



## 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<sup>-1</sup>) 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<sup>-1</sup> 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 $\sigma$  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 $\sigma$  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 geochemical variations from multiple *S. siderea* colonies suggests this species is suitable for paleoclimatic reconstructions, including subfossil corals and microatoll colonies that grow laterally.

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### 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 (~100 mm year<sup>-1</sup>) and massive corals are among the slower growing (up to 25 mm year<sup>-1</sup>) (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

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environmental variations from their skeletal chemistry (see reviews of Druffel, 1997; Gagan et al., 2000; Felis and Patzold, 2004; Corrège, 2006; Grottooli 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*<sup>1</sup> (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 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 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 mm<sup>3</sup>) 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, 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<sup>-1</sup> 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<sup>-1</sup> 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 <5 mm year<sup>-1</sup> (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 >5 mm year<sup>-1</sup> (Alibert and McCulloch, 1997; Woodroffe and Gagan, 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<sup>-1</sup> (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, 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 determined 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, 2014; Hickey et al., 2013). Two of the cores have unknown ages and were dated using high precision <sup>230</sup>Th dating (Shen et al., 2008, 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<sup>-1</sup> 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

<sup>1</sup> 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.

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