



# Reconstructing estuarine conditions: oyster shells as recorders of environmental change, Southwest Florida

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## Abstract

Live-collected shells of the oyster, *Crassostrea virginica*, contain geochemical records of modern temperature and salinity, so records of prehistoric conditions may be obtained from subfossil shells. Restoration of channelized watersheds in Florida is receiving much attention, and plans for targeted watersheds require information about estuarine conditions before channelization. Lack of historical records necessitates alternative methods to understand pre-disturbance conditions. A <sup>14</sup>C-calibrated, amino-acid geochronology based on racemization of glutamic acid yielded ages ranging from 190–1220 AD and from 1270–1860 AD for subfossil oysters from Blackwater River (near-natural watershed) and for Faka-Union Bay (channelized watershed), respectively.  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of subfossil shells from Blackwater River indicate salinity and summer temperatures similar to present. Winter temperatures recorded in shells from 190, 590, 720, and 1050 AD appear 1–5 °C colder than present winter temperatures, whereas the shell from 1220 AD records winter temperatures similar to modern winter temperatures. These temperature shifts may indicate change in climate or natural seasonal variation of winter temperature from year to year. Subfossils from Faka-Union Bay may reflect a complicated hydrology, which cannot be evaluated by isotopic compositions alone and demonstrates the need for development of independent elemental proxies for temperature and salinity. Decreases in  $\delta^{13}\text{C}$  from subfossil to modern shells may in part result from CO<sub>2</sub> added to the atmosphere from fossil fuel burning (the Suess effect). Subfossil  $\delta^{13}\text{C}$  that is >1‰ more positive than modern shells suggest a change in the dominant carbon sources from terrestrial C<sub>4</sub> or aquatic plants to C<sub>3</sub> plants (mangroves). © 2003 Elsevier Ltd. All rights reserved.

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## 1. Introduction

Since the 1930s, many wetlands and estuaries throughout the Everglades have been altered by construction of canals to provide drainage for residential development and agriculture. This modification of natural flow has drastically changed the chemical and biological characteristics of coastal ecosystems, including patterns of seasonal variation in salinity. One way to assess the

environmental impact of human activities is to examine chemical variation in shells to reconstruct natural seasonal conditions before anthropogenic modification of the habitat. Such an assessment can be accomplished by comparing chemistries of shells from undisturbed and anthropogenically disturbed estuaries with shells from mollusks that were alive before and after the disturbance. Shells of the American oyster, *Crassostrea virginica*, can be used to reconstruct seasonal temperature and salinity change (i) because their accretionary growth pattern preserves information about the local environment; and (ii) based on the isotopic variation in their shells (Kirby, 2000; Kirby, Soniat, & Spero, 1998; Surge, Lohmann, & Dettman, 2001). Oysters can potentially live 10 or 12 years (Kent, 1992), but more typically grow to 5 or 6 years of age (Kennedy, Newell, & Eble, 1996).

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This study examines the carbon and oxygen isotope composition of *C. virginica* to reconstruct natural seasonal variation of salinity before construction of Faka-Union Canal during the 1960s in the northwestern 10 Thousand Islands, Florida. Instrument records of environmental conditions before the canal was built are not available and only anecdotal information documents pre-canal conditions. Therefore, oysters provide a potential environmental archive of the natural, pre-canal, seasonal change in water conditions. We established a radiocarbon-calibrated, amino acid geochronology to date shells that were alive before construction of Faka-Union Canal. This calibration required determination of the reservoir age effect of  $^{14}\text{C}$  for marine samples in this part of the Gulf of Mexico, which allowed comparison of environmental reconstructions from live-collected shells and dated subfossil shells within modified and unmodified estuaries. Amino-acid geochronology rather than radiocarbon dating was preferred because the usefulness of radiocarbon dating is hampered by (1) the uncertainties of the reservoir effect in samples from a brackish environment; (2) fluctuation in atmospheric  $^{14}\text{C}$  levels due to natural variability in  $^{14}\text{C}$  production rates and contributions of  $\text{CO}_2$  from the burning of fossil fuels (the Suess effect); and (3) the poor precision of calibrated marine  $^{14}\text{C}$  ages for the last several hundred years (see, e.g. Goodfriend & Rollins, 1998).

Glutamic acid was selected for racemization dating of the oysters. This amino acid has a rate intermediate between the fast-racemizing aspartic acid and the slow-racemizing isoleucine, which have been more widely used for dating of shells. Isoleucine is present at very low amounts in oyster shells, and because of the relative youth of the shells in this study, D-alloisoleucine is present at extremely low levels and cannot be precisely quantified. D/L aspartic acid values were also measured for all shells but the results were found to be less reproducible than D/L glutamic acid values. The kinetics of glutamic acid racemization are also simpler than for aspartic acid (Goodfriend, 1991; Goodfriend & Meyer, 1991). A number of previous studies on glutamic acid racemization have been carried out on Quaternary bivalves (Kvenvolden & Blunt, 1980; Kvenvolden, Blunt, & Clifton, 1979; Muhs, Miller, Whelan, & Kennedy, 1992; Wehmiller, 1977), including a study on oysters (Atwater, Ross, & Wehmiller, 1981).

Once oysters were dated, comparisons were made of stable isotopic compositions in live-collected and subfossil shells from Faka-Union (modified) and Blackwater (unmodified) estuaries. Information gleaned from the environmental records contained in oyster shells will contribute to studies estimating the natural variability of coastal ecosystems (past and present) and provide guidelines for their restoration and management.

### 1.1. History of environmental alteration

Faka-Union Bay receives freshwater via direct point flow following construction of Faka-Union Canal (natural watersheds receive diffusive sheet flow where surface runoff is filtered through marshes and prairie wetlands). Extensive canal systems built throughout southwest Florida drain agricultural lands and residential developments. Faka-Union Canal is part of an extensive canal system that drains one of the largest subdivisions in the country, Golden Gate Estates (110,000 acres) located north of the Tamiami Trail. As a consequence of this construction, the Faka-Union estuary is much fresher relative to other estuaries in the 10 Thousand Islands with the development of a freshwater lens that extends well into Faka-Union Bay (D. Surge and Rookery Bay National Estuary Research Reserve (RBNERR), unpublished data). Moreover, neighboring Fakahatchee and Pumpkin Bays have elevated salinity, probably because much of the overland runoff has been captured by the extensive canal systems that drain Golden Gate Estates (Fig. 1; Delate & Haner, 1994).

