~ 1995), *Oshima tsumugi* production and forestry prospered. In the B-period (1996 ~ 2014), the construction industry and quarries prospered. Farming also prospered during both periods. **(b) Annual mean of low-pass filtered**

skeletal Ba/Ca (in black) compared with the production of *Oshima tsumugi* (in blue). The low-pass filtered skeletal Ba/Ca was isolated by Gaussian bandpass filter (frequency = 0; bandwidth = 0.00137, Paillard et al., 1996) from the raw skeletal Ba/Ca data which shown in Fig. 6-4-f (see 6.6. *Statistical analysis*). The standard unit of the production of *Oshima tsumugi* is “Tan” (in Japanese), which is defined as approximately twelve meters long and thirty-seven centimeters wide. **(c) (d) (e) Detrended skeletal Ba/Ca compared with monthly precipitation.** The detrended skeletal Ba/Ca was obtained by Gaussian bandpass filter (frequency = 0; bandwidth = 0.00137), as notch filtered data (Paillard et al., 1996). The gray line on the detrended skeletal Ba/Ca record indicates the mean seasonal cycles (MSC). The monthly color circles show the skeletal Ba/Ca high-peaks, which determined the difference between the mean value of MSC and the detrended data. When the peak points succeeded one another, the highest point was determined as a representative point. The blue and red precipitation areas show typhoons or heavy rainfall events (blue) and river flood disasters corresponding to typhoons or heavy rainfall (red). The month and year of heavy rainfall or river flooding events are shown as “YYYY/MM.” The yellow bars in Fig. (e) show the landslide events around the coastal area.

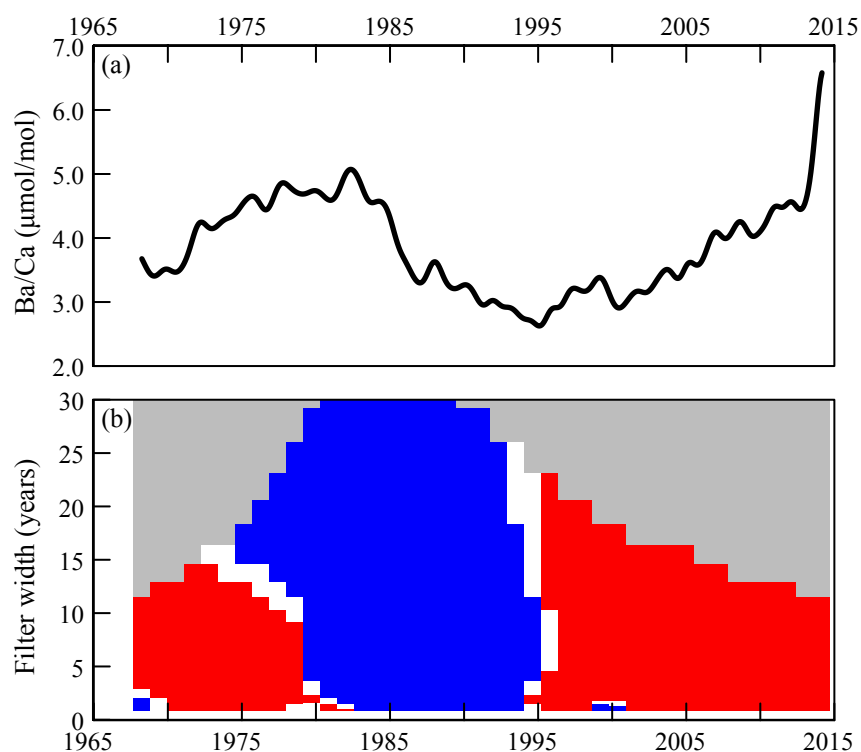


Fig. 6-6 SiZer trend map for the skeletal Ba/Ca record

(a) Low-pass filtered skeletal Ba/Ca. This time series is same as Fig. 6-4-f (in gray line). (b) SiZer trend map for the low-pass filtered skeletal Ba/Ca (Chaudhuri and Marron, 1999; R Core Team, 2018; Sonderegger, 2012). A SiZer map is a way of examining when the p -th derivative of a scatterplot-smoother is significantly negative, possibly zero or significantly positive across a range of smoothing bandwidths (Sonderegger, 2012). The y-axis indicates the bandwidth values for which a smoothing function was calculated. Significant ($p < 0.05$) trends are shown as blue (significant decreasing) and red (significant increasing). The white color shows insignificant trends ($p > 0.05$). The gray color indicates the range that non-enough data in the filter width.

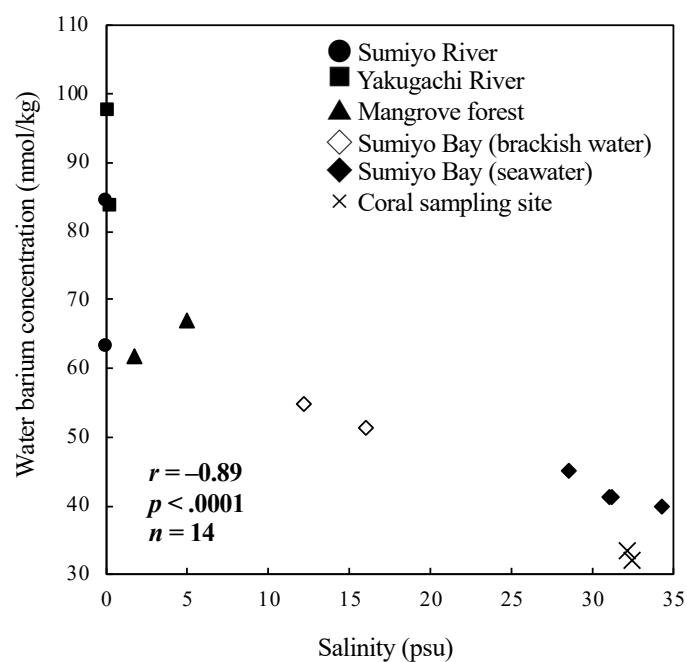


Fig. 6-7 Correlation between the water barium concentration and the salinity in the Sumiyo area.

The 14 water samples were collected from Sumiyo, Amami-Oshima Island (see Fig. 6-2). Two of them were collected from the coral drilling site in October 2014. The other samples were collected from the Sumiyo area (Sumiyo River, Yakugachi River, mangrove forest, and Sumiyo Bay) in July 2017. Salinity (in psu) was *in situ* data. Our water samples and salinity data were not affected by any typhoon, heavy rainfall, river flood, and landslide event.

