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Last Interglacial Climate from *Dendostrea frons* Oysters, Verrill Island, Bermuda

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Abstract

The Bermuda Islands preserve carbonates recording many past changes in sea level, including multiple warm and cool geologic intervals. Several localities expose shell-rich deposits from the Last Interglacial (~125,000 years ago), a time broadly similar to climate today that can potentially serve as an analog for future conditions. Here, we use $\delta^{18}\text{O}$ analyses of fossil mollusks to estimate past temperatures and seasonality and compare our data with those from other species.

Eight *Dendostrea frons* oysters were sampled along their growth axes to reconstruct seasonal temperature curves. We report a mean $\delta^{18}\text{O}$ value of $-0.51 \pm 0.17\text{‰}$, corresponding to a temperature of $\sim 23^\circ\text{C}$. These temperatures are similar to modern Bermuda (~ 16 to $\sim 31^\circ\text{C}$), suggesting that North Atlantic circulation may have been similar to today. Grape Bay and Bird Island *Glycymeris americana* mollusks, well known in isotopic work, were utilized for interspecies analysis and report similar temperature reconstructions, $\sim 22^\circ\text{C}$ and $\sim 24^\circ\text{C}$, respectively. The *Dendostrea frons* oysters require further evaluation to verify biologic effects as well as determine its oceanic depth environment. In comparison to other Last Interglacial temperature reconstructions these data could reflect a Gulf Stream current roughly as strong as today, in contrast to colder temperatures described in other studies.

Introduction

In the North Atlantic Ocean, the Islands of Bermuda lie approximately 1,600 km east of the South Carolina coastline. The geology of Bermuda is dominantly carbonate (limestone) with

sediments reflecting a complex history of warm and cool intervals. Glacial periods denote times where ice covered large parts of the world and sea level was much lower. Interglacials were warmer periods with higher sea level and less ice. Layers of rock in Bermuda preserve aeolianites, or carbonate dunes, in glacial periods. In interglacial periods they reflect marine and storm deposits, including rip up clasts and lag deposits. Bermuda exposes at least five Pleistocene interglacial and corresponding glacial deposits (Hearty et al., 1992).

Of particular relevance to the modern climate system is the Last Interglacial period (~125,000 years ago), equivalent to Marine Isotope Stage 5e (MIS 5e) in oxygen isotope records. The Last Interglacial was the most recent time of similar or slightly warmer climate conditions as today and therefore can perhaps be used as a past analog to modern climate change (CLIMAP, 1984). The climate during MIS 5e was ~1-2°C warmer than today and sea level was as much as ~6 meters higher (Dutton et al., 2015). Bermuda is an ideal location to study Last Interglacial climate due to its position in the North Atlantic Ocean and Gulf Stream, with a climate largely controlled by surrounding ocean circulation. At the same latitude, the South Carolina coastline is less influenced by the Gulf Stream and as a result has a much larger seasonality range (-3°C to 38°C; N.O.A.A., 2019). Here, we study the isotopic composition of Bermuda mollusks to reconstruct temperatures from the Last Interglacial to use as an analog for near future climate conditions and to investigate past ocean circulation.

Localities throughout Bermuda expose carbonate deposits that date to MIS 5e (Minnebo et al., 2020; Figure 1). We utilize *Dendostrea frons* oysters from Verrill Island and two *Glycymeris americana* mollusks from Bird Island and Grape Bay that correspond to this period (Figure 1 and 2). Using $\delta^{18}\text{O}$ isotopic analysis, the ratio of “heavier” to “lighter” oxygen isotopes

was measured in the shell carbonate to reconstruct past temperatures from the fossil mollusks. The objective of this work was to reconstruct paleotemperatures for the Last Interglacial and verify *Dendostrea frons* oysters as a paleoclimate indicator alongside a well-established mollusk species, *Glycymeris americana*.

Figure 1. Mean A/I ratios for Amino Acid Racemization data found in Minnebo et al. (2020) and Hearty et al. (1992). MIS 5e is equivalent to the Last Interglacial period. The error bars signify one standard deviation from the mean.

Bermuda Stratigraphy and Methods

Bermuda is situated on a carbonate platform that preserves at least five interglacial and corresponding glacial cycles (Hearty et al., 1992). Previous stratigraphic work has designated certain sites as part of the Last Interglacial (Minnebo et al., 2020). Samples in this study come from MIS 5e sites Grape Bay, Bird Island, and Verrill Island (Figure 1).

