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A 60-year isotopic record from a Mid-Holocene fossil giant clam (*Tridacna gigas*) in the Ryukyu Islands: Physiological and paleoclimatic implications

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Abstract

We have constructed a 60-year stable isotope record from a ¹⁴C-dated fossil giant clam, *Tridacna gigas* (6216 years BP), at its northernmost latitudinal limit in the geological past, on Kume Island, Central Ryukyu Archipelago, Japan. Stable oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotopic analyses are combined with observations of growth lines seen on the inner shell layer. Sixty pairs of summer/winter growth lines which preserve daily growth increments were observed in the inner shell layer. Two growth phases, characterized by a growth curve and isotopic profiles, are clearly recognized throughout the growth history of this specimen. No significant shifts in average values of the two isotopic ratios were detected during its growth history, although the growth rate varied widely from 1 mm to 15 mm per year over 60 years, including after the onset of sexual maturity. Spectral analysis of the fossil *Tridacna* $\delta^{18}\text{O}$

time-series implies that decadal variability observed in the North Pacific Ocean during the past hundred years also existed 6000 years ago. Our study implies that fossil giant clams are one of the best means of inferring isotopic records of annual to decadal climate variations. Giant clams have the advantages of a dense shell, high growth rate, long lifespan, and geographically and geologically broad distributions.

Key words; *Tridacna gigas*, Oxygen isotope, Carbon isotope, Growth line, Mid-Holocene

1. Introduction

The giant clam, *Tridacna gigas*, is among the largest bivalves in geological history and has been a prominent member of Indo-Pacific coral reef communities from the Eocene to the present (Rosewater, 1965). They characteristically contain symbiotic algae (zooxanthellae) in their mantle lobes and their shell growth rate is very fast (the annual thickness increment is approximately 1 cm; Bonham, 1965). Giant clams sometimes grow to over 1 m in length and have life spans of several decades to a few centuries. In addition, giant clams have hard and dense aragonite shells with daily growth lines in their inner shell layer (Aharon and Chappell, 1986; Pätzold, et al., 1991; Watanabe and Oba, 1999). *Tridacna* shells are potentially useful for reconstructing paleoclimates at a high-resolution, and their usefulness is enhanced because their shells calcify essentially in isotopic equilibrium with surrounding seawater (Aharon, 1983, Aharon and Chappell, 1986; Aharon, 1991; Watanabe and Oba, 1999).

Oxygen isotope ratios ($\delta^{18}\text{O}$) of biogenic carbonates have been widely used for reconstructing paleoenvironments, because they reflect both sea-surface temperature (SST) and the $\delta^{18}\text{O}$ of ambient seawater (Epstein et al., 1953). In regions with salinity and seawater $\delta^{18}\text{O}$, shell $\delta^{18}\text{O}$ can provide an estimate of ambient SST, although in regions where temperature is constant, shell $\delta^{18}\text{O}$ is a useful record of the hydrologic balance. Several paleoenvironmental studies have examined the isotopic composition of *Tridacna* shells (Aharon et al., 1980; Aharon, 1983; Aharon and Chappell, 1986; Jones et al., 1986; Romanek et al., 1987; Romanek and

Grossman, 1989; Pätzold et al., 1991; Aharon, 1991; Watanabe and Oba, 1999), as summarized by Watanabe and Oba (1999). Earlier workers mainly used fossil *Tridacna* shells and examined the evidence for late Quaternary sea-level and temperature changes, although they generally did not have enough sampling resolution for reconstructing past environmental variations on a seasonal scale (Aharon et al., 1980; Aharon, 1983; Aharon and Chappell, 1986). However, some recent studies have examined the isotopic values of modern specimens in order to calibrate *Tridacna* shells against prevailing environmental and physiological variables (Jones et al., 1986; Romanek et al., 1987; Romanek and Grossman, 1989; Pätzold et al., 1991; Aharon, 1991; Watanabe and Oba, 1999). In the present study, we have reconstructed a high-resolution stable isotope record for a ^{14}C -dated fossil shell of the giant clam *Tridacna gigas*. This Mid-Holocene specimen was collected at Kume Island, Central Ryukyu Archipelago, Japan, which is the northern latitudinal limit for this species in the geological record (Rosewater, 1965).

2. Materials and Methods

Tridacna gigas LINNE, 1758, has the largest shells and highest growth rate in the Family *Tridacnidae* (Bonham, 1965). Our study specimen was one of several fossil shells of *T. gigas* discovered beneath a coral-reef flat on Kume Island, Central Ryukyu Archipelago, southern Japan, in January 1991 (Fig. 1), in an underwater trench dredged near the port of Tomari (Fig. 1). We chose a large and well-preserved shell to study: 60 cm high, 93 cm long and weighing 95 kg (Fig. 2a). A 6-mm-thick slice was made from the umbo to the inner surface and parallel to the axis of maximum growth (Fig. 2b). Powder samples for isotopic analysis were obtained along the major growth axis on the inner surface at 1.0-mm intervals, using a low-speed dental drill (Fig. 2b). Samples for AMS ^{14}C measurements were taken 1 mm, 80 mm, and 100 mm from the inner surface. Our analyses were carried out at the Institute of Geological and Nuclear Sciences, as were X-ray diffraction (XRD) measurements. The AMS results were 5839 ± 55 years BP, 5907 ± 60 years BP, and 6216 ± 70 years BP at 1 mm, 80 mm, and 100 mm from the inner surface, respectively. These conventional radiocarbon ages were corrected to 6110 ± 100 years BP,

6184±83 years BP, and 6485±105 years BP, respectively, for the marine-reservoir effect using the Radiocarbon Calibration Program CALIB 4.3 (Stuiver and Reimer, 2000). XRD analysis and thin section observations with an optical microscope did not reveal any secondary calcite.

The powder samples weighed 70-100 µg and were reacted in 100% phosphoric acid at 90.0°C, in an automated carbonate device (Micromass Multiprep) coupled with a Micromass Optima mass spectrometer at the Geological Survey of Japan. Isotopic ratios are expressed as conventional delta notations in ‰ units relative to the Vienna Peedee Belemnite (V-PDB), through measurements of the isotopic ratio of CO₂ gas derived from National Bureau of Standards NBS-19 (δ¹⁸O: -2.20‰; δ¹³C: 1.95‰). The average internal precision for NBS-19 was 0.1‰ for δ¹⁸O and 0.08‰ for δ¹³C (n = 34) in the present study.

We made contact replica films and thin sections from sampled surfaces in order to observe growth lines and microstructures. The surface was polished and leached with 10% acetic acid and then observed under a digital microscope (Keyence VH-6200).

We examined the time-series of sea-surface temperatures (SST) and cloudiness for 1982-1993, which were obtained from ship and buoy observations compiled in Long Marine Reports of Comprehensive Ocean-Atmosphere Date Set for a 2° x 2° box centered at 27°N and 127°W (COADS: Woodruff et al. 1987), and also obtained sea-surface salinity (SSS) measurements from a database at the Japan Oceanographic Data Center (1° x 1° box), sporadically compiled between 1906 and 1994 (n = 313).

