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**Massachusetts Institute of Technology**
**Woods Hole Oceanographic Institution**

**Joint Program in Oceanography/ Applied Ocean Science and Engineering**

## DOCTORAL DISSERTATION

# Geochemistry of Slow-Growing Corals: Reconstructing Sea Surface Temperature, Salinity and the North Atlantic Oscillation

by

Nathalie Fairbank Goodkin

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Geochemistry of Slow-Growing Corals: Reconstructing Sea Surface Temperature, Salinity and the North Atlantic Oscillation

by

Nathalie Fairbank Goodkin

A. B. *cum laude* in Chemistry
Harvard College, 2000

SUBMITTED TO THE DEPARTMENT OF EARTH ATMOSPHERIC AND PLANETARY SCIENCES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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June 2007



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# Abstract

A 225-year old coral from the south shore of Bermuda (64°W, 32°N) provides a record of decadal-to-centennial scale climate variability. The coral was collected live, and sub-annual density bands seen in x-radiographs delineate cold and warm seasons allowing for precise dating. Coral skeletons incorporate strontium (Sr) and calcium (Ca) in relative proportions inversely to the sea surface temperature (SST) in which the skeleton is secreted. $\delta^{18}O$ of the coral skeleton changes based on both temperature and the $\delta^{18}O$ of sea water ($\delta O_w$), and $\delta O_w$ is proportional to sea surface salinity (SSS).

Understanding long-term climate variability requires the reconstruction of key climate parameters, such as sea surface temperature (SST) and salinity, in records extending beyond the relatively short instrumental period. The high accretion rates, longevity, and skeletal growth bands found in coral skeletons make them an ideal resource for well-dated, seasonal climate reconstructions. Growing between 2 and 6 mm/year and reaching more than 1m in length, slow-growing corals provide multi-century records from one colony. Additionally, unlike the fast growing (10-20 mm/year) species *Porites*, slow-growing species are generally found in both tropical and sub-tropical locations greatly expanding the geographical location of these records.

A high resolution record (HRR, ~11 samples per year) was drilled for the entire length of the coral record (218 years). Samples were split and Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ were measured for each sample. Sr/Ca was used to reconstruct winter time and mean-annual SST. Oxygen isotopic measurements were used to determine directional salinity changes, in conjunction with Sr/Ca based SST reconstructions. Winter-time and mean annual SSTs show SSTs ~1.5 °C colder during the end of the Little Ice Age (LIA) relative to today. Simultaneously, SSS is fresher during that time.

Sr/Ca based climate reconstructions from coral skeletons have been met with some skepticism because some reconstructions show temperature changes back in time that are 2-4 times greater than the reconstructions of other marine proxies. In this study, we show that when using bulk-sampled, slow-growing corals, two steps are critical to producing accurate reconstructions: 1) incorporating growth rate into multi-variant regressions with SST and Sr/Ca and 2) using multiple colonies that grew at the same time with varying average growth rates and Sr/Ca. Application of these novel methods over the period of the instrumental record from Hydrostation S (monthly since 1954, 32°10'N, 64°30'W) reduces the root mean square of the residuals between the reconstructed SST and the instrumental SST by as much as 1.52°C to 0.46°C for three coral colonies.

Winter-time SSTs at Bermuda are correlated to phases of the North Atlantic Oscillation (NAO), a meridional oscillation in atmospheric mass. Much uncertainty remains about the relationship between the NAO and the ocean, and one critical outstanding question is whether anthropogenic changes are perturbing the system. Using winter Sr/Ca as a proxy for temperature, we show strong coherence to the NAO at multi-decadal and inter-annual frequencies. These coral records show significant changes in variance in the NAO during the late 20th century compared to the cooler LIA, but limited changes in the mean phase (positive or negative) of the NAO, implying that climate change may be pushing the NAO to extremes but not to a new mean position.

# Acknowledgements

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The coral samples used in this project were collected with funding to Anne Cohen and Michael McCartney. The corals were collected by A. Cohen, S. R. Smith, G. Piniak, J. Pitt, and others at the Bermuda Institute of Ocean Science (BIOS, formerly BBSR). This coral has proved to have been an amazing reservoir of historical, geochemical proxies and I am grateful to have been given access to them.

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# Table of Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

## 1.1 Goals of Thesis

Understanding long-term climate variability requires the reconstruction of key climate parameters, such as sea surface temperature (SST) and salinity (SSS), in records extending beyond the relatively short instrumental period. The focus of this thesis is on the development of ocean paleoclimate reconstructions of temperature, salinity and the North Atlantic Oscillation (NAO) from the sub-tropical North Atlantic at Bermuda. These records are based on geochemical analyses of slow-growing brain corals (*Diploria labyrinthiformis*). The high accretion rates, longevity, and semi-annual growth bands found in coral skeletons make them an ideal resource for well-dated, seasonal-resolution climate reconstructions. Corals incorporate minor elements (Sr) and stable oxygen isotopes ($^{18}O$ and $^{16}O$) as a function of the environmental conditions they experience during growth. During calcification, relatively more Sr and more $^{18}O$ are incorporated into the coral skeletons when temperatures are colder. The $^{18}O$ variations (reported as a ratio of $^{18}O/^{16}O$ relative to a standard in the form $\delta^{18}O$) also depend on SSS, as the $\delta^{18}O$

of sea increases with salinity. Measurements of each proxy in the same coral skeleton should therefore permit SST and SSS to be reconstructed simultaneously.

The goals of this thesis are: 1) to investigate the Sr/Ca (temperature) and $\delta^{18}O$ (salinity/temperature) paleo-proxies in slow-growing (<6mm/yr) corals, including quantification of the influence of growth on these proxies; 2) to examine mean-annual and winter (Dec.-March) changes in temperature and salinity using these coral paleo-proxies, particularly to examine conditions during the Little Ice Age; and 3) to use the record of winter-time Sr/Ca to examine changes in the NAO through time. This introduction presents many of the issues related to these three goals, which will be discussed in depth in subsequent chapters.

## 1.2 Overview of Sr/Ca and $\delta^{18}O$ in Corals as Paleoceanographic Proxies

### 1.2.1 Advantages of Coral Records from Slow Growing Corals

Reef corals, sediment cores, tree rings and ice cores are among the many environmental archives that contain detailed information regarding the earth's climate history on inter-annual to millennial time-scales. Several coral geochemical attributes indicate skeletal aragonite to be one of the most reliable sources of inter-annual to multi-decadal paleoclimate reconstructions during the Holocene. Annual banding in corals identified through x-radiographs, as well as resolvable seasonal cycles in both temperature and salinity proxies, allows precise dating and sampling with monthly resolution [*Alibert and McCulloch*, 1997; *Beck et al.*, 1992; *Gagan et al.*, 1998]. Instrumental records during the time of coral growth allows for the calibration of climate proxies which can then be applied to reconstructions that extend beyond the instrumental record. The sedentary nature of corals eliminates concerns regarding changes in habitats or lateral transportation (e.g. [*Be*, 1977; *Ohkouchi et al.*, 2002]). In addition, sampling of dense aragonite along growth transects greatly diminishes concerns of unobservable diagenetic influences, particularly with respect to Sr concentrations [*Bar-Matthews et al.*, 1993]. Because corals grow abundantly throughout the tropical and sub-tropical oceans (Fig. 1.1) [*NOAA*], they provide the potential to generate large scale spatial reconstructions of sea surface temperature (SST) and sea surface salinity (SSS).

**Figure 1.1:** Distribution of major coral reefs in the world's oceans as designated by red dots. Coral reefs are found throughout the tropical and sub-tropical oceans ranging primarily from 30°N to 30°S. Figure reproduced from a NOAA website

*Diploria labyrinthiformis*, commonly known as brain coral, is a slow growing coral species that can be found throughout the latitudes at which corals grow (Fig. 1.1). Brain corals have slow growth rates, 2-6 mm/yr [*Cardinal et al.*, 2001; *Cohen et al.*, 2004; *Dodge and Thomson*, 1974; *Goodkin et al.*, 2005; *Kuhnert et al.*, 2002], compared to *Porites,* the more commonly used coral genus for paleoclimate reconstructions, which has growth rates from 8-20 mm/yr [*Alibert and McCulloch*, 1997; *deVilliers et al.*, 1994; *Hughen et al.*, 1999]. In addition, brain corals have relatively long life-spans of several hundred years. Therefore, examining brain coral Sr/Ca and $\delta^{18}O$ proxies will enable the paleoclimate community to extract continuous, multi-century records from relatively small geological samples and geographically diverse regions.

Until recently, brain corals have been sparsely used for geochemical records [*Cardinal et al.*, 2001; *Cohen et al.*, 2004; *Dodge and Thomson*, 1974; *Druffel*, 1997; *Kuhnert et al.*, 2002; *Reuer*, 2001], due to the complicated growth structure of the skeletal elements. The coral thecal wall is the densest and most often sampled skeletal element. This area extends rapidly along a cone-shaped surface during the summer. The brain coral continues the extension of the thecal wall during the winter, while simultaneously thickening the wall segment deposited during the summer [*Cohen et al.*, 2004]. This complicates high-resolution sampling in that summer-time aragonite layers may have seen winter-time influences, and the sharp cone-shaped growth surface may lead to discrete samples encompassing a variety of months, depending on the width of the sample [*Hart and Cohen*, 1996]. However, the high density thecal wall ensures both ample material for sampling and diminishes concerns of diagenesis or secondary precipitation [*Bar-Matthews et al.*, 1993]. Concerns have been raised about coral paleoclimate reconstructions due to several complicating factors, including commonly used bulk sampling techniques [*Marshall and McCulloch*, 2002; *Swart et al.*, 2002], as well as environmental, biological, growth rate and symbiotic effects [*Amiel et al.*, 1973; *Cohen et al.*, 2002; *deVilliers et al.*, 1994; *Ferrier-Pages et al.*, 2002; *Greegor et al.*, 1997; *McConnaughey*, 1989a; *McConnaughey*, 1989b; *Reynaud et al.*, 2004]. In this study, efforts are made to account for some of these impacts by incorporating the use of inter-annual, rather than monthly, data and by quantitatively evaluating growth rate influences on reconstructed SST.

### 1.2.2 Sr/Ca as a Temperature Proxy

Sea surface temperature (SST) is one of the climate parameters most often reconstructed in coral records and is a critical parameter for interpreting long-term climate variability. The Sr/Ca content of coral reef $CaCO_3$ is one geochemical proxy used to reconstruct past SSTs. This technique is based on the premise that as temperature increases, corals incorporate relatively less Sr into their $CaCO_3$ structures, thereby recording the temperature of surrounding water as they grow [*Beck et al.*, 1992; *Smith et al.*, 1979].

Despite the promise of the Sr/Ca thermometer, there are several outstanding concerns. While Sr and Ca are both relatively conservative elements in seawater, small changes in their concentration have been observed due to coral symbionts and other biological activity, as well as upwelling and other local effects (e.g. [*Bernstein et al.*, 1987; *Cohen et al.*, 2002; *deVilliers et al.*, 1994; *MacKenzie*, 1964; *Shen et al.*, 1996]). Other studies have indicated that significant levels of coral strontium are deposited as strontanite ($SrCO_3$) onto crystal surfaces rather than in substitution for Ca into the lattice [*Amiel et al.*, 1973; *Greegor et al.*, 1997]. As previously mentioned, coral growth is not often a purely linear process, particularly in slow growth corals where seasonal changes influenced extension rate and in-filling in the coral skeleton [*Barnes and Lough*, 1993; *Cohen et al.*, 2004]. Influences unrelated to SST, such as growth rate [*deVilliers et al.*, 1995] and short term changes in Sr and Ca concentrations in water [*deVilliers et al.*, 1994], can also influence the monthly Sr/Ca relationship, demonstrating the importance of investigating averaged or inter-annual periods.

**Table 1.1:** Table of reported Sr/Ca-SST relationships for monthly resolution sampling. Sr/Ca=m * (SST) + b.

| Author | Year | Slope ($mmol^{1}mol^{-1}{}^{\circ}C^{-1}$) | Intercept ($mmol^{1}mol^{-1}$) | Growth (mm/year) | SST Range (deg C) | Species |
|---|---|---|---|---|---|---|
| Marshall & McCulloch | 2001 | -0.0593 | 10.375 | | 25 - 30 | Porites |
| Gagan et al. | 1998 | -0.0660 | 10.78 | 24 | 20 - 30 | Porites |
| | | -0.0639 | 10.73 | 22 / 12.5 | 22 - 29 | |
| | | -0.0616 | 10.68 | 8 | 20 - 31 | |
| Correge et al. | 2000 | -0.0657 | 10.73 | | 20 - 26 | Porites |
| Marshall & McCulloch | 2001 | -0.0575 | 10.40 | 7.5 - 10 | 23 - 29.5 | Porites |
| | | -0.0587 | 10.40 | 16.2-17.0 | 21 - 30 | |
| Smith et al. | 1979 | -0.071 | 11.01 | | 19 - 29 | Multiple |
| deVilliers et al. | 1994 | -0.0795 | 10.956 | 11 | 23 - 27 | Porites |
| | | -0.0763 | 11.004 | 8 | 23.5 - 27 | Pocillopora |
| | | -0.0675 | 10.646 | 11 | 20 - 25 | Pavona |
| Correge et al. | 2004 | -0.060 | 10.57 | 2 - 5 | 22 - 30 | Diploastrea |
| | | -0.062 | 10.51 | | 22 - 30 | Porites |
| Fallon et al. | 1999 | -0.063 | 10.76 | 5.3 | 14.5 - 28 | Porites |
| Shen et al. | 1996 | -0.0528 | 10.356 | 15-16 | 22 - 28 | Porites |
| | | -0.0505 | 10.307 | 17-23 | 22 - 28 | |
| Alibert & McCulloch | 1997 | -0.0505 | 10.21 | 8 | 22 - 29 | Porites |
| | | -0.0615 | 10.485 | 13 | 23 - 29 | |
| | | -0.0507 | 10.17 | 12 | 22.5 - 28.5 | |
| | | -0.0604 | 10.425 | 14 | 23 - 28.5 | |
| | | -0.0629 | 10.56 | 9 | 22 - 28 | |
| deVilliers et al. | 1995 | -0.0417 | 10.25 | 6 | 19.5 - 25 | Pavona |
| | | -0.0388 | 10.11 | 12 | 19.5 - 25 | |
| | | -0.0331 | 9.92 | 14 | 20 - 24 | |
| Cardinal et al. | 2001 | -0.045 | 10.03 | 3.2 | 19.5 - 28.5 | Diploria |
| | | | | 2.8 | 19.5 - 28.5 | |
| Swart et al. | 2001 | -0.0377 | 9.994 | 6 - 9 | 24 - 30 | Montastrea |
| This Study | | -0.0358 | 10.1 | 3-5 | 18-29 | Diploria |
| | | -0.0376 | 10.1 | 1-5 | 18-29 | |
| | | -0.0436 | 10.3 | 3-5.5 | 18-29 | |
| | | -0.0429 | 10.3 | 1.5-3.5 | 18-29 | |

Two key problems have continued to plague the acceptance and validity of coral Sr/Ca paleo-reconstructions: 1) Each modern coral calibrated to instrumental SST results in a different coral Sr/Ca-SST relationship in both slope and intercept, implying that this is not simply a thermodynamic temperature relationship (e.g. Table 1.1) [*Lough*, 2004; *Marshall and McCulloch*, 2002]; and 2) coral based SST reconstructions have shown 2-4 times greater temperature changes in the tropical oceans from today to the last glacial maximum (LGM) [*Beck et al.*, 1997; *Correge et al.*, 2004; *Guilderson et al.*, 1994; *McCulloch et al.*, 1996] compared to other marine paleoproxies [*Lea et al.*, 2000; *Pelejero et al.*, 1999; *Rosenthal et al.*, 2003; *Rühlemann et al.*, 1999].

This thesis strives to demonstrate that growth rate influences may be accounting for some of the complexities observed in the literature. Incorporation of growth rate, multiple-coral colonies, and inter-annual averaged data generates more robust Sr/Ca-SST coral calibrations and reconstructions.

### 1.2.3 $\delta^{18}O$ as a Salinity and Temperature Proxy

The $\delta^{18}O$ of coral skeleton can be used to reconstruct sea surface salinity in conjunction with a Sr/Ca based SST reconstruction. The relative concentration of stable oxygen isotopes in corals depends on the temperature of the surrounding sea water and the oxygen isotopic composition of that sea water at the time of coral growth. To first approximation, the isotopic composition of sea water is linearly related to sea surface salinity [*Urey*, 1947]. This relationship varies both between geographic locations and between depths in the water column.

Kinetic models predict that slow growing corals should incorporate oxygen isotopes relatively close to thermodynamic equilibrium compared to their fast growing counterparts [*McConnaughey*, 1989a; *McConnaughey*, 1989b]. The isotopic composition of biogenic aragonite from measurements of non-coral species (foraminifera, gastropods, and scaphopods) has been expressed as [*Grossman and Ku*, 1986]:

$$\delta O_c - \delta O_w = -0.23 * (SST) + 4.75 \qquad \text{Eqn. (1)}$$

Slow growing corals are likely to exhibit enrichment in $^{16}O$ relative to other marine organisms, but with fewer kinetic fractionation effects (growth effects) during calcification than faster growing corals. These kinetic effects are thus expected to have small impacts on the $\delta^{18}O$-SST slope, both within and between slow-growing colonies [*deVilliers et al.*, 1995; *Guilderson and Schrag*, 1999; *Linsley et al.*, 1999; *Lough*, 2004; *McConnaughey*, 1989b; *McConnaughey*, 2003], relative to faster growing colonies. Therefore, using the $\delta^{18}O$ to reconstruct temperature and/or salinity should be feasible.

**Table 1.2:** Table of reported $\delta^{18}O$-SST and Sr/Ca- $\delta^{18}O$ monthly relationships by species.

| | | Oxygen - SST | | Sr/Ca - Oxygen | | Growth | SST Range | |
|---|---|---|---|---|---|---|---|---|
| **Author** | **Year** | **Slope** | **Intercept** | **Slope** | **Intercept** | **(mm/year)** | **(deg C)** | **Species** |
| Bagnato et al. | 2004 | -0.15 | -0.84 | | | | 24.5 - 29.5 | Porites |
| | | -0.16 | -0.26 | | | | | |
| Cardinal et al. | 2004 | -0.14 | | 0.30 | | 3.2 | 19.5 - 28.5 | Diploria |
| | | | | 0.18 | | 2.8 | | |
| de Villiers et al. | 1995 | -0.174 | 0.22 | | | 6 | 19.5 - 25 | Pavona |
| | | -0.106 | -1.56 | | | 12 | 19.5 - 25 | |
| Smith et al. | 2006 | -0.101 | -1.24 | 0.28 | 10.31 | 7 | 22 - 31 | Montastrea |
| Dunbar et al. | 1994 | -0.122 | -1.48 | | | 13 | 20 - 28 | Pavona |
| Gagan et al.* | 1998 | -0.174 | 0.002 | | | 12.5 | 22 - 29 | Porites |
| | | -0.189 | 0.447 | | | 22.0 | 22 - 29 | |
| Watanabe et al. | 2003 | -0.18 | 0.23 | | | 2.7 | 20 - 28 | Diplorastrea |
| Beck et al. | 1992 | | | 0.27 | | | 20 - 27 | Porites |
| McCulloch et al. | 1994 | -0.203 | 0.577 | 0.30 | | | | Porites |
| This Study | | -0.105 | -1.17 | 0.28 | 10.3 | 3-5 | 18-29 | Diploria |

* Regressions to Sr/Ca based reconstructed SST

Units on oxygen-SST slopes are ‰/°C and intercepts are ‰.

Units on Sr/Ca Oxygen slopes are mmol/mol/‰ and intercepts are mmol/mol.

Much like the Sr/Ca record, the $\delta^{18}O$ of slow-growing corals may be further complicated by growth structure and smoothing during bulk sampling, [*Cohen et al.*, 2004; *Goodkin et al.*, 2005; *Swart et al.*, 2002]. The $\delta^{18}O$ – SST relationships determined by previous studies are all based on monthly calibrations (Table 1.2). They are not close to the expected values based on the laboratory measurements of aragonite formation (Eqn. 1.1), and slower growing corals are not more consistent between colonies than faster growing colonies (e.g. Table 1.2). These results are contradictory to expectations and may be due to smoothing during bulk sampling. In order to avoid previously discussed complications including growth regimes and bulk sampling, this study aims to develop accurate paleo-temperature and salinity reconstructions using inter-annual calibrations that incorporate potential non-equilibrium processes, including the evaluation of growth rate influences.

## 1.3 Climate Reconstructions

Upon completion of the paleoclimate proxy calibrations, I will use multi-century long geochemical records to reconstruct and examine the interactions between two large scale climatic patterns: one spatial - the North Atlantic Oscillation (NAO) and the other temporal - the last century-scale event of the Little Ice Age (LIA). The NAO is an oscillation of atmospheric mass, commonly measured as a pressure difference between the Icelandic low and the Açores high regions [*Hurrell*, 1995; *Jones et al.*, 1997]. NAO variability can be defined on a wide range of time-scales including synoptic (10 days), seasonal and multi-century. The Little Ice Age, on the other hand, was a multi-century climate event believed to have ended in the late 1800s. It was a period of colder than normal temperatures recorded historically by many communities, particularly in the North Atlantic region [*Grove*, 1988]. Anthropogenic climate changes appear to be causing rapid warming of the earth's temperature, which is subsequently altering a range of climate dynamics. By examining the NAO during the time of the LIA, a better understanding of how this system has behaved during times of rapid climate change and during times of a different mean-temperature than seen today is investigated. Therefore, I use the coral to reconstruct the NAO and ocean state at Bermuda prior to the instrumental record, including the LIA.

The NAO has wide reaching influence over weather and climate patterns across the North Atlantic, the United States and Europe [*Visbeck et al.*, 2001]. The NAO's influence on temperature, precipitation and other ocean conditions is important to society due to its location between the eastern United States and Europe, both large centers of industry and population. The NAO can have significant impacts on wave height in the Atlantic, which can drastically impact shipping, oil drilling, and coastal management [*Hurrell et al.*, 2003; *Kushnir et al.*, 1997]. Precipitation patterns impact agriculture, hydroelectric power generation, and tourism [*Hurrell et al.*, 2003]. Additionally, the negative impacts of the NAO on agriculture, fisheries, and ecosystems can threaten food sources for many regions [*Hurrell et al.*, 2003; *Thompson and Wallace*, 2001]. For example, Fromentin and Planque (2000) suggested that shifts in the NAO cause large fluctuations in plankton communities in the North Atlantic, which in turn can significantly impact pelagic communities such as herring and cod. Changes in precipitation can also have drastic agricultural effects from the mid-western United States to the Middle East [*Visbeck*, 2002]. Improving our ability to predict abrupt, annual shifts in the NAO could also improve our ability to anticipate the economic impacts of such short-term changes in climate. By linking NAO Index (NAOI) variability with events relevant to society, much like El Niño and maize crops in Zimbabwe [*Cane et al.*, 1994], significant improvements in human productivity and quality of life can be achieved.

Instrumental records of the NAOI from Iceland and the Açores [*Hurrell*, 1995] show an extended period of positive phase in the NAO beginning in the early 1970s that is unprecedented in the instrumental record in terms of duration and intensity (Fig. 1.2). The NAOI [*Hurrel,* 1995] is measured by differencing normalized sea level pressure measurements at Portugal ($L_n$) and Iceland ($S_n$). These data lend themselves to the hypothesis that the onset of global climate change resulting from anthropogenic forcing has already influenced the trend of the NAO [*Shindell et al.*, 1999]. Unfortunately, instrumental records are too short to provide information about the long-term behavior of the NAO beyond 1860. This hampers not only our ability to evaluate the importance of

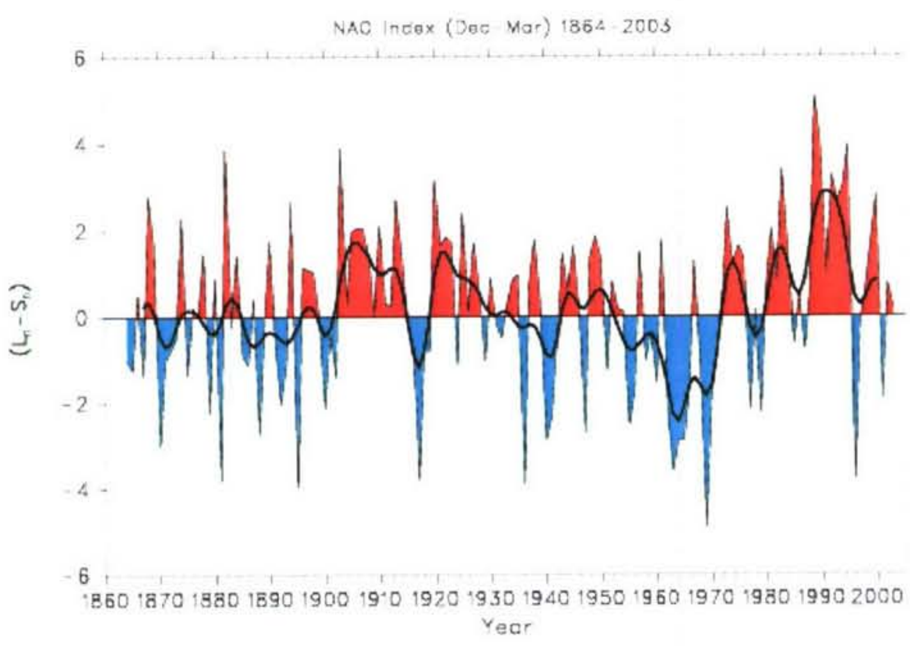


**Figure 1.2:** Instrumental record of the NAOI from 1860 to 2002 shows an unprecedented and extended positive trend for the past 30 years. (http://www.cgd.ucar.edu/cas/jhurrell/nao.stat.winter.html). The NAOI is calculated by differencing the normalized (over the length of the record) sea level pressure measurements at Portugal ($L_n$) and Iceland ($S_n$).

anthropogenic influences, but also our ability to predict the behavior of the NAO in the future. Annually resolved, multi-century records of natural background climate variability are therefore important not only for distinguishing recent anthropogenic impacts, but also for predicting potential future trends. In addition, such information is critical to identifying possible feedbacks, whereby changing NAO dynamics could amplify gradual climate change and introduce abrupt climate shifts, with consequences for the environment and society.

### 1.3.1 Studying Climate at Bermuda

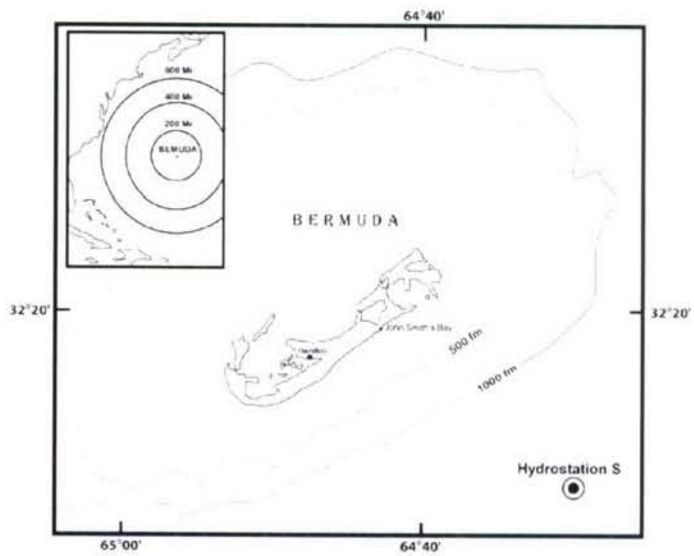


**Figure 1.3**: Map of Bermuda. Bermuda is located roughly 330 km off the coast of North Carolina. Hydrostation S is 30 km southeast of Bermuda and provides approximately 50 years of SST data in proximity to where the corals were taken along the southeastern edge of the platform off John Smith's Bay at 16m depth. (Figure adapted from World Ocean Circulation Experiment Newsletter, Number 8, October 1989)

The island of Bermuda (64°W, 32°N) (Fig. 1.3) located in the western sub-tropical Atlantic is an excellent location for examining long-term climate variability for several reasons. This location is sensitive to the dominant atmospheric process in this region, the NAO [*Visbeck et al.*, 2001], and experiences SST anomalies coherent with the NAO at low (multi-decadal) and high (inter-annual) frequencies. In addition, the site is influenced by the Gulf Stream, the sub-tropical gyre and sub-polar waters of the North Atlantic. The Sargasso Sea, which encompasses Bermuda, is formed by recirculation of Gulf Stream waters [*Hogg*, 1992; *Schmitz and McCartney*, 1993], imprinting Bermuda paleoclimate records with a Gulf Stream signal. Changes in position and strength of the Gulf Stream will impact temperature and salinity properties at Bermuda [*Schmitz and McCartney*, 1993; *Talley*, 1996]. Waters in the Sargasso Sea are also influenced by the larger sub-tropical gyre. Strength in the circulation of this gyre is dependent on the strength of the westerlies and large scale atmospheric processes [*Talley*, 1996]. The sensitivity of this location to two major ocean circulation processes responsible for climatically important ocean heat transport – the Gulf Stream and the sub-tropical gyre – provides the possibility to further inform our knowledge of ocean circulation.

In addition, Bermuda is the site of extensive oceanographic research providing long instrumental SST and SSS records. Hydrostation S, (Fig. 1.3) founded and visited approximately bi-weekly since 1954, provides the longest SST record in the area. Over the history of Hydrostation S, monthly SST has ranged from 18.0 to 28.9°C with annual averages ranging from 22.4-24.3°C. The plethora of corals growing on the Bermuda shelf and the large sedimentary deposits along the Bermuda rise allow for many types of paleo-climate reconstructions [*Draschba et al.*, 2000; *Keigwin*, 1996; *Kuhnert et al.*, 2002; *Sachs and Lehman*, 1999] over an array of timescales, which can serve to strengthen the paleoclimate story at this location.

### 1.3.2 Overview of the North Atlantic Oscillation

Winter-time SST at Bermuda has been shown to correlate with the NAO on high (annual) and low (decadal) frequency time scales [*Eden and Willebrand*, 2001; *Marshall et al.*, 2001; *Visbeck et al.*, 2001], making Bermuda an ideal location to examine this climate system. Reconstructing the NAO requires sub-annual resolution, precisely dated records, which are unique to corals.

The NAO has a widespread impact, on weather affecting the Northern Hemisphere from the Eastern US to Western Europe. In a positive NAO Index (NAOI) phase, both the low (Iceland) and high (Açores) pressure zones are intensified. This leads to an increased frequency of strong winter storms crossing the Atlantic Ocean along a

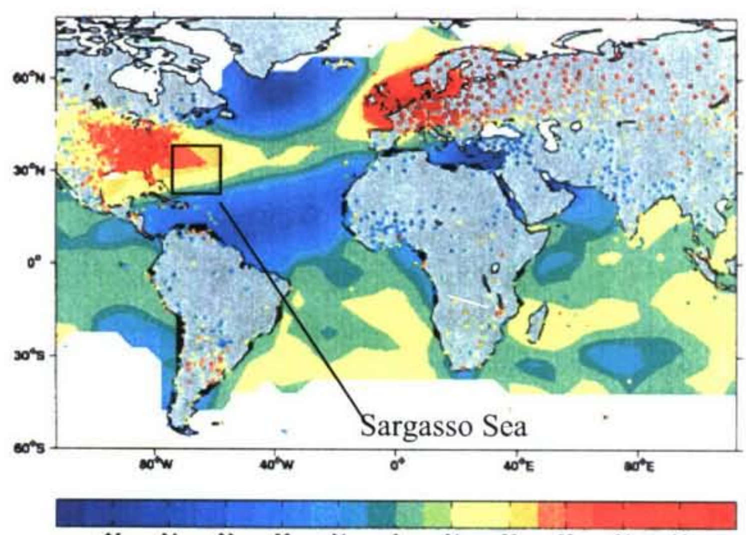


**Figure 1.4**: Correlation of mean winter (Dec., Jan., Feb., March) temperature against the NAOI from 1865-1930 (Visbeck et al., 2001). Yellow-red shows positive correlation (0.1-0.6). Blues show negative correlation (-0.1- -0.6). Greens are approximately no correlation.

northeast transect toward the Icelandic low. The deflection of the winter storm track north into the intensified low pressure zone causes colder temperatures over the Northwestern Atlantic, and warmer and stormier conditions in the eastern United States extending to Bermuda, and to warmer and drier conditions in Southern Europe. In the negative phase of the NAOI, both pressure anomalies are diminished and the gradient weakened. Positive and negative phase NAOI years have a distinct influence on mean winter surface temperature anomalies (Fig. 1.4). On multi-decadal time-scales, extended negative periods lead to warming in the tropics and sub-tropics and cooling in the sub-polar gyre [*Eden and Willebrand*, 2001; *Visbeck et al.*, 2003]. The reverse SST anomaly patterns occur during extended positive NAO periods. The inter-annual patterns are influenced by changes in Ekman pumping and heat flux due to the latitudinal shift and changes in strength of the prevailing winds (trades and westerlies). The multi-decadal response may result either from gradual changes in the strength of meridional overturning circulation (MOC), resulting from prolonged change in location and strength of Ekman pumping and convection in the Labrador Sea or from long-term propagation of inter-annual anomalies [*Eden and Willebrand*, 2001; *Visbeck et al.*, 2003; *Visbeck et al.*, 2001].

Uncertainty remains regarding the relationship between the NAO and the ocean. Currently, during a positive NAO, the SST anomalies form a "tri-pole" pattern with colder than normal waters in the sub-arctic and tropics and warmer than normal temperatures in the subtropics (Fig. 1.4) [*Visbeck et al.*, 2003]. While it is clear that atmospheric processes drive changes in wind speed and subsequent Ekman currents and heat exchange that lead to the tri-pole SST pattern seen in the ocean, it is not clear how relative influences of heat flux and ocean circulation how the presence of this SST pattern impacts the NAO [*Czaja et al.*, 2003]. Recent studies suggest that atmospheric feedbacks driven by SST anomalies may influence the NAO and these feedbacks could lead to enhanced prediction capabilities [*Czaja and Frankignoul*, 2002; *Rodwell et al.*, 1999]. However, short instrumental records make this difficult to assess.

A strong correlation within the tri-pole pattern seen in the North Atlantic between SST anomalies and the NAO has been established for the last 130 years [*Visbeck et al.*, 2003] (Fig. 1.3). However, one of the strongest periods of correlation occurs over the last 30 years when the NAO was already in its strong positive phase.

Joyce (2002) used an extended SST data set from off the coast of the eastern United States to show that over the past 130 years, there are periods between 1910-1930 and 1980-1985 when the correlation between the SST record and the NAO was weak or non-existent. The 1980-1985 period of weak-correlation is also captured in the Bermuda SST record from Hydrostation S, indicating its coherence with regional SST (Fig. 1.5).

Currently, there are several century-long reconstructions of the NAO from ice cores, tree rings, and snow accumulation rates [*Appenzeller et al.*, 1998a; *Appenzeller et al.*, 1998b; *Cook et al.*, 2002; *Glueck and Stockton*, 2001]. The only marine NAO reconstruction comes from the North and Norwegian Seas using mollusk calcification rates [*Schone et al.*, 2003]. This marine record shows a good correlation to NAO over the instrumental period (r=0.67). But, beyond the instrumental period, the correlations between the mollusk NAO reconstruction and other proxy reconstructions are greatly diminished (r=0.44). This decreased correlation supports the Joyce (2002) hypothesis that ocean-based reconstructions which include the last 30 years as a large portion of the calibration period may exaggerate NAO variability back in time. This reinforces the need to fully examine the SST-NAO relationship over longer time scales, prior to the advent of anthropogenic influences. I present a new record of NAO variability from an important region adding a second marine reconstruction to the literature.

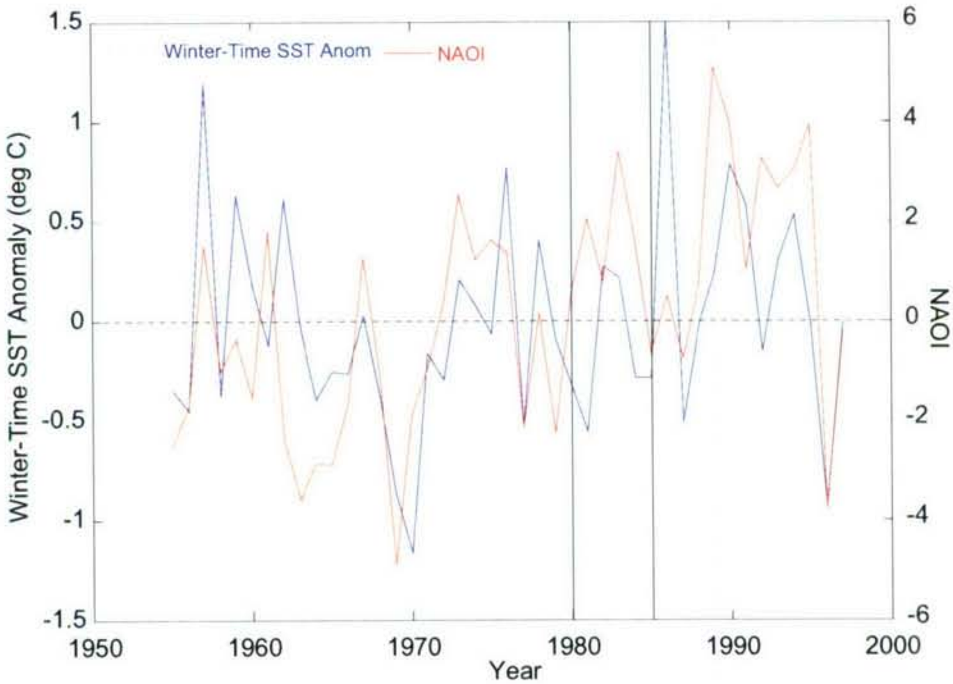


**Figure 1.5:** Winter-time SST anomaly from 1954-1997 average from Hydrostation S (blue) and an instrumental record of the NAOI (red) [*Hurrell*, 1995] plotted versus year. From 1980-1985 a disagreement between both phase and amplitude is seen as has been observed at other locations.

### 1.3.3 Overview of the Little Ice Age

The Little Ice Age (LIA) occurred from 1400s to the late 1800s following the Medieval warm period [*Bradley and Jones*, 1993; *Jones et al.*, 1998; *Overpeck et al.*, 1997]. This period is defined by a well documented series of extended centennial-scale cold periods. Currently, high-resolution records of the LIA exist from tree rings [*Briffa et al.*, 2001; *Esper et al.*, 2002; *Jacoby and D'Arrigo*, 1989], ice cores [*Dahl-Jensen et al.*, 1998; *Dansgard et al.*, 1975], and coral records from the Caribbean Sea [*Druffel*, 1982; *Watanabe et al.*, 2001; *Winter et al.*, 2000]. Proxy reconstructions from throughout the North Atlantic region show a large range of temperature changes, from 0.5 to 5 °C below current temperatures [*deMenocal et al.*, 2000; *Druffel*, 1982; *Dunbar et al.*, 1994; *Glynn et al.*, 1983; *Keigwin*, 1996; *Lund and Curry*, 2006].

The LIA has been proposed as the most recent example of decadal-to-centennial scale climate change during the Holocene. One question is how future anthropogenic climate change will alter climate behavior on short (100 year) periods (Abrupt Climate Change: Inevitable Suprises [*NRC*, 2002]). Two forcing mechanisms have been put forth as a possible cause for the LIA – solar and volcanic activity. Proxy reconstructions indicate that solar activity may have been low during this time [*Crowley*, 2000; *Lean et al.*, 1995; *Wigley and Kelly*, 1990], and volcanic activity may have been high [*Crowley*, 2000] both of which would have lead to cooling. Some studies have suggested that a 1500 year cycle in solar output may be another forcing of the LIA through the MOC [*Bond et al.*, 2001; *Bond et al.*, 1997]. Combined, solar and volcanic activity have the potential to produce wide spread cooling across the globe.

As previously discussed, another climate forcing mechanism in this region is the NAO. The direct influence of NAO processes is limited geographically to the Northern Hemisphere. In contrast to the volcanism and solar activity, the NAO will generate differing responses across the basin and at different frequencies [*Keigwin and Pickart*, 1999; *Visbeck et al.*, 2003]. Although instrumental and proxy reconstructions of this climate system show different results during the end of the LIA [*Cook et al.*, 2002; *Glueck and Stockton*, 2001; *Luterbacher et al.*, 2001; *Schoene et al.*, 2003], the reconstruction by Luterbacher et al. (2001), a record based on historical and multiple proxy records over a large geographical area, shows either a weak positive or neutral NAO at this time. Similarly, our study shows that a low frequency (decadal-to-centennial scale) connection to a positive NAO at Bermuda would be cooling and this would be likely to occur over much of the North Atlantic [*Visbeck et al.*, 2003].

## 1.4 Research Study

This project begins by contributing two new methods of calibrating coral paleoproxy data that quantify biases resulting from both sampling processes and varying growth rates through time. First, the biases introduced from the dampening of the seasonal cycle through bulk sampling on monthly calibrations are investigated and addressed by evaluating calibrations on inter-annual time scales rather than monthly calibrations which are impacted by seasonal biasing. Second, the ability of both inter-annual and long-term average growth rates to generate differences in the Sr/Ca-SST slopes is investigated using multiple coral colonies from the same location. The quantitative addition of growth rates first presented in Chapter 2 and further developed in Chapter 3 is critical to performing Sr/Ca-SST calibrations with these slow-growing corals. While growth rate is found to play a less significant role in the oxygen isotope proxies, bulk sampling effects still lead to the application of inter-annual, rather than monthly calibrations.

Ultimately, this thesis uses the methods and calibrations developed for both Sr/Ca and $\delta^{18}O$ to generate multi-century records of mean-annual and winter-time SST and directional changes in SSS. The records are used to investigate changes in temperature and salinity between today and the end of the LIA (Chapter 4) at Bermuda. Finally, winter Sr/Ca is found to represent the NAO at varying frequencies and a new marine based NAO reconstruction is presented and used to evaluate changes in NAO behavior and in the ocean-atmosphere NAO relationships during periods of different mean-climate (Chapter 5).

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# Chapter 2

# Record of Little Ice Age Sea Surface Temperatures at Bermuda Using a Growth-Dependent Calibration of Coral Sr/Ca



Goodkin, N. F., K. A. Hughen, A. L. Cohen, and S. R. Smith (2005), Record of Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca, *Paleoceanography*, 20, PA4016, doi:10.1029/2005PA001140.

## Abstract

Strontium to calcium ratios (Sr/Ca) are reported for a massive brain coral *Diploria labyrinthiformis* collected from the south shore of Bermuda and are strongly correlated with both sea surface temperature (SST) and mean annual skeletal growth rate. High Sr/Ca ratios correspond with cold SSTs and slow skeletal growth rate and vice versa. We provide a quantitative calibration of Sr/Ca to extension rate and SST along the axis of maximum growth and derive a growth-dependent Sr/Ca–SST calibration equation to reconstruct western subtropical North Atlantic SSTs for the past 223 years. When the influence of growth rate is excluded from the calibration, Sr/Ca ratios yield SSTs that are too cold during cool anomalies and too warm during warm anomalies. Toward the end of the Little Ice Age (~1850), SST changes derived using a calibration that is not growth-dependent are exaggerated by a factor of 2 relative to those from the growth-corrected model that yields SSTs ~1.5°C cooler than today. Our results indicate that incorporation of growth rate effects into coral Sr/Ca calibrations may improve the accuracy of SSTs derived from living and fossil corals.

## 2.1 Introduction

Accurate estimates of past SSTs, not captured in short instrumental records, are key to understanding long-term variability in Earth's climate system. One method of SST reconstruction is based on the inverse correlation between the Sr/Ca content of reef coral skeleton and ocean temperature [*Smith et al.*, 1979]. With this technique, Sr/Ca–SST calibrations derived from living corals are applied to ancient specimens to reconstruct SST [*Beck et al.*, 1992; *Correge et al.*, 2004; *Guilderson et al.*, 1994; *McCulloch et al.*, 1999]. With high accretion rates, longevity, and skeletal annual growth bands, corals can potentially provide seasonally resolved, precisely dated records of SST spanning several centuries. Despite this potential, Sr/Ca–derived SSTs from ancient corals are often several degrees cooler than those derived from other marine proxies [*Lea et al.*, 2000; *Pelejero et al.*, 1999; *Rosenthal et al.*, 2003] and their accuracy has been questioned [*Crowley*, 2000].

There are several indications that growth or calcification rate may influence the Sr/Ca ratio of coral skeleton. Across coral taxa, faster growing species have lower Sr/Ca ratios than slow growing species [*Correge et al.*, 2004; *Weber*, 1973]. Within a single species, fast growing colonies often have lower Sr/Ca ratios than slow growing colonies or slower growing parts within a colony [*Alibert and McCulloch*, 1997; *Cohen and Hart*, 2004; *deVilliers et al.*, 1995]. Corals whose calcification rates are enhanced by symbiont photosynthesis have lower Sr/Ca ratios than conspecifics without symbionts [*Cohen et al.*, 2002]. Culture studies demonstrate that differences in ion transport rates during calcification lead to reduced Sr uptake relative to Ca during periods of rapid calcification and vice versa [*Cohen and McConnaughey*, 2003; *Ferrier-Pages et al.*, 2002; *Ip and*

*Krishnaveni*, 1991]. Hypotheses regarding the mechanisms by which growth may influence coral Sr/Ca ratios include sampling artifacts linked to slow growth, convoluted skeletal architecture [*Cohen et al.*, 2004; *Swart et al.*, 2002], and kinetic effects [*deVilliers et al.*, 1994]. To date, effects related to calcification or growth rates have been examined between colonies of the same species [*deVilliers et al.*, 1995], between fast and slow growing axes of the same colony [*deVilliers et al.*, 1994] and between different times in the life of a coral polyp [*Alibert and McCulloch*, 1997].

Here we present data that demonstrate the impact of variability in skeletal extension rates on the accuracy of Sr/Ca–based SST reconstructed along a single, fast growing axis of a massive brain coral, *Diploria labyrinthiformis*. Growth rate changes of up to factors of 2–3 are associated with anomalously warm and cool Sr/Ca–derived SSTs, compared to recorded temperatures. A Sr/Ca–SST calibration that takes growth rate into account shows improved agreement with instrumental SST, and an application of the growth-corrected model yields late Little Ice Age (LIA), ~1850 AD, SSTs 1.5°C cooler than they are today. In contrast, SSTs derived from Sr/Ca while excluding growth rate effects were up to 3.0°C cooler than today.

## 2.2 Methods

### 2.2.1 Study Site

In May 2000, an ~230-year-old massive brain coral colony was sampled live off John Smith's Bay (JSB) on the southeastern edge of the Bermuda platform at 16-m depth. On Bermuda, growth rates of *Diploria labyrinthiformis* range from 2 to 6 mm/yr [*Cohen et al.*, 2004; *Dodge and Thomson*, 1974; *Logan and Tomascik*, 1991; *Logan et al.*, 1994], compared to 8 mm/yr and up to 20 mm/yr in more widely used species such as *Porites* [*Alibert and McCulloch*, 1997; *Hughen et al.*, 1999; *Mitsuguchi et al.*, 1996; *Shen et al.*, 1996]. *Diploria* spp. inhabit a wide range of water temperatures and are found in both the tropical and subtropical Atlantic. While *Diploria* spp. have not often been widely used for paleoclimate reconstruction [*Cardinal et al.*, 2001; *Cohen et al.*, 2004; *Kuhnert et al.*, 2002] the long life spans and large geographic distribution indicate its promise as a tool for long paleoclimate records.

The south terrace of Bermuda was chosen because of its exposure to open ocean waters and proximity to Hydrostation S located 30 km to the southeast. SST from 0- to 16-m depth has been recorded at Hydrostation S biweekly since 1954. Over that time, monthly averaged SST ranged from 18.0° to 28.9°C with annual averages between 22.4° and 24.3°C. For the calibration period of this study (1976–1997), mean annual SST ranged from 22.8° to 23.5°C with a seasonal range of 18.3° to 28.9°C. The SST record is incomplete over different intervals including 2 or more months of missing data in the years 1978–1980, 1986 and 1989.

### 2.2.2 Sub-sampling and Analysis of Coral

Three 5- to 10-mm-thick slabs were cut from the maximum growth axis of the coral using a diamond blade rock saw (Figure 2.1). The slabs were cleaned in an ultrasonic bath with deionized $H_2O$ 3 times for 10 min and dried in an oven at 50°C. X-radiographs were performed at Falmouth (Massachusetts) Hospital with machine settings of 50 kV and 1.6 mAs, a film focus distance of 1 m and an exposure time of 0.2 s.

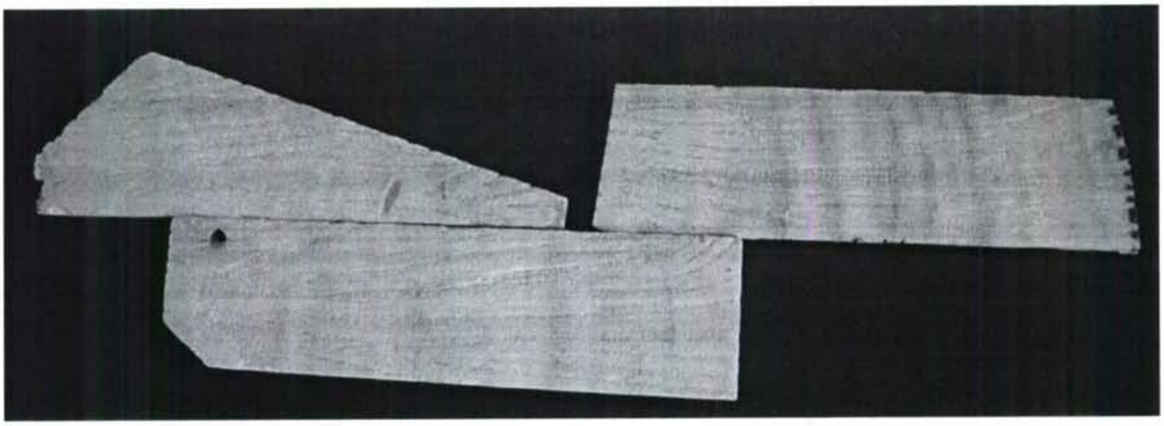

**Figure 2.1.** Three 5- to 10-mm-thick slabs were sliced from the ~1-m-long coral to capture the major growth axis through time. Slabs were cut in an overlapping fashion to ensure proper age model development and consecutive sampling of the entire record.

All samples were drilled from the solid thecal wall (the septotheca) that separates the calyx from the ambulacrum [*Cohen et al.*, 2004]. We targeted the theca to ensure that ample material could be extracted for analysis and to diminish the potential for diagenetic alteration or secondary aragonite precipitation due to the isolation of the center of the wall from skeletal pore spaces filled with seawater. In situ staining studies suggest that extension rates on the theca are higher in the summer (June through September) than they are in the winter [*Cohen et al.*, 2004].

Annual extension rates, calculated from the distance between successive high-density bands in the X-radiograph, indicate an average growth rate of 3.8 mm/yr. From 1976 to 1997, the thecal wall was sampled at 0.33 mm (approximately monthly resolution) with a drill press and micrometer-controlled stage. Approximately 200 mg of powder was collected for each Sr/Ca analysis. The years 1775–1997 were sampled biennially, using a diamond blade band saw. To generate the biennial record, samples were cut between every second high- low-density band interface, and two thecal walls and the ambùlacrum were isolated by grinding away the calyx with a hand-held Dremel tool. Thecal samples (~0.9 g) representing the full 2 years growth were cleaned in an ultrasonic bath with deionized $H_2O$ 3 times for 10 min, and dissolved in 1N $HNO_3^-$ for analysis.

Sr and Ca were measured using Inductively Coupled Plasma–Atomic Emission Spectrometry (ICP-AES) applying solution standards to correct for drift and matrix effects related to interference from varying Ca concentrations [*Schrag*, 1999]. The samples, blanks, and external standard (a homogenized, powdered *Porites* coral) were prepared simultaneously. Repeat measurements on the coral external standard over 12 months showed reproducibility (n = 96, standard deviation = 0.02 mmol/mol).

The age model was constructed from density banding visible in the X-radiographs and refined by tuning Sr/Ca to monthly averaged SSTs at inflection points. While this lessens the independence of the Sr/Ca–SST relationship, maximum and minimum values rather than median values at the inflection points drive the correlation of Sr/Ca to SST. The Sr/Ca data were resampled by linear interpolation at even monthly intervals equivalent to SST data.

Reported annual growth (extension) rates for the high-resolution record (approximately monthly sampling) were calculated from the distance between two successive Januarys in each annual cycle as defined by the Sr/Ca–derived age model. Growth rates for the biennial record were determined using X-radiographs (Figure 2.2) as follows; the distance between every other high- low-density band interface was measured and divided in two to calculate the average growth per year over the 2 years sampled.

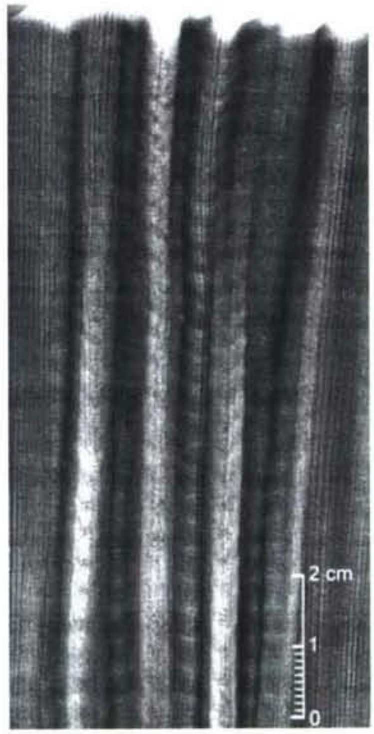


**Figure 2.2**. X-radiograph positive image of the first 97 mm of the top slab. X rays show clear annual banding made up of one low-density and one high-density band.

## 2.3 Results

### 2.3.1 Reproducibility of the Sr/Ca Record Within the Colony

As this *Diploria* colony grew, the position of the maximum growth axis changed relative to the center of the dome (Figure 2.1). Therefore it was difficult for the entire length of the coral to be sampled along one planar growth transect, mandating that sampling transects change between the theca from along the slabs. Parallel transects were drilled for the periods 1979–1986 and 1989–1992. A strong relationship exists between the multiple tracts ($r^2 = 0.83$, $p = 0$, slope = 1.04, intercept = -0.000705), demonstrating the reproducibility of the Sr/Ca signal between parallel sample transects.

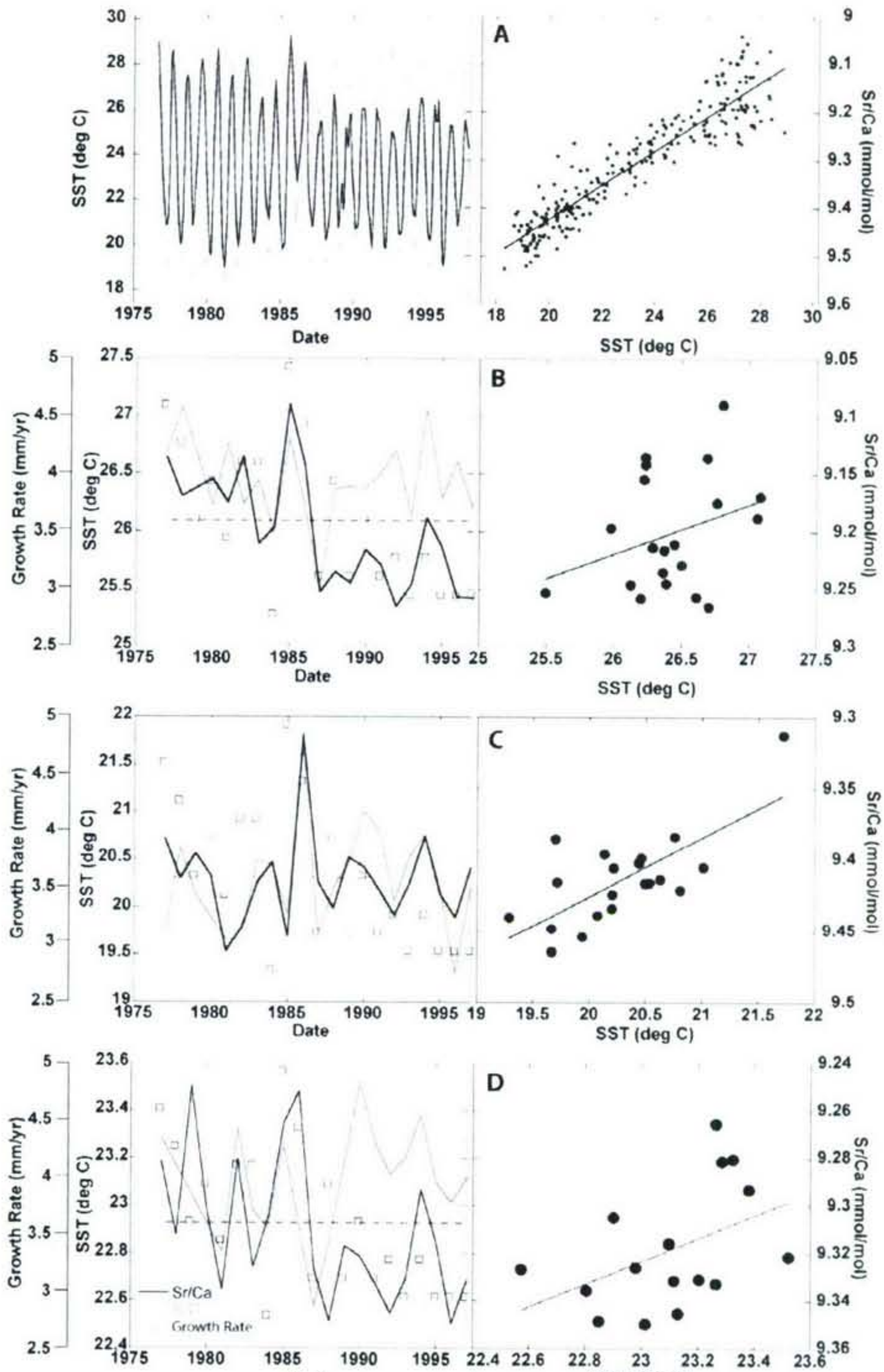


**Figure 2.3**. Coral Sr/Ca (solid line) and Hydrostation S sea surface temperature (SST) (shaded line) plotted versus year and correlated using linear regression. Calibration results for (a) monthly ($r^2$ = 0.86, p << 0.0001), (b) summer (June, July, August, September (JJAS)) ($r^2$ = 0.10, p = 0.17), (c) winter (December, January, February, March (DJFM)) ($r^2$ = 0.51, p = 0.0004), and (d) mean annual ($r^2$ = 0.21, p = 0.077) resolved data. Mean annual coral growth rates (squares) and average growth (dashed line) are shown for the calibration period. Size of circles represents 2σ analytical error.

### 2.3.2 Monthly Resolution Calibration

A linear regression of monthly resolved Sr/Ca ratios to SST yields the following correlation (Figure 2.3a):

$$Sr/Ca = 10.1\ (\pm 0.04) - 0.0358\ (\pm 0.0018) * SST$$

$$(2\sigma,\ 95\%\ \text{conf.},\ r^2=0.86,\ p<<0.0001,\ \text{stdr}=1.2\ °C) \quad (1)$$

where stdr is the standard deviation of the residual. These results are consistent with previous studies of slow to moderately slow growing corals, including a colony of *Diploria* from Bermuda [*Cardinal et al.*, 2001], *Montastraea* from Florida [*Swart et al.*, 2002], and *Diploastrea* from Fiji [*Bagnato et al.*, 2004]. On the basis of results from *Cohen et al.* [2004] using microbeam measurements, our sampling resolution may dampen the full range of Sr/Ca variability over the annual cycle. Owing to this smoothing, the monthly calibration cannot be used to reconstruct interannual variability as the dampened slope would return overestimated changes in SST. For this reason, calibrations using interannual variability were derived.

### 2.3.3 Inter-annual Calibrations

To derive the Sr/Ca–SST calibrations based on interannual variability, 4-month summer (JJAS), 4-month winter (DJFM), and mean annual averages were calculated. Examination of the monthly Sr/Ca calibration (Figure 2.3a) indicates that summertime Sr/Ca reflects SST from 1977 to 1986 differently than from 1987 to 1997, while the wintertime signal continues to capture interannual SST variability. This can be seen clearly when the data are averaged for summer (Figure 2.3b) and winter (Figure 2.3c) periods. Coincident with the change in the summer time Sr/Ca–SST relationship is a decrease in the mean annual extension rate from above average to below average for the calibration period (Figures 2.3b, 2.3c, and 2.3d). Average annual SSTs derived from coral Sr/Ca are essentially a combination of the summer and winter signals and also diverge from instrumental data at the same time as the decrease in mean annual extension rate (Figure 2.3d). Average summer Sr/Ca shows no relationship to SST when correlated over the entire 1977–1997 calibration interval ($r^2 = 0.10$, $p = 0.17$) (Figure 2.3b), and the mean annual record shows a poor correlation ($r^2 = 0.21$, $p = 0.077$) (Figure 2.3d). Average winter Sr/Ca does not show any discrepancy affiliated with growth rate (Figure 2.3c), and a winter linear least squares regression to SST shows a significant relationship:

$$Sr/Ca = 10.3\ (\pm 0.4) - 0.0412\ (\pm 0.0191) * SST$$

$$(2\sigma,\ 95\%\ \text{conf.},\ r^2=0.51,\ p=0.0004,\ \text{stdr}=0.54\ °C) \quad (2)$$

The winter correlation $r^2$ value is diminished in comparison with the monthly calibration, because of the lower signal-to noise ratio (winter SST range = 19°–22°C, annual SST range = 18°–29°C).

Examination of the relationship between Sr/Ca and growth reveals that summer Sr/Ca correlates more strongly to annual skeletal extension rate ($r^2 = 0.64$, $p < 0.0001$) (Figure 2.4a) than to SST ($r^2 = 0.10$, $p = 0.17$). Mean annual Sr/Ca correlates relatively equally to growth rate ($r^2 = 0.36$, $p = 0.014$) and SST ($r^2 = 0.21$, $p = 0.077$), whereas winter Sr/Ca shows no relationship to growth rate ($r^2 = 0.01$, $p = 0.61$) (Figure 2.4a) and a strong relationship to SST ($r^2 = 0.51$, $p = 0.0004$). The impact of growth rate on summer, winter, and mean annual Sr/Ca–SST calibrations is further investigated by correlating growth rate with SST residuals (calculated by subtracting instrumental SST from reconstructed monthly SST). Summer SST residuals are strongly correlated with growth rate ($r^2 = 0.59$, $p < 0.0001$), but no significant relationship is observed between growth rate and winter SST residuals ($r^2 = 0.06$, $p = 0.31$) (Figure 2.4b). Mean annual SST residuals show a correlation with growth rate ($r^2 = 0.37$, $p = 0.013$) that is better than the winter residual Sr/Ca regression but not as good as the summer residual Sr/Ca regression (Figure 2.4b). Thus averaging over the annual cycle does not eliminate the impact of growth rate on Sr/Ca signals, implying that a growth-corrected model must be employed to examine interannual variability.

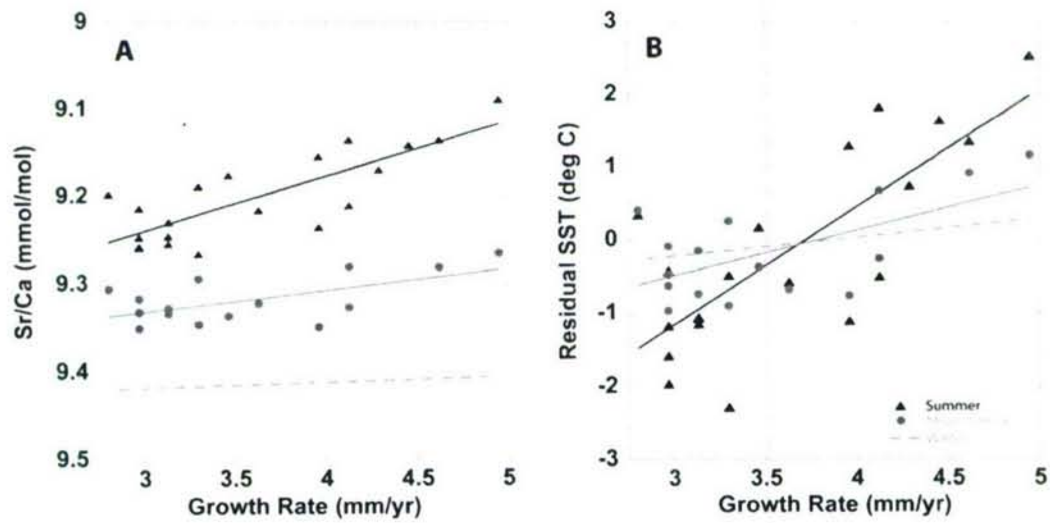


**Figure 2.4**. Mean annual growth rate compared to Sr/Ca and Sr/Ca–based SST residuals. (a) Sr/Ca to growth rate correlations for summer (JJAS) (triangles) ($r^2 = 0.64$, $p < 0.0001$), mean annual (circles) ($r^2 = 0.36$, $p = 0.014$), and winter (DJFM) (squares) ($r^2 = 0.01$, $p = 0.61$) resolved data. (b) Residual SST to growth rate correlations for summer ($r^2 = 0.59$, $p < 0.0001$), mean annual ($r^2 = 0.36$, $p = 0.013$), and winter ($r^2 = 0.06$, $p = 0.31$) resolved data. Residuals are calculated by converting monthly Sr/Ca to SST and then subtracting from instrumental SST.

In the mean annual Sr/Ca regression, mean annual Sr/Ca was linearly regressed on mean annual SST by the preceding equation (Figure 2.3d):

$$Sr/Ca = m * SST + b \quad (3)$$

This regression produced the following result:

$$Sr/Ca = 10.4\ (\pm 1.2) - 0.0481\ (\pm 0.0503) * SST$$

$$(2\sigma,\ 95\%\ conf.,\ r^2=0.21,\ p=0.0766,\ stdr=0.46\ °C) \quad (4)$$

In the growth-corrected mean annual model, the slope (m) of the mean annual Sr/Ca–SST relationship (equation (3)) is hypothesized to change as a linear function of growth rate where

$$m = n * (growth\ rate) + c \qquad (5)$$

and growth rate is the 3-year averaged linear extension rate. The net regressed equation is

$$Sr/Ca = c*(SST) + n*(growth\ rate)*(SST) + b \qquad (6)$$

For the purposes of the growth-corrected model, growth rates were averaged over 3-year periods, providing a more conservative estimate of the continuous calcification rates that occurred as the aragonite was formed by both extension and infilling for the time represented by sampling methods. The linear least squares multiple regression returns the following equation:

$$Sr/Ca = -0.0529\ (\pm 0.0334) * (SST) - 0.00170\ (\pm 0.00078) * (growth\ rate) * (SST) + 10.7\ (\pm 0.8)$$

$$(2\sigma,\ 95\%\ conf.,\ r^2=0.68,\ p_c=0.0074,\ p_n=0.00078,\ stdr=0.24\ °C) \quad (7)$$

where $p_c$ is the significance on slope c from equation (6) and $p_n$ is the significance on slope n from equation (6). The inclusion of this additional relationship into the growth-corrected model leads to a significant improvement in fit ($r^2$ = 0.68, $p_c$ = 0.0074, $p_n$ = 0.00078) compared to the mean annual Sr/Ca–SST regression ($r^2$ = 0.21, p = 0.077). While the variance of the two fits are not comparable because of the change in the number of variables, mean annual Sr/Ca values over the calibration period were converted to SST using the mean annual Sr/Ca–SST regression and the growth-corrected model to demonstrate the improved accuracy in reconstructing SST. SSTs reconstructed with the growth-corrected model agree more closely with instrumental data ($r^2 = 0.49$, $p = 0.0026$) than those with the mean annual Sr/Ca–SST regression ($r^2 = 0.21$, $p = 0.077$) (Figure 2.5). This improvement is exemplified by a decrease in the variance of the residual where the standard deviation equals 0.46°C in the Sr/Ca–SST regression compared to 0.24°C in the growth-corrected model (Figure 2.5).

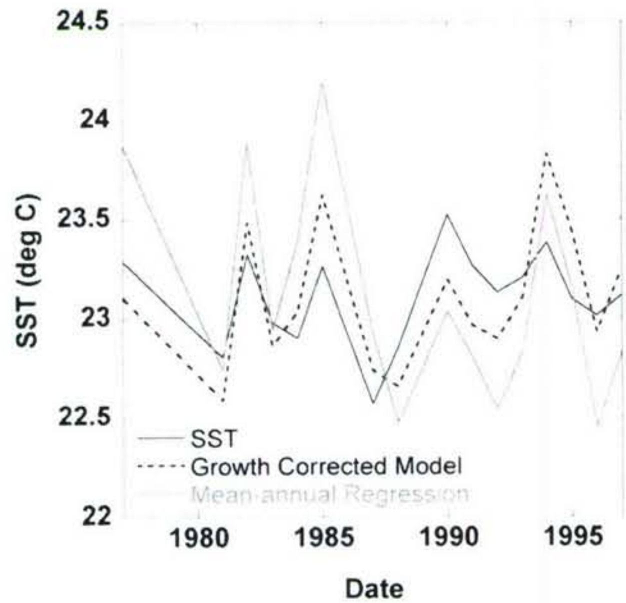


**Figure 2.5**. Mean annual instrumental SST from Hydrostation S (solid line) compared to reconstructed mean annual SST using the mean annual Sr/Ca–SST regression (shaded line) and growth-corrected model (dashed line). The growth-corrected model has a stronger fit to the instrumental records ($r^2 = 0.49$, $p = 0.0026$ compared to $r^2 = 0.21$, $p = 0.077$ for the non-growth dependent mean annual Sr/Ca–SST regression).

### 2.3.4 Application of Calibration Regression

In order to examine the potential effects of the different calibrations on paleotemperature reconstructions, the monthly, mean annual Sr/Ca–SST regression and growth-corrected mean annual model were used to quantify SST from the 223-year biennially sampled Sr/Ca record. Reconstructed SST shows distinct cooling during the

LIA, with an abrupt temperature drop in the 1840s and a gradual warming culminating in the 1960s. However, the amplitude of these changes varies significantly depending on which calibration is applied.

The reconstruction based on the monthly calibration shows that biennial SST changed nearly 5°C from 1960 to the end of the LIA in the late 1840s, 2.5 times the change found using the growth-corrected mean annual model (Figure 2.6). The use of a monthly resolved calibration which does not capture the full amplitude of the seasonal cycle clearly influences the magnitude of interannual SST change calculated back through time. The biennial record does not necessarily capture the exact same months in each sample through time which may lead to some seasonal biases. However, this effect is diminished by looking at 2-year periods and is likely not large enough to account for the changes in temperature seen in this record.

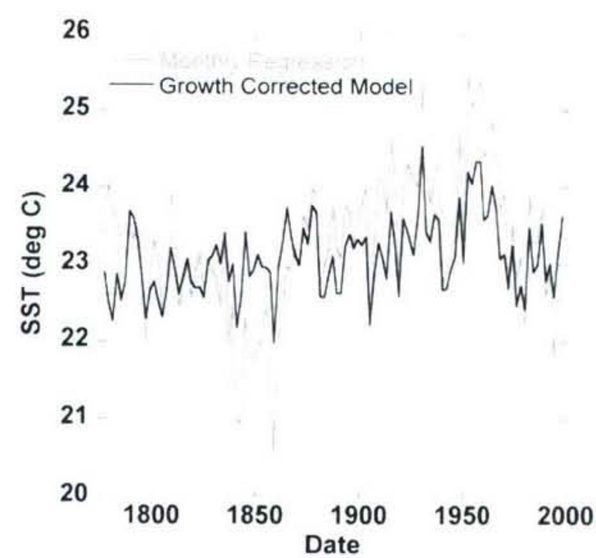


**Figure 2.6**. Biennial-resolution SST reconstructed to 1780. SST was reconstructed using the growth-corrected mean annual model (solid line) and the monthly regression (shaded line). By exaggerating both maximums and minimums, the monthly regression shows an SST change 2.5 times greater than the growth-corrected mean annual model reconstruction.

The mean annual extension rate of the coral is shown to covary with the Sr/Ca record over the length of the biennial record, supporting the initial observation that both growth and SST may influence the Sr/Ca record (Figure 2.7). The highest mean annual Sr/Ca values seen in the mid-to-late 1800s are also the periods of slowest growth. Use of the mean annual Sr/Ca–SST regression yields an SST change of 3.5°C from the 1960s to the 1840s, whereas the growth-corrected model shows a change of only 2°C over this same period (Figure 2.8).

