Chapter 29
Coral-Based Approaches to Paleoclimate Studies, Future Ocean Environment Assessment, and Disaster Research

Atsushi Suzuki

Abstract Global warming causes serious harm to the Earth's environment. A more sophisticated and accurate climate model can be developed by reconstructing climatic change since the Industrial Revolution and for other past periods of global warming. Coral skeletons are an important archive of past climate changes, and advances in the ability to read sea surface temperature and salinity in the coral record have been made by applying state-of-the-art technology. Coral skeletal climatology has been successfully applied to characterize both the recent global warming trend in the Western Pacific and the mid-Pliocene warming that occurred 3.5 million years ago, and it has also been used to investigate biological and environmental issues such as ocean acidification and coral bleaching, which is caused by unusually high seawater temperatures. Coral skeletal climatology methods have also been used to study *Porites* boulders cast ashore by historical tsunamis; such studies have high social value from the perspective of regional disaster prevention. Nevertheless, aspects of coral skeletal climatology still need clarification, including the basic mechanism by which seawater temperature is recorded in coral skeletons, and further research on biomineralization will improve predictions of the future responses of marine calcifying organisms to ocean acidification.

Keywords Coral · Global warming · Ocean acidification · Coral bleaching · Tsunami

29.1 Introduction

Annual banding in the skeletons of modern corals was first described by Ma (1934), then a PhD student at Tohoku University, after a field trip to the northern Ryukyu Islands of Japan (Fig. 29.1). The annual bands of coral skeletons became the subject

A. Suzuki (✉)
Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, Japan
e-mail: a.suzuki@aist.go.jp

K. Endo et al. (eds.), *Biomineralization*,
https://doi.org/10.1007/978-981-13-1002-7_29

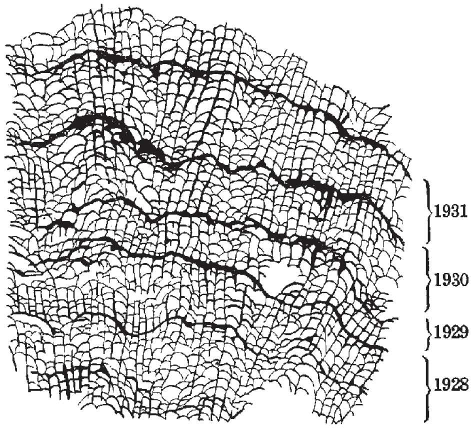


Fig. 29.1 First published illustration of annual banding in modern corals. (Reprinted from Ma 1934 with permission from the Institute of Geology and Paleontology Sendai, Tohoku University)

of active research in the 1990s, but only recently has the research developed into the field of coral skeletal climatology (see Suzuki 2012). Corals provide rich archives of past climatic variability in tropical regions, where instrumental records are relatively few. In this review, I explain why the coral skeleton is such an excellent archive of past global climate change and describe some of the major ways in which coral skeletal analyses have been successfully applied to biological and environmental issues, including coral bleaching events and ocean acidification, as well as to paleo-tsunami research.

29.2 Coral Skeletal Climatology

Geochemists have found useful climate proxies in the coral skeleton. For example, the strontium/calcium (Sr/Ca) ratio is a good, and pure, proxy for sea surface temperature; that is, the skeletal Sr/Ca ratio is controlled only by seawater temperature. In contrast, the oxygen isotope ratio ($\delta^{18}O$) is a mixed proxy for both seawater temperature and salinity, and the uranium/calcium (U/Ca) ratio is a mixed proxy for seawater temperature and pH. By a combined analysis of two proxies, Sr/Ca and $\delta^{18}O$ or Sr/Ca and U/Ca, referred to as a "dual proxy method," it is possible to extract past salinity variation (McCulloch et al. 1994) or past seawater pH from the coral skeletal record (Fig. 29.2).

