**Potential of submarine-cave sediments and oxygen isotope composition of
cavernicolous micro-bivalve as a late Holocene paleoenvironmental record**

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Abstract

A sediment layer (43 cm thick) and surface sediments (5 cm thick) in a submarine limestone cave (31 m water depth) on the fore-reef slope of Ie Island, off Okinawa mainland, Japan, were examined by visual, mineralogical and geochemical means. Oxygen isotope analysis was performed on the cavernicolous micro-bivalve *Carditella iejimensis* from both cored sediments and surface sediments, and the water temperature within the cave was recorded for nearly one year. These data show that: (1) Water temperature within the cave is equal to that at 30 m deep in the open sea; (2) the biotic and non-biotic environments within the cave have persisted for the past 2,000 years; (3) mud-size carbonate detritus is a major constituent of the submarine-cave deposit, and may have come mainly from the suspended carbonate mud produced on the emergent Holocene reef flat over the past two millennia; (4) the $\delta^{18}\text{O}$ -derived temperature ($T_{\delta^{18}\text{O}}$) of *C. iejimensis* suggests that the species grows between April and July; (5) the $T_{\delta^{18}\text{O}}$ of *C. iejimensis* from cored sediments implies that there were two warmer intervals, at AD 340 ± 40 and AD 1000 ± 40 , which correspond to the Roman Warm Period and Medieval Warm Period, respectively. These suggest that submarine-cave sediments provide unique information for Holocene reef development. In addition, oxygen isotope records of cavernicolous *C. iejimensis* are a useful tool to reconstruct century-scale climatic variability for the Okinawa Islands during the Holocene.

Key words: submarine-cave sediments; Okinawa Islands; late Holocene; Palaeoclimatology; micro-bivalve

1. Introduction

In recent years there has been an increased attention of late Holocene climate changes, including the Medieval Warm Period (800–1300 AD) and the Little Ice Age

(1400–1900 AD), because they have significantly influenced human activities and the geographic distribution of many organisms (e.g., DeMenocal, 2001; Mayewski et al., 2004). In tropical and subtropical seas, hermatypic corals with annual growth bands have proved to be excellent archives for the paleoclimate and environment (e.g., Druffel, 1982, Dunbar et al., 1994; Linsley et al., 1994, 2000; Abram et al., 2001). As a result, several regions have climate records covering the past 400 yr (Gagan et al., 2000; Hendy et al., 2002).

Sheltered submarine caves near coral reefs are among the most valuable sites for studying cryptic and deep-sea organisms, and a number of workers have examined their evolutionary significance (Jackson et al., 1971; Jackson and Winston, 1982; Kobluk, 1988, Kase and Hayami, 1992; Reitner and Gautret, 1996; Wörheide, 1998; Kano et al., 2002). Recently, the oxygen isotopic composition of coralline sponges and serpulid tubes within submarine caves has been studied as a proxy for palaeotemperature (Böhm et al., 2000; Antonioli et al., 2001; Haase-Schramm et al., 2003). Although submarine-cave sediments have been reported from many caves (Hayami and Kase, 1993; Vacelet et al., 1994), there is no published study of cave sediments, except for infralittoral caves (Di Geronimo et al., 1997). Submarine-cave sediments may constitute a continuous depositional record, because they are largely sheltered from the physical mixing and erosion from fluid motion that occurs in the open sea. Therefore, these deposits may provide a Holocene record of the environmental variations around coral reefs. Furthermore, the oxygen isotopic composition of cavernicolous bivalves preserved in the cave deposits may have the potential to reconstruct paleoclimate trends.

The main goals in this study are to: (1) describe the lithological features of sediments in a submarine cave on the slope of a fringing coral reef northeast of Ie Island, off

Okinawa Island, Japan, (2) document the stratigraphic distribution of cavernicolous bivalves in the cored sediments, and (3) evaluate the potential of oxygen isotope analysis of the cavernicolous bivalve *Carditella iejimensis* as a tool for reconstructing the late Holocene paleoclimate.

2. Submarine cave on Ie Island

The northward-flowing, tropical Kuroshio Current allows coral reef formation in the Ryukyu Islands of southwestern Japan (Fig. 1), where a large number of submarine limestone caves exist (Hayami and Kase, 1993). We examined sediment samples from a submarine cave named Daidokutsu (“large cave”) on the northeastern coast of Ie Island (Fig. 1). The island is approximately 23 km² in area and covered by the Quaternary Ryukyu Limestone, with a fringing reef close to the Pleistocene limestone sea cliffs, which have been undercut at mean high-water level. The surface of the fringing reef is mostly flat and exposed at ebb tide (mean tidal range is 1.8 m). MacNeil (1950) inferred that the reef flat at Ie Island has been planed down from a reef that in comparatively recent times was at least 1.8 m higher. The sea level at Okinawa Island between 3,500 and 1,700 yr BP was stable and also was the highest of the Holocene (Koba et al., 1982), at less than one meter above the present sea level. This would have been caused by erosion and solution of the original reef after a subsequent fall of sea level after ca. 1,700 yr BP. The lowering of sea level is due to uplift with the rate of 0.7 mm per year (Koba et al., 1982).