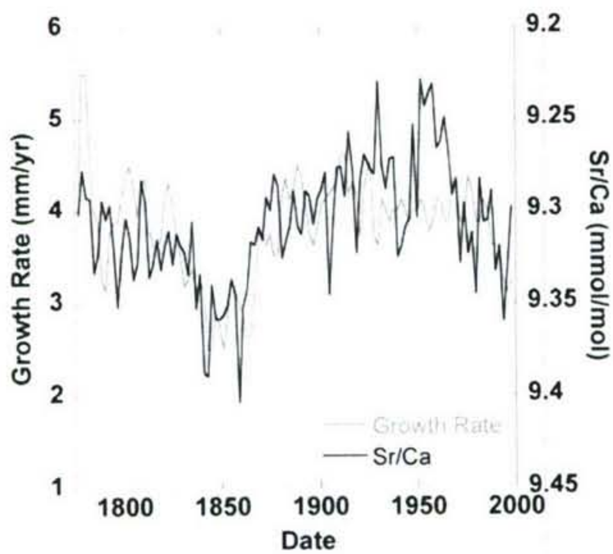


**Figure 2.7**. Biennially averaged mean annual extension (growth) rate (shaded line) and Sr/Ca (solid line) from 1780 to 1997. Extension rate and Sr/Ca have the same large-scale variability patterns over the entire 200-year period ($r^2 = 0.32$, $p << 0.0001$).

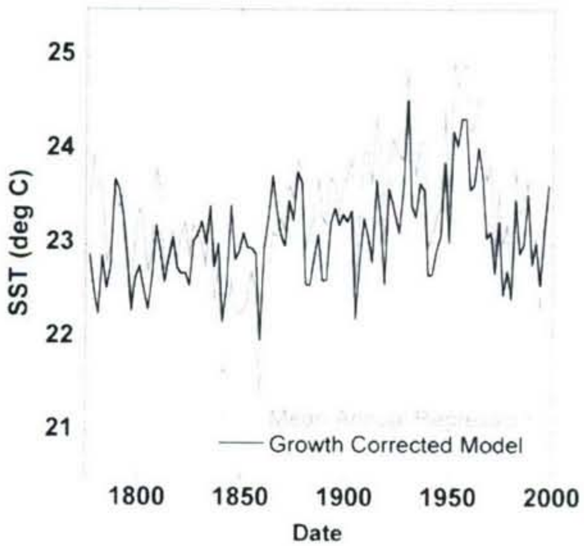


**Figure 2.8**. Biennial-resolution SST reconstructed to 1780. SST reconstructed using the growth-corrected model (solid line), as shown in Figure 4, compared to SST, reconstructed using the mean annual Sr/Ca–SST regression (shaded line). The mean annual Sr/Ca–SST regression exaggerates SST changes from maximum to minimum by a factor of 2.

### 2.3.5 Temperature Trends at Bermuda

The biennially growth-corrected reconstruction agrees with both Hydrostation S and other long coral records from this site. Hydrostation S shows a nearly 2°C cooling from the late 1950s to the late 1960s, simultaneous with the cooling in this record. In coral growth rate records from Bermuda [*Patzold and Wefer*, 1992], growth rate is correlated to SST and shows a >2°C temperature change from approximately the late 1800s to the 1950s consistent with the growth-corrected biennial Sr/Ca record over the same period. A coral $\delta^{18}O$ record from Bermuda shows a similar trend, with an abrupt cooling around 1840 followed by a slow warming coming out of the end of the Little Ice Age [*Draschba et al.*, 2000].

LIA temperature changes at Bermuda have also been investigated using $\delta^{18}O$ of foraminifera [*Keigwin*, 1996] and the alkenone unsaturation index, $U^{k'}_{37}$ [*Ohkouchi et al.*, 2002; *Sachs and Lehman*, 1999]. Unfortunately, foraminiferal $\delta^{18}O$ is influenced both by temperature and the $\delta^{18}O$ of water, which is a function of salinity. *Keigwin* [1996] addressed this problem by assuming that the modern salinity and temperature relationship remained constant back in time, and reconstructed an SST change in the Sargasso Sea back to the middle of the LIA of 1°–2°C. The unsaturation index of alkenones provides an SST proxy that is unaffected by water chemistry [*Sikes and Sicre*, 2002] and has been used to reconstruct abrupt shifts in SST at this location [*Sachs and Lehman*, 1999]. However, $U^{k'}_{37}$ reconstructions of LIA SSTs are much larger (4°–6°C) than suggested by foraminiferal $\delta^{18}O$, and compound specific $^{14}C$ dating of these alkenones shows they are susceptible to resuspension and long distance transport [*Ohkouchi et al.*, 2002], rendering $U^{k'}_{37}$ LIA reconstructions at this location suspect. Our growth-corrected calibration also provides an SST reconstruction not influenced by salinity, yielding late LIA cooling of 1.5°C. Overall, our data show that application of a Sr/Ca–SST calibration that takes growth rate variations into account yields coral-based SSTs in good agreement with the instrumental record (Figure 2.5) and with foraminiferal $\delta^{18}O$ SST estimates [*Keigwin*, 1996].

## 2.4 Discussion

While our data support previous observations of growth-related impacts on coral Sr/Ca, the underlying mechanism, a sampling artifact [*Swart et al.*, 2002], a growth regime [*Cohen et al.*, 2004], or a kinetic effect [*deVilliers et al.*, 1994], is not clear. Microscale analyses of *Diploria labyrinthiformis* reveal that the amplitude of the annual Sr/Ca cycle is greater than that derived by these sampling techniques [*Cohen et al.*, 2004]. Bulk sampling of insufficient resolution smoothes the record as previously suggested [*Swart et al.*, 2002], even though in this study relative winter variability is accurately captured. Examination of the high- and low-density bands in the coral X-rays and duration of summer and winter in the Sr/Ca seasonal cycle shows that winter skeletal extension is consistent from year to year, compared to more variable summer extension. This could lead to a consistent attenuation of the record during sampling of winter skeleton but variable attenuation of summer skeleton, creating the observed growth impact on the summer record but not the winter. *Swart et al.* [2002] show similar results in a 2-year calibration study in which one summer peak has an average growth rate (during the peak) of >8 mm/yr and Sr/Ca values that match the SST maximum, but the second and third summers with lower summer growth rates (<7 mm/yr and <6 mm/yr during the peak) have Sr/Ca values that do not reflect the same magnitude summertime SST. These data clearly support an influence of growth rate on the summer Sr/Ca–SST relationship. Similarly, in studies by *deVilliers et al.* [1994] and *Alibert and McCulloch* [1997], Sr/Ca values associated with relatively slow growth and calcification rates are elevated relative to those from high growth rate and calcification rate intervals. However, in both studies, the records with slower growth or calcification rates appear offset rather than dampened, inconsistent with bulk-sample smoothing as the sole mechanism.

Another hypothesis for the impact of growth on coral Sr/Ca is that different growth mechanisms employed by this coral in the summer and winter may influence the Sr/Ca signal. *Cohen et al.* [2004] proposed that skeleton accreted during the summer is overlain by skeleton accreted during the following winter, dampening the summer peak in reconstructed SSTs. Thus the extent of dampening may differ from year to year depending on whether summer extension is slow or fast and the ratio of summer to winter skeleton is shifted.

Coral culture studies indicate that uptake of Sr relative to Ca might increase at low calcification rates, increasing the Sr/Ca ratio of the skeleton [*Ferrier-Pages et al.*, 2002; *Ip and Krishnaveni*, 1991] which implies the existence of a kinetic effect. Potential evidence supporting a combined growth regime and kinetic effect is seen in the need to average extension rates over 3 years to fully capture the growth effect in our study. Because in-filling may occur within the skeleton for several years, aragonite laid down in the same location will reflect different calcification rates. By averaging the extension rates (effectively a measure of calcification through time) over 3 years, a better estimate of the average calcification rate over the period of skeletal accretion is achieved and allows for the development of the growth-corrected model. Further study of Sr/Ca measurements in conjunction with specific calcification rates could further elucidate the viability of this hypothesis. Independent of the mechanism by which coral growth rate affects Sr/Ca, our data show that changes in growth rate along the axis of maximum growth may cause large excursions in Sr/Ca that do not accurately reflect the SSTs experienced by the coral.

## 2.5 Conclusions

The use of a monthly resolved Sr/Ca–SST calibration to reconstruct biennial temperature records appears to cause exaggeration of decadal SST variability over the end of the LIA by a factor of 2.5. This demonstrates the importance of using calibrations that are appropriate to the desired resolution of temperature reconstructions to prevent such amplification of signals, especially if the full seasonal range of Sr/Ca variability is not captured by bulk sampling techniques. However, the mean annual Sr/Ca–SST regression also exaggerates SST variability by as much as a factor of 2, demonstrating that growth rate variability can also amplify variations in the Sr/Ca reconstructions of temperature. While growth effects are more often referenced for slower growing species such as *Diploria*, the more commonly studied genera *Porites* show that interannual growth rates between colonies and within single sampling transects, can vary by factors of 2–2.8 [*Alibert and McCulloch*, 1997; *Hughen et al*., 1999; *Mitsuguchi et al*., 1996; *Shen et al*., 1996], comparable to the range observed here. It is possible that the influence of growth rate effects on Sr/Ca–SST calibrations could explain previous coral-based SST reconstructions back in time showing larger SST changes [*Beck et al*., 1997; *Correge et al*., 2004; *Guilderson et al*., 1994; *McCulloch et al*., 1996] than seen with other proxies [*Lea et al*., 2000; *Pelejero et al*., 1999; *Rosenthal et al*., 2003; *Rühlemann et al*., 1999]. The quantitative incorporation of growth rate information into coral Sr/Ca reconstructions could improve the thermometer and result in more accurate estimates of past SST changes and should therefore be considered when undertaking site and species specific calibrations where growth rate data are available.

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# Chapter 3

# A multi-coral calibration method to approximate a universal equation relating Sr/Ca and growth rate to sea surface temperature

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## Abstract

Combining strontium-to-calcium ratios (Sr/Ca) with mean annual growth rates in Bermuda *Diploria labyrinthiformis* (brain corals) is shown to improve sea surface temperature (SST) calibrations relative to instrumental data. Growth-corrected Sr/Ca–SST calibrations based on single-coral colonies over the same calibration interval, however, are found to be poorly suited for application to data from different coral colonies. This raises concerns about the accuracy of SST reconstructions from fossil coral measurements that involve extrapolation beyond the range of values seen during the calibration period. Here we pursue a novel approach to this problem by incorporating data from multiple coral colonies into a single growth-corrected Sr/Ca–SST calibration equation, effectively expanding the range of modern values constraining the model. The use of a multiple-colony calibration model for reconstructing SST yields greater precision and accuracy relative to instrumental data than single-colony models, providing greater confidence for applications to fossil coral samples.

## 3.1. Introduction

Understanding long-term climate variability requires the reconstruction of key climate parameters, such as sea surface temperature (SST), in records extending beyond the relatively short instrumental period. The high accretion rates, longevity, and annual growth bands found in coral colonies make this an ideal resource for well-dated, seasonal resolution climate reconstructions. One method used for quantifying past temperature changes from corals involves the inverse relationship between SST and the strontium (Sr) to calcium (Ca) ratio in coral skeleton [*Smith et al.*, 1979]. Typically, this method relies on obtaining a linear regression of Sr/Ca on SST from a modern coral colony and then applying this calibration to Sr/Ca measurements from fossil samples [*Beck et al.*, 1992; *Beck et al.*, 1997; *Correge et al.*, 2004; *McCulloch et al.*, 1999]. However, in many cases reconstructions of past SST from coral Sr/Ca ratios are several degrees cooler than other marine proxies such as alkenones or foraminiferal Mg/Ca (e.g, [*Lea et al.*, 2000; *Pelejero et al.*, 1999; *Rosenthal et al.*, 2003]). Part of this discrepancy may be due to differences in seasonality, differences in the depth at which various proxies record SST, or influences from other environmental factors.

Nevertheless, it has been observed that correlations of coral Sr/Ca to SST vary between individual colonies, time periods, and species [*Alibert and McCulloch*, 1997; *deVilliers et al.*, 1995; *Marshall and McCulloch*, 2002; *Swart et al.*, 2002]. Differences between coral colony Sr/Ca-SST calibrations have been previously investigated, and proposed sources of error include: variations in Sr and Ca concentrations of seawater, particularly in areas of upwelling [*Alibert and McCulloch*, 1997; *deVilliers et al.*, 1994; *Marshall and McCulloch*, 2002; *Shen et al.*, 1996]; the veracity of the instrumental or calibration SST record [*Crowley et al.*, 1999; *Marshall and McCulloch*, 2002]; imprecise age models [*Swart et al.*, 2002]; biological and symbiotic effects [*Cohen et al.*, 2002; *deVilliers et al.*, 1995; *Ferrier-Pages et al.*, 2002]; and the length of the calibration period [*Goodkin et al.*, 2005]. In addition, several studies have indicated that growth rate and/or calcification rate may act as an additional influence on Sr/Ca ratios [*Alibert and McCulloch*, 1997; *Cohen and Hart*, 2004; *deVilliers et al.*, 1995; *Ferrier-Pages et al.*, 2002; *Goodkin et al.*, 2005; *Weber*, 1973]. In a recent study of corals with slow growth rates, the use of a multi-variant regression of Sr/Ca to SST and extension (growth) rate was shown to improve SST reconstructions over the instrumental calibration period [*Goodkin et al.*, 2005]. In addition, applying this regression to a record back to 1775 AD resulted in SST changes consistent with other marine proxies (e.g., [*Keigwin*, 1996]). These studies indicate that growth rate can be an important factor to consider when examining Sr/Ca in modern and fossil corals. However, the concern remains that measurements of past coral growth rates often fall well outside the range seen during the instrumental interval, and thus require extrapolation beyond the constraints of the observed modern calibration relationship. One way to minimize uncertainties due to extrapolating beyond the calibration range is to utilize data simultaneously from several coexisting corals with different growth rates. In addition to extending the range of modern values for comparison, using multiple colonies for calibration can also serve to average away uncertainties due to dating errors and individual metabolic effects. For example, averaging Sr/Ca measurements from multiple corals prior to calibration [*Stephans et al.*, 2004] or averaging coefficients from two or more single-colony calibrations [*Alibert and McCulloch*, 1997; *Smith et al.*, 1979]have previously been shown to reduce errors in reconstructed SSTs.

Here we present a unique approach to coral Sr/Ca-SST calibration, combining data from multiple corals into a single multivariate regression in an effort to derive a universal equation that can be applied with equal confidence to any modern or fossil coral from the same location. Combining multiple colonies into a single SST calibration expands the range of Sr/Ca and growth rate values applied to the calibration, minimizing extrapolation beyond modern coral values during reconstructions of past SST. We demonstrate that a calibration using multiple colonies results in increased accuracy and precision for Sr/Ca-based SST reconstructions. In this study, multivariate regressions of Sr/Ca to SST and growth rate ("single-colony" growth-corrected model) were performed on several colonies of massive *Diploria labyrinthiformis* from Bermuda, following the method of Goodkin et al. (2005). In addition, a similar multivariate regression was performed using measurements from multiple colonies simultaneously ("multi-colony" model) to provide a single calibration equation. The multi-colony and single-colony calibration models were applied to data from each individual colony, and reconstructed SST was compared to instrumental SST over the calibration interval to determine the method that provides the most accurate and precise reconstruction.

## 3.2. Methods

### 3.2.1 Study Site

In April 1999, three 30-50 year old brain corals (*Diploria labyrinthiformis)* (BER 002, BER 003, and BER 004) were sampled live off John Smith's Bay (JSB) on the southeastern edge of the Bermuda platform at 16-meters depth. A fourth, ~230 year old coral (BB 001) was sampled live from the same location in May of 2000. *Diploria labyrinthiformis* was chosen for this study because slow growth rates combined with multi-century life spans and large geographical distribution from tropical to sub-tropical waters makes this species a promising source of paleoceanographic information. Growth rates from brain corals in this region vary from 2-6 mm/yr [*Dodge and Thomson*, 1974; *Goodkin et al.*, 2005; *Logan and Tomascik*, 1991], much slower than more commonly used species such as *Porites,* which exhibits growth rates from 8-20 mm/yr [*Alibert and McCulloch*, 1997; *Hughen et al.*, 1999; *Shen et al.*, 1996].

The south terrace of Bermuda provides exposure to open ocean waters and proximity to instrumental data from Hydrostation S, located 30 km to the southeast. At Hydrostation S, SST from 0-16 m depth has been recorded bi-weekly since 1954. Over that time, monthly averaged SST ranged from 18.0 to 28.9 °C with annual averages between 22.4 and 24.3 °C. The calibration period of this study (1976-1997) has mean annual SST ranging from 22.8 to 23.5 °C with a seasonal range of 18.3 to 28.9 °C. The SST record is incomplete over different intervals including two or more months of missing data in the years 1978-1980, 1986, and 1989, and subsequently these years are omitted from the mean-annual calibrations.

### 3.2.2 Sub-sampling and Analysis of Coral

Corals were sliced into ~1 cm thick slabs along the growth axis using a diamond blade rock saw and cleaned in an ultrasonic bath [*Goodkin et al.*, 2005]. X-radiographs were performed at Falmouth Hospital (Falmouth, MA) with machine settings of 50kV

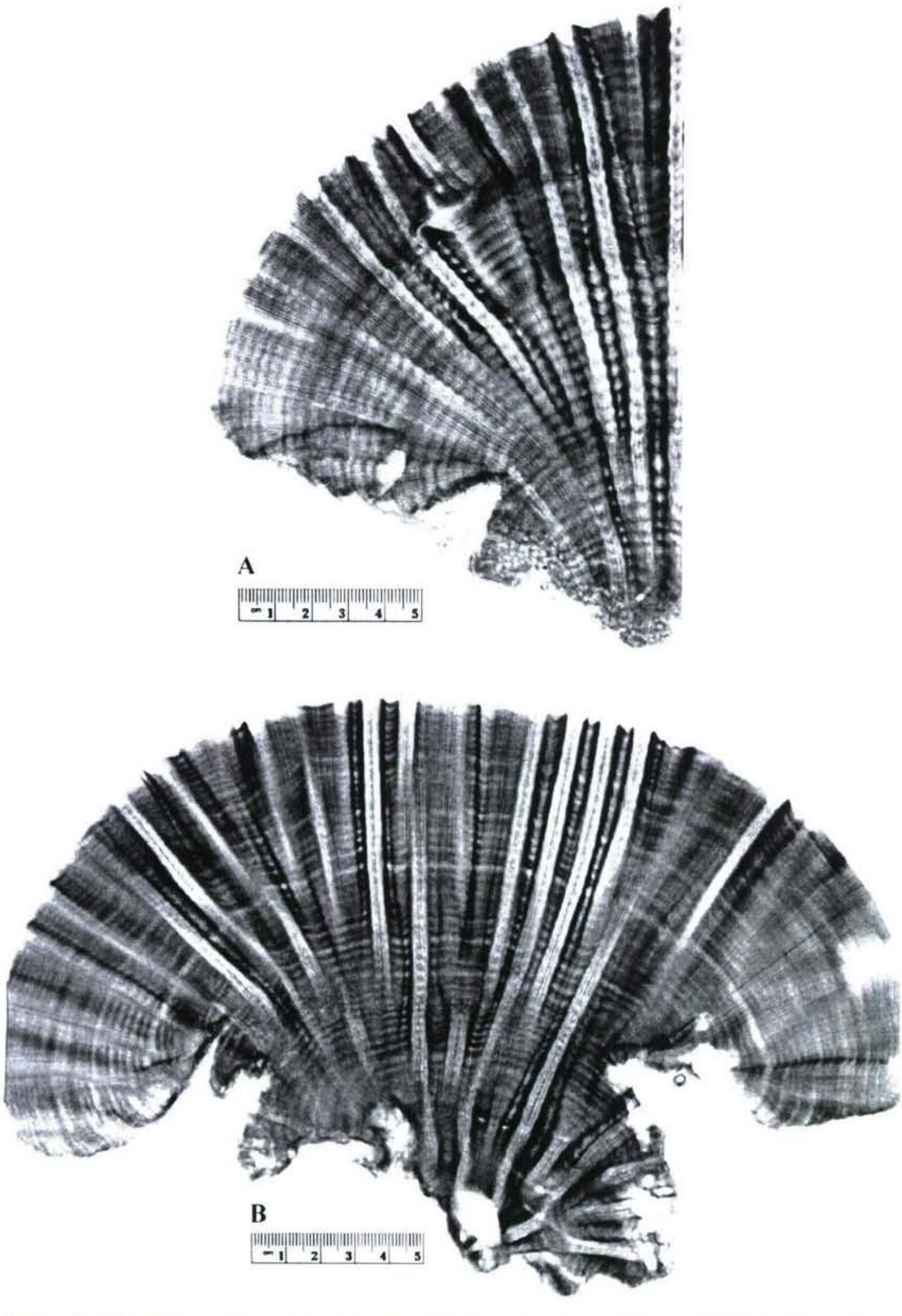


**Figure 3.1**. X-radiograph positive image of a) BER 003 and b) BER 004. X-rays show clear annual banding made up of a low and high density band.

and 1.6 mAs, a film focus distance of 1 m and exposure time of 0.2s. X-rays for BB 001 and BER 002 can be found in Goodkin et al. (2005) and Cohen et al. (2004), respectively. X-radiographs for BER 003 and BER 004 are shown in Fig. 3.1.

Samples for Sr/Ca analysis were drilled along the solid *thecal* wall separating the *ambulacrum* from the *calyx* following the methods of Goodkin et al. (2005). For the calibration period (1976-1997), BER 002, 003, and 004 were sampled every 0.25 mm and BB 001 was sampled every 0.33 mm, using a drill press and micrometer controlled stage.

An Inductively Coupled Plasma–Atomic Emission Spectrometer (ICP-AES) at the Woods Hole Oceanographic Institution (WHOI) was used to measure Sr and Ca simultaneously, applying solution standards to correct for drift and matrix effects related to interference from varying Ca concentrations following the methods of Schrag (1999). The unknowns, blanks and samples of external standard (a homogenized, powdered *Porites* coral) were prepared simultaneously. Repeat measurements on the coral external standard over 12 months showed good reproducibility (RSD = 0.3%, n=847).

Over the calibration interval, age models and annual extension rates for all corals were developed using density banding visible in the x-radiographs (Fig. 3.1), followed by assigning Sr/Ca to monthly averaged SSTs at maxima, minima and inflection points [*Goodkin et al.*, 2005]. Sr/Ca was then interpolated in order to re-sample at even monthly increments, and mean-annual Sr/Ca was calculated by averaging the interpolated monthly values. Average extension rates for each colony used in the multi-colony correlation exercises were calculated based on the entire length of the colony (Table 3.1).

**Table 3.1.** Average extension rates for the colony and the period of calibration.

| Coral | Average Extension Rate (mm/yr) | Time Period of Calibration |
|---|---|---|
| BB 001 | 3.8 | 1977-1997 |
| BER 002 | 3.2 | 1976-1996 |
| BER 003 | 4.2 | 1976-1997 |
| BER 004 | 2.1 | 1976-1997 |

## 3.3. Results

### 3.3.1 Seasonal Cycle

All four corals show strong seasonal cycles in Sr/Ca (Fig. 3.2). Type-I linear regressions of monthly-resolved Sr/Ca ratios to SSTs yield relatively consistent correlations among the four corals:

BB 001: Sr/Ca = 10.1 (±0.04) – 0.0358 (± 0.0018) * SST

(2$\sigma$, 95% conf., $r^2 = 0.86$, $F_{sig} << 0.0001$) [*Goodkin et al.*, 2005]

BER 002: Sr/Ca = 10.1 (±0.07) – 0.0376 (± 0.0030) * SST

(2$\sigma$, 95% conf., $r^2 = 0.73$, $F_{sig} << 0.0001$)

BER 003: Sr/Ca = 10.3 (±0.06) – 0.0436 (±0.0024) * SST

(2$\sigma$, 95% conf., $r^2 = 0.85$, $F_{sig} << 0.0001$)

BER 004: Sr/Ca = 10.3 (±0.07) – 0.0429 (±0.0029) * SST

(2$\sigma$, 95% conf., $r^2 = 0.76$, $F_{sig} << 0.0001$)

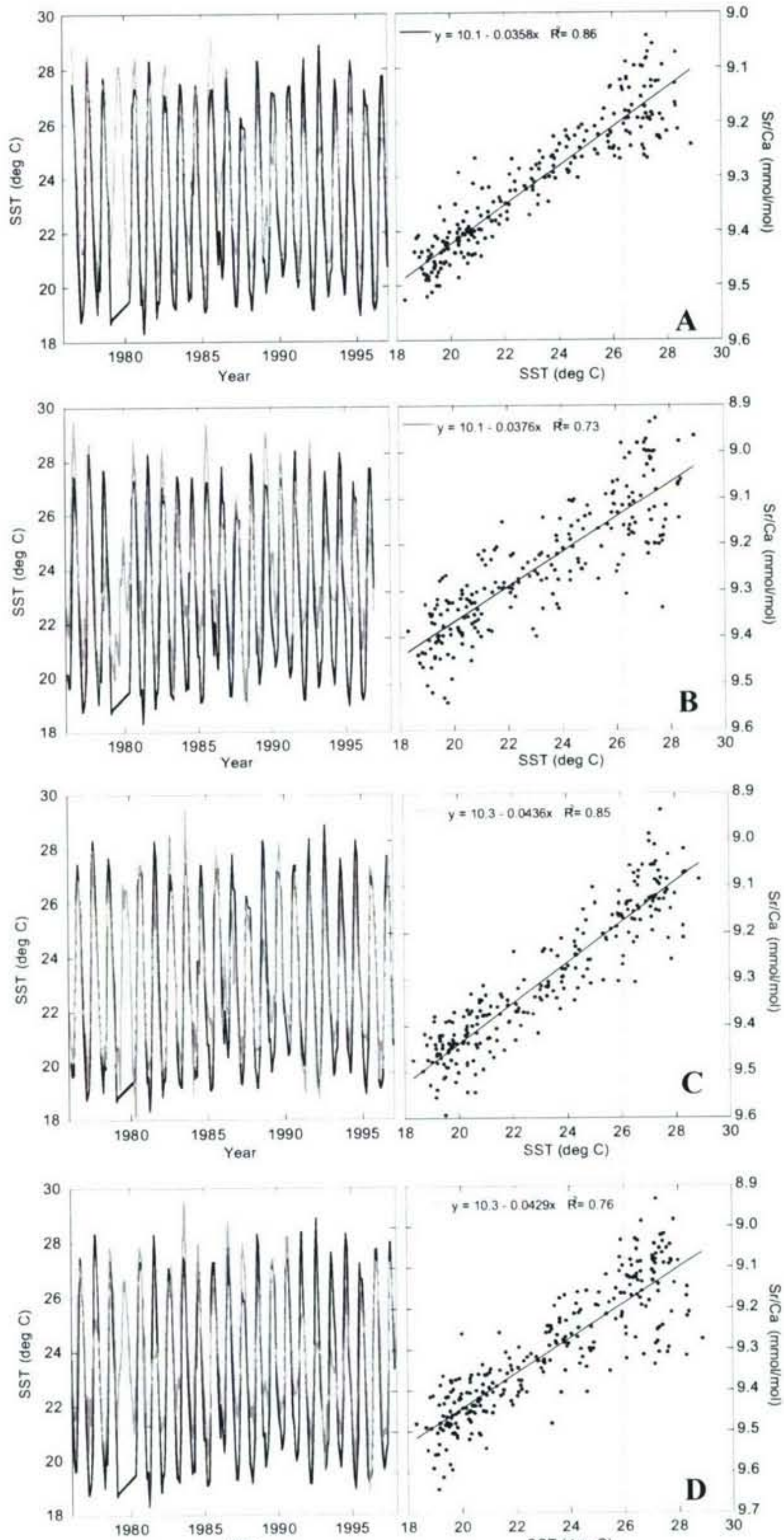


**Figure 3.2.** Coral Sr/Ca (shaded) and Hydrostation S SST (solid) at monthly resolution plotted versus year (left) and correlated using linear regression (right). Calibration results for a) BB 001 ($r^2$=0.86), b) BER 002 ($r^2$=0.73), c) BER 003 ($r^2$=0.85), and d) BER 004 ($r^2$=0.76).

These results are consistent to one another and to other slow to moderately growing corals [*Bagnato et al.*, 2004; *Cardinal et al.*, 2001; *Swart et al.*, 2002]. A larger variance in summer Sr/Ca values than in winter in all four corals suggests a growth effect on the summer Sr/Ca values, as previously found for BB 001 [*Goodkin et al.*, 2005]. Smoothing of the seasonal cycle, as previously identified for bulk sampling methods in slow growing corals, is seen in these colonies, rendering the seasonal calibration ineffective for reconstructing SST back through time [*Cohen and Hart*, 2004; *Cohen et al.*, 2004; *Goodkin et al.*, 2005].

### 3.3.2 Inter-annual Calibrations

Mean annual Sr/Ca regressed (type I) upon mean annual SST shows a significantly reduced correlation coefficient for all four corals relative to the seasonal correlations (Fig. 3.3):

BB 001: Sr/Ca = 10.4 (±1.2) – 0.0481 (± 0.0503) * SST
(2σ, 95% conf., $r^2 = 0.21$, $F_{sig}=0.0766$, rmsr=0.5 °C)

BER 002: Sr/Ca = 11.2 (±1.5) – 0.0844 (± 0.0666) * SST
(2σ, 95% conf., $r^2 = 0.31$, $F_{sig}=0.0238$, rmsr=0.4 °C)

BER 003: Sr/Ca = 10.3 (±1.3) – 0.0451 (±0.0544) * SST
(2σ, 95% conf., $r^2 = 0.15$, $F_{sig}=0.1180$, rmsr=0.6 °C)

BER 004: Sr/Ca = 9.33 (±2.23) – 0.00005467 (±0.0964689) * SST
(2σ, 95% conf., <<0.0001, $F_{sig}=0.9991$, rmsr= not relevant)

where rmsr is the root mean square of the residual.

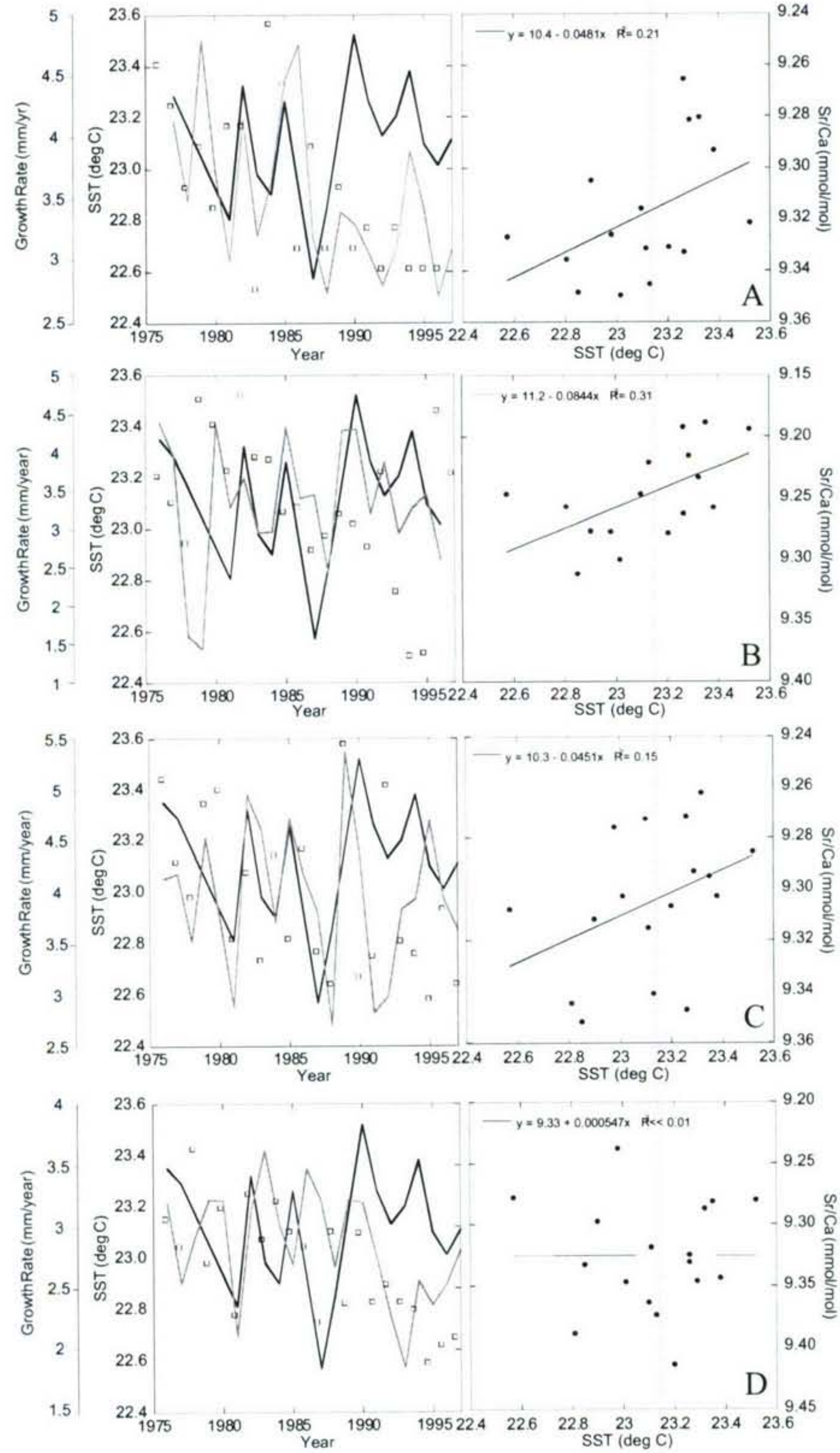


**Figure 3.3**. Coral Sr/Ca (shaded) and Hydrostation S SST (solid) at mean-annual resolution plotted versus year (left) and correlated using linear regression (right). Calibration results for a) BB 001 ($r^2$=0.21), b) BER 002 ($r^2$=0.31), c) BER 003 ($r^2$=0.15), and d) BER 004 ($r^2$<<0.01).

Previous work has demonstrated that growth rate influences do not impact the summer and winter season equally [*Goodkin et al.*, 2005]. In that work, changes in mean-annual growth rates were shown to correlate strongly with anomalous summer and mean-annual Sr/Ca values. Incorporating annual growth rate data into a single-colony, multivariate regression of mean-annual Sr/Ca onto SST resulted in an improved calibration with reduced residual SSTs. The poor correlation observed here in the mean-annual calibrations for each of these corals, combined with the larger spread in summer Sr/Ca relative to winter Sr/Ca values (Fig. 3.2), implies that a similar effect may be impacting the Sr/Ca-SST relationship.

A growth corrected mean-annual model following the method of Goodkin et al. (2005), was therefore fit to each of the four corals to evaluate the influence of growth on the calibration of Sr/Ca versus SST. The following correlations were found:

BB 001: Sr/Ca = -0.0529 (±0.0334) * SST – 0.00170 (±0.00078) * (growth rate) * SST + 10.7 (±0.8)

($2\sigma$, 95% conf., $r^2$ =0.68, $F_{sig}$=0.0006, rmsr=0.2 °C)

BER 002: Sr/Ca = -0.0906 (±0.0679) * SST – 0.000522 (±0.001060) * (growth rate) * SST + 11.4 (±1.6)

($2\sigma$, 95% conf., $r^2$ =0.36, $F_{sig}$=0.0538, rmsr=0.3 °C)

BER 003: Sr/Ca = -0.0502 (±0.0573) * SST + 0.000543 (±0.001584) * (growth rate) * SST + 10.4 (±1.3)

($2\sigma$, 95% conf., $r^2$ =0.18, $F_{sig}$=0.2441, rmsr=0.5 °C)

BER 004: Sr/Ca = -0.000201 (±0.092689) * SST – 0.00194 (±0.00259) * (growth rate) * SST + 9.4 (±2.1)

($2\sigma$, 95% conf., $r^2$ =0.14, $F_{sig}$=0.3525, rmsr=8.2 °C)

BER 004 fails to show enough improvement in the growth corrected model to be used to reconstruct SST. BER 004 has the slowest average annual extension rate (2.1 mm/yr) by more than one mm/yr. A correlation of mean-annual Sr/Ca to average annual extension in BER 004, with an $r^2$ of 0.21 and an $F_{sig}$ of 0.0337, shows a stronger correlation than does Sr/Ca to SST, with an $r^2$ of <<0.0001 and an $F_{sig}$ of 0.9991. The inability to model the Sr/Ca-SST thermometer at the mean-annual level in BER 004 is an indication that extremely slow growing corals are not suitable for bulk sampling of this resolution and should be avoided when both calibrating and reconstructing SST by this sampling method. These results warrant further study of corals growing consistently at or below 2mm/yr, as BER 004 does in the last 10 years of the calibration.

In contrast to BER 004, the growth-corrected models of BB 001, BER 002, and BER 003 more accurately reconstruct SST, decreasing the root mean squares of the residuals in all cases (Table 3.2). BB 001 shows increased significance for the relationship ($F_{sig}$ = 0.0006, growth, and 0.0766, non-growth), an improved $r^2$ (0.68 compared to 0.21) and a strong significance for the added term (p=0.00078). For BER 002 and 003, the explained variance ($r^2$) in Sr/Ca for the growth-corrected model increases slightly from 0.31 to 0.36 and 0.15 to 0.18, respectively. The significance of the equations, however, do not improve in either case from the mean-annual model to the growth-corrected model, and neither coral shows statistical significance for the added term accounting for inter-annual growth rate (p = 0.34 and 0.50 for 002 and 003, respectively).

**Table 3.2.** Root mean squares of the residuals (°C) generated by each calibration/model applied to each coral and to the group as a whole. Values are reported to the $100^{th}$ decimal place for comparison purposes.

| Calibration | BB 001 | BER 002 | BER 003 | Group |
|---|---|---|---|---|
| **Multi-Colony** | 0.43 | 0.47 | 0.47 | 0.46 |
| **BB 001** | | | | |
| Growth-Corrected | 0.24 | 1.53 | 0.53 | 0.94 |
| Mean-Annual | 0.46 | 1.59 | 0.58 | 1.00 |
| Monthly | 0.65 | 2.00 | 0.72 | 1.28 |
| **BER 002** | | | | |
| Growth-Corrected | 0.81 | 0.32 | 0.77 | 0.67 |
| Mean-Annual | 0.88 | 0.43 | 0.74 | 0.71 |
| Monthly | 1.89 | 0.88 | 1.60 | 1.52 |
| **BER 003** | | | | |
| Growth-Corrected | 0.65 | 1.24 | 0.51 | 0.86 |
| Mean-Annual | 0.56 | 1.45 | 0.55 | 0.95 |
| Monthly | 0.62 | 1.40 | 0.57 | 0.94 |

More importantly, the growth-corrected model, when applied to corals 001, 002, and 003, fails to establish a single equation that can be applied reliably for all modern and, by inference, fossil corals – i.e., the slopes and intercepts of the three equations are not consistent (Fig. 3.4). This leads to the conclusion that inter-annual growth rate is not accounting for all of the differences found between these individual corals. An alternate hypothesis is required in order to link the different corals together into a single relationship.

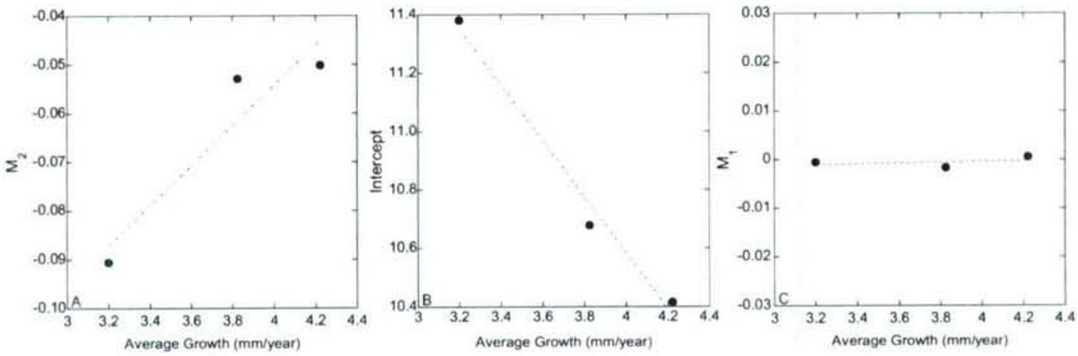


**Figure 3.4.** Single-colony, growth-corrected model intercepts and slopes from each coral model plotted versus average growth (mm/year) of the individual coral colony. (a) $M_2$, b) intercept ($b_o$), and c) $M_1$ versus average growth.

Following the general form of the growth-corrected model:

$$Sr/Ca = m_1 * (\text{inter-annual growth}) * SST + m_2 * SST + b_0 \qquad \text{eqn. 1}$$

we observe that $m_2$ (the SST slope) reveals a correlation to the average growth rate ($r^2$=0.89) for the three colonies (Fig. 3.4a), which in turn influences the values of the intercepts ($b_0$) (Fig. 3.4b). Thus, the intercept also shows a strong correlation to average growth rate ($r^2$=0.98). $M_1$, which already accounts for a growth rate influence, shows relatively little correlation to average growth rates (Fig. 4c) ($r^2$=0.13). Three points do not allow for a statistical evaluation of these observed relationships or determination of the nature (linear, exponential etc.) of these relationships. However, this illustrative result implies that developing a general model applicable to different coral colonies requires incorporation of the average growth rate of each colony. We therefore adopt the simplest hypothesis that a multi-colony calibration model will assume that $m_2$ (the SST slope) changes as a linear function of growth rate, such that:

$m_2 = d_0 * (\text{average growth}) + d_1$ eqn. 2

The net regressed equation is:

$Sr/Ca = m_1 * (ig) * SST + d_0 * (ag) * (SST) + d_1 * (SST) + b_0$ eqn. 3

where (ig) is inter-annual growth and (ag) is average growth for each colony. The linear least square (type I) multiple regression performed on all three data sets simultaneously returns the following equation:

$Sr/Ca = -0.000697 (\pm 0.000751) * (ig) * SST + 0.00304 (\pm 0.00102) * (ag) * SST - 0.0738 (\pm 0.0374) * SST + 10.8 (\pm 0.9)$

($2\sigma$, 95% conf., $r^2=0.51$, $F_{sig} << 0.0001$, rmsr=0.5 °C)

Covariance amongst the slopes and intercepts are reported in Table 3.3. The inter-annual growth term ($m_1$) which previously showed significance only in the individual colony model for coral BB 001, is now significant in this model including data from all three colonies (p=0.0800). The inclusion of the average growth term and the utilization of all three colonies in one regression lead to a highly significant model ($F_{sig} << 0.0001$), a strong significance of the added average growth term ($p << 0.0001$), and a low root mean square of the residual (0.5 °C).

**Table 3.3:** Covariance ($\sigma^2$) amongst the slopes and intercept of the multi-colony model.

| | Intercept | SST | ag * SST |
|---|---|---|---|
| **SST** | $-8.01 \times 10^{-3}$ | | |
| **ag * SST** | $9.57 \times 10^{-6}$ | $-1.09 \times 10^{-6}$ | |
| **ig * SST** | $-1.66 \times 10^{-5}$ | $5.48 \times 10^{-7}$ | $-8.79 \times 10^{-8}$ |

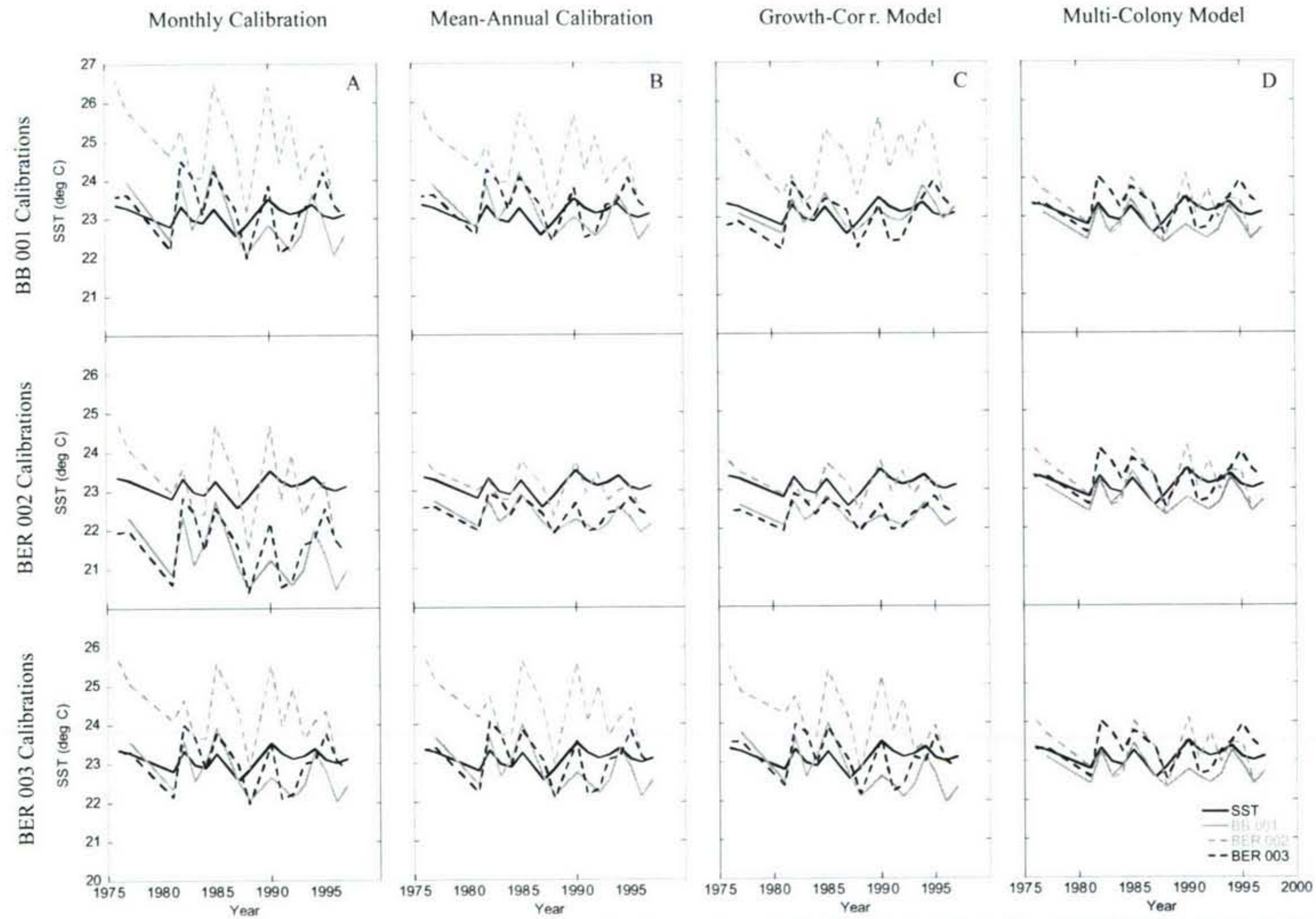


**Figure 3.5**. Hydrostation S (solid) and reconstructed mean-annual SST for BB 001 (shaded), BER 002 (shaded dashed) and BER 003 (solid dashed) plotted versus year. Reconstructed SSTs from (a) monthly calibration of BB 001 (top), BER 002 (middle) and BER 003 (bottom) b) mean-annual calibration of BB 001 (top), BER 002 (middle) and BER 003 (bottom) c) growth-corrected model of BB 001 (top), BER 002 (middle) and BER 003 (bottom) and d) the multi-colony model. The multi-colony model shows the most accurate reconstruction of SST for the colonies as a group with a rmsr of 0.46°C and a minimal off-set from the mean instrumental SST over the period of 0.24°C.

## 3.4 Discussion: Testing the Multi-Colony Regression

In order to evaluate the accuracy and precision of the different calibration methods presented here, each single-colony calibration (monthly, mean-annual, and growth-corrected) for the three corals, as well as the multi-colony calibration, was applied to all of the corals such that there are ten SST reconstructions for each coral (Fig. 3.5). In column A (Fig. 3.5), the monthly calibrations for coral 001, 002, and 003 (top to bottom) are applied to mean-annual Sr/Ca from each coral and compared to mean-annual instrumental SST. In these scenarios, neither the accuracy nor the precision are good. In a single year, the difference between the three records can be as large as 2.5 °C and the records on average are also significantly offset from one another and the instrumental record. In addition, the root mean squares of the SST residuals when applied to the group as a whole are 1.3, 1.5, and 0.9 °C (top to bottom, Table 3.2). If a reconstructed paleotemperature record was compiled from multiple corals using a monthly calibration from any single colony, it would be likely to significantly over- or under-estimate SST changes through time.

In panel B (Fig. 3.5), the mean-annual calibrations of 001, 002, and 003 (top to bottom) are applied to mean-annual Sr/Ca from each coral and compared to instrumental SST. Although minimizing the known artifacts of smoothing from bulk sampling of monthly calibrations (e.g., [*Goodkin et al.*, 2005]), the mean-annual calibrations still lead to significant offsets from the instrumental record (Fig. 3.5b). The mean-annual calibration from BER 003 performs as poorly as the monthly calibration when applied to all three corals, returning a root mean square of the residuals for the group of 1.0 °C, while mean-annual calibrations for BB 001 and BER 002 show improvement (group rmsr of 1.0 and 0.7 °C respectively) (Table 3.2).

**Table 3.4.** Difference between the mean of the reconstructed SST and the mean of the instrumental SST (°C) over the calibration period for each individual colony growth-corrected model and the multi-colony model. Values are reported to the 100th decimal place for comparison purposes.

| | BB 001 | BER 002 | BER 003 | rmsr |
|---|---|---|---|---|
| **BB 001 Growth-Corrected Model** | 0.00 | 1.38 | -0.04 | 0.80 |
| **BER 002 Growth-Corrected Model** | -0.78 | 0.00 | -0.70 | 0.61 |
| **BER 003 Growth-Corrected Model** | -0.35 | -0.36 | 0.00 | 0.29 |
| **Multi-Colony Model** | -0.34 | 0.13 | 0.20 | 0.24 |

In panel C (Fig. 3.5), the single-colony growth-corrected calibrations for corals 001, 002, and 003 (top to bottom) are again applied to mean-annual Sr/Ca from each coral and compared to mean annual SST. These models attempt to account for some of the variability between different coral colonies, but still result in significant errors in SST reconstructions (Fig 3.5c). The growth-corrected model for BB 001 reconstructs SST well for itself (rmsr = 0.2°C). However, it does relatively worse for BER 003 (rmsr = 0.5 °C), and it does poorly for BER 002 (rmsr = 1.5 °C; group rmsr = 0.8 °C). Similarly, single-colony growth-corrected models for BER 002 and 003 result in poor SST reconstructions when applied to other colonies. The BER 002 growth-corrected model provides the most precise reconstruction across the group (rmsr of 0.7 °C) of the three single-colony models, with rmsr of 0.8, 0.3 and 0.8 °C when applied to BB 001, BER 002, and BER 003, respectively. The growth-corrected model of BER 003 reconstructed SST with an rmsr of 0.7, 1.2 and 0.5 °C for the three colonies respectively, and a group rmsr of 0.9 °C. In general, the single-colony, growth-corrected models when applied to other colonies still result in SST reconstructions with significant offsets of the mean from instrumental data (Fig 3.5c; Table 3.4), and demonstrate that reconstructions from fossil corals could possibly over- or under-estimate mean SST by as much as 1.4 °C (Table 3.4).

Finally, shown in triplicate along panel D (Fig. 3.5) and in the top row of Table 3.2 are the results of SST reconstructions using the multi-colony model. With the multi-colony model, both precision and accuracy of reconstructed SSTs are improved over the single-colony models. Although reconstructed SSTs for BB 001 and BER 002 (but not BER 003) fit best using their own single-colony growth-corrected model (Table 3.2), each single-colony model performs poorly when applied to the other colonies. The group rmsr of reconstructed SSTs for the three colonies equal 0.9, 0.7 and 0.9 °C for the single-colony models, compared to only 0.5 °C using the multi-colony model (Table 3.2). Similarly, the means for reconstructed SSTs using single-colony calibrations show greater offsets from instrumental SST (group offsets of 0.8, 0.6 and 0.3 °C) than the multi-colony model (average offset 0.2 °C) (Table 3.4). When reconstructing SST for the group as a whole, the best fit is clearly achieved using the multi-colony calibration. Applying the multi-colony calibration to all three corals shows reconstructed SSTs evenly distributed above and below the instrumental record, with diminished offsets and greatly reduced scatter compared to single-colony monthly, mean-annual, and growth-corrected methods (Fig. 3.5). This implies that the multi-colony calibration approximates a universal equation that may potentially be applied to any individual modern or fossil *Diploria labyrinthiformis* colony from this area with equal confidence.

## 3.5 Conclusion

Individual modern coral colonies often provide distinct independent calibrations of Sr/Ca to SST. Choosing an equation to apply to a fossil coral or even to the non-modern portion of a living coral can be problematic, as the variation in slopes from one calibration to another can have significant implications for reconstructed SST. The application of a single-colony Sr/Ca-SST calibration to different corals can lead to significant offsets between independent records covering the same time interval. Such discrepancies can pass unnoticed when a modern calibration is applied to a fossil coral, particularly if the fossil record shows no overlap with more recent values. In slow-to-moderate growing corals, growth rate can explain some of the differences in the calibrations of individual corals. However, even growth-corrected Sr/Ca-SST calibrations based on a single colony yield large anomalies in reconstructed SST when applied to other colonies.

For this study, data from multiple corals were used simultaneously in a multivariate regression to develop a single multi-colony growth-corrected Sr/Ca-SST calibration. Applying the multi-colony calibration for reconstructing SST reduces the root mean square of the residual as well as mean offsets for three colonies evaluated independently and together as a group, compared to single-colony growth-corrected calibration models. In general, incorporating quantitative interannual and average growth rate information and expanding the calibration range through the inclusion of multiple coral colonies improves the coral Sr/Ca thermometer and provides more accurate reconstructions of SST. Investigating growth influences on other slow-to-moderate growing corals and using multiple colonies in Sr/Ca-SST calibrations may improve the reliability of past SST reconstructions and serve to diminish anomalies relative to other paleotemperature proxies.


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# Chapter 4

# Sea Surface Temperature and Salinity Variability at Bermuda during the End of the Little Ice Age

## Abstract

A 225-year old coral from the south shore of Bermuda (64°W, 32°N) provides a record of decadal-to-centennial scale climate variability. The coral was collected live, and sub-annual density bands seen in x-radiographs delineate cold and warm seasons allowing for precise dating. Coral skeletons incorporate strontium (Sr) and calcium (Ca) in relative proportions inversely to the sea surface temperature (SST) in which the skeleton is secreted. Previous studies on this and other coral colonies from this region document the ability to reconstruct mean-annual and winter-time SST using Sr/Ca measurements [*Goodkin et al.*, in press; *Goodkin et al.*, 2005]. $\delta^{18}O$ of the coral skeleton changes based on both temperature and the $\delta^{18}O$ of sea water ($\delta O_w$), where $\delta O_w$ is proportional to sea surface salinity (SSS). We show in this study that mean-annual and winter-time $\delta^{18}O$ of the carbonate ($\delta O_c$) are correlated to both SST and SSS, but a robust quantitative measure of SSS is not found. In combination, however, the Sr/Ca and $\delta O_c$ qualitatively predict fresher salinities at the end of the LIA. The coral basd records of SST for the past two centuries show abrupt shifts in both decadal and centennial time-scales. Our reconstruction at Bermuda suggests that SST at the end of the Little Ice Age period (between 1830 and 1860) was 1.5 ±0.4 °C colder than today, and the surface sea water was fresher.

## 4.1. Introduction

### 4.1.1 Little Ice Age

The Little Ice Age (LIA) was a series of extended cold periods which occurred from the mid-1400s to the late 1800s, documented primarily in the Northern Hemisphere [*Bradley and Jones*, 1993; *Jones et al.*, 1998; *Overpeck et al.*, 1997]. Currently, high-resolution paleoclimate records of the LIA exist from tree rings [*Briffa et al.*, 2001; *Esper et al.*, 2002; *Jacoby and D'Arrigo*, 1989], ice cores [*Dahl-Jensen et al.*, 1998; *Dansgard et al.*, 1975], and coral records from the Caribbean Sea [*Druffel*, 1982; *Watanabe et al.*, 2001; *Winter et al.*, 2000]. These and other proxy reconstructions from around the North Atlantic show LIA temperatures to be 0.5 to 5 °C colder than today [*deMenocal et al.*, 2000; *Druffel*, 1982; *Dunbar et al.*, 1994; *Glynn et al.*, 1983; *Keigwin*, 1996].

The LIA is the most recent example of decadal-to-centennial scale climate change events during the late Holocene. These events are of interest, in part because it is believed that by improving our understanding of the mechanisms and patterns of such natural climate change, we will greatly improve our ability to anticipate and evaluate future changes on similar time scales. Two forcing mechanisms have been put forth as a possible cause of for the Little Ice Age. Solar activity was low during this time [*Crowley*, 2000; *Lean et al.*, 1995; *Wigley and Kelly*, 1990], whereas volcanic activity is observed to have been high [*Crowley*, 2000]. Solar activity has also been linked to changes in thermohaline circulation leading to a possible millennial paced climate signal [*Bond et al.*, 2001; *Bond et al.*, 1997]. Both solar and volcanic influences have the potential to produce widespread cooling across the globe.

In addition to global processes, regional climate processes will impact the North Atlantic as well. The North Atlantic Oscillation (NAO), measured as a pressure difference between the Icelandic high and Azores low [*Hurrell*, 1995; *Jones et al.*, 1997a], exerts an influence from the eastern United States to western Europe at several frequencies [*Visbeck et al.*, 2003]. The influence of this system, however, is limited geographically to the Northern Hemisphere and produces different responses on varying timescales and at varying locations [*Keigwin and Pickart*, 1999; *Visbeck et al.*, 2003].

### 4.1.2 Coral Based Proxy Records

Coral skeletons provide high-resolution, long records of climate variability in the ocean. The strontium (Sr) to calcium (Ca) ratio of coral skeleton is inversely related to the SST in which the coral grew [*Smith et al.*, 1979] and provides a salinity independent record of local sea surface temperatures (SST) [*Beck et al.*, 1992; *Beck et al.*, 1997]. Skeletal $\delta^{18}O$ ($\delta O_c$) is governed by both SST and the $\delta^{18}O$ of sea water ($\delta O_w$), which is linearly related to sea surface salinity (SSS). Therefore, in combination, $\delta O_c$ and Sr/Ca provide the means to estimate records of both SST and SSS back through time [*Gagan et al.*, 1998; *Iijima et al.*, 2005; *Quinn and Sampson*, 2002; *Watanabe et al.*, 2001].

Here we use Sr/Ca and $\delta^{18}O$ from a slow-growing coral from Bermuda to reconstruct SST and SSS from 1781-1999. Over the past 218 years (1781-1999), we evaluate inter-annual and winter-time SST and SSS/$\delta O_w$ variations based upon monthly resolution records of Sr/Ca and $\delta^{18}O$ from a brain coral (*Diploria labyrinthiformis*). Growth rate, particularly in slow growing corals, has been shown to impact coral Sr/Ca [*Alibert and McCulloch*, 1997; *Cardinal et al.*, 2001; *Cohen and Hart*, 1997; *Cohen et al.*, 2004; *deVilliers et al.*, 1995; *deVilliers et al.*, 1994; *Goodkin et al.*, in press; *Goodkin et al.*, 2005]. Previous studies at Bermuda show how mean-annual and summer Sr/Ca values are impacted by both inter-annual growth rate and average growth rate over the lifespan of the coral used in this study [*Goodkin et al.*, in press; *Goodkin et al.*, 2005]. In contrast, winter (Dec.-March) Sr/Ca values show no correlation to growth rate [*Goodkin et al.*, 2005]. We use a previously developed mean-annual calibration to SST including growth rate and a newly developed non-growth dependent winter time Sr/Ca-SST calibration. Reconstructed mean-annual and winter SSTs are then compared to $\delta^{18}O$ to evaluate directional changes in salinity.

## 4.2. Methods

### 4.2.1 Study Site

In 2000, a 225-year old brain coral species (BB 001) was collected alive from the southeastern edge of the Bermuda platform at 16-meters water depth. Two smaller corals (BER 002 and BER 003) were collected from the same location to examine reproducibility between coral colonies and are used in this work to evaluate winter Sr/Ca. The island of Bermuda (64°W, 32°N) is located in the Sargasso Sea in the sub-tropical North Atlantic. This site is oceanographically important because a large portion of the world's ocean heat transport from low to high latitudes occurs in the North Atlantic via the Gulf Stream. Sargasso Sea water interacts with both warmer tropical and cooler sub-arctic water [*Curry et al.*, 2003; *Talley*, 1996]. Bermuda, a northernmost location for surface coral growth and near a site of high, deep sea sedimentation rates, has been the location for several reconstructions of past climate from coral [*Draschba et al.*, 2000;

*Druffel*, 1997; *Kuhnert et al.*, 2005], foraminifera [*Keigwin*, 1996] and alkenone based proxy reconstructions [*Ohkouchi et al.*, 2002; *Sachs and Lehman*, 1999].

The southern platform of Bermuda is in close proximity to Hydrostation S, which lies 30km to the southeast (32°10'N, 64°30'W). Since 1954, Hydrostation S has been visited bi-weekly for on-going research including the measurement of SST and SSS. Coral geochemistry proxies from multiple coral colonies (including the multi-century coral used in this study) collected off southern Bermuda have previously shown correlations to Hydrostation S temperature averaged above 16 meters depth [*Goodkin et al.*, in press; *Goodkin et al.*, 2005] for the calibration period of 1976 to 1997. At Hydrostation S, monthly averaged SST ranges from 18.0-28.9 °C. Annually averaged SSTs vary between 22.4-24.3 °C. Monthly SSS varies from 36.1-36.8 ‰. Annually averaged SSS has a range of 36.3-36.6 ‰. The Hydrostation S SST and SSS records are incomplete over several intervals, with two or more months of SST and/or SSS missing in 1978-1981, 1986, and 1989. In this paper, we will also compare the coral records to regional, observational SST records (HadISST) from 1870-1997 from the gridded area 31-33° N and 295-296° E [*Rayner et al.*, 2003].

### 4.2.2 Sub-sampling

Coral slabs were cut, cleaned and x-rayed according to methods previously presented [*Goodkin et al.*, 2005]. Approximately monthly samples were drilled using a micro-meter controlled drill press every 0.33 mm along the dense thecal wall [*Cohen et al.*, 2004]. Individual samples averaged 220 μg and were split into a small portion (~8-40 μg) for stable isotope analysis and the remaining portion for Sr/Ca analysis. The thecal wall was chosen, despite complicated skeletal architecture [*Cohen et al.*, 2004], because it is the densest skeletal component with the least potential impact from diagenesis.

### 4.2.3 Sr/Ca Analysis

Sr and Ca were analyzed simultaneously using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) at Woods Hole Oceanographic Institution (WHOI). Samples were dissolved in 1N $HNO_3^-$ to a concentration of ~80 ppm Ca based on mass in order to minimize matrix corrections. Solution standards were employed to evaluate and correct for drift and matrix effects [*Schrag*, 1999]. A homogenized coral (*Porites*) powder external standard was prepared simultaneous to unknowns and blanks to evaluate precision. Repeat measurements on the coral external standard (run at variable concentrations matching the range of unknowns) analyzed over more than a year showed good reproducibility (standard deviation (SD) = 0.0244 mmol/mol, relative SD (RSD) = 0.27%, n=1,493). A small long-term drift (over several months) in the homogenous coral standard was observed on the order of 0.011 mmol/mol and corrections were made to the unknowns as described in Appendix B.

### 4.2.4 Stable Oxygen Isotope Analysis

Stable oxygen isotope analyses were measured on a Finnigan MAT 253 coupled to a Kiel III carbonate device at WHOI. Conversion to the Vienna Pee Dee Belemnite (VPDB) scale was completed using NBS19 ($\delta^{18}O$ = -2.20 ‰). Reproducibility based on Estremoz marble (WHOI internal standard; $\delta^{18}O$ = -5.98 ‰ relative to VPDB), which has values closest to the coral unknowns, were ±0.11 ‰ (n = 660). Corrections for small samples (<0.8 volts, 9% of total) and samples with poorly balanced gas pressure relative to the reference gas (unbalanced, sample/standard voltage > 1.1, 11% of total) samples were required. These corrections were up to 0.2 ‰ for $\delta^{18}O$ and are described in Appendix C.

### 4.2.5 Age Model Development

Age models were developed using density banding visible in the x-radiographs (Appendix H) to identify the annual growth, and then correlating Sr/Ca to monthly averaged SSTs at maxima, minima and inflection points [*Goodkin et al.*, 2005]. Over the length of the entire record, three slabs were cut to capture changes in the primary growth axis through time. Multiple tracks were drilled within each slab as well as across slabs to produce a continuous record along the growth axis. In this situation, x-radiographs and algal bands provided the needed information to overlap samples during transitions between slabs. Overlapping Sr/Ca and $\delta^{18}O$ samples were averaged. The correlation coefficient of Sr/Ca between overlapping slabs (average r = 0.83) is strong, as previously found [*Goodkin et al.*, 2005].

For the record extending beyond the time frame of Hydrostation S, Sr/Ca data were fitted to a monthly-climatology from SST values for the entire Hydrostation S record. All geochemical records were then interpolated to even monthly increments. Before interpolation, the record had an average of 10.5 samples per year and a median of 11 samples per year. Annual averages (January-to-January) were calculated from the interpolated values.

Some error is expected within this age model due to very slow or non-growing years not visible on the x-ray and also not clearly discernible in the Sr/Ca seasonal cycle. While there is potential for error generated by noise in the Sr/Ca or the annual band counting leading to the inappropriate addition of a year, the majority of estimated age error will arise because of missing years, generating a bias in which coral bands are assigned to be more recent than actual dates. For example, if the coral did not grow in 1950, 1949 would be inappropriately assigned the date 1950, generating a bias in all years previous to 1950 (1948, 1947 etc.). Age model bias is expected to increase during the early-to-mid 1800s when growth rates are extremely slow for an extended period of time and hiatuses in growth may be expected.

## 4.3 Results

Sr/Ca and $\delta^{18}O$ records show cyclical seasonal cycles throughout the calibration period (1976-1997, Fig. 4.1) and the length of the record. Sr/Ca and $\delta^{18}O$ show a strong correlation over this period ($r^2 = 0.70$), as they are both driven in large part by SST. An offset in the timing of $\delta^{18}O$ and Sr/Ca cycles is evident, with $\delta^{18}O$ reaching maxima and minima on average one month later than Sr/Ca. This difference in timing likely results from the added influence of SSS on oxygen isotopic values. Within the Hydrostation S record, a similar phase difference is seen between SST and SSS hydrographic properties.

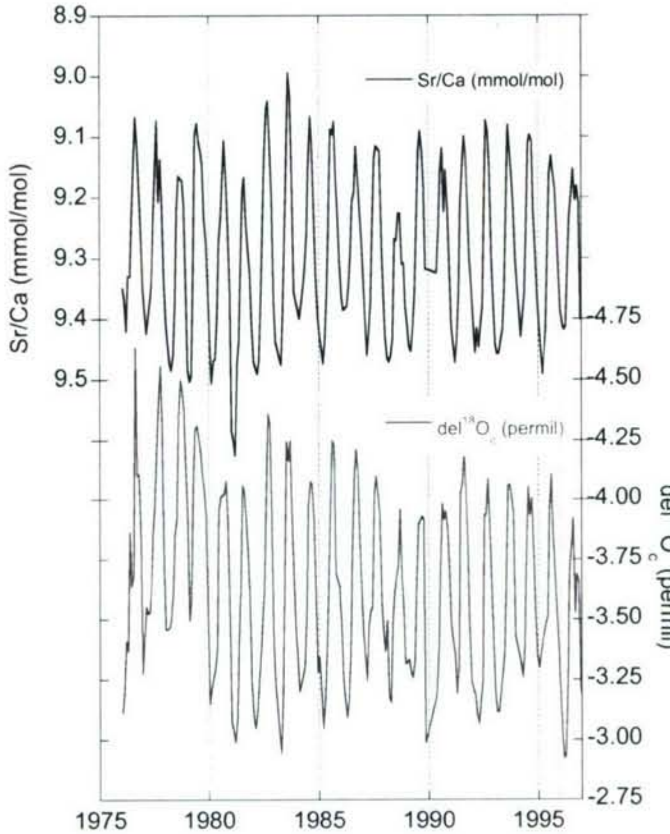


**Figure 4.1:** Sr/Ca (mmol/mol) and $\delta^{18}O$ (‰) plotted versus year over the calibration period of 1976-1997. Both geochemical proxies show an inverse relationship to SST ($r^2 = 0.86$ and 0.69 respectively). $\delta^{18}O$ is additionally influenced by SSS ($r^2 = 0.32$).

### 4.3.1 Sr/Ca - SST

*Mean-Annual:* Sr/Ca in coral is known to be inversely related to SST [*Smith et al.*, 1979]. In addition, previous work has shown mean-annual SST in slow-growing corals to vary according to Sr/Ca (mmol/mol) as well as average mean-annual growth (mm/year) [*Goodkin et al.*, in press; *Goodkin et al.*, 2005]. For this work, mean-annual SST (°C) was calculated using a previously published, multi-coral growth corrected model [*Goodkin et al.*, in press]:

$$Sr/Ca = (-0.000697 * (ig) + 0.00304 * (ag) - 0.0738) * SST + 10.8$$

$$(2\sigma, 95\% \text{ conf.}, r^2=0.51, F_{sig} << 0.0001, \text{rmsr}=0.5\ °C, \text{se}=0.031 \text{ mmol/mol})$$

eqn. (1)

where (ig) is interannual growth (mm/year) and (ag) is the average growth rate (mm/year) of the colony. RMSR is the root mean square of the residuals, when the regression was inverted and used to calculate SST. SE is the standard error on Sr/Ca predicted by the regression. The average growth rate is 3.8 mm/year and interannual growth rates are smoothed using a box window over three years according to Goodkin *et al.* (2005).

We compute error estimates on the application of the mean-annual SST regression to the 218-year Sr/Ca record beginning by inverting eqn. 1 to find SST as a function of Sr/Ca and growth rate. Standard methods of error propagation were used ([*Bevington*, 1969], detailed in Appendix G) including the slope and intercept errors shown with equation (1) and slope and intercept covariance values previously reported ([*Goodkin et al.*, in press], Appendix G). Error on Sr/Ca was based on the standard error of the regression (0.031 mmol/mol), which is larger than the measurement error (0.0244 mmol/mol), providing a more statistically conservative result. We have assumed no error in growth rate estimates. The 1σ SST uncertainty for the mean-annual calibration has an average value of ±0.6 °C (max = 1.0 °C and min = 0.5 °C) back to 1782 (Fig. 4.2).

