EXPRESS LETTER

Coral growth-rate insensitive Sr/Ca as a robust temperature recorder at the extreme latitudinal limits of *Porites*

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Oxygen isotope values of low-growth coral (<5 mm/yr) skeletons may reflect kinetic effects, which is problematic for sea surface temperature (SST) reconstruction. Here, we report a Sr/Ca-based SST reconstruction for a temperate *Porites* coral collected from Kyushu, Japan, near the northern latitudinal extent of hermatypic corals. Results indicate that Sr/Ca variations in a low-growth coral remain independent from growth rate, in contrast to the oxygen isotope ratios of the same coral.

Keywords: skeletal oxygen isotope in the coral, Sr/Ca, high latitudes, coral growth rates

INTRODUCTION

Past sea-surface temperature (SST) and salinity (SSS) are commonly reconstructed from the elemental components of annually-banded coral skeletons (e.g., Corrège, 2006; Yokoyama *et al.*, 2011; Seki *et al.*, 2012). This is complicated, however, by biologic and the kinetic influences on oxygen isotope ratios ($\delta^{18}O$) (e.g., McConnaughey, 1989; Allison *et al.*, 1996: Felis *et al.*, 2003; Fallon *et al.*, 2003; Suzuki *et al.*, 2005; Inoue *et al.*, 2007). Alternately, environmental reconstructions may be accomplished using Sr/Ca ratios, which are in theory a "clean" temperature tracer because of stable seawater proportions through time. While original work with Sr/Ca of coral skeletons failed to recognize any temperature effect due to poor analytical precision, methodological advancements have shown Sr/Ca to be a reliable recorder of SST (see Corrège, 2006). A recent culturing study indicates that Sr/Ca ratios are a more reliable paleotemperature proxy, potentially producing accurate reconstructions from a single *Porites* coral, due to insensitivity to temporal and intercolonial variations in skeletal growth rate (Hayashi *et al.*, 2013). Testing these results requires environmental reconstruction from corals located along the periphery of their habitable range.

Well-developed *Porites* colonies persist near the northerly limit of hermatypic corals at Ushibuka, Japan in the Amakusanada, east of the East China Sea (32°N, 130°E), where they experience large seasonal SST variations (the average amplitude is 11.7°C) and winter minima of approximately 14°C (Omata *et al.*, 2006). This results in very low growth rates at this location (Fallon *et al.*, 1999), as opposed to corals from similar latitudes in Bermuda (32°N) and Western Australia (29°S), the sites of the paleoceanographic mid-latitude hermatypic coral reconstructions reported to date, where winter temperatures remain above 18°C (Kuhnert *et al.*, 1999, 2005). Here, we compare new, high-resolution Sr/Ca data, measured along the growth axes of *Porites* from Ushibuka, to previously published $\delta^{18}O$ data from the same specimens (Omata *et al.*, 2006).

MATERIALS AND METHODS

Specimens were collected on 16 September 1993 from a *Porites* colony at a depth of about 15 m in Ushibuka

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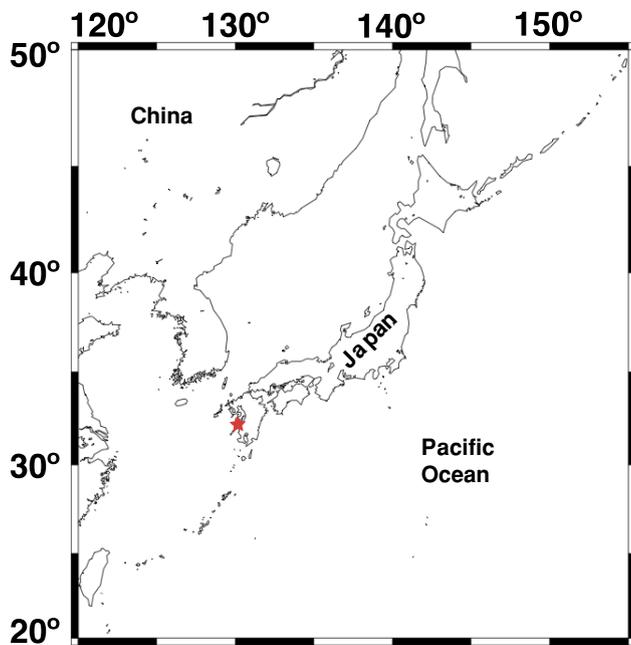*Corresponding author (e-mail: yokoyama@aori.u-tokyo.ac.jp)

Fig. 1. The sampling site of this study.

