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Refining temperature reconstructions with the Atlantic coral *Siderastrea siderea*

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Abstract

Developing coral-based temperature reconstructions for a particular coral species requires determining the optimal sampling path orientation and resolution for geochemical analysis to avoid sampling artifacts and to increase reproducibility. Furthermore, a robust coral archive should have high intracolony and intercolony reproducibility for determining the common environmental signal. Here we assessed sampling path orientation and sampling resolution for *Siderastrea siderea* colonies within the Dry Tortugas National Park in the Gulf of Mexico (24°42'N, 82°48'W) to determine the optimal sampling protocol and to assess reproducibility of coral Sr/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$. We identified a sampling artifact due to extracting samples from the coral columella resulting in cold bias up to 5.2 °C in coral Sr/Ca. We found no shift to higher coral Sr/Ca values (i.e., colder) for years with a 50% reduction in average extension rate (2.1 mm year⁻¹) or for sampling along paths up to 70° off the vertical axis of the colony. Our sampling resolution comparison (1900–1993) indicated that the resolution of ~6 samples year⁻¹ used in a previous study for coral Sr/Ca and $\delta^{18}\text{O}$ may not capture seasonal extremes and thus produces muted seasonal cycles, but that resolution is not biased towards one season. Reproducibility or average deviations, assessed using absolute differences (AD) and root mean square (RMS), among the monthly resolved coral Sr/Ca records for intracolony to intercolony comparisons were within 2 σ of our analytical precisions. Average deviations were reduced by 19 to 61% when assessing interannual variability (36-month smoothed and mean annual) suggesting that subannual dating uncertainties (i.e., assigning a coral Sr/Ca value to a particular month) were the largest source of error in our monthly resolved coral Sr/Ca reconstruction. Similarly, coral $\delta^{18}\text{O}$ was reproducible within 2 σ of our analytical precision (AD = 0.10‰ and RMS = 0.07‰); however, coral $\delta^{13}\text{C}$ and linear extension records were not reproducible. Our assessment of coral

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geochemical variations from multiple *S. siderea* colonies suggests this species is suitable for paleoclimatic reconstructions, including subfossil corals and microatoll colonies that grow laterally.

1. Introduction

A coral colony is comprised of many living polyps located on the surface of the colony residing on top of and within skeletal corallites that the polyps extend incrementally with time by the process of calcification (Barnes, 1973). Each corallite contains a less dense center with vertical plates of septo-costae surrounded by thicker and denser walls (Veron, 2000). The size and structure of corallites vary with genera and species, which are used to identify the coral species (Veron, 1986). Coral colonies have several types of morphologies including boulder-shaped massive corals, pillar-shaped columnar corals, and branching corals (Veron, 2000). Branching corals are among the fastest growing ($\sim 100 \text{ mm year}^{-1}$) and massive corals are among the slower growing (up to 25 mm year^{-1}) (Veron, 1995). Skeletons of massive corals have low and high-density bands that form on a yearly basis thus providing a “calendar” to establish the passage of time (Knutson et al., 1972). Massive corals can live for several centuries and their aragonitic skeletons provide an excellent archive for reconstructing past environmental variations from their skeletal chemistry (see reviews of Druffel, 1997; Gagan et al., 2000; Felis and Patzold, 2004; Corrège, 2006; Grottoli and Eakin, 2007; Jones et al., 2009; Lough, 2010; Sadler et al., 2014; Bradley, 2015).

Geochemical artifacts related to sampling different skeletal elements of an individual corallite have been reported for the massive corals *Montastraea faveolata* and *M. annularis*¹ (Leder et al., 1996; Smith et al., 2006), *Diploria strigosa* (Giry et al., 2010), and *Diploastrea heliopora* (Watanabe et al., 2003; Bagnato et al., 2004; Dassié and Linsley, 2015). The Atlantic

¹ The systematics of the *Montastraea* or *Montastrea* complex (*M. faveolata*, *M. annularis*, and *M. franski*) have varied with reclassifications, in which *M. faveolata* and *M. annularis* are sometimes interchanged (Knowlton and Budd, 2001). A recent reclassification moves *faveolata* and *annularis* to the genus *Orbicella* with *M. franski* remaining unchanged (Budd et al., 2012). For clarity, we use the species name from the original study when referring to that study.

coral *M. faveolata* has larger polyps (~2–3 mm diameter) with less dense central columella and thick higher density parathecal corallite walls that are typically sampled for geochemical analysis. Sampling along horizontal paths parallel to the density bands in *M. faveolata* revealed large variations among skeletal elements equivalent to 2 °C with shifts to higher coral Sr/Ca values (i.e., colder) in the columella (Smith et al., 2006). A study with coral $\delta^{18}\text{O}$ found similar results for *M. annularis* (Leder et al., 1996). An assessment of sampling different skeletal elements in the Atlantic coral *D. strigosa* revealed a shift to higher coral Sr/Ca and $\delta^{18}\text{O}$ values, up to 6 °C colder for coral Sr/Ca, when sampling off of the corallite wall (Giry et al., 2010). *Diploria strigosa* is a brain coral (meandroid) with large, linear corallites, a continuous columella, and high-density septathecal corallite walls. Conversely, studies with the massive Pacific coral *D. heliopora* found sampling along the columella in the center of the corallite produced larger seasonal variations in coral $\delta^{18}\text{O}$ and Sr/Ca compared to the septa walls and therefore the columella is the optimal sampling location for that species (Watanabe et al., 2003; Bagnato et al., 2004; Dassié and Linsley, 2015). *Diploastrea heliopora* has larger polyps (~10 mm diameter) with radial septa that thicken towards to corallite edges forming pronounced synapticulothecal walls.

Massive *Porites* spp., which are typically used for paleoclimatic reconstructions, have small corallites (~1 mm diameter) with even smaller thecal walls and columella, which may or may not be present in some *Porites* species (Veron, 1986). Individual sampling volume (~1–2 mm³) for *Porites* spp. includes more than one corallite and all corallite skeletal elements; to date, no geochemical bias has been reported for any one particular *Porites* corallite skeletal element. However, these massive corals have centimeter-scale skeletal structures with numerous corallites in fan-like structures with “valleys” in between the fans (Darke and Barnes, 1993). Studies that

sampled *Porites* corals in these valleys found a cold bias in coral Sr/Ca and $\delta^{18}\text{O}$ determinations (Alibert and McCulloch, 1997; Cohen and Hart, 1997; DeLong et al., 2013). Additionally, studies that examined *Porites lutea* found that the extending corallite walls not oriented parallel to the sampling or slab surface can produce a warm bias up to 2.3 °C (DeLong et al., 2007; DeLong et al., 2013; Zinke et al., 2016). In summary, the corallite “skeletal element” geochemical bias appears to be present in coral species with larger corallites (>2 mm in diameter) that are sampled along a single skeletal element (corallite wall or columella) whereas corals with smaller corallites (<2 mm in diameter) tend to have a “corallite structure” bias. Therefore, each coral species should be assessed for optimal sampling methods and to identify any potential sampling artifacts among skeletal elements and corallite structures.

Additionally, the sampling resolution used to extract a geochemical time series from a coral skeleton may introduce problems such as failure to record seasonal extremes, reduced seasonal cycles, and seasonal bias. For coral Sr/Ca and $\delta^{18}\text{O}$ in *P. lutea*, sampling resolutions of 4 samples year⁻¹ resulted in a failure to capture winter extremes, reduced amplitude in seasonal cycles, and a bias towards summer months whereas resolutions of 30 and 12 samples year⁻¹ resulted in the same seasonal cycle (Quinn et al., 1996; DeLong et al., 2007). For *Montastraea* spp., approximately weekly sampling resolution may be needed to recover the full annual cycle in coral $\delta^{18}\text{O}$ and Sr/Ca (Leder et al., 1996; Swart et al., 2002). Sampling resolution should be assessed for each geochemical proxy and coral species because optimal sampling technique varies with genera and species.