Hydrostation S, Hadley, and the Sr/Ca based reconstructed SST agree well in absolute value until 1970, when the Sr/Ca reconstructed SST becomes on average higher than both the Hadley and Hydrostation S SST (Fig. 4.2). The error bars (1σ) of the

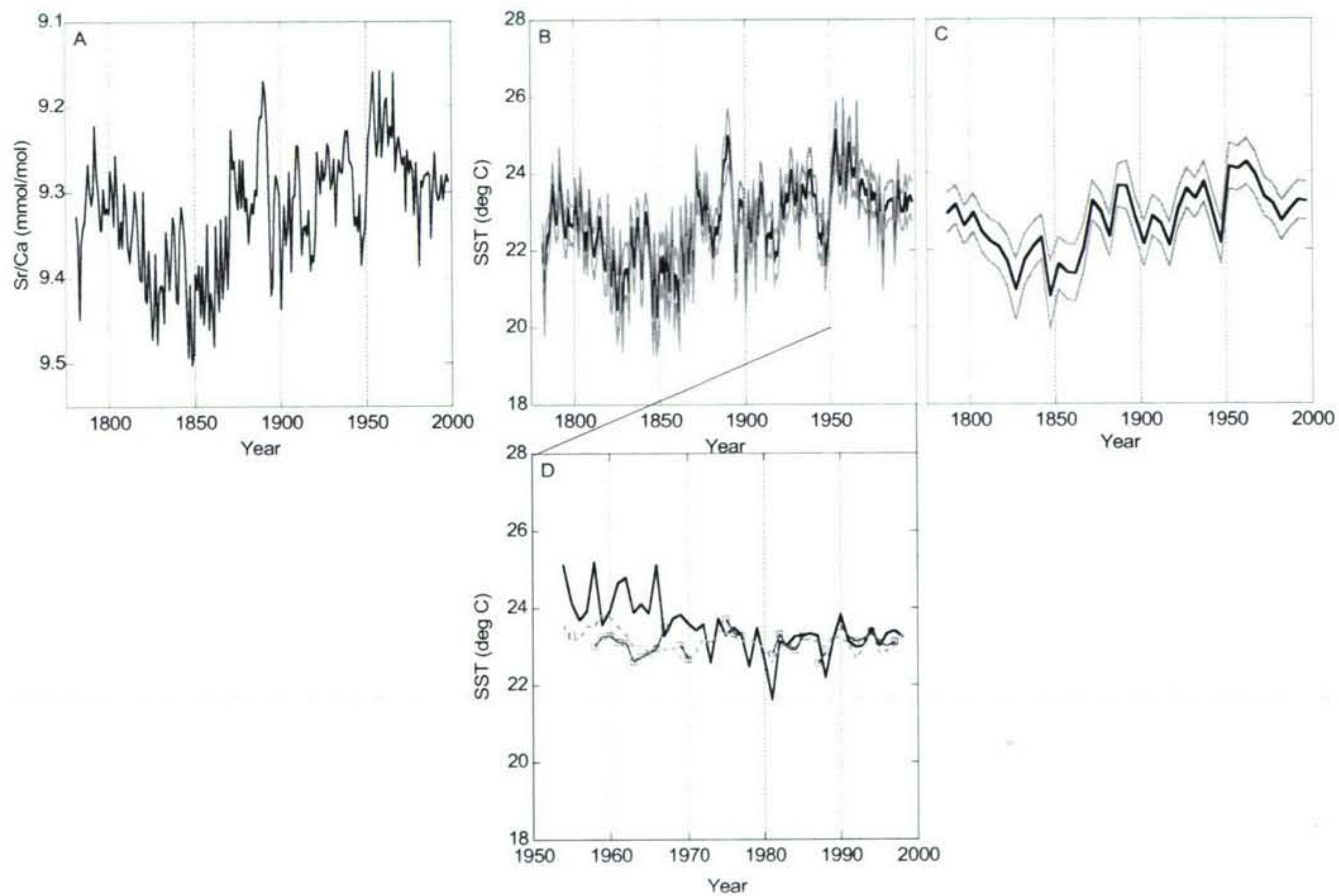


**Figure 4.2:** A) Mean-annual Sr/Ca shown versus time. B) Mean-annual SST generated from Sr/Ca (solid) ($\pm 1\sigma$) using the multi-colony, growth corrected calibration (eqn. 1). Uncertainty resulting from error propagation shown with shaded lines. C) Mean-annual SST generated from Sr/Ca binned into five year averages (solid). Uncertainty shown with shaded lines. D) Mean-annual SST generated from Sr/Ca (solid), HadleySST (shaded-dashed), and Hydrostation S (solid with squares) for the period of 1954-1997.

reconstructed SST do overlap with the instrumental records for this period. Hydrostation S SST and Hadley SST also agree less well prior to 1970, with an r of 0.63 from 1970 to 1997 and an r of 0.37 from 1954-1970. The disagreement amongst all records prior to 1970 may be caused by several factors – for example less homogenous water in the region, changes in the shallow waters at Bermuda that are not representative of deeper waters, changes in SST measurements, or undiagnosed vital effects not present during calibration.

Mean-annual Sr/Ca values range from 9.16 mmol/mol to 9.50 mmol/mol (Fig. 4.2a) over the 218 year record. Reconstructed mean-annual temperature change at Bermuda exhibits both decadal and centennial scale variability with a 5 °C temperature range (20.3-25.2 °C). Temperature minima are found in the coral reconstruction at the end of LIA around 1840 and 1850 (Fig. 4.2b,c). Averaging annual samples into five year bins shows an SST range of 20.8–24.3 °C. Fig. 4.2 shows the Sr/Ca based reconstruction of SST to be cooler during the LIA than today, at a statistically certain level. The large temperature change (2.6 °C ±0.6 °C) of the record occurs between the 1960s and 1840s. Temperatures during the LIA are 1.6 °C ±0.6 °C cooler than the 1990s instrumental average.

*Winter Sr/Ca:* All three corals (BB 001, BER 002, BER 003) show a statistically significant ($F_{sig}$ = 0.0004, 0.0938, and 0.0106 respectively) inverse relationship between winter-time (Dec-March) Sr/Ca and Hydrostation S SST over the calibration period (1976-1997) (Fig. 4.3). Linear regressions of winter Sr/Ca to SST for each coral yield statistically equivalent (1$\sigma$) slopes and intercepts with an average slope of -0.039

mmol/mol/°C and an intercept of 10.2 mmol/mol. Unlike previous work done on mean-annual calibrations for these corals, adding growth rate either through inter-annual changes [*Goodkin et al.*, 2005] or colony averages [*Goodkin et al.*, in press] does not improve these calibrations, confirming the previous conclusion that growth rate is not impacting the winter Sr/Ca [*Goodkin et al.*, 2005]. Winter-time Sr/Ca appears to reflect SST in a linear fashion.

The short calibrations shown in Fig. 4.3, however, do not provide a realistic SST reconstruction over the length of the multi-century record. The BB 001-Hydrostation S winter-time calibration applied to the long record shows winter SSTs as high as 27 °C in the 1960s and as low as 15 °C in the 1850s, a range that is greater than the current seasonal cycle. This result implies a possible problem with the above calibration in that the noise is overwhelming the signal and biasing the regression.

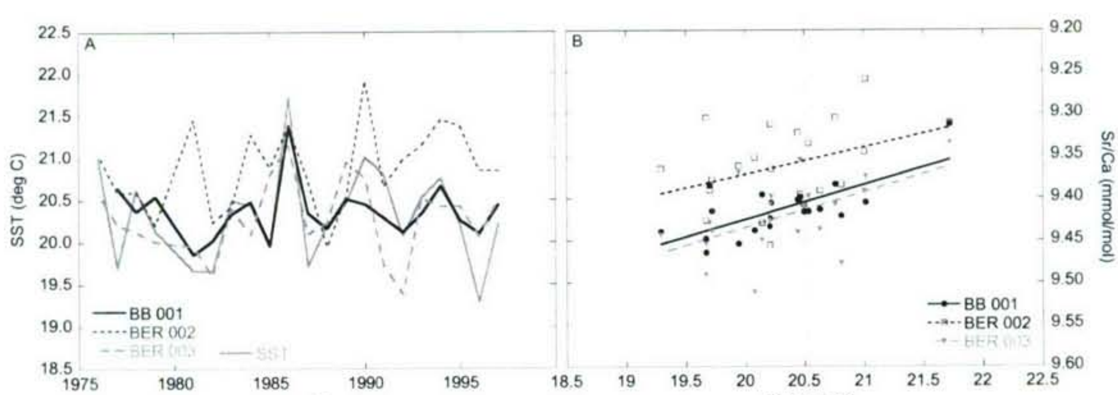


**Figure 4.3:** Coral winter-time (Dec., Jan., Feb. and March) Sr/Ca and Hydrostation S (solid, grey) SST plotted versus year (a) and linearly (b) for BB 001 (solid line, circles), for BER 002 (small dashes, squares), and for BER 003 (large dashes, triangles).

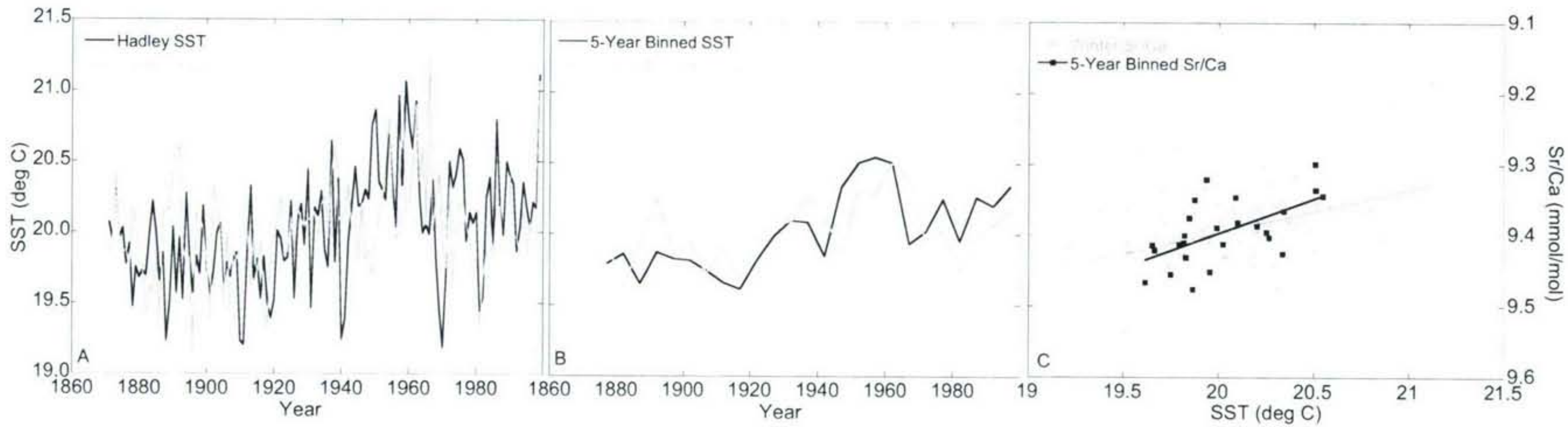


**Figure 4.4**: BB 001 winter-time (Dec-March) Sr/Ca (shaded) and Hadley SST (solid) plotted versus year for a) inter-annual ($r^2 = 0.13$, rmsr = 1.03 °C), b) five-year bins ($r^2 = 0.36$, rmsr = 0.36 °C), and c) linearly with inter-annual (shaded, circles), and five year bins (solid, squares).

In order to address this influence, the long record from BB 001 was correlated to Hadley SST from 1870-1999 both yearly and in five year bins to increase the length and range of signal of the calibration period (Fig. 4.4)[1]. Hadley SST is a compilation of regional observational SST measurements (HadISST, [*Rayner et al.*, 2003]). This study uses the gridded area 31-33° N and 64-65° W. The results are shown in table 4.1.

Table 4.1: Winter-time Sr/Ca regressions at inter-annual (eqn. 2) and five year (eqn. 3) time scales for the equations of the form: Sr/Ca = $\beta + \gamma * SST$. $\sigma^2_{\beta\text{-}\gamma}$ is the covariance on the slope and intercept with units of (mmol/mol)$^2$(°C). $\beta$ has units of mmol/mol and $\gamma$ has units of mmol/mol/°C.

| Time Frame | $\beta$ | 2σ Er. | $\gamma$ | 2σ Er. | $r^2$ | $F_{sig}$ | rmsr (°C) | se (mmol /mol) | $\sigma^2_{\beta\text{-}\gamma}$ |
|---|---|---|---|---|---|---|---|---|---|
| Inter-Annual (2) | 10.6 | 0.6 | - 0.0615 | 0.0279 | 0.13 | <0.0001 | 1.05 | 0.0064 | -0.004 |
| Five Year Bin (3) | 11.3 | 1.1 | - 0.0972 | 0.0531 | 0.36 | 0.0012 | 0.36 | 0.0036 | -0.014 |

Increasing the length of the calibration data sets and then diminishing noise through averaging the SST records into 5-year bins succeeds at increasing the significance of the reconstructions and decreasing the root mean square of the residuals (rmsr) and standard error (se). The increase in slope confirms the hypothesis that the 25-year Hydrostation S calibration period contains too small a signal given the signal-to-noise ratio.

Error propagation was performed for the five year binned winter-time reconstruction (eqn. 3), as applied to the 218 year winter-time Sr/Ca record in five year bins. The equation was first inverted and then standard error propagation methods were

[1] A type I regression minimizes the distance between the dependent variable and the regressed line, whereas the type II regression minimizes the distance between the line and both the dependent and independent variables. Both type I and II linear regressions were performed. Type II regressions were examined to account for the error in Hadley SST, which is reconstructed using varying types and distributions of instrumental records. Type I and II regressions do not return statistically independent results, and therefore, type I regressions are used for consistency.

used (Appendix G). Propagating error returns an average error of ±0.4 °C (max = 0.5 °C and min = 0.3 °C) over the long record (Fig. 4.5b).

Comparing the most-recent 50-years of winter-time Sr/Ca based reconstructed SST to Hadley and Hydrostation S winter-time SSTs for 5-year binned averages shows different results than seen with the mean-annual record (Fig. 4.5c). Between 1970 and 1997 both the Hadley instrumental SST (and the coral reconstructed SST which is

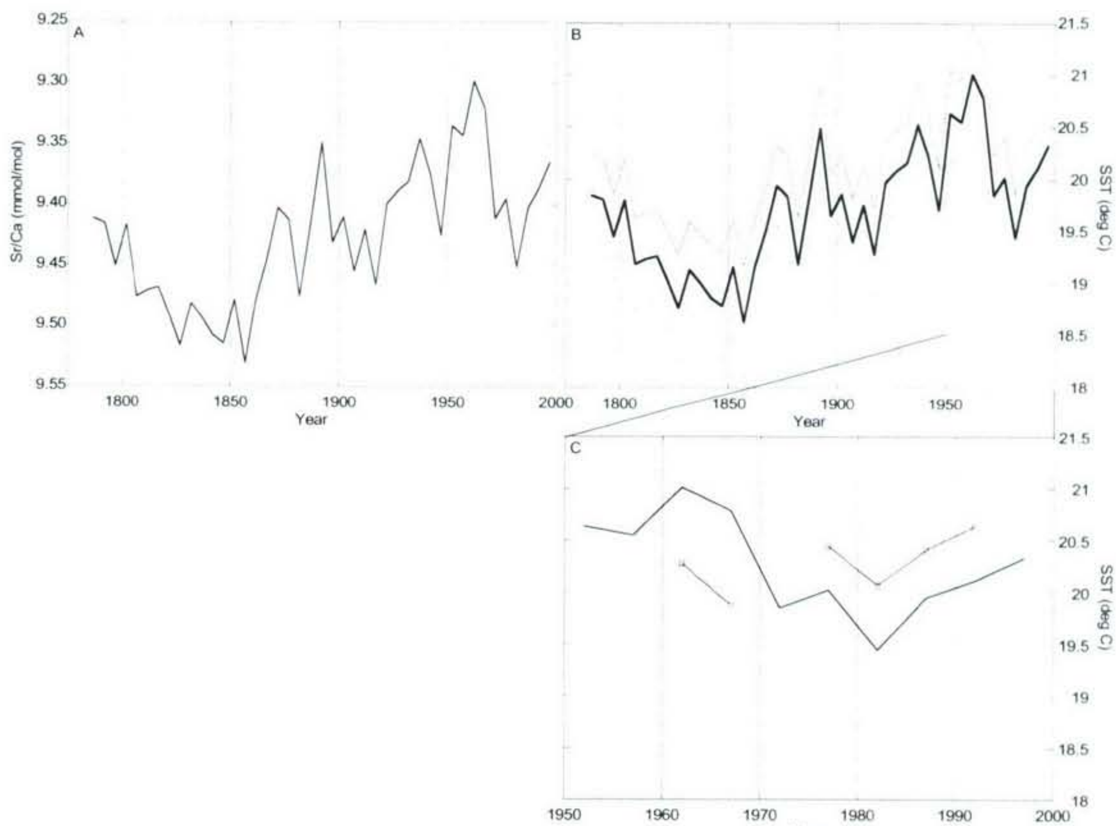


**Figure 4.5:** A) Five-year winter-time Sr/Ca and B) five-year averaged winter-time SST from 1781-1999. C) five-year averaged winter-time SST from 1950-1999 for winter-time SST (solid), Hadley SST (dashed) and Hydrostation S SST (solid, squares). Coral SSTs are reconstructed from Sr/Ca using five year averaged calibration (eqn. 3). Uncertainty resulting from error propagation (1σ) is shown by shaded lines (b).

calibrated to Hadley) agree with the trends of Hydrostation S ($r = 0.97$ and 0.81 respectively) though all three records are offset from one another. The coral record prior to the 1970s is still the warmest of the three records by more than 0.5 °C.

Applying eqn. 3 (Table 4.1) to the Sr/Ca record averaged in five-year bins reconstructs SST at the end of the LIA to be 18.6 °C and to be 21 °C during the time of late 20$^{th}$ century warming (Fig. 4.5a,b). Reconstructed winter-time SST changes between late 20$^{th}$ century warming and the end of the LIA by 2.4 ±0.4 °C, a statistically significant result. The LIA (1840s) is also shown to be 1.5 ±0.4 °C colder than today (1990s instrumental average). Much like the mean-annual record, the warmest temperatures are seen in the 1960s and the coldest temperatures are seen between 1840 and 1860 (Fig. 4.5b).

*Comparison to Instrumental Hadley SST Record:* Comparing both the mean-annual reconstructed SST and the winter-time coral reconstructed SST to Hadley SST (1° x 2° grid) with five-year bins shows similar results (Fig. 4.6). For both the mean-annual and winter-time periods, reconstructed SSTs show largely increased temperature variability relative to the gridded data set throughout the duration of the instrumental record, implying that the bias in our record is to overestimate not underestimate temperature change. In the mean-annual comparison, five year binned instrumental temperature variability from 1871-1997 shows a range of 1 °C whereas the reconstructed SST shows a range slightly greater than 2 °C change ($r = 0.48$). The gridded data and the coral reconstructed SST show no overall trend in temperature from 1871 to 1900, with the reconstructed SST showing much greater variability. Beginning in the early

1900s, both records show increasing temperatures, with the gridded data set peaking in 1959. The reconstructed SST shows a sharper temperature increase in the early 1900s with a distinct cooling during the 1940s and a larger and more extended period of warming in the 1950s and 1960s. Since the 1970s, the records show strong coherence. The periods of greatest disagreement in not only absolute temperature but in temperature trends are during the 1940s to the 1960s, when a disagreement to Hydrostation S is also seen.

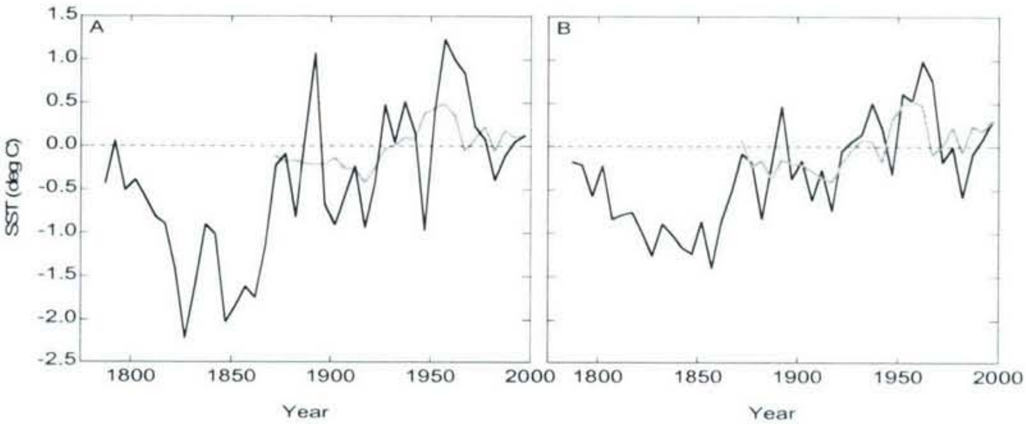


**Figure 4.6:** Five-year average mean-annual SST (a) and winter-SST (b) from coral reconstruction (solid) and Hadley gridded data set (shaded). All four SST records are normalized around each records' 1872-1997 mean.

While not independent because the calibration uses the Hadley instrumental data set, the winter comparison does show similar results as the mean-annual comparison. Five-year binned winter temperature records show a coral based SST range just under 2 °C relative to a 1 °C range for the gridded data set ($r = 0.60$). The instrumental data set shows a slight trend of decreasing temperature from 1871 to 1900, consistent with the coral data set which still shows much greater variability during this time. Similar to the mean-annual records, the winter-time records show generally rising temperatures during the 1900s, with maxima in the 1950s. The winter coral record also peaks later than the winter instrumental data set. Additionally, from 1960s onward the coral is showing cooler temperatures than the instrumental data set, though with similar trends.

There are several factors that could explain some of the temperature differences observed between the Hadley instrumental data product and the reconstructed coral SST records. The first factor is the difference between averaging over many points from a 2° by 1° grid compared to a one point temperature reconstruction. The large scale instrumental record has several sources of error typical of such data sets some of which will serve to dampen variability within its record [*Jones et al.*, 1997b; *Jones et al.*, 2001; *Rayner et al.*, 2003]. The error introduced from changing technology through time is one source of varying error through time with a larger impact the older the data. Non-equal distribution of the number and location of measurements made through out each year and through out the grid can serve to bias the record either seasonally or geographically. Finally, a varying number of samples within the grid through time will produce another source of error.

In addition, the instrumental data are generally collected from off-shore waters rater than shallow coastal where the coral grew. An off-shore water column will average out variability at specific locations, including not only site specific but micro-environmental information. This includes variability from the shallower, well-stratified water, as well as factors such as upwelling at the coral site due to close proximity to a land mass. Additionally, meso-scale eddy processes exert a large influence in this region [*Doney*, 1996; *Sweeney*, 2003]. Three types of eddies are found in the vicinity of

Bermuda supplying both positive and negative temperature anomalies. A 2° by 1° grid box could average eddy temperature anomalies, whereas eddies passing by the coral site over a several months would produce greater variability in SST recorded by the coral.

Although there are concerns as discussed above, we believe that the Sr/Ca-SST calibrations used in this study are robust. Research has shown that calibration error tends to exaggerate temperature change rather than minimize it [*Goodkin et al.*, 2005; *Swart et al.*, 2002]. This is reinforced by the increased variability seen in the coral reconstructions relative to the gridded data. Both the mean-annual and winter-time records show similar variability and similar differences relative to the instrumental data set, following a very different calibration. The coral reconstructed SSTs show changes between the LIA and today of ~2.5 °C between the 1960s and the end of the LIA and of 1.5 °C colder than modern instrumental records. Error propagation suggests these changes are statistically significant. This result implies that some of these discrepancies may result from differences between what the coral experienced locally and what the ocean experienced regionally. This distinction is important for interpreting these results climatologically.

### 4.3.2 $\delta^{18}O$ – SSS

$\delta^{18}O$ of the coral aragonite ($\delta O_c$) is expected to have a negative correlation to SST and a positive correlation to SSS (Fig. 4.8, eqn. 4.4). Trends in mean-annual (-0.0003 ‰/year) and winter-time (<0.0001 ‰/year) $\delta O_c$ are effectively flat over the course of the two hundred year record (Fig. 4.7a,c). Simultaneously, both mean-annual and winter-time Sr/Ca based reconstructed SST show increasing temperatures through time (0.008 °C/year and 0.009 °C/year, respectively) (Fig. 4.7b,d). If $\delta O_c$ were purely a record of

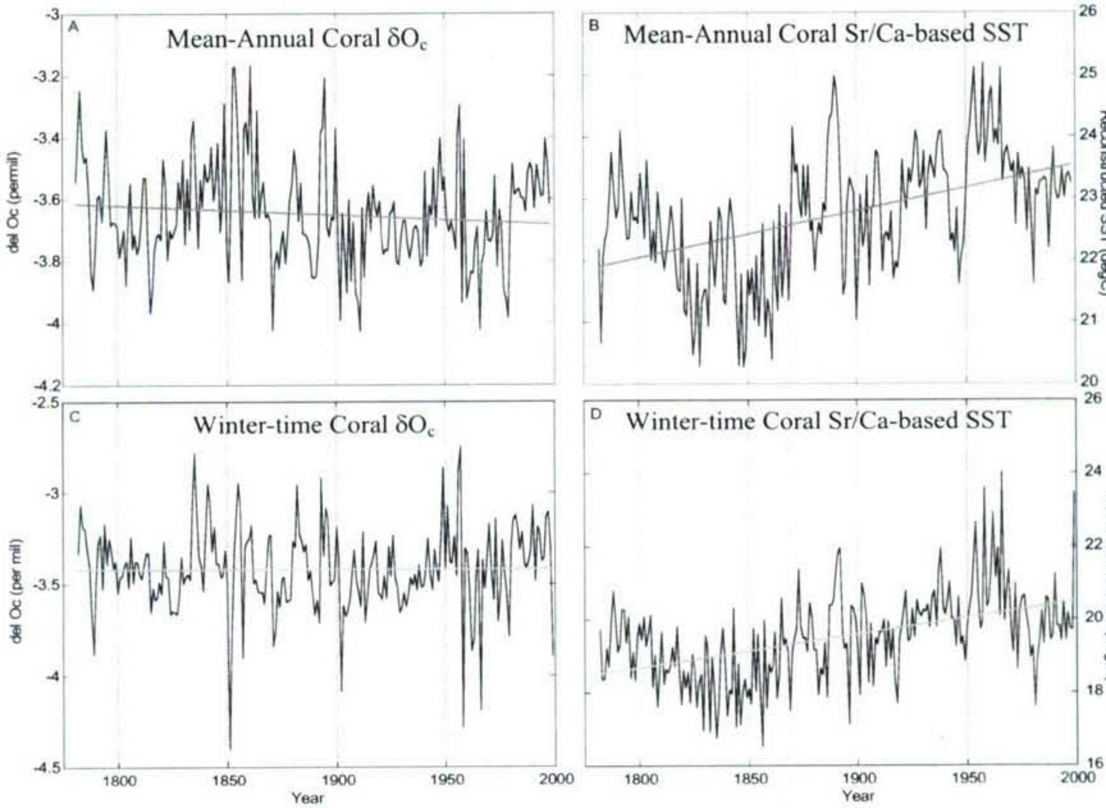


**Figure 4.7:** a) Coral measured mean-annual $\delta O_c$ versus time. b) Coral Sr/Ca based mean-annual reconstructed SST (eqn. 1) versus time. c) Coral measured winter-time $\delta O_c$ versus time. d) Coral Sr/Ca based winter-time reconstructed SST (yearly, eqn. 2) verus time. Linear regressions of each parameter versus time are shown by shaded lines.

SST, a stronger negative trend (more than order of magnitude steeper as predicted by eqn. 1 in Chapter 1) would be visible in the $\delta O_c$ records. In addition, a strong LIA cooling is seen in both Sr/Ca generated SST records, whereas the mean-annual $\delta O_c$ shows minimal indication of this cooling and winter-time shows no indication of this cooling. Therefore, to a first order approximation, Fig. 4.7 implies that both mean-annual and winter-time yearly SSS was lower (fresher) during the end of the LIA than it is today. Because $\delta O_c$ is directly related to SSS, a salinity signal will serve to oppose the expected SST based trend in the $\delta O_c$. The lack of a strongly decreasing trend in the mean-annual record and the presence of a slightly increasing trend in the winter-time $\delta O_c$ measurements imply that $\delta O_c$ is being impacted by increasing SSS over the length of the record.

In the following three sub-sections, we show that with the present coral record and calibration data set, we are unable to derive a robust quantitative estimate of paleo-salinity. There are several reasons that may prevent the quantification of these relationships. The most likely cause is the lack of instrumental data documenting large enough changes in SSS. Over the length of Hydrostation S, salinity (mean-annual and winter) has a range of 0.3 psu and inter-annual temperatures have a range of 2 °C. The SSS range is a very small range over which to establish a significant relationship that is impacted by more than one variable.

There are also several parameters that may be adding variability to the system, which given the small SSS signal makes calibration more difficult. As previously discussed with regards to regional SST records, eddy activity in the region can also alter salinity [*Doney*, 1996]. Eddies could lead to differences between SSS at the coral and Hydrostation S thus adding unexplained variability over the limited calibration period. Furthermore, vital effects and growth rates may be causing varying fractionation of $\delta O_c$ during the calibration. While we were unable to model such effects, if they exist they could further convolve the SSS signal. In the end, we are unable to quantitatively reconstruct salinity. However, the raw data give a strong indication that Bermuda's sea water was fresher during the LIA.

*Monthly Relationships:* Growth rate and bulk sampling effects limit our ability to evaluate $\delta^{18}O$ as an SSS proxy on monthly time-scales. However, for proper comparison to the literature we examine the $\delta^{18}O$ data on monthly time-scales. The $\delta^{18}O$ of the coral

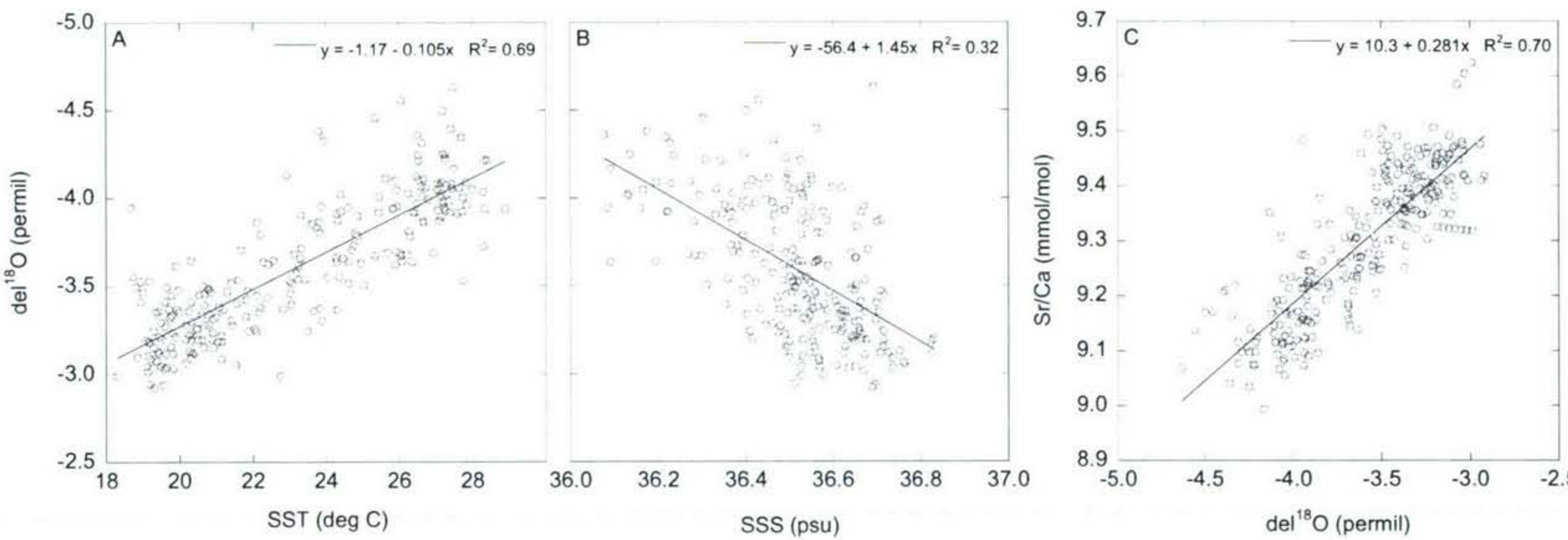


**Figure 4.8**: Monthly BB 001 measurements from 1976-1997. a) $\delta^{18}O$ regressed linearly against monthly Hydrostation S SST and b) SSS. Monthly BB 001 Sr/Ca regressed against $\delta^{18}O$.

($\delta O_c$) is shown to be negatively correlated to SST and positively correlated to SSS at Hydrostation S (Fig. 4.8). Over the calibration period, monthly coral $\delta^{18}O$ values range from -4.63 to -2.92 ‰. The correlation coefficient ($r^2$) of $\delta O_c$ to SST is 0.69. The correlation coefficient ($r^2$) of $\delta O_c$ to salinity is 0.32. The correlation between SST and SSS ($r^2 = 0.31$) over this time period is likely to impact these correlations making them less independent. The correlation of $\delta^{18}O$ to Sr/Ca ($r^2 = 0.70$) is strong, as expected from both proxies' dependence on SST.

Regressions of monthly $\delta^{18}O$ to SST and monthly Sr/Ca to $\delta^{18}O$ are regularly reported in the literature. Reported $\delta^{18}O$ to SST slopes range from -0.101 to -0.179 ‰/°C [*Bagnato et al.*, 2004; *Cardinal et al.*, 2001; *deVilliers et al.*, 1995; *Dunbar et al.*, 1994; *Gagan et al.*, 1998; *Guilderson et al.*, 1994; *McCulloch et al.*, 1994; *Smith et al.*, 2006; *Watanabe et al.*, 2003]. The slope of -0.105 ‰/°C found in this study is at the low end of reported results. Reported Sr/Ca to $\delta^{18}O$ slopes range from 0.27 to 0.30 mmol/mol/‰ (with one reported value of 0.18 [*Cardinal et al.*, 2001] from a coral growing less than 3 mm/year) [*Beck et al.*, 1992; *Cardinal et al.*, 2001; *McCulloch et al.*, 1994; *Smith et al.*, 2006], equivalent to our slope of 0.28 mmol/mol/‰.

Kinetic disequilibrium models indicate that slow growing corals should more closely approach thermodynamic equilibrium than faster growing corals [*McConnaughey*, 1989a; *McConnaughey*, 1989b]. While slow growing corals will exhibit enrichment in $^{16}O$ relative to other marine organisms, fewer growth (kinetic) effects during calcification are expected to impact the $\delta^{18}O$ of these slow-growing coral species. This should include effects found within and between colonies [*deVilliers et al.*, 1995; *Guilderson and Schrag*, 1999; *Linsley et al.*, 1999; *McConnaughey*, 1989b; *McConnaughey*, 2003]. However, in addition to kinetic effects, the $\delta^{18}O$ of slow-growing corals will be further complicated by growth structure and smoothing during bulk sampling [*Cohen et al.*, 2004; *Goodkin et al.*, 2005; *Swart et al.*, 2002]. Therefore, when examining oxygen isotopes to investigate salinity, consideration of inter-annual changes (rather than monthly changes) is critical.

*Mean-Annual Relationship:* The relationship between $\delta^{18}O$, SST, and SSS is analyzed over the same time period as Sr/Ca, from 1976-1997 with the exclusion of years missing instrumental data. First, $\delta^{18}O$ of the water ($\delta O_w$) was calculated using Hydrostation S SSS instrumental data and the following thermocline equilibrium equation [*Schmidt*, 1999]:

$$\delta O_w = 0.49 * (SSS) - 17 \qquad \text{eqn. (4)}$$

A limited set of measurements of $\delta O_w$ (‰) and salinity (psu) from the Bermuda Atlantic Time Series (BATS) and from Surf Bay Beach, Bermuda indicate this to be a sound assumption (Appendix F).

Mean-annual $\delta O_c$ has the expected negative relationship to SST and positive correlation to $\delta O_w$ (SSS) (Fig. 4.9a,b). Therefore, we began by using a multivariate model in which $\delta O_c$ (‰) was linearly regressed against SST (°C) and $\delta O_w$ (‰):

$$\delta O_c = -0.138\ (\pm 0.250) * SST + 0.990\ (\pm 1.35) * \delta O_w - 1.26\ (\pm 5.47)$$

$$(2\sigma,\ 95\%\ \text{conf.},\ r^2 = 0.17,\ F_{sig} = 0.3092,\ \text{rmsr of}\ \delta O_w = 0.098\ ‰,$$

$$\text{se on}\ \delta O_c = 0.108\ ‰) \qquad \text{eqn. (5)}$$

Statistically this regression is insignificant ($F_{sig}$>0.01). In examining Fig. 4.9, we can see the impacts of using this regression to reconstruct salinity. Equation 5 does not sufficiently describe the $\delta O_c$, underestimating the range seen during the calibration period,

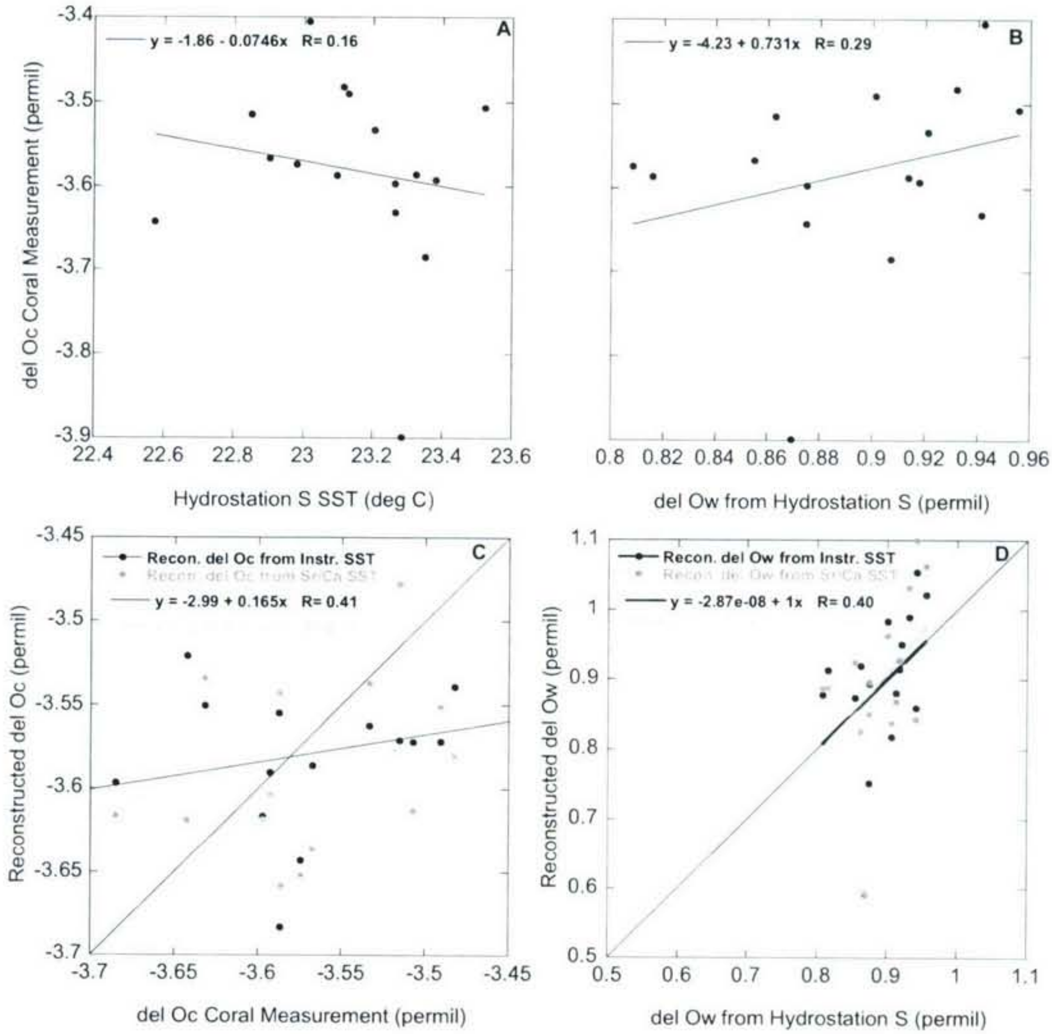


**Figure 4.9:** Results of a multivariate regression of mean-annual $\delta O_c$ versus SST and $\delta O_w$. a) Coral measured $\delta O_c$ versus Hydrostation S SST. b) Coral measured $\delta O_c$ versus Hydrostation S $\delta O_w$ (SSS). c) Reconstructed $\delta O_c$ using eqn. 5 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_c$. d) Reconstructed $\delta O_w$ using eqn. 5 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_w$.

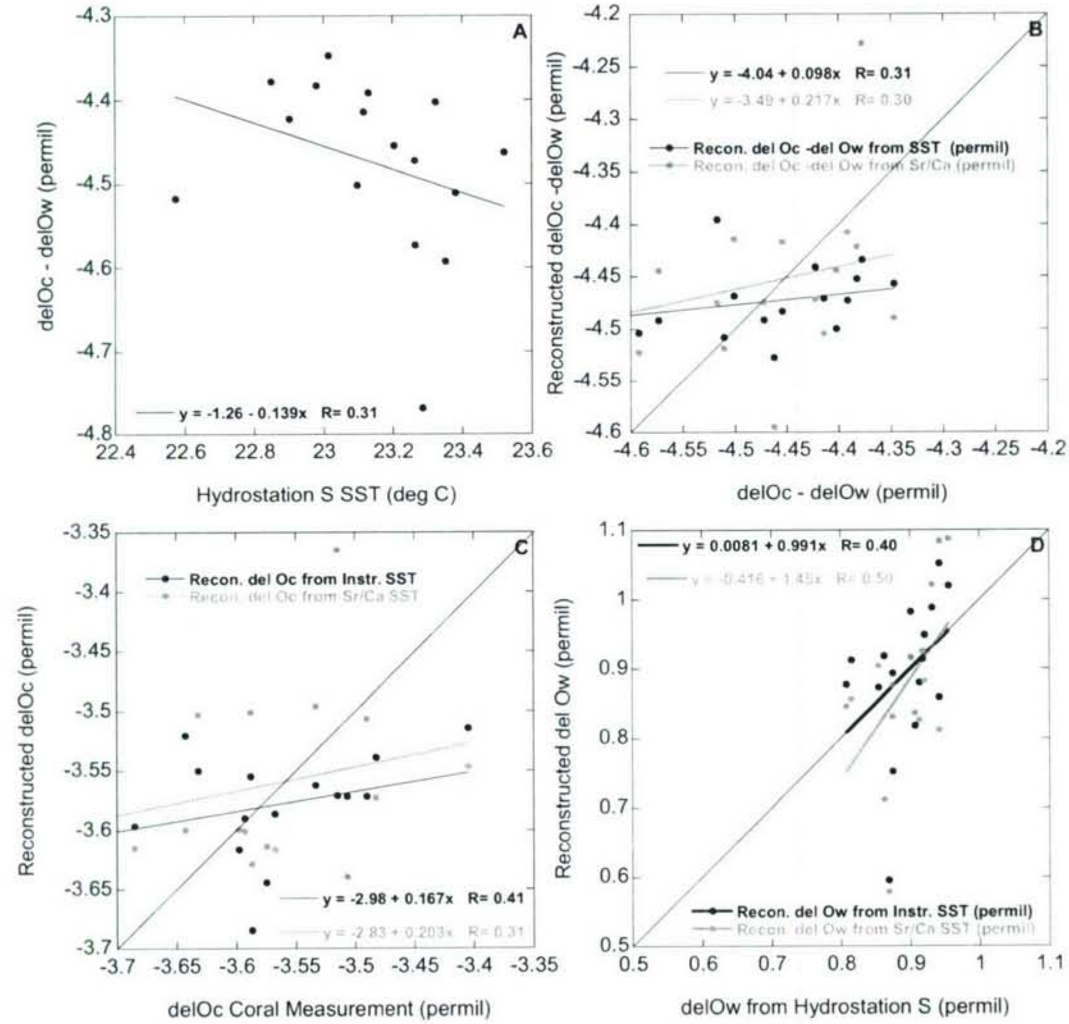


**Figure 4.10:** Results of a single variate regression of mean-annual $\delta O_c - \delta O_w$ versus SST. a) Coral measured $\delta O_c - \delta O_w$ versus Hydrostation S SST. b) Reconstructed $\delta O_c - \delta O_w$ using eqn. 6 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_c$. c) Reconstructed $\delta O_c$ using eqn. 6 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_c$. d) Reconstructed $\delta O_w$ using eqn. 6 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_w$.

when either Hydrostation S or Sr/Ca-based SST is used with Hydrostation S $\delta O_w$ (Fig. 4.9c). $\delta O_w$ is also calculated by inverting equation 5 and using both Hydrostation S and Sr/Ca-based SST with the measured $\delta O_c$. The model dictates that reconstructed $\delta O_w$ over the calibration period will have a 1:1 relationship with the instrumental based $\delta O_w$ (Fig. 4.9d). However, the range of reconstructed $\delta O_w$ (0.6 – 1.1 ‰) overestimates the range seen at Hydrostation S (0.8 – 1.1‰) by a factor of 3 and the RMSR error of the reconstructed $\delta O_w$ is very large.

Therefore, we developed a second model. In this model, instead of regressing $\delta O_c$ vs both SST and $\delta O_w$, we subtracted $\delta O_w$ (‰) from $\delta O_c$ (‰) and linearly regressed the difference against SST (°C). Linear regression of $\delta O_c - \delta O_w$ versus SST returns the following result:

$$\delta O_c - \delta O_w = -0.139\ (\pm 0.226) * (SST) - 1.26\ (\pm 5.22)$$

$$(2\sigma,\ 95\%\ conf.,\ r^2 = 0.10,\ F_{sig} = 0.2378,\ rmsr\ of\ \delta O_w = 0.10‰,$$

$$se\ on\ \delta O_c - \delta O_w = 0.104‰) \qquad \text{eqn. (6)}$$

At a 95% confidence interval, this equation is also insignificant, and has a larger rmsr of $\delta O_w$ than does eqn. 5. One potential problem with this method is that we are differing two large values ($\delta O_c$ and $\delta O_w$) to calculate a small residual, and if the errors in $\delta O_c$ and $\delta O_w$ are large, than we have little constraint on the resulting difference.

Figure 4.10 shows that switching to a single variant regression of $\delta O_c$ - $\delta O_w$ vs. SST does not improve the relationship. As shown in Fig. 4.10d, $\delta O_w$ variability is still overestimated and error in reconstructed $\delta O_w$ remains large. It is important to mention that the inclusion of growth rate in either of these regressions (eqns. 5 or 6) does not improve the significance. In addition, the added growth rate term is never statistically significant (p is never <0.1). This result implies that either growth rate has a much smaller impact on $\delta^{18}O$ relative to SST and SSS than it does on Sr/Ca relative to SST or that the added noise of the $\delta^{18}O_c$ coral record from salinity or vital effects cannot be fully described by growth.

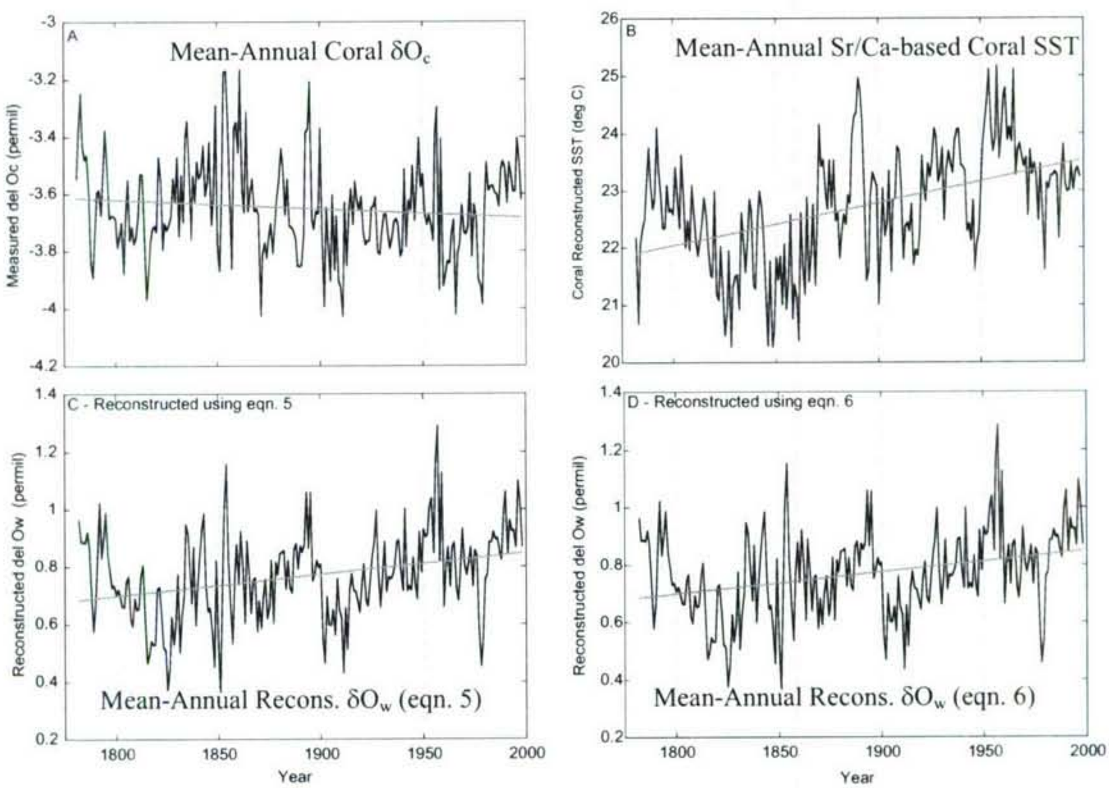


**Figure 4.11:** Two hundred year records of mean-annual data or derived records of a) Coral measured $\delta O_c$, b) Coral-based Sr/Ca reconstructed SST, c) Reconstructed $\delta O_w$ using eqn. 5 and coral-based Sr/Ca reconstructed SST, d) Reconstructed $\delta O_w$ using eqn. 6 and coral-based Sr/Ca reconstructed SST. Linear trends with time are shown by shaded lines.

As previously described, mean annual $\delta O_c$ shows a flat or slightly decreasing trend (-0.0003 ‰/year) from 1782-1998, and coral Sr/Ca-based reconstructed SST shows an increasing trend (Fig. 4.11). Because the $\delta O_c$ does not show a strong trend opposing the SST trend, the two records imply that historical mean-annual SSS ($\delta O_w$) should be fresher than today. Both equations 5 and 6, which return very similar results, applied to the 218 year record of $\delta O_c$ using coral SST estimates demonstrate a trend of increasing SSS ($\delta O_w$) from the late 1700s to today. However, due to the lack of significance in either regression model, we are unable to robustly transform the results into a quantitative salinity change over this period.

*Winter Relationship:* The relationship between winter-time (Dec.-March) $\delta^{18}O$, SST and SSS is evaluated over the same calibration time period as mean-annual $\delta^{18}O$ (1976-1997). Winter trace element ratios have shown no growth impacts, and therefore, are expected to have less vital and or sampling effects than the mean-annual reconstruction. The same two models are used as for the mean-annual calibrations. Beginning by describing $\delta O_c$ (‰) as a function of both SST (°C) (Fig. 4.12a) and $\delta O_w$ (Fig. 4.12b). The multi-variant regression returns the following result:

$$\delta O_c = -0.117\ (\pm 0.100)*(SST) + 1.48\ (\pm 1.42)*(\delta O_w) - 2.28\ (\pm 2.26)$$

$(2\sigma$, 95% conf., $r^2 = 0.34$, $F_{sig} = 0.0299$, rmsr of $\delta O_w = 0.08‰$,

se = 0.125 ‰) eqn. (7)

The winter-time results for the multi-variant regression are comparable to the mean-annual results. The relationship described by eqn. 7 is statistically significant. $\delta O_c$, calculated with Hydrostation S $\delta O_w$ and either Hydrostation S and Sr/Ca-based reconstructed SST with Hydrostation S both underestimate variability relative to the $\delta O_c$ of the coral (Fig. 4.12c). Reconstructed $\delta O_w$ both with SST records and the coral $\delta O_c$ show the expected (or close to expected) ratio of 1:1 relative to the Hydrostation S $\delta O_w$. However, the $\delta O_w$ reconstructed range of 0.7-1.1 ‰ is close to three times the instrumental range of 0.8-1.0 ‰ (Fig. 4.12d) and size of the error is substantial relative to the signal. The winter-time multi-variant regression fails to describe the $\delta O_c$-SST-$\delta O_w$ relationship.

We also investigated the single variant model in which $\delta O_c$ - $\delta O_w$ is regressed against SST. A linear regression of $\delta O_c$ - $\delta O_w$ (‰) versus winter-time SST (°C) returns the following results (Fig. 4.13):

$$\delta O_c - \delta O_w = -0.112\ (\pm 0.097) * (SST) - 1.93\ (\pm 1.98)$$

$(2\sigma$, 95% conf., $r^2 = 0.23$, $F_{sig} = 0.0331$, rmsr of $\delta O_w = 0.12$ ‰,

se of $\delta O_c = 0.123$ ‰) eqn. (8)

At a 95% confidence interval, this equation is significant, with a large amount of noise amongst the data (Fig. 4.13a). Using either the instrumental or Sr/Ca-based reconstructed SST, the $\delta O_w$ is still not accurately reconstructed with a range of 0.6-1.2 ‰ compared to the Hydrostation S $\delta O_w$ range of 0.8-1.0 ‰ (Fig. 4.13d). All of the $\delta O_c$ regressions serve to underestimate variability in $\delta O_c$ and overestimate variability in $\delta O_w$.

Ideally, we could examine these data over average periods as was done with the winter Sr/Ca to reduce the influence of noise. However, due to limited salinity data this will reduce the number of points in the regression, diminishing statistical evaluations.

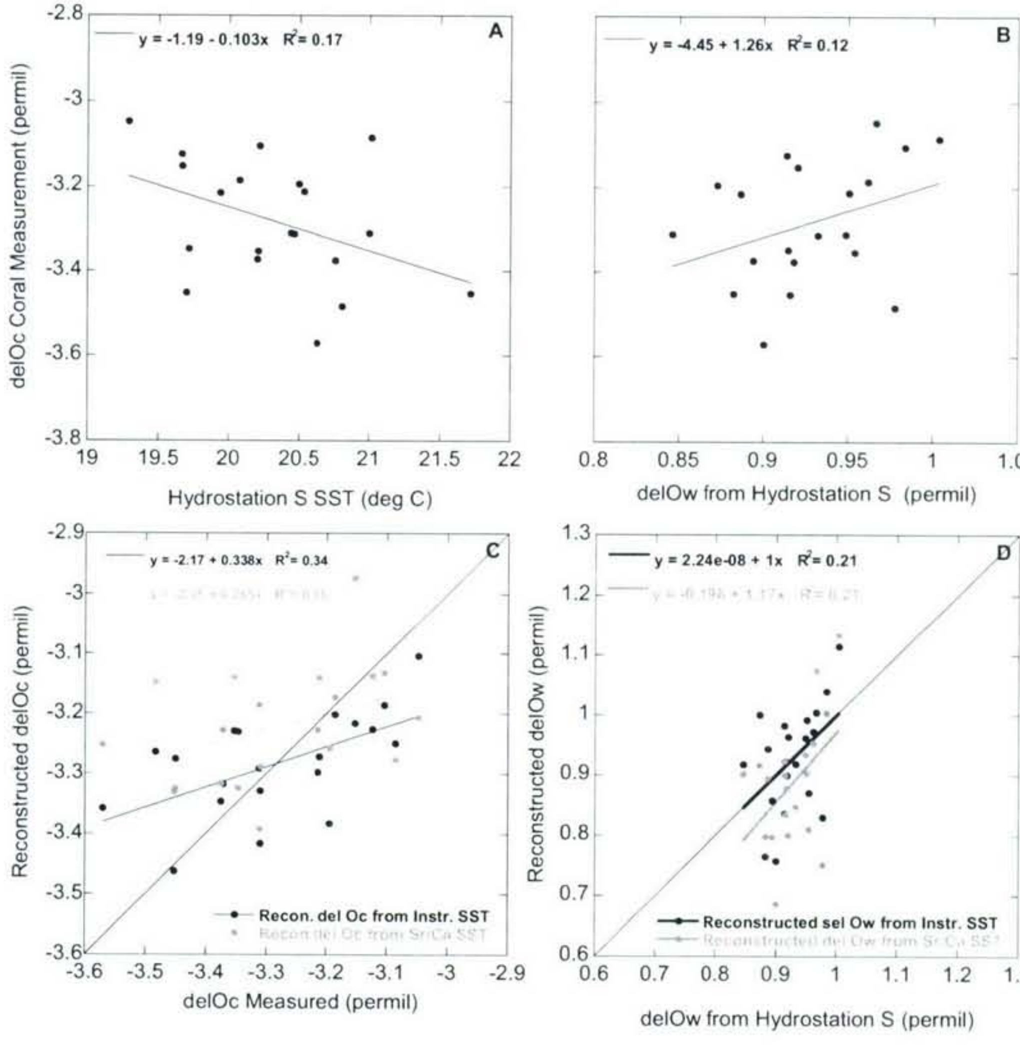


**Figure 4.12:** Results of a multivariate regression of winter-time $\delta O_c$ versus SST and $\delta O_w$. a) Coral measured $\delta O_c$ versus Hydrostation S SST. b) Coral measured $\delta O_c$ versus Hydrostation S $\delta O_w$. c) Reconstructed $\delta O_c$ using eqn. 7 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_c$. d) Reconstructed $\delta O_w$ using eqn. 7 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_w$.

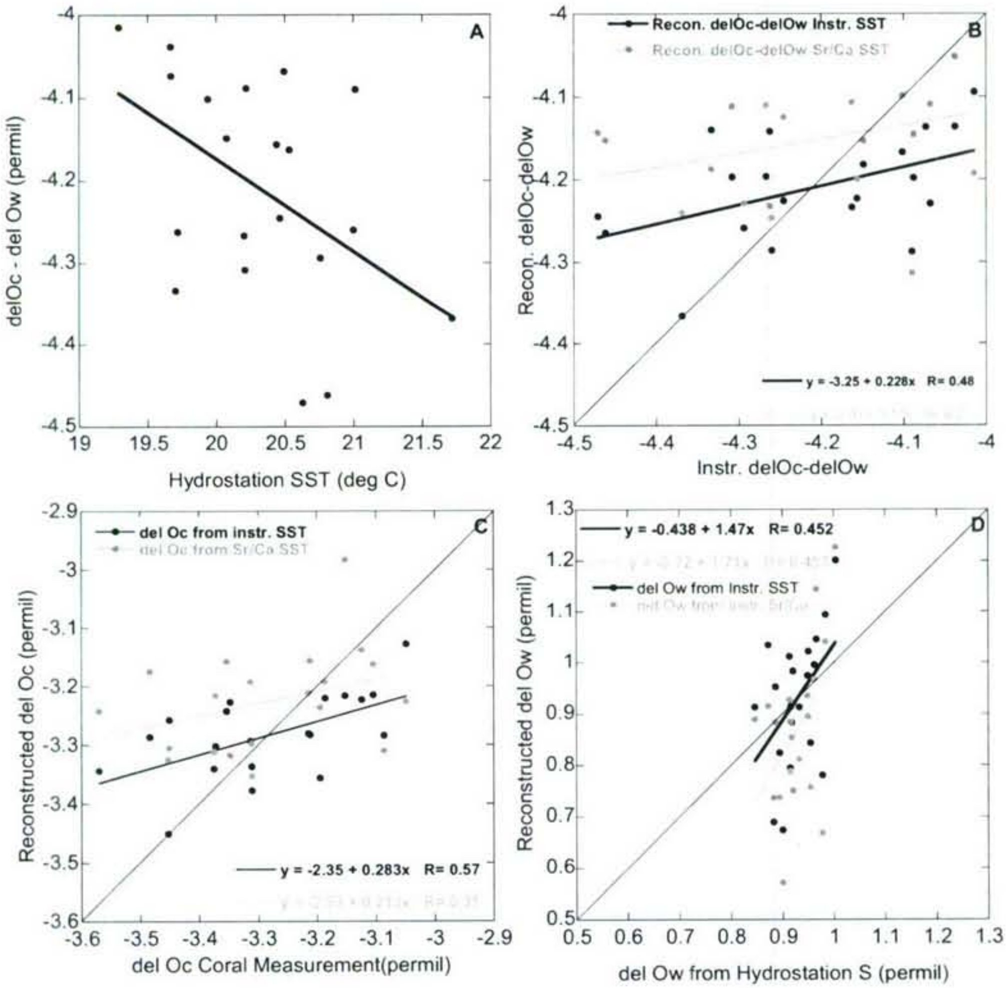


**Figure 4.13:** Results of a single variant regression of winter-time $\delta O_c - \delta O_w$ versus SST. a) Coral measured $\delta O_c - \delta O_w$ versus Hydrostation S SST. b) Reconstructed $\delta O_c - \delta O_w$ using eqn. 8 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_c$. c) Reconstructed $\delta O_c$ using eqn. 8 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_c$. d) Reconstructed $\delta O_w$ using eqn. 8 and both Hydrostation S SST (solid) and coral Sr/Ca reconstructed SST (shaded) versus measured $\delta O_w$.

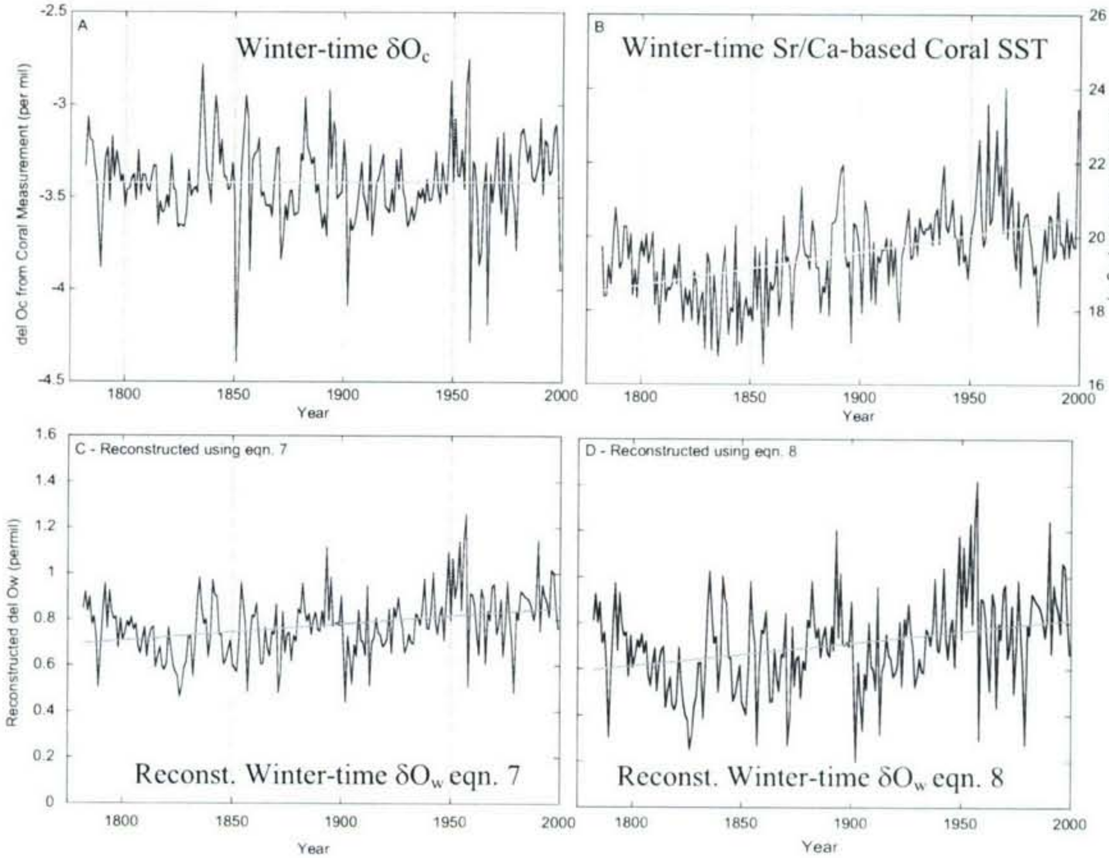


**Figure 4.14:** Two hundred year records of winter-time data or derived records of a) Coral measured $\delta O_c$, b) Coral-based Sr/Ca reconstructed SST, c) Reconstructed $\delta O_w$ using eqn. 7 and coral-based Sr/Ca reconstructed SST, d) Reconstructed $\delta O_w$ using eqn. 8 and coral-based Sr/Ca reconstructed SST. Linear trends with time are shown by shaded lines.

The winter-time 218 year long record shows strong qualitative results in agreement with mean-annual record. $\delta O_c$ shows a slightly increasing or no trend through time (Fig. 4.14a) which combined with an increasing trend in the Sr/Ca-based reconstructed SST implies an increasing salinity ($\delta O_w$) from the late 1700s until today. Both models overestimate variability in $\delta O_w$, and therefore, cannot be used as a quantitative tool for reconstructing SSS. However, both models do return the expected result of increasing salinity, confirming the first order interpretation of the data.

## 4.4 Discussion

### 4.4.1 Climate and Ocean Trends at Bermuda

The Bermuda coral record shows temperature at the end of the LIA to be 1.6 °C cooler than the end of the twentieth century instrumental record. Simultaneous to the LIA cooling and 1950s-1960s warming, $\delta^{18}O_c$ suggests fresher and saltier water, respectively (Fig. 4.7).

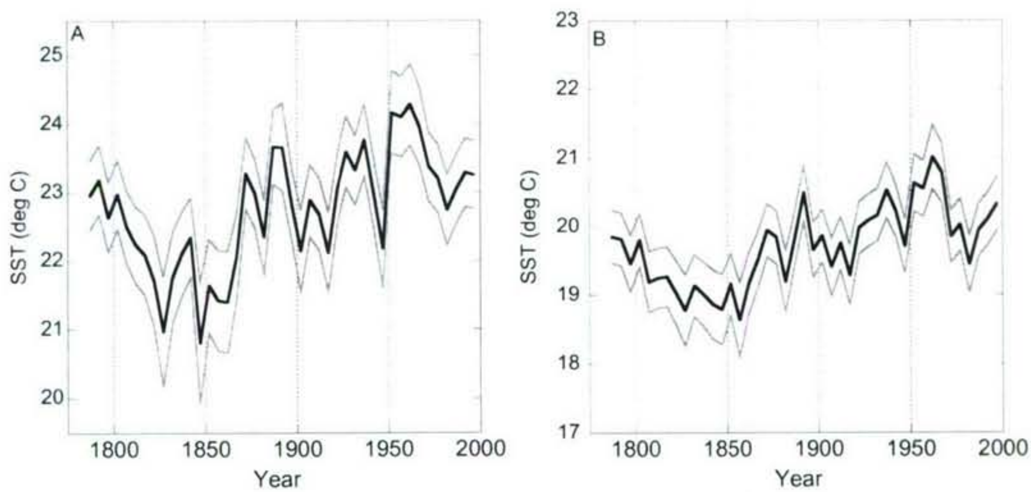


**Figure 4.15:** A) Coral based reconstructed mean-annual SST. B) Coral based reconstructed winter-time SST. Both reconstructions shown in five year averages (solid) with propagated error (shaded).

Temperature trends at Bermuda from this study are in good agreement with trends from other Bermuda coral records. Draschba et al. (2000) show maximum coral $\delta^{18}O$ of ~-3.2 ‰ (minimum temperature) from 1840-1845 and around ~1855 and minimum $\delta^{18}O$

of ~-3.7 ‰ (maximum temperature) at ~1870 [*Draschba et al.*, 2000], in agreement with trends and mean-annual $\delta^{18}O$ values seen in this study (Fig. 4.7). A foraminifera $\delta^{18}O$ Bermuda temperature reconstruction shows a temperature increase of 1.5 °C from the LIA to today [*Keigwin*, 1996], in agreement with the statistically significant change (1.6 °C) found here for both the mean-annual and winter-time SST reconstructions (Fig. 4.15).

The temperature and salinity trends are similar to trends found from sclerosponges collected off the Bahamas (140m depth) that show both increasing temperature (1.6 – 2.0 °C) and salinity (~1 psu) from 1890-1990 [*Rosenheim et al.*, 2005]. Another study from the Bahamas using foraminifera to reconstruct salinity records from the eastern side of the Florida current generally show increasing salinity since the LIA [*Lund and Curry*, 2006].

Several records of SST from proxy reconstructions exist from a variety of locations across the Atlantic. Two coral records near Puerto Rico show temperature changed in the Caribbean Sea between 2 to 3 °C from the LIA to present day [*Watanabe et al.*, 2001; *Winter et al.*, 2000]. A foraminifera based reconstruction in the eastern sub-tropical Atlantic shows larger SST changes (on the order of 3-4 °C) from the LIA to present [*deMenocal et al.*, 2000]. Surface temperature proxy reconstructions based on arctic ice cores show a temperature minimum around 1850 with a rapid increase of ~ 1 °C immediately following the minimum [*Dahl-Jensen et al.*, 1998]. Combined, all of these single location records show that the sub-tropical gyre in the mid-latitudes experienced a large temperature increase between the end of the LIA and today.

Regional surface temperature records from the Northern Hemisphere [*Jones et al.*, 1998] and Arctic [*Overpeck et al.*, 1997], all smoothed over 30-years using a running mean, show a lower magnitude of total temperature change from the temperature minimum in the 1850s to today (~1 °C) compared to the coral record (1.5 °C) (Fig. 4.16). However, these records and the coral record all show very similar patterns of increasing temperature with time from the LIA to present. Correlation coefficients between the Sr/Ca-derived mean-annual SST record and the Arctic and Northern Hemisphere records are 0.40 and 0.47 respectively for the mean-annual records. Each of the records achieves minimum temperatures at the end of the LIA (between 1800 and 1850), followed by warming to maximum averaged temperatures in the 1950s and 60s. Two cool periods are seen in the early 1800s in all records, with an offset of ~10 years in timing between the coral record and the atmospheric records. We believe this is possibly related to a combination of age model error in the coral record and a delayed ocean response to atmospheric cooling. The offset may provide an upper limit of 10-15 years on the error of the age model. A pronounced drop in temperature in the 1970s following the peak warmth (1960) is apparent, primarily in the Bermuda and Arctic records (Fig. 4.16).

Smoothing the records with a 30-year box filter reveals strong coherence in the timing of temperature changes of the past 200 years among all of the proxy records (Fig. 4.16). One large discrepancy between the records occurs between 1870 and 1900, when the Bermuda record shows warming not seen in the other records. The agreement between the smoothed regional records and coral reconstruction is highly significant, with correlation coefficients of 0.86 between the coral record and each regional synthesis.

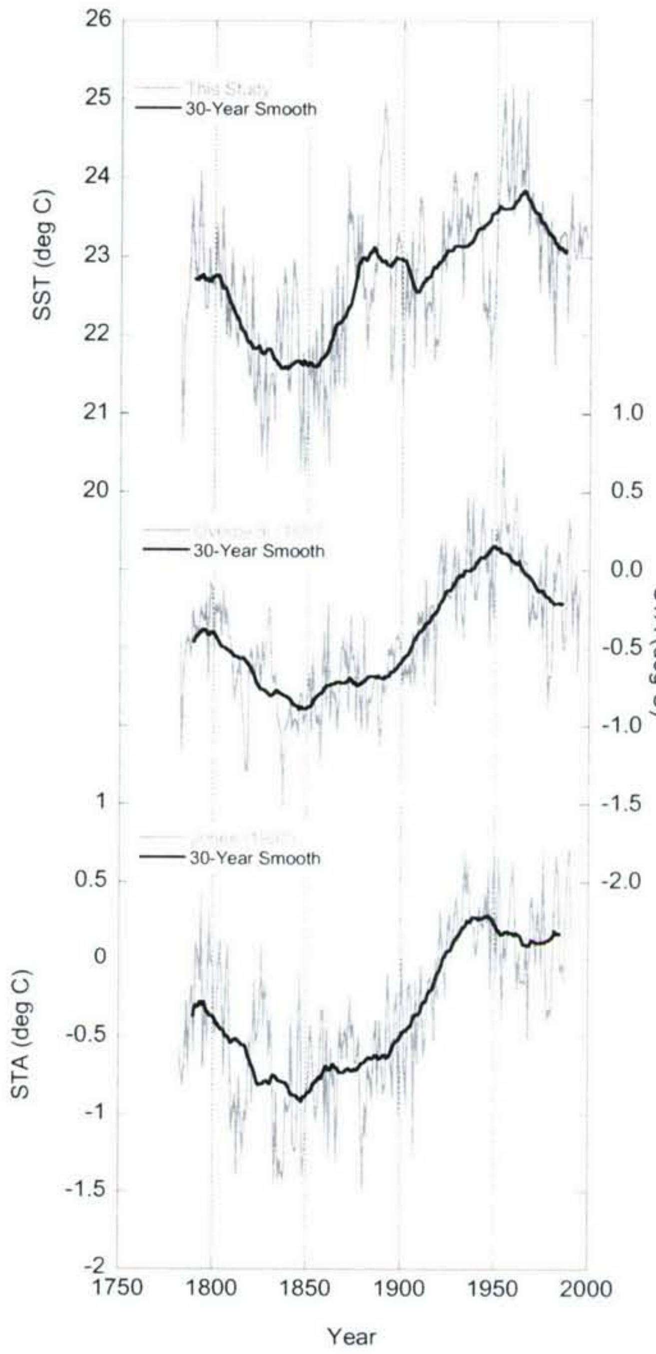


**Figure 4.16**. Mean-annual reconstructed SST from coral Sr/Ca, Arctic land reconstructed record (Overpeck et al., 1997) and Northern Hemisphere land reconstructed record (Jones et al., 1998) (all shaded) and then filtered over 30 years (solid). Coral reconstruction (top) compared to Overpeck et al. (1997) (middle, r = 0.40) and to Jones et al. (1998) (bottom, r = 0.47). The structure of the coral reconstruction as defined by the 30-year running average agrees with Overpeck (1997) (r = 0.86) and Jones (1998) (r = 0.86) after the low-pass filter, despite a difference in the magnitude of the temperature change (2.5 °C vs. 1.5 °C).

While all of the records (regional and local) show cooling in the mid-1800s consistent with a northern hemisphere response mostly due to radiative forcing, the range of temperature changes suggest differing local responses that may be due to process such as changing ocean circulation and the North Atlantic Oscillation (NAO).

### 4.4.2 Influences on Observed Variability

Temperature and salinity changes at Bermuda are likely due to a combination of atmospheric forcing and ocean circulation changes. The largest events over the past 200 years are the end of LIA cooling and 20$^{th}$ century warming, coupled with changes in salinity interpreted from the $\delta O_c$. Several possible influences may have contributed to these changes, including anthropogenic, solar and volcanic forcing. Changes in the strength of the Gulf Stream and the relative influence of tropical, sub-polar, and sub-tropical gyre waters may also be a factor [*Lund et al.*, 2006; *Talley*, 1996]. Additionally, the NAO has been hypothesized to have large influences on the climate of the North Atlantic Basin from the time of the LIA to the modern day [*Luterbacher et al.*, 1999], and may contribute to the differences in reconstructed temperature patterns seen throughout the Atlantic (see also Chapter 5). Local changes in ocean vertical mixing rates may also be a critical factor affecting SST at Bermuda [*Druffel*, 1997].