Eight *Dendostrea frons* oysters collected from Verrill Island are utilized here as a relatively new tool for paleoclimate isotope work. Previous studies explored the oyster species *Crassostrea virginica* and found they form close to isotopic equilibrium and

Figure 2. Map of Bermuda localities presented here: Bird Island, Verrill Island, and Grape Bay.

record seasonal cycles within its growth bands (Kirby et al., 1998; Surge et al., 2001). The *Dendostrea* oysters have not been used as a paleoclimate indicator but will be compared with *Glycymeris* from the same region. Consequently, the potential for vital effects is evaluated, as well as the overall applicability of this species as a paleoclimate tool. Vital effects are factors that influence the isotopic composition of the shell due to biologic processes. Shells that form in isotopic disequilibrium therefore cannot be accurately be used in temperature reconstruction without correcting the biologic interference (Sharp, 2007). Along with the oysters, two *Glycymeris americana* mollusks, used routinely in isotopic work, were collected from Bird Island and Grape Bay are analyzed to verify the reliability of the oysters.

The mollusks were sampled for calcium carbonate along their growth axes for their oxygen isotope composition. Mollusk shells grow in layers outward from the hinge and shell interior. By drilling samples from the initial to the final growth layers a record of the water composition can be reconstructed, potentially showing the warmest and coolest intervals the shell experienced (Figure 3). Subsequent geochemical analysis was completed at the Stable Isotope Laboratory at the University of Michigan. The majority of this study utilizes conventional carbonate stable isotope measurements of oxygen, defined as $\delta^{18}\text{O}$ (Sharp, 2007). This measurement is a function of the

Figure 3. Mollusks analyzed in this study. A) *Dendostrea frons* oyster 201 from Verrill Island cut in half for sampling. B) *Glycymeris americana* from Grape Bay. C) *Glycymeris americana* from Bird Island.

$\delta^{18}\text{O}_{\text{water}}$ value and water temperature the shell grew in. Here, the $\delta^{18}\text{O}_{\text{water}}$ value is assumed constant so the resulting change in carbonate $\delta^{18}\text{O}$ results from sea surface temperature (SST) changes, where the lighter (more negative) values indicate warmth/summer, and the heavier (more positive) values indicate cold/winter.

$\delta^{18}\text{O}$ Results

The $\delta^{18}\text{O}$ analyses are found in Table 1 for the eight Verrill Island *Dendostrea* oysters and the two *Glycymeris* mollusks from Bird Island and Grape Bay. Seven of the eight oyster fossil shells produced relatively short $\delta^{18}\text{O}$ records with a range of -1.11 to 0.39‰ and mean of -0.54 ± 0.16 ‰ (Figure 4). Oyster VI 207 records a peak of 0.39‰, which is the highest value compared to the other oysters. Verrill Island *Dendostrea* oyster 201 produced a longer record with a range of -1.07 to 0.29‰ and a mean of -0.47 ± 0.17 ‰, initially with a gradual trend toward more negative $\delta^{18}\text{O}$ values then an apparent seasonal cycle formed (Figure 5).

The Grape Bay *Glycymeris* mollusk record had a range of -0.54 to 1.31‰ and mean of 0.16 ± 0.23 ‰ (Table 1; Figure 5). The Bird Island *Glycymeris* had a range of -1.00 to 1.24‰ with a mean of -0.10 ± 0.34 ‰ (Table 1; Figure 5). Both of these records present clear seasonal cycles as seen in Figure 5.

Table 1. Summary statistics for each fossil mollusk studied. All $\delta^{18}\text{O}$ values are recorded in ‰VPDB and temperature calculations are based on Kim and O’Neil (1997) and Huyghe et al. (2020).