Early studies with *Pavona clavus* corals (columnar morphology) suggested sampling off the vertical axis of the colony, where growth rates are reduced on the sides of the colony, resulted in a mean shift to higher coral Sr/Ca and $\delta^{18}\text{O}$ values for extension rates less than 5 mm

year⁻¹ (McConnaughey, 1989; de Villiers et al., 1994). Those studies prompted the sampling of the “major growth axis” or the vertical axis of the colony for geochemical analysis to avoid possible kinetic or growth-related effects. Further investigations with massive *Porites* spp., including laterally growing microatolls, found no bias in coral Sr/Ca or $\delta^{18}\text{O}$ for horizontal sampling path orientations in colonies with extension rates greater than 5 mm year⁻¹ (Alibert and McCulloch, 1997; Woodroffe, 2000; Mitsuguchi et al., 2003; Maier et al., 2004; Felis et al., 2009; McGregor et al., 2011; DeLong et al., 2013; Wu et al., 2013). Similarly, no difference in coral $\delta^{18}\text{O}$ was found between the top and the side of a massive *M. annularis* colony with growth rates between 1.4 and 8.1 mm year⁻¹ (Leder et al., 1996). Other studies suggest that thresholds for growth-related effects vary with genera and species because skeletal density (product of calcification rate and linear extension rate) varies with species (DeLong et al., 2011; DeLong et al., 2013). Regardless, sampling the vertical axis remains the de facto standard for coral geochemical studies (Corrège, 2006; Jones et al., 2009; Sadler et al., 2014). However, use of microatolls that grow laterally or subfossil corals with unknown growth orientation for paleoclimatic reconstructions is a compelling reason to test the validity of this premise.

If we assume coral Sr/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$ variations are environmental signals, then coral colonies of the same species in the same environmental setting (i.e., water depth, location) should record the similar geochemical variations within analytical precision. In this study, we assessed reproducibility of coral Sr/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$ in *S. siderea* on spatial scales from within a colony to between reef sites, and on temporal scales ranging from monthly to decadal. Before performing these assessments, we defined ideal sampling methods for *S. siderea* and determine the optimal sampling resolution for extracting monthly temperature records from coral skeletal material. Calibration of coral Sr/Ca to temperature for these corals along with their climate

interpretation was reported in DeLong et al. (2014) as well as an assessment of extension rates.

2. Materials and Methods

This report examined *S. siderea* cores (08PS-A1, 08PS-A2, 08PS-F1, 93DRYSS1, and 93DRYSS2) from previous studies that give descriptions of colony locations (Supplementary Fig. S1), core recovery and processing, and chronology development (Supplementary Figs. S2–4) (Maupin et al., 2008; DeLong et al., 2011; Hickey et al., 2013; DeLong et al., 2014). Two of the cores have unknown ages and were dated using high precision ^{230}Th dating (Shen et al., 2008; Shen et al., 2012); results reported in DeLong et al. (2014). For our sampling resolution assessment, we used a coral core 93DRYSS1 that was sampled at ~ 6 samples year $^{-1}$ in a previous study (Maupin et al., 2008).

Samples for geochemical analysis (300–500 μg) were extracted from each slab surface using a computer-driven micromill system (Taig Micromill with SuperCAM software from Supertech and Associates, Phoenix, AZ) described by Quinn et al. (1996) and modified by DeLong et al. (2011). Samples were extracted continuously at approximately monthly increments (Table 1) with a 1.0 mm diameter dental drill bit at a sampling depth of 1.0 mm with the exception of 93DRYSS1 that was sampled with a 1.4 mm diameter drill bit in a 2 mm wide and 1.5 mm deep path (Maupin et al., 2008). Divots (1.5 mm deep) were milled into the coral slab at regular intervals along sampling paths for aligning geochemical samples to scans of the slab and X-radiographs (Supplementary Figs. S2–4). Sampling paths were selected, after examination of the coral slab under a microscope, parallel to the extending corallites along the synapticulothecal corallite wall, the optimal sampling location for this species (Maupin et al., 2008; DeLong et al., 2011; DeLong et al., 2014). Cores 08PS-A1 and 08PS-A2 were sampled at the United States Geological Survey (USGS) St. Petersburg Coastal and Marine Science Center

(SPCMSC) in Florida whereas the cores 93DRYSS1 and 93DRYSS2 were sampled at the University of South Florida (USF) and University of Texas (UT) at Austin, respectively. Multiple researchers with different experience levels at UT and Louisiana State University (LSU) sampled the core 08PS-F1. Samples were split for isotopic and trace elemental analyses. Monthly-resolved coral Sr/Ca was determined for the entire cores whereas isotopic analysis ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) was determined for a select interval in two cores for reproducibility assessments.

Elemental ratio determinations (Sr/Ca and Mg/Ca) were made using a PerkinElmer 4300 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) at the Analytical Laboratory for Paleoclimate Studies (ALPS) at UT and a PerkinElmer 7300 ICP-OES at the USGS SPCMSC. The UT ICP-OES was formerly at the College of Marine Science at USF and is the same instrument used by Maupin et al. (2008). A laboratory internal gravimetric standard (IGS) was measured before and after each dissolved coral sample to correct for instrumental drift (Schrage, 1999). The average drift-corrected IGS precision for Sr/Ca was $0.025 \text{ mmol mol}^{-1}$ (2σ , $n = 862$; UT) and $0.024 \text{ mmol mol}^{-1}$ (2σ , $n = 212$; USGS). The average drift-corrected precision for Sr/Ca of homogenized powder from a *P. lutea* (PL) coral used as a coral standard was $0.030 \text{ mmol mol}^{-1}$ (2σ , $n = 1194$; UT) and $0.039 \text{ mmol mol}^{-1}$ (2σ , $n = 286$; USGS). The absolute value of Sr/Ca for IGS and PL has been confirmed by thermal ionization mass spectrometry at the University of Minnesota Isotope Laboratory (Kilbourne et al., 2004; Quinn et al., 2006). Sr/Ca values determined for IGS, PL, and aliquots of the same coral samples at these laboratories are consistent within analytical error (DeLong et al., 2011; 2014). Coral Mg/Ca was measured (data not shown) to detect possible diagenesis (Quinn and Taylor, 2006) but was not assessed for reproducibility since it is not a robust temperature proxy.

Isotopic ratio analyses ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) were made using a Thermo Delta V connected to

a Kiel IV carbonate device at ALPS. Coral samples were dissolved in phosphoric acid at 70°C. Average external precision for 08PS-F1 was $\pm 0.06\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.02\text{‰}$ for $\delta^{13}\text{C}$ (1σ , $n = 11$, NBS-19) and for 08PS-A1 was $\pm 0.08\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.03\text{‰}$ for $\delta^{13}\text{C}$ (1σ , $n = 51$, Estremoz). Isotopic values are reported in delta notation (δ) relative to the Vienna PeeDee Belemnite (VPDB) isotopic standard.