With respect to records of atmospheric and ocean forcing, multiple mechanisms appear to have a potential influence on temperature at Bermuda. Coral reconstructed SST is positively correlated to a global proxy reconstruction of solar activity [*Lean et al.*, 1995] ($r = 0.34$) (Fig. 4.17). Cross-spectral analysis performed using a multi-taper method with 10 windows [*Huybers*, 2003] shows significant correlation at sub-decadal and multi-

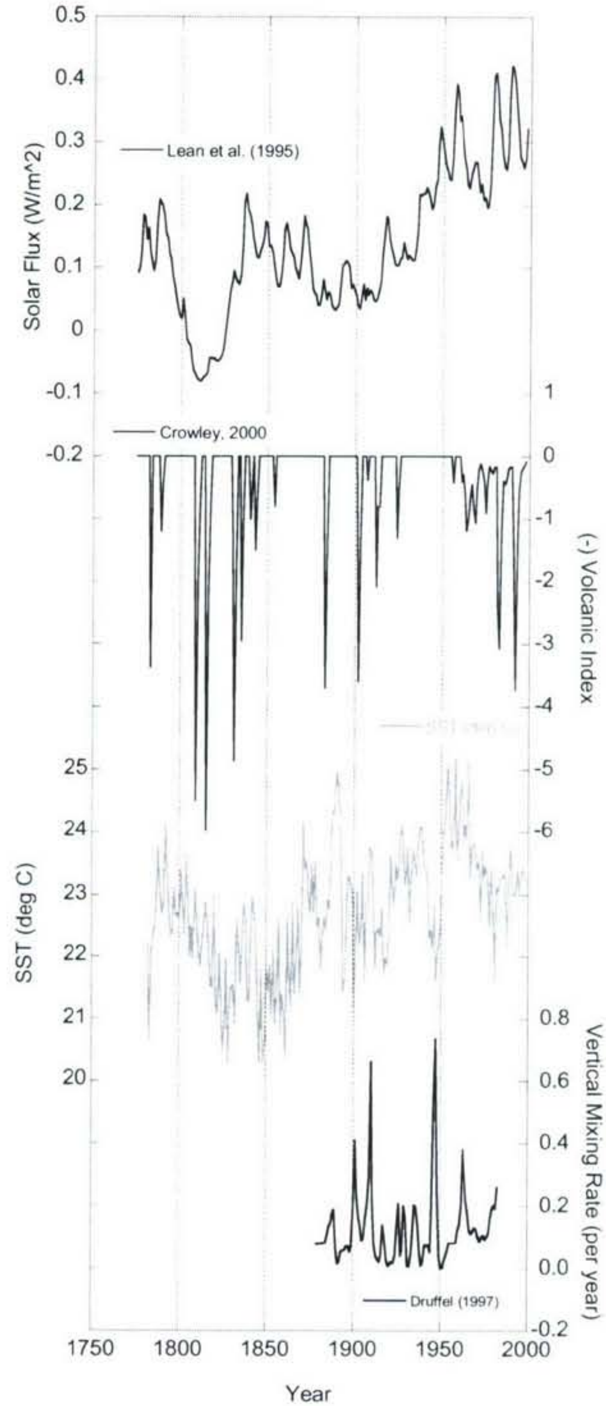


**Figure 4.17**: Records of potential forcing influences on temperature. Annual solar flux (W/m$^2$) proxy [*Lean et al.*, 1995] (top), annual volcanic index (x(-1)) [*Crowley*, 2000] (second), mean-annual reconstructed SST (this record) (°C) (third), and mean-annual reconstructed vertical mixing rates (per year) at Bermuda [*Druffel*, 1997].

decadal frequencies (2.5 years per cycle, $r = 0.55$ and >20 years per cycle, $r > 0.45$ respectively). At high frequencies the two records are in phase with one another, whereas at low frequencies, reconstructed SST lags estimated solar forcing. The lag at low frequencies is likely a combination of the heat capacity of water, ocean mixing and circulation, which could serve to dampen the oceanic response to atmospheric forcing, as well as potential bias in the coral age model.

A sharp decline in estimated solar forcing which begins in the 1790s and continues until the 1830s, coincides with the beginning of late LIA cooling seen in the coral record. However, the lowest SST temperatures are seen after the decline in solar flux has begun to return to pre-1790 values. Estimated solar activity and SST both reach maximum values in the late 1950s, although solar activity shows two more maxima in the 1980s-1990s, and SSTs do not reach maximum values during these periods [*Crowley*, 2000] (Fig. 4.17).

Volcanic activity is believed to cause decreased surface temperatures for 2-4 years post eruption depending on size and location, due to ash and $SO_2$ in the atmosphere blocking solar activity from reaching earth (e.g. [*Wigley et al.*, 2005]). Minimum temperatures at Bermuda are seen during and following times of increased volcanic activity (Fig. 4.17). At the end of the 20$^{th}$ century, anomalously cool temperatures occur at a time of increased anthropogenic forcing and increased estimated solar activity, when relatively warmer temperatures would be expected. During this time an extended period of high to moderate volcanic activity is observed and may have contributed to decreased temperatures at this time [*Crowley*, 2000]. An increased volcanic index value [*Crowley*, 2000] also precedes sharp inter-annual temperature changes and occurs during extended decadal cooling at the end of the LIA from 1820 to 1860. The lack of exact synchronicity of these periods may be due to errors in the age model, which would lead to the actual temperature drops occurring earlier in time and in closer proximity to the volcanic events. Atmospheric forcing in the form of solar flux and volcanic activity is impacting the ocean at this site. Strong correlations are seen between solar, volcanic and atmospheric temperature records and the Bermuda SST record, indicating an atmospheric influence on this location.

There is also evidence that increased vertical mixing rates at this location may contribute to ocean temperature trends (Fig. 4.17). Increased mixing will serve to entrain deeper, colder water at the surface [*Druffel*, 1997] and is reconstructed using $\Delta^{14}C$ in corals. A high frequency correlation is seen between periods of extended increased vertical mixing and similarly long periods of decreased temperatures (Fig. 4.17), including the 1940s and late 20$^{th}$ century. However, corresponding changes in salinity and SST implied by the $\delta O_c$ variability suggest that large-scale circulation changes are occurring as well, even if these are also atmospherically driven. At Bermuda, this could be caused by shifting positions in the Gulf Stream or by variable strength in sub-tropical gyre circulation [*Talley*, 1996; *Worthington*, 1976].

The NAO may be another influence on sea water property variability [*Cayan*, 1992; *Dickson et al.*, 1996; *Reverdin et al.*, 1996; *Talley*, 1996] (see Chapt. 5). During the end of the LIA from 1830 to 1860, the NAO has been shown to be in an extended positive phase (large difference between the pressure centers at Iceland and the Açores) [*Luterbacher et al.*, 1999], which at low frequencies causes decreased temperatures at this location [*Visbeck et al.*, 2003]. Winter-time SST remains relatively low throughout this period but mean-annual SST shows larger variability. Filtering the Luterbacher et al. (1999) NAO record with a five year box window shows a period of extended weak, positive NAO from the mid-1840s to ~1880, coincident with the second extended cooling of the 1800s. This positive phase NAO may also help to explain the varying temperature changes seen across the Atlantic basin. The NAO SST anomaly pattern [*Visbeck et al.*, 2001] dictates positive inter-annual temperature anomalies at Bermuda and the western Caribbean and negative anomalies off the coast of Africa during a positive NAO, consistent with the relatively lower temperature anomalies seen off the coast of Africa at this time.

## 4.5 Conclusions

Quantitative calibration of coral skeletal Sr/Ca to SST from the south shore of Bermuda resulted in long reconstruction of the variability in mean-annual and winter SST for the past two centuries. The records of SST document the end of the LIA event (~1850) with a drop in temperature on the order of ~1.5 °C compared to today. The mean-annual and winter-time SST records combined with $\delta O_c$ imply generally increasing salinity from the end of the LIA to today. Radiative and atmospheric changes explain some of the SST variability, but implied changes in SST and SSS, not explained by atmospheric forcing, indicate circulation impacts as well. The circulation changes may be related to long-term variability in winds and shifts in the NAO.

## 4.6 References


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# Chapter 5

# North Atlantic Oscillation Reconstructed using Winter Sr/Ca Ratios in Bermuda Brain Coral


## Abstract

The North Atlantic Oscillation (NAO) is an important mode of climate variability impacting atmospheric and North Atlantic ocean circulation. Here we reconstruct a marine based NAO signal using 218 years of annually resolved winter-time Sr/Ca ratios, a proxy of sea surface temperature (SST), from a brain coral collected from the south shore of Bermuda. Observed differences between the marine winter-Sr/Ca NAO record and Northern Hemisphere based, atmospheric proxy records from broad geographical regions imply that both NAO behavior and the NAO-ocean relationship have changed through time. In the ocean record, we see coherent changes in both the amplitude and phase at two frequencies - inter-annual (3-5 years per cycle) and multi-decadal (20-100 years per cycle). Changes in the strength of the multi-decadal NAO signal coincide with changes in a mean-hemispheric proxy based temperature record [*Jones et al.*, 1998]. At multi-decadal frequencies, the Sr/Ca-based NAO record exhibits greater variability and spectral power during late 20$^{th}$ century warming (1940-1998) than during the end of the Little Ice Age (LIA, 1800-1850). However, the Sr/Ca-based NAO record shows an extended positive state during the LIA similar to the late 20$^{th}$ century instrumental record. This indicates that changes in mean climate may alter the magnitude and type of variability, but not necessarily the phase of the NAO. At low frequencies, NAO variance increases through time coincident to anthropogenic warming but a positive or negative NAO state does not become dominant.

## 5.1. Introduction

The North Atlantic Oscillation (NAO), a meridional oscillation in atmospheric mass, is commonly measured by surface pressure differences between Iceland (65°N, 23°W) and the Açores (38°N, 26°W) and is reported as the NAO Index (NAOI) [*Hurrell et al.*, 2003; *Hurrell*, 1995]. The NAO is strongest during the boreal winter and identified as the dominant mode of winter pressure variability over the North Atlantic [*Hurrell and VanLoon*, 1997; *Jones et al.*, 2003]. The NAO is connected to the Arctic Oscillation (AO) [*Rogers and McHugh*, 2002], and together, these two systems are sometimes referred to as the Northern Hemisphere Annular Mode (NHAM). The NAO directly impacts surface wind speed and direction, leading to changes in surface temperature, evaporation and precipitation. In a positive NAOI, both the low pressure zone over Iceland and the high pressure zone over the Açores are intensified, resulting in increased strength and incidence of winter storms crossing the Atlantic Ocean. These storms are deflected northward by the intensified pressure gradient, causing warmer and drier conditions in Southern Europe. In addition, a positive NAOI results in warmer and stormier conditions in the eastern United States. In a negative NAOI, the pressure gradient is weakened, and the climate patterns are reversed.

The NAO's influence extends from the eastern United States across the North Atlantic to eastern Europe [*Hurrell et al.*, 2003]. The altered surface wind speed, wave heights and storm tracks, impact human activities such as shipping, oil drilling, fisheries, and coastal management [*Fromentin and Planque*, 2000; *Hurrell et al.*, 2003; *Kushnir et al.*, 1997; *Ottersen and Stenseth*, 2001]. Altered precipitation patterns influence agriculture and hydroelectric power from the mid-western United States to the Middle East. Improving our ability to predict shifts in the phase of the NAO is therefore a prerequisite to anticipating the economic impacts of inter-annual changes in climate [*Hurrell et al.*, 2001; *Rodwell*, 2003].

Beginning in the early 1970s, the North Atlantic has experienced an extended period of positive NAO index that is unprecedented in the instrumental records in terms of duration and intensity (Fig. 5.1) [*Hurrell*, 1995] [see also: http://www.cgd.ucar.edu/cas/jhurrell/indices.html]. This anomalous period has been hypothesized to be linked to anthropogenic forcing [*Hurrell*, 1996; *Shindell et al.*, 1999]. However, our current knowledge of the system does not allow for a complete understanding of the relationship between the NAO and SST, nor an accurate prediction of NAO behavior in the future [*Czaja et al.*, 2003; *Joyce*, 2002]. By expanding the geographical and temporal distribution of NAO reconstructions [*Schmutz et al.*, 2000; *Schone et al.*, 2003], a better understanding of the NAO and its interactions with the ocean can be achieved.

Currently there are two instrumental reconstructions of the NAO [*Hurrell*, 1995; *Jones et al.*, 1997] dating back to 1870 and 1821, respectively. Two records using early measurements of sea level pressure, temperature, and precipitation, as well as proxy data, extend NAO records as far back as 1500 [*Luterbacher et al.*, 2001; *Rodrigo et al.*, 2001]. Finally, several terrestrial based proxy reconstructions exist from ice cores [*Appenzeller et al.*, 1998], tree rings [*Cook et al.*, 2002], snow accumulation rates [*Glueck and Stockton*, 2001] and other multi-proxy combinations [*Cullen et al.*, 2001]. While there are several evaluations of NAO forcing on marine systems (eg. [*Gil et al.*, 2006; *Kuhnert* *et al.*, 2005]), there is only one published marine based reconstruction [*Schoene et al.*, 2003]. This record extends to 1780 (missing years from 1862-1865) and is generated from growth rates of mollusk shells from the Norwegian and North Seas, providing a proxy for nutrient supply and thus mixed layer depth. Additional marine records from the North Atlantic basin could further our understanding of ocean and land responses to the NAO and improve our ability to evaluate model and proxy reconstruction results.

Here we present a new marine based reconstruction of the winter-time NAO index from a 218-year long, continuous brain coral (*Diploria labyrinthiformis*) collected from Bermuda (64°W, 32°N). NAO reconstruction is based on the inverse relationship of winter time (Dec., Jan., Feb., and March) strontium (Sr) to calcium (Ca) ratio to winter-time SST [*Smith et al.*, 1979] (Fig. 5.1a,b). Winter-time SST at Bermuda shows a correlation to the NAO [*Visbeck et al.*, 2003; *Visbeck et al.*, 2001]; thus, the coral Sr/Ca (an SST proxy) can be directly related to the NAO. By filtering the Sr/Ca record to frequencies with significant coherence to the NAO, we can isolate the NAO-SST signal from the hemispheric and global temperature signals. There are two critical questions addressed in this paper. 1) Is the NAO-SST relationship consistent through time, or is it altered by anthropogenic influences as previously hypothesized [*Joyce*, 2002]? 2) Do variations in the amplitude and phase of the NAO correlate to the shift from cool (1800-1849) to warm (1950-1999) conditions in the northern hemisphere, as defined by a multi-proxy record from Jones *et al.* (1998) (here after JSTA) (Fig. 5.1c)? These questions will be addressed by isolating two distinct frequency bands of the NAO and over these two frequencies comparing the new marine based record at Bermuda to instrumental, atmospheric proxy, and marine proxy records [*Cook et al.*, 2002; *Hurrell*, 1995; *Jones et* *al.*, 1997; *Luterbacher et al.*, 2001; *Schoene et al.*, 2003] (Jones *et al.*, 1997 here after JNAO).

## 5.2. Methods

*Generation of the Coral NAO Record from Bermuda*

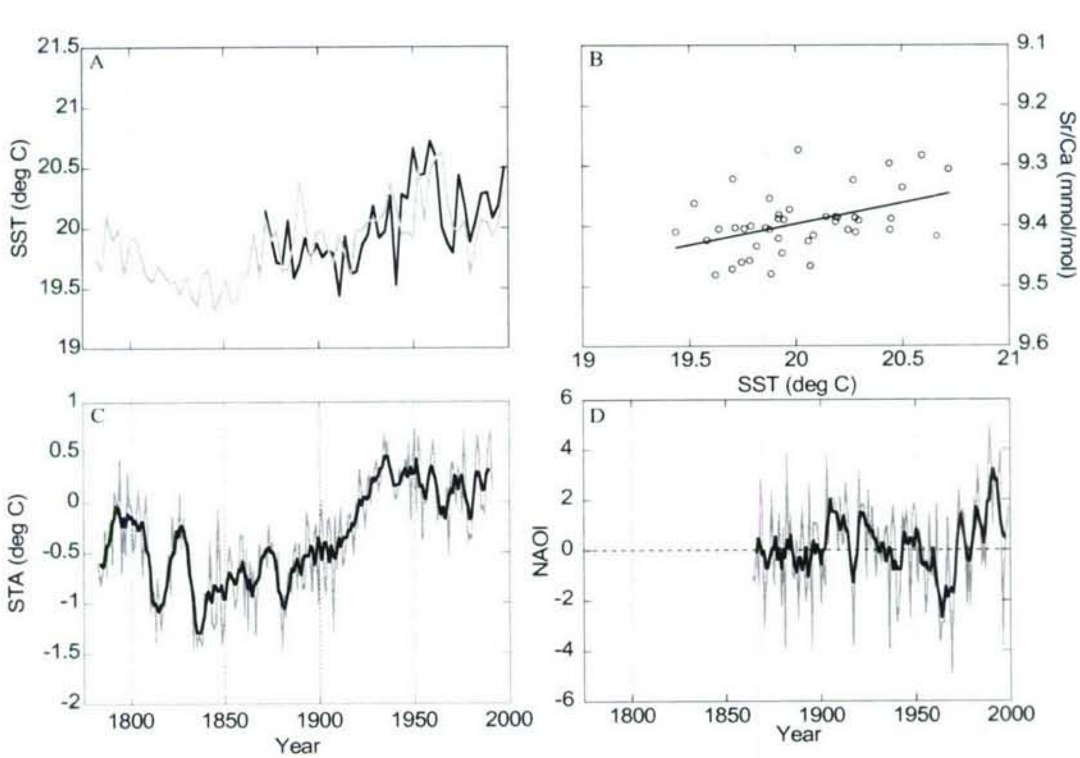


**Figure 5.1**: A) Three year averaged winter-time Sr/Ca (shaded) and observation based instrumental SST (solid) (HadISST, [*Rayner et al.*, 2003]) versus time and B) plotted linearly versus one another. Three year averages are shown as this is the shortest time period of coherence between the winter Sr/Ca and the instrumental NAO. A significant coherence (>95%) is found between the winter Sr/Ca and SST ($F_{sig} = 0.0030$). C) A multi-proxy record of Northern hemisphere surface temperature anomalies (STA) [*Jones et al.*, 1998; JSTA] mean-annual (shaded) and with a 5-year running mean (solid). 1940-1998 shows the longest period of warm temperatures and 1800-1849 encompasses the two extended cold periods marking the end of the LIA. D) Instrumental record of the NAO [*Hurrell*, 1995] annually (shaded, and with a 5-year running mean (solid). 1950-2000 shows the largest variability during the record with both an extended positive and negative phase.

A ~230 year old brain coral (*Diploria labyrinthiformis*) was collected live off John Smith's Bay from the southeastern edge of the Bermuda platform at 16-meters depth in May 2000. Due to its location in the Atlantic, the island of Bermuda (64°W, 32°N) is well suited for an ocean based study of the NAO. Winter-time SST at Bermuda has been shown to correlate with the NAOI on inter-annual (positive correlation) and multi-decadal (negative correlation) frequencies [*Eden and Willebrand*, 2001; *Visbeck et al.*, 2003; *Visbeck et al.*, 2001]. Both responses are impacted by changes in Ekman pumping and heat flux due to the latitudinal wind shift. The multi-decadal response is either caused by gradual changes in the strength of meridional overturning circulation (MOC) [*Eden and Willebrand*, 2001] or by long-term propagation of the inter-annual SST anomalies [*Krahmann et al.*, 2001; *Visbeck et al.*, 1998]. The MOC hypothesis suggests that the observed temperature anomalies results from prolonged change in location and strength of Ekman pumping and intensified winds increasing heat flux from the ocean to atmosphere thus increasing Labrador Sea convection [*Eden and Willebrand*, 2001; *Visbeck et al.*, 2003; *Visbeck et al.*, 2001].

Coral Sr/Ca is inversely related to SST [*Smith et al.*, 1979], and Sr and Ca are both relatively conservative elements in seawater, with small changes in concentration due to coral symbionts and other biological and physical processes (eg. [*Alibert and McCulloch*, 1997; *Bernstein et al.*, 1987; *Culkin and Cox*, 1966; *deVilliers et al.*, 1994; *Marshall and McCulloch*, 2002]). In our previous work, we have shown that winter coral Sr/Ca at Bermuda is inversely correlated to SST at Hydrostation S, located 30 km to the southeast [*Cohen et al.*, 2004; *Goodkin et al.*, 2005], and to regional observational SST measurements (HadISST, [*Rayner et al.*, 2003]) from 1870 to 1997 from the gridded area 31-33 °N and 64-65 °W [*Goodkin et al.*, in prep] (Fig. 5.1).

X-radiographs of 5mm-thick slabs cut along the axis of maximum growth of the brain coral reveal well-defined annual growth bands. Using the x-radiographs as a guide, samples were drilled down the length of the solid septotheca (calyx wall) at 0.33 mm intervals to achieve approximately monthly resolution from 1872 to 1999. Sr and Ca were measured simultaneously on an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES at WHOI). Materials and methods can be found in more detail in Goodkin *et al.* (2005), Goodkin *et al.* (in press), and Goodkin *et al.* (in prep).

Density banding from x-rays was used to construct an annual age model that was refined by correlating Sr/Ca to monthly averaged SSTs measured at Hydrostation S. Beyond the instrumental record, months were assigned based on an average climatology of the Hydrostation S data. The coral data were then re-sampled at evenly spaced monthly intervals to identify winter months (Dec.-March). Age model error is anticipated. Some age model error will be generated from noise in the Sr/Ca record and in counting the annual bands, which could either serve to add or eliminate years inappropriately. However, it is more likely that the coral record (and age model) will be biased because of missing years, resulting from years of no growth. This will lead to the reported date being younger (more recent) than the actual date [*Goodkin et al.*, (in prep)]. For example, if the coral did not grow in 1950, 1949 would be inappropriately assigned the date 1950, generating a bias in all years prior to 1950 (1948,1947 etc.). This bias is likely to reach a maximum between 1830 and 1865 when growth rates are lowest [*Goodkin et al.*, 2005].

*Comparison of the Coral Record to Other Records of the NAO*

Cross-spectral analysis comparing the negative of the winter Sr/Ca record to the other instrumental and proxy NAO records is completed using 10 multi-taper windows [*Huybers*, 2003] without detrending the records. Error estimates on phase relationships were generated using a Monte Carlo simulation in which 50 probable solutions were generated. Wavelet analysis was performed on the raw winter-time Sr/Ca record, using a morlet basis function, following previously published methods [*Torrence and Compo*, 1998a; *Torrence and Compo*, 1998b; *Torrence and Webster*, 1999].

## 5.3. Results and Discussion

Cross-spectral analysis comparing the negative of winter Sr/Ca (equivalent to SST) to instrumental (Fig. 5.2) and proxy (Fig. 5.3) winter NAO records from 1864-1999 show two frequency intervals of significant coherence, one at periodicities less than 15 years (frequency of 0.07 $year^{-1}$) and, the other at periodicities between ~3 to 5 years (frequency of 0.18-0.28 $year^{-1}$). Coherence to the two NAO instrumental records [*Hurrell*, 1995; *Jones et al.*, 1997] deteriorates at periodicities shorter than 3 years (0.33 $year^{-1}$). This limitation would be expected from single-geographic point proxy records [*Huybers*, submitted], for which site specific and proxy noise can overwhelm regional signals. At multi-decadal frequencies the negative of winter Sr/Ca and the NAO are anti-phase, whereas at inter-annual frequencies, the negative of winter Sr/Ca is within error of being in phase (Fig. 5.2). The coral Sr/Ca record's phase relationships to the instrumental and proxy records are consistent with the SST-NAO analysis from model and instrumental results [*Eden and Willebrand*, 2001; *Visbeck et al.*, 2003].

The comparison of the coral Sr/Ca data to the historical and proxy based records

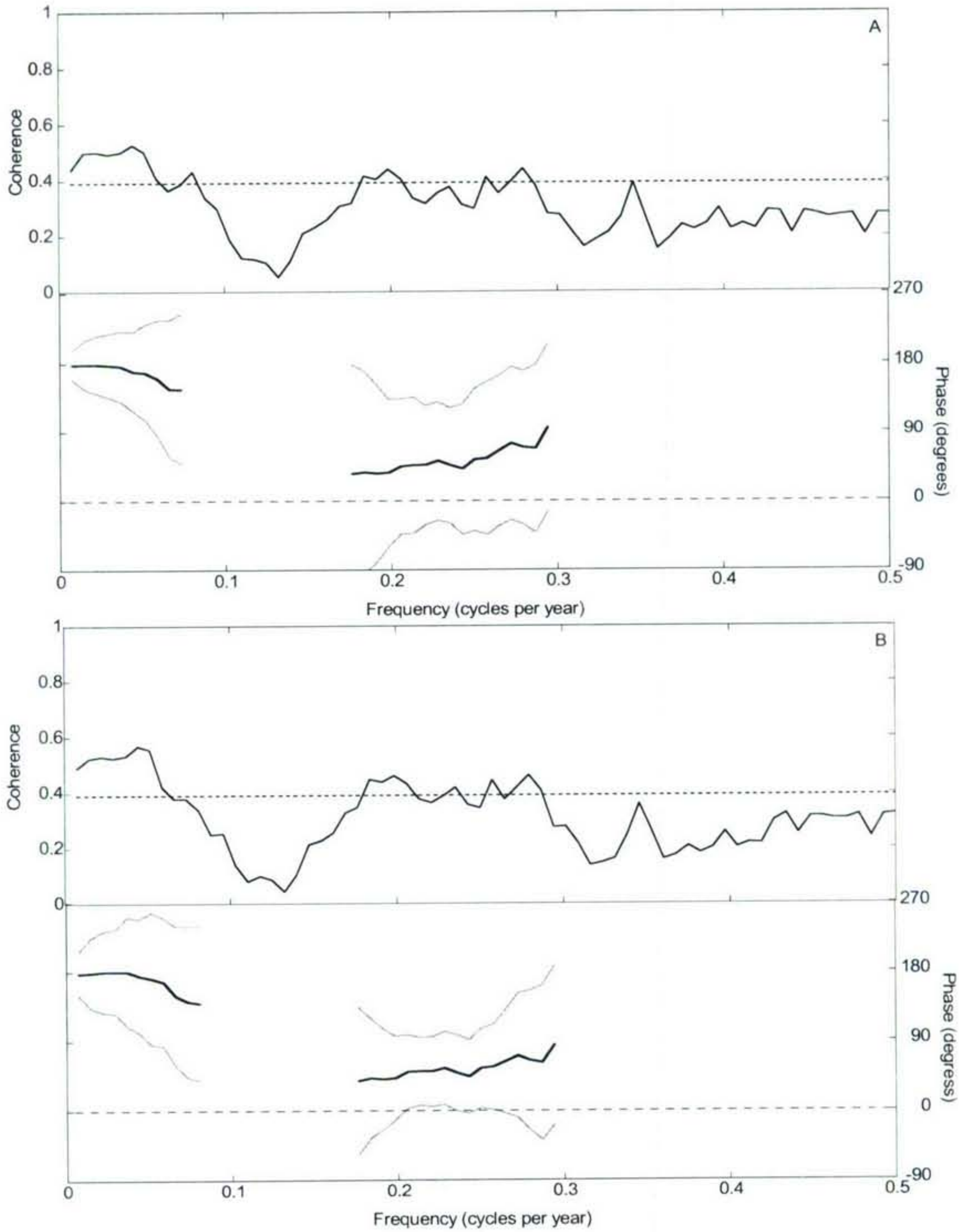


**Figure 5.2:** Spectral analysis of the negative of winter Sr/Ca (equivalent to SST) and instrumental records of the NAOI from a) Hurrel (1995) and b) Jones et al. (1997) (JNAO). Top panel of the a and b subplots shows the coherence (r) (solid) including the 95% confidence interval (dashed). Bottom panels show the phase relationship (solid), including Monte Carlo based error calculation (grey), surrounding periods of significant coherence. Analysis completed using multi-taper method with 10 windows and 50 iterations on Monte Carlo error estimates [*Huybers,* 2003].

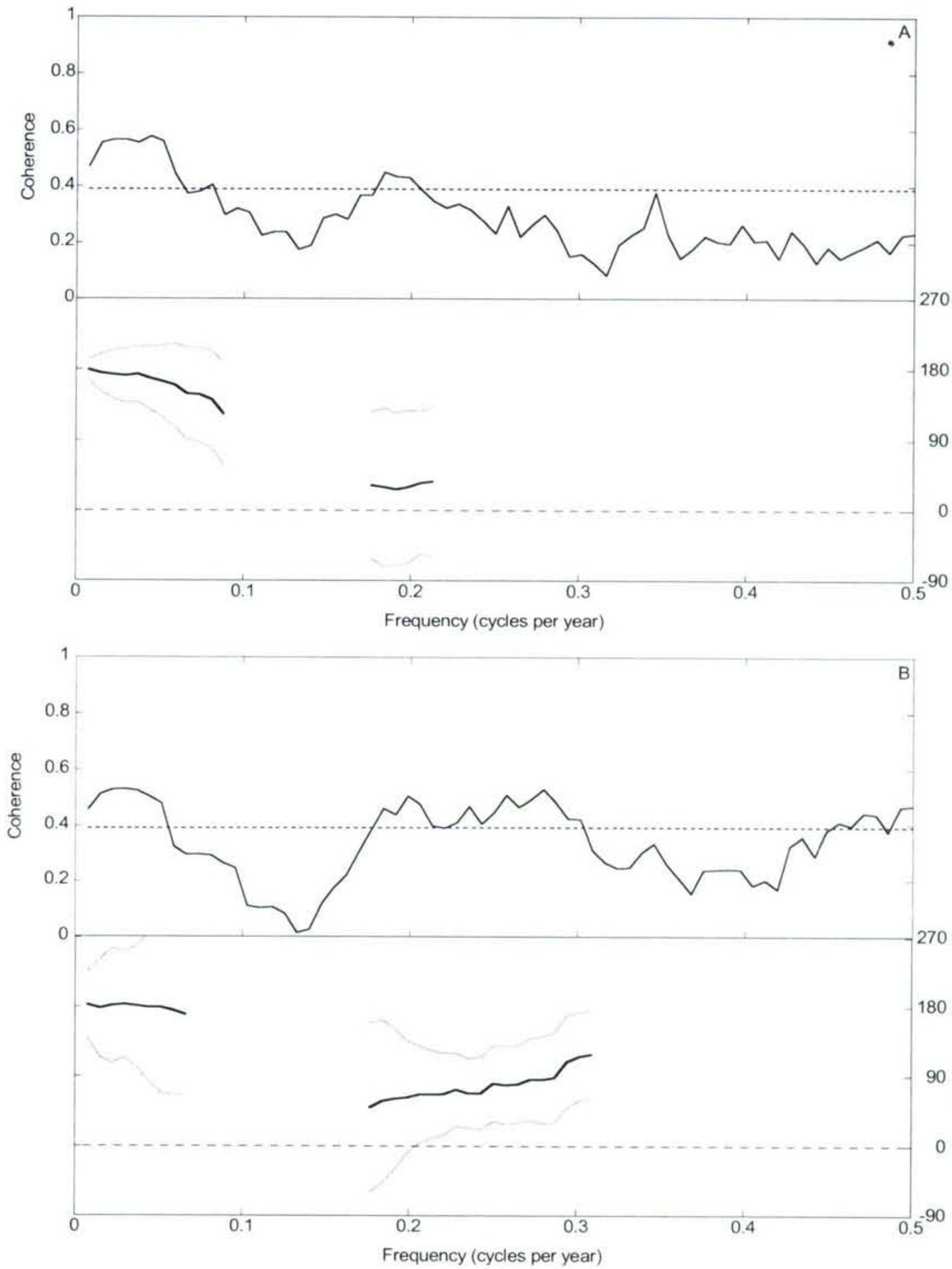


**Figure 5.3:** Spectral analysis of the negative of winter Sr/Ca (equivalent to SST) and proxy records of the NAOI from a) Luterbacher et al. (2001) and b) Cook et al. (2002). Top panel of the a and b subplots shows the coherence (r) (solid) including the 95% confidence interval (dashed). Bottom panels show the phase relationship (solid), including Monte Carlo based error calculation (grey), surrounding periods of significant coherence. Analysis completed using multi-taper method with 10 windows and 50 iterations on Monte Carlo error estimates [*Huybers*, 2003].

show similar results as compared to the instrumental records. Luterbacher *et al.* (2001) and Cook *et al.* (2002) were chosen due to the large geographical distribution of the proxy records used in the reconstructions. The size of the coherent inter-annual frequency band for Sr/Ca and Luterbacher *et al.* (2001) records is narrower than those found in the other NAO comparisons (Fig. 5.3a). At inter-annual frequencies, comparison to the record of Cook *et al.* (2002) shows the longest and most coherent frequency band of all three records, with significant coherence spanning from 3.3 to 5.5 years per cycle (Fig. 5.3b). However, for this frequency band, Sr/Ca appears to lag the NAO reconstruction by 50 degrees, with the error bounds excluding the zero-lag at frequencies higher than 5 years per cycle.

Given these results, two coral Sr/Ca based NAO reconstructions were calculated by filtering the negative of the Sr/Ca record to isolate the two frequency bands where the coral data are coherent with the NAO. For the frequency reconstruction, the data were treated with Hanning window band-pass filters selecting frequencies between 3 and 5 years per cycle and 20 and 100 years per cycle. The multi-decadal reconstruction was performed by shortening the window on each end of the record such that the 100-year pass has averages of atleast 50 years averaged at the record ends executed by shortening the Hanning window.

At low frequencies, the winter-time Sr/Ca record shows significant coherence with the hemispheric STA [*JSTA*] (Fig. 5.4). However, it the winter Sr/Ca and JSTA records are each linearly detrended (from 1781-1999) before cross-correlation analysis, than no low-frequency coherence is found (Fig. 5.4). The strongest agreement between the Sr/Ca and the STA record is marked by a generally increasing trend from the earliest part of the record (1800) to today (Fig. 5.1). We therefore attempted to remove this very low frequency signal in the Sr/Ca record that may be dominated by processes other than the NAO. In choosing a 20-100 year band pass, we balanced 1) capturing a long enough trend to evaluate the prolonged coherence between the coral data and the instrumental NAO [*Hurrell*, 1995] beginning at ~15 years per cycle and 2) removing a lower

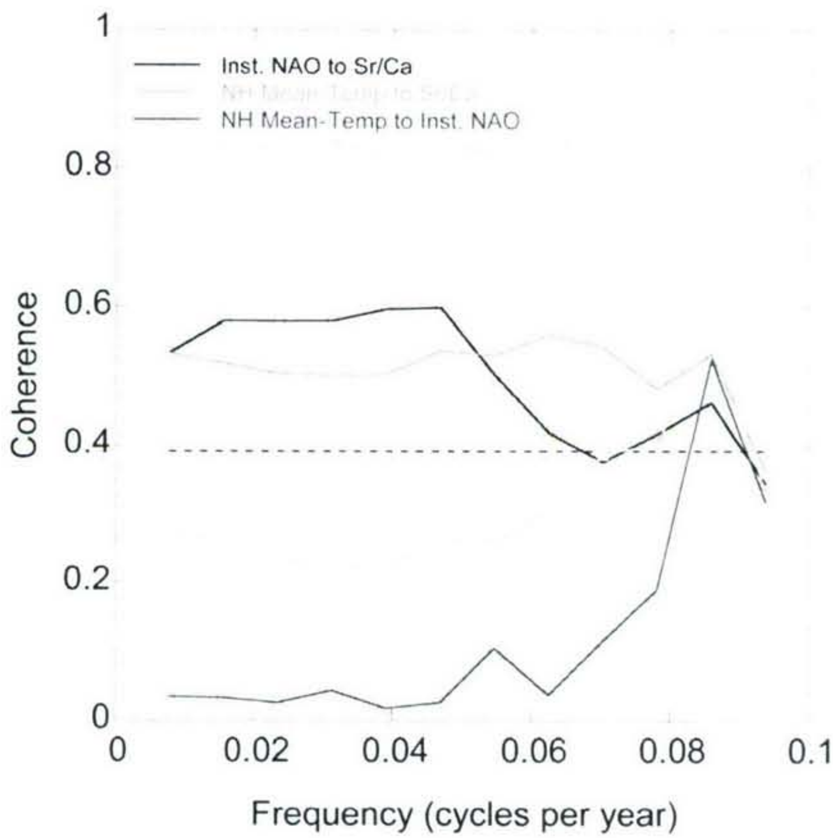


**Figure 5.4**: Cross correlation analysis for frequencies less than 0.1 cycles per year from 1864-1991, the maximum period of overlap for records of the NAO, negative winter Sr/Ca and NH temperature proxies. The negative winter Sr/Ca is compared to the NAO instrumental record [*Hurrel*, 1995] (solid, circles). The negative winter Sr/Ca is also compared to both the mean-annual Northern Hemisphere temperature proxy record (JSTA, [*Jones et al.*, 1998]) with neither record detrended (shaded, circles) and with both records detrended (shaded, squares). The instrumental NAO record and the mean-annual NH proxy record are also compared to one another (solid, squares). The dashed line represents coherence with 95% confidence.

frequency signal correlating to mean temperature. The correlation coefficient of the negative Sr/Ca record to the entire length of the NAO instrumental record [*Hurrel*, 1995] both filtered just with a 15-year Hanning window is -0.60 compared to -0.77 with the 20-100 year filter, which has also removed the secular hemispheric temperature driven trend in the Sr/Ca record. The NAO and hemispheric STA have no correlation over this frequency band, further implying the two signals should be separable.

A critical question to be evaluated from the filtered records is how the characteristics of the NAO-ocean relationship evolve with changes in the mean climate state of the Northern Hemisphere. A reconstruction of Northern Hemisphere surface temperature (JSTA, [*Jones et al.,* 1998]) shows intervals of relatively cold temperatures from 1800-1875, with two strong cooling events between 1800 and 1850 demarking the end of the LIA, and relatively warm temperatures from 1940-today (Fig. 5.1c). These two periods will be used to evaluate how the power and amplitude of the NAO changes between periods of different atmospheric temperature.

The inter-annual band passed Sr/Ca records are coherent, as expected, to similarly filtered instrumental and proxy records [*Hurrel,* 1995; *Jones et al*., 1997; *Luterbacher et al*., 2001; *Cook et al*., 2002; *Schoene et al.,* 2003] (Fig. 5.5). In the three-to-five year frequency band, the winter Sr/Ca has the strongest coherence from 1950-2000 with Sr/Ca lagging the NAO proxy records by one year - in four of the five records - implying either that the NAO leads Bermuda SST by one year or that our age-model accounts for one year too few during this period (Fig. 5.6). The strongest coherence to Cook *et al.* (2002) occurs when Sr/Ca lags the atmospheric record by three years. The most coherent leads and lags between the Sr/Ca and all proxy and instrumental records other than Cook *et al.* (2002) change through time ranging from Sr/Ca lagging by one year (1950-1997) to leading by two years (1850-1899) (Table. 5.1). The 3-5 year frequency band returns periodicities within our age model error which back in time could exceed five years; therefore, the Sr/Ca and atmospheric records cannot be used to evaluate changes between the timing of NAO events and resulting SST anomalies at inter-annual frequencies. The fact that Cook *et al.* (2002) is consistently coherent with a different lead or lag than the other records suggest some age model uncertainty in the tree ring record relative to the other instrumental and proxy records independent of the uncertainty in the Sr/Ca age model.

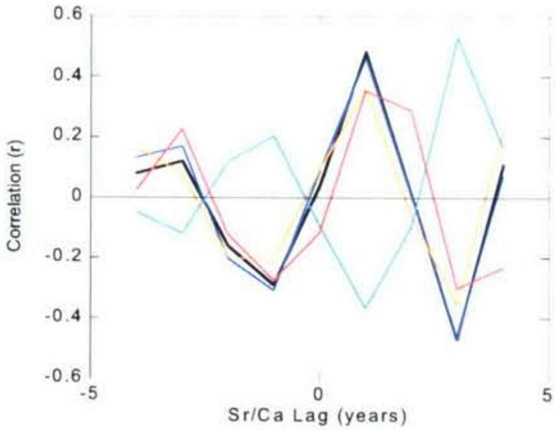


**Figure 5.6**: Covariance of three to five year frequency band filtered record of (-) Sr/Ca to the records of NAO over the time interval of 1948-1997. Comparisons to Hurrell (black), Jones (dark blue), Luterbacher (orange) and Schoene (red) show the strongest covariance with Sr/Ca lagging the other by one year. Comparisons to Cook (light blue) show the strongest correlation with a three year lag.

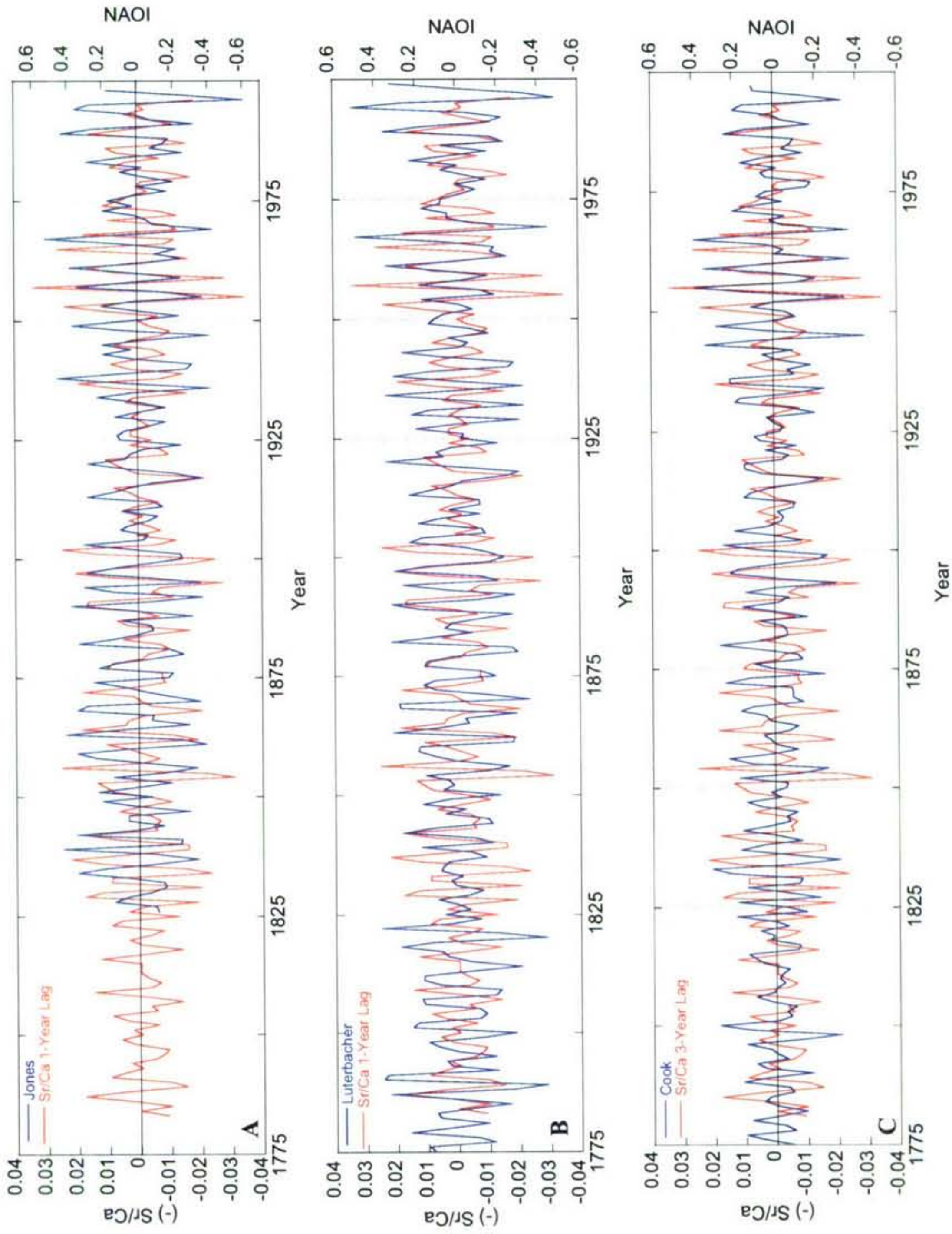


**Figure 5.5:** Band-passed filtered records to frequencies of three to five years per cycle for the negative of winter Sr/Ca (red) compared to Jones et al. (1997) (JNAO) (A), Luterbacher et al. (2001) (B), and Cook et al. (2002) (C) all in blue. Jones and Luterbacher are shown with winter Sr/Ca lagging by one year and Cook is shown with winter Sr/Ca lagging by three years. Prior to 1900, amplitude changes continue to be captured, but winter Sr/Ca goes in and out of phase with the other proxy records. At inter-annual frequencies, it is not possible to distinguish between the two potential causes – changes in the NAO-SST response or error in the coral age model.

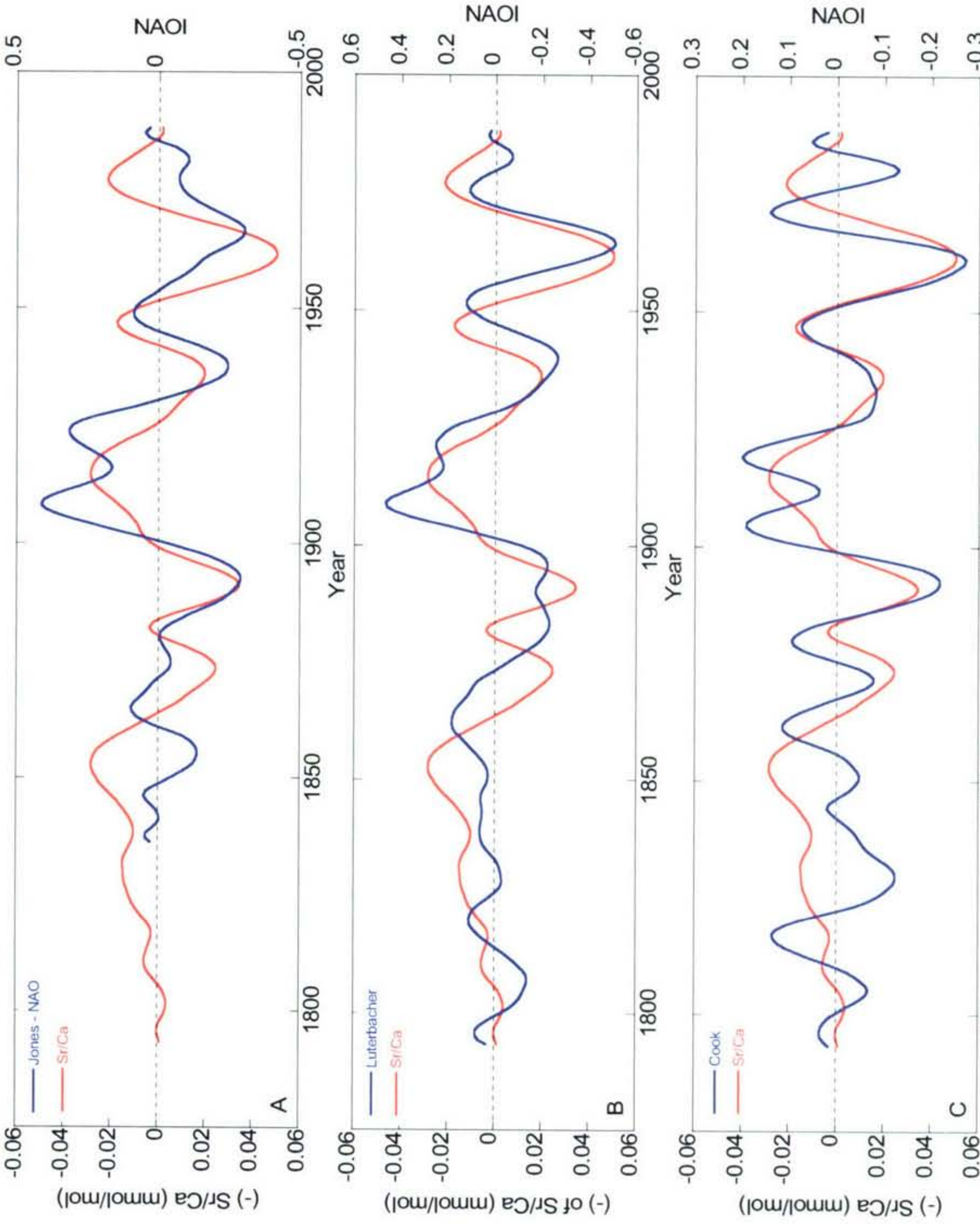


**Figure 5.7:** Band passed filtered records to frequencies of twenty to one hundred years per cycle for the negative of winter Sr/Ca (red) compared to Jones et al. (1997) (JNAO) (A), Luterbacher et al. (2001) (B), and Cook et al. (2002) (C) (all in blue).

**Table 5.1:** Correlation (r) between the negative of winter Sr/Ca record and instrumental and proxy records at 3-5 year frequency bands (top) and 20-100 year frequency band (bottom).

| | Instrumental and Proxy Records | | | | | |
|---|---|---|---|---|---|---|
| | **Hurrel** | **Jones** | **Luterbacher** | **Cook** | **Schoene** | **Lead/Lag Description for Inter-Ann. Freq.** |
| **Inter-Annual Correlations** | | | | | | |
| **1950-1997** | 0.48 | 0.46 | 0.36 | 0.53 | 0.35 | Sr/Ca lags 1 year for all but Cook which lags 3 years. |
| **1900-1949** | 0.44 | 0.45 | 0.46 | 0.32 | 0.35 | Sr/Ca at zero lag for all but Cook which lags three years. |
| **1850-1899** | 0.32 | 0.15 | 0.16 | 0.23 | 0.19 | Sr/Ca leads by 2 years for Jones and Shoene, and lags by two years for Cook and Luterbacher. Sr/Ca lags Hurrel by one year and only goes back to 1866. |
| **1800-1849** | | | 0.29 | 0.40 | 0.33 | Sr/Ca leads by 1 year for Luterbacher and Jones and lags by one year for Cook. |
| **1900s Average** | 0.46 | 0.45 | 0.41 | 0.42 | 0.35 | |
| **1800s Average** | | | 0.23 | 0.32 | 0.26 | |
| **Multi-decadal Correlations** | | | | | | |
| **1950-1992** | -0.82 | -0.50 | -0.80 | -0.65 | -0.06 | |
| **1900-1949** | -0.53 | -0.72 | -0.77 | -0.78 | -0.37 | |
| **1850-1899** | -0.76 | -0.27 | -0.46 | -0.57 | -0.39 | |
| **1800-1849** | | | -0.52 | 0.23 | -0.42 | |
| **1900s Average** | -0.67 | -0.61 | -0.78 | -0.72 | -0.22 | |
| **1800s Average** | | | -0.49 | -0.17 | -0.41 | |

We investigated the agreement between inter-annual filtered NAO reconstructions in fifty year increments to assess how the marine coral reconstruction performs for time periods of different mean-temperature. The maximum lagged correlation coefficients between the Sr/Ca and each record from 1950 to the end of the record are above or close to 95% significance as determined by spectral analysis ($r = 0.39$) (Table 5.1). Maximum correlation coefficients are similar for the periods 1900-1947 and 1950-1997 (Table 5.1), and during the 20$^{th}$ century as a whole, the winter Sr/Ca record represents well both the phase and amplitude of inter-annual variability in the NAO.

Comparing the 19$^{th}$ and 20$^{th}$ century inter-annual results between the warmest periods of the 20$^{th}$ century (1950-1997) and the end of the LIA (1800-1849) shows minimal difference in correlation between Sr/Ca and the other NAO records. The maximum lagged correlations between Sr/Ca and the atmospheric proxy and instrumental records are relatively unchanged (Table 5.1). In addition, the variance does not differ between the two time periods with statistical significance (variance (1950-1997) = 0.0002, variance (1800-1849) = 0.0001, $p = 0.0704$). During the end of the 19$^{th}$ century (1850-1899), when hemispheric temperature records are both colder relative to today and fairly constant, the coral Sr/Ca record shows the weakest correlation to all other records of the NAO (Fig. 5.1c). However, this will also be the time of largest potential age model bias which could serve to weaken coherence through temporal offsets over a 50-year period.

The correlation of the two marine records (coral Sr/Ca and Schoene *et al.*, 2003) during the end of the LIA (1800-1849) is similar to the correlation for the 20$^{th}$ century (Table 5.1). The lowest correlation between the marine records occurs from 1850 to

1899, much like the atmospheric record comparisons. The relative consistency of the correlation through time implies that if changes are occurring in the ocean's inter-annual response to the NAO they are consistent between these two locations. However, the marine records are not particularly well correlated with each other during the calibration period (1950-1997), with a lower correlation than found between the Sr/Ca and instrumental NAO records. This could occur for multiple reasons. The two locations do not have identical responses to the NAO even if the relative responses are consistent through time. NAO process are shifting geographically changing responses at each location, or error in both record's age models are impacting their correlation. However, the Schoene *et al.* (2003) record shows a much larger ($p<0.0001$) variance in amplitude during the cold interval at the end of the LIA, in contrast to a relatively flat or opposing variance trends in the Bermuda record, implying a larger impact than age model error.

In the twenty to one hundred year periodicity band, strong correlations are found between the negative of winter Sr/Ca record and the other proxy and instrumental records during the 20$^{th}$ century (Fig. 5.7, Table 5.1). The Sr/Ca deviates from the other records from 1900-1930. All five instrumental and proxy records show two maxima whereas the Sr/Ca record shows only one maximum. There are changes in coherence between the first and second half of the 20$^{th}$ century; however, depending on which proxy or instrumental record is examined, the interval with stronger (or positive) coherence differs. Low-frequency ocean behavior has been observed in models to lag the atmospheric records by 6-8 years [*Eden and Willebrand*, 2001]. Our record doesn't show consistent behavior of leading or lagging either through time or between the different atmospheric records. A larger geographic distribution of marine records could help to evaluate how the NAO signal propagates through time, whereas a single point location does not provide enough information about possible spatial displacement.

The 19$^{th}$ century shows less consistent results at multi-decadal frequencies than does the 20$^{th}$ century. The Sr/Ca based record has a period of inverse correlation to the Cook *et al.* (2002) record. The winter Sr/Ca shows an interval of positive NAOI in the early 1800s, like the Luterbacher *et al. (*2001). While Cook *et al.* (2002) and Schoene *et al.* (2003) show periods of both positive and negative NAOI at this time. Similar to its inter-annual record, and unlike other records, the Schoene et al. (2003) record shows more amplitude variability in the early 1800s than in the 20$^{th}$ century (variance 1800-1849 = 0.041 and 1945-1994 = 0.002, $p<0.0001$) (Fig. 5.7)

Comparing the beginning of the 19$^{th}$ century (1800-1849) and the end of the 20$^{th}$ century (1939-1988) shows that during times of warm hemispheric mean temperatures (Fig. 5.2) the multi-decadal coral record has a stronger coherence to the atmospheric records (Table 5.1). Between these two time periods of mean-cold and mean-warm temperatures, a larger variance in the Sr/Ca record is also seen during warmer hemispheric temperatures (variance (1800-1849)<0.0001 and (1939-1998)=0.0005, $p<<0.0001$). In contrast, during the end of the LIA, a mean hemispheric cold period, the two atmospheric proxy records show varying agreement both with one another and with the coral Sr/Ca record. These results suggest at a minimum that multi-decadal variability in the NAO response at Bermuda was relatively weak during the end of the LIA relative to the warmest part of the 20$^{th}$ century.

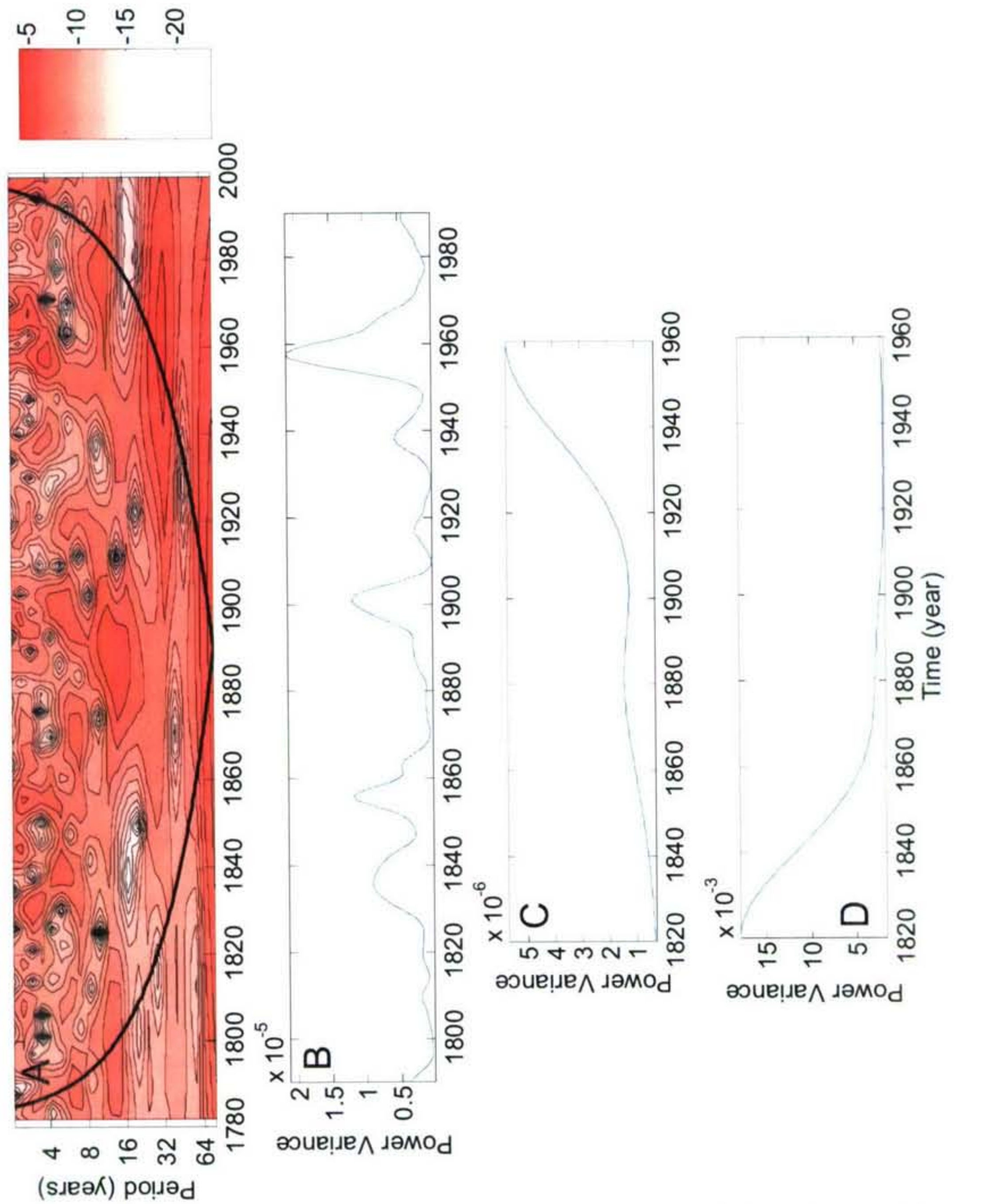


**Figure 5.8:** Wavelet analysis based on Torrence and Compo (1998) using a morlet wavelet function with the raw winter coral Sr/Ca record. A) Spectral power through time at varying frequencies. B) Spectral power through time over a 3-5 year frequency band. C) Spectral variance through time over a 20-50 year frequency band. Results are only useful above the cone of influence shown by black semi-circle, below which the results are not robust due to the windowing effects. D) Spectral variance results of the same analysis on the JSTA record over 20-50 year frequency band. The focus of power at the end of the LIA is in contrast to the results of the Sr/Ca record indicating separation from mean-hemisphere temperature at this frequency.

Wavelet analysis of the raw winter Sr/Ca record is used to examine the timing and strength of individual periodicities over different time intervals [*Torrence and Compo*, 1998a,b]. Spectral power is examined for the 3-5 year frequency band and a 20-50 year frequency band, which allows us to look at the multi-decadal power through time within the confidence limits of the analysis. The strongest spectral power in both bands occurs during the latest portion of the record (Fig. 5.8a). While the strongest spectral power in the 3-5 year frequency band is centered on the 1960 temperature maximum, three other clear peaks exist at 1830, 1850, and 1900 (Fig. 5.8b). These are all times of average or cooler than normal temperatures (Fig. 5.1c), and preclude a relation between NAO variance and mean hemispheric temperature.

The multi-decadal signal, however, does appear to be tied to hemispheric temperatures. For frequencies between 20 and 50 years, the power in the Sr/Ca and temperature records are not similarly distributed (Fig. 5.8c,d), supporting the successful seperation of the hemispheric STA signal in the Sr/Ca. The Sr/Ca power is also not equally distributed through time. The power of the Sr/Ca record is greatest during the warmest part of the record (1820-1860). This result is consistent with the amplitude variance results and is visible in the low frequency records (Fig. 5.7). The differences amongst the marine and terrestrial proxies imply that the ocean, the land or both appear to respond differently (in amplitude or direction) to the NAO through time, and may be influenced by anthropogenic changes. This could result from a change in behavior in the NAO system or a change in oceanic response to the current system. Model and observational results also suggest variations in the strength of the MOC on centennial and inter-annual timescalses (ex. [*Bryden et al.*, 2005; *Villenga and Wu*, 2004]). The differences in amplitude and mean-value observed amongst the multi-decadal records could imply changes in MOC as well as the NAO during mean-warm versus mean-cool hemispheric conditions.

## 5.5 Conclusions

On inter-annual time scales, the NAO influences SST via atmospheric processes which drive changes in wind speed and subsequent Ekman currents. These changes can result in a positive NAO-positive SST (negative Sr/Ca) connection at Bermuda [*Visbeck et al.*, 2001]. At multi-decadal frequencies, it is believed that the MOC is enhanced following extended positive NAO conditions leading to a positive NAO-negative SST (positive Sr/Ca) connection at Bermuda [*Eden and Willebrand*, 2001]. The expected relationships are confirmed by this record through coral Sr to Ca records and found to occur for a longer time interval than previously known.

This new marine record of the NAO provides an insight into the SST-NAO relationship from the center of the Atlantic Basin. The mean-state of the NAOI does not show a clear shift into either a prolonged positive or negative state with extended warm or cold air temperatures. In fact, a prolonged positive NAOI is seen both during the end of the LIA and during the late $20^{th}$ century warming. The inter-annual ocean response to the NAO does change through time. Coherence between the marine and atmospheric records decreases as power at this frequency diminishes in the Bermuda record. However, inter-annual changes in ocean behavior do not correlate with changes in mean atmospheric temperatures. At multi-decadal frequencies behavior is correlated to shifts in atmospheric mean-temperature, with greatly increasing power in the marine record at warmer temperatures. Anthropogenic influences do not appear to be altering the mean-state of the NAOI, but maybe acting to increase multi-decadal variability and the connection between the NAO and SST at Bermuda. In essence, hemispheric warming may be pushing the NAO to higher variability but not to a new mean position. An increased number of marine records from a broad geographical distribution will help to further our understanding of this identified behavior and the role of anthropogenic activity in the state of the NAO.

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# Chapter 6

# Conclusion

Professor Edward Boyle, in his course work at the Massachusetts Institute of Technology, presents his view of the life cycle of a paleoclimate proxy. Boyle suggests that a paleoproxy is first met with a euphoric response, followed by extended work on developing the proxy. After some time, disillusionment with the proxy sets in as complications are uncovered. Ultimately, a manageable way to use the proxy within a set of boundaries is found. Geochemical climate proxies from corals have befallen this path. Initially, there was much excitement over the application of elemental ratios in corals to generate SST records. Corals yielded high-resolution, long climate records from relatively short archives (up to 3m cores). The shallow depths at which corals grow and the uplifted corals on island atolls meant that sample collection was relatively inexpensive.

However, some disillusionment set in as proxy calibrations changed with each colony, and corals appeared to have significant biological effects complicating the inorganic precipitation. This realization made applying modern calibrations to fossil corals suspect, and combined with coral results showing much larger SST changes back in time compared to other marine proxies, led to criticism of the proxy's reliability.

Compounded with these concerns was the difficulty in sampling and analyzing slow-growing corals (e.g. *Diploria.*), which are the only corals to grow outside of the tropics. Without the incorporation of slow-growing coral records, this paleo-proxy would be very geographically limited.

Slow-growing corals appear to exacerbate some of the problems seen with coral SST reconstructions. Bulk-sampling clearly generates smoothing in the seasonal record, and changes in growth (calcification) rates can further alter this signal back through time. Smoothing of the calibration data can lead to exaggerated SST changes in the past with both mean-annual and winter time SST reconstructions showing inter-annual ranges larger than the modern seasonal cycle. Different seasonal calcification processes can lead to additional biasing in how seasons are resolved through time, further complicating even a mean-annual reconstruction.

In this thesis, I have tried to move beyond some of the disillusionment, and I have found that several of these problems are not insurmountable. Careful calibrations should include consideration of how growth rates have influences both within and between colonies. Multiple colonies regressed simultaneously into one calibration have also greatly improved the calibrations and accuracy of reconstructions, as evaluated by residuals and mean SST values. The use of sub-annual samples averaged into longer (mean-annual, winter-time and multi-year) periods has led to statistically significant reconstructions (temperature changes are larger than zero with uncertainty) with full error propagation that are within the range of many other sea surface temperature reconstructions from around the Atlantic between today and the end of the Little Ice Age. In essence, acknowledging the caveats of the methods – biology is a complicating factor, sub-sampling must occur at resolutions higher than the reconstructions – as well as the level of significance of these reconstructions, both from the statistical measures of uncertainty and from the evaluation of the regional versus local significance of the record, will allow for robust reconstructions of temperature and salinity.

In this thesis, I was able to reconstruct both mean-annual and winter-time SST. These records show a statistically significant change in temperature between today and the end of the LIA of 1.6 ±0.5 °C. While this value is within the range of LIA temperature changes generated throughout the Atlantic, proxy reconstructions return temperature changes as varying as 0.5 to 5.0 °C. The range seen throughout the Atlantic implies that regional processes and ocean circulation changes may be at work, serving to amplify and to modify global forcing at specific locations.

Reconstructing salinity proved to be a greater challenge. There is much evidence that the study coral has recorded both temperature and salinity changes within the record of $\delta^{18}O$. The most basic support for this is the large secular trend in the Sr/Ca record which is absent in the $\delta^{18}O$. However, I was unable to quantify the amount of total salinity change with statistical significance. The biggest hurdle to quantifying the salinity impacts may be the limited range of salinity seen at Bermuda during the modern calibration period.

In addition to local conditions, coral geochemistry can also be used to reconstruct records of larger scale climate variability such as the NAO. Coral is one of the best ways in which marine based reconstructions of the NAO can be generated due to the required sub-annual scale. Spectral analysis appears to be a robust tool for evaluating these geochemical records. Our coral record reconstructs the NAO at two frequencies (3-5 years per cycle and 20+ years per cycle). Analysis of this record for time intervals of regionally high and low temperatures shows that while the inter-annual (3-5 years per cycle) behavior does not appear to be changing with increasing temperatures, multi-decadal (20+ years per cycle) behavior appears to exhibit greater amplitude variability during warmer periods, though not a change in the dominant phase of the NAO. In addition, our record shows an increased coherence with atmospheric records during warmer Northern Hemisphere temperatures, which may indicate changing ocean-atmosphere dynamics as the mean climate warms. Unfortunately, with only one ocean record, any conclusion about changes in ocean-atmosphere processes is limited.

The most successful terrestrial based proxy records of the NAO have been generated over large geographical areas and the same will be required to achieve the best marine based record. The record generated in this thesis and that of mollusks collected from the North and Norwegian Seas are a good starting point for generating a larger scale NAO marine reconstruction. Continuing this process with more corals from Bermuda and throughout the Caribbean, as well as mollusk shells and other potential archives from regions beyond coral growth, could lead to a detailed spatial reconstruction of the same caliber of the NAO over the ocean and a better understanding of ocean-atmosphere interactions as a function of different time scales and mean climates.