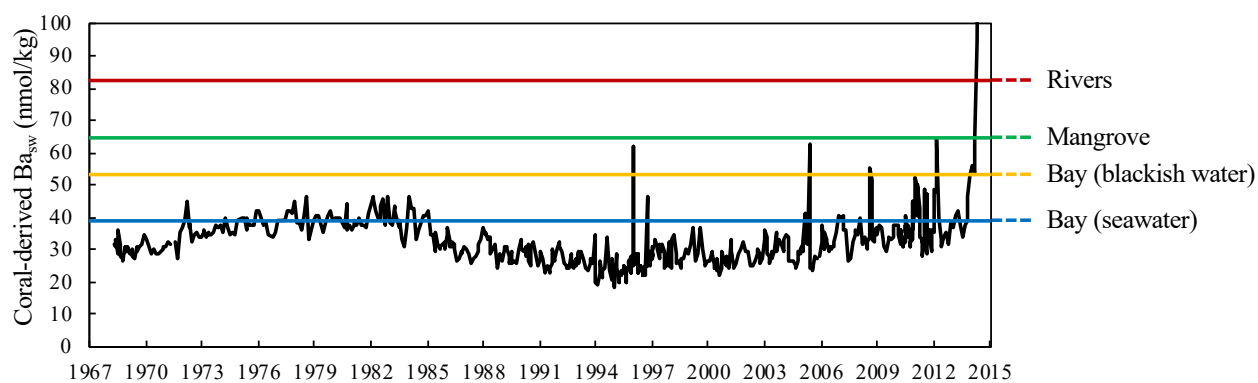


Fig. 6-8 Variable range in measured Ba concentration in water samples and coral-derived Ba_{sw}

The color lines show the mean value of measured Ba concentration in the river- and sea-water samples (the raw data is shown in Fig. 6-7). Coral-derived Ba concentration in seawater (Coral-derived Ba_{sw}) is calculated using a reporting regression for *Porites* sp. (LaVigne et al., 2016, equation (2)).

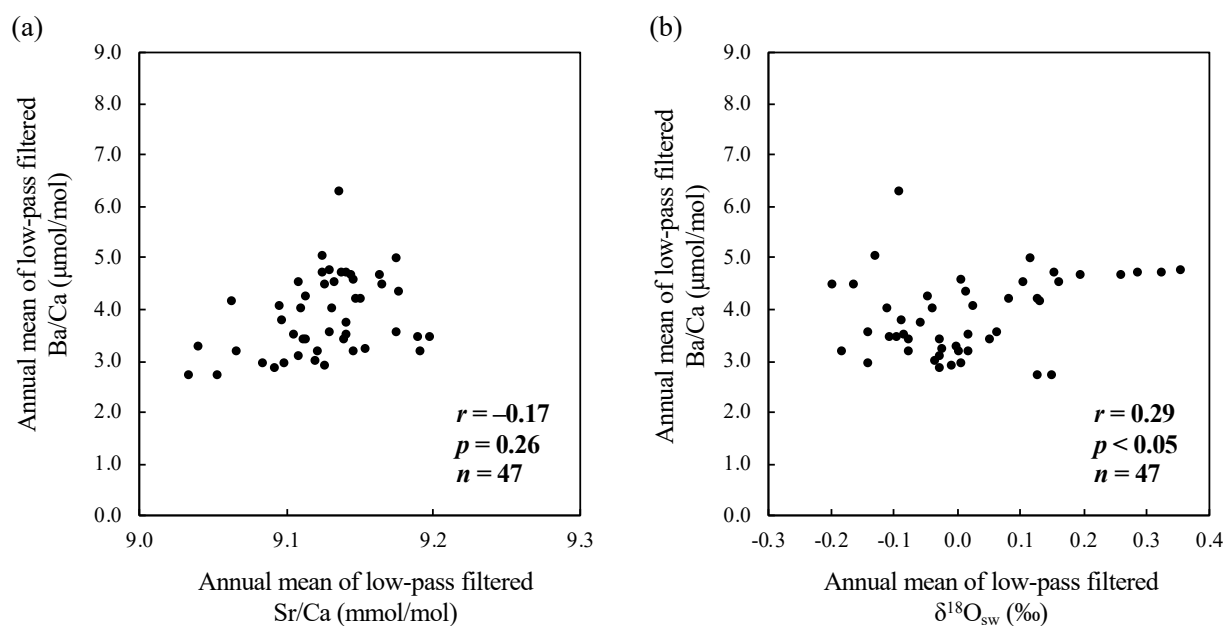


Fig. 6-9 Correlation among low-pass filtered Ba/Ca, Sr/Ca, and coral derived $\delta^{18}\text{O}_{\text{seawater}}$

The time series of the annual mean of low-pass filtered skeletal Ba/Ca are shown in Fig. 6-5-b. Methodology for low-pass filtering for skeletal Sr/Ca and coral derived $\delta^{18}\text{O}_{\text{seawater}}$ was the same as skeletal Ba/Ca (see 6.6. *Statistical analysis*).

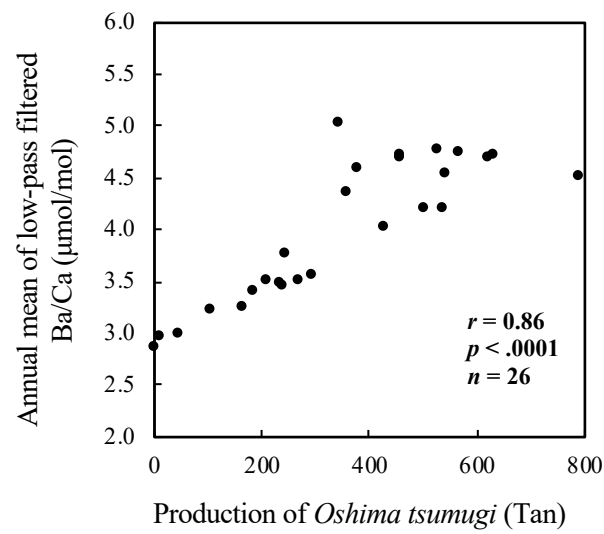


Fig. 6-10 Relationship between annual mean of low-pass filtered skeletal Ba/Ca and the production of *Oshima tsumugi*.

The time series of the annual mean of low-pass filtered skeletal Ba/Ca are shown in Fig. 6-5-b. Note that the period of comparison was from 1968 to 1993.