Core chronologies were developed by assigning maximum coral Sr/Ca values to minimum sea surface temperature (SST) values and vice versa for each annual cycle (see DeLong et al., 2014 for details). The chronology for coral Sr/Ca was applied to the other geochemical records (Mg/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$) and sample location down core or depth using Analyseries software (Paillard et al., 1996) and then linearly interpolated to even monthly intervals. Monthly core depth records were used to calculate annual linear extension between maxima in coral Sr/Ca (i.e., February to February), for which precision is limited by sampling resolution (Table 1). This method removes the subjectivity of measuring distance between indistinct shifts in high to low-density areas in the X-radiographs (Supplementary Figs. S2–4) and is directly comparable to the geochemical variations.

Reproducibility was assessed using two tests of average deviations on various time scales for coral Sr/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$. Root-mean-squared (RMS) is the sum of the deviations of coral geochemical determinations (coral_i) from the mean of those determinations ($\text{coral}_{\text{mean}}$) for any single month normalized by the number of observations for that month (n ; Eq. 1), which assumes the mean is a good estimate of the true coral value for that month (DeLong et al., 2013).

$$\text{RMS} = (\sum (\text{coral}_i - \text{coral}_{\text{mean}})^2 / n)^{1/2} \quad (\text{Eq. 1})$$

Absolute difference (AD) is a measure of the discrepancy between coral geochemical determinations (coral_1 and coral_2) for any single month (Eq. 2) for which the true value is

unknown (DeLong et al., 2007; DeLong et al., 2013).

$$AD = 2^{-1/2} | \text{coral}_1 - \text{coral}_2 | \quad (\text{Eq. 2})$$

Pearson correlation coefficient (r) is not an indicator of discrepancy but it is useful for determining if two time series contain a common signal or covary. To account for serial correlation in quasi-sinusoidal monthly time series, degrees of freedom (df) was determined by the Runs test (Draper and Smith, 1998) and was used instead of the number of observations. Other statistical tests used include the Student's t -test and F -test. Significance testing assumed a 95% confidence interval. Time series were smoothed with a low-pass finite impulse response (LPFIR) filter (Bloomfield, 2000). Coral Sr/Ca-SST was determined using the transfer function ($-0.044 \text{ mmol mol}^{-1} \text{ } ^\circ\text{C}^{-1}$) for these corals (DeLong et al., 2014).

3. Results and Discussion

3.1 Sampling artifacts

3.1.1 Slab extraction from a core

For *S. siderea*, the optimal sampling path is one that follows an extending corallite as it grew with time (Maupin et al., 2008; DeLong et al., 2011; DeLong et al., 2014). Extracting a coral slab from a cylindrical core requires close examination of the core surface to discern the orientation of the corallites inside the core; a coral core is not a sediment core that can be cut at any orientation. For *S. siderea*, look for the cross-sections of the top of corallites to discern direction of growth. Cut the slab where the tops of the corallites are visible on the top or side of the core; this will transect the corallites along the growth axis. An example of a core slab cut at an improper angle appears in Fig. 1 on the left. Examination of the slab surface under magnification reveals oblong tops of corallites where radiating septa are visible from the center of the corallites. The corallite angle with respect to slab surface is $\sim 21^\circ$ at the top of the slab and

~33° at the bottom. The X-radiograph of this slab has a wavy appearance with indistinct annual density bands and corallite walls varying in density. Measurements of annual extension with this slab would be greater than the actual linear extension since the corallites are at an angle with respect to the slab surface. A properly cut slab appears on the right of Fig. 1 and its X-radiograph has more distinct and continuous density bands, and the corallite walls are straight and continuous with the same density. Examining this slab under magnification reveals longitudinal transects of the synapticulothecal corallite walls that are needed for extracting a continuous time series of coral geochemical variability.

Cutting a slab from an entire core section properly may be difficult for some cores. In 08PS-A1-A we cut two slabs, one with suboptimal alignment in the lower 2/3 of the slab (Supplementary Fig. S2). The corallite angle increases to 18° with respect to the slab surface and the annual density bands appear wavy without clear, discernable bands. We abandoned sampling slab 2 from 08PS-A1 at 1985 (Supplementary Fig. S2) once the corallites were no longer parallel to the slab surface. Nevertheless, we do not find any coral Sr/Ca bias between the sampling paths on 08PS-A1 slabs 2 and 3.

3.1.2 Corallite skeletal structures

We sampled three paths parallel to the density bands in 08PS-A2 to assess coral Sr/Ca variability across corallites and their skeletal elements (Fig. 2 and Supplementary Fig. S2), similar to the previous study with *M. faveolata* (Smith et al., 2006). The mean of the coral Sr/Ca determinations from the cyan path is greater ($9.051 \text{ mmol mol}^{-1}$ on average) than the other two paths (8.964 and $8.931 \text{ mmol mol}^{-1}$ on average for green and magenta paths, respectively); therefore, the cyan path represents a colder interval (Fig. 2C). Examination of the X-radiograph reveals the cyan path lies along the darker area (i.e., low density) between two lighter bands or

high-density bands (Fig. 2B); therefore, the low-density bands formed in the winter. The cyan path has the lowest standard deviation or variability ($0.059 \text{ mmol mol}^{-1}$, 1σ) whereas the magenta path has the highest ($0.085 \text{ mmol mol}^{-1}$, 1σ). Along the synapticulothecal corallite walls, the coral Sr/Ca determinations have the greatest range of values (0.256 and $0.193 \text{ mmol mol}^{-1}$ for samples #13 and 23) whereas the columella contains a smaller range of values (0.053 and $0.155 \text{ mmol mol}^{-1}$ for samples #8 and 17). The range in coral Sr/Ca determinations along the walls represents 4.4 to $5.8 \text{ }^{\circ}\text{C}$ or $\sim 2/3$ of the observed SST seasonal cycle ($8.1 \text{ }^{\circ}\text{C}$) and the three sampling paths cover $\sim 2/3$ of the annual density band couplet in the X-radiograph.

We sampled five paths or lines parallel to the corallite growth direction in 08PS-F1 to assess coral Sr/Ca variability within a corallite (Fig. 3), similar to previous studies using *D. strigosa* (Giry et al., 2010) and *M. annularis* (Leder et al., 1996). Coral Sr/Ca variations agree within analytical precision with each other and with sampling paths used in the reconstruction (see Supplementary Fig. S3 for locations) except for line 3, which is in the columella, from 1.0 to 1.65 cm where a shift to higher coral Sr/Ca values ($0.228 \text{ mmol mol}^{-1}$ on average or $5.2 \text{ }^{\circ}\text{C}$ colder) occurs that is greater than analytical precision. This shift also results in a 20% reduction in the annual cycle for line 3. For the same interval, lines 2 and 5 also have a shift to higher coral Sr/Ca values but not to the same extreme. Examination of the coral slab (Fig. 3B) reveals line 2 is partially in the columella from 1.0 to 1.7 cm and line 5 is in the columella from 1.4 to 1.7 cm .

The interval from 1816 to 1820 for 08PS-A2-B has colder summers and a reduced seasonal cycle that did not agree with the coral Sr/Ca determinations from 93DRYSS2 (Fig. 3E). Examination of the coral slab under magnification revealed the sampling path is within the columella. We selected a new sampling path along the corallite wall and these coral Sr/Ca determinations agree within analytical precision with those from 93DRYSS2. The mean of the

suboptimal path ($9.102 \pm 0.077 \text{ mmol mol}^{-1}$, 1σ) is greater than that for the optimal path ($9.055 \pm 0.090 \text{ mmol mol}^{-1}$, 1σ) for the same time interval, a difference of $0.047 \text{ mmol mol}^{-1}$ or $1.1 ^\circ\text{C}$.