3. Geological setting

Kume Island is a well-developed fringing reef located at the northern latitudinal limit of *T. gigas* in the Ryukyu Archipelago in the northwestern Pacific (Rosewater, 1965). The warm Kuroshio Current, which originates as equatorial water, flows northward into the region through the East China Sea. The predominant monsoon winds change direction seasonally. Takahashi et al. (1988) and Kan et al. (1991) inferred a Holocene sea-level curve for Kume Island, based on cores drilled in an emerged Holocene reef flat. Kume Island's relative sea-level rose rapidly at

approximately 10m/1000 years until about 6500 BP, when it stabilized at about 6000 years BP, when the *T. gigas* specimen in this study lived. The Holocene reef has since been raised about 4 m above modern sea level.

The SST has a 9°C range, from 21°C (February) to 30°C (August), and cloudiness is low (4 okta) in summer (July to October) and high (6-6.5 okta) in winter (November to March). The seasonal range of SSS is from 34.8‰ to 34.2‰, being high in winter and spring (December to April) and low in summer to autumn (July to October) (Fig. 3).

4. Results

4.1 Oxygen Isotopes

The range of $\delta^{18}\text{O}$ values for our study specimen of *T. gigas* is 2.45‰, from -1.94 to 0.51‰, with an average value of -0.66‰ (n=228). The profile exhibits a clear seasonal variation from the initial surface to 130 mm, but it was unclear between 130 and 260 mm (Fig. 4). The seasonal amplitudes of $\delta^{18}\text{O}$ in *T. gigas* in the present study are similar to those of a modern *Hippopus* shell described by Watanabe and Oba (1995, 1999), although the measured amplitude depends on the sampling resolution relative to growth rate (1 mm sampling gave a range of 2.0 ‰, in Watanabe and Oba, 1995; 50 μ m sampling of the same shell gave a range of 2.75‰, in Watanabe and Oba, 1999). The $\delta^{18}\text{O}$ variation reflects variations in both sea-surface temperature (SST) and the $\delta^{18}\text{O}$ of ambient seawater, because *Tridacna* calcifies essentially in isotopic equilibrium with surrounding seawater (Aharon, 1983; Aharon and Chappell, 1986; Aharon, 1991; Watanabe and Oba, 1999). Aharon (1983) described the relationship between temperature and the oxygen isotopic ratios of *T. gigas* and water using the following linear equation:

$$T (^{\circ}\text{C}) = 21.30 - 4.42 (\delta^{18}\text{O}_{\text{C}} - \delta^{18}\text{O}_{\text{W}}) \quad (1)$$

where $\delta^{18}\text{O}_{\text{C}}$ is the $\delta^{18}\text{O}$ value of the shell (vs. PDB) and $\delta^{18}\text{O}_{\text{W}}$ is the $\delta^{18}\text{O}$ of seawater (vs. SMOW).

Similar relationships have been observed for other aragonite molluscs (Grossman and Ku, 1986). The variation of $\delta^{18}\text{O}_{\text{W}}$ in this region is unknown, but we have estimated it by using the linear

relationship proposed by Oba (1988) for surface waters extending from the East China Sea to the Kuroshio Current region, which is $\delta^{18}\text{O}\text{‰} = 0.203 \text{ S} - 6.76$ (S =Salinity). Thus, the modern salinity change is expected to cause a 0.12‰ variation between minimum values of 0.18 and maximum values of 0.30‰ for monthly averages in $\delta^{18}\text{O}_w$. This corresponds to less than 5% (2.45‰) of the total range observed on our *Tridacna* shell. Watanabe and Oba (1999) determined that temperature variations are recorded faithfully by $\delta^{18}\text{O}$ values in shells of this type, based on measurements from a giant clam shell (*Hippopus hippopus*) collected from Ishigaki Island in the Ryukyu Archipelago. If the present-day seasonal change in salinity can be applied to the Mid-Holocene, then more than 95% of the observed seasonal variation of $\delta^{18}\text{O}$ in the fossil *Tridacna* shell was controlled by seasonal changes of water temperature.

4.2. Carbon Isotopes

The $\delta^{13}\text{C}$ profile of *T. gigas* also shows strong cyclical variations from 2.35‰ to 3.23‰ (range 0.87‰, n=228), with an average of 2.75‰. As with oxygen isotopes, carbon isotope profiles show a clear seasonal variation from the initial surface to 130 mm, with an irregular pattern beyond 130 mm (Fig. 4). Although carbon isotopic fractionation in *Tridacna* is complex, the two possible sources of carbon for shell carbonates are dissolved inorganic carbon (DIC) in ambient seawater, and metabolic CO_2 passing through the respiration and photosynthesis pathways, which includes symbiotic zooxanthellae within *Tridacna* tissue. In the case of symbiont-bearing corals, which have been studied much more than *Tridacna*, it has been suggested that carbon isotopic variations could be a useful proxy of insolation mediated by water depth, because insolation determines the photosynthetic activity of symbiotic algae in corals (Grottoli, 2000). Jones et al. (1986) and Romanek et al. (1987) showed that a *Tridacna* shell is 2‰ ^{13}C -depleted relative to molluscs with no symbionts, and attributed this difference to the influence of a zooxanthellae-enhanced metabolic rate in the host. However, Romanek and Grossman (1989) found no significant symbiotic effect on $\delta^{13}\text{C}$ in *Tridacna*, compared to non-symbiont-bearing mollusks. Moreover, Tanaka et al. (1986) showed that a *Tridacna* shell is

2‰ ^{13}C -depleted relative to molluscs. In addition, Tanaka et al. (1986) showed that even the $\delta^{13}\text{C}$ of non-symbiont-bearing molluscs reflects the mixing of metabolic carbon derived from food sources and ambient DIC.

In the present study, the $\delta^{13}\text{C}$ value of DIC at Ishigaki Island on 26 July 1995 was 1.3‰, comparable with values of 1.3-1.8‰ reported from the Pacific Ocean between 10°N and 30°N for 1989-1991 (Quay et al., 1992). Adopting this $\delta^{13}\text{C}$ value of DIC together with the fractionation factor of 2.7‰ between aragonite and dissolved bicarbonate (Rubinson and Clayton, 1969; Romanek et al., 1992), the expected equilibrium value for aragonite is 4.0‰. This value is 2.3‰ higher than the $\delta^{13}\text{C}$ of modern *Tridacna* shells at Ishigaki Island (1.67‰ for *H. hippopus*; in Watanabe, 1996, 1.71‰ for *T. squamosa*; in Watanabe unpublished data, and 1.60‰ for *T. crocea*; Koike and Oba, personal comm.). The photosynthesis of symbiotic zooxanthellae conceivably could account for the approximately 2‰ negative shift from equilibrium values. These results suggest that the mean values of $\delta^{13}\text{C}$ in modern *Tridacna* shell are probably determined by the mixing of DIC and metabolic carbon derived from respiration and photosynthesis. We cannot say whether the same applies to our 6000-year-old *Tridacna*.