The reef crest is about 200 m from the shoreline, and 100 m from Daidokutsu cave. The cave’s entrance lies about 20 m deep on the fore-reef slope, and is one meter high and two meters wide (Fig. 2). The cave deepens abruptly inward and there are flat, wide caverns in its middle and innermost parts (Tabuki and Hanai,

1999); the maximum depth of the cave is 31 m. Traces of biogenic activity are not evident in the cave's bottom sediments. Based on the sea-level curve of Fairbanks (1989), Bard et al. (1996) and Toscano and Macintyre (2003), the cave was submerged at ca 9,000 yr BP, and even the entrance might have been completely submerged at about 8,000 yr BP.

3. Methods

3.1. Field work

We measured water temperature hourly in the innermost part of Daidokutsu cave, with a Nichiyu Giken Kogyo NWT-SN self-registering thermometer, from 26 July 2003 to 6 July 2004. Cave sediment was collected by hand with a coring tube 5 cm in diameter, and a 43-cm core was recovered without reaching basement (Fig. 2). In addition, we collected surface sediments (5 cm thick) near the coring site in order to obtain abundant individuals of the cavernicolous bivalve *Carditella iejimensis*.

3.2. Sediment analysis

The sediment core was split and described, and X-ray radiographs were taken of slab samples (6 cm wide X 20 cm long X 1 cm thick) from the split core. Thirty-six 1.2-cm-thick samples were taken along the core to measure grain size, carbonate content and grain composition. Grain sizes were determined using standard sieves (class interval 1 ϕ). The carbonate content of both sand-size (1 g) and mud-size (200 mg) particles were determined by gentle removal in 10% acetic acid. To analyze

grain compositions of sand- and mud-size particles, we prepared two smear slides from one samples. Sand-size particles were examined on the smear slide by point-counting (200 counts per slide). For disarticulated shells of bivalve and ostracods, a separate valve was counted as one individual. We used the Comparison Chart for Visual Percentage Estimation of Terry and Chilingar (1955) for a semi-quantitative visual assessment of mud-size components, except for coccoliths, with the percentages corrected to compensate for the degree of grain dispersal on the smear slides. Since the coccoliths are very small and masked by the coarser grains, their evaluation is difficult using a semi-quantitative visual assessment. In this study, we examined whether or not the sediment samples yielded coccoliths. We analyzed thirteen samples for major minerals. Their mineral composition was analyzed by powder X-ray diffractometry (XRD) using a Rigaku RINT2500V and JDX3536.

Oxygen and carbon isotope analyses were performed on nine samples of mud-size carbonate, since grain-size analysis showed that mud-size grains predominant in the submarine-cave deposits (see below). Powdered samples were analyzed on a Finnigan MAT 251 mass spectrometer at Hokkaido University, Japan. Isotopic values are expressed relative to the isotopic ratio of carbon dioxide gas derived from the Pee Dee Belemnite (PDB) in conventional delta notation using the NBS-20 standard. Analytical precision for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values is 0.08‰ and 0.05‰, respectively, based on multiple analysis of a laboratory standard.

3.3. Analysis of micro-bivalves

All micro-bivalves were picked and counted from the >0.5 mm fraction of thirty-six 1.2-cm-thick samples. Taxonomic identifications are based on Hayami and Kase (1993). For disarticulated shells, a separate valve was counted as one individual. Based on sediment density (here set to 1.25 g/cm³ of grain density for all samples) and sedimentation rate, the accumulation rate of the dominant species is expressed as the number of specimens per cm²/yr.

3.4. Analysis of palaeotemperature

As noted below, the micro-bivalvia *Carditella iejimensis* is suitable for reconstructing palaeotemperature using oxygen isotope analysis. There are no published studies of the oxygen isotope composition of *C. iejimensis*, so we analyzed 30 individuals (articulated and single valves) from surface sediments (5 cm thick). The delicate prodissococonch of all individuals is present, although they lack soft parts. In addition, we recovered 13 individuals of *C. iejimensis* from the core.