Locality	Shell ID	Species	Mineralogy	Mean $\delta^{18}\text{O}$ (‰ VPDB)	1 Standard Deviation (‰)	$\delta^{18}\text{O}$ range (‰)	Max $\delta^{18}\text{O}$ (‰)	Min $\delta^{18}\text{O}$ (‰)	Mean Temperature (°C)	Temperature Range (°C)
Bird Island	BI Layer B Gly	<i>Glycymeris americana</i>	Aragonite	-0.10	0.34	1.7	1.24	-1.00	24	11
Grape Bay	GB Gly	<i>Glycymeris americana</i>	Aragonite	0.16	0.23	1.1	1.31	-0.54	22	9
<i>Glycymeris americana</i> average and total range values				0.03	0.29	2.3	1.31	-1.00	23	11
Verrill Island	VI 201	<i>Dendostrea frons</i>	Calcite	-0.47	0.17	1.36	0.29	-1.07	23	7
Verrill Island	VI 202	<i>Dendostrea frons</i>	Calcite	-0.57	0.12	0.95	-0.12	-1.07	23	5
Verrill Island	VI 203	<i>Dendostrea frons</i>	Calcite	-0.47	0.22	1.18	0.27	-0.91	23	6
Verrill Island	VI 204	<i>Dendostrea frons</i>	Calcite	-0.86	0.07	0.37	-0.74	-1.11	25	2
Verrill Island	VI 205	<i>Dendostrea frons</i>	Calcite	-0.62	0.13	0.59	-0.24	-0.83	24	3
Verrill Island	VI 207	<i>Dendostrea frons</i>	Calcite	-0.56	0.19	1.41	0.39	-1.02	23	7
Verrill Island	VI 209-1	<i>Dendostrea frons</i>	Calcite	-0.25	0.09	0.69	0.02	-0.66	22	3
Verrill Island	VI 209-2	<i>Dendostrea frons</i>	Calcite	-0.46	0.03	0.14	-0.40	-0.54	23	1
<i>Dendostrea frons</i> average and total range values				-0.51	0.17	1.50	0.39	-1.11	23	7

Figure 4. $\delta^{18}\text{O}$ data for seven *Dendostrea frons* oysters: VI 202, VI 203, VI 204, VI 205, VI 207, VI 209-1, and VI 209-2 reported in ‰VPDB. The sample number along the growth axis presents the youngest to oldest values (left to right).

Figure 5. SST reconstruction from two *Glycymeris americana* mollusks and one *Dendostrea frons* oyster (VI 201) from Grape Bay, Bird Island, and Verrill Island, respectively. Calculations are followed from Kim and O’Neil (1997) and Huyghe et al. (2020). The sample number along the growth axis represents the youngest to oldest values (left to right).

Temperature Comparison

Due to their longer sampling records, Verrill Island oyster 201, the Grape Bay *Glycymeris*, and the Bird Island *Glycymeris* records are utilized for an interspecies and locality comparison. The aragonite *Glycymeris* mollusks and calcite *Dendostrea* oysters require a comparison based on temperature reconstructions, not solely $\delta^{18}\text{O}$ values, as the mineralogical difference induces a small difference in shell $\delta^{18}\text{O}$ at identical temperatures. The equation for $\delta^{18}\text{O}$ to temperature for calcite is from Kim and O’Neil (1997) and Huyghe et al. (2020):

$$T = 18030 / (1000 \ln \alpha + 32.17) - 273.15$$

$$\text{where } \alpha = (1000 + \delta^{18}\text{O}_{\text{shell}}) / (1000 + \delta^{18}\text{O}_{\text{water}})$$

The equation for $\delta^{18}\text{O}$ to temperature for aragonite is from Grossman and Ku (1986):

$$T = 17880 / (1000 \ln \alpha + 31.14) - 273.15$$

$$\text{where } \alpha = (1000 + \delta^{18}\text{O}_{\text{shell}}) / (1000 + \delta^{18}\text{O}_{\text{water}})$$

The conversion from VPDB to SMOW was followed according to Huyghe et al. (2020):

$$\delta^{18}O_{carb(SMOW)} = (1.03091) * (\delta^{18}O_{shell(PDB)} - 0.25) + 30.91$$

Additionally, the assumed water value ($\delta^{18}O_{water}$) is 1.0‰ for both the calcite and aragonite conversions based on modern $\delta^{18}O$ values.

The Verrill Island *Dendostrea* oysters mean corresponded to ~23°C with a range of ~7°C. The Grape Bay *Glycymeris* mollusk mean corresponded to ~22°C with a range of ~9°C. The Bird Island *Glycymeris* mollusk mean corresponded to ~24°C with the largest range of ~11°C. The seasonal cycles for these three mollusks can be found in Figure 5.