Two examples of twentieth century coral oxygen isotope records from coral reefs in Japan are shown in Fig. 29.3. Fluctuations of $\delta^{18}O$ in corals from Ishigaki Island (124°E, 24°N), which is very close to Taiwan (Mishima et al. 2010), and Chichijima Island (142°E, 27°N) in the Ogasawara island chain, due south of Tokyo (Felis et al. 2009), record seasonal variations of seawater temperature. In addition, both curves show a shift toward more negative values with time, indicating a long-term seawater temperature increase. Moreover, by applying the dual proxy method, the Ogasawara

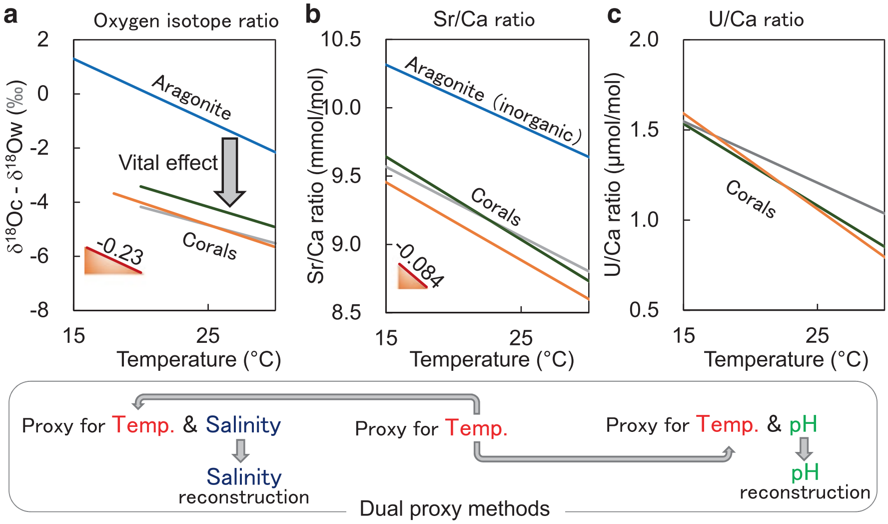


Fig. 29.2 Coral climate proxies that have been developed by geochemists: (**a**) oxygen isotope ratio ($\delta^{18}O$); (**b**) Sr/Ca ratio; and (**c**) U/Ca ratio. The $\delta^{18}Oc$ and $\delta^{18}Ow$ denote oxygen isotope ratio of coral skeleton and seawater, respectively. The skeletal Sr/Ca ratio is controlled only by seawater temperature, whereas $\delta^{18}O$ is a mixed proxy for seawater temperature and salinity and the U/Ca ratio is a mixed proxy for seawater temperature and pH. Through a combined analysis of Sr/Ca and $\delta^{18}O$ (U/Ca), the seawater salinity (pH) variation can be extracted. Ideal temperature dependency of $\delta^{18}O$ and Sr/Ca ratio proposed by Gagan et al. (2012) are shown in panels (**a**, **b**), respectively

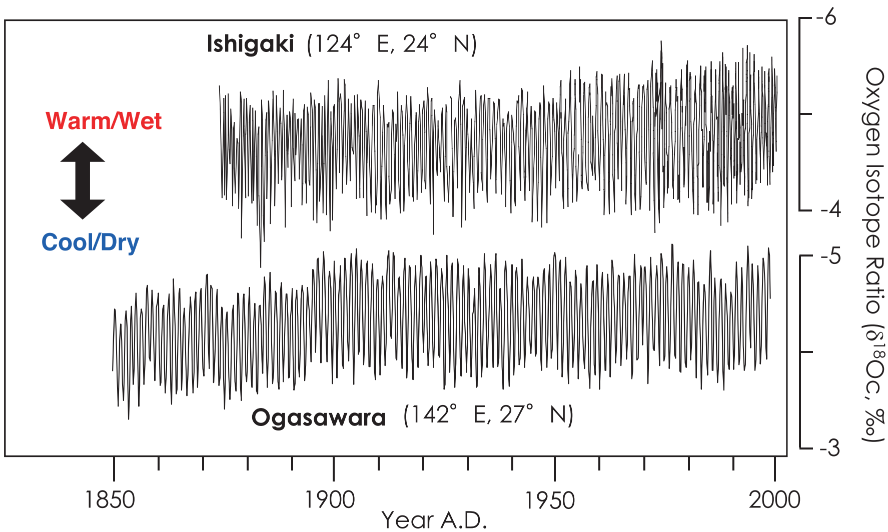


Fig. 29.3 Times series of coral $\delta^{18}O$ records from Ishigaki Island in the southern Ryukyus (Mishima et al. 2010) and Chichijima Island in the Ogasawara Islands (Felis et al. 2009) in the Western Pacific

corals were found to record a long-term freshening of seawater (decrease in salinity) in the region. The long-term warming trend revealed by Ishigaki coral can be attributed to anthropogenic climate change.