Oxygen isotope data from bivalve mollusc shells are valid for climate reconstruction, because they reflect both surface temperature and the $\delta^{18}\text{O}$ of ambient water. Therefore many workers have analyzed a number of shallow-water species (e.g., Chinzei, et al., 1987; Schöne et al., 2003, 2004, 2005; Mueller-Lupp et al., 2004; Watanabe et al., 2004; Jones et al., 2005). These studies estimated seasonal temperature variation from intra-annual oxygen isotope values. Such high temporal resolution requires bivalve specimens that are several centimeters in size. In contrast, the adult shell size of *C. iejimensis* is less than 4 mm, so that we used

the whole shell for oxygen isotope analysis. X-ray diffraction analyses show that *C. iejimensis* consists of 100% aragonite. Samples were not pretreated by roasting. Isotopic determinations were made at CEA/CNRS, France, and Hokkaido University. Isotopic values are expressed relative to the isotopic ratio of carbon dioxide gas derived from the PDB in a conventional delta notation using the NBS-20 standard, with precision better than 0.05‰.

3.5. Radiocarbon dating

The radiocarbon ages of eight well-preserved mollusc shells were conducted by Beta Analytic Inc., using accelerator mass spectrometry. Three samples were mixtures of several species, in order to provide enough volume for dating (Table 1). In addition, the radiocarbon ages of three carbonate-mud samples containing dated molluscs were obtained from the same method. We submitted 0.5 g of carbonate mud to each date. Calibrated age ranges were calculated according to Method A of Stuiver et al. (1998), after applying a local correction for the northwestern Pacific of 355 years ($\Delta R = 35 \pm 25$) (Hideshima et al., 2001).

4. Results

4.1. Modern conditions

Water temperatures within the cave range between 29.6°C (31 August, 2003) and 20.3°C (29 February, 2004). The pattern of the seasonal change in water temperatures within the cave is similar to the mean monthly temperatures at 30 m

deep (T_{30m}) around Okinawa for 1874-2001 (Japan Oceanographic Data Center; J-DOSS) (Fig. 3a). Patterns of daily changes in temperature are synchronous with the tidal cycle (Fig. 3b). This implies that the alternation of water masses within the cave is caused by the tidal cycle.

4.2. *Sedimentology and composition*

Traces of biogenic activity are lacking in the cave's bottom sediment, and burrowing macrobenthos such as polychaetes are absent from the core samples. Sedimentary structures such as laminae and trace fossils are absent. The mud content of the sediment is $70 \pm 5\%$, while particles larger than 1ϕ range from 0.2 to 6.1%, with an average of about 2% by weight (Fig. 4). The carbonate content of sand-size sediment ranges between 78 and 96%, while the content of mud-size sediment ranges from 90 to 97%. In both sand- and mud-size sediments, the carbonate content is significantly low in the lower portion (Fig. 4).

XRD analysis shows that bulk samples consist of 50-58% high-Mg calcite, 30-37% aragonite and 9-19% calcite (Fig. 4), with relative percentages determined by peak-intensity analysis (Neumann, 1965). The magnesium concentrations determined by X-ray diffraction (Goldsmith et al., 1961) were 13.9 ± 1.6 mole % Mg in high-Mg calcite. As noted below, benthic foraminifera are abundant in the cave sediments. It is likely that their shells contribute high-Mg calcite. The $\delta^{18}O$ and $\delta^{13}C$ of carbonate mud are $-1.19 \pm 0.08\text{‰}$ and $1.32 \pm 0.11\text{‰}$ PDB, respectively (Fig. 4). There are no significant changes in the stratigraphic distribution of minerals, or of oxygen and carbon isotope ratios.

Both sand- and mud-size particles are dominated by carbonate debris (Figs. 4 and 5). In sand-size particles, the identified component consists dominantly of

sponge spicules, benthic foraminifera, ostracods and fragments of echinoids (Fig. 4). In addition, many pumice grains occur in the lower part, where the carbonate content is relatively low (Fig. 4). In mud-size particles, the identified component consists dominantly of spicules of both sponges and didemnids (Fig. 5). Coccoliths are common in all samples. There are no systematic changes in the stratigraphic distribution of grain components, except for the pumice grains. The stratigraphic distribution of pumice grains exhibits a pattern similar to that for non-carbonate grains (Fig. 4). From this, we think that the deposition of pumice grains caused the relatively low carbonate content of the lowermost part. We estimate that the contribution of pumice grains to the total sedimentation was less than 20% by weight. The pumice grains were transported to this area by the Kuroshio Current, since there are no active volcanoes around Ie Island or Okinawa mainland.