The area selected on 08PS-F1 for corallite sampling also has an oblong top of a corallite visible in the coral scan (starting at $\sim 0.8 \text{ cm}$ from core top) at an angle of $\sim 22^\circ$ with respect to the slab surface (Fig. 3A). Coral Sr/Ca in line 3 agrees within analytical precision with the other lines from 0 to 0.8 cm and shifts when it reaches the oblong top of the corallite. The coral Sr/Ca values for the lines along the corallite walls and sampling paths in 08PS-F1 used in the reconstruction agree within analytical precision with those from 08PS-A1; however, this interval is quite short for a reproducibility assessment so this corallite angle should not be used without further assessment.

The largest intracolony differences we observed occurred in the interval from 1896 to 1942 between opposing sides of 08PS-F1 with a $0.6 ^\circ\text{C}$ average difference. The angle of the corallites is 13° with respect to the slab surface for this interval with the elongated tops of corallites visible; however, there is no increase in annual extension or increase in summer values, which were previously noted for *P. lutea* (DeLong et al., 2013). For this interval, the average AD is $0.026 \pm 0.019 \text{ mmol mol}^{-1}$ (1σ ; equivalent to $0.6 ^\circ\text{C}$) between parallel paths on 08PS-F1 and the average AD is 0.029 ± 0.022 (1σ ; equivalent to $0.7 ^\circ\text{C}$) between 08PS-F1 and 08PS-A suggesting a $\sim 0.7 ^\circ\text{C}$ cold bias for sampling corallites at a suboptimal angle. However, the corallites are parallel to the slab surface for the interval from 1930 to 1942 and the average AD is larger ($0.035 \pm 0.026 \text{ mmol mol}^{-1}$, 1σ ; equivalent to $0.8 ^\circ\text{C}$); therefore, it is unclear if sampling corallites with small angles ($<20^\circ$) to the slab surface produces a definable bias in *S. siderea*.

In summary, each *S. siderea* corallite contains a spongy center or columella surrounded by septa (Fig. 3D). Septa from adjacent corallites meet to form a thickened synapticulothecal

wall, seen as continuous dense areas in X-radiographs perpendicular to annual density bands. If the sampling path shifts off of the syntacticulothecal wall into the columella, the coral Sr/Ca values will be greater than adjacent Sr/Ca values on the wall and similar to winter Sr/Ca values extracted along the corallite wall, resulting in a reduced seasonal cycle, similar to that noted for coral Sr/Ca and $\delta^{18}\text{O}$ in *D. strigosa* (Giry et al., 2010) and coral $\delta^{18}\text{O}$ in *M. annularis* (Leder et al., 1996). The optimal sampling path for *S. siderea* is along the corallite wall avoiding the columella. Slabbing a core perfectly along the longitudinal cross-sections of the extending corallites may not be possible for the entire length of the core; additional slabs may be needed. Corallites at an angle of 13° or less do not appear to cause a shift in coral Sr/Ca at least within our analytical precision. Larger corallite angles ($>20^\circ$) with respect to the slab surface should be avoided unless reproducibility is assessed.

3.1.3 Sampling resolution

The study of Maupin et al. (2008) sampled a *S. siderea* coral from Dry Tortugas (93DRYSS1; see Supplementary Fig. S1 for location) at ~ 6 samples year⁻¹ from 1900 to 1993 (Table 1). They assessed the effect of sampling resolution (~ 6 samples year⁻¹ and ~ 18 samples year⁻¹) for coral Sr/Ca in a random three-year interval and found no difference within analytical precision for the sampling resolutions tested. We extend their sampling resolution assessment by comparing our monthly resolved coral Sr/Ca variations from two cores (08PS-A1 and 08PS-F1) with their bimonthly resolved coral Sr/Ca record for the longer interval from 1900 to 1993 (Fig. 4A). The mean for 93DRYSS1 (8.999 ± 0.103 mmol mol⁻¹, 1σ) is similar to the means for 08PS-A1 and 08PS-F1 for the same interval (8.999 ± 0.123 mmol mol⁻¹, 1σ , and 9.021 ± 0.122 mmol mol⁻¹, 1σ ; respectively); however, the standard deviation is reduced by 16% and the average amplitude of the seasonal cycle (0.266 ± 0.046 mmol mol⁻¹, 1σ) is reduced by as much as 38%

for the bimonthly record. There are several years where either the bimonthly summer minima in Sr/Ca are colder (12 out of 93 years or 12.9%) or winter maxima are warmer (29 years out of 93 years or 31.2%) than that observed in the monthly resolved cores and these differences are greater than analytical precision (e.g., 1977, 1979, 1981, 1984, and 1985 in Fig. 4A). In one instance, the bimonthly Sr/Ca summer extreme is warmer than that observed in the other cores (1992), which is close to the top of that core. We found that some of the intervals with disagreements between sampling resolutions are years in 93DRYSS1 with slower extension rates (e.g., 1913–1915, 1968–1969, and 1984–1985), thus an effective sampling resolution of less than 6 samples year⁻¹.

We identified 15 years with slower extension rates (≤ 2.6 mm year⁻¹ or $>2\sigma$): 2 years from 08PS-F1, 9 years from 08PS-A2, and 4 years from 93DRYSS2. In general, the coral Sr/Ca determinations for these slower extension years are within 2σ of our analytical precision with contemporaneous determinations from the other colonies, which had higher extension rates (>2.6 mm year⁻¹; e.g., 1779, 1784, and 1785 in Fig. 4B). The exception is 1783 for which both cores have slower extension rates yet the coral Sr/Ca determinations agree within analytical precision and both cores have an average seasonal cycle. There are three years in core 08PS-A2 (1786, 1787, and 1798 in Fig. 4B) with slower extension rates for which the differences with contemporaneous coral Sr/Ca variations are greater than analytical precision. These slower extension years have reduced amplitude in the coral Sr/Ca seasonal cycle but with no evidence of the mean shift in coral Sr/Ca that was previously reported for *P. clavus* (de Villiers et al., 1994). The slowest extension rate and smallest seasonal cycle in coral Sr/Ca for all the cores sampled is 1787 in 08PS-A2 (2.09 mm year⁻¹ and 0.149 mmol mol⁻¹, respectively). This extension rate coupled with the constant sampling increment (Table 1) resulted in a sampling resolution of 5

samples year⁻¹, less than the sampling resolution for 93DRYSS1; therefore, is a sampling resolution artifact. Resampling this year with a higher resolution sampling increment (0.17 mm sample⁻¹) could confirm our assessment. Lastly, two years (1885 and 1886) with slower extension rates in 08PS-A2 (2.5 and 3.3 mm year⁻¹) and 93DRYSS2 (3.2 and 2.8 mm year⁻¹) follow the large volcanic eruption Krakatau in August 1883; these are the coldest years in the SST reconstruction (DeLong et al., 2014). There is no evidence that slower extension rates (2.0 to 5.0 mm year⁻¹) in *S. siderea* cause a mean shift to higher (i.e., colder) coral Sr/Ca values; therefore, these colder temperatures are probably real with the corals reducing their growth.

