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キクメイシ科化石サンゴを用いた

16,000 年前の琉球列島域の氷期古海洋環境復元

Reconstruction of paleoenvironment at 16 ka in the last glacial period by Faviidae coral collected from Ryukyus, southwestern Japan

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1. INTRODUCTION

The East China Sea (ECS) is a marginal sea of the Pacific and located between the South China Sea and the Japan Sea (Fig.1). The ECS is an important site for paleohydrological and paleoceanographic studies because it is under the influence of both coastal water and the Kuroshio Current. Especially the latter transports a large amount of heat from the tropics to middle latitudes and then has a strong influence on the global climate system as well as on regional climates in the East Asia. The Kuroshio Current originated from the North Equatorial Current, crosses between the east side of Taiwan and the southern end of the Ryukyu Island Arc and travels along the Okinawa Trough northward until it goes out to the Pacific Ocean at the Tokara Strait (Jian *et al.*, 2000; Li *et al.*, 2001).

Since the Kuroshio Current is characterized by nutrient–depleted water properties, the phosphate and nitrate concentrations of surface water in the Kuroshio Current are below the detection limit (<0.02 μmol kg^{-1}) around the Ryukyu Islands (Watanabe *et al.*, 1995). Also this current significantly affects the sea surface temperature (SST) in this region. This oligotrophic water property with high temperature and deep thermocline provide the ocean environments suitable for the coral ecosystems although this region is situated at in relatively high latitude for corals. From the point of climatic view in the East Asia, change in the pathway and intensity of the Kuroshio Current during the interglacials and glacials received much attention (Jian *et al.*, 2000; Li *et al.*, 2001; Kawahata, 2004). Based upon the isotopic composition of planktonic foraminifera and pollen assemblage, most of the paleoceanogrpahic investigators has agreed about the contention that the Kuroshio Current showed little change in the pathway even during the last glacial maximum (Jian *et al.*, 2000; Li *et al.*, 2001; Kawahata and Ohshima, 2002, Ijiri *et al.*, 2005).

Up to now, assemblage and/or stable isotopes of foraminifera and alkenon analysis provide the continuous and quantitative record of SST in the ECS. However, these planktons sometimes shift the timing of bloom due to hydrographic change, which might bias the estimate of SST. On the other hand, no study was made on fossil coral skeletons of the glacial period in the Indo–Pacific although scleractinian coral skeletons have been providing powerful archives of modern and ancient surface ocean chemistry and environmental conditions in the tropics and temperate regions. They are especially useful in terms of paleoceanography because corals are widely distributed, can be accurately dated, and contain several geochemical tracers in their skeletons.

The geochemical compositions preserved in the coral skeleton are used to reconstruct the paleorecords, such as SST, salinity, winds and upwelling, cloud cover, pH, ocean mixing, and river discharge histories. Corals are one of the most effective tools with which we can develop the records of environmental variability. (Grottoli and Eakin, 2007) On top of that, corals possibly record the ambient environment with annual, seasonal time resolution or less, that is generally finer than other paleoceanographic recorders such as planktonic foraminiferal assemblage. Therefore, corals could make it possible to discuss paleoenvironments with inter–annual and/or intra–annual timescale when they have been preserved in good condition as a environmental recorder and are analyzed with high resolution along their growth axes.

Coral skeletal $\delta^{18}O$ is the major established paleothermometer, with $\delta^{18}O$ depletion correlating with increases in SST and ocean itself according to salinity (Dunbar and Wellington, 1981; Wellington *et al.*1996). To be more concrete, under colder temperatures, more of the heavier ^{18}O isotope is incorporated into carbonate skeletons, relative to ^{16}O (Urey *et al.* 1947). In fact the isotope ratio in the coral also depends on the ratio in the $\delta^{18}O$ of seawater ($\delta^{18}O$ w), and this has varied with salinity. During ice build up, the lighter ^{16}O is preferentially evaporated from the oceans and subsequently precipitated in the snow that contributes to the ice sheets. The ocean, therefore, tends to have a relatively higher ratio of ^{18}O during glaciations, and this effect accentuates, and largely masks, the direct temperature effect. As for inter/intra–annual fluctuation, evaporation tends to discriminate against the heavier ^{18}O isotope whereas the reverse happens during precipitation (Craig, 1961) Coral $\delta^{18}O$ records also are used to study how "connected" local climate processes are to broader basin or global–scale climate processes. In a large number of century–long or longer coral $\delta^{18}O$ records throughout the global tropics, patterns with 3–7 year frequency associated with ENSO variability and/or 10–30 year inter–decadal timescale patterns often associated with the Pacific Decadal Oscillation (PDO) or Interdecadal Pacific Oscillation (IPO) (Grottoli and Eakin, 2007).

The use of coralline Sr/Ca ratio as a temperature proxy has received the most attention (Beck *et al.*, 1992; Alibert and McCulloch, 1997). There is currently abundant evidence that Sr/Ca in corals can be a highly reliable temperature proxy. By the combination of both $\delta^{18}O$ and Sr/Ca, it is potentially possible to separate the $\delta^{18}O$ w and SST effects in skeletal $\delta^{18}O$ time series. Also $\delta^{13}C$ in coral skeleton is controlled by photosynthetic activity of symbiotic algae, light conditions, and feeding on zooplankton (Grottoli *et al.*,2002; Omata *et al.*, in press). Therefore $\delta^{13}C$ is often considered to be a proxy of solar radiation intensity (Fairbanks *et al.*, 1979; Suzuki *et al.*, 2001)

In this study, I analyzed oxygen and carbon isotopes and Sr/Ca of a fossil Faviidae coral sample, which were collected near the western Miyako Islands, Ryukyus (Fig. 1). This coral recorded the ocean environment at 16 ka in the last glacial period. As the sea level used to be significantly lower at 16 ka, fossil coral in this study is especially valuable because of much difficulty in sampling collection today. Thus, coral–based paleo–environmental study during this period has not been well investigated yet. I explore the application of Faviidae coral as a paleo–thermometer and provide the first report to reconstruct the reliable SST and salinity from fossil Faviidae corals in the western Pacific and to discuss the ocean environments in response to Asian Monsoon during the last glacial period.

2. Materials and Methods

2-1) STUDY AREA

The Ryukyu Arc stretches over approximately 1,200km from Taiwan to Kyushu, in which the Miyako Islands lay approximately 400 km east of Taipei, Taiwan. The Ogasawara Islands in the Pacific Ocean are located 1000 km south from Tokyo, Japan.

The Kuroshio Current enters the East China Sea through the east side of Taiwan. The main axis of the Kuroshio Current shifts seasonally under the alternation influences between cold, dry winter monsoon winds and warm, moist summer monsoon winds. The Kuroshio Current transport also varies on interannual time scales, with less transport during El Nino years and more during La Nina years, but in modern ocean, seasonal variations are greater than those that occur on interannual time scales. (Xiang *et al.*, 2007).