4.3. Radiocarbon age dating

Radiocarbon-dated mollusc shells and carbonate mud are shown in Table 1. The gastropod *Neritopsis radula* (2 cm in shell length) and bivalves *Bentharca irregularis*, *Paravamussium crypticum*, *Cyclopecten ryukyuensis*, *Carditella iejimensis* and *Coralliophaga hyalina* live in submarine caves or cryptic habitats (Hayami and Kase, 1993). All bivalves are very small in adult size, at less than 5 mm in length and height and are epifaunal or semi-infaunal. The small gastropods *Stosicia* (*Isseliella*) *bourguignati*, *Emarginula crassicostata* and *Iniforis poecila* also occur in the intertidal zone and beach drift and are epifaunal or semi-infaunal. In contrast, *Tenagodus* (*Tenagodus*) *cumingi* occurs as clusters buried in sponges attached to cave walls, and its ^{14}C age may be older than that of other molluscs in the same stratigraphic horizon (Kitamura et al., 2003).

The results of ^{14}C dating are plotted in Fig. 6. In the depth interval from 35 cm

to 6 cm, all ages fall nicely along an age-depth line, implying continuous deposition and a constant sedimentation rate of 20.0 cm/kyr. Although pumice grains accumulated during the deposition of the lower part (43 to 35 cm in depth), the relative increase in sedimentation rate was less than 20%, based on their above-noted contribution to total sedimentation. Therefore, we use 20.0 cm/kyr as the sedimentation rate below 35 cm depth. Using this value, the age of the lowest sampled sediments is estimated as AD 100, which agrees closely with the ^{14}C age of AD 0 of the lowest sample including *T. cumingi* (Fig. 6). The sedimentation rate of these submarine cave deposits is similar to that of postglacial deep-sea deposits (400-2,500 m depth) in the Okinawa Trough and Ryukyu Trench slope (Ujiié and Ujiié, 1999; Xu and Oda, 1999; Jian et al., 2000).

Two samples above the 6-cm level contain 100.5 ± 0.4 pMC (percent modern carbon) and 111.5 ± 0.4 pMC (Table 1). According to Stuiver and Polach (1977), these values approximate the $\Delta^{14}\text{C}$ values of $4.5 \pm 3.8\text{‰}$ and $111.5 \pm 4.2\text{‰}$. Such high $\Delta^{14}\text{C}$ values are derived from $^{14}\text{CO}_2$ that was created by atmospheric weapons testing in the 1950s and early 1960s. Based on coral records for the period 1913-1979 from Okinawa, $\Delta^{14}\text{C}$ values increased from -42 to $+175\text{‰}$ between 1954-1956 and 1970, and then remained stable until 1979 (Konishi et al., 1982). This value is higher than 80‰ of the ocean, except for areas influenced by upwelling (Guilderson et al., 2000). Thus, the ages of the upper and lower samples (0-2.2 cm and 3.4-5.8 cm, respectively) correspond to ca. 1960 and the latter half of the 1960s, respectively (Fig. 6). The dated mollusc species are epifaunal or semi-infaunal suspension feeders (Hayami and Kase, 1993). Based on this, the reversed age relationship of the two samples was caused by bioturbation. Therefore, we think that the thickness of the mixed surface layer ranges from 2 to 6 cm.

Because of surface mixing, the temporal resolution of core data is calculated as 100 to 300 years using a value of 20.0 cm/kyr for the sedimentation rate.

The radiocarbon ages of the dated carbonate mud are 1-2 kyr older than those of mollusc samples. Considering the presence of biogenic grains with high $\Delta^{14}\text{C}$ values, the true age differences in the upper 6 cm of sediment are significantly larger than the numerical ages. There is no doubt that the age differences between them tend to increase with time (Fig. 6).

4.4. Micro-bivalves

We identified a total of 25 bivalves (Table 2), which exhibit excellent preservation despite being mostly disarticulated. The prodissoconch can be observed in many individuals. These factors imply that the fossils represent a life assemblage. The micro-bivalvia *Parvamussium crypticum*, *Cosa kinjoi*, *Carditella iejimensis* and *Cyclopecten ryukyuensis* predominate and are suspension feeders. They are endemic to cavernicolous environments (Hayami and Kase, 1993). The stratigraphic distribution of their accumulation rates is shown in Figure 7; the range for a given species is less than 0.03/cm²/yr. There is no significant temporal change in species composition or in the accumulation rate of the dominant species.