Discussion

The majority of the *Dendostrea* oysters do not preserve distinct seasonal cycles. Figure 4 shows the short records average ~7 samples because of the smaller size of the oysters, avoidance of potential contamination within the shell while sampling, as well as potential rapid growth of the oyster as it formed. Although distinct seasonality is not indicated these data do provide context for average water composition and temperatures. These seven oysters have an average $\delta^{18}O$ value of -0.54 ± 0.16 ‰ with a temperature of ~23°C. Oyster VI 207 does report a peak $\delta^{18}O$ value of 0.39‰ (~19°C), but this appears to be an outlier relative to the other values from the shell. Modern Bermuda temperatures average between 16°C and 31°C (N.O.A.A. Buoy Center) and Winkelstern et al. (2017) found SST for the Last Interglacial between 8 to 27°C. These *Dendostrea* oysters from the Last Interglacial therefore overlap with the modern and MIS 5e values, but do not seem to show as cold of temperatures observed in Zhang et al. (2021) and Winkelstern et al. (2017). The data are on the cooler end of modern values, but the warmer end of Last Interglacial values.

The record from *Dendostrea* oyster VI 201 comprised 32 samples from a larger and a seemingly diagenetically uncontaminated specimen. The oyster reports a mean of $-0.47 \pm 0.17\text{‰}$ corresponding to $\sim 23^{\circ}\text{C}$. Similar to the other Verrill Island oysters, VI 201 overlaps modern and MIS 5e Bermuda temperatures and is slightly cooler than modern and slightly warmer than other Last Interglacial values. This oyster presents a more distinct seasonal cycle and currently we have ongoing clumped isotope analyses to further describe the temperature and water compositions.

Figure 5 shows the seasonality of VI 201, as well an initial positive temperature trend that leads into the cyclical pattern. The steady positive temperature trend (negative $\delta^{18}\text{O}$ trend) likely corresponds with the biology of the oyster as a juvenile. As seen in Huyghe et al. (2020), a younger *Magallana gigas* oyster usually depicts faster growth rates and may form in isotopic disequilibrium with seawater from kinetic effects before transitioning to equilibrium in adulthood. After the juvenile period, the *Magallana gigas* oysters more accurately record seawater temperatures, as witnessed with VI 201 where beyond sample 15 the typical seasonal cycle pattern forms. The consistent average $\delta^{18}\text{O}$ value across the shell seems to indicate that *Dendostrea* may also record accurate average water temperatures even during the juvenile phase.

The *Glycymeris* mollusks from Grape Bay and Bird Island both reflect strong seasonal cycles (Figure 5). The Grape Bay *Glycymeris* reports a mean temperature of 22°C with a 9°C range between 17 to 26°C . The Bird Island *Glycymeris* reports a mean temperature of 24°C with the largest range of 11°C from 17 to 28°C . In comparison, the Verrill Island 201 oyster mean is 23°C but has a smaller range of 7°C between 19 to 26°C . It is unlikely that these average temperatures are statistically distinct, but the recorded *Glycymeris* seasonality appears slightly larger. This could reflect a difference in biology, where the oysters may be more resistant to, or

buffered from, temperature changes and thus show less variability in seasonality. *Dendostrea* oyster may also live at a different depth, and therefore record different conditions than the *Glycymeris* mollusks, which may explain the narrower temperature range.

All three localities are consistent with modern and MIS 5e Bermuda temperatures. They all are on the cooler end of modern temperatures, but warmer for previous proxies of the Last Interglacial temperatures. Specifically, Bird Island and Verrill Island are geographically closer together (Figure 2) and present similar means (24°C and 23°C, respectively), however Bird Island reports a larger temperature range (11°C compared to 7°C). The Bird Island and Verrill Island sites are today within the Great Sound of Bermuda and could perhaps have been geographically cut off from the larger ocean in the past, and thus report slightly warmer MIS 5e temperatures. Overall, these temperatures are roughly consistent with modern, which implies a Gulf Stream current operating in the Last Interglacial with similar strength and direction as today.

Conclusions and Dissemination

These data establish *Dendostrea frons* oysters as a new tool for paleoclimatology work. While records generally do not preserve seasonal cycles (with the exception of VI 201), average reconstructed temperatures are indistinguishable from those measured in nearby *Glycymeris americana*. *Dendostrea* should be further investigated as a paleoclimate tool in order to verify any unobserved vital effects, the isotopic pattern from juvenile to adulthood, and the potential difference in growth environments. Both mollusk species record temperatures slightly warmer than previous Last Interglacial studies. Compared to previous Last Interglacial temperature reconstructions, the slightly warmer values reported here could be indicative of a partially

isolated, locally warmer lagoon setting, or could be indicating a Gulf Stream current with a similar degree of poleward heat transport as today.

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Dissemination Plan

This coming October we will present this research at the national Geological Society of America Connects 2021 meeting, taking place in Portland, Oregon. We will be able to interact with other professionals and students working on paleoclimate, paleoecology, and sedimentology.