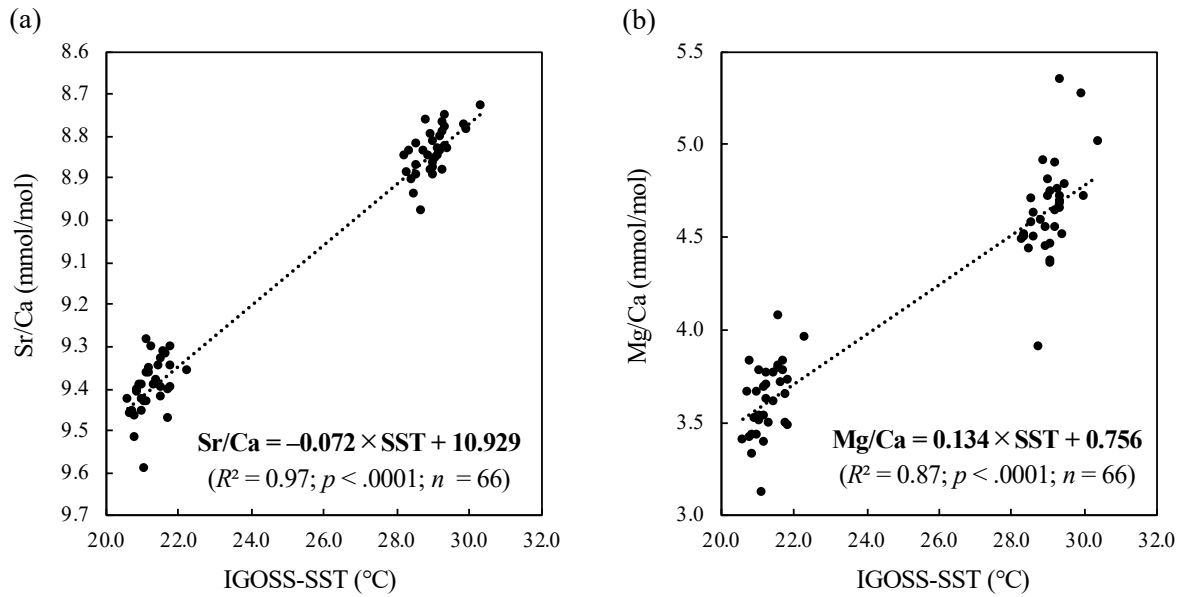


Fig. 6-11 Coral Sr/Ca-SST and Mg/Ca-SST calibration for Sumiyo Bay, Amami Island

The dashed lines in both figure (a) and (b) show the mean calibration for each dataset with the calibration equations shown. The monthly IGOSS-SST time series was derived from the Integrated Global Ocean Services System Products Bulletin (Reynolds et al., 2002,

https://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst/; see also Materials and Methods in the text). Obtained regressions are the following:

$$Sr/Ca \text{ (mmol/mol)} = -0.072 \pm 0.002 \times SST \text{ (}^{\circ}\text{C)} + 10.929 \pm 0.041 \quad (1)$$

$$Mg/Ca \text{ (mmol/mol)} = 0.134 \pm 0.007 \times SST \text{ (}^{\circ}\text{C)} + 0.756 \pm 0.167 \quad (2)$$

The slope of Me/Ca-SST regression for Sumiyo Bay, Amami-Oshima is -0.072 and 0.134 for Sr/Ca-SST and Mg/Ca, respectively. These results mostly agree with the previously published *Porites* Sr/Ca-SST (Corrège, 2006) and Mg/Ca-SST (Mitsuguchi et al., 1996) calibrations.

(A) 1968–1995

(B) 1996–2014

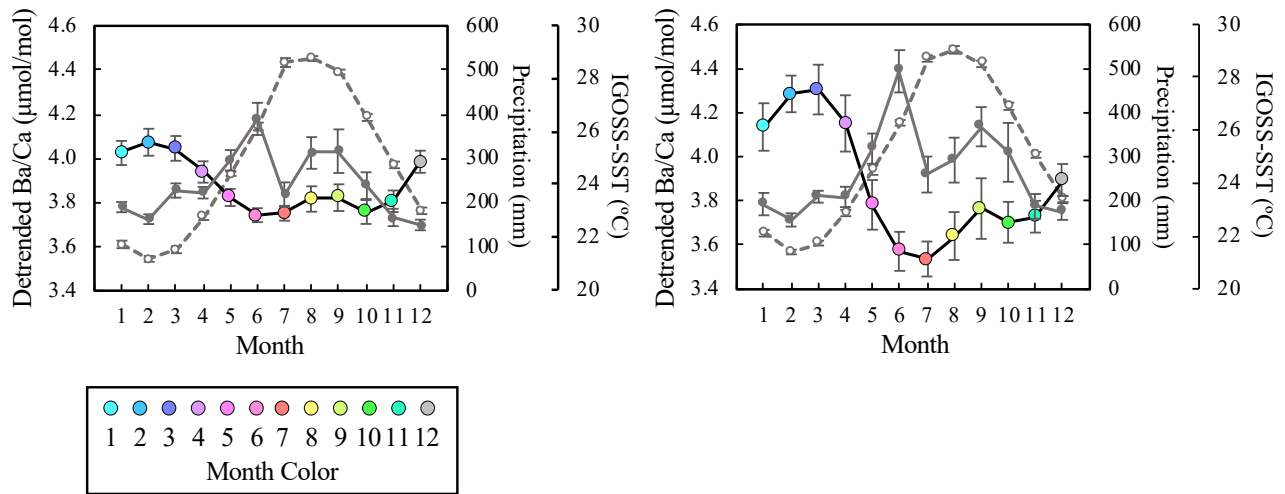


Fig. 6-12 Seasonal pattern in the detrended skeletal Ba/Ca, precipitation, and SST in two periods.

The black line with monthly color circles shows the seasonal pattern in detrended skeletal Ba/Ca (MSC, the gray line on Fig. 6-5-c). The gray-solid line shows the seasonal variation in precipitation. The gray-dashed line shows the seasonal variation in IGOSS-SST (Reynolds et al., 2002). Noted that the IGOSS-SST time series were from 1981 November to October 2014. The error bars show the standard error.