There are positive correlations between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for both the early growth phase (0 – 130 mm) ($r = 0.69$, $n = 96$) and late growth phase (beyond 130 mm) ($r = 0.62$, $n = 132$) of the shell in the present study. This positive correlation has been observed in several modern *Tridacna* species elsewhere, including at Rose Atoll (*Tridacna maxima*; in Jones et al., 1986); Ryukyu Archipelago (*Hippopus hippopus*; in Watanabe, 1996; *Tridacna squamosa*; Koike and Oba, personal comm., *Tridacna squamosa*; in Watanabe unpublished data), the Great Barrier Reef (*Tridacna gigas*; in Aharon, 1991) and in a fossil *Tridacna* shell from a late Quaternary emerged coral reef in New Guinea (Aharon et al., 1980) (Fig. 5) In the present study, there is a negative correlation between SST and cloudiness ($r = 0.77$, $n = 144$). This suggests that the increased photosynthetic rate of symbiotic zooxanthellae under strong sunlight in summer can probably explain the lower $\delta^{13}\text{C}$ values and the positive $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ correlation in *Tridacna*. Romanek and Grossman (1989) summarized several possible environmental mechanisms for this

positive correlation, such as (1) increased phytoplankton productivity in winter and dilution by ^{18}O -depleted water in summer, (2) preferential incorporation of ^{13}C -depleted carbon during periods of rapid growth in the warm season, (3) oxidation of organic matter produced by phytoplankton blooms following spring upwelling, (4) temperature dependence of ^{13}C and ^{18}O fractionation. In study area, low SSS occurs during summer even when high temperature and heavy precipitation (low cloud cover) simultaneously occur (Fig. 3). It is supported the hypothesis that mixing of the Kuroshio water with low salinity (and low $\delta^{18}\text{O}$) water occur during summer. This mixing process is applicable for an additional mechanism of the positive $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ relation.

4.3. Growth records

Sixty pairs of summer/winter growth lines were observed in the inner zone of our *T. gigas* specimen (Fig. 2), and a growth curve was constructed by counting and measuring each annual growth increment (Fig. 6). Because the uncertainty of three corrected radiocarbon ages was not sufficiently small (± 96 years) to determine the life span of this specimen, it was estimated 60 years old by the counting growth lines and oxygen isotopic seasonal profiles. The annual increment ranged from 16 mm/year early in life to 1 mm/year toward the end of its life. Early growth (the first 12 years) was rapid, declining from 16 mm/year to 7 mm/year after 12 years (mean = 10.7 mm/year). The growth rate decreased over the following 48 years from 5 mm to 1 mm/year (mean = 2.9 mm/year). This is consistent with previous studies showing that the growth rate of *Tridacna* decreases with the onset of sexual maturity (Jones et al., 1986; Romanek et al., 1987; Romanek and Grossman, 1989). The first 12-15 years, in which rapid growth facilitated multiple samples within each year, $\delta^{18}\text{O}$ maxima (= temperature minima) correspond to the dark (dense) layers within the annual growth bands. The dark layers thus correspond to winter, and their higher density implies slower growth than in summer. Daily growth increments were also observed within each annual growth line under a microscope (Fig. 7). The intervals of daily growth lines for the adult stage were narrow (approximately from 2 to 25 μm) relative to the

juvenile stage (from 40 to 70 μm).

5. Discussion

5.1. Effects of sexual maturity and growth rate on isotopic composition

Jones et al. (1986) found that the isotopic composition of *Tridacna maxima* changes as the animal reaches maturity. The changeover from juvenile to mature growth at approximately 10 years was accompanied by a decrease in the rate of calcification, and Jones et al. (1986) suggested that energy fractionation between biomineralization and reproduction took place, causing isotopic disequilibrium in the $\delta^{18}\text{O}$ values of the shell in summer. Moreover, Romanek and Grossman (1989) found that the $\delta^{13}\text{C}$ $\delta^{18}\text{O}$ correlation was poor in adult specimens, which they attributed to diminished summer growth and decreased shell $\delta^{13}\text{C}$. For the *T. gigas* shell in the present study, a change from juvenile to adult is clearly present in the slope of the growth-line curve. However, no significant isotopic shift occurs in the annual carbon and oxygen isotope average values (Fig. 4). Moreover, the linear regression equation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ for the juvenile stage ($\delta^{18}\text{O} = 2.14 \delta^{13}\text{C} - 6.44$, $r = 0.69$, $n = 96$) is very similar to that for the adult stage ($\delta^{18}\text{O} = 1.96 \delta^{13}\text{C} - 6.12$, $r = 0.62$, $n = 132$). These results suggest that sexual maturity did not affect the isotopic composition of our *T. gigas* shell.

Our *T. gigas* results present an excellent opportunity to test whether $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in symbiotic molluscs are influenced by the shell growth rate, because the specimen had a large range of growth rates during its 60-years life. Even though growth rate significantly varied from 15 mm/year to 1 mm/year, no growth rate effect can be seen on the two observed isotopic values. However, the relative sampling resolution could depend on the growth interval. In the present study, our isotopic results for the adult stage are not likely to have captured the extremes in climatic signals, especially for winter when the growth interval was small relative to summer (Watanabe and Oba, 1999).

5.2. Mid-Holocene Paleoclimate and the use of giant clams as paleoclimatic recorders

The Mid-Holocene climate is of particular interest because solar radiation in the northern hemisphere summer was higher than at present, and the summer thermal contrast between land and ocean may have been enhanced (COHMAP Members, 1988). In the North Pacific, decadal to interdecadal climate variability has been documented in sea-surface and air temperatures, as well as sea-level barometric pressure, over the past 100 years (Mantua et al., 1997, Minobe, 1997), and has been termed the Pacific Decadal Oscillation (PDO). Although causes of the PDO are unknown, this ocean-atmosphere co-variation suggests that interactions between the ocean and atmosphere are important. As a contribution from this study, we examined our 60-year shell $\delta^{18}\text{O}$ record, to learn whether PDO-like decadal climate variability occurred 6000 years ago. Spectral analysis of the $\delta^{18}\text{O}$ time-series was performed by using AnalySeries software (Paillard et al., 1996). Prior to spectral analysis, the distance scale of the x-axis was converted to a time series by assuming a peak-to-peak annual cycle and constant growth between each $\delta^{18}\text{O}$ peak. The principal spectral peaks were located at about 3 years, and between 11 and 14 years (Fig. 8). Recently decadal SST variability has been observed in coral $\delta^{18}\text{O}$ and Sr/Ca ratio in the western Indian Ocean (Cole et al., 2000) and the southern Pacific Ocean (Linsley et al., 2000). The observed decadal variability of the fossil *Tridacna* $\delta^{18}\text{O}$ record suggests that a similar decadal oscillation existed 6000 years ago, and demonstrates that fossil *Tridacna* shells can record past PDO-like decadal climate variability.