(32°1.8′ N, 130°16′ E, Fig. 1), located slightly south of the northern limit of the coral reef at Iki Island, Japan (33°48′ N; Yamano *et al*., 2001) and at a similar latitude as Shirigai Bay, Japan (32°N; Fallon *et al*., 1999). The nearest instrumental SST record is from Ushibuka Bay (32°12′ N, 130°02′ E), 4–5 km southeast of the sampling site, where average SST from 1964 to 1993 was 20.1°C and ranged from 12.2 to 28.4°C. Winter SST at Ushibuka remains below the previously reported potential thermal limit of hermatypic corals (Omata *et al*., 2006).

Omata *et al*. (2006) performed microsamping of this coral for $\delta^{18}O$ analyses at a 0.2 mm interval along the growth access of the recovered specimens. The internal precision of the mass spectrometer was 0.04‰ for $\delta^{18}O$, based on replicate measurements of the NBS-19 calcite standard (Omata *et al*., 2006). For Sr/Ca analyses by ICP-AES, we dissolved ~100 μg aliquots of the same powdered sample in 5 ml of 2% HNO_3 (Suzuki *et al*., 2003) and standard solutions prepared from JCp-1 (Okai *et al*., 2004) were measured after every third sample measurement. The relative standard deviation (RSD) based on replicate measurements of JCp-1 was 0.4% (see also Mishima *et al*., 2009). The reproducibility by measuring JCp-1 every 12 sample measurements was 8.72 ± 0.066 mmol/mol (2 SD, n = 46), which agreed well with the reference value of 8.72 reported in Okai *et al*. (2004).

Following Omata *et al*. (2006), our age model is based on linear interpolation between peak seasonal environmental proxy values, in this case Sr/Ca. Annual averages and seasonal amplitude (differences from previous win-

ter/summer to next summer/winter) were calculated for Sr/Ca and $\delta^{18}O$.

RESULTS

Based on our age model, this record spans the period from 1964 to 1993. Coral skeletal Sr/Ca exhibits distinct seasonality, with minimum (summer) and maximum (winter) values ranging from 8.71 mmol/mol to 9.86 mmol/mol, and a mean of 9.28 mmol/mol (Fig. 2). Growth rates averaged between seasonal layers range between 0.2 to 5.4 mm/6 months, with a mean value of 2.8 mm/6 months and a period of exceptionally small growth from February 1968 to August 1970 (see Figs. 2A and B). Annually-averaged Sr/Ca and $\delta^{18}O$, as well as seasonal amplitude of Sr/Ca, exhibit no correlation to growth rate. The seasonal amplitude of $\delta^{18}O$ is significantly correlated with growth rate for values <5 mm/yr (R^2 = 0.48, p << 0.01) (Fig. 3).

DISCUSSION

Our field results indicating insensitivity of Sr/Ca to changes in growth rate confirm conclusions of previous culture experiments (Inoue *et al*., 2007). Our reanalysis of previously published $\delta^{18}O$ data (Omata *et al*., 2006) is also consistent with previous work suggesting a strong dependence on growth rate when extension is below 5 mm/yr (McConnaughey, 1989; Felis *et al*., 2003; Suzuki *et al*., 2005) (Fig. 3A). There is no relationship between annually-average Sr/Ca ratios and annual growth rate, suggesting that Sr/Ca can be utilized as a SST proxy as it is not influenced by growth rate changes (Fig. 3B). While there is a similar relationship for $\delta^{18}O$ (Fig. 3C), the amplitude of $\delta^{18}O$ variations are positively correlated with growth rate, indicating that it is not entirely independent, whereas the amplitude of Sr/Ca variations exhibit no relationship to growth rate (Fig. 3A). Thus we can conclude that the Sr/Ca thermometer is more robust for SST than $\delta^{18}O$, as was also reported previously (Hayashi *et al*., 2013).