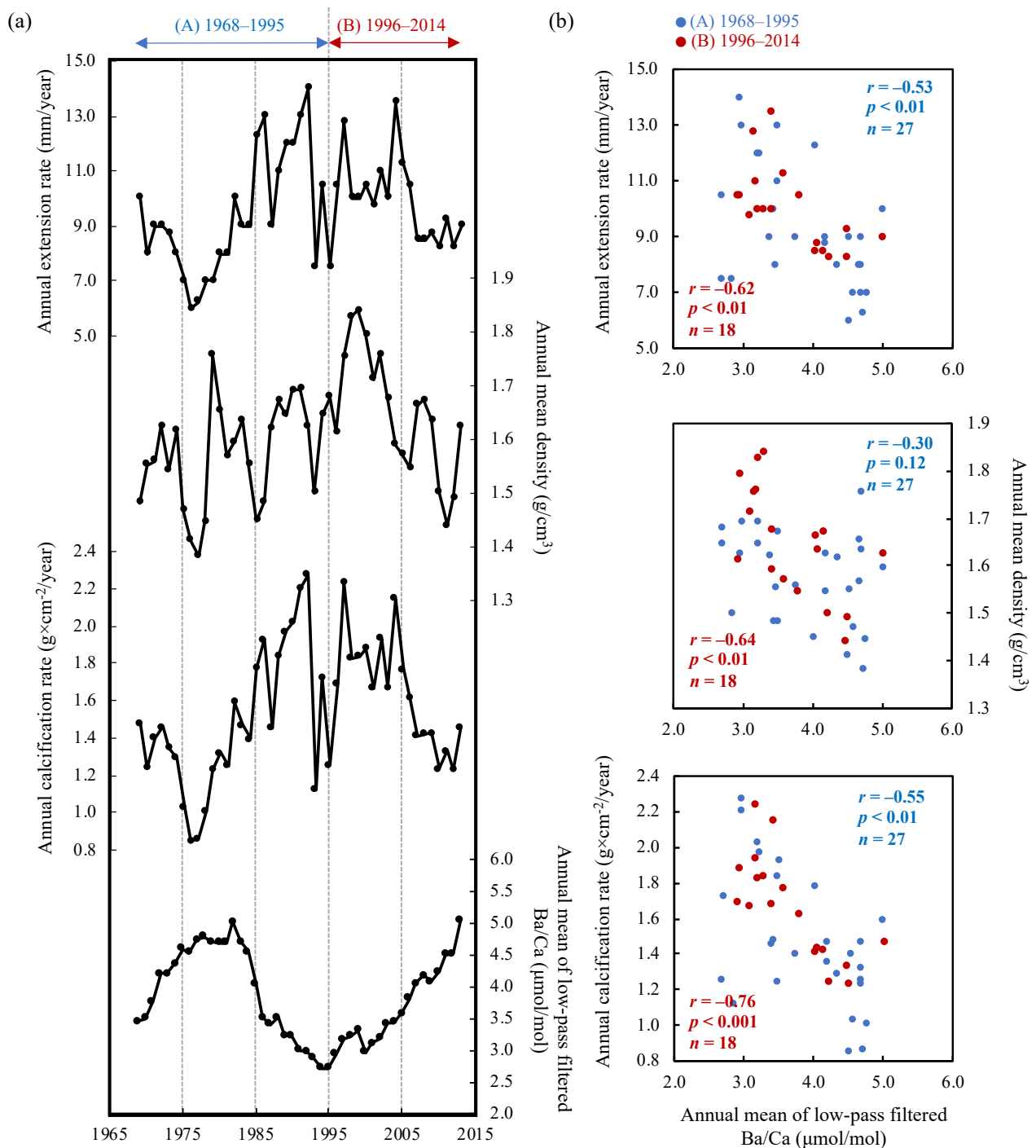


Fig. 6-13 Skeletal growth parameters and correlation with annual mean of low-pass filtered skeletal Ba/Ca.

(a) Time series of skeletal growth parameters and annual mean of low-pass filtered skeletal Ba/Ca. The annual skeletal calcification rate ($\text{g} \times \text{cm}^{-2}/\text{year}$) was obtained from the annual extension rate (mm/year) and annual mean density (g/cm^3). The broken line on the age (year) separates two periods: (A) 1968 ~ 1995 and (B) 1996 ~ 2014. **(b) Relationship between skeletal growth parameters and annual mean of low-pass filtered skeletal Ba/Ca in two periods: (A) and (B).** The x-axis of all figures is the annual mean of low-pass filtered skeletal Ba/Ca.

Site	Ba concentration in seawater (nmol/kg)	Sample	Reference
Lanyu Islet, southern Taiwan	33.4 - 32.8	Seawater	Yu et al. (2015)
Northeastern tropical Pacific	~ 35 - 42	Seawater	Esser & Volpe (2002)
Shirigai Bay, Japan	31 - 41	Estimated from skeletal Ba/Ca record	Fallon et al. (1999)
Ishigaki Island, Japan	26.1 - 32.0	Estimated from skeletal Ba/Ca record	Sowa et al. (2014)
Sumiyo Bay, Japan	32.1 - 45.1	Seawater	This study

Table 6-1 Reported data of the Ba concentration in sea water

The reported data were derived from four sites: Lanyu Islet (Yu et al. 2015); northeastern tropical Pacific that is less affected by upwelling (Esser and Volpe, 2002); Shirigai Bay, Kochi Prefecture, Japan (Fallon et al., 1999); and Ishigaki Island, Okinawa Prefecture, Japan (Sowa et al. 2014). Our data on the Ba concentration in seawater ranged from 32.1 to 45.1 nmol/kg, which seemed to be slightly higher than reported values in previous studies.

Notes

The parts of this chapter have been published as Ito et al. (2020b), by *Scientific Reports*. The samples' name and reference information are below;

<< Reference >>

Ito, S., Watanabe, T., Yano M. and Watanabe, T. K. (2020b) Influence of local industrial changes on reef coral calcification. *Sci. Rep.* **10**, 7892; <https://doi.org/10.1038/s41598-020-64877-6>.

<< Samples' name >>

Coral core: AMI141001

Water sample: 2014.10.01Pt.1; 2014.10.01Pt.2; 2014.10.01Pt.3; AMI170703pt1; AMI170703pt2; AMI170703pt3; AMI170703pt4; AMI170703pt5; AMI170703pt6 AMI170703pt7; AMI170703pt8; AMI170704pt2(10); AMI170704pt3(11); AMI170704pt4(12)

7. Conclusion and future perspectives

Summary

Coral reefs are currently facing numerous disturbances which have the multiple and mixed components of natural and anthropogenic factors at a local and global scale (i.e., human activity, climate change, and land-use change; e.g., Burke et al., 2011; De'ath et al., 2012; Erftemeijer et al., 2012; Pachauri, 2014; Hughes et al., 2017; 2018a; 2018b; Fisher et al., 2019). There are many coastal areas in tropics and subtropics where periodic monitoring surveys and *in situ* environmental data are not available. The massive coral skeletons (e.g., *Porites* sp.) can quantitatively reconstruct reef disturbance events with a high temporal resolution, and it will provide us the worthy key for understanding the skeletal calcification responses to the habitat environmental change. This study showed how natural (e.g., earthquake-related seafloor displacement, tsunami, heavy rainfall, river runoff, and mangrove systems) or anthropogenic (e.g., local industrial history and land use) factors lead to a reef disturbance, and how corals respond to these disturbances. The combined methodology, coral geochemical proxies with skeletal growth parameters, provides a quantitative scale of the impacts of natural and anthropogenic reef disturbance with a long time series. The skeletal geochemical proxies recorded natural/anthropogenic reef disturbance events, and coral calcification responded to these reef disturbances (Table 7-1). The natural/anthropogenic disturbance event will be one of the controlling factors of coral calcification. The summary of each study case was shown as below;

Case 1) Natural reef disturbance: Earthquakes, seafloor displacement, and tsunami event

As shown in *Chapter 4*, the remarkable signals of natural reef disturbances, earthquake events (including coseismic seafloor displacement and tsunami), were observed on the surface of coral skeletons, skeletal growth parameters, and skeletal $\delta^{13}\text{C}$. The earthquake events 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. Besides, a green band on the skeleton slab due to an endolithic algae bloom (*Ostreobium* spp.) and incorporation of the small particles like clay materials were also the remarkable signals of natural reef disturbance associated with the earthquake and tsunami occurrence. Moreover, the significant step change in the skeletal $\delta^{13}\text{C}$ would reflect the uplift-related RLAs. The coral RLA associated with the habitat water depth and the scale of vertical displacement would be a noteworthy key in coral skeletal $\delta^{13}\text{C}$ paleogeodesy. Coral paleo-earthquake archive will provide us with local information on crustal deformation at the decimeter scale. 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.