A shorter interval (3 years) was used to assess sampling resolution differences in coral $\delta^{18}\text{O}$ for 93DRYSS1 (~6 samples year⁻¹) and 08PS-A1 (~12 samples year⁻¹) (Fig. 5A). In general, the coral $\delta^{18}\text{O}$ values between 93DRYSS1 and 08PS-A1 are within analytical precision; however, there is a consistent mean shift between these coral $\delta^{18}\text{O}$ records (0.03‰ on average). The study of Maupin et al. (2008) did not find any differences in coral $\delta^{18}\text{O}$ within analytical precision for their sampling resolution assessment (~6 and 18 samples year⁻¹). However, the study of Leder et al. (1996) noted the amplitude of the $\delta^{18}\text{O}$ seasonal cycle in *M. annularis* decreased with lower sampling resolution (weekly to monthly resolution). That study also showed that the deeper calyxes of *M. annularis* produced a saw-tooth shaped skeletal deposition pattern for which a larger sampling area would lead to more time integration resulting in a reduced seasonal cycle (see Fig. 2 of Leder et al. (1996)). The study of DeLong et al. (2011) examined a *M. faveolata* coral (08PS-B3) that grew in close proximity to the corals sampled in this study (Supplementary Fig. S1). They reported a reduced seasonal cycle in coral Sr/Ca for *M. faveolata* compared to *S. siderea* when using approximately the same sampling resolution, thus highlighting the differences in coral species. This coral $\delta^{18}\text{O}$ sampling resolution assessment was

made for a short interval (3 years) and we suggest a longer interval (>50 years) is needed to fully assess the impact of sampling resolution on coral $\delta^{18}\text{O}$ in *S. siderea*, based on our Sr/Ca results.

One last consideration is possibility that heat produced during microsampling the coral skeleton (>100 °C) produced calcite thus shifting the coral $\delta^{18}\text{O}$ values (Waite and Swart, 2015) that may not have a constant offset (Gaffey et al., 1991). Our micromilling systems were run at the slowest speed (1100 rpm) with a single pass, which is slower than the New Wave Research micromill (1,200–35,000 rpm) used by Waite and Swart (2015), who report a “50% drill speed, 30% approach speed, 3 passes at 50 μm per pass.” Using an infrared thermometer on the coral surface during micromilling at LSU, the hottest temperature was 27.3 °C. Furthermore, the coral $\delta^{18}\text{O}$ between 08PS-F1 and 08PS-A1 agree within analytical precision (Fig. 9a) for which 08PS-A1 and 08PS-F1 were drilled with two different micromill systems at USGS and UT, respectively. If calcite was being produce by the micromilling heat, these two records should have different coral $\delta^{18}\text{O}$ values.

Constant sampling intervals coupled with slower extension rates ($\leq 50\%$ the average) may introduce sampling artifacts such as a failure to record seasonal extremes and reduced seasonal cycles in proxy records extracted from *S. siderea* corals. Our coral Sr/Ca results do not indicate a clear seasonal bias towards winter or summer in *S. siderea* for lower sampling resolutions, as seen in *P. lutea* (DeLong et al., 2007), but may be present in coral $\delta^{18}\text{O}$; however, a longer assessment interval is required for a robust assessment. As long as sampling is continuous (no powder left behind), taking fewer samples per year simply means longer time intervals being represented by each sample, so the extremes would be dampened. *Siderastrea siderea* at this subtropical location is known to calcify 50% faster (linear extension x density = calcification rate) in summer compared to winter (Kuffner et al., 2013); however, these corals appear to

linearly extend with an near constant rate with little seasonal preference suggesting seasonal variability in density, as seen in the annual density bands. Seasonality in linear extension and calcification rates likely varies with latitude; therefore, each location should be assessed. We find no evidence for a shift to higher coral Sr/Ca values (i.e., colder) for slower extension rates (this study ranges from 2.1–6.6 mm year⁻¹), as suggested for the columnar *P. clavus* (de Villiers et al., 1994). *S. siderea* is a denser coral (3.7 g cm⁻³ (Kuffner et al., 2013)) compared to *Porites* spp. (1.1–1.6 g cm⁻³) (Risk and Sammarco, 1991) and *P. clavus* (1.44–1.86 g cm⁻³) (Hughes, 1987) and thus calcification rates are comparable regardless of annual linear extension rates. Since skeletal density varies among corals species, extrapolation of threshold extension rates (e.g., <5 mm year⁻¹ for *Porites*) should not be made to other species.

3.1.4 Sampling path orientation with respect to the colony

The two cores extracted from the same colony (08PS-A) allowed us to assess coral Sr/Ca reproducibility with respect to the vertical axis of the colony, which is typically assumed to be the maximum growth axis of the colony (i.e., vertical versus horizontal sampling paths) (Fig. 6). We sampled the slab 08PS-A1-C along two paths oriented at 45° and 70° from the vertical axis of the colony and we compared these coral Sr/Ca records to contemporaneous coral Sr/Ca records from 08PS-A2-A and 93DRYSS2 along nearly vertical paths (18° and 19° from vertical, respectively). Coral Sr/Ca records from the paths at 45° and 70° are within analytical precision with those from nearly vertical paths except for two winter extremes in 1854 and 1855 and one summer in 1851 for the path at 70°. There is no evidence for a reduction in annual linear extension for any of the non-vertical paths examined (4.59 ± 0.72 mm year⁻¹, 1 σ , and 4.05 ± 0.52 mm year⁻¹, 1 σ ; for 45° and 70°, respectively). The discrepancies noted for the path at 70° do not occur in years with a reduced linear extension, thus the origin of these discrepancies is unknown.

Similarly, the coral Sr/Ca variations from 93DRYSS2 for the interval from 1778 to 1790 have an orientation of 42° from vertical (Supplemental Fig. S4) and the record from this path agrees with those from the near vertical paths on 08PS-A2-B (Fig. 8). For *S. siderea* with extension rates at least 2 mm year⁻¹ or greater, there is no evidence for a shift to higher Sr/Ca values (i.e., colder) for non-vertical sampling paths and we find no difference within analytical precision among horizontal and vertical sampling paths.

The reports of shifts to higher coral Sr/Ca and $\delta^{18}\text{O}$ values (i.e., colder) along the sides of columnar coral colonies (McConnaughey, 1989; de Villiers et al., 1994) may simply be the result of reduced growth rates and not sampling path location within the colony. Columnar and branching corals have different extension rates along their longitudinal and radial axes whereas massive corals typically have the same extension rate throughout the colony. Studies with relatively fast-growing (5–20 mm year⁻¹) massive *Porites* spp. and columnar *P. clavus* suggest a growth-related effect may bias the coral Sr/Ca and $\delta^{18}\text{O}$ signal for annual linear extension rates less than 5 mm year⁻¹ (McConnaughey, 1989; de Villiers et al., 1994; Felis et al., 2003). However, studies with slower extending coral species (3–6 mm year⁻¹) like *D. heliopora* and *S. siderea* indicate that coral Sr/Ca determinations within and among colonies are reproducible and comparable to faster extending coral species (*Porites* and *Montastraea*) in close proximity (Bagnato et al., 2004; DeLong et al., 2011; Dassié and Linsley, 2015). We do not find a mean shift to higher Sr/Ca values for years with the slowest extension rates (see section 3.1.3). Our previous study found no consistent relationship between coral Sr/Ca variations and annual linear extension for these corals, and no significant correlation among extension records (DeLong et al., 2014), or between different coral species on the same reef (Muslic et al., 2013), suggesting that coral Sr/Ca are not affected by linear extension rates (Supplementary Tables S1 and S2).