Restoration efforts are now underway to return these Florida wetlands and estuaries to their natural conditions. Recent investigations and restoration management have focused on southeastern Florida, particularly Florida Bay and the Everglades (Boyer, Fourqurean, & Jones, 1999; Brewster-Wingard & Ishman, 1999; Brewster-Wingard, Ishman, & Willard, 1996; Nelsen et al., 1996; Swart, Dodge, & Hudson, 1996; Swart et al., 1999; Willard & Brewster-Wingard, 1996). Little, however, is known about the natural environmental regimes of the pre- and post-modified estuaries in southwestern Florida.

## 2. Materials and methods

### 2.1. Study area

This study focuses on one oyster reef from each of two estuaries situated in RBNERR: Blackwater River (near-natural watershed) and Faka-Union Bay (extensive channelization) (Fig. 1). The location of each oyster reef was selected based on geomorphologic similarity in order to control for differences in hydrologic regime. Because tides in this area are semi-diurnal, oyster reefs are emergent for a couple of hours twice a day. Water chemistry and estuarine mixing in Blackwater River and Faka-Union Bay are discussed in detail by Surge and Lohmann (2002). Surge et al. (2001) analyzed the geochemistry of oyster (*C. virginica*) shells and provide a calibration study documenting their utility in environmental reconstruction.

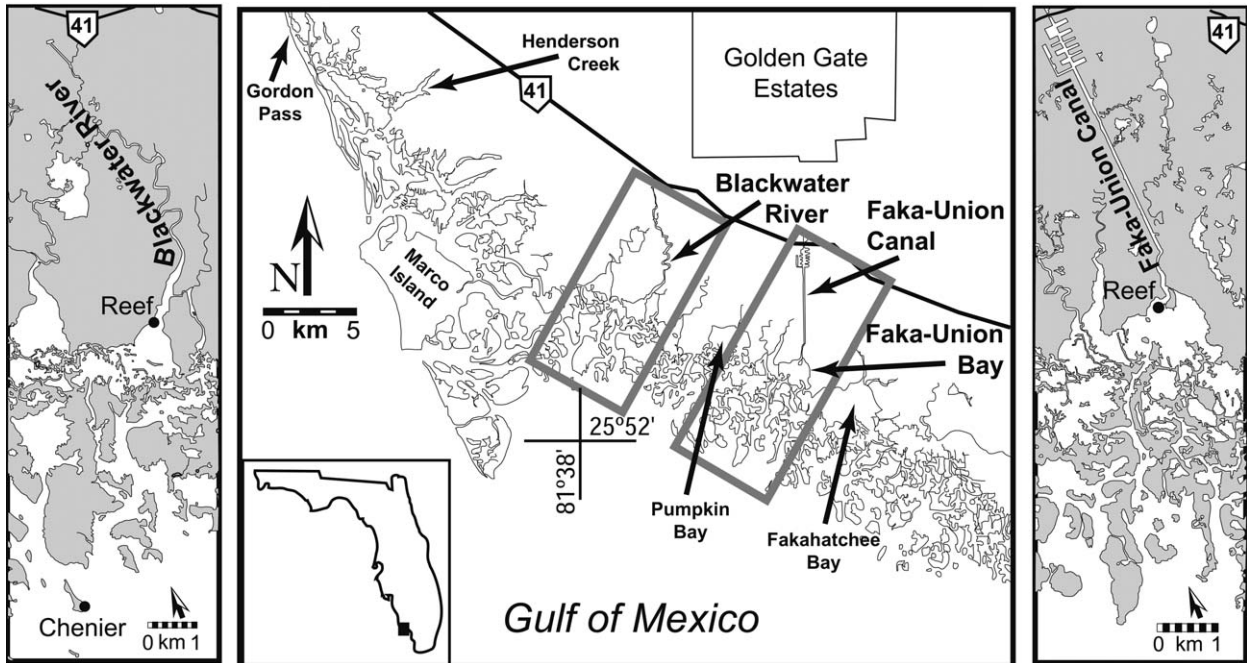


Fig. 1. Map of study area indicating sampling sites. Central panel illustrates northwestern 10 Thousand Islands on the coast of the Gulf of Mexico near Naples, Florida. Right panel is a detailed map of Blackwater River. Left panel is a detailed map of Faka-Union Bay and Canal. Route 41 is the Tamiami Trail.

## 2.2. Shell collection and sampling

Living and dead (subfossil) individuals of *C. virginica* were collected from Blackwater River and Faka-Union Bay (Fig. 1). A total of eight living (harvested in December 1997 and January 1999) and eight subfossil specimens collected from each reef were analyzed for  $\delta^{18}\text{O}_{\text{SHELL}}$  and  $\delta^{13}\text{C}_{\text{SHELL}}$ . Not all shells collected were usable for geochemical analysis because either the sampling area on the hinge of the shell was too small or the individual was too young.

The left valve from each specimen was cut parallel to growth direction from the ventral to dorsal margin. Samples for isotopic analysis were milled from the foliated microstructural area on the hinge of the left valve on the exposed surface of the cross-section (Fig. 2). Surge et al. (2001) provide a more detailed discussion of shell microstructure and biomineralization. Sampling was accomplished using a 0.5 mm dental burr (0.5 mm intervals), yielding  $\sim 30 \mu\text{g}$  of carbonate powder. All samples were roasted under vacuum at  $200^\circ\text{C}$  for 1 h, and reacted with anhydrous phosphoric acid at  $73^\circ\text{C}$  in individual reaction vessels on an on-line, automated Kiel device coupled to a Finnigan-MAT 251 mass spectrometer. The standard deviation for repeated measurements of the internal standard is  $<0.1\%$  for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values. Oxygen isotope ratios were corrected for  $^{17}\text{O}$  contribution (Craig, 1957) and are reported in per mil units with respect to the VPDB standard.