Case 2) Natural reef disturbance: Tsunami event

As shown in *Chapter 5*, the remarkable signals of natural reef disturbances, tsunami event, were observed on skeletal Ba/Ca and skeletal growth parameters. The skeletal Ba/Ca showed a high peak in the aftermath of the tsunami event. The tsunami peak in the skeletal Ba/Ca consisted of the increasing variation for approximately 2 months after the tsunami event. This study showed the evidence for a new possibility of the skeletal Ba/Ca as a

past-tsunami proxy. Besides, the coral skeletal calcification decreased in the year that experienced a tsunami event. It suggested that the tsunami-related sediment load in the seawater could temporarily cause low water visibility (i.e., high turbidity). Though the tsunami event occurs in the short-term, the sediment-related disturbance will have a negative impact on coral calcification, and then the annual skeletal calcification rate reflected the tsunami effect. The tsunami signal detection using skeletal Ba/Ca combined with skeletal growth analysis will also provide us an essential key for understanding the coral response to the tsunami-generated reef disturbance, especially in the areas where the archived data or reports are very limited.

Case 3) Natural reef disturbance: Heavy rainfall, river flood event, and mangrove system

As shown in *Chapter 6*, the remarkable signals of natural reef disturbances, heavy rainfall, and river flood were observed on the skeletal Ba/Ca (isolated < 2 years trend data) and temporary skeletal growth parameters. The skeletal Ba/Ca showed a response of river flood events as a high-peak, and it suggested the increase in the sediment load in the seawater. Especially when the extreme-heavy rainfall or devastating river flood occurred, skeletal Sr/Ca, skeletal Mg/Ca, and coral derived $\delta^{18}\text{O}_{\text{sw}}$ showed the temporal low-SST signal or low-SSS (due to the cold freshwater plume or the cold heavy precipitation). The heavy rainfall and river flood events led to the skeletal growth disturbance, such as an anomalous stress band and the increasing $\Delta\text{Sr/Ca}$. Moreover, the skeletal Ba/Ca record in this study was mainly controlled by the amount of the desorbed Ba^{2+} (in the estuary) from the Ba-containing sediment transported by the rivers and mangrove forests. The skeletal Ba/Ca in the corals that inhabit near the mangrove area or estuarine reflects the mangrove system (affected by both tide level and precipitation) and SST variation on the seasonal scale.

Case 3) Anthropogenic reef disturbance: Local industrial changes and land use

As shown in *Chapter 6*, the remarkable signals of anthropogenic reef disturbances, local industrial history and land use were observed on the skeletal Ba/Ca (isolated > 2 years trend data) and annual skeletal growth parameters. Skeletal Ba/Ca record in this study would reflect the local industry (traditional silk fabric) and the development of quarries and the construction industry. There were significant relationships between the annual mean of the skeletal Ba/Ca and the annual calcification rate. Besides, the two historical periods showed a difference in the skeletal Ba/Ca signal pattern of the response to natural reef disturbance events (as described above). The sensitivity (response) of the reef-building coral to sediment load would reflect the change in the rhythm of sediment outflow into the bay, corresponding to the local industrial history. The directly comparing coral calcification with local industrial histories with multidecadal time series was useful for understanding the relationship between coastal anthropogenic effect and coral calcification response.

Future issues and perspectives on the sclerochronological reef disturbance archives

Massive *Porites* coral provides the quantitative reef disturbance archives through the geochemical proxies and the responses on skeletal calcification. While, there were the other species of reef-building coral which have annual bands (e.g., *Acropora* sp., *Diploria* sp., *Montastraea* sp., *Pavona* sp., *Solenastrea* sp., and *Siderastrea* sp.) were also known as the paleo-environmental proxy (e.g., skeletal $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Me/Ca; Table 7-2). Similar to

Porites sp., these species also provide the skeletal growth records (e.g., Lough and Cooper, 2011; Lough and Cantin, 2014). Applying the methodology in this study (i.e., the combined methodology, coral geochemical proxies with skeletal growth parameters) to the numerous coral species is important because it will provide a detailed discussion of the reef disturbance signals on the coral skeletal proxies and the disturbance effect on the reef system.

For skeletal $\delta^{13}\text{C}$ as a paleo-earthquake proxy, specifying and distinguishing the control factors and the effects are the most important to detect the precise paleogeodesy. Many previous studies described multiple controlling factors on the skeletal $\delta^{13}\text{C}$ (e.g., light availability and coral habitat water depth, the $\delta^{13}\text{C}$ of dissolved inorganic carbon in seawater, coral mass spawning, heterotrophic feeding, and respiration; see *Chapter 3*). The uplift/subsidence-related step change in the skeletal $\delta^{13}\text{C}$ is distinguished from other controlling factors. Besides, the great subduction zone earthquakes often simultaneously trigger the tsunami and coseismic crustal deformation (seafloor displacement). As shown in *Chapter 4* and Table 7-1, both tsunami and coseismic seafloor displacement would influence on skeletal $\delta^{13}\text{C}$. These signals showed the opposite pattern. Therefore, it is necessary to distinguish them when we focus on the specific effect. Besides, there is the possibility of including the responses to earthquake precursors and post-seismic activity. Unfortunately, this study could not precisely distinguish the earthquake precursors (e.g., foreshock), coseismic 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 the coral skeleton. Large sample size and combined analysis using skeletal $\delta^{13}\text{C}$ as a paleo-earthquake proxy, skeletal Ba/Ca as a paleo-tsunami proxy, and the skeletal growth parameter as a paleo-seafloor displacement will lead to the solution for the issues.

For skeletal Ba/Ca as a sediment load proxy, there are multiple sources of anthropogenic sediment load in the bay (e.g., silk fabric, farming, forestry, construction, and quarries, as shown in *Chapter 6*, Study Case-3). The pathway of these anthropogenic sediments to the bay are the same, which is transported by rivers towards the ocean with freshwater/flood plumes, regardless of the sources are different. Corals record the chemical composition of the habitat marine environment while growing by adding calcium carbonate (CaCO_3) skeletons. Because the pathway of anthropogenic sediments to the bay are the same, it is difficult to completely isolate each source of sediment (i.e., each industry) using skeletal geochemical records (skeletal Sr/Ca, Ba/Ca, Mg/Ca, $\delta^{18}\text{O}$, $\delta^{18}\text{O}_{\text{sw}}$, and $\delta^{13}\text{C}$). There were a few previous studies that have detected the signals of the anthropogenic factors on the other skeletal geochemical records, for example, skeletal Cd/Ca (Shen et al., 1987; Shen and Boyle, 1988; Tanaka et al., 2013), Mn/Ca (Moyer et al., 2012), Pb/Ca (Tanaka et al., 2013; Inoue et al., 2014; Shen and Boyle, 1987), Y/Ca (Fallon et al., 2002), V/Ca (Tanaka et al., 2013), Zn/Ca (Fallon et al., 2002), and $\delta^{15}\text{N}$ (Yamazaki et al., 2015; Murray et al., 2019). Because these proxies also have a complexity in the natural controlling factors (e.g., upwelling, ENSO, river discharge, and biological activity, Saha et al., 2016), the additional study cases and combined discussions might be needed in order to isolate each source of natural/anthropogenic factor completely. Moreover, it is necessary for isolating the freshwater plume, SST fluctuation, and upwelling-like Ba uptake effects because these controlling factors may mask the reef disturbance signals in the skeletal Ba/Ca. The distinction of temporary events, such as tsunami events and river flood events, also remains as a future issue (Table 7-1). A combined approach using skeletal Ba/Ca as a tsunami/river flood proxy and coral derived $\delta^{18}\text{O}_{\text{sw}}$ as a rainfall proxy might assist the deep discussion (e.g., *Chapter 6*).