2-2) CORAL SAMPLE

The fossil Faviidae coral MYK90, which was analyzed in this study, was collected from the area of the western Miyako Islands, Ryukyus (Fig. 1), southwestern Japan under the research project of "Techniques for reconstruction and interpretation of reservoir development" by the Technology Research Center (TRC), Japan National Oil Corporation (JNOC, currently Japan Oil, Gas and Metals National Corporation; JOGMEC) (Honda et al., 1993; Sasaki et al. 2006). This program started in 1986 to understand the relationship between 3D sedimentary distribution and its controlling factors and to develop a carbonate depositional model from the insular shelf to the slope around the Miyako Islands, Southern Ryukyus. The MYK90 sample was found in one of the sediment cores, CR14 taken by the drilling ship KAIKO–101 in 1990 by TRC, JNOC (Fig. 1).

The fossil Faviidae coral (sample ID: MYK90) was collected from western offshore of Miyakojima (24°43’N, 124°3’E) at water depth of 125.4 m (Table 1). The columnar–shaped 73 mm coral sample MYK90 is classified in the family Faviidae (Fig. 2). However, it was impossible to subdivide into genus because any definitive correspondence in biological structure with modern Faviidae corals was not identified. Family Faviidae has 24 genera, which is more than any other family. All species in Faviidae have septal structures and columellae are a simple tangle of elongate septal teeth. Walls are composed of thickened septa and cross linkages. Sasaki *et al.*.(2006) conducted mineralogical investigation and age determination of this coral specimen according to the method precisely described by Omura *et al.*. (2004). The $^{230}Th/^{234}U$ age determination provided the age of MYK90 16.17 ± 0.52 ka, which is comparable to their conventional ^{14}C dating (Sasaki *et al.*., 2006). In order to compare the fossil coral MYK90 with modern coral in close location, modern Faviidae coral was analyzed in this study as well. The modern massive *Favia* coral with plocoid–shaped polyps (CJK01) was collected on November 11, 2001 at the depth of 5.1m in Chichijima, the Ogasawara Islands, Japan (Table 1).

2-3) ANALYTICAL METHODS

2-3-1) Microsampling of Fossil Faviidae

Firstly the columnar fossil coral sample MYK90 with phaceroid–shaped polyps was x–radiographed to observe annual bands and the other physical characteristics (Fig. 2). MYK90 was cut in halves and then inside structures such as columella, paliform lobes were removed by dentist drill to expose its wall. The wall was separated from inside structures for microsampling in order to avoid complex information from different part of the coral skeleton. One of the half coral samples, MYK90 was rinsed with Milli–Q water, carried out ultrasonic cleaning and dried in the oven at 40°C.

Microsampling for isotope and Sr/Ca analysis was conducted along the growth axis in the wall at an interval of 200 μ m. I collected 104 powdered subsamples from the 15.2–34.8 mm part from top of the coral out of 73.0 mm, in which the X–radiograph shows most consistent annual bands. Due to the round–shape of MYK, it was necessary to press and drill the sample very carefully to avoid destruction. Isotope and Sr/Ca measurements were carried out at an interval of every 2 samples for the high–resolution microsamples.

2-3-2) Microsampling of Modern Faviidae Coral

The coral sample CJK01 was sliced into 3 mm thick slabs and cleaned by means of same method with the fossil MYK described above. After it was x–radiographed, solid linier–shaped wall along the growth axis was chosen for isotopic and Sr/Ca measurements of this coral CJK01, since the fossil sample MYK90 was microsampled along the septal wall (Fig. 3). I collected 60 powdered subsamples from 0.2–15.0 mm part from top of the coral in which clear annual bands were found in X–radiograph. Isotope and Sr/Ca records were obtained from this CJK01 coral sample at the interval of every 2 subsamples.

2-3-3) δ^{18}O and δ^{13}C Measurement

Each subsample of 90–110 μg for oxygen isotope measurements was reacted with 100% H3PO4 at 90°C in an automated carbonate device (Multiprep, Micromass Co., Ltd.) coupled with a Micromass Optima mass spectrometer at the Geological Survey of Japan, AIST. Isotopic data are reported per mil deviations relative to Vienna Peedee Belemnite (VDPB). The internal precision was 0.03‰ and 0.04‰ (1σ) for δ^{18}O and δ^{13}C, respectively, based on replicate measurements of 23 consecutive samples of the NBS–19 calcite standard (Suzuki *et al.*., 1999).

2-3-4) Sr/Ca Measurement

Each subsample of 90–110 μg was dissolved in 5 ml 2% HNO_3 and concentrations of Ca and Sr were measured with an inductively coupled plasma atomic emission spectrophotometer (ICP–AES, IRIS Advantage, Thermo Electron Co., Ltd.) in the Geological Survey of Japan, AIST. It has been recognized that the low–frequency drift in Sr/Ca analyses could occur due to several factors including temperature changes in the room, drift in the conditions of the plasma, and drift in the electronics (Shrag, 1999). In order to control such an instrumental drift and to improve the precision, standard solutions prepared from JCp–1, a coral standard material provided by geological survey of Japan (GSJ; Okai *et al.*., 2002) were measured after every 3rd sample for data correction. Relative standard deviations based on 45 times replicate of JCp–1 were 0.4%. Two lines were used for this study: Ca (317.93 nm) and Sr (407.77 nm).

3. Results and Discussion

3-1) SKELETAL δ^{18}O, δ^{13}C AND Sr/Ca DATA OF FOSSIL FAVIIDAE

Skeletal δ^{18}O varies between –3.01 and –1.99‰ with the average value of –2.56‰. Skeletal δ^{13}C varies between –1.05 and 2.72‰ with the average value of –1.05‰ (Table 2). The δ^{18}O and δ^{13}C ranges were considerably smaller compared to previous studies of *Porites* corals, which are among the most commonly used genus for coral based paleo-environmental studies (Fig. 4).

Skeletal δ^{18}O of CJK01 varied between –5.23 and –4.16‰ with the average value of –4.67‰. Skeletal δ^{13}C of CJK01 varied between –2.73 and –0.58‰ with the average value of –1.80‰ (Table 2). The δ^{18}O and δ^{13}C ranges were again smaller compared to previous studies of *Porites* corals and also smaller than those of fossil MYK90 (Fig. 4).

Fossil and modern MYK Sr/Ca

As described above, Sr/Ca records were obtained from the same part with $\delta^{18}O$ and $\delta^{13}C$ analysis of MYK90 coral at the interval of every 2 subsamples. Sr/Ca of fossil cores varies between 9.12 and 9.54‰ with the average value of 9.31‰ while Modern skeletal Sr/Ca varies between 8.98 and 9.28‰ with the average value of 9.09‰. Similar to $\delta^{18}O$ and $\delta^{13}C$ values, Sr/Ca values also have a smaller range compare to those reported from modern *Porites* corals (Fig. 4).