Conditions during the Pliocene warm period, about 4.6–3 million years ago, are thought to be similar to the climate conditions expected to result from global warming in the near future. Watanabe et al. (2011), who compared analysis results obtained by the same method between modern corals and well-preserved fossil corals from Luzon Island, the Philippines, showed that El Niño occurred on about the same cycle during the Pliocene warm period as at present. Their study is an example of the successful application of coral skeletal climatology to the distant past.

29.3 Application to Environmental Issues

Coral skeletal climatology can also be applied to the investigation of biological and environmental issues such as coral-bleaching events and ocean acidification.

Coral bleaching at a scale unseen before occurred in coral reefs around the Ryukyu Islands in August 1998, and another major coral bleaching event occurred in the southern Ryukyu Islands, especially around Ishigaki Island, in summer 2016. Suzuki et al. (2003) examined skeletal records of bleached corals and observed an abrupt rise, corresponding to the bleaching period, in the $\delta^{18}O$ profile analyzed at high resolution along the growth axis of the skeleton. They interpreted this jump to reflect a cessation of coral skeletal growth for a few months immediately after bleaching. As global warming progresses and high seawater temperatures occur more frequently, environmental conditions can be expected to further inhibit coral growth.

Another good proxy for the pH of seawater, or, more precisely, that of the calcifying fluid of the organism, is the boron isotope ratio of the coral skeleton. Kubota et al. (2017) conducted high-precision boron isotope measurements of two coral cores collected from Kikai Island (Ryukyu Islands) and Chichijima Island (Ogasawara Islands) and reported that the ratios from the two islands decreased over the long term, indicating decreasing pH. Interestingly, in both cases, the rate of decline increased in the latter half of the twentieth century. Although seawater pH changes have been observed by shipboard measurements since 1985, the coral record confirms the existence of an ocean acidification trend in the Western Pacific.

29.4 Application to Disaster Research

The 2011 Tohoku-oki earthquake (Great East Japan Earthquake) occurred on 11 March 2011, and the tsunami generated by the earthquake caused major damage to the Pacific coasts of the Tohoku and Kanto regions of Japan. To mitigate the effects of future tsunamis, it is urgent to reevaluate past tsunami damage throughout Japan.

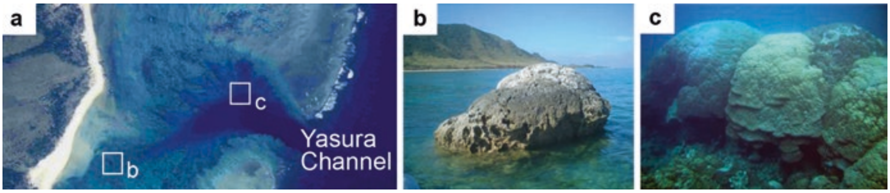


Fig. 29.4 (**a**) Aerial photograph of the fringing coral reef on the eastern shore of Ishigaki Island, Japan (from the Geospatial Information Authority of Japan). (**b**) A tsunami boulder composed of a massive *Porites* coral on the reef flat. This coral was dated to about AD 1771 (Araoka et al. 2010). (**c**) Massive *Porites* coral colonies in the reef channel

Coral skeletal climatology methods have been applied to the analysis of *Porites* boulders cast ashore by past tsunamis (Suzuki et al. 2008; Fig. 29.4). By applying radiocarbon dating and coral skeletal climatological techniques to *Porites* boulders scattered along the eastern coast of Ishigaki Island, southern Ryukyus, Araoka et al. (2010) demonstrated that some of the boulders, at least, were washed ashore by the Meiwa tsunami in 1771. Araoka et al. (2013) extended this approach to neighboring islands in the southern Ryukyus. They selected non-eroded *Porites* coral boulders along shorelines for radiocarbon dating, because they retain characteristics that make it possible to determine the probable timing of their deposition by tsunamis. Their results demonstrate that the southern Ryukyu Islands have repeatedly experienced tsunami events since at least 2400 years ago, with a recurrence interval of about 150–400 years. Their study demonstrates that by reliably dating large numbers of coral boulders, it is possible to ascertain the timing, recurrence interval, and magnitude of past tsunamis in a location where few survey sites exist that include sandy tsunami deposits.