## 2.3. Radiocarbon dating methods

Radiocarbon ages of subfossil shells were determined by AMS analysis at the University of Arizona. The local radiocarbon reservoir age of the Gulf of Mexico was estimated by analyzing three pre-bomb (pre-1950)

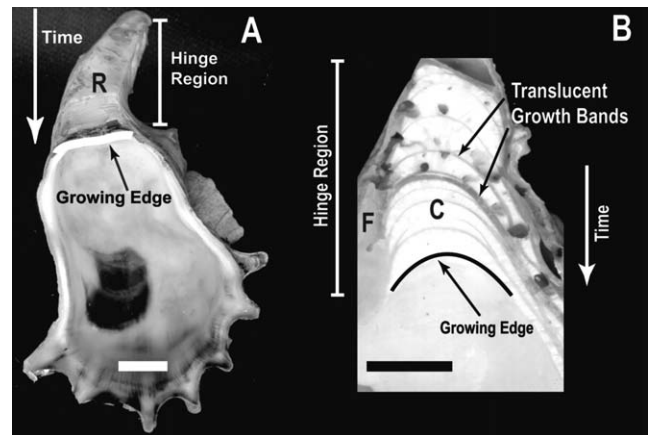


Fig. 2. Left valve of *C. virginica* both in planar (a) and cross-sectional (b) views. Bar = 1 cm. (A) Resilifer (R) is comprised of foliated calcite. (B) Cross-section of left valve cut ventrally to dorsally through the resilifer parallel to growth direction. Foliated calcite (F) underneath the resilifer surface is exposed in cross-section and is the region from which samples were milled at 0.5 mm intervals. Chalky layer (C) contains porous calcite separated by dark, translucent growth bands. Pits in the shell were caused by boring algae or sponges. Foliated calcite on the resilifer surface was sampled for isotopic analysis perpendicular to growth. Shell is secreted incrementally toward the bottom.

museum samples provided by the Division of Malacology, Florida Museum of Natural History, University of Florida, Gainesville (FMNH): *C. virginica* collected live from Gordon Pass off of Keewadin Island in 1932; and *Mercenaria campechiensis* collected live from Marco Island in 1927 and 1937 (Fig. 1). Both localities are subjected to Gulf water at marine salinities, minimizing any mixing effect with estuarine water. An additional four subfossil samples of *C. virginica* were analyzed to calibrate the racemization rate with radiocarbon ages. These four samples were collected from a chenier (elongate shell deposit) in the Gulf of Mexico beyond the Blackwater River estuary system to minimize mixing effects with estuarine water (Fig. 1).

Approximately 12 mg of powdered sample was obtained from each shell, reacted off line with anhydrous phosphoric acid, and a sample split of  $\text{CO}_2$  was analyzed at the University of Michigan for  $\delta^{13}\text{C}$  on a MAT Delta-S Finnigan ratio gas mass spectrometer having a standard precision of  $\pm 0.1\text{‰}$ . The remainder of the samples and corresponding  $\delta^{13}\text{C}$  values were sent to the University of Arizona for radiocarbon determination. Radiocarbon ages are relative to the reference year 1950 AD. We used CALIB version 4.3 to correct  $^{14}\text{C}$  dates for fluctuations in the activity of atmospheric  $^{14}\text{C}$ , as well as adjusting dates for reservoir effects in marine samples (Stuiver & Reimer, 1993). Uncorrected and corrected ages for both variation in the activity of atmospheric  $^{14}\text{C}$  and local reservoir age in the Gulf of Mexico are reported. The abbreviation 'BP' is taken to mean before 1950 AD.

#### 2.4. Amino acid dating methods

Glu is produced by living organisms in its left-handed form (L-Glu) whereby the amine group ( $\text{NH}_3^+$  in this case) is located on the left side of the molecular structure (von Endt, 1979; Wehmiller, 1982). At the time of shell formation, Glu is present only in the form of L-Glu. However, over time, this converts (racemizes) to D-Glu, up to an equilibrium ratio of 1:1. If the rate of racemization is known, the D/L ratio can be used to determine the age of the specimen. This rate is both taxon specific and temperature dependent. Based on chenier deposits in the Colorado River delta, Goodfriend, Flessa, and Kowalewski (1995) determined that no differences in racemization rates were found among samples buried at various depths from 20 to 150 cm. Therefore, to minimize the effect of temperature, all subfossil shells were collected from  $\sim 25$  cm below the surface of the shell deposit where they should be subjected to the same thermal regime. Because surface shells are heated to higher temperatures when the chenier is emergent during the day, they might appear artificially older than shells collected 25 cm below the surface. Care was taken to not collect surface shells that

might have fallen into the excavated pit. Given that many shells are cemented together, effects of bioturbation are negligible.

Subfossil shells were collected from each oyster reef for D/L Glu analysis. After cataloguing each specimen, shells were culled based on the amount of hinge area available for sampling and based on the presence of periostracum which would indicate that the individual had died recently and is probably not of pre-canal age. Of the subfossil shells collected, eight shells from each of the oyster localities in Blackwater and Faka-Union estuaries were selected for analysis. One shell from Blackwater estuary was destroyed during cross-sectioning; therefore, only seven D/L Glu values are reported.

For amino acid analysis, samples were taken from the hinge area of the left valve (Fig. 2) where shell microstructure is predominantly foliated, to avoid possible heterogeneity in racemization rates due to varying microstructures (Goodfriend, Flessa, & Hare, 1997). Samples were cleaned using a Dremel motorized tool fitted with a fine, tapered tip and 20–50 mg aliquots were cut off using a small wire cutter. To account for the racemization induced by the sample preparation, a live-collected shell was also analyzed to determine the D/L Glu value for modern samples. Samples for D/L Glu analysis were prepared and measured via gas chromatography using the procedures outlined in Goodfriend (1991). Analyses were carried out using an HP5890, series II, gas chromatograph, with Chirasil-val column and NP detector. Analytical errors averaged 5% of the D/L value. Calibrated amino acid ages are referenced to 1998 (when the samples were analyzed for D/L Glu) by adding 48 years to each age.