Record of Faviidae corals

The oxygen and carbon isotope records in the fossil coral skeleton MYK90 along the major growth axis are shown in Fig. 2. Both $\delta^{18}O$ and $\delta^{13}C$ records exhibit marked seasonality therefore It can be presumed that the three maxima and minima in $\delta^{18}O$ records correspond to the lowest and highest SSTs of the years. Interestingly the three maxima gave comparable values while the three minima also gave similar values. By comparing the X–radiograph and the isotope records, I conclude that the high–density bands generally have more negative $\delta^{18}O$ compositions and appear to be deposited in winter. MYK90 shows clear negative correlation between $\delta^{18}O$ and $\delta^{13}C$ values with time lags by 1–2 months lag (Fig. 5). Although the interpretation of the $\delta^{13}C$ record in coral skeletons is more problematic (e.g., Swart *et al.*., 1996; Leder *et al.*, 1996), generally speaking, the algal symbiont of corals preferentially takes up the light carbon isotope during photosynthesis, leading to heavy isotope (^{13}C) enrichment of the internal dissolved inorganic carbon (DIC) pool of corals (Fairbanks and Dodge, 1979; McConnaughey, 1989; Weber *et al.*, 1976). In the Ryukyu Islands, The highest and lowest solar irradiation occurs in late June and late December, respectively while the highest and lowest SSTs are observed in August and February, respectively. The observation of 1–2 months lag between $\delta^{13}C$ and $\delta^{18}O$ in MYK90 suggests that this fossil coral could record the marine environments at 1.6 cal.kyr BP and infer the growth direction along the columnar coral.

The amplitude of $\delta^{18}O$ values in Faviidae corals looks much smaller than those observed in *Porites* spp (Fig. 4). In order to examine the temperature–$\delta^{18}O$ relationship of the coral, I compared the $\delta^{18}O$ values in modern Faviidae corals with the SST data between 1999 and 2001 in Chichijima, the Ogasawara Islands, observed by Ogasawara Fisheries Center, Tokyo Metropolitan Government Bureau of General Affairs are shown in Fig. 6. One approach to the calibration of a convention factor is to compare skeletal $\delta^{18}O$ extremes versus corresponding SST extremes within a year (McConnaughey, 1989; Gagan *et al.*, 1998). The other method is to calculate a least squares regression equation between measured $\delta^{18}O$ values and mean SSTs of the periods corresponding to the skeletal portions analyzed (Quinn *et al.*, 1996; Mitsuguchi *et al.*, 1996). I here employed the first approach with assigning annual skeletal $\delta^{18}O$ extremes to annual extremes and the relation was given as follows (Fig. 7):

$$\delta^{18}O\ (‰VPDB) = \text{`}{-1.66} - 0.123\ SST\ (°C) \qquad (R^2=0.99) \qquad \mathbf{(1)}$$

The slope value for the temperature dependence relationship of Eq. (1) is 0.123 (‰°C^{-1}) (Fig. 8). This value is definitely small compared to the relationship obtained by using *Porites* spp. from the western Pacific and from other regions of the Pacific (Fig. 10) (0.134–0.165‰°C^{-1}) Those values from *Porites* ssp. showed a range from 0.174 (Gagan, *et al.*, 1998) to 0.223 (Wellington *et al.*, 1996). Empirical and laboratory experiments using calcite defined the slope term to be 0.22‰°C^{-1} (Epstein *et al.*, 1953; Tarutani *et al.*, 1969; Grossman and Ku, 1986) and this value has been widely recognized as the $\delta^{18}O$–temperature calibration. Since I adopted high–resolution microsampling techniques (Gagan, *et al.*, 1994; Suzuki *et al.*, 1999), the small values can be attributed to the averaging effect in the growth of coral skeletons, not to an artifact of sampling resolution (Quinn *et al.*, 1996).This averaging effect is identified in Sr/Ca ratio of Faviidae corals. Its temperature–Sr/Ca relationship can be obtained by adopting the same approach:

$$Sr/Ca\ (mmol/mol) = 9.92 - 0.0320\ SST\ (°C) \qquad (R^2=0.96) \qquad \mathbf{(2)}$$

As it was observed in $\delta^{18}O$, the corresponding value for the temperature dependence relationship is definitely small compared to those previously reported from *Porites* spp (Fig. 8). The value ranged from 0.0412 to 0.0707 (mmol/mol °C^{-1}) in the Great Barrier Reef (Fallon *et al.*, 2003). I observed what seasonal temperature range is shown in MYK90 by applying Sr/Ca data into Eq. (2) which is not affected by Sea Surface Salinity (SSS) factor. Sr/Ca – based SSTs by Eq. (2) distribute between 11.7°C and 24.9°C with average value of 18.6°C (Fig. 9). This unreasonably large temperature range seems unlikely and coral could rarely live with temperature below 18°C. Naturally, with smaller corresponding value for the temperature dependence relationship, wider seasonal SST range, was given here. These evidences suggest that the Faviidae corals may not provide quantitative seasonal record in $\delta^{18}O$, $\delta^{13}C$ and Sr/Ca ratios but quantitative annual mean values in spite of averaging effect and that the Faviidae corals can be a good potential recorder for marine environments.

In regard to biological averaging effect, Faviidae coral does not record seasonal fluctuation of ambient water environment as full as *Porites* corals although it shows clear annual fluctuations. This may be because of its growth mode. Scleratinia have various growth forms: branching, tabulate, massive, columnar, or encrusting. There is no wonder if some corals' calcification proceeds toward various direction, mingling with adjacent structure while some corals' calcification takes place parallel to the past growth consistently, which can be often seen in *Porites* sp.. As a result of such difference of growth mode, it appears that Faviidae corals in this study showed 'averaged' records, which ended up with small seasonal amplitude compared to *Porites* corals. All scleratinia can in theory be used for geochemical studies, however, it can be said that individual calibration methods according to each species' geochemical characteristics are needed to calibrate into actual SST.

3-2) ESTIMATION OF SST AND SSS AT 16 ka

Sr/Ca Implication

Here I estimated SST shift by applying Sr/Ca–SST regression slope (mmol/mol $°C^{-1}$) rather than discussing seasonality since $\delta^{18}O$ data are often affected by both SST and salinity. Correge (2006) showed a compilation of all the published Sr/Ca versus SST calibration for the genus *Porites* and found there is no "universal" calibration exists. Correge (2006) also gave an overview of the different genera used and of the published equations linking SST to Sr/Ca. Fig. 10 shows slope values, the corresponding value for the temperature dependence relationship, of 38 *Porites* corals and 8 other species' corals. It was revealed that the mean slopes of those are similar to each other (*Porites*: 0.0607 mmol/mol $°C^{-1}$, Other genera: 0.0596 mmol/mol $°C^{-1}$) although certain variation was seen in equations of both *Porites* and other genera. Gagan *et al.* (2000) also mentioned that, despite several previous studies, there is still no single accepted coral Sr/Ca relation however, the slopes of the calibration equations are remarkably similar in his study (mean = 0.062 ± 0.014 mmol/mol $°C^{-1}$, 2σ). Hetzinger *et al.* (2006) discussed Sr/Ca calibration in comparison between monthly and annual time resolutions. They established a linear regression with monthly resolution using only the minimum/maximum values in any given year in their coral samples and monthly SST data, and also a linear regression with annual resolution from 12–months averaged Sr/Ca value and SST. It was pointed out that the correlation between coral Sr/Ca and instrumental SST shows higher on an annual mean scale and slope b value tends to be apparently bigger on an annual scale.

In order to estimate the SST shift from the age of fossil MYK90 to that of modern corals, I chose the slope value 0.060 mmol/mol$°C^{-1}$, which sits between the average value of *Porites* corals and other genera corals in Fig. 10. It is also necessary to evaluate the gap of Sr/Ca value between fossil and modern corals. For this gap, values of 0.22 and 0.31 were adopted by subtracting mean Sr/Ca value of modern CJK01 coral (*Favia* sp.) collected from the Ogasawara

Islands, described before, and it of *Porites* sp..(Mitsuguchi *et al.*, 1996) collected from Ishigaki Island, respectively, from also mean Sr/Ca value of the fossil MYK90. As a result, 3.67°C and 5.17°C SST shifts were given by those modern corals in the Ogasawara Islands and Ishigaki Island, respectively.