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Figure captions

Figure 1

Location map showing sampling site for *Tridacna* specimens.

Figure 2a

(a) *Tridacna gigas*, LINNE, 1758, from Kume Island (b) Optical transmitted-light photograph of the inner shell layer of *Tridacna gigas*.

Figure 3

Seasonal variation in sea surface temperatures (SST: **a**), Cloudiness (**b**), and sea surface salinity (SSS: **c**) in Kume Island. The profiles of SST and cloudiness are averaged for the monthly values during 1982-1993 (n = 144) and that of SSS for sporadically observed values during 1906-1994 (n = 313). Error bars represent standard deviation (2σ) of monthly observed values for SST, cloudiness (n = 12), and SSS (n = 440).

Figure 4

Carbon (open circles; **a**) and oxygen (closed circles; **b**) isotopic profiles for our specimen of *Tridacna gigas*.

Figure 5

Carbon isotopic values plotted as a function of oxygen isotopic values for fossil *Tridacna gigas* (Ryukyu Archipelago, this study; circles), *Tridacna maxima* (Rose Atoll, Jones et al., 1986 and the data from Romanek, 1985; squares), *Hippopus hippopus* (Ryukyu Archipelago, Watanabe, 1996, Watanabe and Oba, 1999; diamonds), modern *Tridacna gigas* (Great Barrier Reef, Aharon, 1991; crosses), *Tridacna squamosa* (Ryukyu Archipelago, Watanabe unpublished data; circles and crosses), and *Tridacna crocea* (Ryukyu Archipelago, Koike and Oba personal comm; Pluses and crosses). Closed circles and squares represent the early growth phase, and open circles and squares the phase after sexual maturity for fossil *Tridacna gigas* (Ryukyu Archipelago, this study) and *Tridacna maxima* (Rose Atoll, Jones et al., 1986).

Figure 6

Growth curve for *Tridacna gigas*; closed circles represent the shell height and open circles the growth-line interval.

Figure 7

Microscopic images showing the daily growth bands in the inner shell layer of *T. gigas*. The daily growth bands of the adult stage at 50 mm from the inner surface (**a**) and of the juvenile stage at 230 mm from the inner surface (**b**).

Figure 8

Periodogram of spectral power of the oxygen isotope time-series in fossil *Tridacna gigas* using the multitaper method (MTM), Blackman-Tukey (BT), and Maximum Entropy Method (MEM) spectral analysis.