### 3. Results

#### 3.1. Geochronology

To correct radiocarbon ages of marine samples, a time-dependent average global ocean reservoir correction ( $\sim 400$  years) can be selected in CALIB 4.3. However, to more accurately correct  $^{14}\text{C}$  ages, a local reservoir correction ( $\Delta R$ ) can be incorporated into the program.  $\Delta R$  is a region-specific term representing the  $^{14}\text{C}$  activity differences of local and average world ocean surface layers (Stuiver & Reimer, 1993). Stuiver, Pearson, and Braziunas (1986) and Stuiver and Reimer (1993) provide values of  $\Delta R$  for some localities on the globe; however, none are reported for southwest Florida. The closest locality to the study area is offshore of the Florida Keys, having a  $\Delta R$  value of 13 ( $\pm 16$ ) years (Stuiver et al., 1986). Given differences in local oceanic upwelling, we determined  $\Delta R$  for the north-western 10 Thousand Islands by analyzing museum samples of pre-bomb marine bivalves collected alive

Table 1  
Calculated local reservoir effect ( $\Delta R$ ) for southwestern Florida based on museum specimens

FMNH No.	Taxon	Year collected	Pre-1950 'True' Age	Model $^{14}\text{C}$ Age <sup>a</sup>	Uncorrected AMS $^{14}\text{C}$ Age <sup>b</sup>	$\Delta R$
15491	<i>C. virginica</i>	1932	18	469	575 ( $\pm 45$ )	106
253220 I357	<i>M. campechiensis</i>	1927	23	465	630 ( $\pm 45$ )	165
16179	<i>M. campechiensis</i>	1937	13	473	595 ( $\pm 45$ )	122
					Mean:	130
					Standard Error:	18

<sup>a</sup> See Table 1 in Stuiver and Reimer (1993).

<sup>b</sup> Standard deviation in parentheses.

near Naples, Florida between 1927 and 1937 AD (Table 1). Uncorrected AMS radiocarbon ages range from 575 to 595 BP ( $\pm 45$  years). To calculate  $\Delta R$ , the predicted marine model  $^{14}\text{C}$  age from Table 1 in Stuiver and Reimer (1993) was subtracted from the uncorrected AMS radiocarbon age for that year. For example, the *C. virginica* shell collected alive in 1932 gave an AMS  $^{14}\text{C}$  age of 575 yr BP. Its model  $^{14}\text{C}$  age (for 1932, from Stuiver & Reimer, 1993) is interpolated as 469 yr BP. The difference ( $\Delta R$ ) between AMS and modeled ages is 106 yr BP. The three shells have a mean  $\Delta R$  of 130 years, with a standard deviation of 30 years. Note that this standard deviation is actually less than the average analytical errors for the individual shells, so all three shells had analytically indistinguishable  $\Delta R$  values. This  $\Delta R$  value of 130 years was used for calibrating the radiocarbon ages of the subfossil shells; the uncertainty of the  $\Delta R$  values, represented by the standard error of the mean or 18 years, was conservatively used for the standard deviation of the  $\Delta R$  values in the calibration procedure. In fact, the analyses demonstrate no variability in  $\Delta R$  over the time period represented. Calibrated radiocarbon ages are reported to the nearest decade given the precision of this method.

$\text{D/L Glu}$  values of subfossil shells used in constructing the calibration curve range from 0.041 to 0.097 (Table 2). The value measured for the live-collected modern shell has a mean of 0.020, and represents the racemization induced during sample preparation. Uncorrected radiocarbon ages range from 575 to 1625 yr BP. One of the shells is possibly post-bomb, whereas for the other, the error is too large relative to its age to be useful in

calibration. Therefore, these two shells were not used to construct the radiocarbon-amino acid calibration equation. The two remaining subfossil shells had corrected  $^{14}\text{C}$  ages of 250 and 1080 yr BP. The following least-squares Model I regression equation describes the relationship between  $\text{D/L Glu}$  and the corrected  $^{14}\text{C}$  age before 1998:

$$\text{Age} = 14372 (\text{D/L Glu} - 0.020)$$

( $F$ -statistic = 30.66;  $F$ -critical = 0.114;  $p = 0.05$ ).

This equation was used to convert  $\text{D/L Glu}$  values of dead shells from the oyster reefs in Blackwater River and Faka-Union Bay to years before 1998 (Table 3). These ages were converted to years AD. Each reef has a characteristically different age distribution.  $\text{D/L Glu}$  values of subfossil shells from Blackwater River range from 0.074 to 0.146. One 'old,' dead shell has a  $\text{D/L Glu}$  value (0.025) that is close to that of the modern shell (0.020) and is interpreted to be recently dead and not subfossil. Blackwater shells range in age from 190–1220 AD. In contrast,  $\text{D/L Glu}$  values of Faka-Union shells ranged from 0.029 to 0.070. Like the recently dead shell from Blackwater River, one shell from Faka-Union has a  $\text{D/L Glu}$  value (0.024) that is similar to the modern shell value. Subfossil shells from the Faka-Union Bay are younger than those from Blackwater River with ages of 1270–1860 AD.

Two explanations can account for the centuries-scale age distribution within a reef: (1) shells were transported to the reef from elsewhere; or (2) age distribution merely reflects the amount of in-situ temporal mixing within a reef. We assumed the latter explanation for the

Table 2  
Calibration data for converting  $\text{D/L Glu}$  values to years before 1998

Sample No.	$\text{D/L Glu}^a$	Reported $^{14}\text{C}$ Age <sup>ab</sup> (years)	$^{14}\text{C}$ Yr BP (1950) per CALIB 4.3 <sup>a</sup>	Corrected $^{14}\text{C}$ Age <sup>c</sup> (years before 1998)
CK02D-2	0.050 ( $\pm 0.002$ )	690 ( $\pm 45$ )	270-128	247
CK02D-3	0.041 ( $\pm 0.002$ )	575 ( $\pm 45$ )	Invalid age	Too young/uninformative
CK02D-8	0.067 ( $\pm 0.001$ )	610 ( $\pm 45$ )	137-0	Too young/uninformative
CK02D-9	0.097 ( $\pm 0.005$ )	1625 ( $\pm 45$ )	1104-966	1083
Modern 1997	0.020 ( $\pm 0.001$ )	N/A	1	1

<sup>a</sup> Standard deviation in parentheses.