Considering SST shift shown from CJK01 coral, in this case, it is required to consider the SST gap between the Ogasawara Islands (27°6’N, 142°12’E) where CJK01 sample was collected, and the Miyako Islands (24°43’N, 124°3’E) because distanced setting of those study sites cannot be ignored. Mean SSTs during 2002–2003 in Ogasawara (data were taken from Japan Oceanographic Data Center) and the Miyako Islands are 24.0 and 25.3°C, respectively. Therefore, this 1.3°C SST gap was added to calculated SST value above, 5.0°C SST shift in the Miyako Islands between 16 ka and present was estimated. Overall, as both SST estimations from modern *Porites* in Ishigaki and modern Faviidae in Ogasawara showed very similar value, I conclude SST shift in the Miyako Islands since 16 ka is approximately 5°C. As Ishigaki Island is supposed to have had similar SST because of its close location to the Miyako Islands (24°21’N, 124°10’ E), geographical SST gap was not taken into account.

$\delta^{18}O$ Implication

Calibration of $\delta^{18}O$ into SST shows various equations according to locality and coral species, as well as Sr/Ca calibration. Moreover, at least three factors, which are SST, ice sheet volume and local salinity effects sit together in $\delta^{18}O$ data. In the same manner as Sr/Ca slope gradient, Weber and Woodhead (1972) concluded that the $\delta^{18}O$ versus temperature curves at annual scale are parallel or nearly parallel. Concerning its slope, gradient of 0.22‰/°C, quoted above, is widely recognized and used as the $\delta^{18}O$–temperature calibration (Epstein *et al.*, 1953; Tarutani *et al.*, 1969; Grossman and Ku, 1986, Grottoli and Eakin, 2007). Therefore I made use of this slope gradient value of $\delta^{18}O$ profile and firstly separated SST effect by applying Sr/Ca–based SST shift calculated above.

As estimated in the previous section, Sr/Ca–based SST in this study area was between 5.0°C and 5.2°C lower around 16 ka compared to the current environment. This temperature range is supposed to be equivalent to 1.09–1.14‰ out of entire $\delta^{18}O$ shift, by applying the $\delta^{18}O$ calibration slope 0.22‰/°C. Regarding to the amount of $\delta^{18}O$ shift, as well as Sr/Ca, it is interesting that annual mean $\delta^{18}O$ values of *Porites* coral and modern CJK01 coral in Ryukyus are similar to each other. Thus, this value presumably shows the mean $\delta^{18}O$ value at the age of 16 ka. Of 2.3‰ shift in $\delta^{18}O$, which is the value subtracted the mean value of modern coral in Ishigaki (Suzuki, *et al.*, 2001) from that of fossil MYK90, 1.16–1.21‰ correspond to salinity effect.

Certain amount of this salinity effect component should be generated by ice sheet built up, as mentioned earlier. Schrag *et al.* (1996) extrapolated from pore fluid $\delta^{18}O$ data for a global mean estimate for the change in $\delta^{18}O$ w in the LGM and it was estimated that the average global effect of ice volume on the oceans is equivalent to 1.0‰ in $\delta^{18}O$ in this period. Applying 1.00‰ as an ice sheet effect, it turned that at least, remaining 0.16–0.21‰ is caused by local salinity effect because ice sheet effect in $\delta^{18}O$ w should have been more or less smaller at 16 ka (Fig, 11). Thus, it can be said that SSS was locally higher, equivalent to at least approximately 0.2‰ in $\delta^{18}O$, at 16 ka in the ECS.

3-3) CLIMATIC OBSERVATIONS

In the last glacial period, it has been well known that global temperature was significantly lower than today and massive ice sheet increased sea–water salinity. In this study, the result on fossil MYK90 showed 5°C lower SST and higher SSS equivalent to at least 0.2‰ without salinity effect derived from ice sheet in $\delta^{18}O$ in the study site at 16 ka. In spite of the peak in ice volume (between 22,000 and 19,000 cal. Kyr. B.P.) (Yokoyama *et al.*, 2000), the thick and large ice sheets existed until the last deglacial warming trend started from 14.8 ka (Xiang *et al.*, 2007).

With respect to the estimated high salinity at Site MYK90 off the Miyako Islands, it could be attributed to the change in intensity of the East Asia Monsoon (EAM) compared to today. The summer monsoon brings moisture from the western Pacific onto the continent and results in heavy precipitation in the East Asia. There are several studies on the behavior of the EAM during the last glacial period. Several studies demonstrated that the winter EAM was strongly intensified (Xiang *et al.*, 2005) although the summer EAM was potentially weaker in the Sulu Sea (Rosenthal *et al.*, 2003) and Indonesia (Stott *et al.*, 2004). Consequently stronger seasonality was expected (Li *et al.*, 1997). Decrease in precipitation by summer monsoon and dry winter monsoon may be responsible for higher salinity off the Miyako Islands than today.

Also, this higher SSS in Site MYK90 implies hydrological contrast between the area offshore Miyako Islands and the western ECS at 16 ka. As written above, Ice sheet built up in glacials had changed the global sea level as well as the global sea water salinity. Cutler *et al.* (2003) showed the sea–level profile since the last interglacial period and it was shown that the sea–level at 16 ka is supposed to be ~100m lower than today globally. To pass the geographic conditions of the ECS in review, around the LGM the continental shelf of the ECS was extensively exposed, probably more than half of the present continental shelf. The mouths of the Yellow and Changjiang Rivers were much closer to the core site compared to today. Thus, the ECS used to be influenced by terrestrial water discharge from mainland China to a great extent. The SSS in the northern ECS is therefore expected to be lower than today, because of the short distance from the continental shore line.

As mentioned before, the southern part of the ECS can be broadly classified not as coastal type but as open ocean type, which has high temperature and high sa;inity due to the influence of the Kuroshio current. Therefore Site MYK90 and the northern part of the ECS correspond to open ocean type and coastal type, respectively. Various SSS estimates have been reported up to now in the ECS. It was pointed out that the core site near Kyushu in the north–western ECS showed low salinity environment (Ijiri *et al.*, 2005) whereas core site in Okinawa Trough indicated 1psu higher salinity water in the last glacial period (Sun *et al.*, 2005). The more saline environment revealed in this study suggests that offshore of the Miyako Islands had open ocean type characterized by Kuroshio Current and accordingly influences of the terrestrial water discharge was not extended to this site around 16 ka.

4. Conclusions

1) Fossil Faviidae coral MYK90 recorded paleo–environment at 16 ka with clear and regular seasonal fluctuation in its O and C isotopic and Sr/Ca data. Those values showed apparent shift toward cold and/or saline water condition. Besides, narrow amplitude of seasonal fluctuations was seen in both fossil and modern Faviidae corals. The small slope value for the SST dependence relationship can be attributed to the averaging effect in the growth of coral skeletons. Regardless of such an averaging effect, annual mean skeletal data of Faviidae are consistent with other genera corals. It was revealed that those data of Faviidae corals with annual or longer time resolution are perhaps highly applicable to paleoceanographic reconstruction.