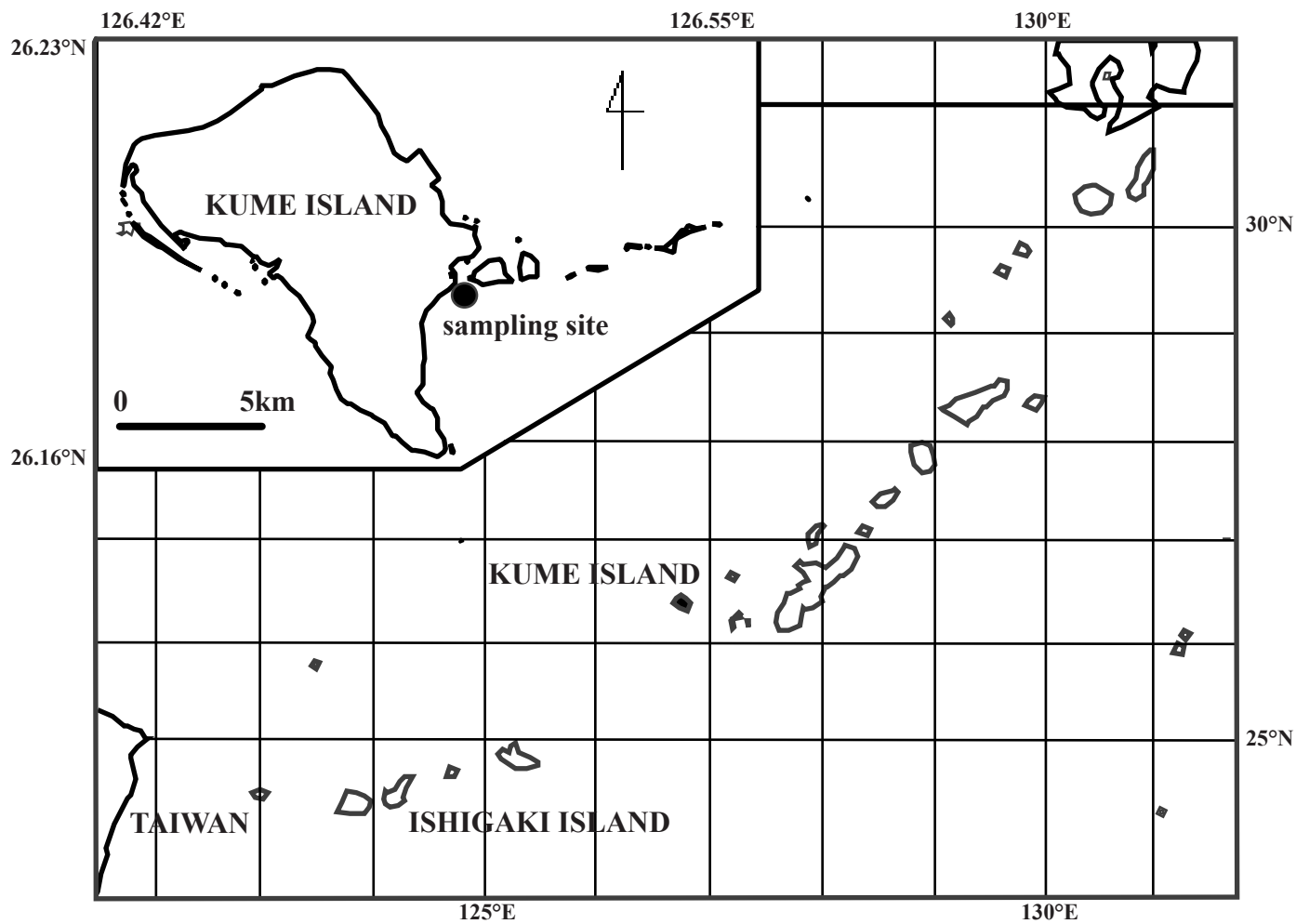


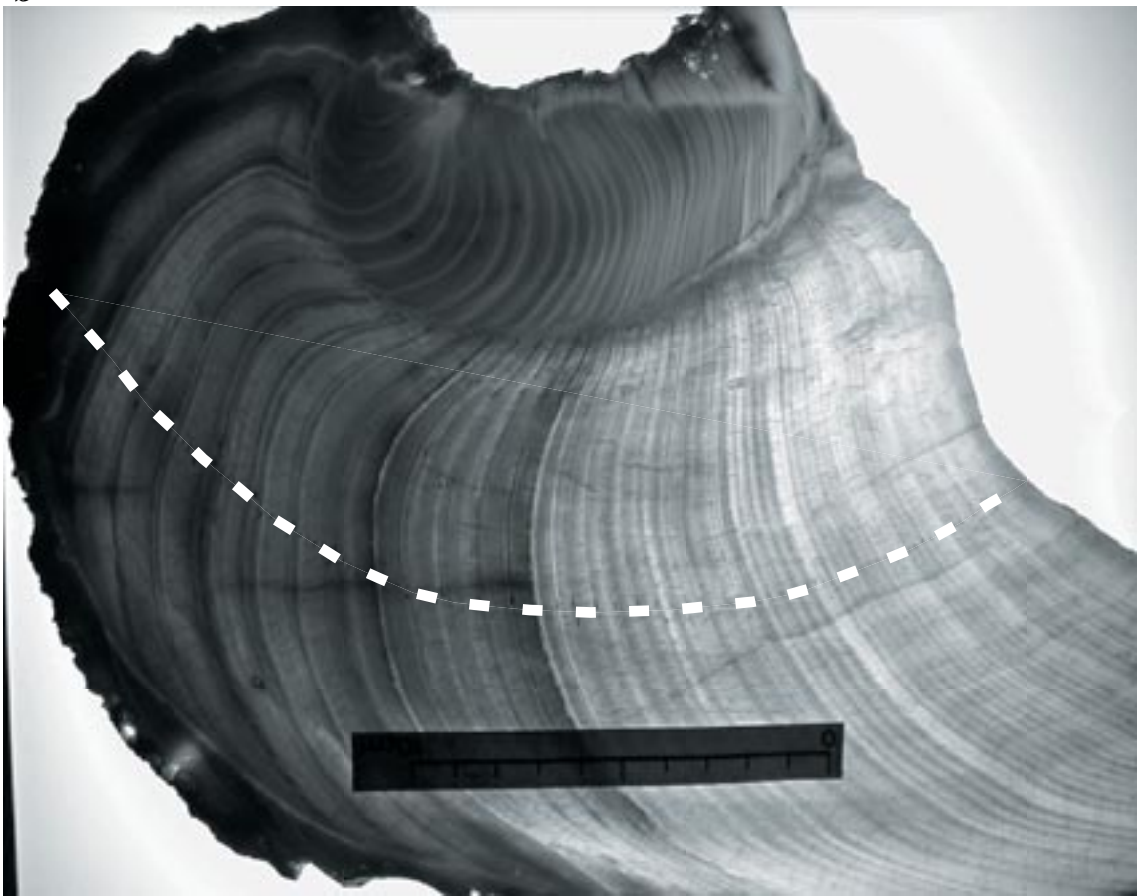
Figure 1

a



10 cm

b



5 cm