3.1.5 Diagenesis

Examination of X-radiographs and scanning electron microscope (SEM) images revealed no evidence of altered primary mineralogy (Supplementary Figs. S2–4) except for the bottom of 08PS-A2-B prior to 1779 (Fig. 7 and Supplementary Fig. S2). X-radiographs of 08PS-A2-B show that the bottom of this core section has a denser skeleton (lighter color in negative images) and evidence of bioerosion (Supplementary Fig. S2). The SEM image from the bottom of 08PS-A2-B (Supplementary Fig. S2) contains a transition from pristine skeletal material (top) to secondary aragonite needles in the pore spaces (bottom). Additional SEM images reveal more secondary aragonite infilling towards to bottom of this core (Fig. 7a) as well as evidence of sponge spicules and boring organisms. Coral Sr/Ca determinations from sampling paths adjacent to the SEM sample at the bottom of this slab contain evidence of diagenesis (Fig. 7a). From 79 to 80 cm in Fig. 7a, the coral Sr/Ca between 08PS-A2-B and 93DRYSS2 do not agree (difference in averages = $0.086 \text{ mmol mol}^{-1}$; equivalent to $2.0 \text{ }^{\circ}\text{C}$) yet annual cycles are present but in 08PS-A2-B are shifted towards higher values (i.e., colder). Below 80 cm, contemporaneous paths from 08PS-A2-B do not agree and the expected annual cycles are not present with shifts to relatively higher values ($>9.1 \text{ mmol mol}^{-1}$) and then to anomalously low values below 82.5 cm ($<8.732 \text{ mmol mol}^{-1}$, the minimal value from all cores; Table 1). The coral Mg/Ca values (an indicator of diagenesis) increase from an average of $4.3 \text{ mmol mol}^{-1}$ for this core to 25 mmol mol^{-1} for the bottom of 08PS-A2-B.

The top of 08PS-A2-A was dead with some evidence of bioerosion (Supplementary Fig. S2). Visual analysis of SEM images from a sample from the near the top of this core (Supplementary Fig. S2) revealed no evidence of secondary aragonite. However, our initial sampling path (~4 years long) penetrated a portion of the coral dissolved by bioerosion that

produced anomalously low Sr/Ca values ($8.7\text{--}8.8\text{ mmol mol}^{-1}$) and loss of annual coral Sr/Ca cycles (Fig. 7b). We selected a new path with intact skeletal material expecting some disagreement in the coral Sr/Ca determinations among cores due to the bioerosion and dissolution. Coral Sr/Ca values from the new path yielded the expected values and differences were within analytical precision for contemporaneous coral Sr/Ca determinations from our new path with those from 08PS-F1 and 08PS-A1 (1955–1967; Fig. 7a).

The shift to relatively higher Sr/Ca values (i.e., lower SST) is consistent with the presence of secondary aragonite and dissolution (Quinn and Taylor, 2006; Hendy et al., 2007; Sayani et al., 2011). Conversely, a shift to relatively lower Sr/Ca values (i.e., higher SST) is consistent with calcite or other cements infilling (McGregor and Gagan, 2003). Sampling paths with evidence of diagenesis from 08PS-A2 are not included in our reproducibility assessment or the final SST reconstruction (DeLong et al., 2014).

3.2 Reproducibility

We assessed reproducibility in coral Sr/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$ for optimally sampled paths using RMS, AD (Eqs. 1 and 2), and correlation (r) on various spatial scales from intracolony to 11.5 km apart and time scales from interannual to decadal. Each core spans a different time interval (Table 1) so comparisons (RMS, AD, and r) were determined for contemporaneous intervals (Tables 2 and 3). Reproducibility of coral Sr/Ca variations among cores was summarized in the SST reconstruction report (DeLong et al., 2014) whereas intracolony reproducibility is presented here as it pertains to coral sampling artifacts. In general, 98.9% of the coral Sr/Ca variations for optimally sampled coral colonies (08PS-A, 08PS-F1, and

93DRYSS2) are within analytical precision (2σ)² after smoothing to 36 months to reduce subannual dating uncertainties related to assigning any single coral Sr/Ca determination to a calendar month (DeLong et al., 2014) (Fig. 8). These colonies are 510 m to 11.5 km apart in shallow water depth (4.3 m for 08PS-A and 3.4 m for 08PS-F1) and unknown water depth for 93DRYSS2, suggesting that coral Sr/Ca variations in *S. siderea* colonies growing under similar conditions are reproducible. Correlations among annual extension records for these corals vary from positive to negative and coral Sr/Ca is not significantly correlated to annual extension (Fig. 8c and Supplementary Table S1) (DeLong et al., 2014), suggesting extension rates are not influencing coral Sr/Ca and that annual extension records in *S. siderea* are not reproducible among colonies, and therefore are not reliable proxies for SST (Supplementary Table S2) (see discussion in DeLong et al., 2014). Furthermore, extension records in *S. siderea*, *M. faveolata*, and *Diploria strigosa* colonies at our study site reveal differing trends and variations among colonies living in the same environmental conditions (Muslic et al., 2013) suggesting biological variable is driving extension rates and not environmental forcing.

We assessed reproducibility for optimally sampled paths on the centimeter scale within a coral colony (i.e., intracolony) between opposing sides of the same slab 08PS-F1 (~5 mm apart), between two slabs from the same core 08PS-A1 (~10 mm apart), and between two cores from the same colony, 08PS-A1 and 08PS-A2 (~330 mm apart; Table 2). The means and standard deviations of the monthly coral Sr/Ca determinations are not significantly different and correlations are high and significant for all of these intracolony comparisons (Tables 1 and 2). The average AD and RMS of the coral Sr/Ca variations are less than or within 2σ of our

² Geochemical determinations are not exact values but an average for which the true value may occur anywhere with the analytical precision. The 95% confidence interval for these determinations is 2σ of the analytical precision or the true value follows a Gaussian distribution with a mean (the determined value) and the standard deviation as the analytical precision.

analytical precisions (0.024 to 0.039 mmol mol⁻¹, 2σ) for all time scales with the lowest average AD and RMS for the two comparisons in closest proximity. For individual monthly coral Sr/Ca determinations, 10% to 14% of the RMS values are greater than 0.026 mmol mol⁻¹ (2σ of average IGS analytical precision) for 08PS-F1 and 08PS-A1; respectively and 28% of the RMS values determined between 08PS-A1 and 08PS-A2. This percentage decreases to zero after low pass filtering to 36 months (Table 2). This suggests that most of the discrepancies are due to subannual dating uncertainties from assigning any one particular coral Sr/Ca determination to a calendar month.

We note that the mean coral Sr/Ca for 08PS-F1 is greater than the 08PS-A (0.030 mmol mol⁻¹ difference in means determined for 1896–2008; equivalent to 0.7 °C) and some intervals have differences greater than 2σ of our analytical precisions (e.g., 1901–1902, 1944–1948, and 1952–1953 in Figure 8). However, there is no consistent mean shift towards greater or lesser values between 08PS-F1 and the other cores, and most intervals agree within analytical precision. We sampled additional paths on the same side of the slab as the original path on 08PS-F1 for the interval from 1898 to 1942 in order to confirm these variations and found the average AD of coral Sr/Ca variations between original and new paths (0.027 ± 0.020 mmol mol⁻¹, 1σ) and the average RMS (0.019 ± 0.014 mmol mol⁻¹, 1σ) are higher than that observed for the opposing sides of 08PS-F1 for the interval from 1994 to 2009. Another possible explanation is that the interval from 1896 to 1942 is close to the apparent year of initial growth (~ 1875) for the colony 08PS-F1 (Supplementary Fig. S3). Little is known about ontogenic effects and coral geochemistry; however, ontogenic shifts have been suggested for massive *Porites* spp. for corals less than 25 years old (Marshall and McCulloch, 2002; Ourbak et al., 2008). We found no evidence of sampling artifacts that could explain these discrepancies (section 3.1); however,

researchers with various levels of experience sampled these paths, so these differences may be related to skill level or ontogenic effects.