2) SST was calibrated by applying a default slope value, –0.0600 mmol/mol $°C^{-1}$ to the gap of skeletal Sr/Ca data between fossil MYK90 and those of two modern corals collected from Ogasawara and Ishigaki. Those implications showed approximately 5.0°C and 5.2°C lower temperatures in the study site at 16 ka. SSS was calibrated by separating SST, ice sheet–derived SSS, and local SSS effects from allover gap of skeletal $\delta^{18}O$ between fossil MYK90 and modern coral collected from the Ishigaki Islands. SST effects were estimated by applying default slope value, –0.022‰$°C^{-1}$. Followed by subtracting ice–sheet derived SSS effect from the entire $\delta^{18}O$ value gap, it was concluded that the environment in the study site locally had higher SSS equivalent to at least 0.2‰ in $\delta^{18}O$.

3) The intensity of winter EAM was presumably stronger although the summer EAM was potentially weaker at 16 ka. Decrease in precipitation by summer monsoon and dry winter

monsoon may be responsible for higher salinity than today. In addition, although the mouths of the Yellow and Changjiang Rivers were much closer to the study site because the massive ice sheet lower the sea level significantly around the LGM, offshore area of the Miyako Islands had open–ocean condition characterized by Kuroshio Current and influences of the terrestrial water discharge was not extended to this site around 16 ka.

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Table 1

Faviidae coral samples and δ 18O and Sr/Ca distributions. The age of MYK90 was determined by Sasaki *et al*. (2006).

Location / sample code	Age of samples	Coral family/genus	Latitude	Longitude	$\delta^{18}O_{VDPB}$ (per mil)		Sr/Ca (mmol/mol)	
					Max	Min	Max	Min
Miyakojima / MYK90	16.17±0.52 ka	Faviidae / unknown	24°43'N	124°03'E	-3.2	-2	9.5	9.1
Chichijima / CJK01	1999–2001	Faviidae / *Favia*	27°06'N	142°12'E	-5.2	-4.2	9.3	9

Table 2

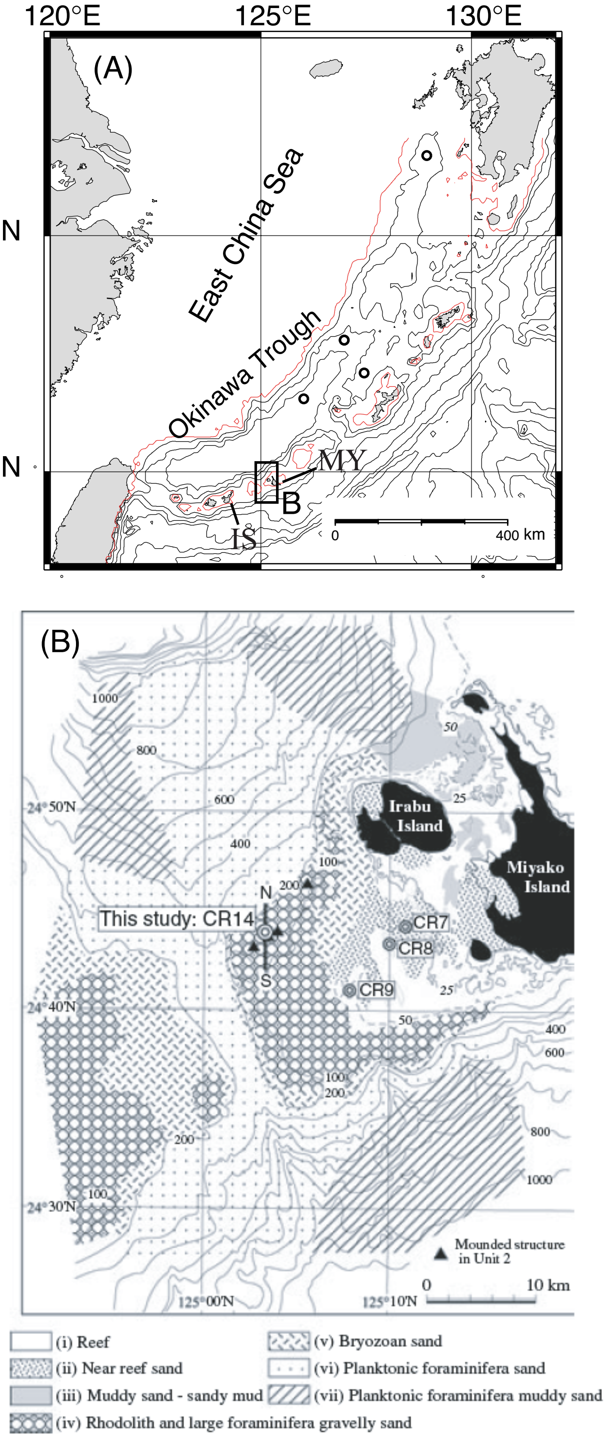
Average, minimum, maximum and standard deviation of coral skeletal data of $\delta^{13}C$, $\delta^{18}O$ and Sr/Ca. Fossil MYK90 (a), and modern IMY corals (b).

a)

MYK90	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Sr/Ca (mmol/mol)
Ave.	0.82	-2.56	9.31
Min.	-1.05	-3.01	9.12
Max.	2.72	-1.99	9.54
Stdev.	0.93	0.26	0.12

b)

CJK90	δ 13C (‰)	$\delta^{18}O$ (‰)	Sr/Ca (mmol/mol)
Ave.	-1.80	-4.67	9.09
Min.	-2.73	-5.23	8.98
Max.	-0.58	-4.16	9.28
Stdev.	0.54	0.30	0.09



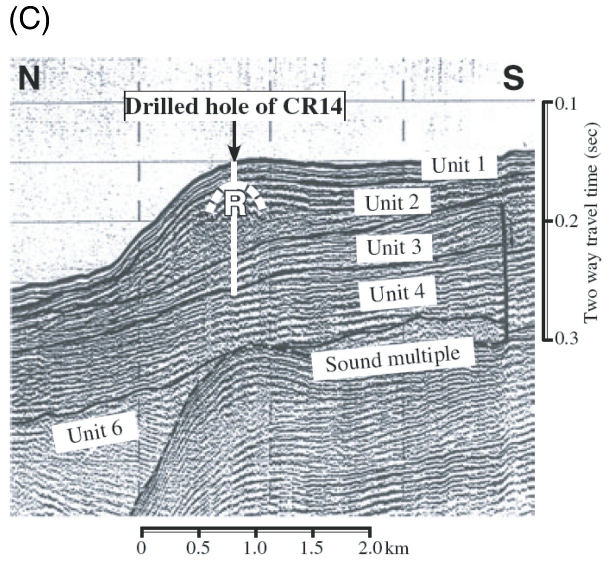


Figure 1. (A) Locality map showing the study area of Miyako Islands. Isobaths of 200 m depth (shown in red lines) and 500-m intervals are shown. MY, Miyako Island; IS, Ishigaki Island.