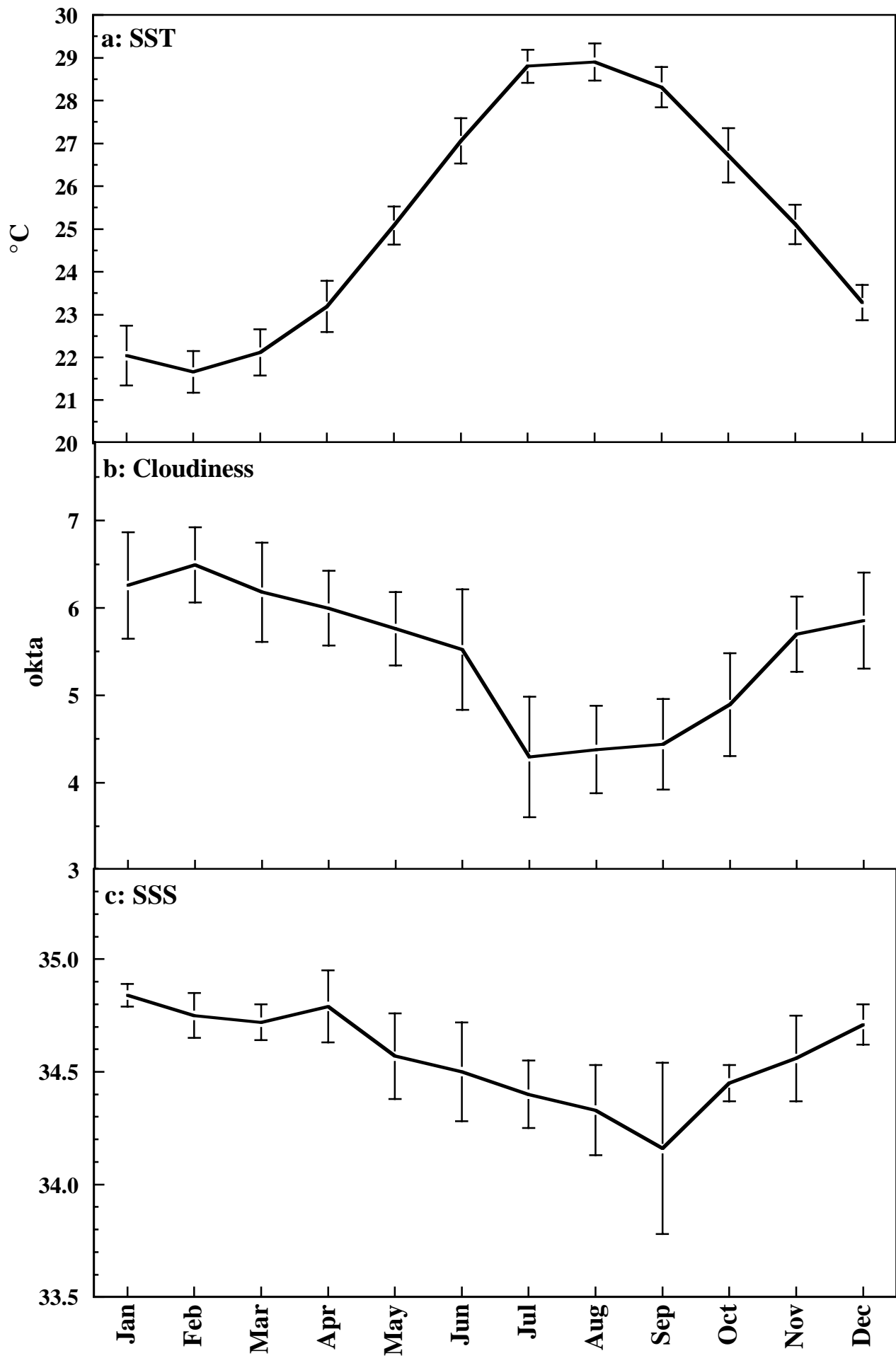


Figure 3

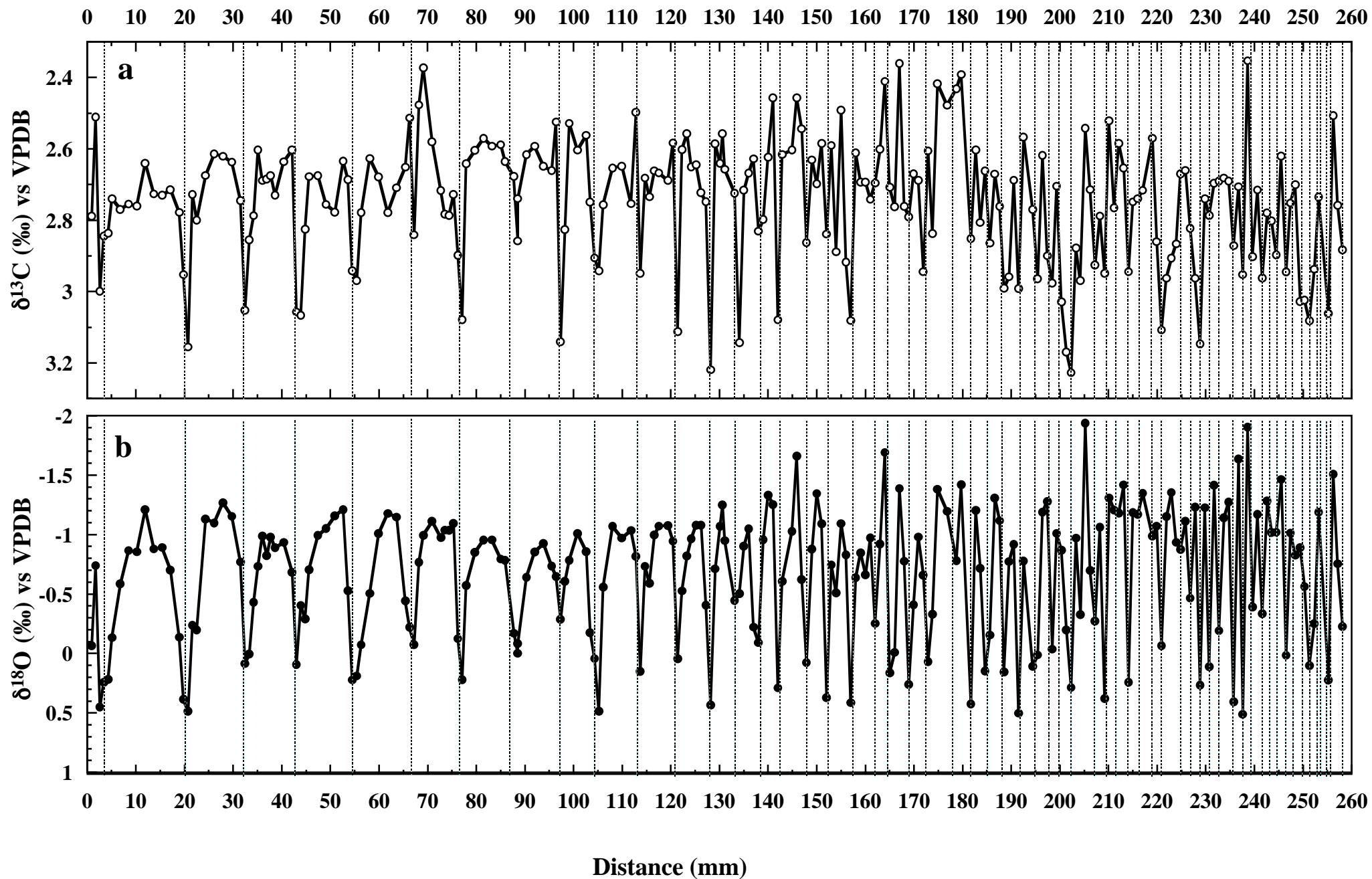


Figure 4