We assessed reproducibility for monthly-resolved coral $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations from two coral colonies as well as bimonthly-resolved coral $\delta^{18}\text{O}$ variations from 93DRYSS1 (Maupin et al., 2008) (Fig. 5 and Table 3). Coral $\delta^{13}\text{C}$ in 08PS-F1 has a larger annual cycle, means between 08PS-F1 and 08PS-A1 are significantly different, and coral $\delta^{13}\text{C}$ is not reproducible within analytical precision, suggesting that colony-specific biological processes and not environmental factors are driving carbon $\delta^{13}\text{C}$ for the short interval examined. A study with multiple *P. lutea* corals found similar results for coral $\delta^{13}\text{C}$ (Stephans et al., 2004). Monthly coral $\delta^{18}\text{O}$ are reproducible (average RMS = 0.07 ± 0.06 , 1σ , and average AD = 0.10 ± 0.09 , 1σ) and differences are within analytical precision (2σ) between these colonies. Discrepancies for coral $\delta^{18}\text{O}$ between bimonthly 93DRYSS1 and monthly 08PS-A1 are greater and this reduced reproducibility may be due to differences in sampling resolution (see section 3.1.3). Similar differences for sampling resolution were found for coral Sr/Ca for these coral colonies and for coral Sr/Ca and $\delta^{18}\text{O}$ in same *P. lutea* colony (DeLong et al., 2007). These results for coral $\delta^{18}\text{O}$, despite the short interval for comparison, suggest this proxy is reproducible in *S. siderea* thus providing support for using coral $\delta^{18}\text{O}$ to develop reconstructions of SST and possibly salinity.

4. Conclusions

In this study, we identified sources of sampling artifacts and suggest ways to improve the sampling of *S. siderea* for the reconstruction of SST using coral Sr/Ca, and by extension to other proxies as well. We find monthly-resolved coral Sr/Ca and $\delta^{18}\text{O}$ determinations are reproducible within analytical precision whereas coral $\delta^{13}\text{C}$ is not, suggesting biological processes influencing coral $\delta^{13}\text{C}$ at least on interannual time scales. The largest source of error in monthly coral Sr/Ca

time series is subannual dating uncertainties from assigning a coral Sr/Ca value to a particular month. Consistent sampling along the corallite wall is need to avoid cold bias that can be subtle and reduce annual cycles as much as 20% when sampling within the columella. Diagenesis can also produce subtle shifts in coral Sr/Ca that still exhibit a annual cycle but shifted to higher (colder) coral Sr/Ca values. For these corals, sampling resolutions of 6 samples year⁻¹ may not recover coral Sr/Ca and $\delta^{18}\text{O}$ seasonal extremes and reduce the amplitude for seasonal cycles, which would be problematic for reconstructions of seasonal and interannual variability such as El Niño Southern Oscillation. There is no difference in coral Sr/Ca among sample path orientations with respect to the *S. siderea* colony (i.e., horizontal versus vertical) suggesting microatolls and subfossil corals of *S. siderea* with unknown growth orientation can be used for reconstructions. For these *S. siderea* colonies, extension rates can vary as slow as 2.1 mm year⁻¹ with no shift to higher (i.e., colder) coral Sr/Ca values related to growth-related or kinetic effects. Coral Sr/Ca and $\delta^{18}\text{O}$ variations extracted from multiple *S. siderea* colonies located up to 11.5 km apart and sampled by multiple workers with similar training display remarkable reproducibility thus, supporting the use of this coral species for developing coral Sr/Ca and $\delta^{18}\text{O}$ reconstructions from live and dead corals.

4.1 Sampling suggestions

- Sampling *S. siderea* for geochemical analysis should avoid the less dense columella in the center of the corallite. The optimal sample path location for *S. siderea* is along the synapticulothecal corallite wall. Cores from *S. siderea* colonies should be slabbed so that the corallite walls are transected in a longitudinal cross-section with the walls parallel to the slab surface.
- Monitor annual extension and amplitude of geochemical seasonal cycles in *S. siderea* as

possible indicators of sampling resolution artifacts or possible growth-related shifts.

- Monthly sampling resolution is preferred to bimonthly resolution for analysis of seasonality in *S. siderea* and to obtain the full annual SST cycle. We suggest increasing sampling interval for years with $\leq 50\%$ reduction in annual extension to avoid a reduction in annual cycle introduced by dampening the seasonal variability as longer time intervals are integrated within each sample.
- Sample path orientation with respect to the *S. siderea* colony can vary from vertical to horizontal for coral Sr/Ca determinations.

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Figures Captions

Fig. 1 Example of improper (left) and proper (right) slabs of a coral core for geochemical analysis. 08PS-A1-A slab 1 on the left has oblong top of corallites visible on the slab surface (inset) and the X-radiograph has a wavy appearance without clear annual density bands compared to the X-radiograph on the right, which has optimal alignment of corallites. Slab on the right (08PS-A1-A slab 3) is a quarter section of the core taken at 90° from 08PS-A1-A slab 1 and the synapticulothecal corallite walls are parallel to the surface.

Fig. 2 Coral Sr/Ca variations across corallites of *S. siderea*. (A) Samples were extracted from the coral slab 08PS-A2-A for the year 1950 (see Supplementary Fig. S2 for location). (B) X-radiograph of the coral with sampling paths superimposed. (c) Coral scan enlarged by 1000% with coral Sr/Ca variations superimposed by sample number (#) and aligned to respective sampling path to ~1 mm. The central spongy columella (C) occurs in the center of the corallite and thick synapticulothecal corallite walls (W) are on either side. Sr/Ca axis is reversed so that

warm values are up. Errors bars are 2σ analytical precision.

Fig. 3 Coral Sr/Ca variations along different portions of a *S. siderea* corallite in 08PS-F1 (see Supplementary Fig. S3 for location). (A) Scan of coral shown in (B) before sampling with corallite walls and columella labeled. (C) Coral Sr/Ca variations along the sampling lines in (B) and with two sampling paths (see Supplementary Fig. S3 for location) used in the SST reconstruction (DeLong et al., 2014). (D) Drawing of *S. siderea* in cross section along the growth axis with central spongy columella and thick synapticulothecal corallite walls, which are the optimal sample path locations. (E) Example of a problematic sampling interval (gray area) in the columella from 08PS-A2-B (see Supplementary Fig. S2 for location). Sr/Ca axes are reversed so that warm values are up and are scaled to the same interval. Errors bars are 2σ analytical precision.

Fig. 4 Sampling resolution and extension rate assessment. (A) Sampling resolution comparison among coral Sr/Ca variations with resolution of ~ 12 samples year^{-1} (08PS-A1 and 08PS-F1; this study and DeLong et al., 2014) and ~ 6 samples year^{-1} (93DRYSS1; (Maupin et al., 2008) for a select interval. (B) Contemporary coral Sr/Ca variations from two colonies with boxes enclosing years with slower extension (< 2.6 mm) with extension given for each year. One year (1783; black box) had slower extension in both cores. Sr/Ca axes are reversed so that warm values are up and are scaled to the same interval. Errors bars are 2σ analytical precision.

Fig. 5 Comparison of coral (A) $\delta^{18}\text{O}$ and (B) $\delta^{13}\text{C}$ variations among colonies. Sampling resolution is ~ 12 samples year^{-1} for 08PS-A1 and 08PS-F1 (this study and DeLong et al., 2014) and ~ 6 samples year^{-1} for 93DRYSS1 (Maupin et al., 2008). Isotopic axes are reversed. Errors bars are 2σ analytical precision.