(B) Present-day carbonate sedimentary facies and distribution of mounded structures within Unit 2 (black triangles; panel C) offshore of the western Miyako Islands, southwestern Japan. There are seven sedimentary facies identified: (i) reef facies; (ii) near-reef facies; (iii) muddy-sandy mud facies; (iv) rhodolith and large foraminiferal gravel facies; (v) bryozoan sand facies; (vi) planktonic foraminiferal sand facies; and (vii) planktonic foraminiferal muddy sand facies. Doubled circles show localities of the well in this study (CR14) and others. Water depths are shown in meters. After Sasaki et al. (2006).

(C) Interpreted seismic cross-section, running from north to south, of the well CR14 shown in panel B. The mounded structure is highlighted by the white line with R. After Sasaki et al. (2006).

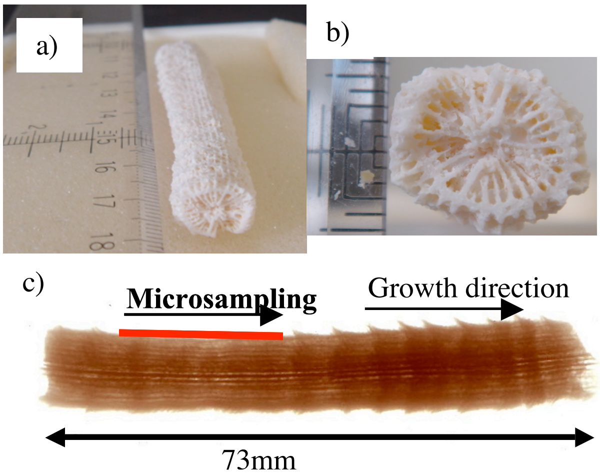


Figure 2. Faviidae fossil coral MYK90 collected from the Miyako Islands. Photos of overview (a), cross-section (b), positive X-ray image (c) .

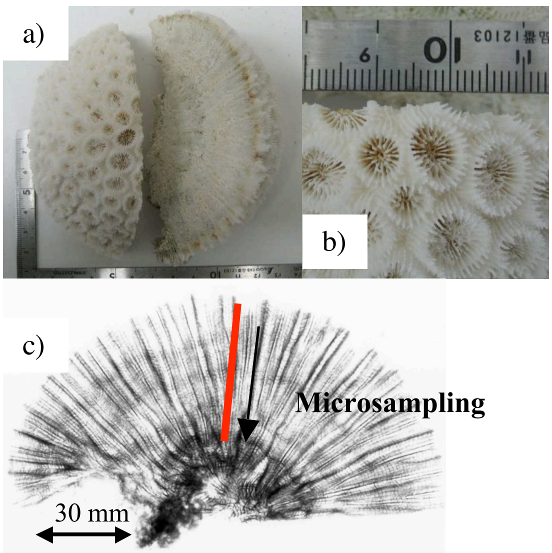
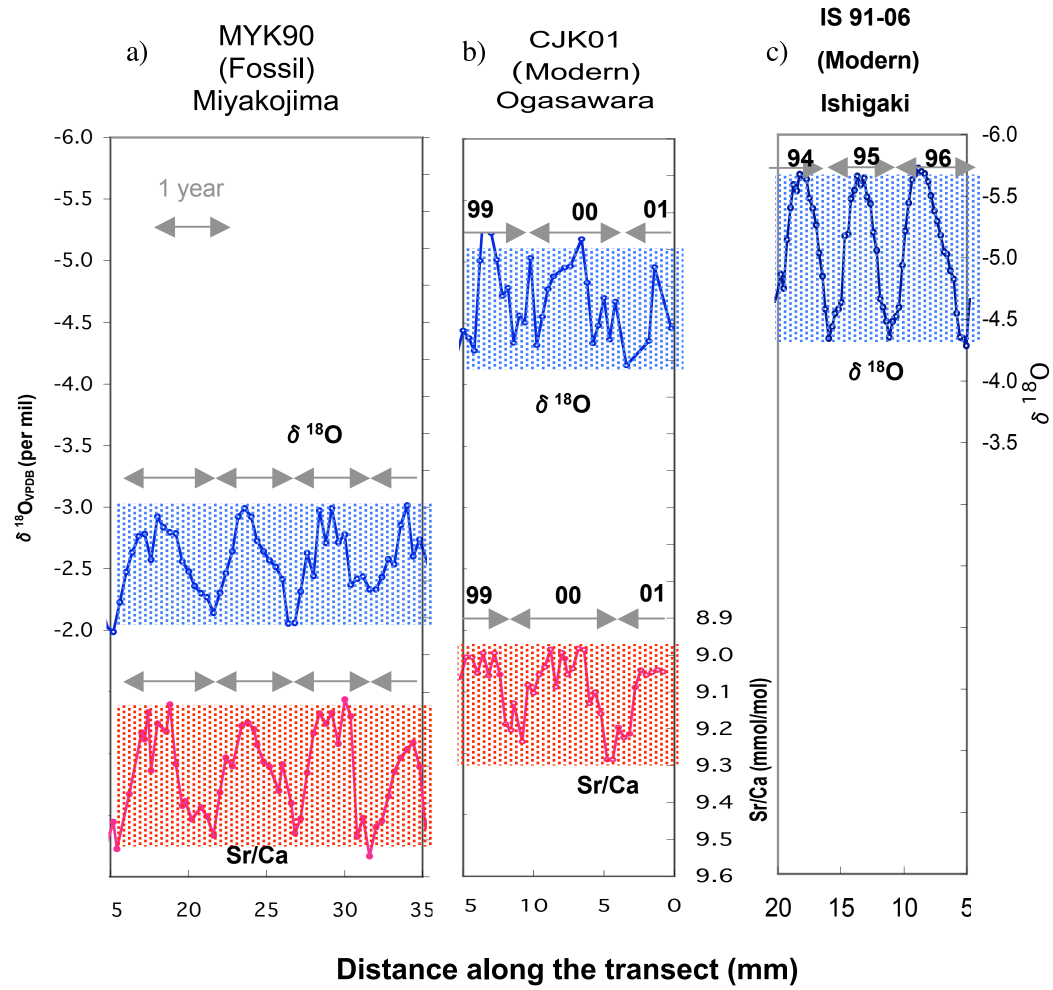


Figure 3. Faviidae modernl coral CJK01 collected from Ogasawara Islands in 2001. Photos of overview (a), polyps (b), and positive X-ray image（c).



Fugure 4. Coral skeletal data of $\delta^{18}O$ (open) and Sr/Ca (solid), for MYK90 a), CJK01 b), IS 91-06 c), respectively. IS 91-06 were studied by Suzuki *et al*. (1999). Each grey arrow represents one year.