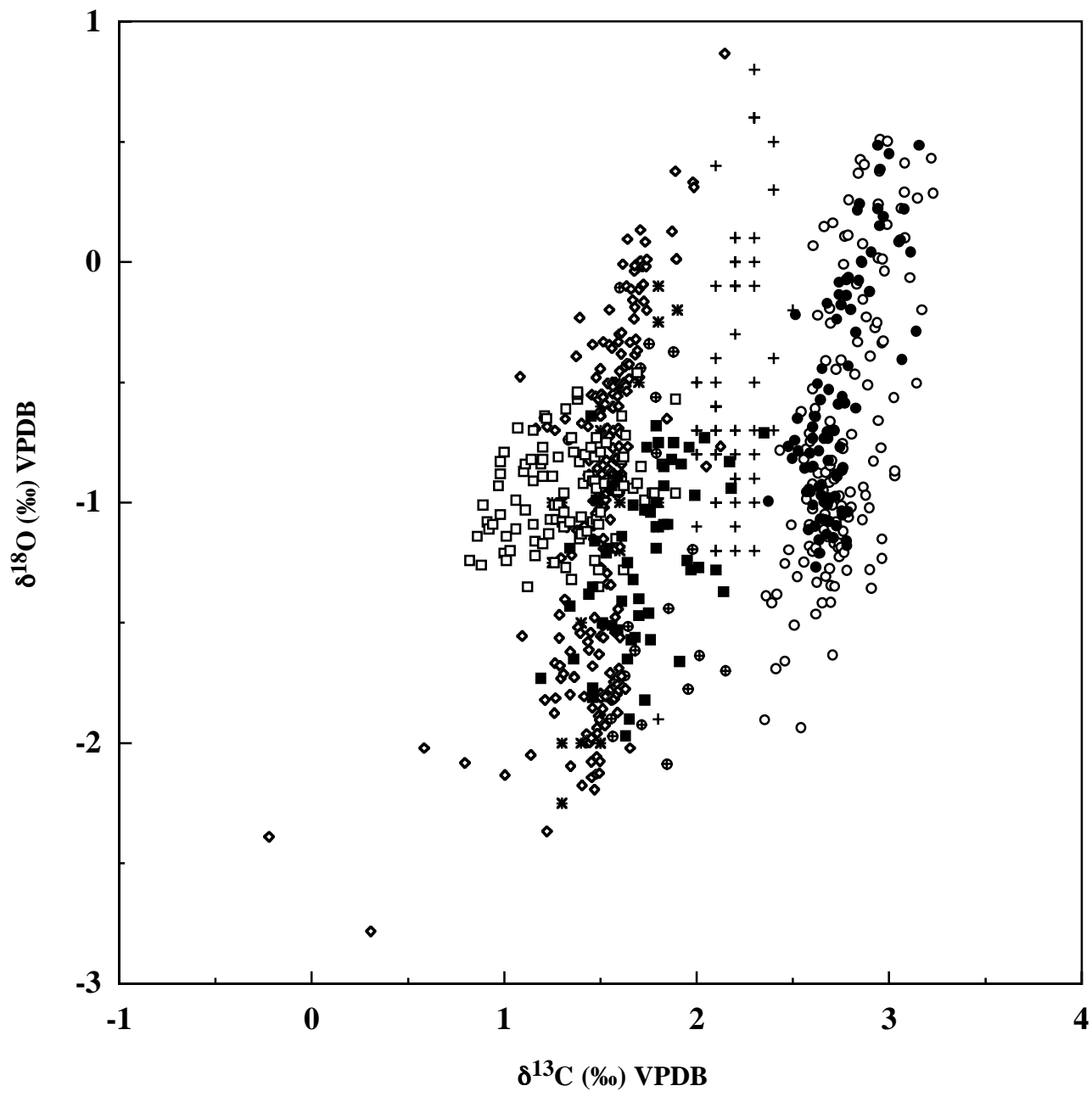


Figure 5

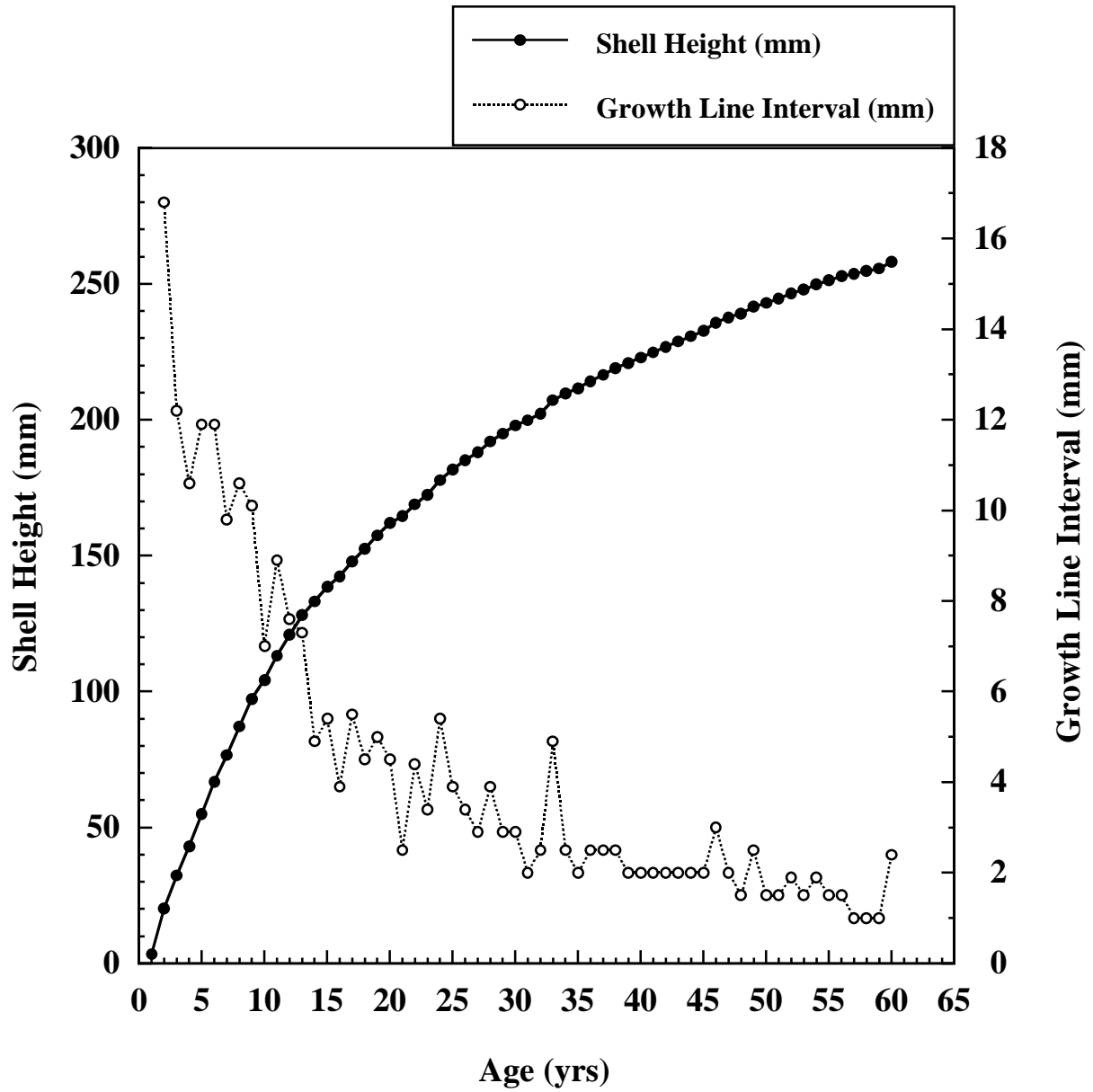
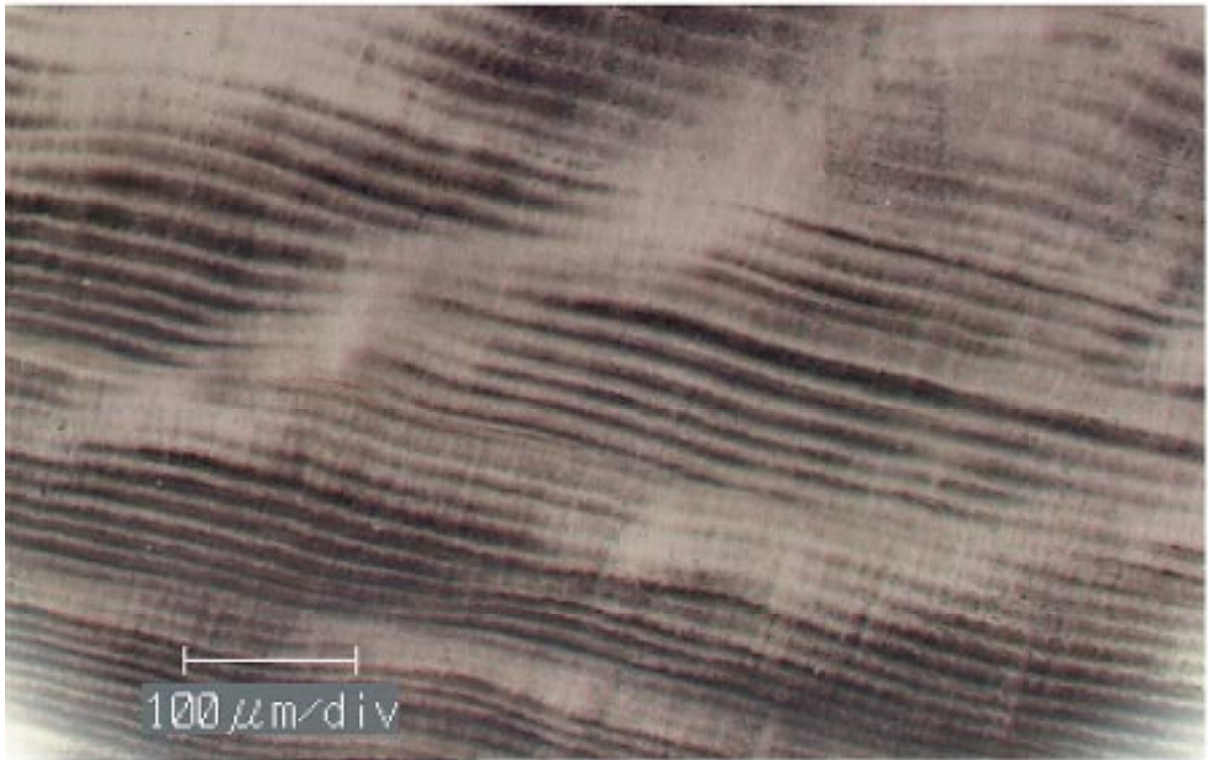