# Appendix A

# Low Resolution Record Data

| Date | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Growth Rate (mm/year) |
|---|---|---|---|---|
| Top Piece Shown in Fig. 2.1 | | | | |
| 1998 | 9.2979 | | | 3.0 |
| 1996 | 9.3292 | -3.8893 | -2.9911 | 3.5 |
| 1994 | 9.3597 | -3.8397 | -3.4800 | 3.0 |
| 1992 | 9.3192 | -3.6193 | -3.8701 | 3.0 |
| 1990 | 9.3328 | -3.8947 | -3.5190 | 4.0 |
| 1988 | 9.2888 | -3.8743 | -3.0571 | 3.5 |
| 1986 | 9.3053 | -3.8717 | -3.3430 | 3.5 |
| 1984 | 9.3064 | -3.8663 | -3.7201 | 4.0 |
| 1982 | 9.2820 | -3.9817 | -3.1140 | 4.5 |
| 1980 | 9.3450 | -3.8833 | -3.0621 | 3.5 |
| 1978 | 9.3121 | -3.8387 | -3.1290 | 4.0 |
| 1976 | 9.3234 | -3.7833 | -2.6311 | 4.0 |
| 1974 | 9.2956 | -3.7687 | -2.4520 | 5.0 |
| 1972 | 9.3285 | -3.6043 | -2.3511 | 3.5 |
| 1970 | 9.2825 | -3.9737 | -2.0860 | 3.5 |
| 1968 | 9.2913 | -3.8613 | -2.1351 | 5.0 |
| 1966 | 9.2668 | -3.9253 | -2.0051 | 4.0 |
| 1964 | 9.2489 | -3.4195 | -1.9811 | 4.0 |
| 1962 | 9.2624 | -4.1607 | -2.6560 | 3.5 |
| 1960 | 9.2660 | -3.7843 | -1.9181 | 4.5 |
| 1958 | 9.2305 | -3.6517 | -1.3560 | 4.0 |
| 1956 | 9.2358 | | | 4.0 |
| 1954 | 9.2431 | -3.7907 | -2.2820 | 3.5 |
| 1952 | 9.2282 | -3.7553 | -2.3141 | 4.0 |
| 1950 | 9.3042 | -3.3297 | -2.0040 | 4.5 |

| Date | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Growth Rate (mm/year) |
|---|---|---|---|---|
| 1948 | 9.2532 | -3.6883 | -2.5546 | 3.5 |
| 1946 | 9.3047 | -3.8437 | -2.1200 | 4.5 |
| 1944 | 9.3091 | -3.7953 | -2.1961 | 3.5 |
| 1942 | 9.3192 | -3.7077 | -2.3370 | 4.0 |
| 1940 | 9.3251 | -3.6233 | -2.1271 | 4.5 |
| 1938 | 9.2708 | -3.8697 | -1.8410 | 3.5 |
| 1936 | 9.2715 | -3.8373 | -1.7541 | 4.5 |
| 1934 | 9.2880 | -3.7287 | -1.7550 | 3.5 |
| 1932 | 9.2755 | -3.7749 | -1.7207 | 4.0 |
| 1930 | 9.2294 | -3.6707 | -1.3460 | 4.5 |
| 1928 | 9.2801 | -3.8593 | -2.0631 | 3.5 |
| 1926 | 9.2770 | -3.3837 | -1.1030 | 3.0 |
| 1923 | 9.2691 | -3.5083 | -1.5551 | 5.3 |
| 1921 | 9.2673 | -3.7867 | -1.9940 | 4.5 |
| 1919 | 9.3128 | -3.6693 | -1.3031 | 3.0 |
| 1917 | 9.2841 | -3.6345 | -1.3696 | 4.5 |
| 1915 | 9.2635 | -3.4567 | -1.3380 | 4.0 |
| 1913 | 9.2636 | -3.6203 | -1.7021 | 4.0 |
| 1911 | 9.2597 | -3.5777 | -2.0150 | 6.0 |
| 1909 | 9.2478 | -3.5543 | -1.5141 | 4.0 |
| 1907 | 9.2670 | -3.6167 | -1.9760 | 4.0 |
| 1905 | 9.3128 | -3.7003 | -1.3941 | 4.0 |
| 1903 | 9.2778 | -3.6627 | -1.5950 | 5.0 |
| 1901 | 9.2974 | -3.7043 | -1.4881 | 3.5 |
| 1899 | 9.2664 | -3.7043 | -1.4881 | 4.0 |
| 1897 | 9.3082 | -3.5577 | -1.3570 | 3.5 |
| 1895 | 9.2954 | | | 3.5 |
| 1893 | 9.2835 | | | 4.0 |
| Middle piece seen in Fig. 2.1 | | | | |
| 1921 | 9.2979 | | | 2.5 |
| 1919 | 9.3337 | | | 5.0 |
| 1917 | 9.2710 | | | 5.0 |
| 1915 | 9.2499 | | | 3.0 |
| 1913 | 9.3213 | | | 4.5 |
| 1911 | 9.2916 | | | 5.0 |
| 1909 | 9.3048 | | | 4.5 |
| 1907 | 9.3442 | | | 4.5 |

| Date | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Growth Rate (mm/year) |
|---|---|---|---|---|
| 1905 | 9.3783 | | | 3.5 |
| 1903 | 9.2801 | | | 4.5 |
| 1901 | 9.2793 | -3.7865 | -1.6076 | 4.5 |
| 1899 | 9.3204 | -3.0363 | -0.7451 | 4.0 |
| 1897 | 9.3076 | -3.3477 | -0.8870 | 3.5 |
| 1895 | 9.2885 | -3.6623 | -1.4211 | 3.5 |
| 1893 | 9.2945 | -3.4297 | -1.2630 | 4.0 |
| 1891 | 9.3133 | -3.4393 | -1.6501 | 4.5 |
| 1889 | 9.3088 | -3.5367 | -1.7250 | 4.5 |
| 1887 | 9.2890 | -3.5673 | -1.6271 | 4.5 |
| 1885 | 9.3089 | -3.1147 | -1.3490 | 3.5 |
| 1883 | 9.3167 | -3.4843 | -1.5481 | 5.0 |
| 1881 | 9.3258 | -3.4467 | -1.6290 | 4.0 |
| 1879 | 9.2863 | -3.5523 | -1.3461 | 3.5 |
| 1877 | 9.2798 | -3.4087 | -1.3490 | 3.0 |
| 1875 | 9.3000 | -3.4983 | -1.6431 | 4.5 |
| 1873 | 9.2926 | -3.3447 | -2.2560 | 3.0 |
| 1871 | 9.3162 | -3.4683 | -2.0141 | 4.0 |
| 1869 | 9.3089 | -3.4670 | -1.7426 | 4.0 |
| 1867 | 9.3187 | -3.5737 | -1.7230 | 3.0 |
| 1865 | 9.3169 | -3.4953 | -1.8301 | 2.5 |
| 1863 | 9.3431 | -3.5277 | -1.4910 | 2.5 |
| 1861 | 9.3517 | -3.3083 | -1.8811 | 3.0 |
| 1859 | 9.4036 | -3.5857 | -1.6420 | 3.0 |
| 1857 | 9.3456 | -3.3153 | -1.4941 | 3.0 |
| 1855 | 9.3370 | -3.3947 | -1.7110 | 3.5 |
| 1853 | 9.3513 | -2.9393 | -1.3841 | 3.0 |
| 1851 | 9.3567 | -3.7517 | -2.4050 | 2.0 |
| 1849 | 9.3588 | -3.2325 | -1.1601 | 3.0 |
| 1847 | 9.3585 | -3.4853 | -1.0641 | 3.0 |
| 1845 | 9.3400 | -3.4037 | -1.6090 | 2.5 |
| 1843 | 9.3896 | -3.4723 | -1.2661 | 2.0 |
| 1841 | 9.3877 | -3.4847 | -1.2990 | 3.5 |
| 1839 | 9.3341 | -3.6533 | -1.2621 | 3.5 |
| 1837 | 9.3660 | -3.3297 | -0.9610 | 3.0 |
| 1835 | 9.3064 | -3.3613 | -0.8331 | 5.0 |
| 1833 | 9.3541 | -3.7287 | -0.8780 | 3.0 |
| 1831 | 9.2950 | -3.2393 | -1.3471 | 3.0 |

| Date | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Growth Rate (mm/year) |
|---|---|---|---|---|
| 1829 | 9.3146 | -3.5835 | -1.0366 | 4.0 |
| 1827 | 9.3420 | -3.6957 | -1.3730 | 4.0 |
| 1825 | 9.3390 | -3.3313 | -1.2261 | 4.0 |
| 1823 | 9.3405 | -3.3997 | -1.7790 | 4.5 |
| 1821 | 9.3332 | -3.6103 | -1.3051 | 4.5 |
| 1819 | 9.3420 | | | 3.0 |
| 1817 | 9.3371 | | | 3.0 |
| Bottom piece seen in Fig. 2.1 | | | | |
| 1837 | 9.3405 | | | 2.0 |
| 1835 | 9.3048 | | | 3.0 |
| 1833 | 9.3153 | | | 3.0 |
| 1831 | 9.3503 | | | 3.0 |
| 1829 | 9.3228 | | | 3.5 |
| 1827 | 9.2835 | | | 3.0 |
| 1825 | 9.3193 | | | 4.5 |
| 1823 | 9.2815 | | | 4.0 |
| 1821 | 9.3049 | -3.4517 | -1.3030 | 4.5 |
| 1819 | 9.3218 | -3.5400 | -1.3641 | 3.5 |
| 1817 | 9.2942 | -3.5993 | -1.1221 | 4.5 |
| 1815 | 9.3288 | -3.5927 | -1.5010 | 4.0 |
| 1813 | 9.3362 | -3.3733 | -1.2041 | 3.5 |
| 1811 | 9.2955 | -3.5117 | -1.4410 | 4.5 |
| 1809 | 9.2829 | -3.4083 | -1.0371 | 4.5 |
| 1807 | 9.3284 | -3.4937 | -1.2280 | 3.5 |
| 1805 | 9.3374 | -3.3903 | -1.1911 | 4.5 |
| 1803 | 9.3147 | -3.6247 | -1.5080 | 4.5 |
| 1801 | 9.3042 | -3.7073 | -1.3591 | 4.5 |
| 1799 | 9.3213 | -3.6070 | -0.7661 | 4.0 |
| 1797 | 9.3524 | -3.5427 | -0.8120 | 4.0 |
| 1795 | 9.3202 | -3.7033 | -1.3031 | 3.5 |
| 1793 | 9.2970 | -3.7407 | -1.1690 | 4.5 |
| 1791 | 9.3049 | -3.3933 | -1.1161 | 2.5 |
| 1789 | 9.2944 | -3.3957 | -1.2240 | 3.0 |
| 1787 | 9.3240 | -3.0413 | -1.0611 | 4.5 |
| 1785 | 9.3336 | -3.5527 | -1.2840 | 3.5 |
| 1783 | 9.2934 | -3.5843 | -1.3161 | 4.5 |

| Date | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Growth Rate (mm/year) |
|---|---|---|---|---|
| 1781 | 9.2929 | -3.5967 | -1.1150 | 5.5 |
| 1779 | 9.2775 | -3.6037 | -1.3600 | 6.5 |
| 1777 | 9.3021 | -3.5513 | -1.3011 | 3.5 |

# Appendix B

# Sr/Ca Measurements

## B.1 Sr/Ca Long-Term Drift Correction

Strontium and calcium measurements were made simultaneously on an Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP-AES). The measurement of the high resolution (~monthly) record (HRR) from coral BB 001 presented in Chapters four and five took place from September 2005 to February 2006. Corrections were applied to raw data each day for error stemming from drift during the run and matrix interference, using solution standards (Schrag, 1999). Additionally, samples from a *Porites* coral (powder standard) which had been crushed and homogenized were prepared simultaneously with unknowns and measured randomly throughout each run to evaluate precision of the instrumentation through time.

During the measurements of the HRR, six hundred and seventy-three powder standard measurements were made with an average value of 0.01951 ppm Sr / ppm Ca (8.9231 mmol Sr / mol Ca), a standard deviation of 0.00004585 ppm Sr / ppm Ca or a relative standard deviation of 0.24% (n=646). On average, 16 powder standards were run for every 100 unknowns. In addition, entire runs of powder standard were measured in advance of a series of days on which unknowns were measured.

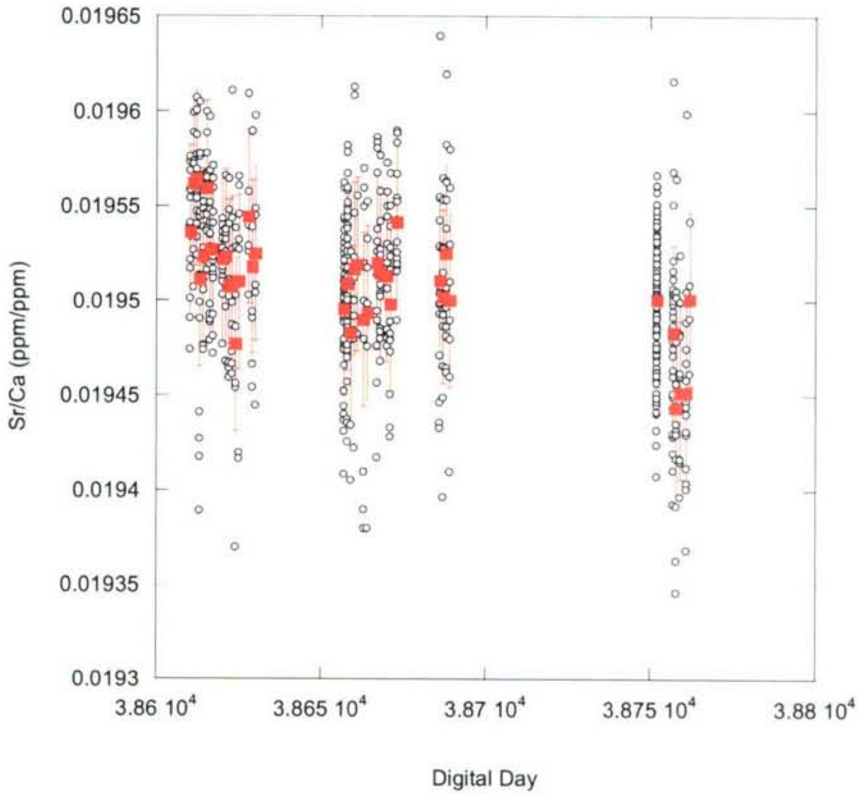


**Figure B.1:** Coral powder standard Sr/Ca (ppm/ppm) values are plotted versus digital day, with each measurement (circle) and the daily average (square) with one standard deviation error bars. The range of Sr/Ca seen on any given day remains relatively consistent through time, while the daily average shows a distinct drop in the last group of days.

Over the six months during which measurements occurred, there appears to be a slight drift in the Sr/Ca value (Fig. B.1). Primarily, this drift is driven by a drop in the average value seen in the last runs during February 2006. The first two hundred and twelve samples of the HRR were re-sampled and re-measured after completion of the measurements, and therefore, unlike the other measurements of this record, the first set was not fully randomized into the measuring sequence with the rest of the record. While the range of powder standard values measured in Feb. is equivalent to those seen throughout the measurements and the offset in these measurements is small (~0.00004), on order of one standard deviation, the re-measurement of the first samples at this time may have contributed to an offset or bias in the HRR record.

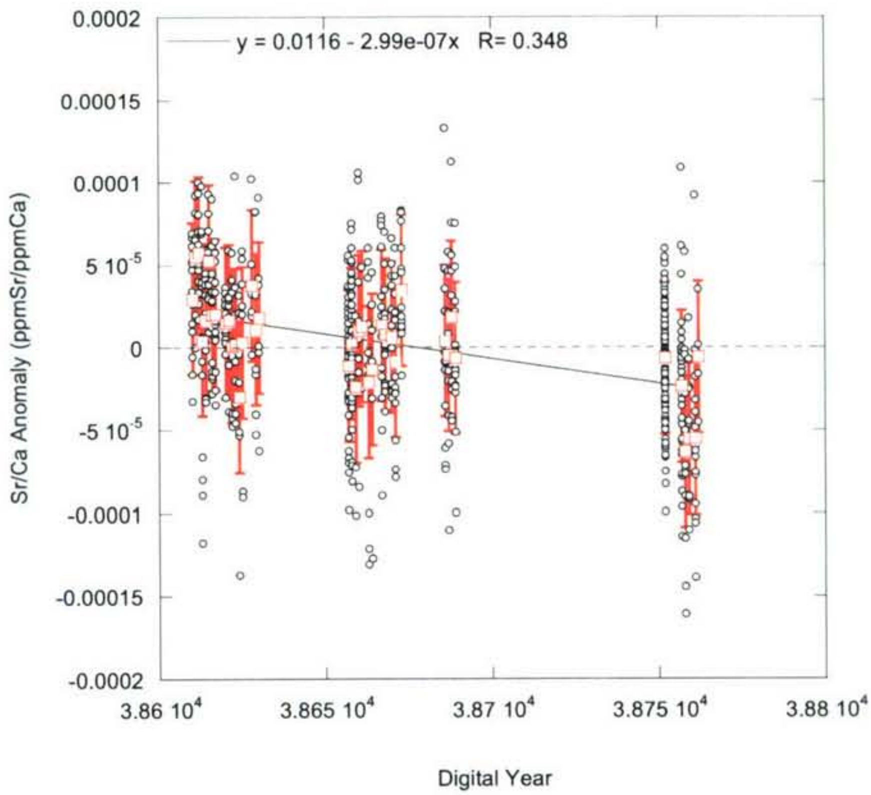


**Figure B.2:** Sr/Ca anomaly versus digital day for each measurement (circles) and the daily average (square) with one standard deviation error bars on daily average. A linear regression of Sr/Ca on time shows a trend of decreasing anomalies with time.

In order to eliminate an artifact from this drift in the standards, a correction was applied to all data which were run from Sept. 2005-Feb. 2006. The correction is defined by a Sr/Ca anomaly calculated by subtracting the average Sr/Ca (ppm/ppm) values from each individual value, which is linearly regressed against time (Fig. B.2). The linear regression returned the following result:

$$\text{Sr/Ca Anom.} = -2.99\text{E-}7\ (\pm 3.17\text{E-}8) * (\text{digital day}) - 0.0116\ (\pm 0.0012)$$

$$(\sigma,\ 95\%\ \text{confidence},\ F_{sig}=7.85\text{E-}20,\ r^2=0.12) \qquad (1)$$

This calculated Sr/Ca anomaly per day was then used to correct for the long-term drift in the standards. While this correction is two orders of magnitude smaller than our seasonal signal and generally smaller than the standard deviation, I believe that it removes any questions that may have arisen from lack of randomization of the first 200 samples from the rest of the record.

## B.2 References

Schrag D. P. (1999) Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates. *Paleoceanography* **14**(2), 97-102.

# Appendix C

# Stable Oxygen and Carbon Isotope Measurements

## C.1 Introduction

Stable isotopic data was measured on relatively small samples ranging from 10-30 μg. Under these conditions, the mass spectrometer system is performing at its stability limits. As the sample size and subsequent voltage decreases, the flow through the capillaries can be altered impacting the isotopic measurement in the source. Additionally, the adjustable standard bellows malfunctioned during the generation of this record which led to significantly unbalanced sample/standard voltage on measurements on several days of runs. Unbalanced voltages between the sample and standard scans, which primarily occurred at relatively large voltages, appear to have impacted the isotopic values. Therefore, an analysis of external powder standards was conducted to evaluate the influence of these two effects – small sample size and sample-standard imbalance – on the measurements of unknowns.

Three external standards were used for this analysis: B1-2 (a Pee Dee Belemnite), carrara marble, and estremoz marble. Estremoz has a $\delta^{18}O$ value of -5.98‰ relative to Vienna Pee Dee Belemnite (VPDB) with a standard deviation of 0.11‰ and a $\delta^{13}C$ value of 1.63‰ relative to VPDB with a standard deviation of 0.07‰. These values are close in isotopic composition to corals used in this study. B1-2 has a $\delta^{18}O$ value of 0.17‰ relative to VPDB with a standard deviation of 0.14‰ and a $\delta^{13}C$ of 0.66‰ relative to VPDB with a standard deviation of 0.15‰. Finally, carrara marble has $\delta^{18}O$ value of -1.99‰ relative to VPDB with a standard deviation of 0.12‰ and $\delta^{13}C$ value of 2.01‰ relative to VPDB with a standard deviation of 0.14‰.

## C.2: Small Sample Measurements

Small samples are defined as those analyses producing source pressure voltages of less than 0.800V (Ostermann and Curry, 2000), a signal intensity that results from ~15μg of $CaCO_3$. All samples generating a voltage of <0.400V are considered too small for inclusion in the dataset. As can be seen in Figure C.1, the oxygen isotope measurements show a large range (0.8‰) for all three standards (Fig. C.1a,b,c) with a group standard deviation of 0.18‰. As voltage decreases all three standards show trends of increasing isotopic values and in looking at all the measurements as a group (Fig C.1d) the same trend is found. Fitting a least squares regression on the data as a group (Fig. C.1d) returns the following equations:

$$\text{Oxygen Anomaly} = -0.565\ (\pm 0.182) * (\text{sample voltage}) + 0.444\ (\pm 0.116)$$

$$(\sigma,\ 95\%\ \text{confidence},\ F_{sig}=0.0027,\ r^2=0.12,\ n=73) \quad (1)$$

Carbon measurements show decreased scatter relative to oxygen and in general a diminished trend of increasing anomalies relative to decreasing voltages (Fig. C.2). The measurements show a spread of 0.5‰ with a standard deviation of 0.10‰. B1-2 (Fig. C.2a) shows an increasing trend of the same magnitude as the oxygen measurements (Fig. C.1a), but carrara (Fig. C.2b), estremoz (Fig. C.2c) and the group as a whole (Fig.

C.2d) all show a reduced trend relative to oxygen. Fitting a least squares regression on the data as a group (Fig. C.2d) returns the following equations:

$$\text{Carbon Anomaly} = -0.339\ (\pm 0.106) * (\text{sample voltage}) + 0.223\ (\pm 0.068)$$

$$(\sigma,\ 95\%\ \text{confidence},\ F_{sig}=0.0020,\ r^2=0.13,\ n=71) \qquad (2)$$

Finally, if mass fractionation was occurring at these small voltages a 2:1 relationship of oxygen:carbon would be expected. The expected impact of mass fractionation on carbon and. oxygen measurements is not found (Fig. C.3). B1-2 (Fig. C.3a) shows no relationship between the carbon anomaly and the oxygen anomaly. A very similar relationship is found for carrara and estremoz with an oxygen:carbon ratio of ~1.5 (Fig. C.2b,c). Carrara and estremoz fall short of this 2:1 ratio as does the group fit (Fig. C.2d) and the lack on any relationship for B1-2 do not provide an strong indication that mass fractionation is occurring.

In conclusion, while there is limited evidence for mass fractionation, the clear trends in the small standard data allow for correction of small samples. Therefore, all sample data with voltage >0.400V and <0.800V are corrected by calculating the anomaly relative to zero as predicted by the sample voltage in equations 1 & 2 and adding it to the isotope value.. Applying these corrections to the standard data minimally improve the standard deviation for the oxygen anomalies to 0.17‰ from 0.18‰, while successfully removing the trend found in the anomalies (Fig. C.4a). A similar result is found for the carbon anomalies with a standard deviation improvement to 0.095‰ from 0.102‰ with a successful removal of the trend (Fig. C.4b). Two hundred and nine samples out of 2,332 total samples or 9.0% of the long, high-resolution record have voltages that are less than 0.800 V and greater than 0.400 V.

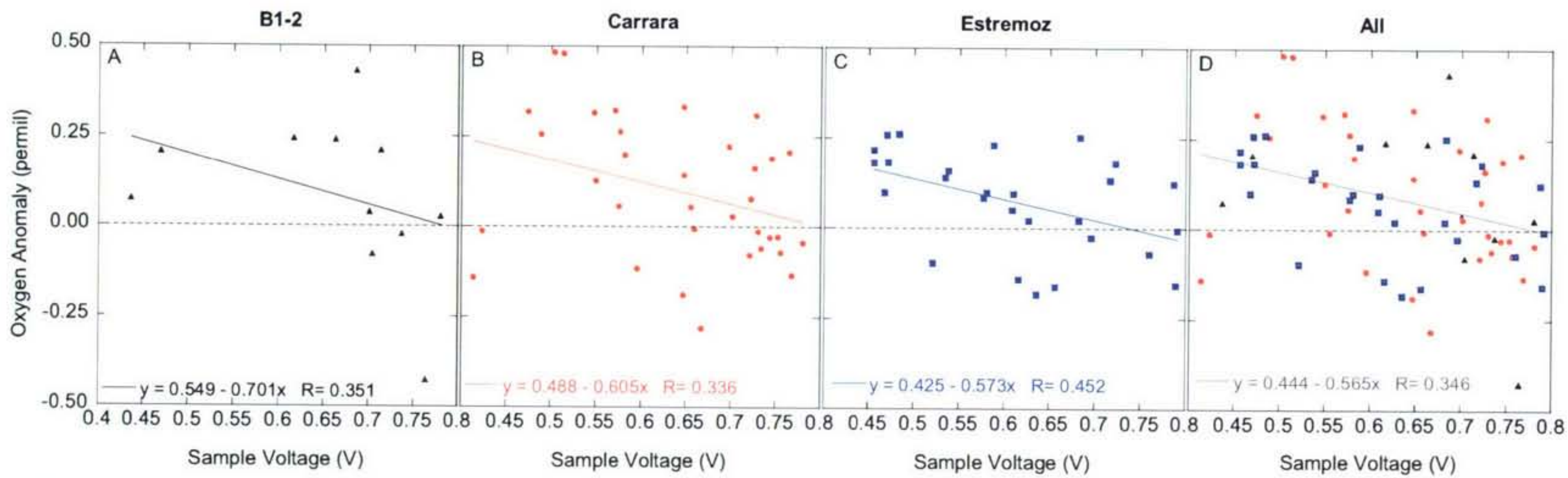


**Figure C.1:** Oxygen anomaly versus sample voltage (0.4-0.8V) for a) B1-2, b) carrara, c) estremoz, and d) all.

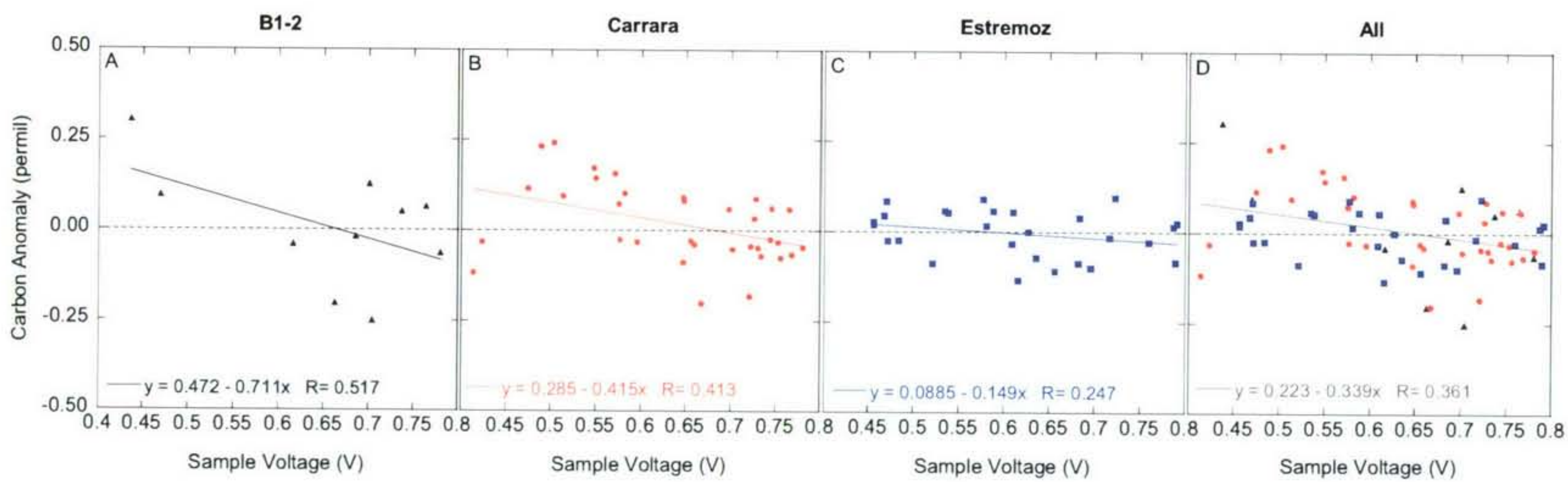


**Figure C.2:** Carbon anomaly versus sample voltage (0.4-0.8V) for a) B1-2, b) carrara, c) estremoz, and d) all.

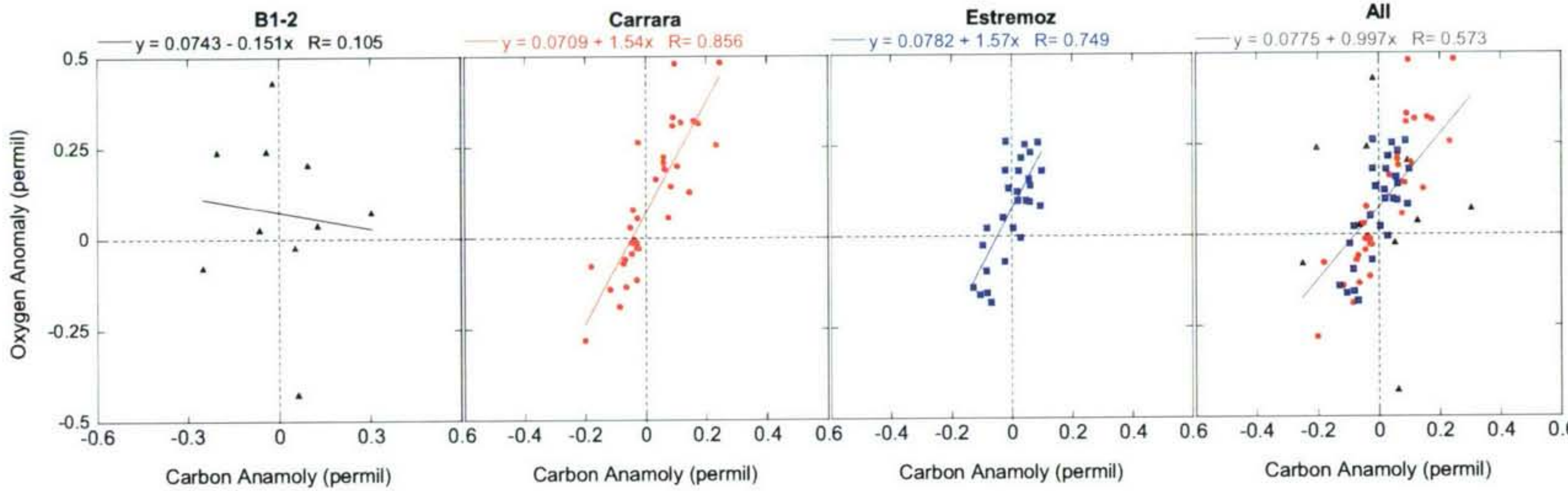


**Figure C.3:** Oxygen anomaly versus carbon anomaly for sample voltage (0.4-0.8V) for a) B1-2, b) carrara, c) estremoz, and d) all.

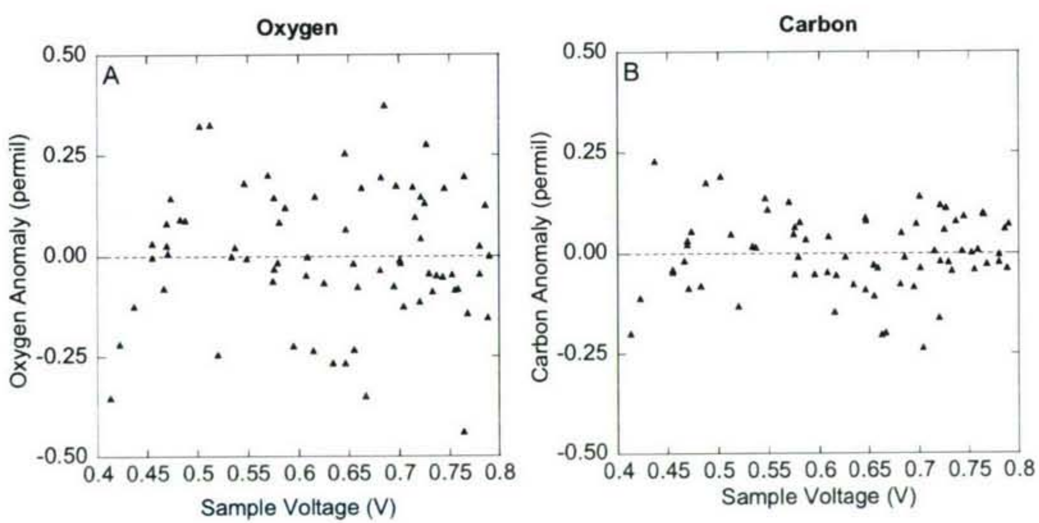


**Figure C.4:** Corrected anomaly versus sample voltage for a) oxygen and b) carbon.

## C.3: Unbalanced Sample Measurements

The second source of an increased standard deviation in the dataset is unbalanced sample/standard voltage data. Unbalanced data resulted from two causes. The majority resulted from a jammed pin in the bellows preventing the bellows from properly adjusting for larger voltage samples. The second source of error was samples larger than ~35μg that were run using a sample method optimized for samples smaller than 30μg (lower maximum reference gas pressure, greater balancing accuracy and small voltage correction).

The standard deviation on all of the "non-small" oxygen anomalies for B1-2, carrara, and estremoz is 0.10‰ and for carbon is 0.11‰. As can be seen in Fig. C.5, there is an increasing trend in oxygen measurements that have a sample/standard voltage ratio of >1.1, the normal cut off for an acceptable measurement. B1-2 (Fig. C.5a) and estremoz (Fig. C.5c) show similar trends with slopes in proximity to 0.1 (permil/(sample/standard voltage)). Carrara (Fig. C.5b) does not show as strong a trend, but the measurements are still positively offset from mean values. As a group (Fig. C.5d), the data does show an upward trend as samples become increasingly unbalanced. Beyond a sample standard voltage ratio of 2.5 these relationships fall apart. Therefore, measurements with an unbalance of greater than 2.5 have been removed from the dataset. Fitting a least squares regression to the remaining data returns the following equation:

Oxy. Anom. = 0.0967 (±0.0148) * (sample voltage/standard voltage) – 0.0547 (±0.0225)

($\sigma$, 95% confidence, $F_{sig}$=8.02E-10, $r^2$=0.21, n=164) (3)

After applying this correction equation to all the non-small data the standard deviation is reduced from 0.10 to 0.09 and as can be seen in Fig. C.6 removes the trend from the unbalanced anomalies. Therefore, this correction is applied to the unknowns by calculating the expected anomalies based on the sample/standard voltage and then adding it to the measured value.

Similar results are found for carbon measurements (Fig. C.7). Each standard has an increasing trend as the sample/standard voltage increases. B1-2 (Fig. C.7a) has the sharpest slope at 0.135, but the largest spread of both positive and negative anomalies. Carrara (Fig. C.7b) and estremoz (Fig. C.7c) show all positive anomalies with slopes of 0.0361 and 0.0603 respectively. Fitting a least squares regression on the data as a group (Fig. C.7d) returns the following equations:

$$\text{Carbon Anom.} = 0.0620\ (\pm 0.0108) * (\text{sample voltage/standard voltage}) - 0.0374\ (\pm 0.0164)$$

$$(\sigma,\ 95\%\ \text{confidence},\ F_{sig}=4.54\text{E-}8,\ r^2=0.17,\ n=174) \qquad (4)$$

After applying this correction equation to the data the standard deviation on all non-small carbon measurements is reduced from 0.11 to 0.10 and as can be seen in Fig. C.8 removes the trend from the unbalanced anomalies. Therefore, this correction is applied to the unknowns by calculating the expected anomalies based on the sample/standard voltage and then adding it to the measured value. .

These corrections were applied to 267 out of 2,332 samples or 11% of the record.

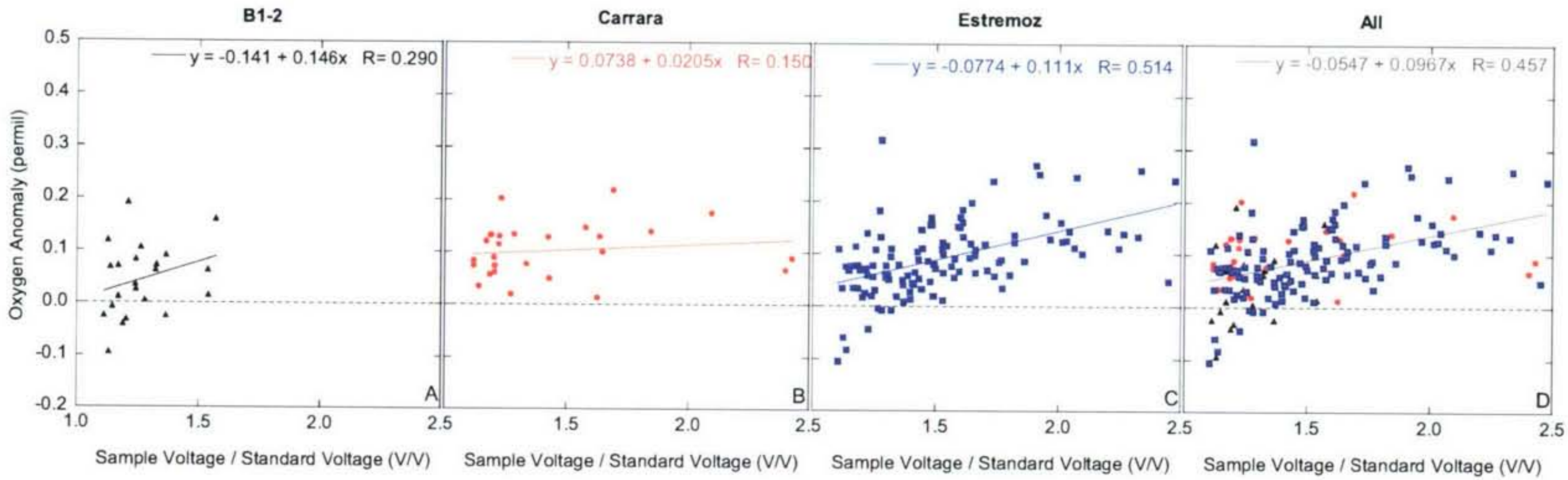


**Figure C.5:** Oxygen anomaly versus sample/standard voltage for a) B1-2, b) carrara, c) estremoz, and d) all.

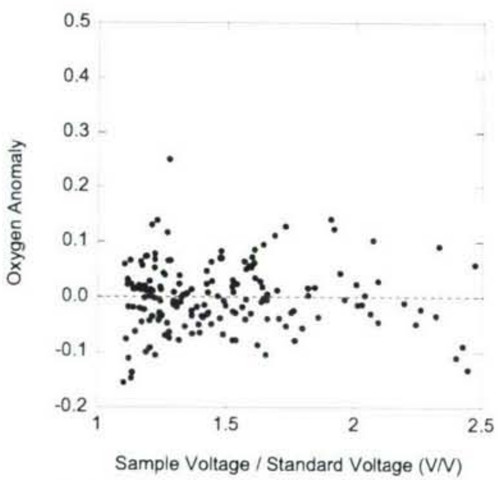


**Figure C.6:** Corrected oxygen anomaly versus sample/standard voltage.

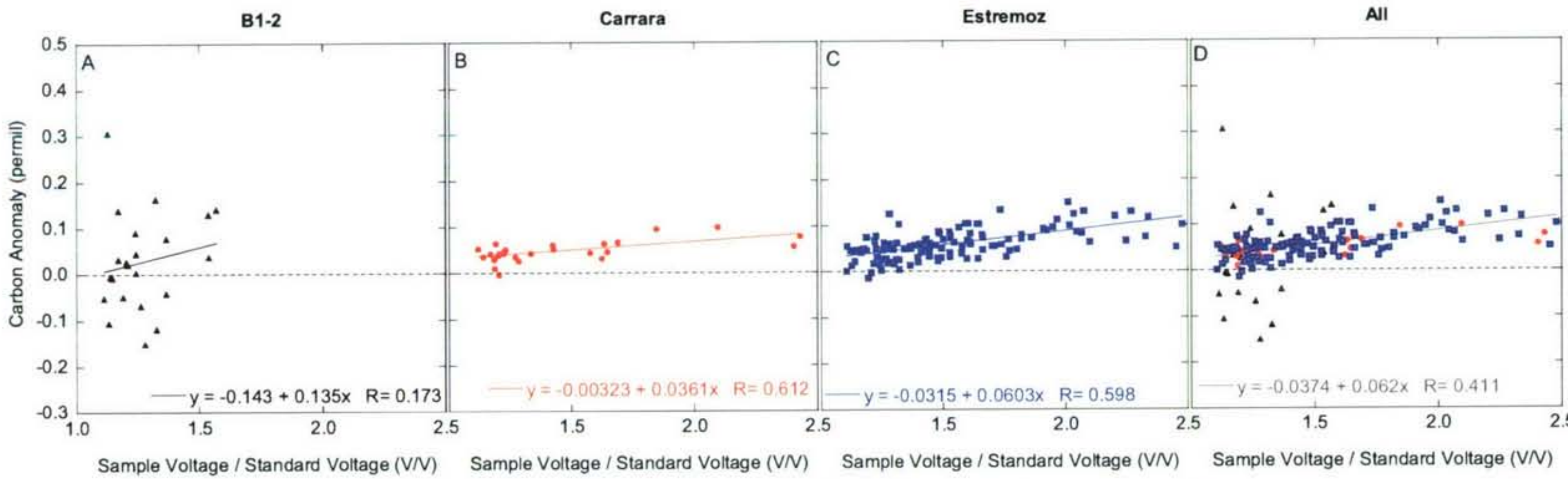


**Figure C.7:** Carbon anomaly versus sample/standard voltage for a) B1-2, b) carrara, c) estremoz, and d) all.

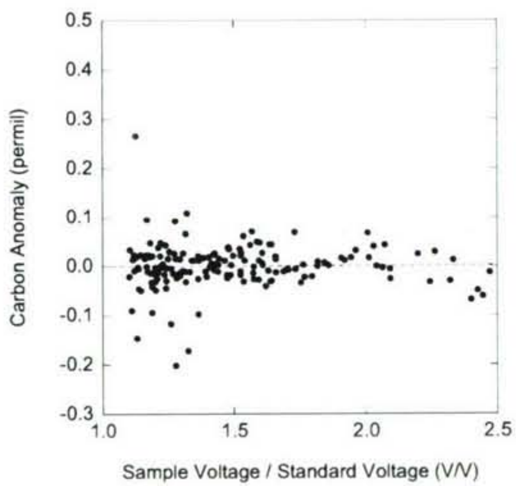


**Figure C.8:** Corrected carbon anomaly versus sample/standard voltage.

## C.5: Conclusion

In conclusion, before corrections all (n=660) of the oxygen standards have a standard deviation of 0.11‰. After both the small voltage and imbalance correction the standard deviation of the oxygen anomalies is 0.10‰. The carbon anomalies as a group have a lower standard deviation of 0.098‰ compared to an initial standard deviation of 0.105‰. While these changes are small, successful removal of trends in the standards which may be introduced due to measurements based on sample size or voltage imbalances (Figs. C.4, C.6, & C.8).

## C.6: References

Ostermann D. R. and Curry W. B. (2000) Calibration of stable isotopic data: An enriched del18O standard used for source gas mixing detection and correction. *Paleoceanography* 15(3), 353-360.