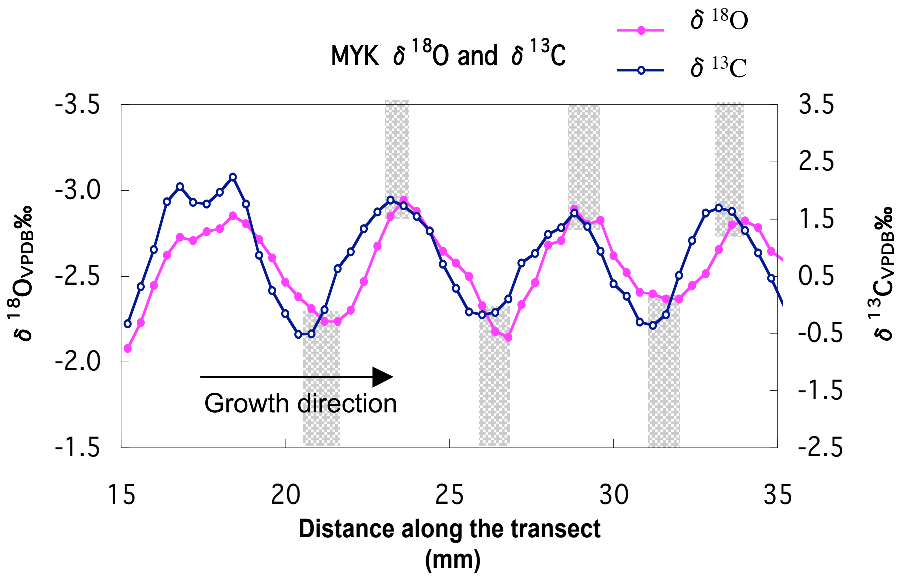


Figure 5. Comparison of measured $\delta^{18}O_{VPDB}$ (solid circle) and $\delta^{13}C_{VPDB}$ (open circle), of fossil MYK90 coral.These curves show the 1-2 month(s) lag between those annual cycles (shaded areas).

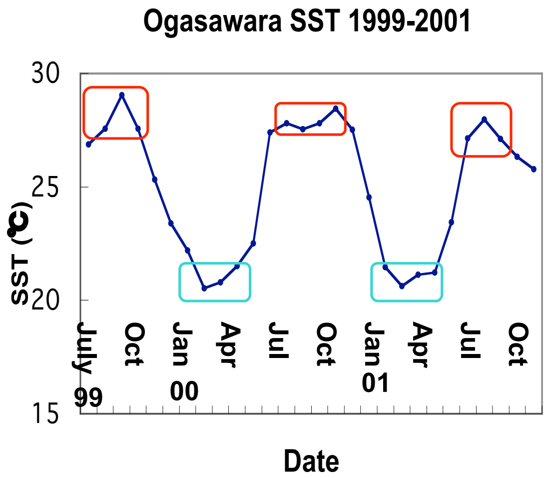


Figure 6. Monthly mean sea SSTs between July 1999 and November 2001, observed by Ogasawara Marine Resource Center. Data in boxes were used for calculating correlation with Sr/Ca and δ ^{18}O profiles of coral CJK01 sample (Fig.3), respectively.

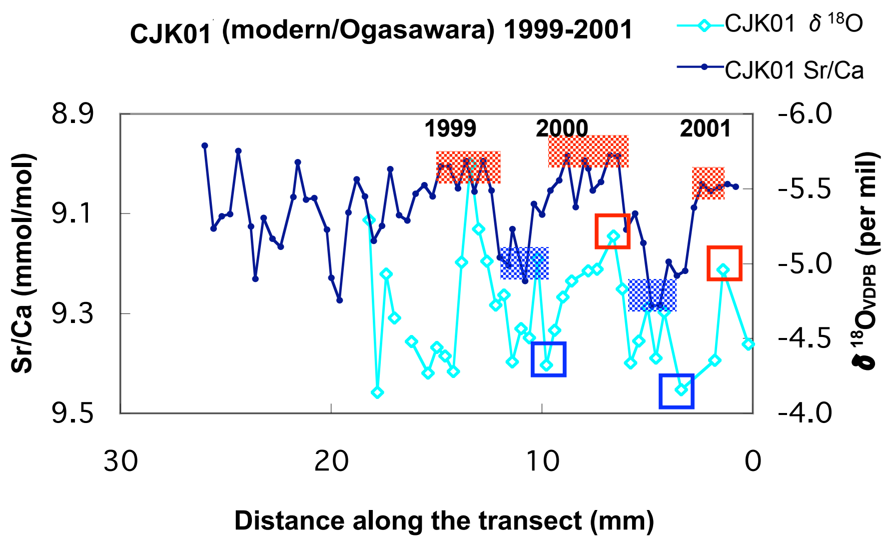


Figure 7. Summer and winter minima/maxima data (within boxes) between 1999 and 2001 of coral CJK01 sample which were used for SST calibration. Red and blue markers indicate summer and winter, respectively.

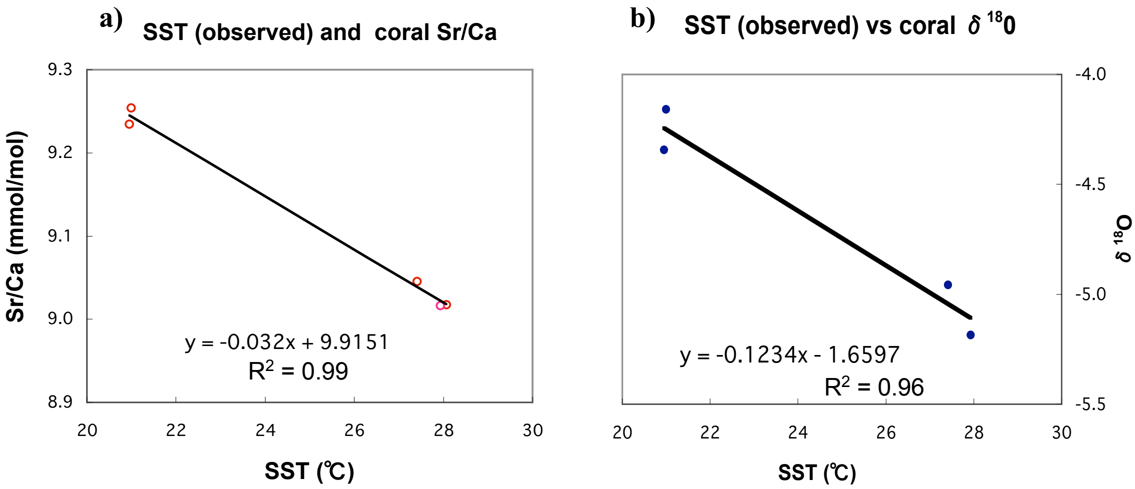


Figure 8. Regression slopes between SST and skeletal data of modern coral CJK01 collected in Chichijima, Ogasawara; Sr/Ca (a). δ^{18}O (b), respectively.

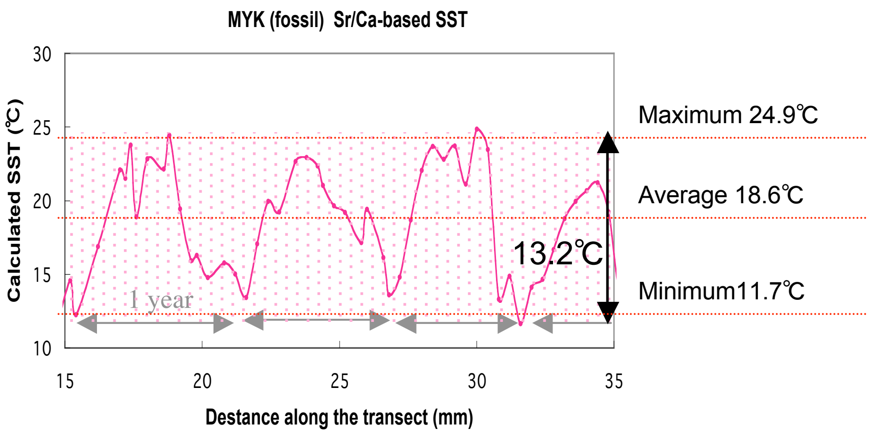


Figure 9. Calibrated SST by Sr/Ca data of fossil MYK90 with Eq. (1). See main text for explanation.