P. crypticum, *C. kinjoi* and *C. ryukyuensis* are not suitable for the reconstruction of palaeotemperature from oxygen isotope composition. This is because *C. kinjoi* and *C. ryukyuensis* are too small (<100 mg) for such analysis, while *P. crypticum* consists of a mixture of calcite and aragonite. The isotope composition of *C. iejimensis*, which consists of 100% aragonite, is alone useful for the reconstruction of palaeotemperature.

4.5. Oxygen isotopic analysis of *Carditella iejimensis*

McConnaughey (1989a) has shown that calcifying organisms with a fast growth rate may have lower $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values than would be expected based on equilibrium criteria alone. This depletion of the heavier stable isotopes of both elements is caused by kinetic isotope fractionation during the CO_2 hydration and hydroxylation, with rapid calcification favoring strong kinetic effects (McConnaughey, 1989b; McConnaughey and Whelan, 1997; Zeebe and Wolf-Gladrow, 2001). Since kinetic effects result in simultaneous depletion of ^{18}O and ^{13}C , the relationship between them can be used to check whether kinetic isotope effect influences ^{18}O value of *C. iejimensis*. There is no significant correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ ratios of the specimens from surface sediment (Fig. 8). We think that kinetic effects are not significant for the oxygen isotope composition of *C. iejimensis*. The composition is controlled by both the temperature and the isotopic composition of the ambient seawater in which the animals live.

As noted above, our temperature record indicates that the mean monthly water temperature within the cave is almost the same as the water temperature at 30 m depth ($T_{30\text{m}}$) off the southwestern Okinawa Island (Fig. 2). We did not measure salinity within Daidokutsu cave. However, its value is likely equal with that of ocean surface water, since water has flowed continuously into and out of the cave for the past 2,000 years, as noted below.

All $\delta^{18}\text{O}$ values were calculated using the following equation of Goodwin et al. (2001):

$T_{\delta^{18}\text{O}} = 20.6 - 4.34[\delta^{18}\text{O}_{\text{aragonite}} - (\delta^{18}\text{O}_{\text{water}} - 0.2)]$, where $\delta^{18}\text{O}_{\text{aragonite}}$ is measured relative to the PDB scale and $\delta^{18}\text{O}_{\text{water}}$ is relative to the SMOW scale.

Oba (1988) reported the following linear relationship between water salinity (S) and $\delta^{18}\text{O}$ of seawater in the region from the East China Sea to the Kuroshio Current off the southern Japanese Island:

$$\delta^{18}\text{O}_{\text{water}} = -6.76 + 0.203S$$

Instrumental records from Sesoko Marine Science Center, 10 km from our sampling point, show that the salinity of the surface waters ranges from 34.5 p.s.u. in summer to 35.1 p.s.u. in winter (Nakano and Nakamura, 1993a, b). Based on these data, we infer the salinity to be 34.8 p.s.u. Changes in $\delta^{18}\text{O}_{\text{water}}$ derived from seasonal variation of salinity are estimated at 0.12‰ and correspond to small difference in estimated temperature of 0.4°C.

The results of radiocarbon dating suggest that the duration of samples from the surface sediments is approximately the last 50 yrs. For specimens of *C. iejimensis* from surface sediment, there exists a statistically significant correlation between the shell sizes and $\delta^{18}\text{O}$ values ($r=-0.55$, $n=30$, $p<0.01$) (Fig. 9). Their $T_{\delta^{18}\text{O}}$ ranges between 22.4 and 26.6°C (Fig. 10). For the same sized individuals, the difference of $T_{\delta^{18}\text{O}}$ is 2°C. The $T_{\delta^{18}\text{O}}$ ranges between 23.5 and 26.5°C in samples of the cored sediments (Fig. 10).

5. Discussion

5.1. Paleoenvironmental changes within the cave

The occurrences of coccoliths and pumice indicate that sea water has flowed continuously into Daidokutsu cave. This is supported by occurrences of the cavernicolous bivalve species (Fig. 7). Since the level of predation pressure is low in a submarine cave, the biomass of suspension feeders approaches the carrying capacity (Hayami and Kase, 1993). In the case of micro-bivalves, food supply is a more important factor for the carrying capacity than is competition for space. Thus, the constant accumulation rate of the dominant bivalves implies that an amount of nutrition, which has been brought from outside the cave, was not varied over the past 2,000 years. It seems probable that this influx of water is related to the fluctuation of water masses within the cave related to the tidal cycle. The current velocity was not measured within the cave, although it is very low, because mud-size particles have deposited continuously over the past 2,000 yrs. In summary, it seems that the cave has remained sheltered, with low hydrodynamic energy, and we believe that the sediments constitute a continuous depositional record.