# Appendix D

# High Resolution Record Data

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| **Top Piece Shown in Fig. 2.1** | | | | |
| 0.0 | 9.2182 | | | 1999.67 |
| 0.3 | 9.1727 | -3.6895 | -3.4854 | 1999.58 |
| 0.7 | 9.1668 | -3.7770 | -3.1513 | 1999.50 |
| 1.0 | 9.0830 | -4.0976 | -3.5943 | 1999.42 |
| 1.3 | 9.0325 | -4.4030 | -3.8533 | 1999.33 |
| 1.7 | 9.0764 | -4.2346 | -3.9273 | 1999.25 |
| 2.0 | 9.1053 | -4.2117 | -3.4747 | 1999.17 |
| 2.3 | 9.1677 | -3.9966 | -3.0993 | 1999.08 |
| 2.7 | 9.2170 | -3.6615 | -2.6552 | 1999.00 |
| 3.0 | 9.4285 | -3.2186 | -2.0723 | 1998.92 |
| 3.3 | 9.3930 | -3.2430 | -2.1803 | 1998.83 |
| 3.7 | 9.2879 | | | 1998.75 |
| 4.0 | 9.1840 | -3.8110 | -2.4413 | 1998.67 |
| 4.3 | 9.1181 | -4.1476 | -2.5913 | 1998.58 |
| 4.7 | 9.1341 | -4.0774 | -3.0427 | 1998.50 |
| 5.0 | 9.1001 | -4.2616 | -3.1363 | 1998.42 |
| 5.3 | 9.1731 | -3.7516 | -2.5464 | 1998.33 |
| 5.7 | 9.3963 | -3.4586 | -2.1753 | 1998.25 |
| 6.0 | 9.5252 | -3.1950 | -2.1549 | 1998.17 |
| 6.3 | 9.4292 | -3.2686 | -2.2903 | 1998.08 |
| 6.7 | 9.3520 | -3.2810 | -2.4933 | 1998.00 |
| 7.0 | 9.3029 | -3.4246 | -2.6113 | 1997.92 |
| 7.3 | 9.1952 | -3.9940 | -2.7433 | 1997.83 |
| 7.7 | 9.0981 | -3.8096 | -2.8963 | 1997.73 |
| 8.0 | 9.0851 | -4.0500 | -2.7793 | 1997.63 |
| 8.3 | 9.1712 | -3.9136 | -2.9663 | 1997.56 |
| 8.7 | 9.1646 | -3.7013 | -3.0063 | 1997.49 |
| 9.0 | 9.3718 | -3.2362 | -2.2957 | 1997.42 |
| 9.3 | 9.4268 | -2.9925 | -1.6898 | 1997.17 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 9.7 | 9.3968 | -3.2186 | -1.8013 | 1996.96 |
| 10.0 | 9.2042 | -3.6670 | -1.9103 | 1996.87 |
| 10.3 | 9.1689 | -3.6976 | -1.6793 | 1996.75 |
| 10.7 | 9.2062 | -3.5220 | -2.0713 | 1996.71 |
| 11.0 | 9.1329 | -3.9756 | -2.4493 | 1996.67 |
| 11.3 | 9.2316 | -3.7052 | -2.5437 | 1996.46 |
| 11.7 | 9.2514 | -3.3926 | -2.1933 | 1996.40 |
| 12.0 | 9.4069 | -2.9450 | -1.5613 | 1996.33 |
| 12.3 | 9.4216 | -2.9136 | -1.5043 | 1996.17 |
| 12.7 | 9.3743 | -3.3040 | -2.3983 | 1996.00 |
| 13.0 | 9.2014 | -3.6286 | -2.5283 | 1995.83 |
| 13.3 | 9.1697 | -3.7500 | -2.8893 | 1995.75 |
| 13.7 | 9.1311 | -4.1076 | -2.7933 | 1995.63 |
| 14.0 | 9.1681 | -3.9160 | -2.5483 | 1995.53 |
| 14.3 | 9.2348 | -3.5200 | -2.5383 | 1995.47 |
| 14.7 | 9.3996 | | | 1995.42 |
| 15.0 | 9.4906 | -3.4114 | -2.3575 | 1995.21 |
| 15.3 | 9.3948 | -3.2700 | -2.4633 | 1995.00 |
| 15.7 | 9.3070 | -3.4826 | -2.8163 | 1994.89 |
| 16.0 | 9.2112 | -3.8500 | -3.1843 | 1994.78 |
| 16.3 | 9.0455 | -4.0956 | -3.2313 | 1994.67 |
| 16.7 | 9.0968 | -3.9337 | -2.8023 | 1994.63 |
| 17.0 | 9.0508 | -4.1286 | -2.9483 | 1994.58 |
| 17.3 | 9.1320 | -4.0320 | -3.0773 | 1994.53 |
| 17.7 | 9.2310 | -3.8027 | -3.1758 | 1994.47 |
| 18.0 | 9.3425 | -3.5290 | -2.9553 | 1994.42 |
| 18.3 | 9.3730 | -3.2283 | -2.2967 | 1994.33 |
| 18.7 | 9.4301 | -3.3190 | -2.1773 | 1994.21 |
| 19.0 | 9.2801 | -3.4506 | -2.5663 | 1993.92 |
| 19.3 | 9.2130 | -3.9460 | -2.5983 | 1993.88 |
| 19.7 | 9.1161 | -4.0656 | -3.0643 | 1993.71 |
| 20.0 | 9.0813 | -4.0565 | -3.2222 | 1993.63 |
| 20.3 | 9.1609 | -3.8953 | -2.9334 | 1993.58 |
| 20.7 | 9.2953 | -3.3990 | -2.0643 | 1993.50 |
| 21.0 | 9.4074 | | | 1993.42 |
| 21.3 | 9.4651 | -3.0750 | -2.1913 | 1993.17 |
| 21.7 | 9.4437 | -3.1916 | -2.1363 | 1993.04 |
| 22.0 | 9.3038 | -3.6450 | -2.4263 | 1992.88 |
| 22.3 | 9.1764 | -3.7516 | -2.6463 | 1992.81 |
| 22.7 | 9.1036 | -4.1661 | -2.8119 | 1992.75 |
| 23.0 | 9.0733 | -3.9386 | -2.7823 | 1992.63 |
| 23.3 | 9.1088 | -4.0530 | -2.9353 | 1992.58 |
| 23.7 | 9.2121 | -3.9406 | -3.0133 | 1992.54 |
| 24.0 | 9.3610 | -3.2860 | -2.5633 | 1992.50 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 24.3 | 9.4637 | -3.0212 | -2.3133 | 1992.25 |
| 24.7 | 9.4135 | -3.1050 | -2.2264 | 1992.21 |
| 25.0 | 9.4822 | -3.1699 | -2.5432 | 1992.17 |
| 25.3 | 9.3262 | -3.2568 | -2.5645 | 1991.92 |
| 25.7 | 9.2766 | -3.6626 | -3.1063 | 1991.83 |
| 26.0 | 9.1330 | -4.0030 | -3.2743 | 1991.73 |
| 26.3 | 9.0986 | -4.2136 | -3.2843 | 1991.63 |
| 26.7 | 9.1711 | -4.0060 | -2.8453 | 1991.50 |
| 27.0 | 9.2142 | -4.0226 | -3.0763 | 1991.46 |
| 27.3 | 9.3053 | -3.4070 | -2.6113 | 1991.42 |
| 27.7 | 9.4284 | -3.1526 | -2.2013 | 1991.31 |
| 28.0 | 9.4715 | -3.3510 | -2.3043 | 1991.21 |
| 28.3 | 9.4114 | -3.4676 | -2.5303 | 1991.04 |
| 28.7 | 9.2526 | -3.8240 | -2.8023 | 1990.92 |
| 29.0 | 9.1843 | -3.9216 | -2.7623 | 1990.83 |
| 29.3 | 9.1260 | -3.9851 | -2.7756 | 1990.75 |
| 29.7 | 9.1412 | -4.2406 | -2.9843 | 1990.73 |
| 30.0 | 9.2256 | -3.9100 | -3.1393 | 1990.71 |
| 30.3 | 9.1455 | -4.0116 | -3.1663 | 1990.69 |
| 30.7 | 9.0999 | -4.1280 | -3.4013 | 1990.67 |
| 31.0 | 9.1772 | -3.5416 | -3.1603 | 1990.50 |
| 31.3 | 9.3255 | -3.2010 | -2.7003 | 1990.42 |
| 31.7 | 9.3178 | -2.9876 | -2.5273 | 1989.88 |
| 32.0 | 9.2187 | -3.5590 | -2.7053 | 1989.83 |
| 32.3 | 9.1606 | -3.6516 | -3.2363 | 1989.81 |
| 32.7 | 9.1822 | -3.9130 | -3.0533 | 1989.79 |
| 33.0 | 9.1352 | -4.0786 | -3.3083 | 1989.77 |
| 33.3 | 9.1383 | -3.9380 | -2.8623 | 1989.75 |
| 33.7 | 9.0743 | -3.9046 | -2.9873 | 1989.58 |
| 34.0 | 9.1771 | -3.8780 | -3.0963 | 1989.50 |
| 34.3 | 9.3277 | -3.3626 | -2.0663 | 1989.42 |
| 34.7 | 9.4477 | -3.2210 | -1.8013 | 1989.25 |
| 35.0 | 9.4611 | -3.3376 | -2.3923 | 1989.17 |
| 35.3 | 9.3624 | -3.3103 | -2.5643 | 1988.92 |
| 35.7 | 9.3087 | -3.5406 | -3.1363 | 1988.88 |
| 36.0 | 9.2231 | -3.4449 | -3.5036 | 1988.83 |
| 36.3 | 9.3111 | -3.6696 | -3.3503 | 1988.79 |
| 36.7 | 9.2266 | -4.0300 | -3.2033 | 1988.75 |
| 37.0 | 9.2259 | -3.9586 | -3.3693 | 1988.71 |
| 37.3 | 9.1951 | -3.7555 | -3.3093 | 1988.67 |
| 37.7 | 9.2727 | | | 1988.56 |
| 38.0 | 9.2687 | -3.6150 | -2.3163 | 1988.46 |
| 38.3 | 9.4192 | -3.6476 | -2.4923 | 1988.42 |
| 38.7 | 9.4727 | -2.9916 | -1.7965 | 1988.25 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 39.0 | 9.4692 | -3.5106 | -2.1283 | 1988.14 |
| 39.3 | 9.4224 | -3.3445 | -2.1713 | 1988.03 |
| 39.7 | 9.2770 | -3.5726 | -2.5423 | 1987.88 |
| 40.0 | 9.2435 | -3.5520 | -2.5413 | 1987.87 |
| 40.3 | 9.1239 | -3.9396 | -2.8683 | 1987.79 |
| 40.7 | 9.1130 | -4.1400 | -3.1413 | 1987.58 |
| 41.0 | 9.1443 | -3.9856 | -3.4313 | 1987.53 |
| 41.3 | 9.3214 | -3.2880 | -2.6773 | 1987.42 |
| 41.7 | 9.3456 | -3.5649 | -2.9644 | 1987.42 |
| 42.0 | 9.4529 | -3.4460 | -3.1923 | 1987.25 |
| 42.3 | 9.4597 | -3.2456 | -2.9971 | 1987.21 |
| 42.7 | 9.2989 | -3.5004 | -3.4112 | 1987.00 |
| 43.0 | 9.2159 | | | 1986.87 |
| 43.3 | 9.1676 | -3.9710 | -3.6033 | 1986.83 |
| 43.7 | 9.1677 | -4.2746 | -3.7973 | 1986.75 |
| 44.0 | 9.0145 | -4.0900 | -3.2683 | 1986.63 |
| 44.3 | 9.1485 | -4.2506 | -3.1193 | 1986.64 |
| 44.7 | 9.2321 | -4.1613 | -3.4748 | 1986.61 |
| 45.0 | 9.1491 | -4.0636 | -3.0633 | 1986.58 |
| 45.3 | | -3.7840 | -2.9553 | 1986.54 |
| 45.7 | 9.2621 | -3.4676 | -3.1149 | 1986.50 |
| 46.0 | 9.3776 | -3.0510 | -2.5363 | 1986.33 |
| 46.3 | 9.3874 | -3.2976 | -2.8043 | 1986.08 |
| 46.7 | 9.3424 | -3.6280 | -3.5823 | 1986.00 |
| 47.0 | | -3.6506 | -3.6923 | 1985.90 |
| 47.3 | 9.1649 | -3.6920 | -3.4593 | 1985.79 |
| 47.7 | 9.1007 | -3.9786 | -3.3983 | 1985.71 |
| 48.0 | 9.1166 | -4.2470 | -3.5553 | 1985.75 |
| 48.3 | 9.0777 | -4.2186 | -3.4243 | 1985.71 |
| 48.7 | 9.0324 | -4.3240 | -3.6343 | 1985.67 |
| 49.0 | 9.0968 | -4.2476 | -3.6593 | 1985.63 |
| 49.3 | 9.0873 | -3.9722 | -3.1085 | 1985.54 |
| 49.7 | 9.2748 | -3.5659 | -2.6741 | 1985.45 |
| 50.0 | 9.4336 | -3.1660 | -2.4863 | 1985.30 |
| 50.3 | 9.4739 | -3.0436 | -2.3123 | 1985.21 |
| 50.7 | 9.4271 | -3.3410 | -2.8193 | 1985.04 |
| 51.0 | 9.4048 | -3.1836 | -2.8053 | 1984.98 |
| 51.3 | 9.3753 | -3.4790 | -2.8873 | 1984.92 |
| 51.7 | 9.2314 | -3.9216 | -3.6583 | 1984.79 |
| 52.0 | 9.2122 | -3.8480 | -3.7583 | 1984.79 |
| 52.3 | 9.1782 | -4.1486 | -3.6483 | 1984.75 |
| 52.7 | 9.0454 | -3.9810 | -3.2013 | 1984.67 |
| 53.0 | 9.0871 | -4.1796 | -3.6273 | 1984.58 |
| 53.3 | 9.2159 | | | 1984.50 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 53.7 | 9.3083 | -3.3216 | -2.2233 | 1984.42 |
| 54.0 | 9.3999 | -3.1990 | -2.0373 | 1984.13 |
| 54.3 | 9.3697 | -3.4727 | -2.9933 | 1983.96 |
| 54.7 | 9.3591 | -3.4810 | -2.8813 | 1983.92 |
| 55.0 | 9.3552 | -3.6806 | -2.9378 | 1983.88 |
| 55.3 | 9.1573 | | | 1983.79 |
| 55.7 | 9.1389 | -3.9845 | -3.2377 | 1983.78 |
| 56.0 | 9.0408 | -4.2603 | -3.7096 | 1983.72 |
| 56.3 | 8.9937 | -4.1639 | -3.5060 | 1983.63 |
| 56.7 | 9.1394 | -4.2430 | -3.0533 | 1983.54 |
| 57.0 | 9.1402 | -4.2276 | -3.3633 | 1983.53 |
| 57.3 | 9.3445 | -3.3011 | -2.0497 | 1983.42 |
| 57.7 | 9.4756 | -2.9426 | -1.4783 | 1983.29 |
| 58.0 | 9.4320 | -3.2680 | -2.2713 | 1983.00 |
| 58.3 | 9.4058 | -3.4216 | -2.4843 | 1982.97 |
| 58.7 | 9.3357 | -3.3660 | -2.7013 | 1982.94 |
| 59.0 | 9.2855 | -3.6726 | -3.2463 | 1982.92 |
| 59.3 | 9.1554 | -4.0490 | -3.0223 | 1982.85 |
| 59.7 | 9.1161 | -4.3126 | -3.1993 | 1982.79 |
| 60.0 | 9.0031 | -4.3817 | -3.2306 | 1982.67 |
| 60.3 | 9.0653 | -4.3740 | -3.1763 | 1982.65 |
| 60.7 | 9.0545 | -4.0456 | -2.2113 | 1982.63 |
| 61.0 | 9.1510 | -4.0592 | -2.3687 | 1982.60 |
| 61.3 | 9.1385 | -3.6366 | -2.1463 | 1982.54 |
| 61.7 | 9.5236 | -3.1703 | -1.2686 | 1982.25 |
| 62.0 | 9.4590 | -3.0652 | -1.3311 | 1982.17 |
| 62.3 | 9.5011 | -3.0273 | -2.0508 | 1982.08 |
| 62.7 | 9.4263 | -3.0696 | -2.1686 | 1981.96 |
| 63.0 | 9.3373 | -3.5006 | -2.6883 | 1981.85 |
| 63.3 | 9.2749 | -3.4766 | -3.1713 | 1981.74 |
| 63.7 | 9.1327 | -3.8226 | -2.5903 | 1981.63 |
| 64.0 | 9.1570 | -4.0397 | -3.3426 | 1981.60 |
| 64.3 | 9.1414 | -3.8886 | -2.8363 | 1981.54 |
| 64.7 | 9.1800 | -3.6300 | -2.3343 | 1981.48 |
| 65.0 | 9.4467 | -3.2868 | -1.8761 | 1981.38 |
| 65.3 | 9.3998 | -3.0780 | -1.8823 | 1981.31 |
| 65.7 | 9.6123 | -2.9743 | -2.0412 | 1981.21 |
| 66.0 | 9.6079 | -3.0370 | -1.9303 | 1981.04 |
| 66.3 | 9.3885 | -3.0661 | -2.0970 | 1981.00 |
| 66.7 | 9.2433 | -3.4450 | -2.1693 | 1980.88 |
| 67.0 | 9.1626 | -3.9069 | -2.7306 | 1980.83 |
| 67.3 | 9.1828 | -4.0219 | -2.7950 | 1980.71 |
| 67.7 | 9.1524 | -4.0090 | -2.4682 | 1980.50 |
| 68.0 | 9.1636 | -4.0616 | -2.4572 | 1980.47 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 68.3 | | -3.4798 | -1.6598 | 1980.40 |
| 68.7 | 9.3193 | -3.3800 | -1.5213 | 1980.38 |
| 69.0 | 9.5056 | -2.8698 | -1.2844 | 1980.33 |
| 69.3 | 9.4904 | -2.8564 | -1.5069 | 1980.23 |
| 69.7 | 9.4768 | -2.9225 | -1.7685 | 1980.13 |
| 70.0 | 9.4086 | -3.3960 | -2.1543 | 1980.02 |
| 70.3 | 9.2654 | -3.8928 | -1.8693 | 1979.92 |
| 70.7 | 9.1945 | -3.9940 | -2.1553 | 1979.81 |
| 71.0 | 9.1146 | -3.9246 | -1.8543 | 1979.71 |
| 71.3 | 9.1171 | | | 1979.61 |
| 71.7 | 9.2099 | | | 1979.50 |
| **Track Shift** | | | | |
| 62.7 | 9.3865 | -3.4009 | -2.6157 | 1981.96 |
| 63.0 | 9.2548 | -3.9012 | -2.8271 | 1981.85 |
| 63.3 | 9.2677 | -4.2679 | -3.3657 | 1981.74 |
| 63.7 | 9.2011 | -4.2452 | -3.5111 | 1981.63 |
| 64.0 | 9.2697 | | | 1981.60 |
| 64.3 | 9.2417 | -4.2302 | -3.2491 | 1981.54 |
| 64.7 | 9.3369 | -3.8189 | -2.6227 | 1981.48 |
| 65.0 | 9.4299 | -3.5182 | -2.2751 | 1981.38 |
| 65.3 | 9.4695 | -3.1469 | -2.1967 | 1981.31 |
| 65.7 | 9.6369 | -3.0042 | -2.2451 | 1981.21 |
| 66.0 | 9.5606 | -3.1069 | -2.5337 | 1981.04 |
| 66.3 | 9.4308 | -3.5812 | -3.0091 | 1981.00 |
| 66.7 | 9.2474 | -4.3609 | -3.1277 | 1980.88 |
| 67.0 | 9.2472 | -4.3132 | -2.8081 | 1980.83 |
| 67.3 | 9.0295 | | | 1980.71 |
| 67.7 | 9.3793 | -4.0042 | -2.1441 | 1980.50 |
| 68.0 | 9.3455 | -3.9649 | -2.5367 | 1980.47 |
| 68.3 | 9.3607 | -3.9152 | -2.0151 | 1980.40 |
| 68.7 | 9.4709 | | | 1980.38 |
| 69.0 | 9.4369 | -3.7439 | -2.3467 | 1980.33 |
| 69.3 | 9.4274 | -3.6882 | -2.1481 | 1980.23 |
| 69.7 | 9.5387 | -3.4943 | -2.3356 | 1980.13 |
| 70.0 | 9.4455 | -2.8642 | -2.7001 | 1980.02 |
| 70.3 | 9.3088 | -3.8199 | -2.7057 | 1979.92 |
| 70.7 | 9.3164 | -4.0842 | -3.3131 | 1979.81 |
| 71.0 | 9.1761 | -4.2879 | -2.9587 | 1979.71 |
| 71.3 | 9.1206 | -4.2262 | -3.4491 | 1979.61 |
| 71.7 | 8.9876 | | | 1979.50 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 72.0 | 9.0456 | -4.3472 | -3.1711 | 1979.40 |
| 72.3 | 9.3050 | -4.0729 | -2.3867 | 1979.29 |
| 72.7 | 9.5364 | -3.4622 | -1.4871 | 1979.19 |
| 73.0 | 9.4814 | -3.5169 | -2.1987 | 1979.08 |
| 73.3 | 9.5108 | -3.9402 | -2.5811 | 1979.06 |
| 73.7 | 9.4853 | -3.9419 | -2.5357 | 1979.04 |
| 74.0 | 9.4147 | -4.0762 | -2.6561 | 1979.02 |
| 74.3 | 9.2741 | -4.1529 | -2.5907 | 1979.00 |
| 74.7 | 9.3787 | -4.2242 | -2.9811 | 1978.97 |
| 75.0 | 9.3234 | -4.0409 | -3.0097 | 1978.94 |
| 75.3 | 9.2659 | -4.2222 | -3.5031 | 1978.92 |
| 75.7 | 9.1568 | -4.5319 | -3.9907 | 1978.83 |
| 76.0 | 9.1842 | -4.3782 | -3.4941 | 1978.75 |
| 76.3 | 9.1549 | -4.6209 | -4.0757 | 1978.67 |
| 76.7 | 9.1767 | -3.9369 | -2.6147 | 1978.56 |
| 77.0 | 9.3804 | -3.8482 | -2.6771 | 1978.46 |
| 77.3 | 9.4793 | -3.5522 | -2.6094 | 1978.35 |
| 77.7 | 9.4895 | -3.4652 | -3.0211 | 1978.25 |
| 78.0 | 9.3906 | -3.4548 | -3.3086 | 1978.00 |
| 78.3 | 9.2396 | -4.2972 | -3.7791 | 1977.90 |
| 78.7 | 9.1373 | -4.4519 | -3.8417 | 1977.79 |
| 79.0 | 9.1468 | -4.6112 | -3.0671 | 1977.83 |
| 79.3 | 9.2172 | -4.5079 | -3.3711 | 1977.76 |
| 79.7 | 9.2035 | | | 1977.69 |
| 80.0 | 9.0734 | -4.2162 | -3.3879 | 1977.63 |
| 80.3 | 9.1164 | -4.2931 | -3.3812 | 1977.59 |
| 80.7 | 9.1857 | -4.2629 | -2.8837 | 1977.56 |
| 81.0 | 9.1643 | -3.8282 | -2.9861 | 1977.53 |
| 81.3 | 9.1516 | -4.0259 | -3.0927 | 1977.50 |
| 81.7 | 9.3303 | -3.7010 | -2.3459 | 1977.42 |
| 82.0 | | -3.5019 | -2.6187 | 1977.27 |
| 82.3 | 9.4238 | -3.5532 | -2.8331 | 1977.13 |
| 82.7 | 9.3477 | -3.2749 | -2.6937 | 1976.96 |
| 83.0 | 9.2212 | -4.1142 | -2.8871 | 1976.83 |
| 83.3 | 9.1156 | -4.1019 | -3.3447 | 1976.71 |
| 83.7 | 9.0678 | -4.6322 | -2.9679 | 1976.63 |
| 84.0 | 9.1043 | -3.8729 | -2.5567 | 1976.58 |
| 84.3 | 9.1855 | -3.4842 | -2.7941 | 1976.50 |
| 84.7 | 9.3240 | -3.9189 | -2.6797 | 1976.38 |
| 85.0 | 9.3486 | -3.6722 | -2.3001 | 1976.35 |
| 85.3 | 9.3025 | -3.3553 | -2.1954 | 1976.32 |
| 85.7 | 9.4205 | -3.4112 | -2.6341 | 1976.21 |
| 86.0 | 9.3608 | -3.3759 | -2.5337 | 1976.17 |
| 86.3 | 9.3781 | -3.0072 | -2.6059 | 1976.08 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 86.7 | 9.2887 | -3.3244 | -3.1845 | 1975.96 |
| 87.0 | 9.1103 | -3.9892 | -3.6341 | 1975.75 |
| 87.3 | 9.1765 | -4.4319 | -3.2517 | 1975.73 |
| 87.7 | 9.0963 | -4.2182 | -2.6761 | 1975.71 |
| 88.0 | 9.1923 | -4.0439 | -2.4697 | 1975.50 |
| 88.3 | 9.3700 | -3.5472 | -1.9711 | 1975.35 |
| 88.7 | 9.3403 | -3.5529 | -2.0457 | 1975.31 |
| 89.0 | 9.4564 | -2.8956 | -1.3637 | 1975.29 |
| 89.3 | 9.4146 | -3.2319 | -1.5597 | 1975.21 |
| 89.7 | 9.4397 | -3.0961 | -1.7071 | 1975.13 |
| 90.0 | 9.3880 | | | 1975.02 |
| 90.3 | 9.1861 | -4.1892 | -2.6091 | 1974.96 |
| 90.7 | 9.2342 | -4.0368 | -3.0447 | 1974.91 |
| 91.0 | 9.0646 | -4.2172 | -3.0091 | 1974.84 |
| 91.3 | 9.0109 | -4.6859 | -3.1237 | 1974.79 |
| 91.7 | 9.0085 | -4.7262 | -3.3181 | 1974.73 |
| 92.0 | 8.9937 | -4.7739 | -3.2137 | 1974.67 |
| 92.3 | 9.1163 | -3.6253 | -2.3863 | 1974.58 |
| 92.7 | 9.3365 | -3.6159 | -1.6657 | 1974.50 |
| 93.0 | 9.3574 | -3.3682 | -1.5831 | 1974.42 |
| 93.3 | 9.4678 | -2.7249 | -1.2977 | 1974.33 |
| 93.7 | 9.3824 | -3.4304 | -1.7422 | 1974.20 |
| 94.0 | 9.3946 | -3.8289 | -1.9437 | 1974.05 |
| 94.3 | 9.3411 | | | 1973.92 |
| 94.7 | 9.3055 | -4.0789 | -2.2007 | 1973.89 |
| 95.0 | 9.1303 | | | 1973.79 |
| 95.3 | 9.0906 | -4.4329 | -3.0167 | 1973.78 |
| 95.7 | 9.1220 | -4.4542 | -3.6071 | 1973.78 |
| 96.0 | 9.0771 | -4.2453 | -2.8044 | 1973.72 |
| 96.3 | 9.0650 | -4.1966 | -2.4625 | 1973.71 |
| 96.7 | 9.1582 | -3.6089 | -1.5557 | 1973.54 |
| 97.0 | 9.2879 | | | 1973.50 |
| 97.3 | 9.2747 | -3.4049 | -1.2427 | 1973.42 |
| 97.7 | 9.5028 | -2.4032 | -0.5781 | 1973.33 |
| 98.0 | 9.6012 | -2.9839 | -1.7567 | 1973.17 |
| 98.3 | 9.2372 | -3.5922 | -2.8951 | 1972.88 |
| 98.7 | 9.1474 | | | 1972.79 |
| 99.0 | 9.1373 | -3.7000 | -1.4468 | 1972.77 |
| 99.3 | 9.0932 | -4.7359 | -2.7857 | 1972.75 |
| 99.7 | 9.0430 | -4.3522 | -2.2431 | 1972.71 |
| 100.0 | 9.0288 | -4.3623 | -2.5025 | 1972.63 |
| 100.3 | 9.1257 | -4.2842 | -2.5741 | 1972.58 |
| 100.7 | 9.2391 | | | 1972.50 |
| 101.0 | 9.3372 | -3.6644 | -1.8160 | 1972.42 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 101.3 | 9.3730 | -2.6299 | -1.8687 | 1972.32 |
| 101.7 | 9.4128 | -3.4002 | -1.9861 | 1972.29 |
| 102.0 | 9.3551 | -3.5309 | -2.4147 | 1972.12 |
| 102.3 | 9.3112 | | | 1972.02 |
| 102.7 | 9.2537 | -3.7849 | -2.5057 | 1971.92 |
| 103.0 | 9.1528 | -3.8802 | -2.5051 | 1971.87 |
| 103.3 | 9.0854 | | | 1971.75 |
| 103.7 | 9.0354 | -4.5332 | -3.0161 | 1971.74 |
| 104.0 | 9.0169 | | | 1971.72 |
| 104.3 | 9.0053 | -4.3212 | -2.4091 | 1971.71 |
| 104.7 | 9.1092 | -4.1949 | -2.1847 | 1971.54 |
| 105.0 | 9.2846 | -3.5460 | -1.6904 | 1971.47 |
| 105.3 | 9.4920 | -3.2299 | -1.6307 | 1971.21 |
| 105.7 | 9.4817 | | | 1971.10 |
| 106.0 | 9.4248 | -3.4309 | -2.1487 | 1971.00 |
| 106.3 | 9.3216 | -4.1122 | -2.9251 | 1970.92 |
| 106.7 | 9.1975 | -3.7939 | -2.7137 | 1970.83 |
| 107.0 | 9.1666 | -3.8152 | -2.6391 | 1970.84 |
| 107.3 | 9.1077 | | | 1970.85 |
| 107.7 | 9.0700 | -4.5042 | -2.5931 | 1970.82 |
| 108.0 | 9.0403 | -4.1329 | -2.7417 | 1970.78 |
| 108.3 | 8.9906 | -4.2412 | -1.8921 | 1970.75 |
| 108.7 | 9.0217 | -4.4278 | -2.2382 | 1970.67 |
| 109.0 | 9.1347 | | | 1970.54 |
| 109.3 | 9.2576 | -3.6569 | -1.9737 | 1970.46 |
| 109.7 | 9.4695 | | | 1970.13 |
| 110.0 | 9.3485 | -3.1809 | -2.6287 | 1970.11 |
| 110.3 | 9.4008 | -3.0452 | -2.5101 | 1969.96 |
| 110.7 | 9.3535 | | | 1969.93 |
| 111.0 | 9.2606 | -3.0282 | -1.8871 | 1969.91 |
| 111.3 | 9.2542 | -3.8269 | -3.0187 | 1969.88 |
| 111.7 | 9.1829 | -3.8532 | -2.4681 | 1969.86 |
| 112.0 | 9.1548 | -4.0419 | -1.9607 | 1969.83 |
| 112.3 | 9.0555 | | -2.4236 | 1969.63 |
| 112.7 | 9.0435 | -4.3249 | -1.8557 | 1969.54 |
| 113.0 | 9.0672 | -4.2092 | -1.9281 | 1969.53 |
| 113.3 | 9.1918 | | -1.8974 | 1969.51 |
| 113.7 | 9.2501 | -4.0212 | -1.5925 | 1969.50 |
| 114.0 | 9.2586 | -3.2590 | -1.7481 | 1969.46 |
| 114.3 | 9.3618 | | | 1969.21 |
| 114.7 | 9.2170 | -3.4620 | -2.9498 | 1968.83 |
| 115.0 | 9.0882 | -4.6052 | -2.8141 | 1968.75 |
| 115.3 | 8.9951 | -3.8109 | -2.0757 | 1968.67 |
| 115.7 | 9.0075 | -4.6292 | -2.4311 | 1968.63 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 116.0 | 9.0140 | | | 1968.58 |
| 116.3 | 9.1658 | -4.4344 | -2.2831 | 1968.54 |
| 116.7 | 9.1331 | | | 1968.50 |
| 117.0 | 9.2847 | -3.7992 | -1.3991 | 1968.46 |
| 117.3 | 9.3512 | -3.6789 | -1.5867 | 1968.42 |
| 117.7 | 9.3425 | -3.4813 | -1.6433 | 1968.38 |
| 118.0 | 9.3943 | -3.2979 | -2.3137 | 1968.33 |
| 118.3 | 9.3672 | -3.4002 | -2.1041 | 1968.29 |
| 118.7 | 9.4209 | -3.4399 | -2.0747 | 1968.21 |
| 119.0 | 9.2871 | -3.5720 | -2.1303 | 1967.99 |
| 119.3 | 9.2909 | -3.9349 | -2.6927 | 1967.85 |
| 119.7 | 9.1392 | -4.4336 | -2.4561 | 1967.79 |
| 120.0 | 9.0810 | -4.3798 | -2.3082 | 1967.71 |
| 120.3 | 9.0710 | -4.4175 | -2.3714 | 1967.67 |
| 120.7 | 8.9830 | -4.3369 | -1.8847 | 1967.63 |
| 121.0 | 9.0725 | -4.3932 | -2.4381 | 1967.58 |
| 121.3 | 9.4517 | -3.5499 | -1.6737 | 1967.38 |
| 121.7 | 9.3646 | -3.4342 | -1.6051 | 1967.21 |
| 122.0 | 9.4425 | | | 1967.13 |
| 122.3 | 9.4209 | -3.1559 | -1.8077 | 1967.04 |
| 122.7 | 9.3397 | -3.8152 | -2.6741 | 1966.92 |
| 123.0 | 9.2087 | -3.9449 | -2.8347 | 1966.89 |
| 123.3 | 9.1700 | -4.0628 | -2.2198 | 1966.86 |
| 123.7 | 9.1621 | -4.4419 | -2.1237 | 1966.83 |
| 124.0 | 8.9588 | -4.9192 | -2.6251 | 1966.67 |
| 124.3 | 8.9833 | -4.1099 | -1.7637 | 1966.58 |
| 124.7 | 9.0119 | -4.2412 | -1.7081 | 1966.58 |
| 125.0 | 9.1889 | -3.9049 | -1.6247 | 1966.52 |
| 125.3 | 9.2202 | -3.3212 | -1.5351 | 1966.45 |
| 125.7 | 9.2395 | -3.2949 | -2.2587 | 1966.38 |
| 126.0 | 9.2330 | -3.4552 | -2.2461 | 1966.32 |
| 126.3 | 9.2413 | -3.4478 | -1.9549 | 1966.25 |
| 126.7 | 9.1208 | -4.4752 | -2.5261 | 1966.13 |
| 127.0 | 9.1919 | -3.7949 | -2.5887 | 1965.75 |
| 127.3 | 9.0387 | -4.0612 | -1.9401 | 1965.73 |
| 127.7 | 9.0528 | -4.9104 | -1.4424 | 1965.71 |
| 128.0 | 9.0077 | -4.4472 | -1.5901 | 1965.69 |
| 128.3 | 8.9615 | | | 1965.63 |
| 128.7 | 8.9967 | -4.3319 | -0.7014 | 1965.60 |
| 129.0 | 9.0514 | -3.7882 | -0.9171 | 1965.58 |
| 129.3 | 9.1255 | -3.7039 | -0.5737 | 1965.50 |
| 129.7 | 9.3258 | -2.9230 | -0.6867 | 1965.42 |
| 130.0 | 9.4410 | -3.3029 | -1.4457 | 1965.21 |
| 130.3 | 9.3802 | -3.1282 | -1.3941 | 1964.96 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 130.7 | 9.3498 | -3.4059 | -1.9097 | 1964.98 |
| 131.0 | 9.3319 | -3.3862 | -2.1201 | 1965.00 |
| 131.3 | 9.1852 | -3.8739 | -2.2937 | 1964.83 |
| 131.7 | 9.0802 | -3.9822 | -2.4871 | 1964.63 |
| 132.0 | 9.0600 | -4.2081 | -2.8380 | 1964.60 |
| 132.3 | 9.0361 | -4.5512 | -2.2551 | 1964.58 |
| 132.7 | 9.0057 | -4.3459 | -1.6187 | 1964.56 |
| 133.0 | 8.9901 | -4.2642 | -1.4641 | 1964.54 |
| 133.3 | 9.1675 | -4.1976 | -0.9689 | 1964.50 |
| 133.7 | 9.4434 | -3.4886 | -0.7808 | 1964.33 |
| 134.0 | 9.2672 | -3.4129 | -1.2747 | 1964.25 |
| 134.3 | 9.3218 | -3.1719 | -2.8050 | 1964.17 |
| 134.7 | 9.2620 | -3.8471 | -2.7810 | 1964.08 |
| 135.0 | 9.2413 | -3.3362 | -2.1741 | 1964.00 |
| 135.3 | 9.3183 | -3.5462 | -2.2064 | 1963.92 |
| 135.7 | 9.1921 | | -1.9600 | 1963.83 |
| 136.0 | 9.0397 | -4.3769 | -2.3417 | 1963.75 |
| 136.3 | 9.1122 | -4.3528 | -2.3737 | 1963.71 |
| 136.7 | 9.0307 | -4.3597 | -1.9768 | 1963.63 |
| 137.0 | 9.2385 | -3.7572 | -1.5801 | 1963.53 |
| 137.3 | 9.2246 | -4.2559 | -1.5927 | 1963.50 |
| 137.7 | 9.2473 | -3.5392 | -1.7861 | 1963.47 |
| 138.0 | 9.2929 | -3.7479 | -1.7307 | 1963.40 |
| 138.3 | 9.3584 | -3.6172 | -1.8761 | 1963.29 |
| 138.7 | 9.3466 | -3.8209 | -2.4047 | 1963.08 |
| 139.0 | 9.2591 | -3.8758 | -2.6240 | 1962.92 |
| 139.3 | 9.1645 | -4.0404 | -2.6408 | 1962.88 |
| 139.7 | 9.1941 | -3.7492 | -2.2491 | 1962.83 |
| 140.0 | 9.1037 | -4.0577 | -2.2982 | 1962.79 |
| 140.3 | 8.9734 | -4.1092 | -1.9531 | 1962.71 |
| 140.7 | 9.1692 | -3.5629 | -1.9147 | 1962.58 |
| 141.0 | 9.2846 | -3.7492 | -1.9701 | 1962.29 |
| 141.3 | 9.1425 | -4.0079 | -2.4917 | 1961.83 |
| 141.7 | 9.0383 | -4.2672 | -2.2721 | 1961.81 |
| 142.0 | 9.0454 | -4.4959 | -2.6207 | 1961.78 |
| 142.3 | 9.0110 | -4.8422 | -2.6531 | 1961.75 |
| 142.7 | 9.0138 | -4.5719 | -2.3947 | 1961.72 |
| 143.0 | 8.9948 | -4.5432 | -1.8391 | 1961.69 |
| 143.3 | 8.9367 | -4.4556 | -1.6171 | 1961.63 |
| 143.7 | 9.1167 | -3.9546 | -1.6445 | 1961.58 |
| 144.0 | 9.3272 | -3.7659 | -1.2097 | 1961.42 |
| 144.3 | 9.3327 | -3.3413 | -1.3377 | 1961.13 |
| 144.7 | 9.2888 | -3.6999 | -2.0117 | 1961.11 |
| 145.0 | 9.2724 | -3.4192 | -1.8411 | 1961.05 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 145.3 | 9.2718 | -3.6569 | -2.2887 | 1960.99 |
| 145.7 | 9.2827 | -4.0705 | -2.4390 | 1960.93 |
| 146.0 | 9.2356 | -3.8419 | -2.5397 | 1960.87 |
| 146.3 | 9.0987 | -4.2442 | -2.6711 | 1960.81 |
| 146.7 | 9.0855 | -5.2185 | -2.3653 | 1960.75 |
| 147.0 | 9.2509 | | | 1960.73 |
| 147.3 | 9.1443 | | | 1960.72 |
| 147.7 | 9.0081 | | | 1960.71 |
| 148.0 | 9.0191 | -4.4559 | -1.3848 | 1960.63 |
| 148.3 | 9.1959 | -4.3579 | -1.8377 | 1960.50 |
| 148.7 | 9.3333 | -3.1723 | -1.4473 | 1960.33 |
| 149.0 | 9.4223 | -3.4739 | -1.5507 | 1960.21 |
| 149.3 | 9.3187 | -3.2830 | -1.7867 | 1960.00 |
| 149.7 | 9.3133 | -3.0079 | -1.7167 | 1959.92 |
| 150.0 | 9.2273 | -4.0522 | -2.3031 | 1959.83 |
| 150.3 | 9.1576 | -3.1362 | -1.9987 | 1959.79 |
| 150.7 | 9.1027 | -3.7277 | -2.3569 | 1959.75 |
| 151.0 | 8.9853 | | | 1959.71 |
| 151.3 | 9.0166 | -3.8835 | -1.2292 | 1959.70 |
| 151.7 | 9.0328 | -3.6553 | -1.1786 | 1959.70 |
| 152.0 | 9.0546 | -3.6707 | -0.3434 | 1959.67 |
| 152.3 | 9.2298 | -3.4006 | -0.6997 | 1959.50 |
| 152.7 | 9.4287 | -3.3586 | -0.5585 | 1959.13 |
| 153.0 | 9.3756 | -3.1780 | -1.5243 | 1959.00 |
| 153.3 | 9.2563 | -3.2822 | -1.8442 | 1958.94 |
| 153.7 | 9.1909 | -3.5208 | -2.1739 | 1958.88 |
| 154.0 | 9.0540 | -4.0938 | -2.2983 | 1958.81 |
| 154.3 | 9.0021 | -4.5692 | -2.7384 | 1958.75 |
| 154.7 | 9.0423 | | | 1958.71 |
| 155.0 | 8.9948 | | | 1958.67 |
| 155.3 | 9.0581 | -4.0086 | -1.1309 | 1958.63 |
| 155.7 | 9.0261 | -3.4376 | -0.5193 | 1958.58 |
| 156.0 | 9.3147 | -3.2824 | -1.2902 | 1958.42 |
| 156.3 | 9.1586 | -3.9145 | -1.9906 | 1958.36 |
| 156.7 | 9.1620 | -4.3442 | -2.3311 | 1958.31 |
| 157.0 | 9.2015 | | | 1958.25 |
| 157.3 | 9.1647 | -4.3165 | -2.8412 | 1958.00 |
| 157.7 | 9.1619 | -3.4550 | -2.2046 | 1957.79 |
| 158.0 | 9.0854 | -4.3369 | -2.7367 | 1957.75 |
| 158.3 | 8.9875 | -4.1876 | -2.2293 | 1957.71 |
| 158.7 | 9.0015 | -4.2801 | -2.5531 | 1957.69 |
| 159.0 | 9.0145 | -4.0390 | -1.5234 | 1957.67 |
| 159.3 | 9.0952 | -4.6459 | -1.8887 | 1957.62 |
| 159.7 | 9.0744 | -3.2735 | -1.0853 | 1957.58 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 160.0 | 9.2699 | -2.7909 | -0.7873 | 1957.42 |
| 160.3 | 9.4601 | -2.4917 | -0.5568 | 1957.25 |
| 160.7 | 9.3987 | -2.6623 | -1.0158 | 1957.09 |
| 161.0 | 9.3426 | -3.1658 | -1.7824 | 1956.92 |
| 161.3 | 9.2776 | -3.4287 | -1.9134 | 1956.88 |
| 161.7 | 9.1325 | -3.7093 | -2.3787 | 1956.83 |
| 162.0 | 9.0724 | -4.1191 | -2.4900 | 1956.73 |
| 162.3 | 9.0434 | -3.8892 | -1.6071 | 1956.63 |
| 162.7 | 9.0430 | | | 1956.54 |
| 163.0 | 9.1303 | -3.7823 | -1.2208 | 1956.50 |
| 163.3 | 9.4005 | -3.3593 | -0.8547 | 1956.38 |
| 163.7 | 9.2644 | -2.7970 | -0.6377 | 1956.25 |
| 164.0 | 9.5364 | -2.8414 | -1.3829 | 1956.08 |
| 164.3 | 9.3657 | -3.0080 | -2.0477 | 1955.96 |
| 164.7 | 9.2276 | | | 1955.88 |
| 165.0 | 9.0678 | -4.3019 | -1.8457 | 1955.83 |
| 165.3 | 9.0201 | -4.4022 | -2.1071 | 1955.79 |
| 165.7 | 8.9822 | -4.5799 | -1.6087 | 1955.75 |
| 166.0 | 9.0312 | | | 1955.71 |
| 166.3 | 8.9561 | -4.4152 | -1.9851 | 1955.67 |
| 166.7 | 8.9623 | -4.3099 | -1.3287 | 1955.61 |
| 167.0 | 9.1803 | -3.8822 | -1.4771 | 1955.50 |
| 167.3 | 9.1936 | -3.7269 | -0.9807 | 1955.48 |
| 167.7 | 9.3783 | -3.4242 | -1.1951 | 1955.29 |
| 168.0 | 9.3343 | -3.4799 | -1.4997 | 1954.92 |
| 168.3 | 9.2942 | | | 1954.90 |
| 168.7 | 9.1812 | -4.1549 | -1.9977 | 1954.88 |
| 169.0 | 9.0900 | -3.9742 | -2.2191 | 1954.83 |
| 169.3 | 9.0061 | -4.4528 | -1.9228 | 1954.79 |
| 169.7 | 8.9769 | -4.6042 | -2.2801 | 1954.75 |
| 170.0 | 8.9588 | -4.6559 | -2.3157 | 1954.71 |
| 170.3 | 8.9500 | -4.2582 | -1.3731 | 1954.67 |
| 170.7 | 9.1050 | -4.1729 | -1.4697 | 1954.58 |
| 171.0 | 9.1161 | -3.8342 | -1.5371 | 1954.50 |
| 171.3 | 9.1838 | -3.3889 | -1.0107 | 1954.38 |
| 171.7 | 9.1910 | -3.0782 | -1.0591 | 1954.30 |
| 172.0 | 9.3063 | -3.0789 | -1.7357 | 1954.21 |
| 172.3 | 9.2272 | -3.0809 | -1.8475 | 1954.10 |
| 172.7 | 9.1960 | -3.4379 | -2.1047 | 1953.99 |
| 173.0 | 9.1539 | -3.7222 | -1.8961 | 1953.88 |
| 173.3 | 9.0232 | -4.3265 | -2.5579 | 1953.76 |
| 173.7 | 9.0500 | -4.1846 | -2.4614 | 1953.63 |
| 174.0 | 9.0242 | -4.3969 | -2.3247 | 1953.57 |
| 174.3 | 9.1039 | -3.8802 | -1.6231 | 1953.52 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 174.7 | 9.1715 | -3.6359 | -1.8867 | 1953.46 |
| 175.0 | 9.2240 | -3.5082 | -1.5061 | 1953.38 |
| 175.3 | 9.3623 | -2.9839 | -1.1317 | 1953.29 |
| 175.7 | 9.3822 | -3.1692 | -1.7081 | 1953.21 |
| 176.0 | 9.2640 | -3.4466 | -2.2224 | 1953.04 |
| 176.3 | 9.2112 | -3.7722 | -2.7395 | 1952.88 |
| 176.7 | 9.1188 | -3.5690 | -1.7624 | 1952.82 |
| 177.0 | 9.1018 | -4.1622 | -2.6641 | 1952.77 |
| 177.3 | 8.9916 | -4.7355 | -2.1155 | 1952.71 |
| 177.7 | 9.0048 | -4.3532 | -2.0041 | 1952.65 |
| 178.0 | 9.0592 | -4.2659 | -1.9237 | 1952.58 |
| 178.3 | 9.1656 | -3.9052 | -2.1501 | 1952.52 |
| 178.7 | 9.1810 | -3.5299 | -2.0587 | 1952.46 |
| 179.0 | 9.2493 | -3.5102 | -1.4721 | 1952.38 |
| 179.3 | 9.3644 | -3.3531 | -1.5402 | 1952.29 |
| 179.7 | 9.4150 | -3.1332 | -1.5911 | 1952.21 |
| 180.0 | 9.4067 | -3.1719 | -1.8057 | 1952.10 |
| 180.3 | 9.2687 | -3.7258 | -2.6076 | 1951.99 |
| 180.7 | 9.2360 | -3.8379 | -2.6297 | 1951.88 |
| 181.0 | 9.1397 | -4.0612 | -3.2101 | 1951.82 |
| 181.3 | 9.0724 | | -2.6131 | 1951.76 |
| 181.7 | 9.0731 | -4.2512 | -3.4811 | 1951.69 |
| 182.0 | 9.0406 | -4.3189 | -2.3507 | 1951.63 |
| 182.3 | 9.0620 | -3.9348 | -2.4284 | 1951.51 |
| 182.7 | 9.3044 | -3.5779 | -1.8407 | 1951.38 |
| 183.0 | 9.4095 | -3.6272 | -1.5521 | 1951.32 |
| 183.3 | 9.4248 | -3.0969 | -1.2617 | 1951.27 |
| 183.7 | 9.4508 | -3.0112 | -1.9411 | 1951.21 |
| 184.0 | 9.3602 | -3.0179 | -1.5857 | 1951.04 |
| 184.3 | 9.2520 | -3.4542 | -2.2921 | 1950.88 |
| 184.7 | 9.3176 | -3.4289 | -2.0447 | 1950.82 |
| 185.0 | 9.2753 | -3.2308 | -2.4428 | 1950.75 |
| 185.3 | 9.1426 | -3.9829 | -2.9457 | 1950.69 |
| 185.7 | 9.0599 | | -2.3174 | 1950.63 |
| 186.0 | 9.1425 | -4.2109 | -2.7507 | 1950.59 |
| 186.3 | 9.1361 | -4.2612 | -2.6691 | 1950.55 |
| 186.7 | 9.2075 | -3.9849 | -2.7647 | 1950.50 |
| 187.0 | 9.2511 | -3.6022 | -2.5481 | 1950.46 |
| 187.3 | 9.4049 | -3.1029 | -1.8187 | 1950.34 |
| 187.7 | 9.4439 | -3.3302 | -1.9021 | 1950.21 |
| 188.0 | 9.4068 | -3.4110 | -2.1814 | 1950.04 |
| 188.3 | 9.3025 | -3.7191 | -2.4090 | 1949.88 |
| 188.7 | 9.2967 | -3.7649 | -2.6427 | 1949.80 |
| 189.0 | 9.1871 | -3.8462 | -2.8841 | 1949.71 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 189.3 | 9.1731 | -4.1089 | -3.3667 | 1949.63 |
| 189.7 | 9.1822 | -3.8662 | -3.2641 | 1949.59 |
| 190.0 | 9.2572 | -4.2019 | -2.2617 | 1949.54 |
| 190.3 | 9.2140 | -4.0862 | -2.4431 | 1949.50 |
| 190.7 | 9.2786 | -4.0339 | -2.7877 | 1949.46 |
| 190.7 | | -3.7522 | -2.3681 | 1949.40 |
| 191.0 | 9.4131 | -3.4370 | -1.6779 | 1949.33 |
| 191.3 | 9.5103 | -3.3592 | -1.5421 | 1949.21 |
| 191.7 | 9.4624 | -2.3817 | 0.5506 | 1949.05 |
| 192.0 | 9.3566 | -3.2722 | -2.4181 | 1948.88 |
| 192.3 | 9.2994 | -3.5049 | -2.6547 | 1948.80 |
| 192.7 | 9.2308 | -3.4682 | -2.9931 | 1948.72 |
| 193.0 | 9.2361 | -3.8519 | -2.4627 | 1948.63 |
| 193.3 | 9.2327 | -3.8570 | -2.1826 | 1948.60 |
| 193.7 | 9.2593 | -3.8374 | -2.4826 | 1948.56 |
| 194.0 | 9.2515 | -3.8922 | -2.4521 | 1948.53 |
| 194.3 | 9.3167 | -3.6869 | -2.0987 | 1948.49 |
| 194.7 | 9.3432 | -3.5682 | -2.1331 | 1948.46 |
| 195.0 | 9.4547 | -3.3693 | -1.9411 | 1948.33 |
| 195.3 | 9.4499 | -3.1682 | -1.8481 | 1948.21 |
| 195.7 | 9.4375 | -3.2029 | -2.4477 | 1948.11 |
| 196.0 | 9.3964 | -3.3482 | -2.8001 | 1948.00 |
| 196.3 | 9.3945 | -3.1959 | -2.5377 | 1947.89 |
| 196.7 | 9.3045 | -3.6422 | -2.7121 | 1947.79 |
| 197.0 | 9.2573 | -3.6209 | -2.8327 | 1947.63 |
| 197.3 | 9.3399 | -3.9302 | -2.4001 | 1947.59 |
| 197.7 | 9.3369 | -3.7649 | -2.3427 | 1947.55 |
| 198.0 | 9.3600 | -4.0292 | -2.4361 | 1947.50 |
| 198.3 | 9.3498 | -3.7509 | -1.7767 | 1947.46 |
| 198.7 | 9.4354 | -3.7792 | -2.1471 | 1947.38 |
| 199.0 | 9.4746 | -3.6411 | -2.3216 | 1947.29 |
| 199.3 | 9.4652 | -3.3522 | -1.9581 | 1947.21 |
| 199.7 | 9.5125 | -3.5119 | -2.4067 | 1947.13 |
| 200.0 | 9.3738 | -3.5432 | -2.3671 | 1947.00 |
| 200.3 | 9.3333 | -3.5379 | -2.2797 | 1946.88 |
| 200.7 | 9.3245 | -3.7492 | -2.5961 | 1946.83 |
| 201.0 | 9.2410 | -3.7389 | -2.0207 | 1946.78 |
| 201.3 | 9.2440 | -3.9772 | -2.0871 | 1946.73 |
| 201.7 | 9.2389 | -3.9449 | -2.1787 | 1946.68 |
| 202.0 | 9.2015 | -4.0802 | -2.4571 | 1946.63 |
| 202.3 | 9.1881 | -4.1379 | -2.9597 | 1946.51 |
| 202.7 | 9.3249 | -3.5622 | -1.7161 | 1946.38 |
| 203.0 | 9.3963 | -3.4839 | -1.8517 | 1946.21 |
| 203.7 | 9.3555 | -3.2942 | -1.6941 | 1946.08 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 204.0 | 9.3531 | -3.5649 | -2.3687 | 1946.02 |
| 204.3 | 9.3133 | -3.3661 | -2.3739 | 1945.95 |
| 204.7 | 9.3599 | -3.1564 | -2.3632 | 1945.89 |
| 205.0 | 9.3070 | -3.6712 | -3.0221 | 1945.82 |
| 205.3 | 9.2242 | -3.9149 | -2.4597 | 1945.76 |
| 205.7 | 9.2848 | -3.6262 | -1.8221 | 1945.70 |
| 206.0 | 9.2015 | -4.0909 | -2.4377 | 1945.63 |
| 206.3 | 9.2410 | -3.7182 | -2.8821 | 1945.58 |
| 206.7 | 9.2106 | -3.8389 | -2.3267 | 1945.53 |
| 207.0 | 9.2371 | -3.8032 | -2.1931 | 1945.48 |
| 207.3 | 9.3119 | -3.7739 | -2.5087 | 1945.43 |
| 207.7 | 9.4147 | -3.1272 | -1.7951 | 1945.38 |
| 208.0 | 9.5200 | -3.3263 | -2.3218 | 1945.21 |
| 208.3 | 9.4208 | -3.2112 | -2.1741 | 1945.10 |
| 208.7 | 9.4021 | -3.3659 | -2.5767 | 1944.99 |
| 209.0 | 9.3841 | -3.4432 | -2.6671 | 1944.88 |
| 209.3 | 9.2687 | -3.7272 | -2.5273 | 1944.83 |
| 209.7 | 9.2463 | -3.9492 | -2.4231 | 1944.78 |
| 210.0 | 9.1496 | -4.1329 | -2.4997 | 1944.73 |
| 210.3 | 9.1412 | -4.1234 | -2.7398 | 1944.68 |
| 210.7 | 9.1250 | -4.2529 | -2.5577 | 1944.63 |
| 211.0 | 9.1594 | -4.0572 | -2.7341 | 1944.57 |
| 211.3 | 9.2107 | -3.8440 | -2.3764 | 1944.52 |
| 211.7 | 9.3259 | -3.5232 | -1.8911 | 1944.46 |
| 212.0 | 9.4650 | -3.3759 | -1.7097 | 1944.33 |
| 212.3 | 9.4738 | -3.3952 | -2.0941 | 1944.21 |
| 212.7 | 9.4067 | -3.4539 | -2.3267 | 1944.13 |
| 213.0 | 9.3762 | -3.6062 | -2.5611 | 1944.04 |
| 213.3 | 9.3246 | -3.6589 | -2.3477 | 1943.96 |
| 213.7 | 9.3507 | -3.6652 | -2.1591 | 1943.88 |
| 214.0 | 9.2405 | -3.9559 | -2.5295 | 1943.79 |
| 214.3 | 9.1843 | -4.0792 | -2.2731 | 1943.71 |
| 214.7 | 9.1835 | -4.0479 | -2.3967 | 1943.63 |
| 215.0 | 9.3148 | -3.6402 | -1.9551 | 1943.54 |
| 215.3 | 9.3562 | -3.4969 | -1.5697 | 1943.46 |
| 215.7 | 9.4385 | -3.3372 | -1.5401 | 1943.34 |
| 216.0 | 9.4740 | -3.2199 | -1.5547 | 1943.21 |
| 216.3 | 9.4516 | -3.4482 | -2.5781 | 1943.13 |
| 216.7 | 9.3326 | -3.5699 | -2.2897 | 1943.05 |
| 217.0 | 9.3292 | -3.5322 | -2.5511 | 1942.96 |
| 217.3 | 9.3026 | -3.8299 | -2.7177 | 1942.88 |
| 217.7 | 9.2000 | -4.2522 | -2.7791 | 1942.82 |
| 218.0 | 9.2006 | -3.9939 | -2.4117 | 1942.75 |
| 218.3 | 9.1855 | -4.2152 | -2.9731 | 1942.69 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 218.7 | 9.1548 | -4.0619 | -1.6047 | 1942.63 |
| 219.0 | 9.1883 | -4.0982 | -2.4541 | 1942.50 |
| 219.3 | 9.2987 | -3.9039 | -2.3177 | 1942.38 |
| 219.7 | 9.3577 | -3.6702 | -2.1741 | 1942.29 |
| 220.0 | 9.3431 | -3.3129 | -1.6357 | 1942.24 |
| 220.3 | 9.3369 | -3.4272 | -1.9961 | 1942.18 |
| 220.7 | 9.3715 | -3.3949 | -2.1027 | 1942.13 |
| 221.0 | 9.2931 | -3.0282 | -1.7601 | 1941.96 |
| 221.3 | 9.1549 | -3.7809 | -2.8747 | 1941.79 |
| 221.7 | 9.1484 | -4.0172 | -3.1201 | 1941.75 |
| 222.0 | 9.0956 | -3.9599 | -2.8937 | 1941.71 |
| 222.3 | 9.0932 | -3.8872 | -1.6811 | 1941.67 |
| 222.7 | 9.0764 | -4.1569 | -2.3877 | 1941.63 |
| 223.0 | 9.1773 | -4.0261 | -1.9640 | 1941.57 |
| 223.3 | 9.2328 | -3.5189 | -1.5617 | 1941.52 |
| 223.7 | 9.1699 | -3.5432 | -1.8011 | 1941.46 |
| 224.0 | 9.3704 | -3.2619 | -1.7417 | 1941.38 |
| 224.3 | 9.3998 | -3.3462 | -2.1491 | 1941.29 |
| 224.7 | 9.5036 | -3.0529 | -2.2747 | 1941.21 |
| 225.0 | 9.3141 | -3.4672 | -2.6491 | 1941.08 |
| 225.3 | 9.2784 | -3.7569 | -2.8937 | 1940.96 |
| 225.7 | 9.2989 | -3.8372 | -2.5371 | 1940.85 |
| 226.0 | 9.1834 | -4.0569 | -2.8277 | 1940.74 |
| 226.3 | 9.0080 | -4.5170 | -2.9029 | 1940.63 |
| 226.7 | 9.1068 | -4.3329 | -2.3867 | 1940.55 |
| 227.0 | 9.1594 | -3.9862 | -2.6141 | 1940.46 |
| 227.3 | 9.2876 | -3.6259 | -2.3387 | 1940.41 |
| 227.7 | 9.3340 | -3.5322 | -2.3381 | 1940.36 |
| 228.0 | 9.3948 | -3.2769 | -2.7067 | 1940.31 |
| 228.3 | 9.4026 | -3.2102 | -2.2831 | 1940.26 |
| 228.7 | 9.4141 | -3.2769 | -2.1257 | 1940.21 |
| 229.0 | 9.4063 | -3.4642 | -2.8741 | 1940.10 |
| 229.3 | 9.3847 | -3.6559 | -2.8887 | 1939.99 |
| 229.7 | 9.2077 | -4.1102 | -2.9641 | 1939.88 |
| 230.0 | 9.0811 | -4.2029 | -2.3577 | 1939.75 |
| 230.3 | 8.9891 | -4.0582 | -2.4931 | 1939.63 |
| 230.7 | 9.1997 | -4.2559 | -2.5737 | 1939.55 |
| 231.0 | 9.0845 | -3.8832 | -2.1681 | 1939.46 |
| 231.3 | 9.2645 | -3.6789 | -1.8337 | 1939.38 |
| 231.7 | 9.3178 | -3.3432 | -1.8501 | 1939.34 |
| 232.0 | 9.2901 | -3.3819 | -1.7037 | 1939.29 |
| 232.3 | 9.4164 | -3.1482 | -2.0191 | 1939.25 |
| 232.7 | 9.4165 | -3.4309 | -2.1957 | 1939.21 |
| 233.0 | 9.3681 | -3.4612 | -2.5791 | 1939.10 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 233.3 | 9.3786 | -3.5869 | -2.7107 | 1938.99 |
| 233.7 | 9.2542 | -3.8302 | -2.6161 | 1938.88 |
| 234.0 | 9.1672 | -4.1369 | -3.0507 | 1938.80 |
| 234.3 | 9.1501 | -4.0042 | -3.0311 | 1938.71 |
| 234.7 | 9.0590 | -4.3669 | -2.9867 | 1938.63 |
| 235.0 | 9.1265 | -3.8732 | -2.2701 | 1938.54 |
| 235.3 | 9.1917 | -3.7339 | -2.0847 | 1938.46 |
| 235.7 | 9.2830 | -3.4862 | -2.0751 | 1938.38 |
| 236.0 | 9.3112 | -3.3719 | -2.2457 | 1938.29 |
| 236.3 | 9.2723 | -3.3352 | -2.3251 | 1938.21 |
| 236.7 | 9.2996 | -3.3599 | -2.3627 | 1938.05 |
| 237.0 | 9.2179 | -3.6892 | -2.3891 | 1937.88 |
| 237.3 | 9.1621 | -3.6359 | -2.3497 | 1937.80 |
| 237.7 | 9.1265 | -3.9892 | -2.3041 | 1937.71 |
| 238.0 | 9.2148 | -3.8789 | -2.0907 | 1937.68 |
| 238.3 | 9.2645 | -3.9532 | -2.7321 | 1937.66 |
| 238.7 | 9.0956 | -4.2409 | -2.8227 | 1937.63 |
| 239.0 | 9.1107 | -4.2132 | -2.3461 | 1937.55 |
| 239.3 | 9.2645 | -3.6099 | -2.4387 | 1937.46 |
| 239.7 | 9.2829 | -3.5312 | -2.0201 | 1937.38 |
| 240.0 | 9.3802 | -3.3869 | -2.3377 | 1937.29 |
| 240.3 | 9.3448 | -3.4232 | -1.8681 | 1937.21 |
| 240.7 | 9.3758 | -3.4709 | -2.5367 | 1937.09 |
| 241.0 | 9.2272 | -3.6972 | -2.7641 | 1936.96 |
| 241.3 | 9.2741 | -3.7219 | -2.8527 | 1936.88 |
| 242.3 | 9.0375 | -4.3302 | -1.9331 | 1936.63 |
| 242.7 | 9.1005 | -4.3579 | -2.4807 | 1936.55 |
| 243.0 | 9.2311 | -4.0332 | -2.3231 | 1936.46 |
| 243.3 | 9.4050 | -2.9189 | -1.4807 | 1936.38 |
| 243.7 | | | | |
| 244.0 | 9.4819 | -3.2642 | -2.0281 | 1936.21 |
| 244.3 | 9.3362 | -3.6269 | -1.7287 | 1935.96 |
| 244.7 | 9.2719 | | | 1935.88 |
| 245.0 | 9.1201 | -4.1809 | -2.1367 | 1935.63 |
| 245.3 | 9.1476 | -4.1692 | -2.1091 | 1935.55 |
| 245.7 | 9.2106 | -4.1319 | -2.2587 | 1935.46 |
| 246.0 | 9.2745 | -4.0272 | -2.9381 | 1935.43 |
| 246.3 | 9.2100 | -3.2129 | -1.8687 | 1935.41 |
| 246.7 | 9.3490 | -3.3792 | -2.2321 | 1935.38 |
| 247.0 | 9.3008 | -3.4939 | -1.9747 | 1935.32 |
| 247.3 | 9.4147 | -3.1092 | -2.2371 | 1935.27 |
| 247.7 | 9.3558 | -3.3349 | -2.1297 | 1935.21 |
| 248.0 | 9.4191 | -3.6492 | -2.4281 | 1935.08 |
| 248.3 | 9.2723 | -3.5309 | -2.3347 | 1934.96 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 248.7 | 9.2517 | -3.9342 | -2.7881 | 1934.85 |
| 249.0 | 9.1299 | -4.4229 | -2.6447 | 1934.74 |
| 249.3 | 9.1310 | -4.5862 | -2.8581 | 1934.63 |
| 249.7 | 9.1329 | -4.0839 | -2.1947 | 1934.55 |
| 250.0 | 9.2347 | -3.7342 | -2.6441 | 1934.46 |
| 250.3 | 9.4176 | -3.2259 | -1.6597 | 1934.21 |
| 250.7 | 9.3457 | -3.5302 | -1.4831 | 1934.05 |
| 251.0 | 9.2639 | -3.8439 | -1.6547 | 1933.88 |
| 251.3 | 9.1493 | -3.8042 | -1.6941 | 1933.71 |
| 251.7 | 9.2496 | -3.9719 | -1.8547 | 1933.63 |
| 252.0 | 9.1236 | -4.2562 | -1.6671 | 1933.54 |
| 252.3 | 9.2040 | -4.0439 | -1.7447 | 1933.49 |
| 252.7 | 9.2888 | -3.7602 | -1.7691 | 1933.43 |
| 253.0 | 9.3209 | -3.5719 | -1.2157 | 1933.38 |
| 253.3 | 9.3264 | -3.3722 | -1.6351 | 1933.30 |
| 253.7 | 9.4957 | -3.5689 | -1.4797 | 1933.21 |
| 254.0 | 9.3429 | -3.5282 | -1.9481 | 1933.04 |
| 254.3 | 9.3838 | -3.6077 | -1.0248 | 1932.96 |
| 254.7 | 9.2754 | -3.7525 | -1.2558 | 1932.88 |
| 255.0 | 9.3402 | -3.6749 | -2.1827 | 1932.80 |
| 255.3 | 9.2794 | -3.9552 | -2.1591 | 1932.71 |
| 255.7 | 9.2081 | -3.8219 | -2.1607 | 1932.63 |
| 256.0 | 9.4097 | -3.5682 | -1.6511 | 1932.38 |
| 256.3 | 9.3471 | -3.5629 | -1.7947 | 1932.30 |
| 256.7 | 9.4237 | -3.4120 | -2.3566 | 1932.21 |
| 257.0 | 9.4181 | -3.6674 | -1.9286 | 1932.08 |
| 257.3 | 9.2746 | -3.7962 | -2.2991 | 1931.96 |
| 257.7 | 9.2246 | -3.7549 | -2.5437 | 1931.88 |
| 258.0 | 9.1788 | -3.6652 | -2.2271 | 1931.79 |
| 258.3 | 9.1586 | | -1.7453 | 1931.71 |
| 258.7 | 9.0788 | -4.0942 | -2.4181 | 1931.63 |
| 259.0 | 9.1191 | -3.7289 | -1.4727 | 1931.57 |
| 259.3 | 9.1132 | -3.6157 | -1.6700 | 1931.51 |
| 259.7 | 9.3294 | -3.4169 | -1.4447 | 1931.44 |
| 260.0 | 9.2606 | -3.5962 | -1.7791 | 1931.38 |
| 260.3 | 9.4361 | -3.5029 | -2.1067 | 1931.21 |
| 260.7 | 9.3323 | -3.5902 | -2.5821 | 1930.96 |
| 261.0 | 9.1998 | -4.1389 | -2.8397 | 1930.79 |
| 261.3 | 9.1619 | -4.1992 | -2.7281 | 1930.71 |
| 261.7 | 9.1576 | -3.7439 | -1.7087 | 1930.63 |
| 262.0 | 9.1787 | | -2.2222 | 1930.55 |
| 262.3 | 9.1536 | -3.8089 | -2.3597 | 1930.46 |
| 262.7 | 9.3135 | -3.4482 | -2.2211 | 1930.38 |
| 263.0 | 9.4278 | -3.4399 | -2.3617 | 1930.29 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 263.3 | 9.4414 | -3.6412 | -2.3761 | 1930.13 |
| 263.7 | 9.2904 | -3.6699 | -2.9377 | 1929.96 |
| 264.0 | 9.2298 | -4.1602 | -3.0821 | 1929.88 |
| 264.3 | 9.2209 | -4.2709 | -2.3017 | 1929.80 |
| 264.7 | 9.1777 | -4.1762 | -2.6721 | 1929.72 |
| 265.0 | 9.1469 | -4.1539 | -2.4097 | 1929.63 |
| 265.3 | 9.1504 | -4.2022 | -2.4211 | 1929.54 |
| 265.7 | 9.3457 | -3.7419 | -2.1977 | 1929.50 |
| 266.0 | 9.2577 | -3.4068 | -1.8570 | 1929.46 |
| 266.3 | 9.4363 | -3.4879 | -1.5927 | 1929.34 |
| 266.7 | 9.4611 | -3.6004 | -2.7166 | 1929.21 |
| 267.0 | 9.4226 | -3.4559 | -1.7217 | 1929.10 |
| 267.3 | 9.3313 | -3.8042 | -3.0411 | 1928.99 |
| 267.7 | 9.2127 | -4.1679 | -3.0587 | 1928.88 |
| 268.0 | 9.0225 | -4.2762 | -2.7331 | 1928.71 |
| 268.3 | 9.0453 | -4.2229 | -2.3027 | 1928.59 |
| 268.7 | 9.1710 | -3.8543 | -1.6689 | 1928.46 |
| 269.0 | 9.3563 | -3.3769 | -1.2887 | 1928.40 |
| 269.3 | 9.4164 | -3.1722 | -1.6271 | 1928.35 |
| 269.7 | 9.4352 | -2.9989 | 0.1353 | 1928.29 |
| 270.0 | 9.3625 | -3.4362 | -1.3281 | 1928.21 |
| 270.3 | 9.4781 | -3.6079 | -1.3103 | 1928.13 |
| 270.7 | 9.2311 | -3.3982 | -0.8121 | 1927.88 |
| 271.0 | 9.0605 | -4.1129 | -1.8627 | 1927.63 |
| 271.3 | 9.0943 | -4.0552 | -1.7571 | 1927.55 |
| 271.7 | 9.1684 | -3.6446 | -1.1147 | 1927.46 |
| 272.0 | 9.3125 | -3.4242 | -1.2861 | 1927.33 |
| 272.3 | 9.3964 | -3.3359 | -0.7527 | 1927.21 |
| 272.7 | 9.3825 | -3.4592 | -1.3341 | 1927.05 |
| 273.0 | 9.2172 | -3.8129 | -1.9027 | 1926.88 |
| 273.3 | 9.1069 | -4.1272 | -1.9331 | 1926.80 |
| 273.7 | 9.0907 | -4.1659 | -2.3137 | 1926.72 |
| 274.0 | 9.0430 | -4.1712 | -2.6551 | 1926.63 |
| 274.3 | 9.1470 | -3.9179 | -1.5327 | 1926.55 |
| 274.7 | 9.2198 | -3.8113 | -1.6507 | 1926.47 |
| 275.0 | 9.3676 | -2.9129 | -0.7197 | 1926.38 |
| 275.3 | 9.4805 | -3.4769 | -1.3035 | 1926.29 |
| 275.7 | 9.4957 | -3.2069 | -1.7377 | 1926.21 |
| 276.0 | 9.3596 | -3.2522 | -2.3241 | 1925.96 |
| 276.3 | 9.2328 | -3.7719 | -1.8627 | 1925.88 |
| 276.7 | 9.1322 |  | -2.1178 | 1925.80 |
| 277.0 | 9.0556 | -4.1189 | -2.1827 | 1925.71 |
| 277.3 | 9.3423 | -2.8362 | -0.9631 | 1925.63 |
| 277.7 | 9.0776 | -4.3849 | -1.9607 | 1925.54 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 278.0 | 9.0992 | -3.8372 | -1.5951 | 1925.50 |
| 278.3 | 9.2248 | -3.8409 | -1.2847 | 1925.46 |
| 278.7 | 9.4241 | -3.7388 | -1.1992 | 1925.34 |
| 279.0 | 9.4075 | -3.3569 | -1.6207 | 1925.21 |
| 279.3 | 9.4345 | -3.3922 | -1.7921 | 1925.13 |
| 279.7 | 9.3941 | -3.5189 | -1.7227 | 1925.05 |
| 280.0 | 9.2838 | -3.5442 | -2.1721 | 1924.96 |
| 280.3 | 9.2202 | | | 1924.88 |
| 280.7 | 9.1153 | -4.3212 | -2.3471 | 1924.80 |
| 281.0 | 9.1088 | -4.1297 | -1.4676 | 1924.71 |
| 281.3 | 9.0974 | -4.2562 | -1.9941 | 1924.63 |
| 281.7 | 9.1163 | -4.0989 | -1.8007 | 1924.55 |
| 282.0 | 9.1265 | -4.1522 | -1.8671 | 1924.46 |
| 282.3 | 9.3283 | -3.8239 | -1.8197 | 1924.38 |
| 282.7 | 9.4019 | -3.2572 | -0.9071 | 1924.30 |
| 283.0 | 9.4755 | -3.2439 | -1.6697 | 1924.21 |
| 283.3 | 9.4387 | -3.1862 | -2.4661 | 1924.09 |
| 283.7 | 9.3714 | -3.4499 | -1.7547 | 1923.96 |
| 284.0 | 9.1795 | -3.9002 | -1.8821 | 1923.79 |
| 284.3 | 9.1686 | -4.0389 | -2.1407 | 1923.74 |
| 284.7 | 9.1450 | -4.2962 | -2.2861 | 1923.68 |
| 285.0 | 9.0947 | -4.5722 | -2.3151 | 1923.63 |
| 285.3 | 9.1115 | -4.1122 | -1.9301 | 1923.56 |
| 285.7 | 9.1674 | -3.9539 | -1.2957 | 1923.49 |
| 286.0 | 9.2165 | -3.6212 | -0.9981 | 1923.43 |
| 286.3 | 9.4701 | -3.3149 | -0.9967 | 1923.36 |
| 286.7 | 9.5058 | -3.5582 | -1.7561 | 1923.29 |
| 287.0 | 9.4452 | -3.4959 | -1.9267 | 1923.25 |
| 287.3 | 9.4045 | | -1.8938 | 1923.21 |
| 287.7 | 9.4233 | -3.4599 | -2.2317 | 1923.17 |
| 288.0 | 9.4680 | -3.5322 | -2.2931 | 1923.13 |
| 288.3 | 9.4192 | -3.6873 | -2.2875 | 1922.96 |
| 288.7 | 9.2133 | -4.0949 | -2.5527 | 1922.79 |
| 289.0 | 9.1851 | -3.9859 | -2.6707 | 1922.76 |
| 289.3 | 9.1892 | -4.1982 | -2.7471 | 1922.74 |
| 289.7 | 9.1094 | -4.2859 | -2.2267 | 1922.71 |
| 290.0 | 9.3263 | -4.0892 | -2.1391 | 1922.62 |
| 290.3 | 9.1002 | -4.2649 | -2.2557 | 1922.54 |
| 290.7 | 9.1210 | -3.9522 | -1.7871 | 1922.46 |
| 291.0 | 9.2830 | -3.8250 | -0.0677 | 1922.38 |
| 291.3 | 9.4013 | -3.2222 | -1.3641 | 1922.29 |
| 291.7 | 9.3199 | -3.4562 | -1.8029 | 1922.24 |
| 292.0 | 9.3936 | -3.3352 | -2.2861 | 1922.18 |
| 292.3 | 9.3932 | -2.9669 | -2.3607 | 1922.13 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 292.7 | 9.3268 | -3.6762 | -2.4431 | 1922.05 |
| 293.0 | 9.3251 | -3.7359 | -3.0497 | 1921.96 |
| 293.3 | 9.1788 | -3.7368 | -2.4998 | 1921.88 |
| 293.7 | 9.1578 | -4.0969 | -3.1197 | 1921.82 |
| 294.0 | 9.1010 | -4.0512 | -2.8891 | 1921.75 |
| 294.3 | 9.0806 | -4.2937 | -3.0498 | 1921.69 |
| 294.7 | 9.0526 | -4.1522 | -2.5511 | 1921.63 |
| 295.0 | 9.1473 | -3.6889 | -2.0467 | 1921.54 |
| 295.3 | 9.1988 | -3.6862 | -1.7491 | 1921.46 |
| 295.7 | 9.3964 | -3.4699 | -1.3777 | 1921.40 |
| 296.0 | 9.3640 | -3.3802 | -1.8871 | 1921.33 |
| 296.3 | 9.3404 | -3.3899 | -1.9887 | 1921.27 |
| 296.7 | 9.3951 | -3.6459 | -2.2103 | 1921.21 |
| 297.0 | 9.3896 | -3.4369 | -1.9497 | 1921.04 |
| 297.3 | 9.2921 | -3.9912 | -1.6831 | 1920.88 |
| 297.7 | 9.2752 | -3.7649 | -2.4327 | 1920.82 |
| 298.0 | 9.2917 | -3.8952 | -2.0581 | 1920.75 |
| 298.3 | 9.3056 | -3.9049 | -1.9187 | 1920.69 |
| 298.7 | 9.1898 | -3.6772 | -1.2101 | 1920.63 |
| 299.0 | 9.3111 | -3.5019 | -1.4467 | 1920.52 |
| 299.3 | 9.4033 | -3.3602 | -1.2781 | 1920.42 |
| 299.7 | 9.4244 | -3.2667 | -1.8154 | 1920.32 |
| 300.0 | 9.4497 | -3.5652 | -1.6121 | 1920.21 |
| 300.3 | 9.3800 | -3.5617 | -1.6998 | 1920.11 |
| 300.7 | 9.3998 | -3.4162 | -1.4851 | 1920.00 |
| 301.0 | 9.4107 | -4.0059 | -1.6299 | 1919.89 |
| 301.3 | 9.3045 | -3.8872 | -1.4591 | 1919.79 |
| 301.7 | 9.3694 | -3.6589 | -1.3337 | 1919.71 |
| 302.0 | 9.2371 | -3.9042 | -1.7851 | 1919.63 |
| 302.3 | 9.2965 | -3.8659 | -2.1143 | 1919.52 |
| 302.7 | 9.3880 | -3.3382 | -0.9301 | 1919.41 |
| 303.0 | 9.4673 | -3.4479 | -1.4727 | 1919.29 |
| 303.3 | 9.4645 | -3.3522 | -1.5011 | 1919.21 |
| 303.7 | 9.4869 | -3.4869 | -1.5537 | 1919.13 |
| 304.0 | 9.3486 | -3.7282 | -1.6991 | 1918.96 |
| 304.3 | 9.2253 | -3.6579 | -1.5251 | 1918.79 |
| 304.7 | 9.2236 | -4.0872 | -1.7751 | 1918.71 |
| 305.0 | 9.1698 | -4.1619 | -2.3567 | 1918.63 |
| 305.3 | 9.2459 | -3.9172 | -2.1651 | 1918.57 |
| 305.7 | 9.1933 | -4.1826 | -2.3661 | 1918.51 |
| 306.0 | 9.3273 | -3.7922 | -1.9361 | 1918.44 |
| 306.3 | 9.4663 | -3.3709 | -1.2547 | 1918.38 |
| 306.7 | 9.6237 | -3.1542 | -0.8261 | 1918.21 |
| 307.0 | 9.3936 | -3.4429 | -1.1717 | 1917.88 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 307.3 | 9.2988 | -3.9229 | -1.4297 | 1917.80 |
| 307.7 | 9.3838 | -3.6417 | -1.5611 | 1917.72 |
| 308.0 | 9.2196 | -3.6739 | -1.4611 | 1917.63 |
| 308.3 | 9.2312 | -4.0799 | -2.2417 | 1917.55 |
| 308.7 | 9.2999 | -3.8988 | -1.4744 | 1917.46 |
| 309.0 | 9.3717 | -3.7119 | -1.4737 | 1917.38 |
| 309.3 | 9.4931 | -3.0982 | -0.1541 | 1917.29 |
| 309.7 | 9.5635 | | | 1917.21 |
| 310.0 | 9.5166 | -3.1966 | -0.7977 | 1917.13 |
| 310.3 | 9.4834 | -3.4699 | -2.3747 | 1917.04 |
| 310.7 | 9.4212 | -3.4982 | -1.7001 | 1916.96 |
| 311.0 | 9.2935 | -3.9787 | -1.8666 | 1916.88 |
| 311.3 | 9.1582 | -4.0102 | -2.3771 | 1916.63 |
| 311.7 | 9.2297 | -4.1603 | -2.2397 | 1916.51 |
| 312.0 | 9.3557 | -3.7532 | -1.6371 | 1916.38 |
| 312.3 | 9.4313 | -3.1279 | -0.8137 | 1916.30 |
| 312.7 | 9.4836 | -3.1382 | -0.6241 | 1916.21 |
| 313.0 | 9.4091 | -3.3489 | -1.2827 | 1916.14 |
| 313.3 | 9.3709 | -3.4672 | -1.7951 | 1916.08 |
| 313.7 | 9.3789 | -3.4999 | -1.6697 | 1916.01 |
| 314.0 | 9.4015 | -3.5522 | -1.0501 | 1915.95 |
| 314.3 | 9.2627 | -3.6739 | -1.0667 | 1915.88 |
| 314.7 | 9.1900 | -4.0212 | -1.7391 | 1915.76 |
| 315.0 | 9.1402 | -3.9149 | -1.8017 | 1915.63 |
| 315.3 | 9.3069 | -3.6072 | -1.3871 | 1915.55 |
| 315.7 | 9.3074 | -3.3929 | -1.1227 | 1915.46 |
| 316.0 | 9.5024 | -3.4102 | -1.3391 | 1915.33 |
| 316.3 | 9.5358 | -3.3219 | -1.6667 | 1915.21 |
| 316.7 | 9.4371 | -3.4402 | -2.6011 | 1915.05 |
| 317.0 | 9.3511 | -3.6109 | -2.9047 | 1914.88 |
| 317.3 | 9.3289 | -3.7252 | -2.5111 | 1914.80 |
| 317.7 | 9.2629 | -3.9799 | -2.3317 | 1914.72 |
| 318.0 | 9.2134 | -4.0972 | -2.1901 | 1914.63 |
| 318.3 | 9.2247 | -3.8099 | -1.5177 | 1914.57 |
| 318.7 | 9.2563 | -4.0132 | -2.1311 | 1914.51 |
| 319.0 | 9.2825 | -3.5869 | -1.2467 | 1914.45 |
| 319.3 | 9.3267 | -3.3682 | -0.8371 | 1914.39 |
| 319.7 | 9.3968 | -3.3089 | -1.2847 | 1914.33 |
| 320.0 | 9.4017 | -3.4442 | -1.4511 | 1914.27 |
| 320.3 | 9.4684 | -3.4109 | -1.9717 | 1914.21 |
| 320.7 | 9.3327 | -3.7372 | -2.3431 | 1913.96 |
| 321.0 | 9.3116 | -3.8779 | -2.3077 | 1913.88 |
| 321.3 | 9.1957 | -3.9932 | -2.2291 | 1913.76 |
| 321.7 | 9.1594 | -4.1719 | -1.6867 | 1913.63 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 322.0 | 9.1960 | -4.0362 | -1.5991 | 1913.58 |
| 322.3 | 9.2470 | -4.0339 | -1.9877 | 1913.54 |
| 322.7 | 9.4951 | -3.6992 | -1.2341 | 1913.29 |
| 323.0 | 9.4351 | -3.6049 | -1.2117 | 1913.26 |
| 323.3 | 9.4721 | -3.3912 | -1.2701 | 1913.24 |
| 323.7 | 9.4873 | -3.5059 | -1.3207 | 1913.21 |
| 324.0 | 9.4314 | -3.6842 | -1.6531 | 1913.10 |
| 324.3 | 9.5427 | -3.9209 | -1.3187 | 1912.99 |
| 324.7 | 9.3202 | -3.7782 | -1.0611 | 1912.88 |
| 325.0 | 9.3446 | -3.8409 | -1.2297 | 1912.82 |
| 325.3 | 9.2754 | -4.3202 | -1.4621 | 1912.76 |
| 325.7 | 9.2844 | -3.7909 | -1.0767 | 1912.69 |
| 326.0 | 9.2132 | -4.1212 | -1.7191 | 1912.63 |
| 326.3 | 9.3850 | -3.8539 | -1.3277 | 1912.46 |
| 326.7 | 9.4403 | -3.7422 | -1.1731 | 1912.34 |
| 327.0 | 9.5100 | -2.3059 | -1.1117 | 1912.21 |
| 327.3 | 9.3513 | -3.6422 | -1.7951 | 1912.05 |
| 327.7 | 9.2523 | -4.1189 | -2.1017 | 1911.88 |
| 328.0 | 9.1872 | -4.1532 | -2.2631 | 1911.82 |
| 328.3 | 9.0725 | -4.4359 | -2.2447 | 1911.76 |
| 328.7 | 9.0514 | -4.6282 | -2.2291 | 1911.69 |
| 329.0 | 8.9917 | -4.8249 | -2.1937 | 1911.63 |
| 329.3 | 9.0037 | -4.7972 | -2.2011 | 1911.59 |
| 329.7 | 9.1528 | -4.4289 | -2.3257 | 1911.55 |
| 330.0 | 9.1202 | -4.4218 | -1.5501 | 1911.50 |
| 330.3 | 9.3038 | -4.3263 | -1.7695 | 1911.46 |
| 330.7 | 9.4399 | -3.9292 | -1.4121 | 1911.40 |
| 331.0 | 9.4765 | -3.6050 | -1.5145 | 1911.33 |
| 331.3 | 9.5309 | -3.4673 | -1.4471 | 1911.27 |
| 331.7 | 9.5351 | -3.3969 | -1.7897 | 1911.21 |
| 332.0 | 9.4403 | -3.5482 | -1.8191 | 1911.13 |
| 332.3 | 9.3573 | -3.6199 | -1.9907 | 1911.05 |
| 332.7 | 9.3456 | -3.8832 | -2.0311 | 1910.96 |
| 333.0 | 9.2641 | -4.3419 | -2.4697 | 1910.88 |
| 333.3 | 9.0851 | -4.2782 | -2.8471 | 1910.80 |
| 333.7 | 8.9917 | -4.4909 | -2.8797 | 1910.72 |
| 334.0 | 8.9433 | -4.5502 | -2.5281 | 1910.63 |
| 334.3 | 8.9553 | -4.3419 | -2.2537 | 1910.55 |
| 334.7 | 9.1317 | -3.8852 | -1.6231 | 1910.46 |
| 335.0 | 9.4314 | -3.3969 | -1.0917 | 1910.37 |
| 335.3 | 9.4720 | -3.5972 | -1.4141 | 1910.29 |
| 335.7 | 9.4024 | -3.3099 | -1.5667 | 1910.21 |
| 336.0 | 9.5331 | -3.3942 | -2.0521 | 1910.13 |
| 336.3 | 9.3137 | -3.8129 | -2.4357 | 1909.96 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 336.7 | 9.0804 | -4.4036 | -2.4419 | 1909.79 |
| 337.0 | 9.0076 | -4.7129 | -2.7847 | 1909.71 |
| 337.3 | 8.9296 | -4.6062 | -2.6676 | 1909.63 |
| 337.7 | 9.1096 | -4.4619 | -2.4617 | 1909.56 |
| 338.0 | 9.0703 | -4.1932 | -2.2071 | 1909.49 |
| 338.3 | 9.0309 | -4.1179 | -1.6787 | 1909.42 |
| 338.7 | 9.4443 | -2.9302 | -1.2671 | 1909.35 |
| 339.0 | 9.4862 | -3.1919 | -1.2017 | 1909.28 |
| 339.3 | 9.6175 | -3.2952 | -1.6801 | 1909.21 |
| 339.7 | 9.4612 | -3.2587 | -1.8490 | 1909.13 |
| 340.0 | 9.3979 | -3.6292 | -2.2561 | 1909.04 |
| 340.3 | 9.2874 | -3.7279 | -2.4637 | 1908.96 |
| 340.7 | 9.1771 | -3.8692 | -2.6121 | 1908.88 |
| 341.0 | 9.1285 | -4.3359 | -2.3637 | 1908.79 |
| 341.3 | 9.1357 | -4.1052 | -2.7971 | 1908.71 |
| 341.7 | 9.0842 | -4.4359 | -2.8327 | 1908.63 |
| 342.0 | 9.1283 | -4.2862 | -1.7231 | 1908.57 |
| 342.3 | 9.0968 | -4.2552 | -1.8371 | 1908.51 |
| 342.7 | 9.4487 | -3.4002 | -0.5521 | 1908.45 |
| 343.0 | 9.4854 | -3.4049 | -0.6057 | 1908.39 |
| 343.3 | 9.4711 | | -0.8309 | 1908.33 |
| 343.7 | 9.4131 | -3.3169 | -0.8707 | 1908.27 |
| 344.0 | 9.5395 | -2.3879 | -0.7157 | 1908.21 |
| 344.3 | 9.4477 | | | 1908.09 |
| 344.7 | 9.3235 | -4.1402 | -2.4561 | 1907.98 |
| 345.0 | 9.2366 | -4.1616 | -2.4301 | 1907.86 |
| 345.3 | 9.1749 | -4.1622 | -2.5891 | 1907.75 |
| 345.7 | 9.0779 | -4.2669 | -2.2427 | 1907.63 |
| 346.0 | 9.1546 | -4.1629 | -1.8779 | 1907.55 |
| 346.3 | 9.1862 | -4.0159 | -1.3617 | 1907.48 |
| 346.7 | 9.2982 | | -1.1895 | 1907.40 |
| 347.0 | 9.4169 | -3.4459 | -0.8287 | 1907.32 |
| 347.3 | 9.4498 | -3.5842 | -0.8561 | 1907.25 |
| 347.7 | 9.5145 | -3.2609 | -0.8767 | 1907.17 |
| 348.0 | 9.5664 | -3.4102 | -0.7831 | 1907.09 |
| 348.3 | 9.5185 | -3.4719 | -1.2047 | 1907.01 |
| 348.7 | 9.4487 | -3.6452 | -1.3431 | 1906.94 |
| 349.0 | 9.3825 | -3.8019 | -0.9297 | 1906.86 |
| 349.3 | 9.3320 | -3.7932 | -1.0791 | 1906.78 |
| 349.7 | 9.3098 | -4.0019 | -1.4737 | 1906.71 |
| 350.0 | 9.2553 | -3.8322 | -0.7891 | 1906.63 |
| 350.3 | 9.2785 | -3.9129 | -1.3117 | 1906.53 |
| 350.7 | 9.4469 | -3.6352 | -0.8731 | 1906.43 |
| 351.0 | 9.4819 | -2.6926 | 0.6974 | 1906.33 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 351.3 | 9.5303 | -3.2242 | -0.8911 | 1906.23 |
| 351.7 | 9.4331 | -3.5329 | -1.2687 | 1906.13 |
| 352.0 | 9.3551 | -3.7932 | -0.4711 | 1906.03 |
| 352.3 | 9.2945 | -3.6879 | -2.0767 | 1905.93 |
| 352.7 | 9.1964 | -3.9082 | -1.3421 | 1905.83 |
| 353.0 | 9.0865 | -4.2899 | -2.0567 | 1905.73 |
| 353.3 | 9.0787 | -4.2802 | -2.1271 | 1905.63 |
| 353.7 | 9.1290 | -4.2349 | -2.3387 | 1905.54 |
| 354.0 | 9.1715 | -4.0882 | -1.9671 | 1905.45 |
| 354.3 | 9.2409 | -3.9309 | -1.6467 | 1905.36 |
| 354.7 | 9.3723 | -3.6222 | -1.4121 | 1905.27 |
| 355.0 | 9.5716 | -3.4009 | -1.6817 | 1905.18 |
| 355.3 | 9.5671 | -3.5899 | -1.7469 | 1905.09 |
| 355.7 | 9.4520 | -3.8317 | -1.2798 | 1905.00 |
| 356.0 | 9.3712 | -3.9862 | -0.9551 | 1904.90 |
| 356.3 | 9.2987 | -3.8479 | -1.7107 | 1904.81 |
| 356.7 | 9.3195 | -3.6862 | -0.8991 | 1904.72 |
| 357.0 | 9.2426 | -3.8919 | -1.4747 | 1904.63 |
| 357.3 | 9.2573 | -3.5882 | -0.6731 | 1904.55 |
| 357.7 | 9.2791 | -3.8279 | -1.2327 | 1904.46 |
| 358.0 | 9.3293 | -3.3212 | -0.7011 | 1904.38 |
| 358.3 | 9.3831 | -4.3019 | -1.8557 | 1904.29 |
| 358.7 | 9.4006 | -3.6122 | -0.6621 | 1904.21 |
| 359.0 | 9.2960 | -3.7099 | 0.0983 | 1904.17 |
| 359.3 | 9.4213 | -3.6842 | -0.4581 | 1904.13 |
| 359.7 | 9.3910 | -3.7369 | 0.4363 | 1904.03 |
| 360.0 | 9.3688 | -3.6512 | -1.2881 | 1903.93 |
| 360.3 | 9.3615 | -4.0049 | -1.2667 | 1903.83 |
| 360.7 | 9.3329 | -3.6892 | -0.5721 | 1903.73 |
| 361.0 | 9.3289 | -3.5119 | -0.3507 | 1903.63 |
| 361.3 | 9.3706 | -3.5632 | -1.1651 | 1903.42 |
| 361.7 | 9.4098 | -3.7340 | -1.6341 | 1903.21 |
| 362.0 | 9.3612 | -3.6382 | -1.8521 | 1903.11 |
| 362.3 | 9.3242 | -3.3629 | -1.0307 | 1903.02 |
| 362.7 | 9.3102 | -3.8235 | -2.1399 | 1902.92 |
| 363.0 | 9.3546 | -4.3839 | -1.6617 | 1902.82 |
| 363.3 | 9.2675 | -4.2972 | -1.4441 | 1902.73 |
| 363.7 | 9.2493 | -3.9559 | -1.2377 | 1902.63 |
| 364.0 | 9.3251 | -3.8402 | -2.0191 | 1902.42 |
| 364.3 | 9.3569 | -3.8919 | -1.7357 | 1902.21 |
| 364.7 | 9.3215 | -4.2447 | -2.1822 | 1902.02 |
| 365.0 | 9.3116 | -4.0859 | -1.9127 | 1901.82 |
| 365.3 | 9.1694 | -4.4723 | -2.1869 | 1901.63 |
| 365.7 | 9.3277 | -3.7179 | -0.6297 | 1901.51 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 366.0 | 9.4787 | -3.4132 | -0.8551 | 1901.38 |
| 366.3 | 9.5065 | -3.1559 | -0.3627 | 1901.32 |
| 366.7 | 9.4671 | -3.1392 | -0.7511 | 1901.27 |
| 367.0 | 9.5448 | -3.2039 | -0.5127 | 1901.21 |
| 367.3 | 9.5146 | | | 1901.09 |
| 367.7 | 9.5057 | -3.4889 | 0.3133 | 1900.96 |
| 368.0 | 9.4510 | -3.5792 | 0.2249 | 1900.83 |
| 368.3 | 9.3535 | -3.5869 | -0.9847 | 1900.71 |
| 368.7 | 9.4555 | | -0.1694 | 1900.65 |
| 369.0 | 9.3579 | -3.4502 | -0.2161 | 1900.60 |
| 369.3 | 9.3489 | -3.6414 | -1.0400 | 1900.54 |
| 369.7 | 9.4034 | -2.9749 | -0.7587 | 1900.43 |
| 370.0 | 9.4817 | -3.5730 | -1.3423 | 1900.32 |
| 370.3 | 9.5017 | -2.9319 | -0.7217 | 1900.21 |
| 370.7 | 9.4597 | | | 1900.10 |
| 371.0 | 9.4030 | -3.3789 | -1.0397 | 1899.98 |
| 371.3 | 9.1933 | -3.9592 | -2.0121 | 1899.86 |
| 371.7 | 9.1822 | -4.1539 | -1.5067 | 1899.75 |
| 372.0 | 9.1440 | -3.9922 | -1.3491 | 1899.63 |
| 372.3 | 9.4263 | -3.3309 | -1.0657 | 1899.29 |
| 372.7 | 9.4016 | -3.3359 | -0.7903 | 1899.26 |
| 373.0 | 9.3773 | -3.2829 | -1.3287 | 1899.24 |
| 373.3 | 9.4334 | -3.2011 | -1.1883 | 1899.21 |
| 373.7 | 9.3977 | -3.4409 | -2.0237 | 1899.17 |
| 374.0 | 9.4213 | -3.4262 | -2.1083 | 1899.13 |
| 374.3 | 9.3985 | -3.5609 | -2.0617 | 1899.02 |
| 374.7 | 9.2715 | -3.8482 | -2.8831 | 1898.91 |
| 375.0 | 9.1806 | -3.9229 | -2.0157 | 1898.79 |
| 375.3 | 9.1426 | -3.9482 | -1.6951 | 1898.63 |
| 375.7 | 9.2057 | -3.8119 | -1.4067 | 1898.57 |
| 376.0 | 9.3503 | -3.3752 | -0.8851 | 1898.52 |
| 376.3 | 9.2134 | -3.5789 | -1.2357 | 1898.46 |
| 376.7 | 9.4167 | -3.3882 | -1.3351 | 1898.21 |
| 377.0 | 9.3931 | -3.2719 | -1.6707 | 1898.10 |
| 377.3 | 9.3610 | -3.4042 | -1.9351 | 1898.00 |
| 377.7 | 9.3257 | -3.5864 | -2.0115 | 1897.90 |
| 378.0 | 9.2631 | -4.0702 | -1.7091 | 1897.79 |
| 378.3 | 9.2007 | -3.7899 | -1.0527 | 1897.71 |
| 378.7 | 9.1334 | -4.0972 | -0.8761 | 1897.63 |
| 379.0 | 9.2163 | -3.9779 | -1.7077 | 1897.59 |
| 379.3 | 9.2576 | -4.2052 | -2.4521 | 1897.55 |
| 379.7 | 9.2377 | -4.0789 | -1.7217 | 1897.50 |
| 380.0 | 9.2449 | -3.9742 | -1.3651 | 1897.46 |
| 380.3 | 9.3752 | -3.6929 | -1.4437 | 1897.40 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 380.7 | 9.3712 | -3.2732 | -1.4121 | 1897.34 |
| 381.0 | 9.3593 | -3.4183 | -1.5882 | 1897.27 |
| 381.3 | 9.3931 | -3.3242 | -1.3581 | 1897.21 |
| 381.7 | 9.3923 | -3.4197 | -1.3567 | 1897.05 |
| 382.0 | 9.3201 | -3.5437 | -0.9375 | 1896.88 |
| 382.3 | 9.1850 | -3.9401 | -0.9416 | 1896.80 |
| 382.7 | 9.1575 | -4.1362 | -1.1341 | 1896.72 |
| 383.0 | 9.2168 | -3.9869 | -1.6797 | 1896.63 |
| 383.3 | 9.1871 | -3.9194 | -1.7961 | 1896.55 |
| 383.7 | 9.1678 | -3.8710 | -1.7603 | 1896.47 |
| 384.0 | 9.3005 | -3.5482 | -1.6671 | 1896.38 |
| | | | | |
| **Middle Piece Seen in Fig. 2.1** | | | | |
| 376.7 | 9.4752 | -3.5939 | -1.7887 | 1898.21 |
| 377.0 | 9.4742 | -3.3652 | -1.0951 | 1898.10 |
| 377.3 | 9.2058 | -3.7669 | -1.8867 | 1898.00 |
| 377.7 | 9.2590 | -3.7862 | -1.6291 | 1897.90 |
| 378.0 | 9.1643 | -4.1799 | -2.1337 | 1897.79 |
| 378.3 | 9.0398 | | | 1897.71 |
| 378.7 | 9.0255 | -4.4849 | -2.1957 | 1897.63 |
| 379.0 | 9.1042 | -4.4402 | -2.2721 | 1897.59 |
| 379.3 | 9.1157 | -3.9389 | -1.8727 | 1897.55 |
| 379.7 | 9.3211 | -4.0972 | -2.2271 | 1897.50 |
| 380.0 | 9.1898 | -3.5589 | -1.7837 | 1897.46 |
| 380.3 | 9.3549 | -3.5242 | -1.4501 | 1897.40 |
| 380.7 | 9.4140 | -3.2259 | -1.3657 | 1897.34 |
| 381.0 | 9.4552 | -3.2852 | -1.4261 | 1897.27 |
| 381.3 | 9.4608 | -3.4059 | -2.1527 | 1897.21 |
| 381.7 | 9.3377 | -3.7542 | -2.2061 | 1897.05 |
| 382.0 | 9.2090 | -3.6559 | -2.3077 | 1896.88 |
| 382.3 | 9.1901 | -4.0572 | -2.3461 | 1896.80 |
| 382.7 | 9.1062 | -4.2659 | -2.3987 | 1896.72 |
| 383.0 | 9.0951 | -4.1212 | -2.0821 | 1896.63 |
| 383.3 | 9.0823 | -4.6459 | -2.4917 | 1896.55 |
| 383.7 | 9.1206 | -4.2162 | -2.0721 | 1896.47 |
| 384.0 | 9.3424 | -3.6924 | -1.2704 | 1896.38 |
| 384.3 | 9.3102 | -3.6182 | -1.4611 | 1896.32 |
| 384.7 | 9.3880 | -3.3479 | -0.8847 | 1896.27 |
| 385.0 | 9.5902 | -3.1972 | -0.7551 | 1896.21 |
| 385.3 | 9.5736 | -3.0719 | -0.5267 | 1896.00 |
| 385.7 | 9.3693 | -3.2752 | -0.6581 | 1895.79 |
| 386.0 | 9.3467 | -3.3959 | -0.6547 | 1895.63 |
| 386.3 | 9.3710 | -3.3192 | -0.7571 | 1895.38 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 386.7 | 9.4507 | -2.8899 | -0.6457 | 1895.21 |
| 387.0 | 9.4217 | -3.2712 | -1.2051 | 1894.96 |
| 387.3 | 9.3322 | -3.4039 | -1.4817 | 1894.63 |
| 387.7 | 9.3899 | -3.4482 | -1.4621 | 1894.59 |
| 388.0 | 9.3784 | -3.6249 | -1.0607 | 1894.54 |
| 388.3 | 9.5414 | -3.2212 | -0.9761 | 1894.21 |
| 388.7 | 9.4671 | -3.2399 | -1.0467 | 1894.13 |
| 389.0 | 9.3949 | -3.4002 | -1.4781 | 1894.04 |
| 389.3 | 9.3799 | -3.5099 | -1.2367 | 1893.96 |
| 389.7 | 9.3148 | -3.7182 | -1.1841 | 1893.88 |
| 390.0 | 9.2218 | -4.1469 | -1.3777 | 1893.79 |
| 390.3 | 9.1591 | -4.3872 | -1.4801 | 1893.75 |
| 390.7 | 9.1196 | -4.2599 | -1.3497 | 1893.71 |
| 391.0 | 9.1120 | -3.9732 | -1.1711 | 1893.67 |
| 391.3 | 9.0906 | -3.7739 | -1.3487 | 1893.63 |
| 391.7 | 9.2239 | -3.4742 | -1.3141 | 1893.55 |
| 392.0 | 9.2487 | -3.3309 | -1.4097 | 1893.46 |
| 392.3 | 9.5254 | -2.7313 | 1.8721 | 1893.21 |
| 392.7 | 9.3938 | -2.8504 | 0.4696 | 1893.05 |
| 393.0 | 9.2547 | -3.6562 | -1.9501 | 1892.88 |
| 393.3 | 9.2596 | -4.2419 | -2.2137 | 1892.80 |
| 393.7 | 9.0357 | -4.3492 | -2.2651 | 1892.72 |
| 394.0 | 9.0455 | -4.2809 | -1.8477 | 1892.63 |
| 394.3 | 9.0858 | -4.3122 | -1.7331 | 1892.59 |
| 394.7 | 9.1139 | -3.9629 | -1.8497 | 1892.54 |
| 395.0 | 9.2012 | -3.4642 | -1.8401 | 1892.43 |
| 395.3 | 9.2651 | -3.2849 | -1.7687 | 1892.32 |
| 395.7 | 9.3643 | -3.4042 | -2.0891 | 1892.21 |
| 396.0 | 9.3113 | -3.6940 | -1.8378 | 1892.13 |
| 396.3 | 9.2622 | -3.6532 | -1.9977 | 1892.05 |
| 396.7 | 9.1810 | -4.0659 | -2.5327 | 1891.96 |
| 397.0 | 9.1141 | -4.2102 | -2.6051 | 1891.88 |
| 397.3 | 9.1060 | -4.5729 | -2.4437 | 1891.76 |
| 397.7 | 8.9362 | -4.2992 | -2.5871 | 1891.63 |
| 398.0 | 9.0742 | -3.6359 | -2.2177 | 1891.60 |
| 398.3 | 9.0363 | -3.7222 | -1.5441 | 1891.57 |
| 398.7 | 9.0888 | -3.9709 | -2.1357 | 1891.54 |
| 399.0 | 9.3222 | -3.2592 | -1.6481 | 1891.29 |
| 399.3 | 9.3063 | -3.5599 | -1.5247 | 1891.21 |
| 399.7 | 9.3898 | -3.3572 | -1.6551 | 1891.13 |
| 400.0 | 9.3541 | -3.0199 | -2.1157 | 1891.09 |
| 400.3 | 9.3073 | -3.3542 | -2.0611 | 1891.05 |
| 400.7 | 9.2124 | -4.0129 | -2.5477 | 1891.00 |
| 401.0 | 9.1551 | -4.0642 | -2.2231 | 1890.96 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 401.3 | 9.1352 | -4.2509 | -2.4897 | 1890.85 |
| 401.7 | 9.0197 | -4.3695 | -2.2962 | 1890.74 |
| 402.0 | 8.9577 | -4.3279 | -2.3907 | 1890.63 |
| 402.3 | 9.0189 | -3.8582 | -1.8321 | 1890.55 |
| 402.7 | 9.1825 | -3.6199 | -1.5137 | 1890.46 |
| 403.0 | 9.2097 | -3.4532 | -1.4141 | 1890.38 |
| 403.3 | 9.3180 | -3.3979 | -1.6867 | 1890.26 |
| 403.7 | 9.3576 | -3.5102 | -2.0551 | 1890.13 |
| 404.0 | 9.3096 | -3.7089 | -2.1277 | 1890.04 |
| 404.3 | 9.2671 | -3.9942 | -1.7411 | 1889.96 |
| 404.7 | 9.1622 | -3.9019 | -1.7787 | 1889.88 |
| 405.0 | 9.0628 | -4.3132 | -1.9831 | 1889.79 |
| 405.3 | 9.0029 | -4.4159 | -2.2797 | 1889.71 |
| 405.7 | 8.9999 | -4.2350 | -1.7841 | 1889.63 |
| 406.0 | 9.0318 | -4.1509 | -1.8757 | 1889.50 |
| 406.3 | 9.2950 | -3.6552 | -1.2921 | 1889.38 |
| 406.7 | 9.2300 | -3.3869 | -1.0767 | 1889.34 |
| 407.0 | 9.4219 | -3.1982 | -1.5471 | 1889.29 |
| 407.3 | 9.3803 | -3.3439 | -1.8827 | 1889.25 |
| 407.7 | 9.4146 | -3.1672 | -1.7361 | 1889.21 |
| 408.0 | 9.3839 | -3.7579 | -2.4107 | 1889.04 |
| 408.3 | 9.1493 | -3.9022 | -2.4731 | 1888.88 |
| 408.7 | 8.9544 | -4.5889 | -2.2727 | 1888.71 |
| 409.0 | 9.0101 | -4.4182 | -1.9941 | 1888.67 |
| 409.3 | 8.9619 | -4.3629 | -1.6867 | 1888.63 |
| 409.7 | 9.0424 | -3.9792 | -1.4791 | 1888.55 |
| 410.0 | 9.2075 | -3.7989 | -1.1067 | 1888.46 |
| 410.3 | 9.2771 | -3.3899 | -0.9833 | 1888.38 |
| 410.7 | 9.4195 | -3.1269 | -1.1237 | 1888.30 |
| 411.0 | 9.4438 | -3.0582 | -1.4171 | 1888.21 |
| 411.3 | 9.3963 | -3.1979 | -1.7897 | 1888.11 |
| 411.7 | 9.3209 | -3.8212 | -2.3551 | 1888.00 |
| 412.0 | 9.2473 | -4.0189 | -2.0517 | 1887.89 |
| 412.3 | 9.1205 | -4.4872 | -2.2531 | 1887.79 |
| 412.7 | 9.0649 | -3.9139 | -1.9037 | 1887.75 |
| 413.0 | 9.0930 | -4.4262 | -1.9261 | 1887.71 |
| 413.3 | 9.0199 | -4.4399 | -1.8027 | 1887.67 |
| 413.7 | 8.9705 | -3.6516 | -2.0024 | 1887.63 |
| 414.0 | 8.9906 | -3.8719 | -1.4587 | 1887.55 |
| 414.3 | 9.1775 | -3.4812 | -1.1741 | 1887.46 |
| 414.7 | 9.2757 | -3.5511 | -0.7682 | 1887.38 |
| 415.0 | 9.3905 | -3.0492 | -0.5841 | 1887.32 |
| 415.3 | 9.4643 | -3.1229 | -0.8597 | 1887.27 |
| 415.7 | 9.4648 | -3.3992 | -1.2797 | 1887.21 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 416.0 | 9.3243 | -3.3889 | -1.5707 | 1887.04 |
| 416.3 | 9.3111 | -3.7242 | -1.1321 | 1886.96 |
| 416.7 | 9.1258 | -4.1439 | -1.2547 | 1886.84 |
| 417.0 | 9.0801 | -4.1872 | -1.1641 | 1886.71 |
| 417.3 | 9.1397 | -4.4198 | -1.5235 | 1886.68 |
| 417.7 | 9.0542 | -4.3072 | -1.7031 | 1886.66 |
| 418.0 | 9.0365 | -4.2609 | -1.5347 | 1886.63 |
| 418.3 | 9.1614 | -4.0412 | -1.7871 | 1886.51 |
| 418.7 | 9.3910 | -3.4369 | -0.6857 | 1886.38 |
| 419.0 | 9.4979 | -3.0712 | -0.5821 | 1886.32 |
| 419.3 | 9.4714 | -3.2469 | -1.2667 | 1886.27 |
| 419.7 | 9.5893 | -3.1372 | -1.0121 | 1886.21 |
| 420.0 | 9.5731 | -3.2639 | -0.9267 | 1886.13 |
| 420.3 | 9.5018 | -3.3172 | -1.7261 | 1886.05 |
| 420.7 | 9.4484 | -3.3909 | -1.6077 | 1885.96 |
| 421.0 | 9.3324 | -3.5712 | -1.6991 | 1885.88 |
| 421.3 | 9.1690 | -4.2532 | -1.6256 | 1885.71 |
| 421.7 | 9.1174 | -4.0592 | -1.6501 | 1885.68 |
| 422.0 | 9.1217 | -4.3619 | -1.6157 | 1885.66 |
| 422.3 | 9.0821 | -4.2572 | -1.7181 | 1885.63 |
| 422.7 | 9.0889 | -4.2749 | -1.8697 | 1885.55 |
| 423.0 | 9.1195 | -3.9382 | -1.9091 | 1885.46 |
| 423.3 | 9.3015 | -3.7399 | -1.2277 | 1885.38 |
| 423.7 | 9.4818 | -3.1622 | -0.9351 | 1885.21 |
| 424.0 | 9.4210 | -3.2359 | -1.2177 | 1885.15 |
| 424.3 | 9.4523 | -3.2360 | -1.2635 | 1885.09 |
| 424.7 | 9.4743 | -3.4359 | -1.2777 | 1885.02 |
| 425.0 | 9.3603 | -3.5022 | -1.3871 | 1884.96 |
| 425.3 | 9.3114 | -3.6209 | -1.4837 | 1884.90 |
| 425.7 | 9.2752 | -3.6782 | -1.6821 | 1884.85 |
| 426.0 | 9.1300 | -4.0221 | -1.0269 | 1884.79 |
| 426.3 | 9.1094 | -4.0772 | -1.5411 | 1884.74 |
| 426.7 | 9.1343 | -4.2269 | -1.2407 | 1884.68 |
| 427.0 | 9.0844 | -3.9472 | -1.1541 | 1884.63 |
| 427.3 | 9.1707 | -3.8129 | -1.3017 | 1884.54 |
| 427.7 | 9.4449 | -3.3272 | -1.0231 | 1884.38 |
| 428.0 | 9.5440 | -3.2429 | -0.5227 | 1884.21 |
| 428.3 | 9.4771 | -3.0065 | -0.5623 | 1884.13 |
| 428.7 | 9.4687 | -3.0199 | -0.7057 | 1884.05 |
| 429.0 | 9.4725 | -3.7612 | -1.7551 | 1883.96 |
| 429.3 | 9.2910 | -3.7779 | -1.6647 | 1883.88 |
| 429.7 | 9.2348 | -3.9722 | -2.1321 | 1883.82 |
| 430.0 | 9.1185 | -4.2379 | -1.9517 | 1883.77 |
| 430.3 | 9.0464 | -4.4502 | -1.9441 | 1883.71 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 430.7 | 9.0862 | -4.3109 | -2.0587 | 1883.67 |
| 431.0 | 9.0477 | -4.1764 | -2.1458 | 1883.63 |
| 431.3 | 9.1162 | -4.2159 | -2.2647 | 1883.55 |
| 431.7 | 9.2036 | -3.6218 | -1.5605 | 1883.46 |
| 432.0 | 9.3785 | -3.3369 | -1.1627 | 1883.38 |
| 432.3 | 9.4844 | -3.1822 | -0.8481 | 1883.29 |
| 432.7 | 9.5443 | | | 1883.21 |
| 433.0 | 9.5375 | -3.0642 | -1.3761 | 1883.16 |
| 433.3 | 9.4866 | -2.9969 | -1.0797 | 1883.12 |
| 433.7 | 9.4933 | -3.2722 | -1.5301 | 1883.07 |
| 434.0 | 9.5105 | -3.3749 | -1.4757 | 1883.02 |
| 434.3 | 9.3731 | -3.1522 | -1.7441 | 1882.97 |
| 434.7 | 9.3484 | -4.0022 | -1.5691 | 1882.93 |
| 435.0 | 9.2415 | -4.2662 | -1.0961 | 1882.88 |
| 435.3 | 9.1581 | -4.0599 | -1.4367 | 1882.82 |
| 435.7 | 9.1636 | -3.9472 | -0.7441 | 1882.76 |
| 436.0 | 9.0903 | -4.0789 | -1.2807 | 1882.69 |
| 436.3 | 9.0737 | -4.0922 | -1.5561 | 1882.63 |
| 436.7 | 9.2571 | -3.8083 | -1.6367 | 1882.51 |
| 437.0 | 9.3083 | -3.3146 | -0.7987 | 1882.38 |
| 437.3 | 9.5281 | -2.8599 | -0.1337 | 1882.30 |
| 437.7 | 9.6411 | -2.6362 | 0.2509 | 1882.21 |
| 438.0 | 9.5228 | | | 1882.13 |
| 438.3 | 9.5265 | -3.0242 | -0.6771 | 1882.04 |
| 438.7 | 9.4002 | -3.3219 | -1.2167 | 1881.96 |
| 439.0 | 9.3071 | -3.5202 | -1.3311 | 1881.79 |
| 439.3 | 9.1267 | -4.0079 | -1.9007 | 1881.63 |
| 439.7 | 9.1599 | -4.3112 | -1.7471 | 1881.61 |
| 440.0 | 9.2180 | -4.5039 | -2.0077 | 1881.59 |
| 440.3 | 9.1659 | -4.3692 | -2.0151 | 1881.58 |
| 440.7 | 9.2521 | -3.7429 | -1.4037 | 1881.56 |
| 441.0 | 9.2783 | -3.5382 | -0.8041 | 1881.54 |
| 441.3 | 9.5582 | -3.1299 | -1.1687 | 1881.21 |
| 441.7 | 9.5306 | -3.1482 | -1.5221 | 1881.16 |
| 442.0 | 9.4562 | -3.1179 | -1.6767 | 1881.12 |
| 442.3 | 9.4591 | -3.2711 | -1.9602 | 1881.07 |
| 442.7 | 9.2669 | | -1.9301 | 1881.02 |
| 443.0 | 9.4632 | | -1.4436 | 1880.97 |
| 443.3 | 9.2836 | -3.6819 | -1.9839 | 1880.93 |
| 443.7 | 9.2261 | -3.6122 | -1.5631 | 1880.88 |
| 444.0 | 9.1892 | -3.9663 | -2.1469 | 1880.83 |
| 444.3 | 9.0829 | | -2.2304 | 1880.78 |
| 444.7 | 9.0833 | -3.2529 | -1.7147 | 1880.73 |
| 445.0 | 9.0923 | -4.2732 | -1.7811 | 1880.68 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 445.3 | 9.0604 | | -1.3475 | 1880.63 |
| 445.7 | 9.1447 | -4.1732 | -1.6471 | 1880.60 |
| 446.0 | 9.2684 | -3.7379 | -1.6987 | 1880.57 |
| 446.3 | 9.1735 | -3.7982 | -1.9781 | 1880.54 |
| 446.7 | 9.3779 | -3.4748 | -1.2682 | 1880.48 |
| 447.0 | 9.4239 | -3.7973 | -1.7225 | 1880.41 |
| 447.3 | 9.3486 | -2.9219 | -1.2077 | 1880.34 |
| 447.7 | 9.4568 | -3.4222 | -1.4151 | 1880.28 |
| 448.0 | 9.4992 | -3.2839 | -1.5307 | 1880.21 |
| 448.3 | 9.4540 | -3.3597 | -1.7625 | 1880.11 |
| 448.7 | 9.4244 | -3.0379 | -1.7817 | 1880.00 |
| 449.0 | 9.3393 | -3.6072 | -2.8451 | 1879.89 |
| 449.3 | 9.2008 | -3.8919 | -2.7287 | 1879.79 |
| 449.7 | 9.1135 | -4.3892 | -2.4781 | 1879.74 |
| 450.0 | 9.1344 | -4.0129 | -1.9397 | 1879.68 |
| 450.3 | 9.0686 | -4.3052 | -2.7121 | 1879.63 |
| 450.7 | 9.1368 | -4.1249 | -1.6363 | 1879.60 |
| 451.0 | 9.0834 | -3.4802 | -1.5501 | 1879.57 |
| 451.3 | 9.1268 | -3.6939 | -1.9217 | 1879.54 |
| 451.7 | 9.4519 | -3.0802 | -1.2221 | 1879.46 |
| 452.0 | 9.4344 | -3.3821 | -2.0456 | 1879.37 |
| 452.3 | 9.4549 | -3.2892 | -1.9391 | 1879.29 |
| 452.7 | 9.4835 | | | 1879.21 |
| 453.0 | 9.3691 | -3.6502 | -2.4421 | 1879.04 |
| 453.3 | 9.2059 | -3.8589 | -2.1687 | 1878.88 |
| 453.7 | 9.1793 | -4.1392 | -2.3831 | 1878.76 |
| 454.0 | 9.1052 | -3.6229 | -2.3657 | 1878.63 |
| 454.3 | 9.1125 | -4.0882 | -2.4421 | 1878.55 |
| 454.7 | 9.2164 | -3.7329 | -1.6277 | 1878.47 |
| 455.0 | 9.3345 | -3.5014 | -1.4770 | 1878.38 |
| 455.3 | 9.4409 | | -1.2093 | 1878.21 |
| 455.7 | 9.4403 | | -1.8190 | 1878.15 |
| 456.0 | 9.3600 | -3.4789 | -2.2967 | 1878.08 |
| 456.3 | 9.2629 | -3.5342 | -2.4921 | 1878.02 |
| 456.7 | 9.3311 | -3.8582 | -2.1819 | 1877.96 |
| 457.0 | 9.2064 | -3.9602 | -1.7311 | 1877.85 |
| 457.3 | 9.1503 | -4.3229 | -2.1677 | 1877.74 |
| 457.7 | 9.1729 | -4.5993 | -2.8715 | 1877.63 |
| 458.0 | 9.1601 | -4.0161 | -2.1448 | 1877.55 |
| 458.3 | 9.2396 | -3.7622 | -1.7291 | 1877.46 |
| 458.7 | 9.4089 | -3.4089 | -1.6107 | 1877.38 |
| 459.0 | 9.4764 | -3.2942 | -1.3591 | 1877.25 |
| 459.3 | 9.5211 | -3.4552 | -1.7477 | 1877.13 |
| 459.7 | 9.4523 | -3.3592 | -1.7191 | 1877.09 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 460.0 | 9.4653 | -3.5049 | -2.1547 | 1877.04 |
| 460.3 | 9.3944 | -3.7416 | -2.2797 | 1877.00 |
| 460.7 | 9.3362 | -4.0849 | -1.8107 | 1876.96 |
| 461.0 | 9.1792 | -4.1162 | -2.1091 | 1876.88 |
| 461.3 | 9.0727 | -4.2139 | -1.5277 | 1876.79 |
| 461.7 | 9.0360 | -4.4412 | -2.0751 | 1876.71 |
| 462.0 | 9.0920 | -4.1149 | -1.4947 | 1876.67 |
| 462.3 | 9.0412 | -4.1722 | -1.7171 | 1876.63 |
| 462.7 | 9.1606 | -3.9209 | -1.6557 | 1876.55 |
| 463.0 | 9.2202 | -3.6922 | -1.7171 | 1876.46 |
| 463.3 | 9.3915 | -2.5922 | 0.4807 | 1876.34 |
| 463.7 | 9.4642 | -3.2552 | -1.5121 | 1876.21 |
| 464.0 | 9.4346 | -3.4029 | -1.4807 | 1876.10 |
| 464.3 | 9.4166 | -3.4692 | -1.7891 | 1876.00 |
| 464.7 | 9.3179 | -4.1844 | -1.7688 | 1875.90 |
| 465.0 | 9.1946 | -4.0558 | -1.7094 | 1875.79 |
| 465.3 | 9.2035 | -4.2551 | -1.2192 | 1875.74 |
| 465.7 | 9.2740 | -4.2722 | -1.5551 | 1875.68 |
| 466.0 | 9.0516 | -4.2359 | -2.0397 | 1875.63 |
| 466.3 | 9.1961 | -4.4472 | -2.1891 | 1875.59 |
| 466.7 | 9.1742 | -3.7076 | -1.4959 | 1875.54 |
| 467.0 | 9.4854 | -3.3922 | -1.1601 | 1875.29 |
| 467.3 | 9.4319 | -3.3559 | -1.0937 | 1875.24 |
| 467.7 | 9.4655 | -3.4352 | -1.3101 | 1875.18 |
| 468.0 | 9.4714 | -3.3069 | -1.3737 | 1875.13 |
| 468.3 | 9.4137 | -3.5892 | -1.3731 | 1875.01 |
| 468.7 | 9.2715 | -3.7677 | -1.1124 | 1874.88 |
| 469.0 | 9.1774 | -3.9402 | -1.0921 | 1874.82 |
| 469.3 | 9.1558 | -4.0939 | -1.2997 | 1874.76 |
| 469.7 | 9.1301 | -4.1107 | -1.7115 | 1874.69 |
| 470.0 | 9.0893 | -4.6463 | -2.0437 | 1874.63 |
| 470.3 | 9.2036 | -3.6742 | -1.7871 | 1874.54 |
| 470.7 | 9.3797 | -4.1032 | -1.5333 | 1874.38 |
| 471.0 | 9.4305 | -3.1792 | -1.3011 | 1874.29 |
| 471.3 | 9.4706 | -3.7310 | -1.8548 | 1874.21 |
| 471.7 | 9.3714 | -3.5292 | -1.9481 | 1874.00 |
| 472.0 | 9.2215 | -3.6619 | -2.1367 | 1873.79 |
| 472.3 | 9.1285 | -4.2492 | -1.4521 | 1873.71 |
| 472.7 | 9.1136 | -4.2989 | -2.7247 | 1873.63 |
| 473.0 | | -4.3462 | -2.2411 | 1873.57 |
| 473.3 | 9.1700 | -4.2489 | -2.0477 | 1873.52 |
| 473.7 | 9.1523 | -4.0739 | -2.1767 | 1873.46 |
| 474.0 | 9.3553 | -3.5699 | -1.5107 | 1873.40 |
| 474.3 | 9.3528 | -3.3412 | -1.4691 | 1873.35 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 474.7 | 9.3978 | -3.5059 | -1.8647 | 1873.29 |
| 475.0 | 9.3621 | -3.6572 | -1.9981 | 1873.23 |
| 475.3 | 9.3760 | -3.4699 | -2.0927 | 1873.21 |
| 475.7 | 9.2530 | -3.6042 | -2.4321 | 1872.96 |
| 476.0 | 9.2114 | -3.8951 | -2.1708 | 1872.92 |
| 476.3 | 9.1658 | -3.9784 | -1.2142 | 1872.88 |
| 476.7 | 9.1317 | -4.1529 | -1.5087 | 1872.83 |
| 477.0 | 9.0943 | -4.2242 | -2.2881 | 1872.79 |
| 477.3 | 9.0103 | -4.2419 | -2.6707 | 1872.63 |
| 477.7 | 9.0379 | -4.1265 | -2.4544 | 1872.56 |
| 478.0 | 9.2418 | -3.7989 | -1.6077 | 1872.49 |
| 478.3 | 9.4091 | -3.5022 | -1.5361 | 1872.43 |
| 478.7 | 9.4642 | -3.3679 | -1.6267 | 1872.36 |
| 479.0 | 9.4758 | -3.4022 | -1.9891 | 1872.29 |
| 479.3 | 9.3931 | -3.5456 | -2.1689 | 1872.21 |
| 479.7 | 9.5275 | -3.6222 | -1.9161 | 1872.13 |
| 480.0 | 9.1037 | -4.3939 | -1.4867 | 1871.79 |
| 480.3 | 8.8899 | | | 1871.63 |
| 480.7 | 9.0791 | -4.2369 | -2.0107 | 1871.51 |
| 481.0 | 9.2944 | -3.7612 | -1.8511 | 1871.38 |
| 481.3 | 9.3125 | | -2.0830 | 1871.35 |
| 481.7 | 9.3803 | -3.3342 | -1.6521 | 1871.31 |
| 482.0 | 9.3675 | -3.8549 | -2.1447 | 1871.28 |
| 482.3 | 9.3686 | -3.6432 | -2.2261 | 1871.24 |
| 482.7 | 9.4813 | | -3.2118 | 1871.21 |
| 483.0 | 9.3484 | -4.0902 | -2.2391 | 1870.88 |
| 483.3 | 9.1856 | -4.1009 | -2.4397 | 1870.80 |
| 483.7 | 9.1880 | -4.2582 | -2.7441 | 1870.72 |
| 484.0 | 9.1681 | -4.1879 | -1.8627 | 1870.63 |
| 484.3 | 9.2056 | -3.7942 | -1.3441 | 1870.57 |
| 484.7 | 9.3395 | -4.0349 | -2.0187 | 1870.52 |
| 485.0 | 9.2769 | -3.5952 | -1.7631 | 1870.46 |
| 485.3 | 9.5034 | -3.1959 | -1.6007 | 1870.34 |
| 485.7 | 9.5194 | -3.0412 | -1.3191 | 1870.21 |
| 486.0 | 9.4906 | -3.1249 | -1.1717 | 1870.12 |
| 486.3 | 9.4409 | -3.3162 | -1.5541 | 1870.04 |
| 486.7 | 9.3510 | | | 1869.96 |
| 487.0 | 9.4083 | -3.5538 | -1.3456 | 1869.87 |
| 487.3 | 9.2953 | -3.7799 | -1.9927 | 1869.79 |
| 487.7 | 9.2740 | -4.0492 | -2.4051 | 1869.63 |
| 488.0 | 9.3545 | -4.0479 | -2.3357 | 1869.46 |
| 488.3 | 9.5916 | -3.3932 | -1.4601 | 1869.21 |
| 488.7 | | -2.9827 | -0.7174 | 1869.19 |
| 489.0 | 9.4709 | -3.5212 | -0.8171 | 1869.17 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 489.3 | 9.4463 | -2.8901 | -0.6408 | 1869.15 |
| 489.7 | 9.6000 | -2.9642 | -1.6301 | 1869.13 |
| 490.0 | 9.4734 | | | 1868.96 |
| 490.3 | 9.0252 | -4.2731 | -2.8492 | 1868.63 |
| 490.7 | 9.1966 | | | 1868.57 |
| 491.0 | | -3.9449 | -2.5727 | 1868.52 |
| 491.3 | 9.2471 | -3.7742 | -2.5801 | 1868.46 |
| 491.7 | 9.3711 | -3.4619 | -2.0227 | 1868.38 |
| 492.0 | 9.4830 | -3.4812 | -1.7841 | 1868.29 |
| 492.3 | 9.4378 | | | 1868.21 |
| 492.7 | 9.4823 | -3.1899 | -1.7977 | 1868.13 |
| 493.0 | 9.4277 | -3.6572 | -0.8821 | 1867.96 |
| 493.3 | 9.3681 | -3.5859 | -0.6027 | 1867.80 |
| 493.7 | 9.3078 | -3.3602 | -0.8841 | 1867.63 |
| 494.0 | 9.3426 | -3.6936 | -1.6727 | 1867.49 |
| 494.3 | 9.4261 | -3.4132 | -1.6001 | 1867.36 |
| 494.7 | 9.4154 | | | 1867.23 |
| 495.0 | 9.4506 | | | 1867.09 |
| 495.3 | 9.4142 | -3.6949 | -1.2757 | 1866.96 |
| 495.7 | 9.4127 | -3.5486 | -1.5503 | 1866.83 |
| 496.0 | 9.4334 | -3.6998 | -1.2394 | 1866.69 |
| 496.3 | 9.4277 | | -1.6298 | 1866.56 |
| 496.7 | 9.4018 | -3.5959 | -1.2337 | 1866.43 |
| 497.0 | 9.3981 | -3.4271 | -1.5858 | 1866.29 |
| 497.3 | 9.4540 | -3.6079 | -2.2937 | 1866.16 |
| 497.7 | 9.4599 | -3.5212 | -1.8551 | 1866.03 |
| 498.0 | 9.3483 | -3.4939 | -1.7197 | 1865.89 |
| 498.3 | 9.3156 | -3.7102 | -2.1261 | 1865.76 |
| 498.7 | 9.2603 | -3.9599 | -1.9327 | 1865.63 |
| 499.0 | 9.3463 | -3.5392 | -1.9531 | 1865.47 |
| 499.3 | 9.3060 | -3.7439 | -1.9667 | 1865.31 |
| 499.7 | 9.3505 | -3.6257 | -1.7190 | 1865.16 |
| 500.0 | 9.3838 | -3.4969 | -1.5377 | 1865.00 |
| 500.3 | 9.3560 | -3.0684 | -1.4016 | 1864.84 |
| 500.7 | 9.4215 | -3.4639 | -1.3377 | 1864.68 |
| 501.0 | 9.4111 | -3.2642 | -1.3101 | 1864.52 |
| 501.3 | 9.4397 | -3.0441 | -2.4130 | 1864.37 |
| 501.7 | 9.5744 | -3.3889 | -2.5991 | 1864.21 |
| 502.0 | 9.3519 | -3.7809 | -2.7637 | 1863.88 |
| 502.3 | 9.2444 | -3.9852 | -3.2371 | 1863.63 |
| 502.7 | 9.2755 | -3.9077 | -2.6982 | 1863.55 |
| 503.0 | 9.3653 | -3.8102 | -2.3271 | 1863.46 |
| 503.3 | 9.4344 | -3.4419 | -2.3097 | 1863.38 |
| 503.7 | 9.5885 | -3.2112 | -1.7091 | 1863.21 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 504.0 | 9.5742 | -3.5409 | -2.1157 | 1863.13 |
| 504.3 | 9.5180 | -3.5072 | -3.0911 | 1863.04 |
| 504.7 | 9.4289 | -3.6159 | -3.0037 | 1862.96 |
| 505.0 | 9.2524 | -3.9009 | -2.3023 | 1862.79 |
| 505.3 | 9.2161 | -4.0229 | -2.1307 | 1862.63 |
| 505.7 | 9.3010 | -2.9702 | -0.2541 | 1862.52 |
| 506.0 | 9.3512 | -3.3969 | -1.5787 | 1862.41 |
| 506.3 | 9.4043 | -3.4632 | -1.9861 | 1862.30 |
| 506.7 | 9.4120 | -3.4879 | -1.5307 | 1862.19 |
| 507.0 | 9.3927 | -3.5972 | -0.8311 | 1862.07 |
| 507.3 | 9.4463 | -3.4229 | -0.8877 | 1861.96 |
| 507.7 | 9.4740 | -2.9782 | -0.8071 | 1861.85 |
| 508.0 | 9.4859 | -3.0709 | -0.2807 | 1861.74 |
| 508.3 | 9.4731 | -3.1692 | -0.4091 | 1861.63 |
| 508.7 | 9.4440 | -3.2295 | -0.5641 | 1861.52 |
| 509.0 | 9.5226 | -3.1842 | -0.6611 | 1861.41 |
| 509.3 | 9.5121 | -3.2258 | -0.4856 | 1861.30 |
| 509.7 | 9.4724 | -3.3092 | -0.7561 | 1861.19 |
| 510.0 | 9.4980 | -2.8859 | -0.3467 | 1861.07 |
| 510.3 | 9.4445 | -3.3112 | -0.9391 | 1860.96 |
| 510.7 | 9.4130 | -3.7779 | -1.8687 | 1860.85 |
| 511.0 | 9.3349 | -3.8092 | -1.8811 | 1860.74 |
| 511.3 | 9.3092 | -3.9829 | -2.5207 | 1860.63 |
| 511.7 | 9.3557 | -3.7883 | -2.6019 | 1860.57 |
| 512.0 | 9.4071 | -3.2909 | -1.7187 | 1860.52 |
| 512.3 | 9.4327 | -3.2812 | -1.6491 | 1860.46 |
| 512.7 | 9.4789 | -2.9731 | -0.9520 | 1860.38 |
| 513.0 | 9.5613 | -3.3172 | -0.8191 | 1860.29 |
| 513.3 | 9.4829 | -3.2189 | -1.1557 | 1860.09 |
| 513.7 | 9.4119 | -3.2892 | -0.7871 | 1859.88 |
| 514.0 | 9.3302 | -3.5479 | -1.4217 | 1859.63 |
| 514.3 | 9.3510 | -3.4332 | -1.7151 | 1859.55 |
| 514.7 | 9.3895 | -3.4209 | -1.4247 | 1859.46 |
| 515.0 | 9.5116 | -3.2222 | -1.2151 | 1859.21 |
| 515.3 | 9.4522 | -3.2789 | -1.0937 | 1859.04 |
| 515.7 | 9.3738 | -3.4032 | -0.8831 | 1858.71 |
| 516.0 | 9.4331 | -3.4819 | -0.6697 | 1858.67 |
| 516.3 | 9.4429 | -3.6392 | -1.3331 | 1858.63 |
| 516.7 | 9.3605 | -4.0621 | -1.1578 | 1858.58 |
| 517.0 | 9.3551 | -3.5152 | -1.4761 | 1858.54 |
| 517.3 | 9.3962 | -3.7809 | -2.1257 | 1858.42 |
| 517.7 | 9.5702 | -3.0602 | -1.6961 | 1858.29 |
| 518.0 | 9.5758 | -3.2079 | -1.1117 | 1858.24 |
| 518.3 | 9.5581 | -3.2892 | -0.8491 | 1858.18 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 518.7 | 9.5997 | -3.0848 | -1.8537 | 1858.13 |
| 519.0 | 9.5276 | -3.2442 | -2.4471 | 1858.00 |
| 519.3 | 9.3449 | -4.4109 | -3.3267 | 1857.88 |
| 519.7 | 9.1976 | -3.9858 | -2.4908 | 1857.63 |
| 520.0 | 9.2481 | -3.7119 | -2.1757 | 1857.50 |
| 520.3 | 9.3337 | -3.5992 | -2.5111 | 1857.38 |
| 520.7 | 9.4176 | -3.3481 | -2.2522 | 1857.29 |
| 521.0 | 9.4188 | -3.8592 | -2.1331 | 1857.21 |
| 521.3 | 9.4325 | -3.7234 | -2.3154 | 1857.13 |
| 521.7 | 9.3108 | -4.2655 | -2.5790 | 1856.88 |
| 522.0 | 9.2303 | -3.8399 | -2.4857 | 1856.63 |
| 522.3 | 9.3674 | -3.6312 | -1.5691 | 1856.46 |
| 522.7 | 9.4944 | -3.1119 | -0.7557 | 1856.41 |
| 523.0 | 9.5368 | -3.1712 | -1.1981 | 1856.36 |
| 523.3 | 9.5094 | -3.1329 | -1.1717 | 1856.31 |
| 523.7 | 9.5304 | -3.0922 | -0.8321 | 1856.26 |
| 524.0 | 9.6693 | -2.9769 | -0.3657 | 1856.21 |
| 524.3 | 9.5897 | -3.0102 | -1.0171 | 1856.09 |
| 524.7 | 9.5619 | -3.2159 | -1.2787 | 1855.96 |
| 525.0 | 9.1599 | -3.6612 | -2.6351 | 1855.63 |
| 525.3 | 9.4221 | -3.7699 | -2.2597 | 1855.46 |
| 525.7 | 9.3917 | -3.5562 | -2.3071 | 1855.38 |
| 526.0 | 9.5010 | -3.1199 | -1.8597 | 1855.29 |
| 526.3 | 9.6720 | -2.8862 | -1.4261 | 1855.21 |
| 526.7 | 9.6829 | | | 1855.04 |
| 527.0 | 9.5179 | | -2.6774 | 1854.96 |
| 527.3 | 9.2861 | -3.1653 | -1.7183 | 1854.63 |
| 527.7 | 9.3127 | -3.2802 | -1.5311 | 1854.49 |
| 528.0 | 9.3511 | -3.3079 | -1.5187 | 1854.35 |
| 528.3 | 9.4343 | -3.2202 | -0.6101 | 1854.21 |
| 528.7 | 9.4051 | -3.0431 | -0.3334 | 1853.92 |
| 529.0 | 9.3786 | -3.0582 | -0.8609 | 1853.63 |
| 529.3 | 9.4196 | -3.3909 | -0.8597 | 1853.53 |
| 529.7 | 9.4270 | -2.9452 | -0.3121 | 1853.42 |
| 530.0 | 9.4751 | -3.3749 | -1.2727 | 1853.31 |
| 530.3 | 9.5452 | -3.3112 | -1.2711 | 1853.21 |
| 530.7 | 9.5294 | -3.2720 | -0.7838 | 1853.05 |
| 531.0 | 9.3864 | -3.5962 | -1.3331 | 1852.88 |
| 531.3 | 9.3060 | -3.5679 | -0.7907 | 1852.80 |
| 531.7 | 9.3105 | -3.7152 | -0.6471 | 1852.72 |
| 532.0 | 9.2801 | -3.9139 | -0.9737 | 1852.63 |
| 532.3 | 9.3607 | -3.2850 | -0.7076 | 1852.55 |
| 532.7 | 9.3874 | -3.7099 | -1.1947 | 1852.46 |
| 533.0 | 9.4240 | | -1.2668 | 1852.37 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 533.3 | 9.4555 | -2.9649 | -1.5197 | 1852.29 |
| 533.7 | 9.3993 | -3.4102 | -1.4621 | 1852.21 |
| 534.0 | 9.4566 | -3.9764 | -2.2924 | 1852.13 |
| 534.3 | 9.3930 | -3.7682 | -1.7991 | 1852.03 |
| 534.7 | 9.3880 | -3.7989 | -2.2777 | 1851.93 |
| 535.0 | 9.2864 | -4.0812 | -1.2841 | 1851.83 |
| 535.3 | 9.3080 | -3.9549 | -2.3647 | 1851.73 |
| 535.7 | 9.2272 | -3.8352 | -1.9151 | 1851.63 |
| 536.0 | 9.3223 | -3.5589 | -1.9697 | 1851.54 |
| 536.3 | 9.4005 | -3.5232 | -1.9551 | 1851.46 |
| 536.7 | 9.5171 | -3.2969 | -1.6567 | 1851.38 |
| 537.0 | 9.5164 | -3.2052 | -2.1091 | 1851.29 |
| 537.3 | 9.5876 | -4.5182 | -2.9041 | 1851.21 |
| 537.7 | 9.4865 | | | 1850.96 |
| 538.0 | 9.2690 | -4.0439 | -2.5277 | 1850.71 |
| 538.3 | 9.2647 | -3.3052 | -1.7331 | 1850.63 |
| 538.7 | 9.3289 | -3.7539 | -1.7787 | 1850.42 |
| 539.0 | 9.5274 | -3.7705 | -1.4031 | 1850.21 |
| 539.3 | 9.5108 | -3.3609 | -1.1487 | 1850.07 |
| 539.7 | 9.4853 | -3.3372 | -0.9991 | 1849.92 |
| 540.0 | 9.4578 | -3.3389 | -0.7357 | 1849.77 |
| 540.3 | 9.4311 | -3.5662 | -0.9261 | 1849.63 |
| 540.7 | 9.4833 | -3.0129 | -0.4587 | 1849.49 |
| 541.0 | 9.4733 | -3.3922 | -1.3031 | 1849.35 |
| 541.3 | 9.5722 | -2.9779 | -0.6807 | 1849.21 |
| 541.7 | 9.4672 | -3.7392 | -1.3991 | 1848.92 |
| 542.0 | 9.4622 | -3.9492 | -0.9431 | 1848.63 |
| 542.3 | 9.5936 | -3.2492 | -1.6031 | 1848.21 |
| 542.7 | 9.4595 | -3.3689 | -1.6177 | 1848.05 |
| 543.0 | 9.3580 | -4.2218 | -2.0280 | 1847.88 |
| 543.3 | 9.3520 | -3.8389 | -1.7307 | 1847.76 |
| 543.7 | 9.1943 | -3.9752 | -1.8431 | 1847.63 |
| 544.0 | 9.3266 | -3.8899 | -1.7237 | 1847.50 |
| 544.3 | 9.4767 | -3.3762 | -1.2771 | 1847.38 |
| 544.7 | 9.5372 | -3.2019 | -1.1117 | 1847.30 |
| 545.0 | 9.5655 | -3.5182 | -1.1591 | 1847.21 |
| 545.3 | 9.4497 | -3.3879 | -0.7117 | 1846.92 |
| 545.7 | 9.4015 | -3.3942 | 0.5179 | 1846.63 |
| 546.0 | 9.4163 | -3.7639 | -1.3477 | 1846.52 |
| 546.3 | 9.4721 | -3.2402 | -0.5331 | 1846.42 |
| 546.7 | 9.5717 | -3.5149 | -0.7627 | 1846.32 |
| 547.0 | 9.6487 | -3.2902 | -0.8421 | 1846.21 |
| 547.3 | 9.4461 | -3.5449 | -1.2227 | 1845.88 |
| 547.7 | 9.4363 | -3.7562 | -1.2781 | 1845.80 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 548.0 | 9.2988 | -3.9929 | -1.0967 | 1845.71 |
| 548.3 | 9.2692 | -4.1312 | -1.8241 | 1845.63 |
| 548.7 | 9.2874 | -3.8129 | -0.5507 | 1845.59 |
| 549.0 | 9.3257 | -3.6402 | -0.9051 | 1845.54 |
| 549.3 | 9.4693 | -3.3759 | -1.1897 | 1845.42 |
| 549.7 | 9.5377 | -3.2852 | -1.2121 | 1845.29 |
| 550.0 | 9.5284 | -3.2049 | -1.3637 | 1845.13 |
| 550.3 | 9.4029 | -3.6782 | -1.7011 | 1845.01 |
| 550.7 | 9.3416 | -3.3339 | -1.9977 | 1844.88 |
| 551.0 | 9.1937 | -4.1502 | -2.0371 | 1844.75 |
| 551.3 | 9.1045 | -4.2359 | -1.8537 | 1844.63 |
| 551.7 | 9.1526 | -4.1892 | -2.0661 | 1844.55 |
| 552.0 | 9.2444 | -3.8019 | -1.3387 | 1844.46 |
| 552.3 | 9.4474 | -3.1132 | -0.9711 | 1844.34 |
| 552.7 | 9.6433 | -3.0309 | -1.1797 | 1844.21 |
| 553.0 | 9.6086 | -3.4219 | -1.9065 | 1844.07 |
| 553.3 | 9.4198 | -3.0179 | -1.9097 | 1843.93 |
| 553.7 | 9.2701 | -3.4582 | -2.2211 | 1843.79 |
| 554.0 | 9.1603 | -4.0109 | -1.9047 | 1843.71 |
| 554.3 | 9.1322 | -4.1562 | -1.8361 | 1843.63 |
| 554.7 | 9.1798 | -3.8049 | -1.0887 | 1843.54 |
| 555.0 | 9.3390 | -3.4062 | -0.7981 | 1843.41 |
| 555.3 | 9.4934 | -2.9719 | -0.5597 | 1843.29 |
| 555.7 | 9.5135 | -3.0052 | -0.5151 | 1843.21 |
| 556.0 | 9.1581 | -3.8289 | -1.4957 | 1842.88 |
| 556.3 | 9.2629 | -3.4192 | -1.8601 | 1842.84 |
| 556.7 | 9.1669 | -3.8779 | -2.1537 | 1842.79 |
| 557.0 | 9.0593 | -4.2232 | -2.1531 | 1842.63 |
| 557.3 | 9.1571 | -4.0139 | -1.3767 | 1842.55 |
| 557.7 | 9.2692 | -3.7642 | -0.5771 | 1842.47 |
| 558.0 | 9.4223 | -3.2309 | -0.3937 | 1842.38 |
| 558.3 | 9.5958 | -2.8742 | -0.6117 | 1842.21 |
| 558.7 | 9.5329 | -2.9169 | -1.0987 | 1842.07 |
| 559.0 | 9.3909 | -3.4682 | -1.1971 | 1841.93 |
| 559.3 | 9.2838 | -3.9289 | -1.2967 | 1841.79 |
| 559.7 | 9.1563 | -4.0362 | -2.0581 | 1841.63 |
| 560.0 | 9.1912 | -4.1019 | -1.0227 | 1841.52 |
| 560.3 | 9.2221 | -3.8012 | -0.7121 | 1841.42 |
| 560.7 | 9.3943 | -3.3069 | 0.2393 | 1841.32 |
| 561.0 | 9.6080 | -2.8902 | -0.0361 | 1841.21 |
| 561.3 | 9.3598 | -3.0519 | -0.4137 | 1840.88 |
| 561.7 | 9.4986 | | | 1840.84 |
| 562.0 | 9.2998 | -3.8599 | -1.5227 | 1840.79 |
| 562.3 | 9.2722 | -4.1362 | -1.7751 | 1840.63 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 562.7 | 9.3593 | -3.5829 | -1.4557 | 1840.49 |
| 563.0 | 9.5541 | -3.3732 | -1.4631 | 1840.35 |
| 563.3 | 9.5414 | -3.3319 | -1.8747 | 1840.21 |
| 563.7 | 9.5908 | -3.1082 | -1.2951 | 1840.05 |
| 564.0 | 9.4729 | | | 1839.88 |
| 564.3 | 9.3131 | -3.8002 | -1.4871 | 1839.71 |
| 564.7 | 9.3110 | -3.9859 | -1.4177 | 1839.54 |
| 565.0 | 9.4329 | -3.8622 | -1.7601 | 1839.43 |
| 565.3 | 9.4873 | -3.4909 | -1.7037 | 1839.32 |
| 565.7 | 9.4743 | -3.4020 | -1.3669 | 1839.21 |
| 566.0 | | -3.4019 | -1.5407 | 1839.10 |
| 566.3 | 9.4874 | -3.7402 | -1.7661 | 1838.99 |
| 566.7 | 9.3176 | -3.8249 | -2.0717 | 1838.88 |
| 567.0 | 9.3503 | -3.8372 | -2.4881 | 1838.75 |
| 567.3 | 9.1535 | -4.0859 | -1.8467 | 1838.63 |
| 567.7 | 9.2177 | -3.4172 | -1.1821 | 1838.55 |
| 568.0 | 9.2814 | -3.2199 | -0.8797 | 1838.46 |
| 568.3 | 9.4728 | -3.3392 | -1.2351 | 1838.21 |
| 568.7 | 9.3842 | -3.2289 | -1.2217 | 1838.04 |
| 569.0 | 9.3575 | -3.7582 | -1.7851 | 1837.96 |
| 569.3 | 9.2704 | -3.9699 | -1.2857 | 1837.88 |
| 569.7 | 9.0952 | -4.2312 | -1.6651 | 1837.63 |
| 570.0 | 9.1768 | -4.1119 | -1.4517 | 1837.54 |
| 570.3 | 9.3037 | -4.0612 | -0.9781 | 1837.46 |
| 570.7 | 9.4663 | -3.5659 | -0.8907 | 1837.34 |
| 571.0 | 9.5463 | -3.2052 | -0.8791 | 1837.21 |
| 571.3 | 9.4850 | -2.9909 | -0.9197 | 1837.10 |
| 571.7 | 9.3788 | -3.6932 | -1.5261 | 1836.99 |
| 572.0 | 9.2695 | -4.0029 | -1.5617 | 1836.88 |
| 572.3 | 9.2307 | -4.0888 | -1.6108 | 1836.76 |
| 572.7 | 9.1160 | -3.8719 | -1.6997 | 1836.63 |
| 573.0 | 9.4930 | -3.3762 | -0.8751 | 1836.38 |
| 573.3 | 9.5957 | -2.9079 | -0.7847 | 1836.21 |
| 573.7 | 9.5654 | -3.0432 | -1.1411 | 1836.05 |
| 574.0 | 9.3138 | -3.6079 | -1.8237 | 1835.88 |
| 574.3 | 9.2054 | -4.0862 | -1.6811 | 1835.79 |
| 574.7 | 9.1749 | -4.1259 | -1.7817 | 1835.63 |
| 575.0 | 9.2557 | -3.4872 | -0.7831 | 1835.54 |
| 575.3 | 9.5211 | -3.0169 | -0.4347 | 1835.38 |
| 575.7 | 9.6515 | -2.8162 | -0.8821 | 1835.21 |
| 576.0 | 9.6126 | -2.6569 | -1.1697 | 1835.04 |
| 576.3 | 9.3488 | -3.1642 | -1.2751 | 1834.88 |
| 576.7 | 9.2483 | -3.5089 | -1.8827 | 1834.76 |
| 577.0 | 9.1044 | -4.1022 | -1.5171 | 1834.63 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 577.3 | 9.1202 | -4.1139 | -1.6917 | 1834.55 |
| 577.7 | 9.3609 | -3.5502 | -0.8551 | 1834.46 |
| 578.0 | 9.5810 | -3.1079 | -1.1937 | 1834.21 |
| 578.3 | 9.5422 | -2.9432 | -1.1581 | 1834.09 |
| 578.7 | 9.3893 | -3.2349 | -1.9817 | 1833.96 |
| 579.0 | 9.2561 | -3.9158 | -2.0425 | 1833.79 |
| 579.3 | 9.1559 | -4.1049 | -2.2867 | 1833.63 |
| 579.7 | 9.3406 | -3.9882 | -1.6441 | 1833.46 |
| 580.0 | 9.2724 | -3.8639 | -1.5207 | 1833.33 |
| 580.3 | 9.3922 | -3.4502 | -0.9931 | 1833.21 |
| | | | | |
| **Track Shift** | | | | |
| 580.0 | 9.5398 | -3.3552 | 0.4439 | 1833.33 |
| 580.3 | 9.5768 | -3.2319 | 0.0303 | 1833.21 |
| 580.7 | 9.4698 | -3.4242 | -0.1151 | 1833.09 |
| 581.0 | 9.4204 | -3.6579 | -0.0987 | 1832.96 |
| 581.3 | 9.3504 | -3.8602 | -0.4041 | 1832.80 |
| 581.7 | 9.2864 | -3.6879 | -0.0837 | 1832.63 |
| 582.0 | 9.3479 | -3.4662 | -0.0141 | 1832.54 |
| 582.3 | 9.4329 | -3.5579 | -0.0847 | 1832.46 |
| 582.7 | 9.5472 | -3.2392 | -0.0241 | 1832.34 |
| 583.0 | 9.6314 | -3.2023 | | 1832.21 |
| 583.3 | 9.5179 | -3.7550 | -0.0079 | 1831.92 |
| 583.7 | 9.3305 | -3.9759 | -0.7197 | 1831.63 |
| 584.0 | 9.3406 | -3.7422 | -0.1881 | 1831.55 |
| 584.3 | 9.3749 | -3.7669 | -0.0607 | 1831.46 |
| 584.7 | 9.3587 | -4.1282 | -0.7461 | 1831.38 |
| 585.0 | 9.3866 | -3.6289 | -0.2107 | 1831.30 |
| 585.3 | 9.3992 | -3.3862 | -0.1911 | 1831.21 |
| 585.7 | 9.4655 | -3.4129 | -0.3247 | 1831.13 |
| 586.0 | 9.4230 | -3.7412 | 0.0899 | 1831.03 |
| 586.3 | 9.4921 | -3.1109 | 0.3933 | 1830.92 |
| 586.7 | 9.3834 | -3.6662 | -0.2251 | 1830.82 |
| 587.0 | 9.3586 | -3.6069 | -0.6597 | 1830.71 |
| 587.3 | 9.3878 | -3.6972 | -0.8361 | 1830.67 |
| 587.7 | 9.3484 | -3.2269 | -0.4247 | 1830.63 |
| 588.0 | 9.3844 | -3.6332 | -1.2111 | 1830.42 |
| 588.3 | 9.4630 | -3.4569 | -1.0637 | 1830.21 |
| 588.7 | 9.4480 | -3.4152 | -0.3341 | 1830.10 |
| 589.0 | 9.3703 | -3.6269 | -0.0687 | 1829.98 |
| 589.3 | 9.3342 | -3.3782 | -0.0711 | 1829.86 |
| 589.7 | 9.3847 | | | 1829.75 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 590.0 | 9.2139 | -3.9422 | -0.9301 | 1829.63 |
| 590.3 | 9.2774 | -3.8459 | -0.9597 | 1829.55 |
| 590.7 | 9.3590 | -4.0672 | -1.3741 | 1829.46 |
| 591.0 | 9.4130 | -3.7169 | -0.8037 | 1829.38 |
| 591.3 | 9.5304 | -3.5012 | 0.2129 | 1829.29 |
| 591.7 | 9.6621 | -3.3659 | -0.3027 | 1829.21 |
| 592.0 | 9.5730 | -3.4552 | 0.0809 | 1829.09 |
| 592.3 | 9.5101 | -3.2259 | 0.2563 | 1828.96 |
| 592.7 | 9.4463 | -3.5328 | -1.0026 | 1828.84 |
| 593.0 | 9.4191 | -3.6999 | -1.3827 | 1828.71 |
| 593.3 | 9.5516 | -3.9722 | -1.2421 | 1828.68 |
| 593.7 | 9.4375 | -3.6449 | -0.5917 | 1828.66 |
| 594.0 | 9.4038 | -3.5982 | -0.7711 | 1828.63 |
| 594.3 | 9.5337 | -3.5539 | 0.4403 | 1828.29 |
| 594.7 | 9.5437 | -3.5212 | -0.3001 | 1828.21 |
| 595.0 | 9.5342 | -3.5489 | -0.6757 | 1828.12 |
| 595.3 | 9.4714 | -3.6002 | -0.7901 | 1828.04 |
| 595.7 | 9.0976 | -3.6449 | -0.8437 | 1827.63 |
| 596.0 | 9.3803 | -3.8892 | -0.9581 | 1827.54 |
| 596.3 | 9.4283 | -3.8569 | -0.8757 | 1827.50 |
| 596.7 | 9.3975 | -3.8812 | -0.6861 | 1827.46 |
| 597.0 | 9.4343 | -3.6899 | -0.8667 | 1827.43 |
| 597.3 | 9.4250 | -3.7922 | -0.9951 | 1827.40 |
| 597.7 | 9.4328 | -3.6629 | -0.4647 | 1827.37 |
| 598.0 | 9.4537 | -3.4512 | 0.1159 | 1827.34 |
| 598.3 | 9.4413 | -3.6949 | 0.1903 | 1827.30 |
| 598.7 | 9.4733 | -3.5252 | 0.3129 | 1827.27 |
| 599.0 | 9.4622 | -3.6809 | 0.7523 | 1827.24 |
| 599.3 | 9.5319 | -3.6332 | 0.6999 | 1827.21 |
| 599.7 | 9.5062 | -3.6539 | 0.0373 | 1827.05 |
| 600.0 | 9.4003 | -3.7752 | -0.3541 | 1826.88 |
| 600.3 | 9.2961 | -3.8129 | -0.4977 | 1826.63 |
| 600.7 | 9.3646 | -3.5932 | -0.1001 | 1826.54 |
| 601.0 | 9.5633 | -3.7639 | -0.7127 | 1826.29 |
| 601.3 | | | | |
| 601.7 | 9.4788 | -3.4692 | -0.4491 | 1826.23 |
| 602.0 | 9.5220 | -3.3539 | -0.4717 | 1826.19 |
| 602.3 | 9.5265 | -3.3892 | -0.6091 | 1826.16 |
| 602.7 | 9.5889 | -3.7379 | -1.1657 | 1826.13 |
| 603.0 | 9.3900 | -3.7202 | -0.9931 | 1825.63 |
| 603.3 | 9.4065 | | | 1825.52 |
| 603.7 | 9.5295 | -3.9612 | -1.7881 | 1825.42 |
| 604.0 | 9.4737 | -3.7039 | -1.1857 | 1825.31 |
| 604.3 | 9.5782 | -3.4962 | -1.1051 | 1825.21 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 604.7 | 9.4414 | -3.5259 | -1.3967 | 1825.17 |
| 605.0 | 9.5078 | -3.6202 | -0.9661 | 1825.13 |
| 605.3 | 9.4118 | -3.7239 | -0.5927 | 1825.03 |
| 605.7 | 9.3951 | -3.7789 | -0.5291 | 1824.92 |
| 606.0 | 9.3803 | -3.8416 | -0.6146 | 1824.81 |
| 606.3 | 9.3055 | -3.7712 | -0.8391 | 1824.71 |
| 606.7 | 9.4364 | -3.6759 | -0.5697 | 1824.67 |
| 607.0 | 9.3376 | -3.7032 | -0.7791 | 1824.63 |
| 607.3 | 9.3792 | -3.8999 | -0.7547 | 1824.55 |
| 607.7 | 9.4458 | -3.8442 | -0.4301 | 1824.46 |
| 608.0 | 9.4436 | -3.6319 | -0.2277 | 1824.38 |
| 608.3 | 9.4262 | -3.7889 | -0.2129 | 1824.29 |
| 608.7 | 9.4516 | -3.4839 | 0.3193 | 1824.21 |
| 609.0 | 9.4155 | -3.8602 | -0.3341 | 1824.10 |
| 609.3 | 9.4117 | -3.7997 | -0.5048 | 1823.99 |
| 609.7 | 9.3297 | -4.2352 | -1.2761 | 1823.88 |
| 610.0 | 9.3157 | -4.1109 | -1.2997 | 1823.83 |
| **Bottom Piece Seen in Fig. 2.1** | | | | |
| 607.7 | 9.4807 | -3.8412 | -1.6721 | 1824.46 |
| 608.0 | 9.4845 | -3.5459 | -1.0337 | 1824.38 |
| 608.3 | 9.4738 | -3.1232 | -0.6541 | 1824.29 |
| 608.7 | 9.6035 | -3.3009 | -1.1827 | 1824.21 |
| 609.0 | 9.4957 | -3.5247 | -1.0540 | 1824.10 |
| 609.3 | 9.4033 | -3.8104 | -1.7897 | 1823.99 |
| 609.7 | 9.2766 | -3.9752 | -1.9151 | 1823.88 |
| 610.0 | 9.1697 | -4.0909 | -1.3527 | 1823.83 |
| 610.3 | 9.1858 | -4.0422 | -1.6031 | 1823.78 |
| 610.7 | 9.1307 | -4.2319 | -1.7887 | 1823.73 |
| 611.0 | 9.1114 | -4.2442 | -2.0741 | 1823.68 |
| 611.3 | 9.0751 | -4.1059 | -1.6647 | 1823.63 |
| 611.7 | 9.2692 | -3.9862 | -1.5551 | 1823.55 |
| 612.0 | 9.3696 | -3.6219 | -1.1477 | 1823.46 |
| 612.3 | 9.4198 | -3.7382 | -1.3101 | 1823.38 |
| 612.7 | 9.5788 | -3.5719 | -1.1797 | 1823.30 |
| 613.0 | 9.6132 | -3.3487 | -1.6348 | 1823.21 |
| 613.3 | 9.4069 | -3.6439 | -1.8157 | 1822.88 |
| 613.7 | 9.3004 | -4.0682 | -1.8011 | 1822.63 |
| 614.0 | 9.3473 | -3.6459 | -2.2367 | 1822.59 |
| 614.3 | 9.4175 | -3.5722 | -0.9771 | 1822.55 |
| 614.7 | 9.3829 | -3.2779 | -0.9317 | 1822.50 |
| 615.0 | 9.4134 | | | 1822.46 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 615.3 | 9.5467 | -3.2949 | -0.8577 | 1822.21 |
| 615.7 | 9.4329 | -3.5792 | -1.1771 | 1822.02 |
| 616.0 | 9.4712 | -3.4882 | -1.6461 | 1821.82 |
| 616.3 | 9.1488 | -4.0312 | -1.7461 | 1821.63 |
| 616.7 | 9.1793 | -4.1549 | -1.3947 | 1821.59 |
| 617.0 | 9.2208 | -3.7688 | -0.3221 | 1821.54 |
| 617.3 | 9.4092 | -4.0609 | -1.3517 | 1821.50 |
| 617.7 | 9.3204 | -3.3366 | -1.2947 | 1821.46 |
| 618.0 | 9.5971 | -3.2490 | -0.6648 | 1821.33 |
| 618.3 | 9.6794 | -3.0638 | -0.5006 | 1821.21 |
| 618.7 | 9.5335 | -2.9296 | -0.6029 | 1821.15 |
| 619.0 | 9.4645 | -3.3442 | -0.8701 | 1821.08 |
| 619.3 | 9.4543 | -3.4939 | -1.4257 | 1821.02 |
| 619.7 | 9.3972 | -3.4792 | -1.7041 | 1820.96 |
| 620.0 | 9.2777 | -3.4759 | -1.8917 | 1820.85 |
| 620.3 | 9.0680 | -4.3562 | -2.3511 | 1820.74 |
| 620.7 | 9.0147 | -4.3079 | -2.1467 | 1820.63 |
| 621.0 | 9.0810 | -4.3052 | -2.4201 | 1820.58 |
| 621.3 | 9.0849 | -4.1379 | -2.1567 | 1820.54 |
| 621.7 | 9.4394 | -3.7272 | -1.4461 | 1820.50 |
| 622.0 | 9.2719 | -3.5189 | -1.0127 | 1820.46 |
| 622.3 | 9.5330 | -3.5582 | -0.9951 | 1820.21 |
| 622.7 | 9.4589 | -3.4389 | -1.3177 | 1820.10 |
| 623.0 | 9.4794 | -3.5182 | -1.5261 | 1819.99 |
| 623.3 | 9.3471 | -4.2309 | -1.5037 | 1819.88 |
| 623.7 | 9.2991 | -4.0222 | -1.8951 | 1819.76 |
| 624.0 | 9.1961 | -3.9519 | -1.9447 | 1819.63 |
| 624.3 | 9.2008 | -4.1102 | -2.0601 | 1819.57 |
| 624.7 | 9.3630 | -3.7229 | -1.0977 | 1819.52 |
| 625.0 | 9.3553 | -3.4042 | -0.5511 | 1819.46 |
| 625.3 | 9.3982 | -3.3679 | -1.0887 | 1819.41 |
| 625.7 | 9.4491 | -3.4182 | -1.5421 | 1819.36 |
| 626.0 | 9.5058 | -4.1029 | -1.7615 | 1819.31 |
| 626.3 | 9.5116 | -3.2802 | -2.3671 | 1819.26 |
| 626.7 | 9.6270 | -2.7699 | -0.3567 | 1819.21 |
| 627.0 | 9.5063 | -3.9152 | -0.5111 | 1819.04 |
| 627.3 | 9.3967 | -3.8994 | -0.3776 | 1818.88 |
| 627.7 | 9.1385 | -4.2122 | -0.9671 | 1818.63 |
| 628.0 | 9.4778 | -3.1479 | -0.4807 | 1818.54 |
| 628.3 | 9.3601 | -3.7632 | -1.0671 | 1818.46 |
| 628.7 | 9.3846 | -3.7049 | -1.1367 | 1818.38 |
| 629.0 | 9.5345 | -3.4122 | -1.2011 | 1818.29 |
| 629.3 | 9.5539 | -3.3737 | -1.3430 | 1818.21 |
| 629.7 | 9.2626 | -4.1582 | -2.2451 | 1817.71 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 630.0 | 9.2408 | -4.3279 | -2.5637 | 1817.67 |
| 630.3 | 9.2078 | -4.3452 | -2.6291 | 1817.63 |
| 630.7 | 9.2338 | -3.3868 | -1.6314 | 1817.60 |
| 631.0 | 9.2994 | -3.8920 | -1.7129 | 1817.57 |
| 631.3 | 9.2934 | -3.9939 | -1.4727 | 1817.54 |
| 631.7 | 9.3798 | | | 1817.43 |
| 632.0 | 9.4536 | -3.5269 | -1.0757 | 1817.32 |
| 632.3 | 9.4760 | | | 1817.21 |
| 632.7 | 9.4693 | -3.3299 | -0.9707 | 1817.13 |
| 633.0 | 9.3722 | -3.4372 | -1.7641 | 1817.04 |
| 633.3 | 9.3249 | -4.1449 | -1.5397 | 1816.96 |
| 633.7 | 9.1799 | -4.0442 | -1.7041 | 1816.88 |
| 634.0 | 9.0905 | -4.2919 | -1.4607 | 1816.80 |
| 634.3 | 9.0881 | -4.4802 | -1.8821 | 1816.71 |
| 634.7 | 9.0470 | -4.3619 | -1.7387 | 1816.63 |
| 635.0 | 9.0467 | | | 1816.58 |
| 635.3 | 9.3828 | -4.5019 | -1.2357 | 1816.54 |
| 635.7 | 9.2305 | | | 1816.49 |
| 636.0 | 9.3528 | -3.8019 | -1.0017 | 1816.44 |
| 636.3 | 9.3792 | | | 1816.40 |
| 636.7 | 9.5020 | -3.3529 | -0.7377 | 1816.35 |
| 637.0 | 9.5001 | -3.6422 | -1.3231 | 1816.30 |
| 637.3 | 9.5651 | -3.4919 | -1.4947 | 1816.26 |
| 637.7 | 9.5791 | -3.4362 | -1.4471 | 1816.21 |
| 638.0 | 9.4863 | -2.9647 | -1.6502 | 1816.08 |
| 638.3 | 9.3609 | -4.1642 | -2.0521 | 1815.96 |
| 638.7 | 9.1276 | -4.1099 | -2.3747 | 1815.88 |
| 639.0 | 9.2332 | -4.6032 | -1.9871 | 1815.79 |
| 639.3 | 9.0384 | -4.6499 | -1.8967 | 1815.71 |
| 639.7 | 8.9865 | -4.6102 | -1.7021 | 1815.63 |
| 640.0 | 9.2703 | -4.0779 | -0.4457 | 1815.60 |
| 640.3 | 9.1565 | -4.1948 | -1.2231 | 1815.57 |
| 640.7 | 9.1913 | -3.8849 | -1.0997 | 1815.54 |
| 641.0 | 9.3439 | -3.7442 | -0.6901 | 1815.43 |
| 641.3 | 9.4918 | -3.3789 | -1.0527 | 1815.32 |
| 641.7 | 9.5033 | -3.6012 | -1.3241 | 1815.21 |
| 642.0 | 9.4092 | -3.6509 | -1.6697 | 1815.00 |
| 642.3 | 9.2147 | -4.1852 | -1.5961 | 1814.79 |
| 642.7 | 9.2072 | -4.5059 | -1.9177 | 1814.74 |
| 643.0 | 9.0834 | -4.1862 | -1.4091 | 1814.68 |
| 643.3 | 9.0975 | -4.3759 | -1.2207 | 1814.63 |
| 643.7 | 9.0968 | -4.4812 | -1.3671 | 1814.60 |
| 644.0 | 9.1675 | -3.9785 | -1.0079 | 1814.57 |
| 644.3 | 9.2250 | -3.9742 | -1.3861 | 1814.54 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 644.7 | 9.4049 | -3.3859 | -0.7424 | 1814.38 |
| 645.0 | 9.5368 | -3.1512 | -0.1201 | 1814.21 |
| 645.3 | 9.4612 | -3.1979 | -0.5427 | 1814.15 |
| 645.7 | 9.4591 | -3.5572 | -0.7281 | 1814.10 |
| 646.0 | 9.4815 | -3.2939 | -1.0927 | 1814.04 |
| 646.3 | 9.2772 | | | 1813.79 |
| 646.7 | 9.1721 | -4.0579 | -1.2077 | 1813.71 |
| 647.0 | 9.2018 | -3.9522 | -0.9411 | 1813.65 |
| 647.3 | 9.2811 | -3.7719 | -0.2417 | 1813.60 |
| 647.7 | 9.1743 | -3.7282 | -1.1151 | 1813.54 |
| 648.0 | 9.3391 | -3.5479 | -0.7407 | 1813.46 |
| 648.3 | 9.3520 | -3.3892 | -0.4101 | 1813.38 |
| 648.7 | 9.4680 | -3.2049 | -0.4527 | 1813.30 |
| 649.0 | 9.5517 | -3.1284 | -0.5548 | 1813.21 |
| 649.3 | 9.4840 | -2.9959 | -0.4947 | 1813.10 |
| 649.7 | 9.4581 | -3.7602 | -0.8661 | 1812.99 |
| 650.0 | 9.3233 | -3.7019 | -1.0577 | 1812.88 |
| 650.3 | 9.3743 | -3.9012 | -0.5461 | 1812.76 |
| 650.7 | 9.1917 | | | 1812.63 |
| 651.0 | 9.3275 | -3.4982 | -0.4511 | 1812.46 |
| 651.3 | 9.4527 | -3.2967 | -0.8118 | 1812.38 |
| 651.7 | 9.4067 | -2.9683 | -1.4144 | 1812.30 |
| 652.0 | 9.5651 | -3.3409 | -1.2617 | 1812.21 |
| 652.3 | 9.3407 | -3.4692 | -1.3501 | 1811.88 |
| 652.7 | 9.2188 | -3.9453 | -2.0880 | 1811.79 |
| 653.0 | 9.4159 | -4.0818 | -2.2990 | 1811.71 |
| 653.3 | 9.0867 | -4.5359 | -2.3297 | 1811.63 |
| 653.7 | 9.0842 | -4.3512 | -1.7761 | 1811.59 |
| 654.0 | 9.1594 | -4.1739 | -1.4357 | 1811.54 |
| 654.3 | 9.2839 | -3.8242 | -1.1261 | 1811.50 |
| 654.7 | 9.2506 | -3.8706 | -1.0437 | 1811.46 |
| 655.0 | 9.4775 | -3.0072 | -0.0321 | 1811.33 |
| 655.3 | 9.5553 | -3.2169 | -0.8377 | 1811.21 |
| 655.7 | 9.4988 | -3.5632 | -0.9941 | 1811.05 |
| 656.0 | 9.3818 | -3.7939 | -1.5947 | 1810.88 |
| 656.3 | 9.2450 | -3.4402 | -1.5891 | 1810.82 |
| 656.7 | 9.2081 | -4.2059 | -1.7107 | 1810.76 |
| 657.0 | 9.0809 | -4.4962 | -1.7771 | 1810.69 |
| 657.3 | 9.0204 | -4.5419 | -1.6817 | 1810.63 |
| 657.7 | 9.0812 | -4.2782 | -1.8011 | 1810.59 |
| 658.0 | 9.1079 | -4.4139 | -1.5907 | 1810.54 |
| 658.3 | 9.1905 | -4.0012 | -1.4301 | 1810.50 |
| 658.7 | 9.2992 | -3.6283 | -0.9579 | 1810.46 |
| 659.0 | 9.4812 | -3.1562 | -0.6431 | 1810.33 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 659.3 | 9.4704 | -3.4799 | -1.4317 | 1810.21 |
| 659.7 | 9.4723 | -3.4092 | -1.7591 | 1810.10 |
| 660.0 | 9.3413 | -3.3309 | -2.0597 | 1809.99 |
| 660.3 | 9.2570 | -3.9394 | -2.4087 | 1809.88 |
| 660.7 | 9.1192 | -4.2609 | -2.4567 | 1809.82 |
| 661.0 | 9.0711 | -4.5512 | -2.3201 | 1809.77 |
| 661.3 | 8.9840 | -4.4219 | -2.2497 | 1809.71 |
| 661.7 | 9.0945 | -3.9542 | -1.1545 | 1809.67 |
| 662.0 | 9.0177 | -4.5199 | -1.4367 | 1809.63 |
| 662.3 | 9.0479 | -4.4452 | -1.5761 | 1809.55 |
| 662.7 | 9.2365 | -3.7239 | -0.9027 | 1809.47 |
| 663.0 | 9.3587 | -3.2812 | -0.3631 | 1809.38 |
| 663.3 | 9.5259 | -3.3099 | -0.6517 | 1809.30 |
| 663.7 | 9.6184 | -3.0762 | -0.4901 | 1809.21 |
| 664.0 | 9.4926 | -3.3843 | -0.9231 | 1809.08 |
| 664.3 | 9.3606 | -3.6662 | -1.2721 | 1808.96 |
| 664.7 | 9.2648 | -4.0319 | -1.3167 | 1808.88 |
| 665.0 | 9.2329 | -4.3868 | -2.0982 | 1808.79 |
| 665.3 | 9.1286 | -4.1529 | -0.8787 | 1808.71 |
| 665.7 | 9.1431 | -4.1332 | -0.5111 | 1808.63 |
| 666.0 | 9.2456 | | -0.4745 | 1808.54 |
| 666.3 | 9.3349 | -3.4762 | -0.2871 | 1808.46 |
| 666.7 | 9.4933 | -3.5119 | -0.5887 | 1808.34 |
| 667.0 | 9.5860 | -3.2972 | -0.5811 | 1808.21 |
| 667.3 | 9.5761 | | | 1808.11 |
| 667.7 | 9.5043 | -3.3792 | -1.3411 | 1808.00 |
| 668.0 | 9.4084 | -3.7149 | -1.3587 | 1807.89 |
| 668.3 | 9.2601 | -3.8470 | -1.7591 | 1807.79 |
| 668.7 | 9.1008 | -4.5119 | -1.9177 | 1807.71 |
| 669.0 | 9.0891 | -4.3432 | -1.9561 | 1807.63 |
| 669.3 | 9.0843 | -4.3329 | -1.1557 | 1807.59 |
| 669.7 | 9.1440 | -4.2452 | -0.9201 | 1807.55 |
| 670.0 | 9.1837 | -3.9026 | -1.0065 | 1807.50 |
| 670.3 | 9.3099 | -3.7242 | -0.5771 | 1807.46 |
| 670.7 | 9.3751 | | | 1807.38 |
| 671.0 | | | | 1807.29 |
| 671.3 | 9.5048 | -3.2652 | -0.9001 | 1807.21 |
| 671.7 | 9.4325 | -3.6556 | -0.7825 | 1807.00 |
| 672.0 | 9.2401 | -3.8002 | -1.3451 | 1806.79 |
| 672.3 | 9.2374 | -4.0740 | -1.3291 | 1806.75 |
| 672.7 | 9.1875 | -4.3502 | -1.4171 | 1806.71 |
| 673.0 | 9.1958 | -3.9229 | -0.4837 | 1806.67 |
| 673.3 | 9.1088 | -3.7293 | -1.1641 | 1806.63 |
| 673.7 | | -3.7719 | -0.7387 | 1806.51 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 674.0 | 9.4600 | -3.1256 | -0.0547 | 1806.38 |
| 674.3 | 9.3903 | -3.3569 | -0.7367 | 1806.38 |
| 674.7 | 9.6177 | -3.1032 | -0.6821 | 1806.21 |
| 675.0 | 9.5443 | -3.1029 | -1.0017 | 1806.13 |
| 675.3 | 9.4882 | -3.2362 | -1.4571 | 1806.04 |
| 675.7 | 9.3930 | -3.4942 | -1.6875 | 1805.96 |
| 676.0 | 9.2206 | -4.1002 | -1.8421 | 1805.88 |
| 676.3 | 9.2061 | -4.0659 | -1.6127 | 1805.80 |
| 676.7 | 9.1624 | -3.9472 | -0.9151 | 1805.71 |
| 677.0 | 9.1258 | -4.2519 | -1.3002 | 1805.63 |
| 677.3 | 9.1905 | -4.0232 | -1.0481 | 1805.53 |
| 677.7 | 9.4399 | -3.6120 | -0.9747 | 1805.42 |
| 678.0 | 9.4839 | -3.1759 | -0.9611 | 1805.31 |
| 678.3 | 9.5112 | -3.0515 | -0.8457 | 1805.21 |
| | | | | |
| **Track Shift** | | | | |
| 676.7 | 9.0720 | -4.0962 | -1.4161 | 1805.71 |
| 677.0 | 9.0445 | -4.2399 | -2.0417 | 1805.63 |
| 677.3 | 9.1431 | -3.9922 | -1.6111 | 1805.53 |
| 677.7 | 9.3740 | -3.5228 | -1.6943 | 1805.42 |
| 678.0 | 9.4835 | -3.0502 | -1.4221 | 1805.31 |
| 678.3 | | | | 1805.21 |
| 678.7 | 9.2716 | -3.9649 | -1.8677 | 1804.96 |
| 679.0 | 9.1059 | -4.1972 | -1.9221 | 1804.71 |
| 679.3 | 9.0913 | -4.3839 | -1.6457 | 1804.68 |
| 679.7 | 9.0507 | -4.5792 | -1.8511 | 1804.66 |
| 680.0 | 9.0006 | -4.7369 | -1.4127 | 1804.63 |
| 680.3 | 9.0999 | -4.0542 | -1.1831 | 1804.59 |
| 680.7 | 9.1117 | -4.2981 | -1.4804 | 1804.54 |
| 681.0 | 9.3217 | -3.7162 | -1.5801 | 1804.37 |
| 681.3 | 9.4609 | -3.3998 | -1.4608 | 1804.21 |
| 681.7 | 9.4343 | -3.0823 | -1.2706 | 1804.16 |
| 682.0 | 9.4210 | -3.2859 | -1.1417 | 1804.10 |
| 682.3 | 9.3971 | -3.3682 | -1.4591 | 1804.05 |
| 682.7 | 9.4136 | -3.4019 | -1.3937 | 1803.99 |
| 683.0 | 9.3710 | -3.6452 | -1.4371 | 1803.93 |
| 683.3 | 9.1954 | -4.0729 | -0.9287 | 1803.88 |
| 683.7 | 9.2707 | -4.0312 | -1.0181 | 1803.82 |
| 684.0 | 9.1765 | -3.9499 | -0.9697 | 1803.75 |
| 684.3 | 9.2054 | -4.2162 | -1.3191 | 1803.69 |
| 684.7 | 9.1268 | -4.1919 | -1.0847 | 1803.63 |
| 685.0 | 9.1997 | -3.9952 | -1.1721 | 1803.54 |
| 685.3 | 9.3800 | -3.7679 | -0.9917 | 1803.43 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 685.7 | 9.5012 | -3.4022 | -0.8371 | 1803.32 |
| 686.0 | 9.5613 | -3.0799 | -0.5977 | 1803.21 |
| 686.3 | 9.5528 | -3.2272 | -1.0621 | 1803.17 |
| 686.7 | 9.5423 | -3.2339 | -1.0637 | 1803.13 |
| 687.0 | 9.3319 | -3.4092 | -1.4041 | 1803.04 |
| 687.3 | 9.3336 | -3.8489 | -1.3367 | 1802.96 |
| 687.7 | 9.1552 | -4.2612 | -1.0831 | 1802.63 |
| 688.0 | 9.1883 | -4.1919 | -1.2727 | 1802.59 |
| 688.3 | 9.1816 | -4.0082 | -0.9421 | 1802.55 |
| 688.7 | 9.1888 | -4.3649 | -0.9557 | 1802.50 |
| 689.0 | 9.2599 | -3.5774 | -1.5198 | 1802.46 |
| 689.3 | 9.3822 | -3.2599 | -0.7837 | 1802.34 |
| 689.7 | 9.4513 | -3.4512 | -0.9711 | 1802.21 |
| 690.0 | 9.3795 | -3.4639 | -1.3017 | 1802.10 |
| 690.3 | 9.3726 | -3.4302 | -1.5771 | 1802.00 |
| 690.7 | 9.3026 | -3.5119 | -1.3947 | 1801.90 |
| 691.0 | 9.1640 | -3.6622 | -1.4171 | 1801.79 |
| 691.3 | 9.0759 | -4.3653 | -0.7881 | 1801.74 |
| 691.7 | 9.0577 | -4.3872 | -1.0194 | 1801.68 |
| 692.0 | 8.9757 | -4.4150 | -1.6452 | 1801.63 |
| 692.3 | 9.1522 | -4.2322 | -1.1601 | 1801.59 |
| 692.7 | 9.0115 | -4.3299 | -1.5877 | 1801.54 |
| 693.0 | 9.3311 | -3.6369 | -1.3577 | 1801.46 |
| 693.3 | 9.4009 | -4.1163 | -1.4187 | 1801.38 |
| 693.7 | 9.3588 | -3.5532 | -1.2601 | 1801.29 |
| 694.0 | 9.4568 | -3.6259 | -1.3707 | 1801.21 |
| 694.3 | 9.4454 | -3.2832 | -1.3541 | 1801.05 |
| 694.7 | 9.2972 | -3.6269 | -1.4287 | 1800.88 |
| 695.0 | 9.2204 | -3.7402 | -1.2971 | 1800.75 |
| 695.3 | 9.1864 | -4.0629 | -0.6437 | 1800.63 |
| 695.7 | 9.2392 | -3.9752 | -0.2721 | 1800.55 |
| 696.0 | 9.2940 | -3.9209 | -0.9417 | 1800.46 |
| 696.3 | 9.3937 | -3.6572 | -1.1801 | 1800.38 |
| 696.7 | 9.3663 | -3.5699 | -1.0687 | 1800.30 |
| 697.0 | 9.4803 | -3.5182 | -1.1291 | 1800.21 |
| 697.3 | 9.3994 | -3.5589 | -1.3197 | 1800.15 |
| 697.7 | 9.4341 | -3.4142 | -1.0391 | 1800.10 |
| 698.0 | 9.4055 | -3.4439 | -1.5067 | 1800.04 |
| 698.3 | 9.2778 | -3.8602 | -2.0131 | 1799.93 |
| 698.7 | 9.1870 | -3.8899 | -1.1467 | 1799.82 |
| 699.0 | 9.1722 | -3.9472 | -1.7401 | 1799.71 |
| 699.3 | 9.2212 | | | 1799.69 |
| 699.7 | 9.2236 | -3.9242 | -0.4631 | 1799.67 |
| 700.0 | 9.2566 | -4.1439 | -0.6567 | 1799.65 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 700.3 | 9.1373 | -4.0482 | -0.8421 | 1799.63 |
| 700.7 | 9.4834 | -3.4659 | -0.2707 | 1799.29 |
| 701.0 | 9.4743 | -3.2832 | -0.1841 | 1799.25 |
| 701.3 | 9.5232 | -3.1979 | 0.0353 | 1799.21 |
| 701.7 | 9.3894 | -3.3482 | -0.8281 | 1799.05 |
| 702.0 | 9.2803 | -3.9349 | -0.8367 | 1798.88 |
| 702.3 | 9.1517 | -4.0612 | -0.9321 | 1798.80 |
| 702.7 | 9.1079 | -4.1329 | -1.3827 | 1798.72 |
| 703.0 | 9.0306 | -4.2592 | -1.3351 | 1798.63 |
| 703.3 | 9.0329 | -4.1811 | -1.2464 | 1798.57 |
| 703.7 | 9.2060 | -3.7838 | -1.0642 | 1798.52 |
| 704.0 | 9.2783 | -3.6999 | -0.9727 | 1798.46 |
| 704.3 | 9.5140 | -3.4042 | -0.8611 | 1798.38 |
| 704.7 | 9.5791 | -3.1409 | -0.5697 | 1798.30 |
| 705.0 | 9.5961 | -2.8352 | -0.5981 | 1798.21 |
| 705.3 | 9.5032 | -3.4839 | -0.9277 | 1798.13 |
| 705.7 | 9.4024 | -3.5082 | -0.9481 | 1798.05 |
| 706.0 | 9.4950 | -3.8269 | -0.8537 | 1797.96 |
| 706.3 | 9.2989 | -3.6082 | -1.1161 | 1797.88 |
| 706.7 | 9.3739 | -4.2209 | -1.4987 | 1797.80 |
| 707.0 | 9.0658 | -4.1322 | -1.4291 | 1797.71 |
| 707.3 | 9.0515 | -4.3293 | -1.2479 | 1797.63 |
| 707.7 | 9.1131 | -3.5722 | -1.0771 | 1797.46 |
| 708.0 | 9.4144 | -3.3028 | -0.5810 | 1797.29 |
| 708.3 | 9.4861 | -3.3772 | -0.6951 | 1797.25 |
| 708.7 | 9.4996 | -3.2859 | -0.5507 | 1797.21 |
| 709.0 | 9.4249 | -3.2922 | -0.2531 | 1797.00 |
| 709.3 | 9.2265 | -3.8079 | -0.9787 | 1796.79 |
| 709.7 | 9.2084 | -3.7082 | -1.3241 | 1796.74 |
| 710.0 | 9.2147 | -3.9009 | -1.5057 | 1796.68 |
| 710.3 | 9.0764 | -3.8042 | -2.0891 | 1796.63 |
| 710.7 | 9.1989 | -3.9639 | -1.3807 | 1796.55 |
| 711.0 | 9.2810 | -3.5842 | -0.7111 | 1796.46 |
| 711.3 | 9.4552 | -3.4069 | -0.4217 | 1796.34 |
| 711.7 | 9.5744 | -3.1332 | -0.1981 | 1796.21 |
| 712.0 | 9.4663 | -3.1569 | -0.1497 | 1796.10 |
| 712.3 | 9.4783 | -3.3633 | -0.7449 | 1796.00 |
| 712.7 | 9.3644 | -3.5299 | -1.6597 | 1795.90 |
| 713.0 | 9.2972 | -3.3942 | -1.9161 | 1795.79 |
| 713.3 | 9.1932 | -3.8049 | -1.8137 | 1795.63 |
| 713.7 | 9.2902 | -4.0172 | -0.9571 | 1795.61 |
| 714.0 | 9.2114 | -4.0289 | -0.5987 | 1795.59 |
| 714.3 | 9.2647 | -3.8402 | -0.4341 | 1795.56 |
| 714.7 | 9.2464 | -3.2859 | -0.5557 | 1795.54 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 715.0 | 9.3258 | -3.2772 | -0.7101 | 1795.46 |
| 715.3 | 9.4010 | -3.0889 | -0.8237 | 1795.34 |
| 715.7 | 9.4201 | -3.1912 | -0.9001 | 1795.21 |
| 716.0 | 9.4315 | -3.1322 | -0.7612 | 1795.10 |
| 716.3 | 9.3379 | -3.7712 | -1.4221 | 1795.00 |
| 716.7 | 9.3397 | -3.6497 | -0.9945 | 1794.90 |
| 717.0 | 9.2017 | -3.9390 | -1.4735 | 1794.79 |
| 717.3 | 9.2505 | -3.6759 | -0.8557 | 1794.74 |
| 717.7 | 9.0974 | -3.9685 | -1.2031 | 1794.68 |
| 718.0 | 9.0562 | -4.0859 | -1.2247 | 1794.63 |
| 718.3 | 9.1429 | -3.7132 | -1.3321 | 1794.55 |
| 718.7 | 9.1980 | -3.6463 | -1.0485 | 1794.46 |
| 719.0 | 9.4326 | -3.1812 | -0.9121 | 1794.33 |
| 719.3 | 9.5096 | -3.1359 | -0.8727 | 1794.21 |
| 719.7 | 9.4276 | -3.0532 | -0.7041 | 1794.10 |
| 720.0 | 9.4149 | -3.2419 | -1.4177 | 1793.99 |
| 720.3 | 9.2237 | -3.5212 | -1.4489 | 1793.88 |
| 720.7 | 9.2669 | -3.7289 | -0.8807 | 1793.82 |
| 721.0 | 9.4211 | -3.9962 | -1.5721 | 1793.75 |
| 721.3 | 9.0716 | -3.9320 | -1.8678 | 1793.69 |
| 721.7 | 9.0153 | -4.2602 | -1.7721 | 1793.63 |
| 722.0 | 9.2313 | -3.6649 | -1.0537 | 1793.46 |
| 722.3 | 9.2463 | -3.6292 | -0.9001 | 1793.38 |
| 722.7 | 9.3698 | -3.4619 | -0.7367 | 1793.29 |
| 723.0 | 9.3506 | -3.9480 | -1.3680 | 1793.27 |
| 723.3 | 9.4174 | -3.2229 | -0.9867 | 1793.26 |
| 723.7 | 9.3788 | -3.2861 | -1.2909 | 1793.24 |
| 724.0 | 9.3311 | -3.4009 | -1.6947 | 1793.23 |
| 724.3 | 9.4922 | -3.4442 | -1.6041 | 1793.21 |
| 724.7 | 9.2681 | -3.6009 | -1.9117 | 1792.96 |
| 725.0 | 9.1891 | -4.0252 | -1.2231 | 1792.83 |
| 725.3 | 8.9819 | -4.1799 | -2.2837 | 1792.71 |
| 725.7 | 8.9817 | -4.0982 | -2.1261 | 1792.63 |
| 726.0 | 9.1858 | -3.4209 | -1.2917 | 1792.46 |
| 726.3 | 9.4803 | -3.0962 | -1.5261 | 1792.13 |
| 726.7 | 9.4031 | -3.1291 | -1.6976 | 1792.08 |
| 727.0 | 9.3114 | -3.1832 | -1.1221 | 1792.03 |
| 727.3 | 9.3134 | -3.4879 | -1.7707 | 1791.98 |
| 727.7 | 9.2828 | -3.4602 | -1.8881 | 1791.93 |
| 728.0 | 9.2692 | -3.7539 | -1.9187 | 1791.88 |
| 728.3 | 9.6003 | -3.7712 | -1.5571 | 1791.82 |
| 728.7 | 9.1655 | -4.1869 | -1.4562 | 1791.76 |
| 729.0 | 9.0614 | -4.0182 | -1.4251 | 1791.69 |
| 729.3 | 8.9972 | -3.9324 | -1.3160 | 1791.63 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 729.7 | 9.1435 | -4.0820 | -1.3872 | 1791.59 |
| 730.0 | 9.1469 | -3.8406 | -1.5164 | 1791.54 |
| 730.3 | 9.3114 | -3.4922 | -0.9401 | 1791.38 |
| 730.7 | 9.5104 | -3.1019 | -0.9217 | 1791.21 |
| 731.0 | 9.4776 | -3.1882 | -0.7441 | 1791.19 |
| 731.3 | 9.4576 | -3.2209 | -1.0137 | 1791.17 |
| 731.7 | 9.4299 | -3.2582 | -0.5991 | 1791.15 |
| 732.0 | 9.4818 | -3.1890 | -0.1981 | 1791.13 |
| 732.3 | 9.3818 | -3.4053 | -1.1787 | 1791.01 |
| 732.7 | 9.3078 | -3.5922 | 0.0251 | 1790.88 |
| 733.0 | 9.1562 | -4.4442 | -1.0371 | 1790.80 |
| 733.3 | 9.2298 | -3.9579 | -1.1967 | 1790.71 |
| 733.7 | 9.0049 | -4.4272 | -1.8701 | 1790.63 |
| 734.0 | 9.1024 | -4.1411 | -1.3101 | 1790.55 |
| 734.3 | 9.3305 | -3.6762 | -0.8811 | 1790.46 |
| 734.7 | 9.3776 | -3.4929 | -0.0467 | 1790.38 |
| 735.0 | 9.2837 | -3.6802 | -0.7891 | 1790.34 |
| 735.3 | 9.4891 | -3.3479 | -0.0617 | 1790.30 |
| 735.7 | 9.4053 | -3.4529 | -0.9187 | 1790.25 |
| 736.0 | 9.5150 | -3.4742 | -1.0211 | 1790.21 |
| 736.3 | 9.4891 | -3.1629 | -1.0427 | 1790.17 |
| 736.7 | 9.5272 | | -1.2199 | 1790.13 |
| 737.0 | 9.4295 | -3.6129 | -1.4647 | 1790.07 |
| 737.3 | 9.3920 | -3.4744 | -1.3646 | 1790.02 |
| 737.7 | 9.3545 | -3.6308 | -1.1400 | 1789.96 |
| 738.0 | 9.2864 | -3.8882 | -1.9031 | 1789.85 |
| 738.3 | 9.1662 | -4.0019 | -1.7597 | 1789.74 |
| 738.7 | 9.1467 | -4.0521 | -1.6526 | 1789.63 |
| 739.0 | 9.4354 | -3.7957 | -1.4478 | 1789.21 |
| 739.3 | 9.3859 | | | 1789.04 |
| 739.7 | 9.0896 | -4.1819 | -1.9157 | 1788.63 |
| 740.0 | 9.1738 | -3.8422 | -1.7991 | 1788.54 |
| 740.3 | 9.3002 | -3.6716 | -1.7687 | 1788.46 |
| 740.7 | 9.3303 | -3.7754 | -1.4202 | 1788.29 |
| 741.0 | 9.4224 | -3.3629 | -1.3067 | 1788.21 |
| 741.3 | 9.3999 | -3.5812 | -1.4071 | 1788.14 |
| 741.7 | 9.2291 | -3.6999 | -1.4627 | 1788.08 |
| 742.0 | 9.2896 | -3.7202 | -1.5911 | 1788.01 |
| 742.3 | 9.3764 | -3.9299 | -1.6477 | 1787.95 |
| 742.7 | 9.2195 | -3.9072 | -2.2161 | 1787.88 |
| 743.0 | 9.1969 | -3.9699 | -2.3417 | 1787.75 |
| 743.3 | 9.0881 | -3.8062 | -1.5921 | 1787.63 |
| 743.7 | 9.3148 | -3.4372 | -1.0657 | 1787.46 |
| 744.0 | 9.4412 | -3.2072 | -0.6431 | 1787.29 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 744.3 | 9.3018 | -3.1729 | -1.1317 | 1787.26 |
| 744.7 | 9.3901 | -3.3421 | -0.9592 | 1787.23 |
| 745.0 | 9.3337 | -3.3126 | -0.7405 | 1787.19 |
| 745.3 | 9.3732 | -3.4052 | -0.4527 | 1787.16 |
| 745.7 | 9.4607 | | -0.4154 | 1787.13 |
| 746.0 | 9.3395 | -3.4512 | -1.1241 | 1786.88 |
| 746.3 | 9.1275 | -4.0091 | -1.4678 | 1786.63 |
| 746.7 | 9.1445 | -3.9936 | -1.5852 | 1786.59 |
| 747.0 | 9.2127 | -3.8822 | -1.7994 | 1786.55 |
| 747.3 | 9.2326 | -3.6132 | -1.7571 | 1786.51 |
| 747.7 | 9.1965 | -3.5959 | -1.5274 | 1786.46 |
| 748.0 | 9.3431 | -3.4512 | -1.2291 | 1786.42 |
| 748.3 | 9.3440 | -3.1569 | -1.2107 | 1786.38 |
| 748.7 | 9.5236 | -2.9722 | -0.5431 | 1786.21 |
| 749.0 | 9.4740 | -3.1529 | -0.2467 | 1786.10 |
| 749.3 | 9.4682 | -3.7362 | -0.9151 | 1785.99 |
| 749.7 | 9.2965 | -3.6242 | -1.0798 | 1785.88 |
| 750.0 | 9.3178 | -3.7032 | -1.5951 | 1785.80 |
| 750.3 | 9.1696 | -4.0129 | -1.4037 | 1785.71 |
| 750.7 | 9.1050 | -4.0402 | -1.1751 | 1785.63 |
| 751.0 | 9.2705 | -3.4809 | -1.0767 | 1785.57 |
| 751.3 | 9.3553 | -3.1817 | -1.0098 | 1785.51 |
| 751.7 | 9.3584 | -3.2189 | -1.1237 | 1785.44 |
| 752.0 | 9.3280 | -3.5122 | -1.1881 | 1785.38 |
| 752.3 | 9.3999 | -3.2719 | -0.2297 | 1785.30 |
| 752.7 | 9.4996 | -2.9442 | -0.8063 | 1785.21 |
| 753.0 | 9.4280 | -3.2986 | -0.4869 | 1785.04 |
| 753.3 | 9.3385 | -3.5123 | -0.4112 | 1784.88 |
| 753.7 | 9.2099 | -3.8109 | -0.5767 | 1784.63 |
| 754.0 | 9.2339 | -3.6392 | -1.2571 | 1784.58 |
| 754.3 | 9.2523 | -3.7289 | -1.2727 | 1784.53 |
| 754.7 | 9.1924 | -3.7112 | -0.8271 | 1784.48 |
| 755.0 | 9.2786 | -3.5519 | -0.6057 | 1784.43 |
| 755.3 | 9.3997 | -3.1682 | -0.4261 | 1784.38 |
| 755.7 | 9.4678 | -2.9629 | -0.6337 | 1784.33 |
| 756.0 | 9.4496 | -3.2302 | -0.9321 | 1784.28 |
| 756.3 | 9.4986 | -3.0819 | -0.1897 | 1784.23 |
| 756.7 | 9.4420 | -3.1782 | -0.5891 | 1784.18 |
| 757.0 | 9.5297 | -3.1499 | -1.1497 | 1784.13 |
| 757.3 | 9.4724 | -3.2685 | -1.0876 | 1783.96 |
| 757.7 | 9.3630 | -3.5649 | -0.4217 | 1783.63 |
| 758.0 | 9.3787 | -3.4762 | -0.2501 | 1783.59 |
| 758.3 | 9.4149 | -3.3032 | -0.7594 | 1783.55 |
| 758.7 | 9.3468 | -3.5862 | -0.9041 | 1783.51 |