29.5 Future Directions

Several points still need clarification, including the basic mechanisms by which climatological factors such as seawater temperature are recorded in the chemical and isotope compositions of coral skeletons. Further, the influence of the coral growth rate on coral climate proxies such as $\delta^{18}O$ is still problematic (Fig. 29.5). Special attention needs to be paid to diagenetic alteration of coral proxy signals. In addition to the geochemical methods, culture experiments should be conducted and molecular biological methods should be applied to clarify the biological mechanism of calcification. Recent papers have recognized that coral primary polyps are particularly suitable for biomineralization studies because of their small size and simple form (Iwasaki et al. 2016; Ohno et al. 2017). An integrated approach that brings various perspectives to bear on these problems is needed, because coral biomineralization reflects synergetic effects (Fig. 29.6).

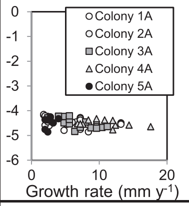
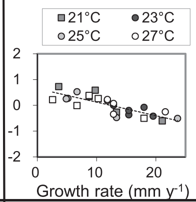
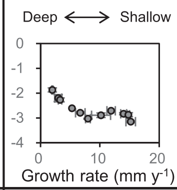
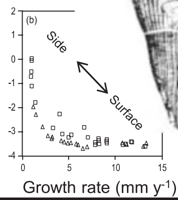
Genus	*Porites*			*Pavona*
Reference	Hayashi et al. (2013)	Suzuki et al. (2005)	Felis et al. (2003)	McConnaughey (1989)
Factors	Intercolony (intra-species)	Intercolony/Temperature (inter-species)	Water depth	Position in colony 
Growth rate influence on δ18O				
Growth rate	2 - 14 mm y^{-1}	5 - 22 mm y^{-1}	2 - 15 mm y^{-1}	1 - 13 mm y^{-1}
$\delta^{18}O$	~ 0.8‰	~ 1.5‰	~ 1.3‰	~ 3.5‰

Fig. 29.5 Influence of the skeletal growth rate on the skeletal oxygen isotope ratio ($\delta^{18}O$) as reported in the literature (The image of the coral skeleton has been reprinted from McConnaughey 1989 with permission from Elsevier). Hayashi et al. (2013) reported a relatively small growth rate dependency of skeletal $\delta^{18}O$ values, but most previous studies have reported considerable dependence of climate proxies on the skeletal growth rate (Felis et al. 2003; Suzuki et al. 2005)

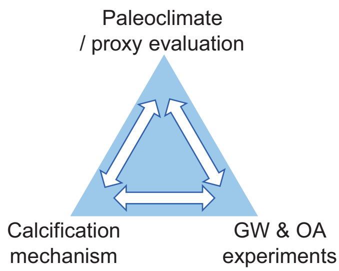


Fig. 29.6 Graphical summary of the integrated approach used by the author's research group. Research is conducted from various perspectives simultaneously because we expect synergetic effects for better understanding biomineralization of corals. *GW* global warming, *OA* ocean acidification

Acknowledgments This paper is based on joint research with H. Kawahata, A. Iguchi, Y. Ohno, M. Inoue, D. Araoka, T. Watanabe, and many other collaborators. To all of them, I express my sincere gratitude. This study was supported by KAKENHI grant 15H02813 and 18H03366 to AS.