<sup>b</sup> Age has not been corrected for the marine  $^{14}\text{C}$  reservoir age nor calibrated, but is corrected for isotopic fractionation.

<sup>c</sup> Age has been corrected for the marine  $^{14}\text{C}$  reservoir age and calibrated.

Table 3  
d/L Glu values and calculated age before 1998

Sample No.	d/L Glu	Years before 1998 <sup>a</sup>	Year AD <sup>b</sup>
BW20D1	0.0864	954	1050
BW20D2	0.119	1423	580
BW20D3	0.109	1279	720
BW20D4	0.0744	782	1220
BW20D6	0.146	1811	190
BW20D7	0.0252	75 (recently dead)	Recent
FU90D2	Below detection limits	Recently dead	Recent
FU90D3	0.0579	545	1450
FU90D8	0.0298	141	1860
FU90D9	0.0366	178	1820
FU90D10	0.044	345	1650
FU90D11	0.0366	239	1760
FU90D13	0.0708	730	1270
FU90D20	0.0243	62 (recently dead)	Recent

<sup>a</sup> Age calculation based on calibration equation.

<sup>b</sup> Rounded up to the nearest decade.

following reasons. Kidwell and Flessa (1995) have reported that the fauna comprising shelly coastal deposits represent the accumulation of species occupying that area over a period of time (i.e. they were probably not transported in from another environment) and that dated shells from such deposits are especially useful for reconstructing past environments over extended time intervals. With this in mind, the oyster reefs selected for this study are the most upstream reefs in each estuary, and, in general, oyster reefs in this area are isolated mounds that are several meters to tens of meters apart. It is unlikely that a shell from one reef would be picked up by storm or tidal action and selectively placed on another reef. Given the coarse grain size of individual shells, these would most likely be deposited in inter-reef areas. Moreover, shells as old as hundreds to thousands of years are common in many coastal deposits (Flessa & Kowalewski, 1994; Kidwell & Bosence, 1991; Kowalewski, Goodfriend, & Flessa, 1998; Stapor & Mathews, 1983; Stapor, Mathews, & Lindfors-Kearns, 1988). Kowalewski et al. (1998) demonstrate time-averaging on the order of hundreds to thousands of years within chenier deposits from the Colorado delta. They also assert that “if a major storm hit the Colorado delta, the resulting deposit, even though formed in several hours rather than several decades, would be made of the same bioclasts that make up the cheniers.” Thus, the range of ages seen in oyster reefs in this study are rather typical. A more precise test of a lack of transport would compare numbers of right valves versus numbers of left valves, assuming that preferential sorting would occur during transport.

### 3.2. Oyster isotopic composition

Temporal variation in oxygen and carbon isotope composition within a shell is more or less sinusoidal

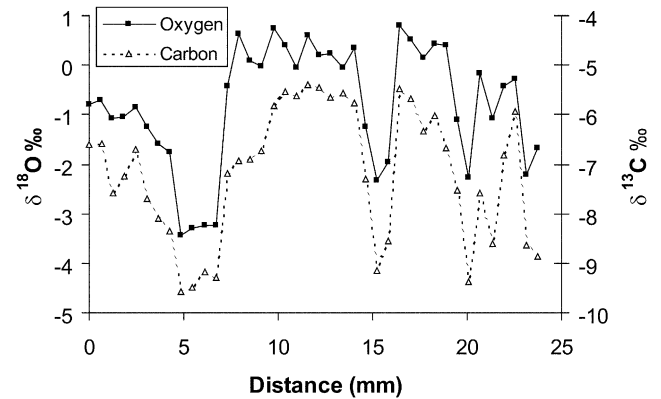


Fig. 3. Profiles of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  of live-collected specimen FU90L5 from umbo to growth margin. Black square are  $\delta^{18}\text{O}$  and open triangles are  $\delta^{13}\text{C}$ . Left y-axis corresponds to  $\delta^{18}\text{O}$  and right y-axis refers to  $\delta^{13}\text{C}$ .

(Fig. 3 and Table 4). One complete cycle represents 1 year of growth (see Section 4). Cross-plots of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  reveal covariant trends, and shells from live and dead assemblages plot in different fields (Fig. 4). Mean  $\delta^{18}\text{O}$  of shells from Faka-Union Bay are more negative than that of shells from Blackwater River (Faka-Union modern:  $-0.98\text{‰}$ , Faka-Union subfossil:  $-0.52\text{‰}$ ; Blackwater modern:  $-0.44\text{‰}$ ; Blackwater subfossil:  $-0.10\text{‰}$ ). Modern shells from both estuaries have more negative mean  $\delta^{13}\text{C}$  than subfossil shells (Faka-Union modern:  $-7.25\text{‰}$ , Faka-Union subfossil:  $-5.99\text{‰}$ ; Blackwater modern:  $-6.89\text{‰}$ ; Blackwater subfossil:  $-4.49\text{‰}$ ). To test the statistical significance of these similarities and differences *within* and *among* given assemblages (an assemblage is defined as a collection of shells from a given estuary that were either collected live or are subfossil; e.g. all subfossil shells from Blackwater River are considered an assemblage), the GT2 method for unplanned comparisons as modified by Gabriel (1978) was employed because the number of samples for each shell is unequal (Fig. 5). This statistical method constructs lower and upper comparison (not confidence) limits for each parameter (mean  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) such that two shells are considered significantly different (at 95% confidence in this case) if and only if their intervals do not overlap. The following equations proposed by Gabriel (1978) were used to calculate the lower and upper comparison limits:

$$l_i = \bar{Y}_i - \sqrt{1/2}m_{z[k,v]}s$$

$$u_i = \bar{Y}_i + \sqrt{1/2}m_{z[k,v]}s$$

where  $l_i$  is the lower comparison limit,  $u_i$  is the upper comparison limit,  $\bar{Y}_i$  is the shell mean,  $m$  is the critical value obtained from the two-tailed studentized maximum modulus statistical table (Rohlf & Sokal, 1995),