5.2. Sources of carbonate debris

Our analyses of grain distribution and grain compositions show that mud-size carbonate debris predominates in the submarine-cave deposits (mean of $67.4 \pm 5.5\%$ and range of 55.2 to 76.5%). Both the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ratios of mud-size carbonate in the submarine cave deposit are nearly 0‰ PDB (Fig. 4). This indicates that the main source of carbonate mud was marine carbonate, rather than carbonate precipitated on the surface of the cave walls and ceiling (e.g., stalactites and stalagmites) before the cave was submerged. Because the latter has significant low values for both the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ratios (Allan and Matthews, 1982). As noted above, the radiocarbon ages of the carbonate mud sediments are 1-2 kyr older than those of the mollusc samples (Fig. 6). Considering the presence of calcareous shells

such as coccoliths and the spicules of didemnids, the ages of unidentified grains are older than the dated carbonate-mud sediments. These factors imply that these grains are detritus from the emergent reef flat that has been reduced to its modern level by erosion (MacNeil, 1950). This process also explains the expansion of age differences between the unidentified mud-size particles and the mollusc samples. The water movement has transported suspended carbonate detritus into the cave, and these fine grains (including coccoliths) settled in the cave and were aggregated into pellets by suspension feeders such as coralline sponges, bivalves and brachiopods. Our results imply that there were no significant changes in condition of the hinterland during the past 2,000 years, except for the drift of pumice grains. In summary, the submarine cave deposits provide high-resolution records of the development of coral reef and volcanic activity around Ryukyu and Philippine Islands.

5.3. Potential of *C. iejimensis* as an archive of Holocene palaeotemperature

For specimens of *C. iejimensis* from surface sediment, there is a significant correlation between $\delta^{18}\text{O}$ values and the shell sizes (Fig. 9). We calculated the $T_{\delta^{18}\text{O}}$ during the precipitation of the outer shell portion, which is 3.0 mm or more from the umbo, based on the relationship between the size and weight of *C. iejimensis* (Fig. 11) and the equation of the regression line. The calculated value is 26.8°C and corresponds to $T_{30\text{m}}$ during July ($27.0 \pm 1.4^\circ\text{C}$). The average value of $T_{\delta^{18}\text{O}}$ for small shells is between $T_{30\text{m}}$ during May ($23.6 \pm 1.0^\circ\text{C}$) and June ($24.8 \pm 1.1^\circ\text{C}$). From these data, we believe that shell deposition began in early April and ended in July. Shell growth of bivalves is generally influenced by a number of

environmental factors such as water temperature, salinity, and food availability. As noted above, there are not significant seasonal changes in salinity within the cave. Around Okinawa Island, the phytoplankton becomes most abundant in winter and remains at low levels in the other seasons (Imai et al., 1988; Xu et al, 2005). From these, the growth pattern of *C. iejimensis* is mainly controlled by temperature.

As noted above, the environment within the cave has been maintained over the past two millennia. Therefore we infer that the $\delta^{18}\text{O}$ values of sea water and the temperatures both within and outside of the cave were the same for the past 2,000 yrs. Based on this assumption, we compare the $T_{\delta^{18}\text{O}}$ values of fossil and recent shells of *C. iejimensis* (Fig. 10). Except for two shells, the values derived from fossil fall within the range for recent specimens. In contrast, two shells have values that are 2°C higher than the estimated temperature derived from the equation of the regression line. The ages of these horizons are estimated to be AD 340 ± 40 ($26.2 \pm 0.1^\circ\text{C}$) and AD 1000 ± 40 ($26.1 \pm 0.2^\circ\text{C}$), respectively. According to the J-DOSS database, this value corresponds to a May and June $T_{30\text{m}}$ of 26.2°C at Kume Island, which is located between the study site (100 km to the west) and the main path of the Kuroshio Current (Fig. 1).

According to Yang et al. (2002), warm conditions prevailed in eastern China at AD 0-300 and AD 800-1100. These two intervals correspond to the Roman Warm Period and Medieval Warm Period, respectively. However, we detected no evidence in the $\delta^{18}\text{O}$ record of *C. iejimensis* of the cool conditions in the Little Ice Age (LIA; AD 1400-1900). Glacial advances in both hemispheres (Grove, 1988) and enhanced polar atmospheric circulation (Kreutz et al., 1997) suggest that the LIA was a global event. Unfortunately, there are no proxy climate data, or historical documents,

which allowed these workers to reconstruct the climatic conditions of Okinawa during the LIA. There is abundant evidence of LIA cool conditions in the terrestrial records of China (Qian and Zhu, 2002; Yang et al., 2002). However, Rind (1998, 2000) has suggested that cooler LIA conditions were possibly restricted to higher latitudes. None of the few LIA reconstructions of the tropics identify cold periods synchronous with those in Northern Hemisphere composite reconstructions (Hendy et al., 2002; Gagan et al., 2004). It is therefore probable that the shallow seas around Okinawa Island did not experience cool conditions from AD 1400 to 1900.