Figure 6

a



b

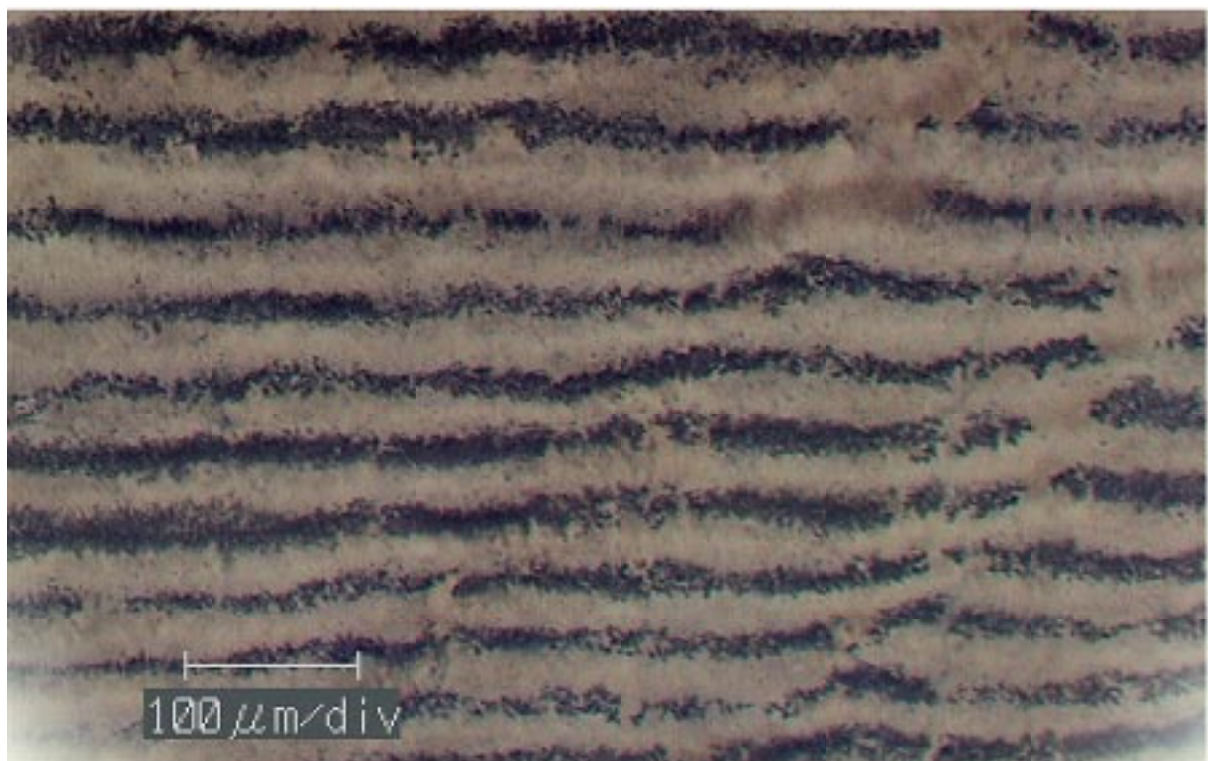


Figure 7

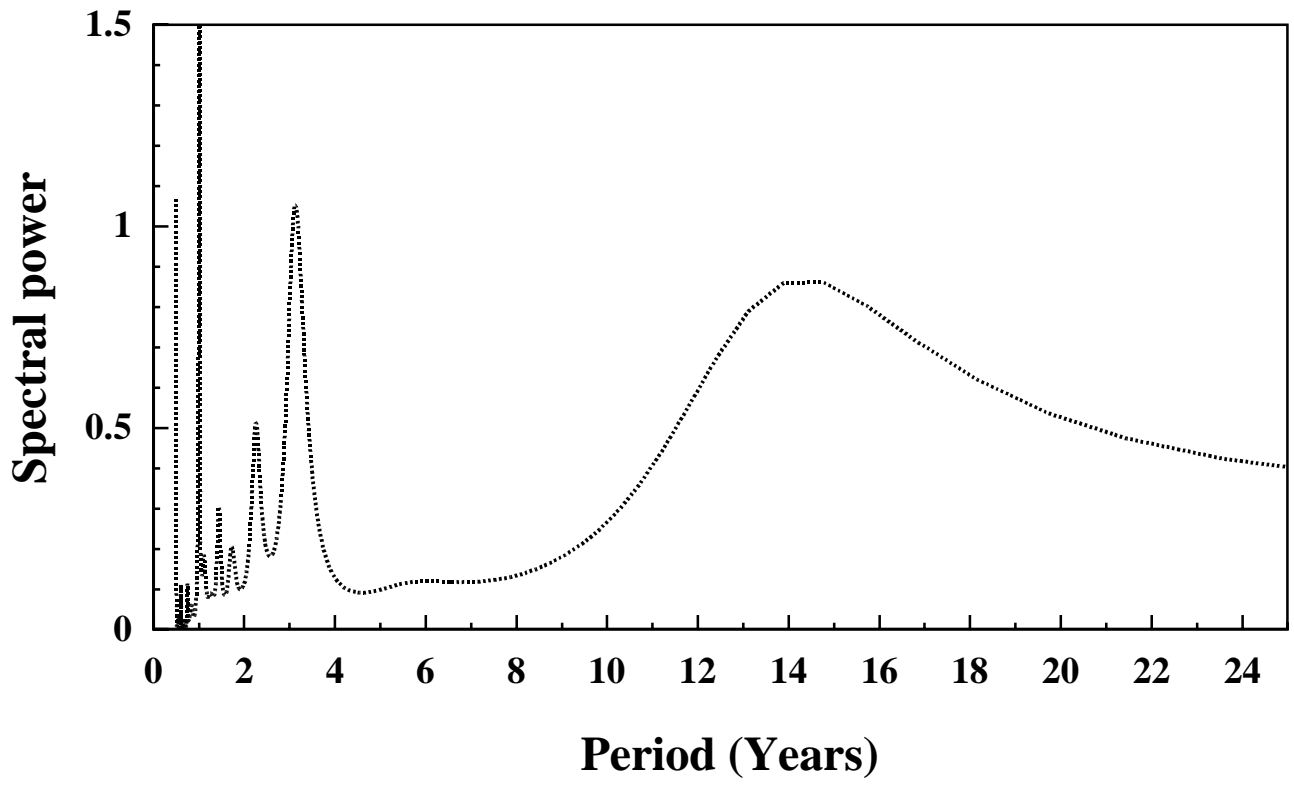


Figure 8