Table 4  
Isotopic composition of modern and subfossil oyster shells

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
Blackwater modern shells				
BW20L1	0.37	1997	-0.14	-6.77
BW20L1	0.78	1997	-0.58	-6.44
BW20L1	1.20	1997	-0.92	-8.04
BW20L1	1.61	1997	-0.95	-7.63
BW20L1	2.02	1997	-1.07	-7.59
BW20L1	2.43	1997	-0.73	-6.99
BW20L1	3.25	1997	0.77	-5.75
BW20L1	3.67	1997	0.38	-6.01
BW20L1	4.08	1997	1.23	-5.63
BW20L1	4.49	1997	1.02	-5.02
BW20L1	4.90	1997	1.00	-5.27
BW20L1	5.31	1997	1.02	-4.78
BW20L1	5.72	1997	0.47	-4.88
BW20L1	6.14	1997	0.65	-6.03
BW20L1	6.55	1997	0.17	-5.31
BW20L1	6.96	1997	0.38	-5.19
BW20L1	7.37	1997	0.29	-4.95
BW20L1	7.78	1997	0.71	-5.69
BW20L1	8.19	1997	0.05	-5.27
BW20L1	8.61	1997	0.65	-5.84
BW20L1	9.02	1997	-0.10	-5.58
BW20L1	9.43	1997	0.04	-6.03
BW20L1	9.84	1997	-0.88	-6.28
BW20L1	10.25	1997	-0.97	-6.68
BW20L1	10.66	1997	-1.52	-7.42
BW20L1	11.08	1997	-1.07	-7.69
BW20L1	11.49	1997	-0.73	-7.22
BW20L1	11.90	1997	-0.45	-8.03
BW20L2	0.00	1997	0.37	-6.29
BW20L2	0.63	1997	0.47	-6.00
BW20L2	1.27	1997	0.41	-6.05
BW20L2	1.90	1997	0.88	-5.62
BW20L2	2.54	1997	0.65	-5.85
BW20L2	3.17	1997	0.32	-7.27
BW20L2	3.81	1997	-0.50	-7.16
BW20L2	4.44	1997	0.05	-6.28
BW20L2	5.08	1997	0.70	-6.24
BW20L2	5.71	1997	0.39	-6.78
BW20L2	6.35	1997	0.16	-6.77
BW20L2	6.98	1997	0.14	-5.66
BW20L2	7.62	1997	0.22	-5.80
BW20L2	8.25	1997	-0.53	-6.74
BW20L2	8.89	1997	-0.80	-7.00
BW20L2	9.52	1997	-0.57	-7.29
BW20L2	10.16	1997	-0.78	-8.30
BW20L2	10.79	1997	-1.34	-8.37
BW20L2	11.43	1997	-1.05	-8.08
BW20L2	12.06	1997	-1.02	-8.30
BW20L2	12.70	1997	-0.95	-8.67
BW20L2	13.33	1997	-0.60	-7.89
BW20L2	13.97	1997	0.32	-7.20
BW20L2	14.60	1997	-0.19	-7.52
BW20L3	0.00	1999	-0.08	-6.48
BW20L3	0.47	1999	0.10	-6.34
BW20L3	0.95	1999	0.03	-6.10
BW20L3	1.42	1999	0.09	-6.42
BW20L3	1.89	1999	-0.18	-6.35
BW20L3	2.37	1999	-0.42	-6.67
BW20L3	2.84	1999	-0.14	-5.58
BW20L3	3.31	1999	-0.61	-6.44
BW20L3	3.78	1999	-1.45	-7.24

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
BW20L3	4.26	1999	-0.95	-7.40
BW20L3	4.73	1999	-1.98	-8.64
BW20L3	5.20	1999	-1.61	-8.10
BW20L3	5.68	1999	-0.42	-7.98
BW20L3	6.15	1999	-1.26	-8.21
BW20L3	6.62	1999	-0.88	-7.93
BW20L3	7.10	1999	-1.04	-8.09
BW20L3	7.57	1999	0.19	-7.01
BW20L3	8.04	1999	0.44	-6.66
BW20L3	8.52	1999	-1.34	-8.40
BW20L3	8.99	1999	-0.37	-7.59
BW20L3	9.46	1999	0.11	-6.97
BW20L3	9.94	1999	0.08	-7.18
BW20L3	10.41	1999	0.43	-6.85
BW20L3	10.88	1999	-0.37	-6.82
BW20L3	11.35	1999	-0.05	-5.57
BW20L3	11.83	1999	-0.19	-5.31
BW20L3	12.30	1999	-1.33	-7.40
BW20L3	12.77	1999	-0.75	-8.17
BW20L3	13.25	1999	-1.92	-8.88
BW20L3	13.72	1999	-0.44	-6.49
BW20L4	0.00	1999	-0.10	-6.82
BW20L4	0.49	1999	-1.03	-6.55
BW20L4	0.97	1999	-0.16	-5.99
BW20L4	1.46	1999	-0.24	-5.77
BW20L4	1.95	1999	-0.51	-5.64
BW20L4	2.43	1999	-0.30	-5.37
BW20L4	2.92	1999	-0.48	-5.53
BW20L4	3.41	1999	-1.68	-6.61
BW20L4	3.90	1999	-1.53	-6.66
BW20L4	4.38	1999	-1.47	-6.57
BW20L4	4.87	1999	-0.99	-6.18
BW20L4	5.36	1999	-1.16	-6.37
BW20L4	5.84	1999	-1.83	-7.71
BW20L4	6.33	1999	-1.22	-7.86
BW20L4	6.82	1999	-1.51	-8.84
BW20L4	7.30	1999	-0.75	-8.22
BW20L4	7.79	1999	-1.63	-9.00
BW20L4	8.28	1999	-2.29	-9.32
BW20L4	8.77	1999	-0.78	-8.48
BW20L4	9.25	1999	-1.50	-8.18
BW20L4	9.74	1999	-1.75	-8.32
BW20L4	10.23	1999	-0.67	-7.04
BW20L4	10.71	1999	0.00	-6.87
BW20L4	11.20	1999	0.08	-5.74
BW20L5	0.00	1999	-1.53	-8.70
BW20L5	0.47	1999	-0.43	-7.71
BW20L5	1.07	1999	0.62	-6.81
BW20L5	1.64	1999	-1.41	-8.46
BW20L5	2.11	1999	0.24	-7.56
BW20L5	2.45	1999	0.31	-7.09
BW20L5	2.97	1999	0.54	-7.37
BW20L5	3.47	1999	-0.04	-7.38
BW20L5	3.92	1999	0.37	-7.28
BW20L5	4.34	1999	0.04	-7.04
BW20L5	4.71	1999	0.36	-6.14
BW20L5	5.24	1999	0.24	-6.06
BW20L5	5.71	1999	0.06	-6.03
BW20L5	6.18	1999	-0.29	-5.79
BW20L5	6.59	1999	-1.12	-6.51
BW20L5	7.07	1999	-1.00	-7.27
BW20L5	7.49	1999	-1.08	-7.98