Skeletal growth parameter is a useful tool for assessing the impact of reef disturbances. The coral skeleton observations using an optical microscope and an electron microscope are also useful for finding the signals of temporary growth disturbance. Because there are some controlling factors on the coral calcification (e.g., thermal stress, sediment stress, shore effects, and light availability; see *Chapter 1*), the skeletal growth parameters should be used in combination with skeletal geochemical proxies.

How should we approach the acclimatization/adaptation/“*Ingenious Paradox*” on corals and reefs?

“*Ingenious Paradox*” –*biologically fragile but geologically robust*. (Buddemeier and Smith, 1999)

Coral reefs (including the reef-building corals and the reef communities) should have certain mechanisms of acclimation and adaptation towards the numerical environmental change over a long geological (over tens of thousands of years). However, coral reefs and communities are currently declining due to the significant environmental change in the very short-term scale. Thus, there appears like a paradox in the acclimation or adaptation of coral reefs. Buddemeier and Smith (1999) called the paradox in the coral reefs “*Ingenious Paradox*.”

In order to explain the “*Ingenious Paradox*” completely, it is necessary to understand the stress responses of the corals, acclimatization/adaptation (Coles and Brown, 2003) of coral reefs, and reef environmental changes (including the history of the reef-human community) through the multi-academic field with long-time scale. The sights of coral acclimatization will allow us to develop an understanding of the mechanisms of coral response to disturbance factors in the local scale with the short-term. The field studies have been carried on the marginal and extreme environments (i.e., high-latitude, thermally extreme habitats, mesophotic depths, high-turbidity areas, extreme-salinity areas, low-pH areas, low-dissolved oxygen zones, and mangrove lagoons; e.g., Oliver and Palumbi, 2011a; Manzello et al., 2012; Howells et al., 2016; Loya et al., 2016; Bauman et al., 2017; Krueger et al., 2017; Thomas et al., 2017; Camp et al., 2017; 2019; Smallhorn-West et al., 2019) are worth sights to figure out the response of the reef environmental change in the future. Biological/Physiological approach and discussions focused on the symbiotic coral-zooxanthellae system (e.g., Buddemeier and Fautin, 1993; Brown et al., 2002; Baker, 2004; Lewis and Coffroth, 2004; Fabricius, 2005; Thornhill et al., 2005; Crawley et al., 2009; Ries et al., 2009; Winters et al., 2009; Holcomb et al., 2010; Chauvin et al., 2011) serve an important function to clarify the mechanisms of stress response and acclimatization. Besides, paleo-environmental/paleoclimatology/paleoceanography approach such as sclerochronological reef disturbance archives (i.e., massive and long-lived coral skeleton; this study) shows us information on reef disturbance factors and skeletal growth/calcification response patterns in the local or regional scale with long-term. The coral specimens of this study (*Porites* sp.) indicates that they can acclimate/adapt to environmental changes (i.e., chronic climate or sediment stress) if it is temporary change (e.g., < 1 year) or a gradual change over a long period (e.g., > approximately 50 years). If a sudden, multiple, and larger environmental change than the natural/anthropogenic events reconstructed in this study occurs consecutively, it might have a more substantial negative impact on the corals and reefs. While, several previous studies have reported on the interspecies difference in the mechanisms of stress response and acclimatization. There is a possibility of the numerical factors, for example, colony form (e.g., Loya et al., 2001; Chavanich et al., 2008), zooxanthellae composition (e.g., Baker et al., 2003; 2004; Fabricius, 2006; Winter et al., 2009), microbial community (Oliver and Palumbi, 2011b; Camp et al., 2020), the efficiency of metabolism/exchange materials (e.g., Patterson, 1992; Gates & Edmunds, 1999), habitat

water depth (e.g., Rowan et al., 1997; Winter et al., 2009; Chavanich et al., 2008), and energy allocation for sexual reproduction (e.g., Howells et al., 2016). The acclimatization of each reef-building coral would be an original component of the adaptation or survival strategy in the multidecadal/hundreds-year scale. For example, the high-turbidity condition had been considered be negative impacts on coral growth/calcification and reef expansion (Brown and Howard, 1985; Rogers, 1990; Erftemeijer et al., 2012; Jokiel et al., 2014). While, there are some recent reports which have described that some coral species inhabit in a certain high-turbidity condition have the thermal stress-tolerant (e.g., Guest et al., 2016a; 2016b; Morgan et al., 2016; 2017), and they can recover rapidly from stressors or bleaching, relatively (Guest et al., 2016b). Thus, additional research focused on the variation of the interspecies differences and the relationship between the stress-tolerant and habitat conditions is expected to be able to understand the mechanism of adaptation in reef-building corals and reefs. Besides, genetic/ocean ecological/geographic approach using multi-species in regional scale (e.g., Van Oppen and Gates, 2006; Barshis et al., 2010; 2013; Yamano et al., 2011; Bay and Palumbi, 2014; Ruiz-Jones and Palumbi, 2017; Thomas et al., 2017; Liew et al., 2020) can make an effective discussion against the research question: how do the corals adapt the environmental change (i.e., the survival strategy in the stress response and calcification) in the multidecadal/hundreds-year scale? The long-term sclerochronological archives in the history of the reef-human environment (community) and coral calcification response also derive the new knowledge of reef adaptability. Furthermore, the natural integration of coral adaptabilities would be the origin of coral reefs. It is necessary to understand the species distribution on the reef and the calcification/carbonate budget in the reef (i.e., CaCO_3 productivity in the reef, Stearn et al., 1977; Perry et al., 2008; 2012; 2018) from the past to the present, based on the changes in coral acclimation, adaptation, and coral reef communities. Ultimately, these approaches and knowledge help us to grasp a figure that shows the future of coral and coral reefs will look like, and it will be an essential key for the development of the strategy for stable health on the reef-human community (e.g., bottom-up supporting on the regional advocacy and governmental policy).

A sustainable healthy relationship for reef environments and human society

Climate change associated with global warming/An increase in human activity will trigger a local or regional upheaval (drastic change) of the coral reef environment in the future. The threats and situation will intensify and be complexed by global stressors (global warming and ocean acidification; e.g., Baker et al., 2008; Hoegh-Guldberg et al., 2017), local stressors (human activities and depletion of dissolved oxygen in the ocean that so-called “dead zones”; e.g., Diaz and Rosenberg, 2008). There are still many areas in the world that lack *in situ* water quality data and reef monitoring. In addition to conventional qualitative monitoring methods, the coral skeleton-made quantitative time-series of environmental changes and the quantitative calcification record will be an important tool. It can be essential to the discussion of survival strategies for reef-building corals in which precipitation and human activities will increase. As mentioned above, it is required to understand the calcification response from the past to present based on paleoclimatology or paleo-oceanography (i.e., the reconstruction of paleo-environments), and then it will finally allow approaching to the future aspects of coral reef environments. Awaiting the solution in the next stage of this study is to assess the calcification response using suitable proxies under classifying complex factors of reef disturbance. Furthermore, the cross-discussion through the multi-academic fields and multi-species of reef-building corals are also strongly needed. Approximately 40% of the worlds’ population live within 100 km of

coastline. As research continues to grow, we will gain the various and comprehensive answers to “how natural/anthropogenic factors lead to a reef disturbance” and “how corals and reef-systems respond to these disturbances,” in order to create a sustainable human society that can benefit from coral reefs. Finally, keeping the balance between natural/anthropogenic reef disturbance and the coral calcification response may also be needed to maintain reef health and reef biodiversity in the future.