| Depth from Top of Coral (mm) | Sr/Ca (mmol/mol) | Oxygen Isotope (permil) | Carbon Isotope (permil) | Date |
|---|---|---|---|---|
| 759.0 | 9.4077 | -3.3879 | -0.5047 | 1783.46 |
| 759.3 | 9.4946 | -3.2752 | 0.0219 | 1783.42 |
| 759.7 | 9.4347 | -3.0673 | -0.1894 | 1783.38 |
| 760.0 | 9.4626 | -3.1962 | 0.1219 | 1783.29 |
| 760.3 | 9.5541 | -2.8446 | 0.1219 | 1783.21 |
| 760.7 | 9.5216 | -2.9864 | -1.0364 | 1783.09 |
| 761.0 | 9.4108 | -3.3479 | -0.3397 | 1782.96 |
| 761.3 | 9.3221 | -3.5514 | -0.5441 | 1782.80 |
| 761.7 | 9.1873 | -3.4609 | -0.2087 | 1782.63 |
| 762.0 | 9.3114 | -3.4939 | -1.0325 | 1782.57 |
| 762.3 | 9.3502 | -3.4189 | -0.9861 | 1782.51 |
| 762.7 | 9.2360 | -3.5872 | -0.7151 | 1782.44 |
| 763.0 | 9.3754 | -3.2827 | -0.1817 | 1782.38 |
| 763.3 | 9.4245 | -3.1472 | 0.4419 | 1782.34 |
| 763.7 | 9.4217 | -3.1409 | -0.3507 | 1782.30 |
| 764.0 | 9.3622 | -3.2972 | -0.1981 | 1782.25 |
| 764.3 | 9.4837 | -3.2419 | -0.0487 | 1782.21 |
| 764.7 | 9.3796 | -3.2857 | -0.1375 | 1782.04 |
| 765.0 | 9.3320 | -3.7669 | -0.5747 | 1781.88 |
| 765.3 | 9.2647 | -3.8020 | -0.6986 | 1781.63 |
| 765.7 | 9.3171 | -3.6239 | -0.9897 | 1781.60 |
| 766.0 | 9.2610 | -3.3562 | -0.5981 | 1781.56 |
| 766.3 | 9.2689 | -3.6107 | -0.0350 | 1781.52 |
| 766.7 | 9.3320 | -3.6924 | -0.1785 | 1781.49 |
| 767.0 | 9.2110 | -3.7378 | -0.6406 | 1781.45 |
| 767.3 | 9.2729 | -3.4471 | -0.3204 | 1781.42 |
| 767.7 | 9.3355 | -3.4666 | -0.2798 | 1781.38 |
| 768.0 | 9.4345 | -3.0102 | -0.3961 | 1781.29 |
| 768.3 | 9.4492 | -3.1419 | -0.8827 | 1781.21 |