This dependency on growth rate is especially apparent between 1968 and 1969, during which skeletal extension was exceptionally small. Over this period, the instrumental summer SSTs were in excess of 27°C, with typical seasonal amplitude, but winter SSTs were below average. While persistent seasonality that tracks SST is recognized in Sr/Ca, none is observed in $\delta^{18}O$, which instead highly reflects the low growth rates (Fig. 2). We interpret this to indicate that $\delta^{18}O$ is affected by the low growth rate resulting from anomalously cold winter SST. Though the Sr/Ca summer value for 1969 is relatively depressed, seasonality is still readily identified, suggesting Sr/Ca is impacted minimally by growth rate varia-
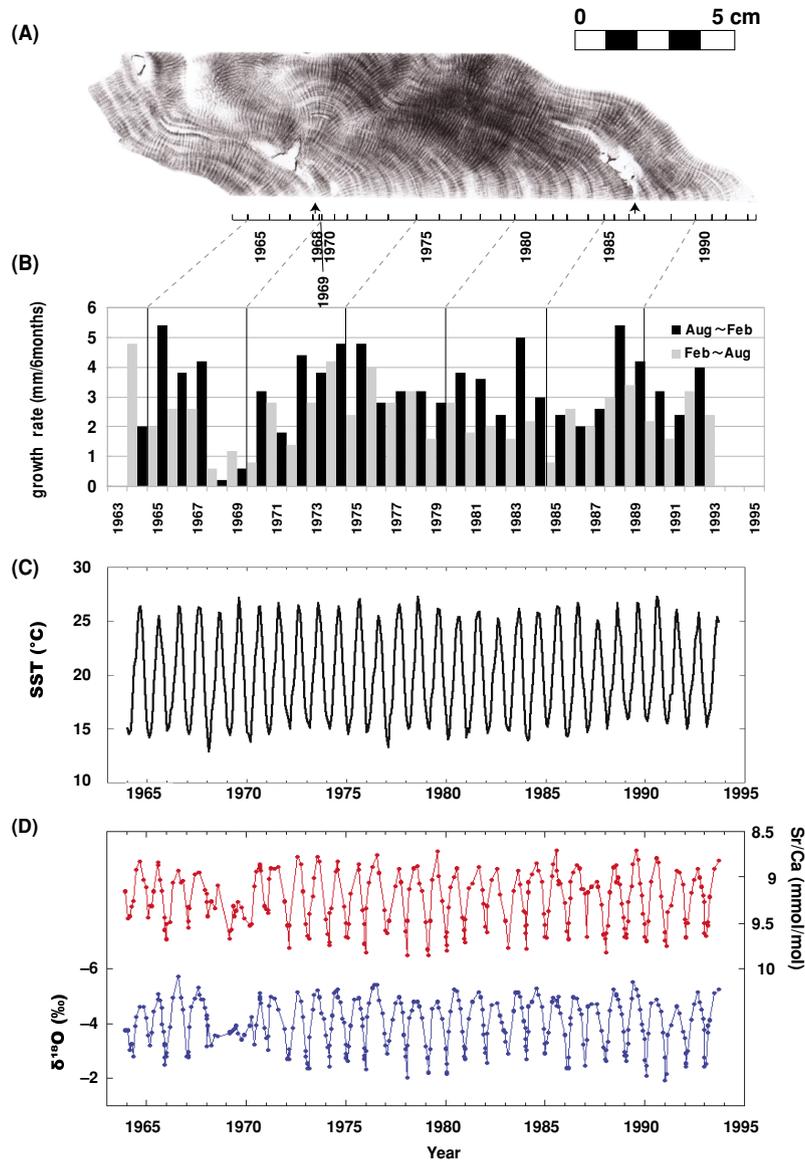
Fig. 2. (A) X-ray radiograph of the coral specimen (Omata et al., 2006). (B) Linear growth rate of Porites coral examined in this study. Linear growth rates were calculated based on the distance between maximum and minimum in Sr/Ca. (C) Ten-day average SST at Ushibuka (32°12′N, 130°02′E) based on the monthly reports of the Japan Meteorological Agency. (D) $\delta^{18}O$ (blue, Omata et al., 2006) and Sr/Ca (red) of Porites versus time over the period from 1964 to 1993.

tions.

There are two intervals that do not exhibit these relationships. According to the instrumental record, SST during the winter of 1976 was particularly cold yet $\delta^{18}O$ exhibits typical seasonal variability. This is likely because the 1976 to 1977 annual growth rate remained well above >5 mm/yr. Neither $\delta^{18}O$ nor Sr/Ca appear to capture the SST minima, which may be due to the cessation of growth that winter (Fallon *et al.*, 1999). Omata *et al.* (2006) noted that the annual growth rate was below average from 1984 to 1987, during which the average annual minimum SST

was not exceptionally cold. Thus, the anomalously low growth rate of 1985 appears to be in response to factors other than SST, such as local environmental stress perhaps making the coral more susceptible to bioerosion. In spite of the slow growth rate during this period, seasonal variability in $\delta^{18}O$ is clearly observed that the combination of cold winter SST and slow growth rate (<5 mm/yr) together may result in depressed $\delta^{18}O$ amplitude.