Tables

A. Geochemical proxies

	Factors of reef disturbances				
	Coseismic seafloor displacement	Tsunami	Heavy rainfall (without river flood)	Heavy rainfall (with river flood)	Local industrial development
$\delta^{18}\text{O}$	<i>n.s.</i>	<i>n.s.</i>	<i>n.s.</i>	<i>n.s.</i>	-
$\delta^{13}\text{C}$	Positive step change [Large RLA]	Negative peak [Inshore; Huge tsunami]	<i>n.s.</i>	<i>n.s.</i>	-
$\delta^{18}\text{O}_{\text{sw}}$	-	-	<i>n.s.</i>	Low-SSS	-
Sr/Ca	<i>n.s.</i>	<i>n.s.</i>	<i>n.s.</i>	Low-SST	-
Mg/Ca	<i>n.s.</i>	<i>n.s.</i>	<i>n.s.</i>	Low-SST	-
Ba/Ca	-	Positive peak	Positive peak [< 2 years trend data]	Clear positive peak [< 2 years trend data]	Significant relationship [> 2 years trend data]

B. Skeletal growth and characteristics

	Factors of reef disturbances				
	Coseismic seafloor displacement	Tsunami	Heavy rainfall (without river flood)	Heavy rainfall (with river flood)	Local industrial development
Stress band	Observed (factors were not isolated) [Inshore; Shallow depth]		<i>n.s.</i>	Observed	<i>n.s.</i>
Green band Clay-like material	<i>n.s.</i>	Observed [Algae bloom]	<i>n.s.</i>	<i>n.s.</i>	<i>n.s.</i>
$\Delta\text{Sr}/\text{Ca}$ (temporal)	-	-	<i>n.s.</i>	Clear peak (slow growth)	-
Skeletal growth	Increasing (due to coseismic uplift)	Decreasing	<i>n.s.</i>	Decreasing (incl. the other factors)	Significant relationship

Table 7-1 Summary for the reef disturbances archives in the sclerochronological proxies and the responses on skeletal calcification

The detailed results and discussions were described in *Chapter 4 ~ 6*. The notation “*n.s.*” means the nonsignificant signal. The notation “-” shows no data or no discussion in this study.

Coral Species	Proxy	Location	Reference
<i>Acropora</i> sp.	Sr/Ca	French Polynesia	Ribaud-Laurenti et al. (2001)
<i>Acropora</i> sp.	$\delta^{18}\text{O}$, Mg/Ca, Sr/Ca	[Under controlled conditions]	Reynaud et al. (2007)
<i>Acropora</i> sp. (3 species)	$\delta^{18}\text{O}$, Mg/Ca, Sr/Ca	[Under controlled conditions]	Xiao et al. (2014)
<i>Acropora digitifera</i>	Ba/Ca, Mg/Ca, Sr/Ca	[Under controlled conditions]	Tanaka et al. (2015)
<i>Acropora humilis</i>	Sr/Ca	Great Barrier Reef	Sadler et al. (2016a)*
<i>Acropora millepora</i>	Sr/Ca	Great Barrier Reef	Sadler et al. (2016b)*
<i>Acropora nobilis</i>	Mg/Ca, Sr/Ca, U/Ca	Okinawa	Shirai et al. (2008)
<i>Acropora palmata</i>	$\delta^{18}\text{O}$, Sr/Ca	Barbados	Guilderson et al. (1994)
<i>Acropora palmata</i>	Sr/Ca	Caribbean	Gallup et al. (2006)
<i>Acropora samoensis</i>	Sr/Ca	Great Barrier Reef	Sadler et al. (2016a)*
<i>Diploria labyrinthiformis</i>	Ba/Ca	Bermuda	Lea et al. (1989)*
<i>Diploria labyrinthiformis</i>	$\delta^{18}\text{O}$	Bermuda	Draschba et al. (2000)
<i>Diploria labyrinthiformis</i>	$\delta^{18}\text{O}$, Sr/Ca, U/Ca	Bermuda	Cardinal et al. (2001)
<i>Diploria labyrinthiformis</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca	Bermuda	Kuhnert et al. (2002)*
<i>Diploria labyrinthiformis</i>	$\delta^{18}\text{O}$, Sr/Ca	Bermuda	Cohen et al. (2004)
<i>Diploria labyrinthiformis</i>	Sr/Ca	Bermuda	Goodkin et al. (2005)
<i>Diploria labyrinthiformis</i>	Sr/Ca	Bermuda	Cohen and Thorrold (2007)
<i>Diploria labyrinthiformis</i>	Sr/Ca	Bermuda	Goodkin et al. (2007)
<i>Diploria labyrinthiformis</i>	$\delta^{18}\text{O}$, Sr/Ca	Bermuda	Goodkin et al. (2008)*
<i>Diploria labyrinthiformis</i>	Sr/Ca, U/Ca	Bermuda	Alpert et al. (2017)*
<i>Diploria labyrinthiformis</i>	Sr/Ca, U/Ca	Curacao	Alpert et al. (2017)*
<i>Diploria strigosa</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca	Bermuda	Kuhnert et al. (2005)*
<i>Diploria strigosa</i>	$\delta^{18}\text{O}$, Sr/Ca	Guadeloupe	Hetzinger et al. (2006)
<i>Diploria strigosa</i>	$\delta^{18}\text{O}$	Venezuela	Hetzinger et al. (2008)
<i>Diploria strigosa</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca	Bonaire Island (Caribbean Sea)	Giry et al. (2010)
<i>Diploria strigosa</i>	Sr/Ca	Bonaire Island (Caribbean Sea)	Giry et al. (2012)
<i>Diploria strigosa</i>	Sr/Ca	Virgin Islands	Xu et al. (2015)*
<i>Diploastrea heliophora</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	New Caledonia	Watanabe et al. (2003)
<i>Diploastrea heliophora</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca	SPCZ (Pacific)	Bagnato et al. (2004)*
<i>Diploastrea heliophora</i>	$\delta^{18}\text{O}$, Sr/Ca	Vanuatu	Corrège et al. (2004)*
<i>Diploastrea heliophora</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca	SPCZ (Pacific)	Bagnato et al. (2005)*
<i>Diploastrea heliophora</i>	$\delta^{18}\text{O}$	Tanzania	Damassa et al. (2006)*
<i>Diploastrea heliophora</i>	$\delta^{18}\text{O}$	Fiji	Dassié and Linsley (2015)
<i>Diploastrea heliophora</i>	$\delta^{18}\text{O}$, Sr/Ca	Philippines	Ramos et al. (2017)*
<i>Favia Speciosa</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Pirotan Island (Arabian Sea)	Chakraborty and Ramesh (1998)*
<i>Goniopora hilli</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Dominican Republic	Weiss et al. (2017)*
<i>Hydnophora microconos</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Mn/Ca	Tawara Atoll	Cole et al. (1993)*
<i>Isopora</i> sp.	$\delta^{18}\text{O}$, Sr/Ca	Great Barrier Reef	Brenner et al. (2017)*
<i>Isopora palifera</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Okinawa	Nishida et al. (2014)
<i>Montastraea annularis</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Jamaica, Barbados, Bermuda	Fairbanks and Dodge (1979)
<i>Montastraea annularis</i>	Ba/Ca	Garapagos	Lea et al. (1989)
<i>Montastraea annularis</i>	$\delta^{18}\text{O}$	Florida	Leder et al. (1996)
<i>Montastraea annularis</i>	$\delta^{18}\text{O}$, Sr/Ca	Florida	Swart et al. (2002)
<i>Montastraea faveolata</i>	$\delta^{13}\text{C}$	Florida	Swart et al. (1996b)*