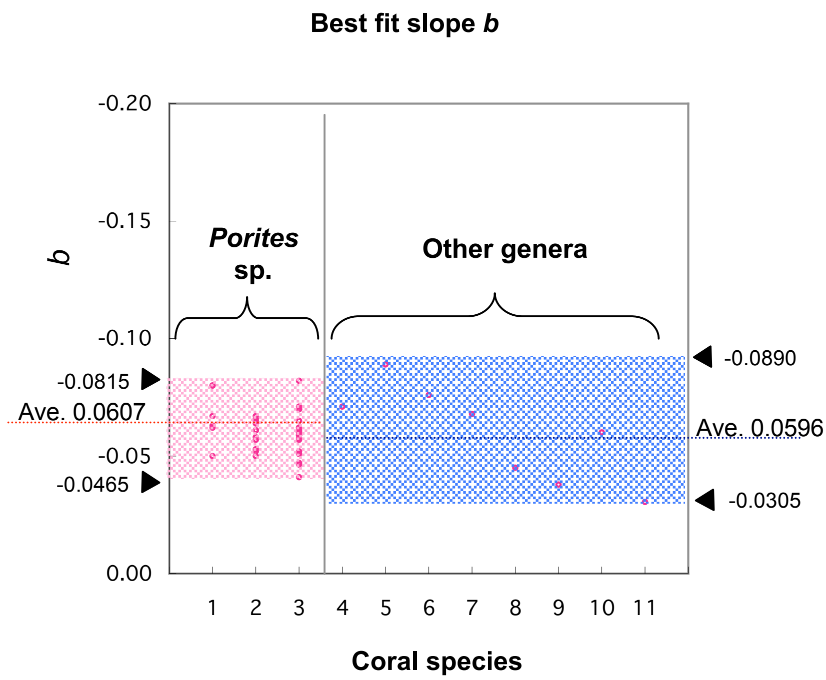


Figure 10. Coral species and their best fit SST–Sr/Ca calibration slope *b*. (Correge, 2006). Calibrations are of the type: Sr/Ca (mmol/mol) = a + b* SST (℃). Species refer to; 1. *Porites lobata* (various locations) 2. *P. lutea* (various locations) 3. Other *Porites*, sp. (various locations) 4. *Pocillopora damicornis* (Hawaii) 5. *Montipora verrucosa* (Hawaii) 6. *P. eydouxi* (Hawaii) 7. *P. clavus* (Galapagos) 8. *Diploria labyrinthiformis* (Bermuda) 9. *Montastrea annualaris* (Florida) 10. *Diploastrea heliopora* (Indonesia/New Cal) 11. *Goniopora* sp. (South China Sea)

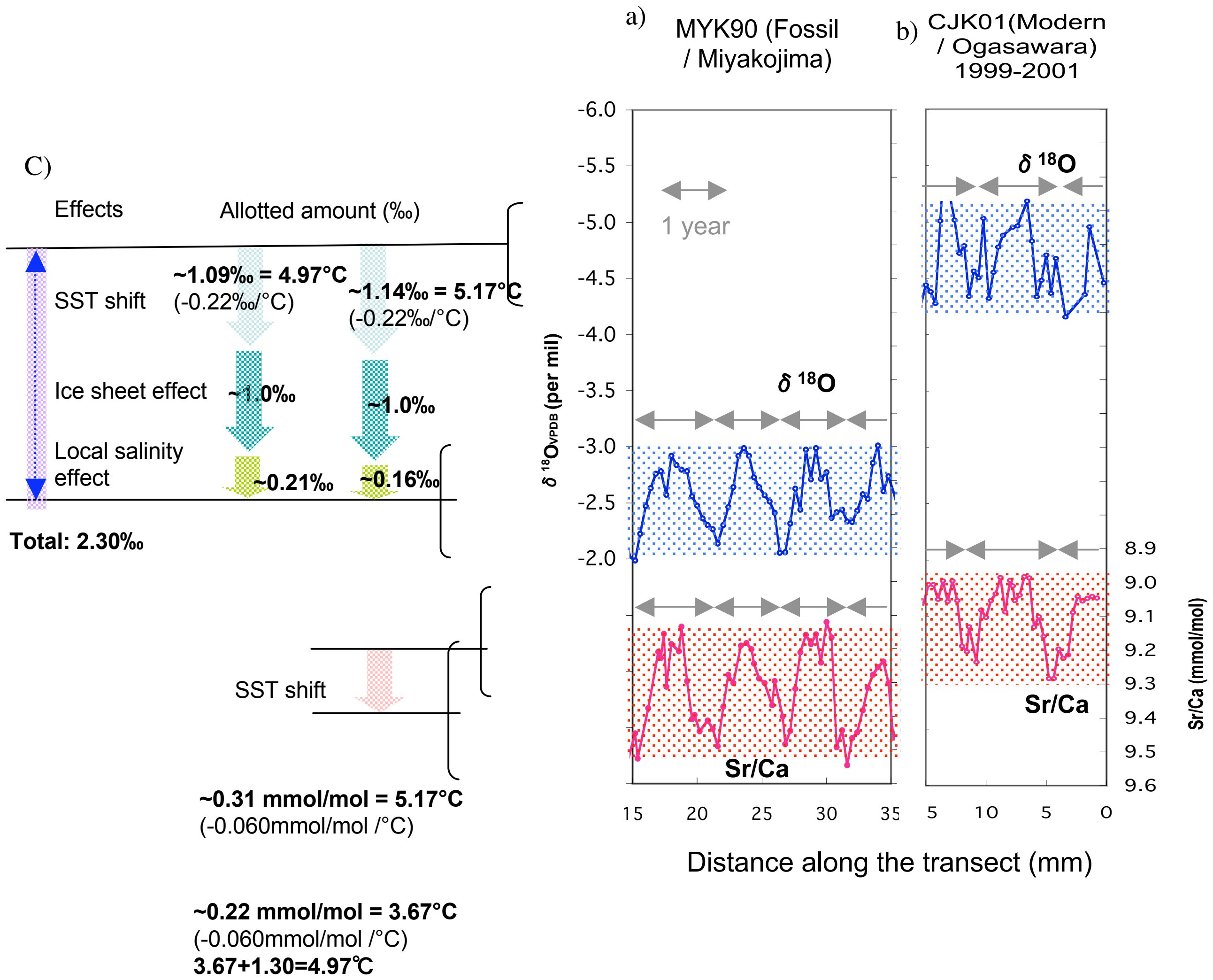


Figure 11. Data distribution of fossil coral MYK90 (a), and modern coral CJK01 (b). (Same with Fig. 5 (1) and (2), respectively.) Solid and open profiles show Sr/Ca (mmol/mol) and $\delta^{18}O_{VDPB}$(per mil), respectively. A schematic drawing of estimating SST and/or SSS is shown in c). See the main text for details.