In summary, paleoclimatic records based on oxygen isotope analyses of *C. iejimensis* are not inconsistent with other proxy series from the Northern Hemisphere, including China, except for the LIA. We thus believe that $\delta^{18}\text{O}$ analysis of *C. iejimensis* is a reliable source of information about paleoclimatic fluctuations in the Okinawa area. Reconstructing additional paleoclimate data would require improved sampling for millimeter-size shells of *C. iejimensis*.

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Figure caption

Fig. 1 Location of Daidokutsu submarine cave on Ie Island, off Okinawa Island, Japan.

Fig. 2 Simplified transverse section and horizontal projection of Daidokutsu cave.

We observed air bubbles rising from the sea floor (2 m depth) above Daidokutsu during sediment sampling (duration of sampling was about 20 minutes).

Fig. 3 Observed temperatures within the cave. (a) Comparison of observed temperatures with mean monthly water temperature at 30 m depth (the Japan Oceanographic Data Center), (b) Comparison of observed temperatures with tidal records through September 2003.

Fig. 4 Columnar diagrams of submarine-cave sediment core, showing stratigraphic change in grain distribution, carbonate content, mineral composition, isotopic ratios of mud-size carbonate and components of sand-size particles. M-C: Mg calcite, C: calcite, A: aragonite.

Fig. 5 Columnar diagrams of submarine-cave sediment core, showing stratigraphic change in component of mud-size particles.

Fig. 6 Results of AMS ^{14}C dating of molluscs and mud-size carbonate.

Fig. 7 Stratigraphic distribution of the accumulation rate of the four dominant bivalves.

Fig. 8 $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ plot for the cavernicolous micro-bivalve *C. iejimensis* in 5-cm-thick surface sediments.

Fig. 9 Relationship between the $\delta^{18}\text{O}$ and shell height of *C. iejimensis* in surface sediments.

Fig. 10 Relationship between the $\delta^{18}\text{O}$ -derived temperature and shell height of the

683 cavernicolous micro-bivalve *C. iejimensis* in 5-cm-thick surface sediments and the
684 cored sediments. The regression line is calculated from the data of specimens from
685 surface sediments.

686 Fig. 11 Relationship between the shell height and shell weight of *C. iejimensis*.

687 Table 1 Result of mollusc ^{14}C -dating. All samples were analyzed with an accelerator
688 mass spectrometry by Beta-Analytic Corporation.

689 Table 2 List of bivalve species from Daidokutsu. A: articulated shells, R: right
690 valve, L: left valve.

691

Kitamura et al. Fig. 1

- sample site of cored sediments
- ▤ thermometer

Kitamura et al. Fig. 2

Kitamura et al. Fig. 3

Fig. 5 Kitamura et al

Fig. 6 Kitamura et al

Kitamura et al Fig. 7

Kitamura et al Fig. 8

Kitamura et al Fig. 9

◆ specimens from surface sediments

○ specimens from cored sediments

The regression line is calculated from the data of specimens from surface sediments

Kitamura et al Fig. 10

Kitamura et al Fig. 11

depth (cm)	laboratory number	sample	measured ¹⁴ C age (BP)	$\delta^{13}\text{C}$	conventional ¹⁴ C age* (BP)	Calibrated age	
						intercept** (cal BP)	age ranges (cal BP)
0–2.2	Beta-185831	mix of <i>Parvamussium crypticum</i> (one individual), <i>Carditella iejimensis</i> (one individual) and <i>Iniforis poecila</i> (one individual)	106±0.4 pMC	+1.4	100.5±0.4 pMC	–	–
3.4–5.8	Beta-185832	mix of <i>Parvamussium crypticum</i> (one individual), <i>Cyclopecten ryukyuensis</i> (one individual), <i>Carditella iejimensis</i> (one individual) and <i>Coralliophaga hyalina</i> (one individual)	118±0.4 pMC	+2.5	111.5±0.4 pMC	–	–
13	Beta-167418	<i>Neritopsis radula</i> (one individual)	220±40	+1.5	650±40	320	300–250
19.6	Beta-180894	<i>Acar</i> sp. aff. <i>A. plicata</i> (one individual)	590±40	+2.7	1040±40	610	630–540
25	Beta-167416	<i>Stosicia</i> (<i>Isseliella</i>) <i>bourguignati</i> (one individual)	1080±40	+2.9	1540±40	1100	1172–1056
34	Beta-185221	<i>Septifer</i> sp. (one individual)	1530±40	+2.8	1530±40	1520	1560–1460
35.5	Beta-167415	<i>Mitrella</i> sp. (one individual)	1570±40	+1.7	2010±40	1580	1640–1540
43	Beta-167414	mix of <i>Bentharca irregularis</i> (one individual), <i>Emarginula crassicostata</i> (one individual) and <i>Tenagodus</i> (<i>Tenagodus</i>) <i>cumingi</i> (one individual)	1920±40	+3.2	2380±40	2000	2050–1940
0–0.8	Beta-194743	Carbonate mud	2090±40	+0.5	2510±40	2150	2250–2120
19.0–20.2	Beta-194742	Carbonate mud	2160±40	+0.9	2580±40	2290	2310–2200
41.8–43.0	Beta-194741	Carbonate mud	2960±40	+0.8	3380±40	3250	3310–3200