# Appendix E

# Low Resolution Record (Biennial) versus High Resolution Record (Sub-Annual) Sampling

## E.1 Introduction

In Chapter 2 of this work (Goodkin et al., 2005), the BB 001 single colony calibrations are applied to a biennially sampled 225-year long record (Low Resolution Record - LRR) from the same coral. As the research continued, the sub-annual resolution sampling was extended over the length of the entire 225-year long record (High Resolution Record - HRR). Noticeable differences are found between the two Sr/Ca records (Fig. E-1), particularly during the time of maximum (~1850) and minimum (~1960) values. Applying the same calibration to these records generates large SST differences. For instance, application of the mean-annual group reconstruction, defined in Chapter 3 of this work and developed using sub-annual resolution sampling, demonstrates a 3.0°C temperature change from 1850 to 1960 for the HRR and roughly half that or 1.5°C for the LRR. Differences are large in both the values of the Sr/Ca and the long-term patterns of the records. Calibrations in this thesis were developed using sub-annual resolution records, which have better constrained age models and allow for seasonally based calibrations. As a result, it is best to draw all climatic conclusions from the sub-annual resolution record and not the initially sampled biennial record. However, the reasons behind these differences should be investigated.

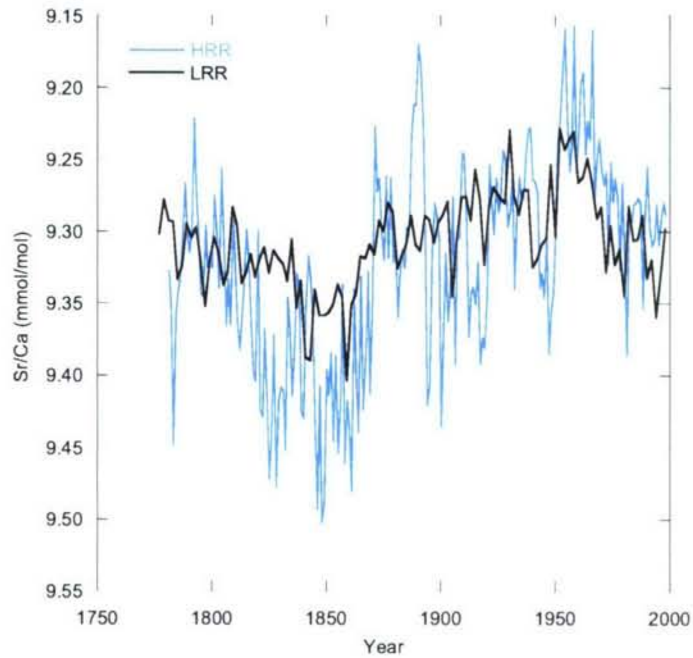


**Figure E.1:** Sr/Ca (mmol/mol) for the sub-annual resolution record (HRR-blue) and the biennial resolution record (LRR-black) from ~1780 to 1998. Large differences can be seen throughout the records and particularly during the time of maximum (~1850) and minimum (~1960) values.

## E.2 Complications of Biennial Sampling

Biennial samples were cut across theca, including two thecal walls and a narrow ambulacrum. These lines were cut between every other high-low density band interface occurring during the fall season. *Diploria labyrinthiformis* grow in a cone shaped pattern with in the thecal wall with the greatest extension in summer and less extension in winter (Fig. E.2) whereas in the ambulacrum winter extension exceeds summer extension

(Cohen et al., 2004). As seen in Fig. E.2, cutting along density bands will cut through the wave patterns seen with the pink dye. If a cut were to be made through the 9/24/00, line material would be collected from as late as 1/01 and from earlier times in the summer though not as early as 6/01/00. In effect, the record will include material beyond the biennial period by 6-12 months, with the most smoothing between September and January where our cuts were made.

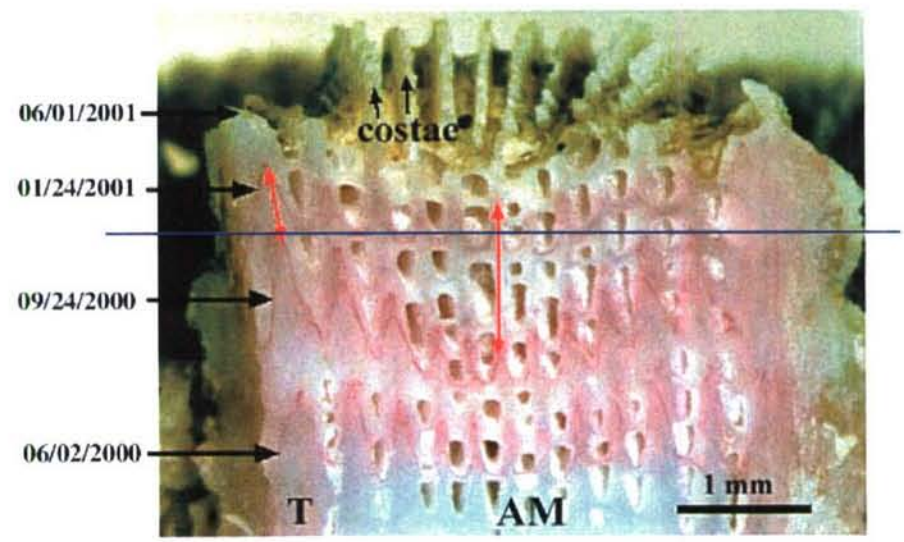


**Figure E.2:** Staining experiment conducted and published by Cohen et al. (2004) shows the cone shaped growth of a *Diploria labyrinthiformis* with varying extension in summer and winter throughout the theca-ambulacrum pairs. (Cohen et al., 2004) Blue line indicates approximately where cuts were made for the LRR record. T indicates Theca and AM indicates Ambulacrum.

Previous to the generation of the HRR, this smoothing was deemed to be minimal, but extensive smoothing of the HRR can confirm this hypothesis. For this analysis, the mean-annual Sr/Ca values of the HRR were treated with low-pass filters for three, five and seven years. As can be seen in Fig. E.3, additional smoothing beyond the biennial bins is not shown to be significant by smoothing the HRR. Differences in max and min values are not eliminated even by a seven year smooth which is significantly more than would be expected from the growth patterns. However, smoothing does appear to better describe the 1960s period in which LRR Sr/Ca values are higher than HRR Sr/Ca values than it does the 1850s period when the relationship is reversed. The largest differences between these two periods is the growth rate which are on average 4 mm/year in the 1960s and closer to 2 mm/year in the 1850s. This relationship will be further investigated later in the text.

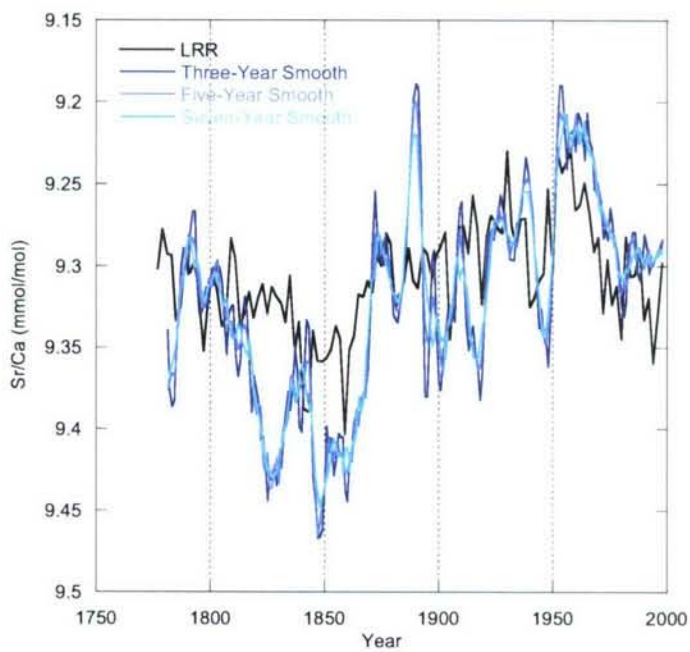


**Figure E.3:** Sr/Ca (mmol/mol) for the biennial record (LRR-black) and the sub-annual resolution record (HRR) filtered with three (dark blue), five (medium blue) and seven (light blue) year windows.

Sampling differences also arises from the incorporation of material from the ambulacrum in the LRR sampling though not the HRR samples. Samples were chosen with deliberately narrow ambulacrums and the significantly larger widths and densities of the theca lead to the hypothesis that influence from the abulacrum is as minimal as the extended smoothing. Additionally, the effect would be to more heavily weight the winter months (Fig. E.2) than does the HRR which is not the case throughout the whole record (Fig. E.1).

## E.3 Unaccounted Growth Influence

Another hypothesis is that growth rate has impacts on the biennial record either through the two influences above or from factors not yet identified that are not accounted for in the sub-annual based calibration. If the relative influences of the ambulacrum and the smoothing change with growth rate, this could lead to changes in the shape and magnitude of the biennial record, though it is unlikely that they would explain the entire change in magnitude. Another possible scenario is that lower growth time periods during which samples weigh less would be increasingly effected by powder lost during cutting. While a diamond wire band saw was used to diminish sample loss, some sample was lost and could have increased as a percentage of total weight with the smaller samples. This could also increase smoothing of the record or serve to dampen winter signals lost to cutting, as the cut occurs at the fall-winter interface. As seen in Fig. E.3, the slow growth period of the early to mid-1800s appears to have larger differences in Sr/Ca than does the 1960s with an average growth rate of 4 mm/year, supporting this hypothesis.

Possible growth rate impacts were evaluated both from the Sr/Ca records and from reconstructed SSTs using the mean-annual growth-corrected group model (Chapter 3). The HRR records were binned biennially and then the LRR were subtracted. These differences were then compared to growth rates determined by the biennial record and smoothed (Goodkin et al., 2005). Figure E.4 shows a low correlation (r) between both the Sr/Ca anomalies (0.22) and the SST anomalies (0.33). The left panels, in which the

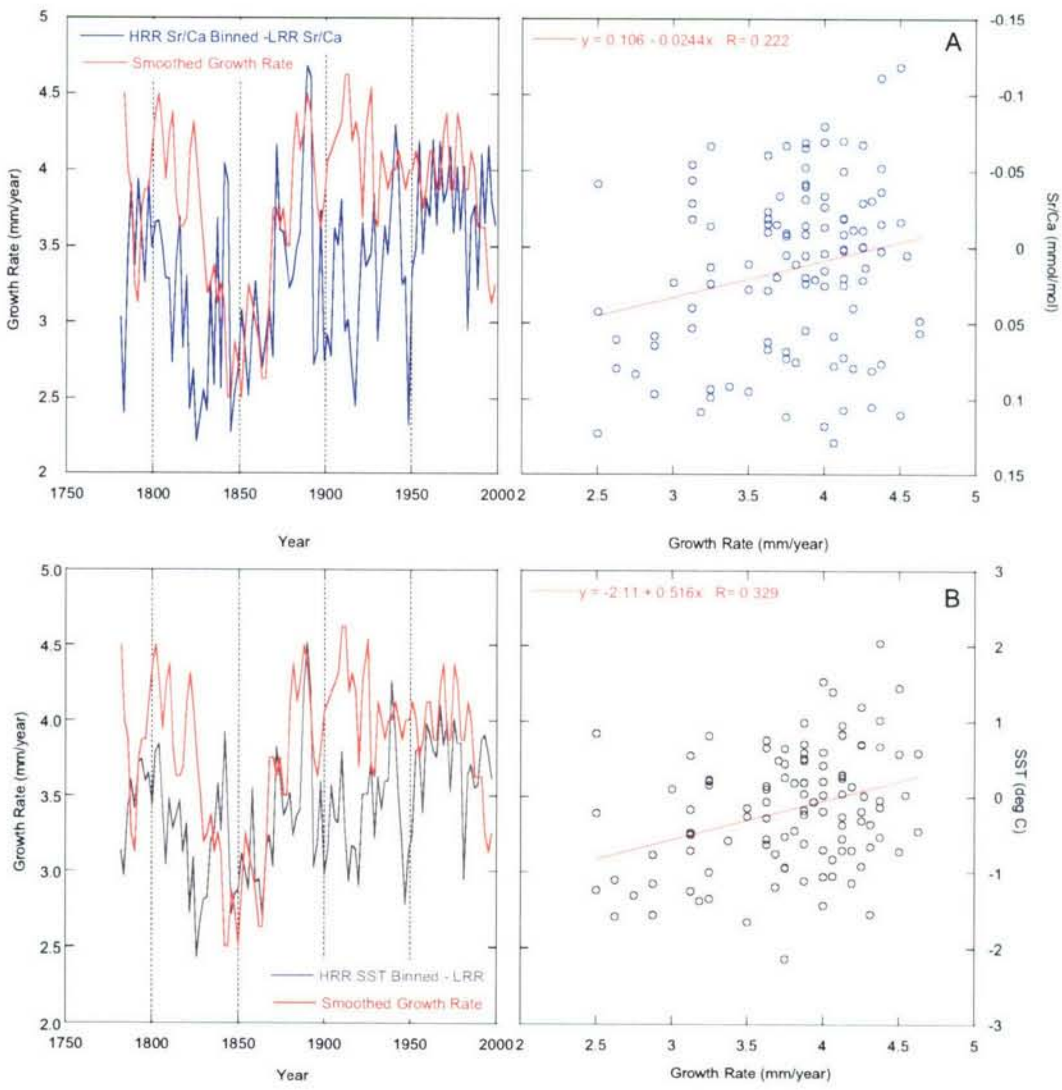


**Figure E.4:** Difference between the HRR binned biennially and the LRR compared to the mean annual smoothed growth rate (red) versus time and linearly for a) the Sr/Ca records (blue) and b) the reconstructed SST records (grey) using the mean-annual group model.

differences and growth rates are plotted versus time, show the strongest correlation for both records during the lowest growth period around 1850, lending support to the conclusion that the large discrepancies during this time may be due to impacts on low-growth periods that result either from the ambulacrum or the sampling error hypothesis which cannot be described simply by the smoothing hypothesis.

## E.4 Inapplicability of Sub-annual Calibration to Biennial Samples

More than one factor appears to be causing the discrepancy between the two Sr/Ca records. This conclusion indicates that when given the opportunity it is best to use a calibration sampled identically to the record to which it will be applied. Further evidence to support this conclusion is the increase in correlation between the difference of the two records and growth rate once the Sr/Ca is converted to SST (Fig. E.4). The growth rate influence becomes stronger after the growth-correction of the calibration is applied demonstrating the calibration is inappropriate.

Developing a biennial calibration raises many concerns. First, determining the calibration SST values is a challenge. Corals are cut based on high and low density bands, and it has not been determined either which month this transition occurs or if this timing remains consistent within these species through time. Smoothing beyond a biennial period is hypothesized to be occurring. Given these concerns generating an equivalent SST record is difficult. Given these caveats which will add error to any biennial calibration, SST records were binned over two year periods from November to November and correlated to the biennial Sr/Ca from 1975-1997. Three hypothesis were put forward in Chapter 2 (Goodkin et al., 2005) as to why growth rate could impact

Sr/Ca-SST relationships: 1) bulk (sub-annual) sampling biases, 2) kinetic effects and 3) convoluted skeletal architecture. Biennial sampling should eliminate concerns about summer in-filling as the samples do not get re-weighted while developing an age-model. However, skeletal architecture will effect the LRR samples as already discussed, and the hypothesis one and two could still impact a correlation. Therefore, a growth-corrected biennial model, in the form of the growth-corrected mean-annual model (Chapter 2) was generated. The exercise returns the following result:

$$Sr/Ca = -0.0389\ (\pm 0.0385) * (SST) - 0.00144\ (\pm 0.00081) * (SST) * (Growth\ Rate) + 10.3\ (\pm 0.9)$$

$$(95\%\ conf.,\ \sigma,\ r^2 = 0.46,\ F_{sig} = 0.16)$$

This is not a statistically significant relationship at the 95% confidence interval which may result from both the low number of observations (n=9) and the SST concerns expressed previously. (Note: it is more significant than a non-growth model which returns an $r^2$ of 0.18 and an $F_{sig}$ of 0.25.) Application of the biennial growth-corrected model to the biennial Sr/Ca record returns a result in line with magnitude of SST change seen with the SST reconstruction generated by applying the mean-annual growth-corrected group model to the HRR (Fig. E.5). Both records show a total SST change on

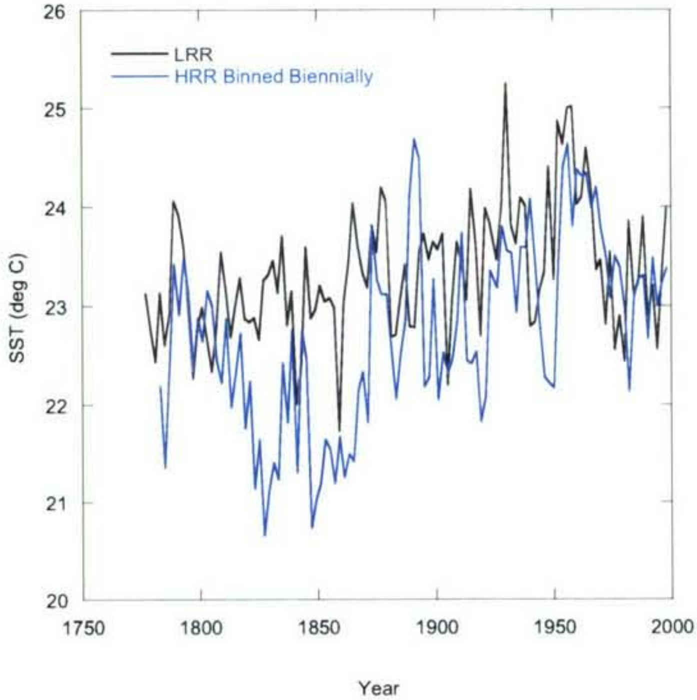


**Figure E.5:** SST reconstructed from the LRR Sr/Ca record using the biennial growth-corrected model (black) and SST reconstructed from the HRR Sr/Ca record using the group model (blue).

the order of ~3.0°C from max to min. There continue to be differences mainly seen in the 1800s in the shape of the curves, where a longer period of cooling is seen in the HRR consistent with other Northern Hemisphere records (Overpeck et al., 1997; Jones et al., 1998). Further development of a biennial calibration using multiple corals could help to continue to clarify these issues, though is not necessary for the goals of this thesis.

## E.5 Results of Chapter Two

In chapter two, we used the biennially sampled record to illustrate the differences of the variously scaled calibrations/models presented. The analysis presented in this appendix calls into questions these illustrations if indeed the biennially sampled record is not applicable. Therefore, I have redone this analysis (Fig. E.6) to demonstrate that illustration is still relevant. In this figure, reconstructions of SST from the HRR record using the BB 001 monthly and mean-annual calibrations are compared to the growth-dependent model (a and b). The monthly calibration shows an SST change of ~10°C two times that of the growth-corrected model as found with the biennial record. The mean-annual calibration returns an SST change of 7°C more than 35% larger than that found with the growth-corrected model. Finally, the BB 001 growth-corrected model is compared to the group reconstruction (Fig. E.6c). The temperature changes are relatively consistent with maximum to minimum changes of 5.3 and 4.9 °C respectively with a small shift in the absolute value of the SST through time. In conclusion, the illustration made by the biennial results hold true when the same series of calibrations are applied to the HRR data.

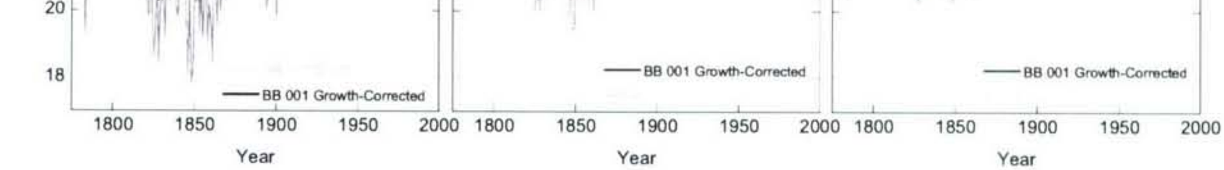


**Figure E.6**: SST reconstructions from the HRR comparing the BB 001 growth-corrected model (solid) to a) BB 001 monthly calibration (shaded), b) the BB 001 mean-annual calibration (shaded), and c) the group, growth-corrected model (shaded).

## E.6 Conclusions

The complications of using Sr/Ca to reconstruct SST have long been recognized (Devilliers et al., 1995; Alibert and Mcculloch, 1997; Marshall and Mcculloch, 2002; Cohen et al., 2004). This is yet another example of how carefully these records must be treated. Goodkin et al. (2005) (this work) emphasizes the importance of applying calibrations of the same temporal resolution as the samples. This analysis shows that both temporal resolution and consistent sampling regimes are critical for reconstructions in this species.

## E.7 References

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# Appendix F

# Oxygen Isotope – Salinity Relationship in Bermuda Waters

In order to investigate the assumption in Chapter Four that surface waters near Bermuda will have a $\delta^{18}O$ – sea surface salinity (SSS) relationship similar to the global thermocline relationship of $\delta^{18}O = 0.49*SSS - 17$ [*Schmidt*, 1999], two one-year time series of seawater were collected at Surf Bay Beach Bermuda (Table F.1) and at the Bermuda Atlantic Time-Series (BATs) Station (Table F.2). Each samples' salinity and $\delta^{18}O$ was measured at WHOI and Harvard University respectively, and *in situ* temperature was taken for most samples. These samples combined with samples from the global data base were used to evaluate the relationship in this region (Figure F.1). The global database, the Surf Bay Beach and all three sources of data together return a result similar to the global thermocline relationship. The BATs site, which has the fewest samples and the smallest range of salinity, shows a steeper slope (0.86 ‰/psu). These results are not definitive as a longer time-series is required, but they do support the use of the thermocline relationship in reconstructing salinity.

**Table F.1:** Seawater measurements from Surf Bay Beach, Bermuda (32° 20' N, 64° 45'W). Water collected from the top 3 meters.

| Date | Digital Date | Temperature (°C) | Salinity (psu) | $\delta^{18}O$ (‰) |
|---|---|---|---|---|
| 07/31/2005 | 2005.58 | 29.1 | 36.67 | 1.20 |
| 10/11/2005 | 2005.78 | 26.6 | 36.71 | 1.46 |
| 11/26/2005 | 2005.90 | 23.2 | 36.45 | 1.15 |
| 01/01/2006 | 2006.00 | 20.7 | 36.73 | 1.19 |
| 01/22/2006 | 2006.06 | 20.2 | 36.68 | 1.16 |
| 03/22/2006 | 2006.22 | 16.9 | 36.72 | 1.23 |
| 04/15/2006 | 2006.29 | 20.8 | 36.69 | 1.24 |
| 05/06/2006 | 2006.35 | 23.2 | 36.62 | 1.18 |
| 06/18/2006 | 2006.46 | 25.6 | 36.47 | 1.08 |
| 07/30/2006 | 2006.58 | 28.0 | 36.56 | 1.26 |

**Table F.2:** Seawater measurements from BATs (31° 40' N, 64° 10'W).

| Date | Digital Date | Depth (m) | Temperature (°C) | Salinity (psu) | $\delta^{18}O$ (‰) |
|---|---|---|---|---|---|
| 10/12/2005 | 2005.78 | 15 | 25.9 | 36.68 | 1.48 |
| 12/11/2005 | 2005.95 | 15 | 22.8 | 36.71 | 1.27 |
| 01/31/2006 | 2006.08 | 15 | 20.0 | 36.62 | 1.08 |
| 02/23/2006 | 2006.15 | 15 | 19.3 | 36.63 | 1.19 |
| 04/06/2006 | 2006.26 | 15 | 19.5 | 36.68 | 1.15 |
| 06/28/2006 | 2006.49 | 15 | NA | 36.57 | 1.08 |
| 07/18/2006 | 2006.55 | 15 | NA | 36.59 | 1.28 |
| 09/06/2006 | 2006.68 | 15 | NA | 36.53 | 1.16 |
| 08/08/2006 | 2006.77 | 15 | NA | 36.64 | 1.15 |

**Table F.3:** $\delta^{18}O$ and SSS measurements from global seawater oxygen-18 database.

| Longitude (W) | Latitude (N) | Depth (m) | Salinity (psu) | $\delta^{18}O$ (‰) |
|---|---|---|---|---|
| 64.00 | 32.00 | 0 | 36.30 | 1.17 |
| 64.00 | 32.00 | 0 | 36.40 | 1.05 |
| 64.00 | 32.00 | 0 | 36.80 | 1.36 |
| 64.00 | 32.00 | 0 | 35.40 | 1.01 |
| 67.98 | 35.99 | 7 | 36.43 | 1.22 |
| 64.00 | 32.00 | 18 | 35.40 | 1.05 |
| 60.82 | 28.08 | 25 | 36.80 | 1.39 |
| 60.82 | 28.08 | 500 | 36.30 | 0.89 |
| 60.82 | 28.08 | 2000 | 35.00 | 0.34 |
| 60.82 | 28.08 | 6000 | 34.90 | 0.20 |

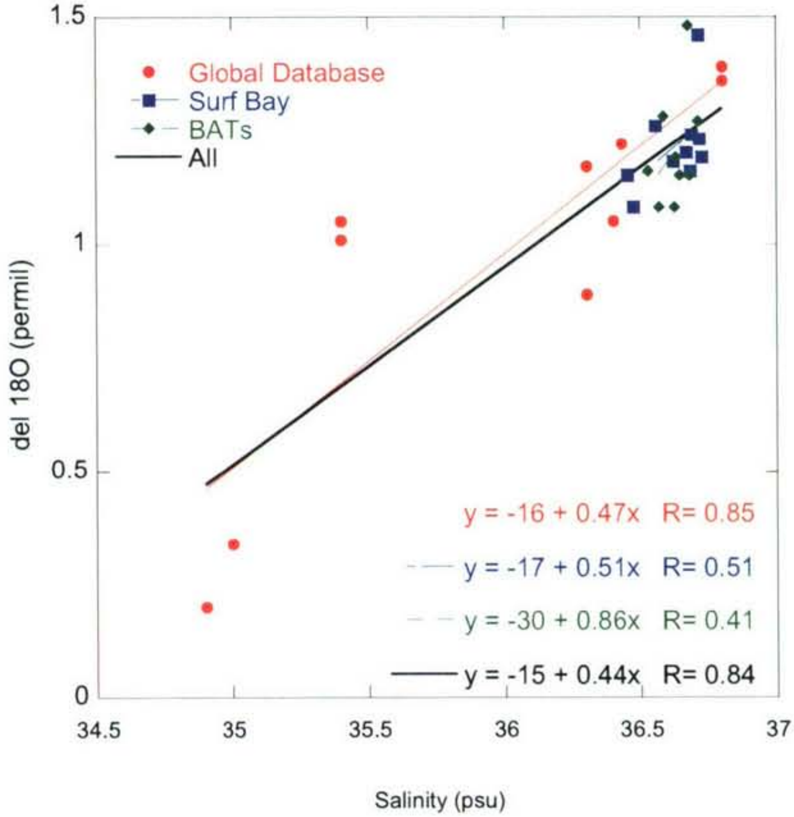


**Figure F.1:** $\delta^{18}O$ plotted versus salinity for the global database (red circles), Surf Bay Beach (blue squares), and BATs (green diamonds). Linear regressions of the global database (red), Surf Bay (blue) and all (black) values return results in proximity to the thermocline relationship generated globally. The BATs data, with the smallest salinity range, shows a steeper slope.

## Acknowledgements

The BATs team and R. Stanley (WHOI) collected the BATs samples, and R. Stanley and D. Toole (WHOI) transported these samples. A. Emami aided in collection of the Surf Bay Samples. D. Wellwood (WHOI) performed the salinity measurements and the oxygen isotope measurements were performed in the laboratory of D. Schrag (Harvard University).

## References

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# Appendix G

# Error Propagation on SST and SSS for Chapter Four

*Mean Annual SST*

(1) $Sr/Ca = (m_1*(ig) + m_2*(ag) + m_3) * SST + b$

(2) $SST = ((Sr/Ca) - b) / (m_1*(ig) + m_2*(ag) + m_3)$

(3) $$\sigma_{SST}^2 = \sigma^2_{Sr/Ca}*(\partial_{SST}/\partial_{Sr/Ca})^2 + \sigma^2_b*(\partial_{SST}/\partial_b)^2 + \sigma^2_{m1}*(\partial_{SST}/\partial_{m1})^2 + \sigma^2_{m2}*(\partial_{SST}/\partial_{m2})^2$$
$$+ \sigma^2_{m3}*(\partial_{SST}/\partial_{m3})^2 + 2*\sigma^2_{m1\text{-}m2}*(\partial_{SST}/\partial_{m1})*(\partial_{SST}/\partial_{m2})$$
$$+ 2*\sigma^2_{m1\text{-}m3}*(\partial_{SST}/\partial_{m1})*(\partial_{SST}/\partial_{m3}) + 2*\sigma^2_{m2\text{-}m3}*(\partial_{SST}/\partial_{m3})*(\partial_{SST}/\partial_{m2})$$
$$+ 2*\sigma^2_{m1\text{-}b}*(\partial_{SST}/\partial_{m1})*(\partial_{SST}/\partial_b) + 2*\sigma^2_{m2\text{-}b}*(\partial_{SST}/\partial_{m2})*(\partial_{SST}/\partial_b)$$
$$+ 2*\sigma^2_{m3\text{-}mb}*(\partial_{SST}/\partial_{m3})*(\partial_{SST}/\partial_b)$$

where: $\sigma^2_{Sr/Ca}$ = (the standard error on the regression)$^2$
all other $\sigma$ are the 1-sigma error on the regression results
$\partial_{SST}/\partial_{Sr/Ca} = 1/(m_1*(ig) + m_2*(ag) + m_3)$
$\partial_{SST}/\partial_b = -1/(m_1*(ig) + m_2*(ag) + m_3)$
$\partial_{SST}/\partial_{m1} = -((Sr/Ca - b)*(ig)) / (m_1*(ig) + m_2*(ag) + m_3)^2$
$\partial_{SST}/\partial_{m2} = -((Sr/Ca - b)*(ag)) / (m_1*(ig) + m_2*(ag) + m_3)^2$
$\partial_{SST}/\partial_{m3} = -(Sr/Ca - b) / (m_1*(ig) + m_2*(ag) + m_3)^2$

**Table G.1:** Values of equation 1 parameters.

| Parameter | Value | Units |
|---|---|---|
| $m_1$ | -0.000697 | (mmol/mol)(mm/year)$^{-1}$(°C)$^{-1}$ |
| $m_2$ | 0.00304 | (mmol/mol)(mm/year)$^{-1}$(°C)$^{-1}$ |
| $m_3$ | -0.0738 | (mmol/mol)(°C)$^{-1}$ |
| b | 10.8 | (mmol/mol) |

**Table G.2:** Errors and covariances ($\sigma^2$) on the parameters from the regression of eqn. (1) above.

| Parameter | Value | Units |
|---|---|---|
| Sr/Ca | $9.630 \times 10^{-4}$ | mmol/mol |
| b | 0.1858 | mmol/mol |
| $m_1$ | $1.410 \times 10^{-7}$ | (mmol/mol)(mm/year)$^{-1}$(°C)$^{-1}$ |
| $m_2$ | $2.615 \times 10^{-7}$ | (mmol/mol)(mm/year)$^{-1}$(°C)$^{-1}$ |
| $m_3$ | $3.488 \times 10^{-4}$ | (mmol/mol)(°C)$^{-1}$ |
| $m_1$- $m_2$ | $-8.787 \times 10^{-8}$ | (mm/year)$^{-2}$(mmol/mol)$^2$(°C)$^{-2}$ |
| $m_1$- $m_3$ | $5.482 \times 10^{-7}$ | (mm/year)$^{-1}$(mmol/mol)$^2$(°C)$^{-2}$ |
| $m_2$- $m_3$ | $-1.085 \times 10^{-6}$ | (mm/year)$^{-1}$(mmol/mol)$^2$(°C)$^{-2}$ |
| $m_1$- b | $-1.660 \times 10^{-5}$ | (mm/year)$^{-1}$(mmol/mol)$^2$(°C)$^{-1}$ |
| $m_2$- b | $9.572 \times 10^{-6}$ | (mm/year)$^{-1}$(mmol/mol)$^2$(°C)$^{-1}$ |
| $m_3$- b | $-8.014 \times 10^{-3}$ | (mmol/mol)$^2$(°C)$^{-1}$ |

*Winter-Time SST*

(4) $$Sr/Ca = m*SST + b$$

(5) $$SST = (Sr/Ca - b) / m$$

(6) $$\sigma_{SST}^2 = \sigma^2_{Sr/Ca}*(\partial_{SST}/\partial_{Sr/Ca})^2 + \sigma^2_b*(\partial_{SST}/\partial_b)^2 + \sigma^2_m*(\partial_{SST}/\partial_m)^2 + 2*\ \sigma^2_{m\text{-}b}*(\partial_{SST}/\partial_m) *(\partial_{SST}/\partial_b)$$

where: $\sigma^2_{Sr/Ca}$ = (the standard error on the regression)$^2$

all other $\sigma$ are the 1-sigma error on the regression results

$\partial_{SST}/\partial_{Sr/Ca} = 1 / (m)$

$\partial_{SST}/\partial_b = -1 / (m)$

$\partial_{SST}/\partial_{m1} = -(Sr/Ca - b) / m^2$

**Table G.3:** Values of equation 4 parameters.

| Parameter | Value | Units |
|---|---|---|
| m | -0.0972 | (mmol/mol)(°C)$^{-1}$ |
| b | 11.3 | (mmol/mol) |

**Table G.4:** Errors and covariances ($\sigma^2$) on the parameters from the regression of eqn. (4) above.

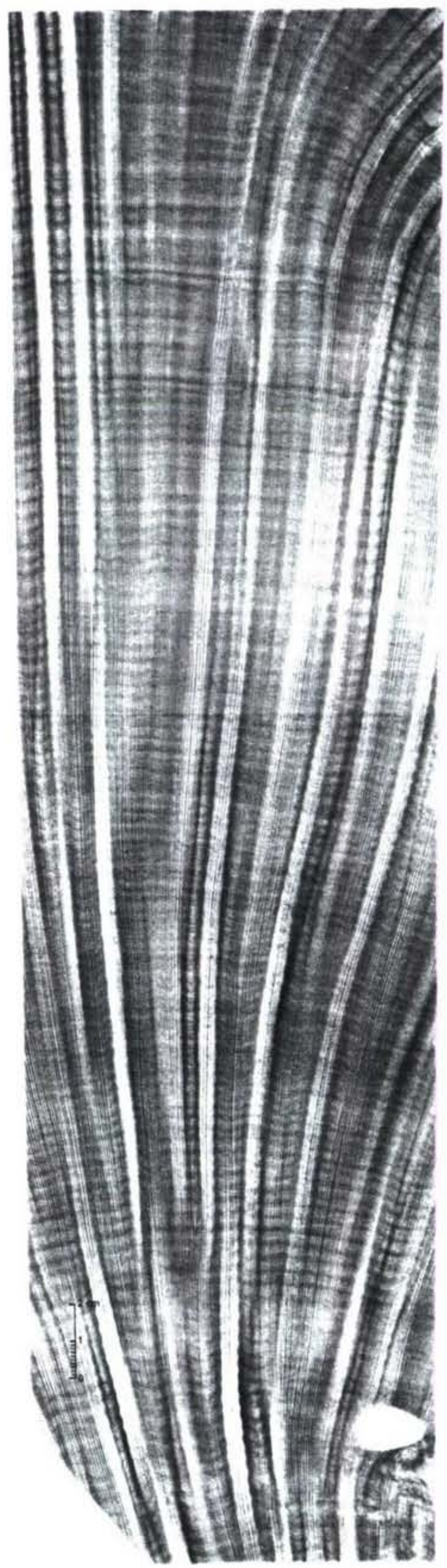
| Parameter | Value | Units |
|---|---|---|
| Sr/Ca | $1.328 \times 10^{-3}$ | mmol/mol |
| b | 0.2829 | mmol/mol |
| m | $7.0545 \times 10^{-4}$ | (mmol/mol)(°C)$^{-1}$ |
| m - b | $-1.413 \times 10^{-2}$ | (mmol/mol)$^2$(°C)$^{-1}$ |

## Appendix H

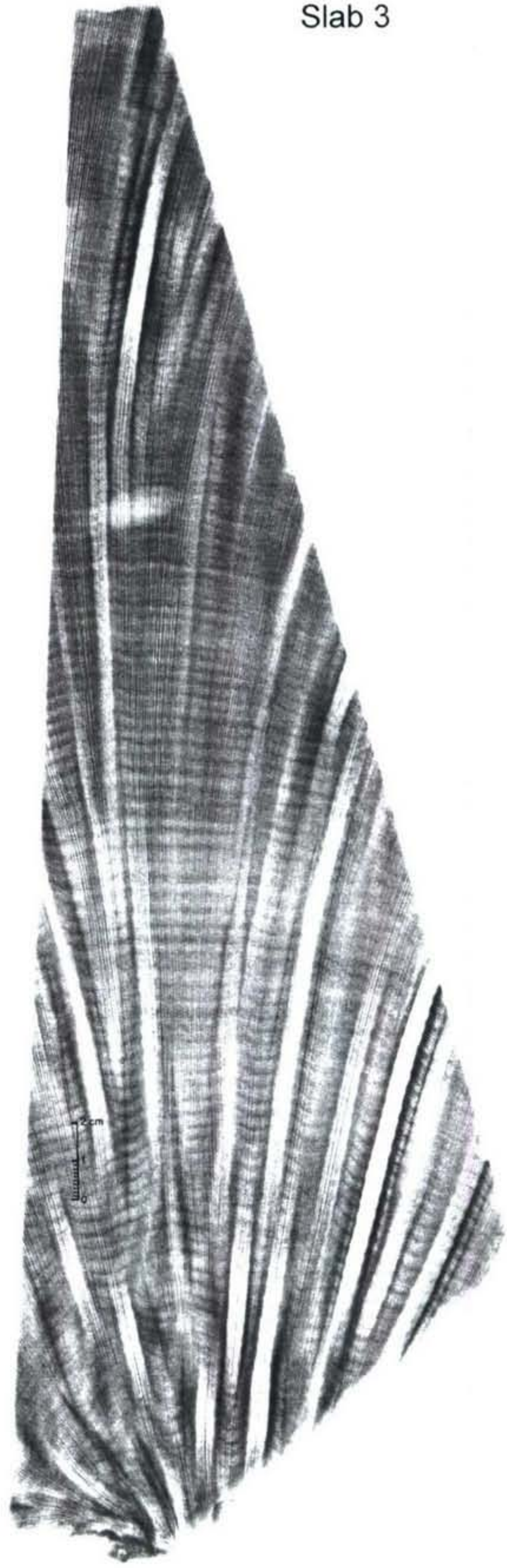
# BB001 X-Radiographs

Slab 1

Slab 2



Slab 3



# Appendix I

# Sr/Ca Calibration Data Sets

*Mean-Annual Data*

| Year | Mean-Annual Sr/Ca (mmol/mol) | Inter-annual Growth (Smoothed, mm/year) | Average Growth (mm/year) | Hydrostation S SST (deg C) | Coral ID |
|---|---|---|---|---|---|
| 1997 | 9.315 | 3.49 | 4.22 | 23.115 | BER 003 |
| 1996 | 9.303 | 3.32 | 4.22 | 23.014 | BER 003 |
| 1995 | 9.273 | 3.42 | 4.22 | 23.097 | BER 003 |
| 1994 | 9.303 | 3.31 | 4.22 | 23.381 | BER 003 |
| 1993 | 9.307 | 4.01 | 4.22 | 23.204 | BER 003 |
| 1992 | 9.341 | 4.00 | 4.22 | 23.130 | BER 003 |
| 1991 | 9.347 | 3.89 | 4.22 | 23.264 | BER 003 |
| 1990 | 9.285 | 4.02 | 4.22 | 23.522 | BER 003 |
| 1988 | 9.352 | 4.01 | 4.22 | 22.850 | BER 003 |
| 1987 | 9.308 | 3.67 | 4.22 | 22.573 | BER 003 |
| 1985 | 9.272 | 4.12 | 4.22 | 23.263 | BER 003 |
| 1984 | 9.312 | 3.76 | 4.22 | 22.901 | BER 003 |
| 1983 | 9.276 | 3.98 | 4.22 | 22.980 | BER 003 |
| 1982 | 9.262 | 3.71 | 4.22 | 23.324 | BER 003 |
| 1981 | 9.345 | 4.26 | 4.22 | 22.805 | BER 003 |
| 1977 | 9.293 | 4.47 | 4.22 | 23.285 | BER 003 |
| 1976 | 9.295 | 4.58 | 4.22 | 23.352 | BER 003 |
| 1996 | 9.301 | 3.24 | 3.20 | 23.014 | BER 002 |
| 1995 | 9.247 | 2.45 | 3.20 | 23.097 | BER 002 |
| 1994 | 9.258 | 1.67 | 3.20 | 23.381 | BER 002 |
| 1993 | 9.279 | 2.45 | 3.20 | 23.204 | BER 002 |
| 1992 | 9.221 | 2.93 | 3.20 | 23.130 | BER 002 |
| 1991 | 9.263 | 3.22 | 3.20 | 23.264 | BER 002 |
| 1990 | 9.194 | 3.03 | 3.20 | 23.522 | BER 002 |
| 1988 | 9.312 | 2.97 | 3.20 | 22.850 | BER 002 |
| 1987 | 9.247 | 3.00 | 3.20 | 22.573 | BER 002 |
| 1985 | 9.192 | 3.50 | 3.20 | 23.263 | BER 002 |
| 1984 | 9.277 | 3.72 | 3.20 | 22.901 | BER 002 |
| 1983 | 9.278 | 4.23 | 3.20 | 22.980 | BER 002 |
| 1982 | 9.234 | 4.18 | 3.20 | 23.324 | BER 002 |
| 1981 | 9.258 | 4.32 | 3.20 | 22.805 | BER 002 |
| 1977 | 9.216 | 3.31 | 3.20 | 23.285 | BER 002 |
| 1976 | 9.189 | 3.55 | 3.20 | 23.352 | BER 002 |
| 1997 | 9.331 | 2.97 | 3.82 | 23.115 | BB 001 |
| 1996 | 9.350 | 2.97 | 3.82 | 23.014 | BB 001 |
| 1995 | 9.316 | 3.08 | 3.82 | 23.097 | BB 001 |
| 1994 | 9.293 | 3.08 | 3.82 | 23.381 | BB 001 |
| 1993 | 9.331 | 3.19 | 3.82 | 23.204 | BB 001 |
| 1992 | 9.345 | 3.13 | 3.82 | 23.130 | BB 001 |
| 1991 | 9.333 | 3.35 | 3.82 | 23.264 | BB 001 |
| 1990 | 9.321 | 3.30 | 3.82 | 23.522 | BB 001 |
| 1988 | 9.348 | 3.41 | 3.82 | 22.850 | BB 001 |
| 1987 | 9.327 | 3.85 | 3.82 | 22.573 | BB 001 |
| 1985 | 9.266 | 4.07 | 3.82 | 23.263 | BB 001 |
| 1984 | 9.305 | 3.96 | 3.82 | 22.901 | BB 001 |
| 1983 | 9.326 | 3.68 | 3.82 | 22.980 | BB 001 |
| 1982 | 9.280 | 3.90 | 3.82 | 23.324 | BB 001 |
| 1981 | 9.336 | 3.85 | 3.82 | 22.805 | BB 001 |
| 1977 | 9.281 | 4.45 | 3.82 | 23.285 | BB 001 |
| 1997 | 9.319 | 2.03 | 2.15 | 23.115 | BER 004 |
| 1996 | 9.347 | 1.97 | 2.15 | 23.014 | BER 004 |
| 1995 | 9.364 | 2.05 | 2.15 | 23.097 | BER 004 |
| 1994 | 9.344 | 2.17 | 2.15 | 23.381 | BER 004 |
| 1993 | 9.414 | 2.38 | 2.15 | 23.204 | BER 004 |
| 1992 | 9.374 | 2.40 | 2.15 | 23.130 | BER 004 |
| 1991 | 9.325 | 2.59 | 2.15 | 23.264 | BER 004 |
| 1990 | 9.280 | 2.54 | 2.15 | 23.522 | BER 004 |
| 1988 | 9.278 | 2.49 | 2.15 | 22.850 | BER 004 |
| 1987 | 9.278 | 2.65 | 2.15 | 22.573 | BER 004 |
| 1985 | 9.253 | 2.98 | 2.15 | 23.263 | BER 004 |
| 1984 | 9.297 | 3.00 | 2.15 | 22.901 | BER 004 |
| 1983 | 9.238 | 3.10 | 2.15 | 22.980 | BER 004 |
| 1982 | 9.287 | 2.79 | 2.15 | 23.324 | BER 004 |
| 1981 | 9.389 | 2.88 | 2.15 | 22.805 | BER 004 |
| 1977 | 9.279 | 3.16 | 2.15 | 23.285 | BER 004 |
| 1976 | 9.281 | 2.68 | 2.15 | 23.352 | BER 004 |

*Winter-Time*

| Year | Winter-time Sr/Ca (mmol/mol) | Hydrostation S SST (deg C) | Coral ID |
|---|---|---|---|
| 1997 | 9.37 | 20.218 | BER 002 |
| 1996 | 9.37 | 19.291 | BER 002 |
| 1995 | 9.31 | 20.208 | BER 002 |
| 1994 | 9.30 | 20.759 | BER 002 |
| 1993 | 9.33 | 20.534 | BER 002 |
| 1992 | 9.35 | 20.075 | BER 002 |
| 1991 | 9.38 | 20.808 | BER 002 |
| 1990 | 9.26 | 21.013 | BER 002 |
| 1989 | 9.40 | 20.465 | BER 002 |
| 1988 | 9.46 | 20.203 | BER 002 |
| 1987 | 9.38 | 19.717 | BER 002 |
| 1986 | 9.31 | 21.720 | BER 002 |
| 1985 | 9.36 | 19.941 | BER 002 |
| 1984 | 9.32 | 20.443 | BER 002 |
| 1983 | 9.41 | 20.496 | BER 002 |
| 1982 | 9.43 | 19.666 | BER 002 |
| 1981 | 9.30 | 19.669 | BER 002 |
| 1979 | 9.43 | 20.137 | BER 002 |
| 1978 | 9.39 | 20.630 | BER 002 |
| 1977 | 9.39 | 19.701 | BER 002 |
| 1976 | 9.34 | 20.999 | BER 002 |
| 1997 | 9.40 | 20.218 | BER 003 |
| 1996 | 9.44 | 19.291 | BER 003 |
| 1995 | 9.41 | 20.208 | BER 003 |
| 1994 | 9.41 | 20.759 | BER 003 |
| 1993 | 9.40 | 20.534 | BER 003 |
| 1992 | 9.51 | 20.075 | BER 003 |
| 1991 | 9.48 | 20.808 | BER 003 |
| 1990 | 9.37 | 21.013 | BER 003 |
| 1989 | 9.35 | 20.465 | BER 003 |
| 1988 | 9.43 | 20.203 | BER 003 |
| 1987 | 9.44 | 19.717 | BER 003 |
| 1986 | 9.33 | 21.720 | BER 003 |
| 1985 | 9.37 | 19.941 | BER 003 |
| 1984 | 9.44 | 20.443 | BER 003 |
| 1983 | 9.41 | 20.496 | BER 003 |
| 1982 | 9.49 | 19.666 | BER 003 |
| 1981 | 9.45 | 19.669 | BER 003 |
| 1979 | 9.45 | 20.137 | BER 003 |
| 1978 | 9.44 | 20.630 | BER 003 |
| 1977 | 9.43 | 19.701 | BER 003 |
| 1976 | 9.39 | 20.999 | BER 003 |
| 1997 | 9.41 | 20.218 | BB 001 |
| 1996 | 9.44 | 19.291 | BB 001 |
| 1995 | 9.42 | 20.208 | BB 001 |
| 1994 | 9.38 | 20.759 | BB 001 |
| 1993 | 9.42 | 20.534 | BB 001 |
| 1992 | 9.44 | 20.075 | BB 001 |
| 1991 | 9.42 | 20.808 | BB 001 |
| 1990 | 9.41 | 21.013 | BB 001 |
| 1989 | 9.40 | 20.465 | BB 001 |
| 1988 | 9.43 | 20.203 | BB 001 |
| 1987 | 9.42 | 19.717 | BB 001 |
| 1986 | 9.31 | 21.720 | BB 001 |
| 1985 | 9.45 | 19.941 | BB 001 |
| 1984 | 9.40 | 20.443 | BB 001 |
| 1983 | 9.42 | 20.496 | BB 001 |
| 1982 | 9.45 | 19.666 | BB 001 |
| 1981 | 9.46 | 19.669 | BB 001 |
| 1979 | 9.40 | 20.137 | BB 001 |
| 1978 | 9.41 | 20.630 | BB 001 |
| 1977 | 9.39 | 19.701 | BB 001 |

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16. Abstract (Limit: 200 words)

A 225-year old coral from the south-shore of Bermuda (64°W, 32°N) provides a record of decadal-to-centennial scale climate variability. The high accretion rates, longevity, and skeletal growth bands found in coral skeletons make them an ideal resource for well-dated, seasonal climate reconstructions. Coral skeletons incorporate strontium (Sr) and calcium (Ca) in relative proportions inversely to the sea surface temperature (SST) in which the skeleton is secreted. $\delta^{18}O$ of the coral skeleton changes based on both temperature and the $\delta^{18}O$ of sea water ($\delta O_w$), and $\delta O_w$ is proportional to sea surface salinity (SSS).

Sr/Ca was used to reconstruct winter-time and mean-annual SST, employing the first growth-corrected Sr/Ca-SST model. SSTs are ~1.5°C colder during the end of the Little Ice Age than today. SSS is fresher during that time. Winter-time SSTs at Bermuda are correlated to phases of the North Atlantic Oscillation (NAO). Using winter Sr/Ca as a proxy for temperature, we show strong coherence to the NAO at multi-decadal and inter-annual frequencies. These coral records show changes in variance in the NAO during the late 20th century, but limited changes in the mean phase of the NAO, implying that climate change may be pushing the NAO to extremes but not to a new mean position.

17. Document Analysis a. Descriptors

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$\delta^{18}O$
NAO

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

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