Fig. 6 Comparison of coral Sr/Ca variations with respect to colony orientation. (A) Two cores

were extracted from a large *S. siderea* colony (08PS-A) that has a flat top, (B) one in the center with a dead top (08PS-A2) and one offset from center with a live top (08PS-A1). (C) X-radiographs of slabs extracted from 08PS-A; labels as in Supplementary Fig. S2, with slabs visually aligned since density variations are continuous between cores. Note: secondary density patterns 8 to 12 years that span the colony. Growth direction of 08PS-A1 changes to almost horizontal towards the bottom of the core. (D) Contemporaneous coral Sr/Ca variations compared among the three paths in 08PS-A with different growth orientations with respect to the vertical axis of the colony and with variations from 93DRYSS2 that has a sampling orientation of 19° from vertical (Supplementary Fig. S4). Sr/Ca axis is reversed so that warm values are up. Error bars are 2σ analytical precision.

Fig. 7 Comparison among sampling paths that have evidence of diagenesis. (A) Coral Sr/Ca variations from the bottom section of the slab 08PS-A2-B (1778 to bottom of core; Supplementary Fig. S2). SEM image reveals the presence of secondary aragonite (inset; scale bar = 200 μm). (B) Coral Sr/Ca variations from the top section of the slab 08PS-A2-A that was dead (Supplementary Fig. S2). One path in 08PS-A2-A through a region with altered skeleton is compared to a second path from the same slab and other coral colonies. Sr/Ca axes are reversed so that warm values are up. Error bars are analytical precision (2σ).

Fig. 8 Interannual coral Sr/Ca reproducibility. (A) Number (#) of cores sampled for each month. (B) Monthly coral Sr/Ca determinations smoothed with a 36-month LPFIR filter (90% pass = 62.5 months) (Bloomfield, 2000) to minimize subannual dating uncertainties and highlight variability greater than seasonal. The range of possible values is shown in shaded areas representing analytical precision ($\pm 0.024 \text{ mmol mol}^{-1}$, 2σ) and error bars showing analytical for IGS and PL coral standard (± 0.026 to $0.039 \text{ mmol mol}^{-1}$, 2σ ; black and red respectively). Areas

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where shaded colors overlap are not different within analytical precision ($\pm 0.024 \text{ mmol mol}^{-1}$, 2σ). Coral Sr/Ca axis is reversed so that warm values are up. (C) Annual linear extension (Ext.) determined between Sr/Ca maxima (February to February). (D) Absolute differences (AD) for any single month in (B) with gray dashed line denoting the average AD ($0.010 \text{ mmol mol}^{-1}$) and black dashed line is analytical error ($0.026 \text{ mmol mol}^{-1}$, 2σ).

Table 1 Summary of monthly-resolved coral Sr/Ca variations.

Statistic	08PS-A1	08PS-A2	08PS-F1	93DRYSS2	93DRYSS1 ^a
Mean	8.990	9.015	9.017	9.019	8.999
Median	8.981	9.012	9.017	9.016	9.001
Std. deviation	0.124	0.121	0.123	0.118	0.103
Maximum	9.314	9.378	9.338	9.367	9.255
Minimum	8.732	8.734	8.740	8.747	8.792
Seasonal ^b	0.356 (± 0.051)	0.349 (± 0.065)	0.366 (± 0.052)	0.352 (± 0.056)	0.266 (± 0.046)
Extension ^c	4.82 (± 0.59)	4.01 (± 0.69)	3.83 (± 0.53)	3.93 (± 0.66)	4.94 (± 0.73)
n ^d	765	2266	1342	2048	561
Years	1945–2008	1779–1967	1896–2008	1733–1904	1990–1993
Sampling ^e	0.417	0.417	0.3175	0.3175	0.75

Determined in the time domain. Units are mmol mol^{-1} unless otherwise indicated.

^a Core from previous study of Maupin et al. (2008).

^b Average seasonal cycle ($\pm 1\sigma$) determined between winter maxima (February) in Sr/Ca for each year.

^c Average extension ($\pm 1\sigma$) determined between winter maxima (February) in Sr/Ca for each year. Units are mm year^{-1} .

^d Number of observations (n).

^e Sampling interval is mm sample^{-1} .

Table 2 Reproducibility statistics for coral Sr/Ca.

	Opposing sides of same slab 08PS-F1			Two slabs, same colony 08PS-A1 slabs 2 and 3			Two cores, same colony 08PS-A1 and 08PS-A2			Two colonies, in close proximity 08PS-A and 08PS-F1			Two colonies, same reef 08PS-A and 93DRYSS2		
Years ^a	1994–2008 (146)			1984–2008 (287)			1945–1967 (276)			1896–1967 (857)			1779–1904 (1504)		
Water depth	3.4 m			4.3 m			4.3 m			3.4 and 4.5 m			4.3 m and ?		
Distance	5 mm			10 mm			330 mm			510 m			11.5 km		
Statistic ^b	RMS	AD	<i>r</i>	RMS	AD	<i>r</i>	RMS	AD	<i>r</i>	RMS	AD	<i>r</i>	RMS	AD	<i>r</i>
Monthly	0.013	0.019	0.96	0.013	0.018	0.97	0.018	0.026	0.95	0.021	0.029	0.95	0.019	0.027	0.92
Anomalies ^c	0.013	0.019	0.66	0.013	0.018	0.64	0.018	0.026	0.46	0.021	0.029	0.45	0.019	0.027	0.29
7 months ^d	0.010	0.015	0.64	0.009	0.013	0.68	0.015	0.022	0.57	0.019	0.027	0.49	0.017	0.024	0.32
MA ^e	0.009	0.012	0.63	0.006	0.009	0.66	0.013	0.018	0.63	0.017	0.024	0.51	0.013	0.018	0.35
36 months ^d	0.008	0.011	0.42	0.005	0.007	0.61	0.012	0.017	0.77	0.017	0.024	0.49	0.012	0.017	0.32
10 years ^d	NA	NA	NA	0.003	0.005	0.53	0.012	0.016	0.57	0.010	0.022	0.43	0.010	0.014	0.19

NA is not applicable.

^a Years of the common interval with number of pairs used in determinations in parentheses.

^b RMS is the average RMS (Eq. 1) and AD is the average AD (Eq. 2) for all common years; units are mmol mol⁻¹. Pearson correlation coefficient (*r*) for all common years; all correlations are significant ($p \leq 0.05$) and assessed with df.

^c Monthly anomalies are calculated with respect to the interval from 1971 to 1990.

^d Monthly anomalies are smoothed with LPFIR filter (Bloomfield, 2000) with 90% pass = 11 months for 7 months, 62.5 months for 36 months, and 16.7 years for 10 years.

^e Mean annual (MA) values are calculated for February to January (winter maxima in coral Sr/Ca).

Table 3 Reproducibility statistics for coral $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$.

	08PS-A1 and 08PS-F1			08PS-A1 and 93DRYSS1 ^c		
Years ^a	2001–2007 (67)			1991–1993 (16)		
Statistic ^b	RMS	AD	<i>r</i>	RMS	AD	<i>r</i>
Monthly $\delta^{18}\text{O}$	0.07	0.10	0.89	Bimonthly $\delta^{18}\text{O}$	0.13	0.18
Monthly $\delta^{13}\text{C}$	0.20	0.28	0.70	NA	NA	NA

NA is not applicable.

^a Years of the common interval with number of pairs used in determinations in parentheses.

^b RMS is the average RMS (Eq. 1) and AD is the average AD (Eq. 2) for all common years; units are mmol mol^{-1} . Pearson correlation coefficient (*r*) for all common years; all correlations are significant ($p \leq 0.05$) and assessed with df.

^c 08PS-A1 averaged to bimonthly intervals similar to 93DRYSS1.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8