(continued on next page)

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
BW20L5	8.02	1999	-1.83	-8.79
BW20L5	8.40	1999	-0.92	-8.43
BW20L5	8.92	1999	-2.22	-8.39
BW20L5	9.25	1999	-2.30	-8.57
BW20L5	9.59	1999	-1.09	-7.55
BW20L5	9.98	1999	-0.95	-6.79
BW20L5	10.42	1999	-0.19	-6.85
BW20L5	10.85	1999	0.17	-6.64
BW20L5	11.27	1999	0.16	-5.87
BW20L5	11.57	1999	0.39	-6.17
Blackwater subfossil shells				
BW20D6	0.00	190	0.11	-2.88
BW20D6	0.44	190	-0.61	-3.66
BW20D6	0.88	190	-0.99	-4.08
BW20D6	1.32	190	-0.69	-3.91
BW20D6	1.77	190	-1.10	-5.21
BW20D6	2.21	190	-3.43	-7.08
BW20D6	2.65	190	-2.44	-6.70
BW20D6	3.97	190	-0.90	-5.26
BW20D6	4.41	190	-1.65	-5.80
BW20D6	4.86	190	-2.32	-5.85
BW20D6	5.30	190	-1.64	-5.56
BW20D6	5.74	190	-1.05	-4.77
BW20D6	6.18	190	-0.51	-4.24
BW20D6	6.62	190	0.04	-3.98
BW20D6	7.06	190	0.77	-3.14
BW20D6	7.50	190	1.19	-3.30
BW20D6	7.94	190	0.50	-3.07
BW20D6	8.39	190	0.25	-2.78
BW20D6	8.83	190	0.40	-3.34
BW20D6	9.27	190	0.46	-2.85
BW20D6	9.71	190	0.41	-2.78
BW20D6	10.15	190	-0.52	-5.29
BW20D6	10.59	190	-1.17	-5.81
BW20D6	11.03	190	-2.24	-6.60
BW20D6	11.48	190	-0.62	-5.00
BW20D6	11.92	190	1.16	-3.59
BW20D6	12.36	190	0.62	-3.81
BW20D6	12.80	190	0.48	-3.97
BW20D2	0.00	590	0.56	-5.91
BW20D2	0.32	590	0.54	-4.89
BW20D2	0.64	590	0.57	-5.33
BW20D2	0.96	590	0.64	-4.91
BW20D2	1.27	590	0.64	-4.65
BW20D2	1.59	590	-0.62	-5.78
BW20D2	1.91	590	-1.03	-6.57
BW20D2	2.23	590	-0.93	-6.72
BW20D2	2.55	590	0.37	-5.55
BW20D2	2.87	590	0.14	-5.22
BW20D2	3.19	590	0.83	-4.77
BW20D2	3.51	590	0.65	-5.00
BW20D2	3.82	590	0.92	-3.96
BW20D2	4.14	590	0.20	-3.65
BW20D2	4.46	590	-0.66	-5.99
BW20D2	4.78	590	0.08	-5.42
BW20D2	5.10	590	0.74	-5.48
BW20D2	5.42	590	0.29	-5.57
BW20D2	5.74	590	0.24	-4.96
BW20D2	6.05	590	1.21	-5.05
BW20D2	6.37	590	1.49	-4.59
BW20D2	6.69	590	0.69	-4.40
BW20D2	7.01	590	0.43	-4.01
BW20D3	0.02	720	-2.17	-7.49