The Sr/Ca-sea surface temperature sensitivity determined from this work (Table 1) is within the range compiled from published tropical coral SST reconstructions
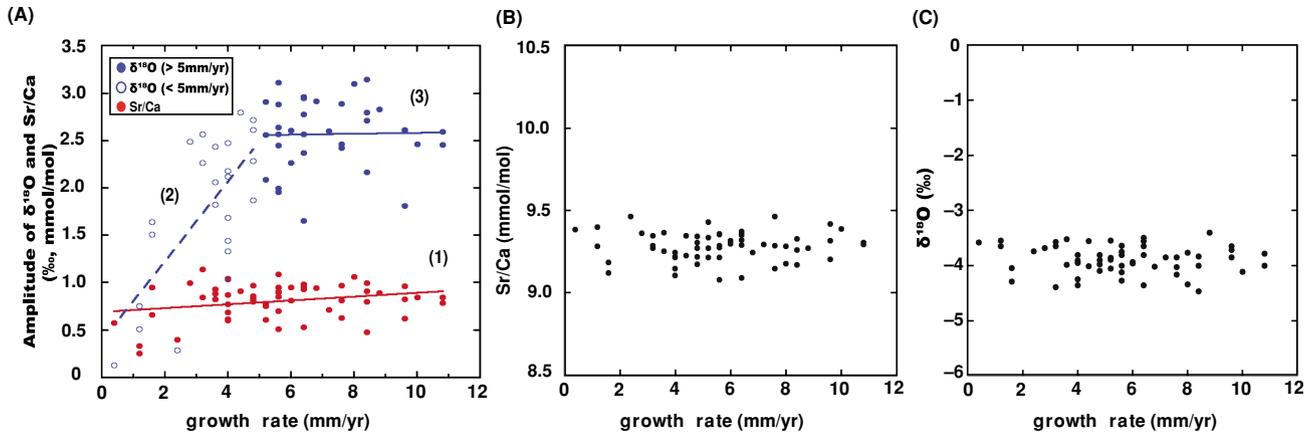
Fig. 3. (A) The relationship of growth rate and $\delta^{18}O$ amplitude (blue filled circles (>5 mm/yr) and blue open circles (<5 mm/yr), Omata et al., 2006) and Sr/Ca (red). In this figure, the formula obtained for the Sr/Ca-growth rate relationship was (1) Sr/Ca = 0.691 + 0.0407 growth rate ($R^2 = 0.07$, $p = 0.03$). For the $\delta^{18}O$, the relationships were (2) $\delta^{18}O$ (<5 mm/yr) = 0.389 + 0.841 growth rate ($R^2 = 0.48$, $p << 0.01$) and (3) $\delta^{18}O$ (>5 mm/yr) = 02.53 + 0.0102 growth rate ($R^2 = 0.0005$, $p = 0.92$). (B) The relationship of growth rate and annual average of Sr/Ca. (C) The relationship of growth rate and annual average of $\delta^{18}O$ (Omata et al., 2006).

Table 1. Summary of the Sr/Ca and $\delta^{18}O$ vs. SST calibrations

	Reference	*a*	*b*	R^2
Sr/Ca-temperature sensitivity	Corrège (2006)	10.553	−0.0607	
	Our Study	10.641	−0.0668	0.90
$\delta^{18}O$-temperature sensitivity	Gagan *et al.* (2012)		−0.167 ± 0.028	
	Our study (all data)	−0.305	−0.1746	0.78
	Our study (>5 mm/yr)	0.306	−0.2027	0.85

*Note: Calibrations are of the type: Sr/Ca (mmol/mol) = a + b*SST (℃) and $\delta^{18}O$ (‰) = a + b*SST (℃). R^2 is the correlation coefficient. All correlations of our study are significant with $p < 0.05$.*

(Corrège, 2006), indicating that Sr/Ca based SST reconstructions provide a reliable record from low-growth rate corals from temperate regions. We calculated the $\delta^{18}O$-SST sensitivity in two ways, using all $\delta^{18}O$ data and only high-growth (>5 mm/yr) coral data. Both sensitivities are within the range of values reported by Gagan *et al.* (2012) (Table 1). However, $\delta^{18}O$ from high-growth intervals is more highly correlated with SST than that of low-growth intervals, indicating growth-rate dependent sensitivity in $\delta^{18}O$. Conversely, Sr/Ca sensitivity is independent of growth rate making it a more robust environmental indicator in low-growth corals.

CONCLUSIONS

We measured Sr/Ca on a temperate *Porites* coral using aliquots of the same sample material from which previously published $\delta^{18}O$ data (Omata *et al.*, 2006) was pro-

duced. A combination of cold SST and slow growth (<5 mm/yr) reduces the coral $\delta^{18}O$ seasonal amplitude. Therefore, $\delta^{18}O$ should only be used if growth rates are in excess of 5 mm/yr, especially for high-latitude corals. However results clearly indicate that Sr/Ca robustly reproduces SST variations from regions along the extreme latitudinal limits of hermatypic coral habitat, independent of growth rate variations.

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