References

Araoka D, Inoue M, Suzuki A, Yokoyama Y, Edwards RL, Cheng H, Matsuzaki H, Kan H, Shikazono N, Kawahata H (2010) Historic 1771 Meiwa tsunami confirmed by high-resolution U/Th dating of massive *Porites* coral boulders at Ishigaki Island in the Ryukyus, Japan. Geochem Geophys Geosyst 11:Q06014

Araoka D, Yokoyama Y, Suzuki A, Goto K, Miyagi K, Miyazawa K, Matsuzaki H, Kawahata H (2013) Tsunami recurrence revealed by *Porites* coral boulders in the southern Ryukyu Islands, Japan. Geology 41:919–922

Felis T, Pätzold J, Loya Y (2003) Mean oxygen-isotope signatures in *Porites* spp. corals: intercolony variability and correction for extension-rate effects. Coral Reefs 22:328–336

Felis T, Suzuki A, Kuhnert H, Dima M, Lohmann G, Kawahata H (2009) Subtropical coral reveals abrupt early 20th century freshening in the western North Pacific Ocean. Geology 37:527–530

Gagan MK, Dunbar GB, Suzuki A (2012) The effect of skeletal mass accumulation in *Porites* on coral Sr/Ca and $\delta^{18}O$ paleothermometry. Paleoceanography 27:PA1203

Hayashi E, Suzuki A, Nakamura T, Iwase A, Ishimura T, Iguchi A, Sakai K, Okai T, Inoue M, Araoka D, Murayama S, Kawahata H (2013) Growth-rate influences on coral climate proxies tested by a multiple colony culture experiment. Earth Planet Sci Lett 362:198–206

Iwasaki S, Inoue M, Suzuki A, Sasaki O, Kano H, Iguchi A, Sakai K, Kawahata H (2016) The role of symbiotic algae in the formation of the coral polyp skeleton: 3-D morphological study based on X-ray microcomputed tomography. Geochem Geophys Geosyst 17:3629–3637. https://doi.org/10.1002/2016GC006536

Kubota K, Yokoyama Y, Ishikawa T, Suzuki A, Ishii M (2017) Rapid decline in pH of coral calcification fluid due to incorporation of anthropogenic CO_2. Sci Rep 7:7694

Ma TYH (1934) On the growth rate of reef corals and the sea water temperature in the Japanese Islands during the latest geological times. Science reports of the Tohoku Imperial University 2nd series. Geology 16(3):165–189

McConnaughey T (1989) ^{13}C and ^{18}O isotopic disequilibrium in biological carbonates: I. Patterns. Geochim Cosmochim Acta 53:151–162

McCulloch MT, Gagan MK, Mortimer GE, Chivas AR, Isdale PJ (1994) A high resolution Sr/Ca and ^{18}O coral record from the Great Barrier Reef, Australia, and the 1982–1983 El Niño. Geochim Cosmochim Acta 58:2747–2754

Mishima M, Suzuki A, Nagao N, Ishimura T, Inoue M, Kawahata H (2010) Abrupt shift toward cooler condition in the earliest 20th century detected in a 165 year coral record from Ishigaki Island, southwestern Japan. Geophys Res Lett 37:L15609

Ohno Y, Iguchi A, Shinzato C, Inoue M, Suzuki A, Sakai K, Nakamura T (2017) An aposymbiotic primary coral polyp counteracts acidification by active pH regulation. Sci Rep 7:40324

Suzuki A (2012) Paleoclimate reconstruction and future forecast based on coral skeletal climatology –understanding the oceanic history through precise chemical and isotope analyses of coral annual bands. Synthesiology 5:78–87

Suzuki A, Gagan MK, Fabricius K, Isdale PJ, Yukino I, Kawahata H (2003) Skeletal isotope microprofiles of growth perturbations in *Porites* corals during the 1997–1998 mass bleaching event. Coral Reefs 22:357–369

Suzuki A, Hibino K, Iwase A, Kawahata H (2005) Intercolony variability of skeletal oxygen and carbon isotope signatures of cultured *Porites* corals: temperature controlled experiments. Geochim Cosmochim Acta 69:4453–4462

Suzuki A, Yokoyama Y, Kan H, Minoshima K, Matsuzaki H, Hamanaka N, Kawahata H (2008) Identification of 1771 Meiwa Tsunami deposits using a combination of radiocarbon dating and oxygen isotope microprofiling of emerged massive *Porites* boulders. Quat Geochronol 3:226–234

Watanabe T, Suzuki A, Minobe S, Kawashima T, Kameo K, Minoshima K, Aguilar YM, Wani R, Kawahata H, Sowa K, Nagai T, Kase T (2011) Permanent El Niño during the Pliocene warm period not supported by coral evidence. Nature 471:209–211