<i>Montastraea faveolata</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Puerto Rico	Winter et al. (2000)*
<i>Montastraea faveolata</i>	Mg/Ca, Sr/Ca	Puerto Rico	Watanabe et al. (2001)
<i>Montastraea faveolata</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Puerto Rico	Watanabe et al. (2002)
<i>Montastraea faveolata</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Tobago	Moses and Swart (2006)*
<i>Montastraea faveolata</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Mg/Ca, Sr/Ca	Florida	Smith et al. (2006)
<i>Montastraea faveolata</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Mg/Ca, Sr/Ca	Puerto Rico	Kilbourne et al. (2008)*
<i>Montastraea faveolata</i>	Al/Ca, B/Ca, Ba/Ca, Cd/Ca, Co/Ca, Cr/Ca, Cu/Ca, Fe/Ca, Mg/Ca, Mn/Ca, Ni/Ca, Pb/Ca, Sn/Ca, Sb/Ca, U/Ca, V/Ca, Zn/Ca	Mesoamerican Caribbean Reef	Prouty et al. (2008)
<i>Montastraea faveolata</i>	$\delta^{18}\text{O}$, Sr/Ca	Virgin Islands	Saenger et al. (2008)
<i>Montastraea faveolata</i>	Sr/Ca	Mexico	DeLong et al. (2011)*
<i>Montipora verrucosa</i>	Sr/Ca	[Under controlled conditions]	Smith et al. (1979)
<i>Siderastrea</i> spp.	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Guinea	Swart et al. (1998)*
<i>Siderastrea radians</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Ba/Ca	Florida	Swart et al. (1999)
<i>Siderastrea siderea</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Tobago	Moses and Swart (2006)*
<i>Siderastrea siderea</i>	Sr/Ca	Mexico	DeLong et al. (2014)*
<i>Siderastrea siderea</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca	Mexico	DeLong et al. (2016)
<i>Siderastrea siderea</i>	Sr/Ca, U/Ca	Yucatan	Alpert et al. (2017)*
<i>Siderastrea siderea</i>	$\delta^{13}\text{C}$	Belize	Fowell et al. (2018)
<i>Solenastrea bournoni</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Florida	Swart et al. (1996a)*
<i>Orbicella annularis</i>	Sr/Ca, U/Ca	Puerto Rico	Alpert et al. (2017)*
<i>Orbicella faveolata</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Florida	Swart et al. (1996c)*
<i>Orbicella faveolata</i>	$\delta^{18}\text{O}$	Tobago	Moses and Swart (2006)*
<i>Orbicella faveolata</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Meso America	Carilli et al. (2013)*
<i>Pavona clavus</i>	Ba/Ca, Sr/Ca	Garapagos	Lea et al. (1989)*
<i>Pavona clavus</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Ba/Ca, Cd/Ca, Mg/Ca	Garapagos	Shen et al. (1992)*
<i>Pavona clavus</i>	Sr/Ca	Hawaii	de Villiers et al. (1994)
<i>Pavona clavus</i>	$\delta^{18}\text{O}$	Garapagos	Dunbar et al. (1994)*
<i>Pavona clavus</i>	$\delta^{18}\text{O}$, Sr/Ca	Garapagos	de Villiers et al. (1995)
<i>Pavona clavus</i>	$\delta^{18}\text{O}$	Garapagos	Wellington et al. (1996)*
<i>Pavona clavus</i>	Cd/Ca	Panama	Matthews et al. (2008)
<i>Pavona clavus</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Garapagos	Druffel et al. (2014)*
<i>Pavona clavus</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Garapagos	Druffel et al. (2015)*
<i>Pavona clavus</i>	Ba/Ca	Panama	LaVigne et al. (2016)
<i>Pavona gigantea</i>	$\delta^{18}\text{O}$	Garapagos	Dunbar et al. (1994)*
<i>Pavona gigantea</i>	$\delta^{18}\text{O}$	Garapagos	Wellington et al. (1996)*
<i>Pavona gigantea</i>	Cd/Ca	Panama	Matthews et al. (2008)
<i>Pavona gigantea</i>	Ba/Ca	Panama	LaVigne et al. (2016)
<i>Pocillopora damicornis</i>	Sr/Ca	[Under controlled conditions]	Smith et al. (1979)
<i>Pocillopora damicornis</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, B/Ca, Ba/Ca, Sr/Ca	Panama	Toth et al. (2015)*
<i>Pocillopora damicornis</i>	Sr/Ca, U/Ca	Panama	Alpert et al. (2017)*
<i>Pocillopora eydoiuxi</i>	Sr/Ca	Hawaii	de Villiers et al. (1994)

<i>Platygyra lamellina</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Vanuatu	Quinn et al. (1993)
<i>Platygyra lamellina</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Vanuatu	Quinn et al. (1996)*
<i>Platygyra ryukyuensis</i>	$\delta^{18}\text{O}$	Okinawa	Shimamura et al. (2008)
<i>Platygyra sinensis</i>	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca	Larak Island (Persian Gulf)	Forouzan et al. (2014)
<i>Pseudodiploria strigosa</i>	$\delta^{18}\text{O}$, Sr/Ca	Guadeloupe	Hetzinger et al. (2010)*
inter species (> 5 species)	Pb/Ca	[see Shen and Boyle (1987)]	Shen and Boyle (1987)*
inter species (> 5 species)	Sr (ppm)	[see Weber (1973)]	Weber (1973)

Table 7-2 Published coral species list for geochemical proxies (excluding *Porites* sp.)

The published skeletal $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and Me/Ca using the coral species excluding *Porites* sp. are listed. Noted that the species were shown as reported in the papers (some species have been reclassified). The Notation “*” means that it is available on *Paleoclimatology Data* by NOAA (<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/coral-sclerosponge>). Fossils and moderns were included.

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