*reservoir correction was not applied.

**intercepts between the conventional ¹⁴C age and the calibration curve of Stuiver *et al.* (1998).

All errors are 1 σ .

pMC: percent modern carbon

Species \ Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
<i>Acar</i> sp. aff. <i>A. plicata</i>		R1	L1		L1														R1	L2																
<i>Bentharca excavata</i>													R1																							
<i>Bentharca</i> sp.						L1																												R1		
<i>Cosa kinjoi</i>			R1/L1	A1	A1/R1/L1	R2/L1	R1	R1	R1	R1	R2/L1		L1	R3/L1		R1	L4	R1/L1	A1/R1/L1	L1	R1		A1/R1		R1	R1/L1		R1	R3	L1	A1/R1	L1	A1		L1	
<i>Cosa uchimae</i>			R1	R2				L1		L1	R2												L1				L1		R1				L1			
<i>Limopsoidea?</i> gen. et sp. Indet.														R1													L1						L1			R1
<i>Brachidontes</i> sp.					R1			R1/L1	L1						R1						L1															
<i>Septifer</i> sp.						R1		R1																												
<i>Dacrydium zebra</i>			R1																											R1						
<i>Parvamussium crypticum</i>	R1	L1		L1	A2/L1/R1	R2/L3	R1		L3	R1/L3		R1	R1	R2/L1	L1	L1	L3	R1/L1	R2	L1	R2/L1		R2			L1	R1	R1/L1	L1	R1		R3	L1	R1		R2/L2
<i>Cyclopecten ryukyuensis</i>	R1		R4/L2	L1	A1	L3	R1		L1	L1	L2					L1	L2				L1							L1		L1				R1		
<i>Chlamydeilla incubata</i>																																L1				
<i>Chlamydeilla tenuissima</i>											L1																									R1
<i>Divarilima elegans</i>	R1				R1/L1	R1/L2	R1		L1		R1	A1						L2		R1	R1									R1		L1	R1			
<i>Limaria</i> sp.																																	L1	R1		
<i>Cardita uruma</i>																														R1						
<i>Carditella iejimensis</i>				L2		R4/L1		L3			R1			L1	R1/L1	L1	R1/L1	A1	L1	L1	R1/L1		R1	R1/L1		R1	R1	L1		R2			R2	L3	R2	A1/L1
<i>Salaputium unicum</i>										L1																			L1							
<i>Kelliella japonica</i>			L1		L1											L1																				A1
<i>Periglyta chemnitzii</i>						L1																														
<i>Gafrarium pectinatum</i>		R1																																		
<i>Coralliophaga hyalina</i>																																	R1			
<i>Hiatella</i> sp. aff. <i>H. orientalis</i>																																				L1
<i>Poromydæ</i> sp.													R1	L1			R1													R1					R1	
<i>Halonympha asiatica</i>												L1																						L1		
Depth (cm)	43.0-41.8	41.8-40.6	40.6-39.4	39.4-38.2	38.2-37.0	37.0-35.8	35.8-34.6	34.6-33.4	33.4-32.2	32.2-31.0	31.0-29.8	29.8-28.6	28.6-27.4	27.4-26.2	26.2-25.0	25.0-23.8	23.8-22.6	22.6-21.4	21.4-20.2	20.2-19.0	19.0-17.8	17.8-16.6	16.6-15.4	15.4-14.2	14.2-13.0	13.0-11.8	11.8-10.6	10.6-9.4	9.4-8.2	8.2-7.0	7.0-5.8	5.8-4.6	4.6-3.4	3.4-2.2	2.2-1.1	1.1-0