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
BW20D3	0.45	720	-1.31	-6.85
BW20D3	0.87	720	-0.99	-6.41
BW20D3	1.29	720	-1.46	-6.04
BW20D3	1.72	720	-1.39	-6.34
BW20D3	2.14	720	-1.51	-7.02
BW20D3	2.56	720	-1.09	-6.16
BW20D3	2.98	720	0.21	-5.31
BW20D3	3.41	720	0.61	-4.17
BW20D3	3.83	720	0.10	-4.68
BW20D3	4.25	720	0.23	-5.18
BW20D3	4.68	720	0.58	-4.92
BW20D3	5.10	720	1.01	-3.78
BW20D3	5.52	720	0.43	-3.85
BW20D3	5.95	720	1.09	-3.51
BW20D3	6.37	720	0.46	-3.99
BW20D3	6.79	720	-0.03	-3.97
BW20D3	7.22	720	0.47	-3.28
BW20D3	7.64	720	0.70	-3.28
BW20D3	8.06	720	0.08	-3.16
BW20D3	8.48	720	-2.03	-6.85
BW20D3	8.91	720	-0.87	-6.66
BW20D3	9.33	720	-0.93	-6.08
BW20D3	9.75	720	0.95	-4.53
BW20D3	10.18	720	1.53	-3.71
BW20D3	10.60	720	1.23	-3.26
BW20D1	0.00	1050	-2.38	-6.50
BW20D1	0.44	1050	-2.14	-6.66
BW20D1	1.32	1050	-1.22	-6.32
BW20D1	1.76	1050	-0.47	-5.83
BW20D1	2.19	1050	-0.98	-6.15
BW20D1	2.63	1050	-0.85	-5.98
BW20D1	3.07	1050	-0.94	-6.32
BW20D1	3.51	1050	-0.38	-5.65
BW20D1	3.95	1050	0.26	-4.94
BW20D1	4.39	1050	0.48	-4.73
BW20D1	4.83	1050	0.85	-4.22
BW20D1	5.27	1050	1.60	-3.69
BW20D1	5.71	1050	1.49	-3.24
BW20D1	6.14	1050	0.83	-2.81
BW20D1	6.58	1050	1.08	-2.82
BW20D1	7.02	1050	0.77	-2.94
BW20D1	7.46	1050	0.64	-2.99
BW20D1	7.90	1050	0.54	-3.37
BW20D1	8.34	1050	1.04	-3.60
BW20D1	8.78	1050	0.72	-2.85
BW20D1	9.22	1050	0.17	-3.40
BW20D1	9.66	1050	0.06	-3.64
BW20D1	10.09	1050	-1.72	-5.74
BW20D1	10.53	1050	-1.78	-6.20
BW20D1	10.97	1050	-0.92	-5.08
BW20D1	11.41	1050	0.78	-3.78
BW20D1	11.85	1050	0.82	-3.96
BW20D1	12.29	1050	0.71	-5.07
BW20D1	12.73	1050	0.77	-3.41
BW20D1	13.17	1050	0.65	-2.97
BW20D1	13.61	1050	0.23	-3.12
BW20D1	14.48	1050	0.20	-3.68
BW20D1	14.92	1050	0.89	-4.21
BW20D1	15.36	1050	0.91	-3.56
BW20D1	15.80	1050	1.11	-3.34
BW20D1	16.24	1050	0.84	-2.93
BW20D1	17.12	1050	0.26	-2.76
BW20D1	17.56	1050	-0.46	-4.36

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
BW20D1	18.00	1050	-0.30	-4.96
BW20D1	18.43	1050	0.33	-4.05
BW20D1	18.87	1050	0.16	-4.77
BW20D1	19.31	1050	0.51	-4.26
BW20D1	19.75	1050	0.64	-4.30
BW20D1	20.19	1050	0.57	-4.84
BW20D1	20.63	1050	0.85	-3.54
BW20D1	21.07	1050	0.68	-3.59
BW20D1	21.51	1050	0.81	-3.49
BW20D1	21.95	1050	0.64	-4.96
BW20D1	22.82	1050	0.39	-3.16
BW20D1	23.70	1050	0.04	-3.77
BW20D4	0.00	1220	-0.22	-4.42
BW20D4	0.54	1220	0.58	-3.70
BW20D4	1.07	1220	0.63	-2.74
BW20D4	1.61	1220	0.89	-2.09
BW20D4	2.14	1220	0.96	-1.80
BW20D4	2.68	1220	0.85	-2.41
BW20D4	3.21	1220	0.75	-2.04
BW20D4	3.75	1220	-0.01	-2.36
BW20D4	4.28	1220	-0.16	-2.16
BW20D4	4.82	1220	0.04	-2.77
BW20D4	5.35	1220	0.59	-3.00
BW20D4	5.89	1220	-1.23	-4.54
BW20D4	6.42	1220	-2.15	-5.58
BW20D4	6.96	1220	-1.34	-4.94
BW20D4	7.49	1220	-1.07	-5.48
BW20D4	8.03	1220	-1.28	-5.72
BW20D4	9.10	1220	-0.10	-4.40
BW20D4	9.63	1220	0.56	-2.60
BW20D4	10.17	1220	0.10	-2.46
BW20D4	10.70	1220	-0.53	-3.60
BW20D4	11.24	1220	-1.70	-5.58
BW20D4	11.77	1220	-1.99	-6.28
BW20D4	12.31	1220	-1.67	-5.59
BW20D4	12.84	1220	-0.12	-4.18
BW20D4	13.38	1220	-0.14	-3.46
BW20D4	13.91	1220	-2.47	-5.70
BW20D4	14.45	1220	-1.96	-5.65
BW20D4	14.98	1220	-1.59	-5.22
BW20D4	15.52	1220	-0.74	-5.02
Faka-Union modern shells				
FU90L1	0.00	1999	0.06	-5.86
FU90L1	0.93	1999	-0.27	-6.00
FU90L1	1.40	1999	-0.25	-5.82
FU90L1	1.87	1999	-0.37	-5.72
FU90L1	3.27	1999	-0.34	-6.11
FU90L1	3.73	1999	-0.29	-5.91
FU90L1	4.20	1999	0.03	-5.99
FU90L1	4.67	1999	-1.26	-6.87
FU90L1	5.13	1999	-2.46	-7.96
FU90L1	5.60	1999	-1.96	-7.73
FU90L1	6.07	1999	-1.65	-7.85
FU90L1	6.53	1999	-1.29	-7.49
FU90L1	7.47	1999	-2.27	-9.00
FU90L1	7.93	1999	-2.72	-9.40
FU90L1	8.40	1999	-2.39	-9.31
FU90L1	8.87	1999	-2.31	-9.52
FU90L1	9.33	1999	-2.25	-9.21
FU90L1	9.80	1999	-1.95	-9.20
FU90L1	10.27	1999	-2.71	-9.46
FU90L1	10.73	1999	-2.02	-8.90
FU90L1	11.20	1999	-0.40	-7.44

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
FU90L1	11.67	1999	0.05	-7.44
FU90L1	12.13	1999	0.97	-6.29
FU90L1	12.60	1999	0.45	-6.23
FU90L1	13.07	1999	0.91	-5.90
FU90L1	13.53	1999	0.52	-5.91
FU90L1	14.00	1999	0.33	-6.31
FU90L1	14.47	1999	0.48	-6.09
FU90L1	14.93	1999	0.03	-7.12
FU90L1	15.40	1999	-0.20	-7.13
FU90L1	15.87	1999	-0.41	-7.79
FU90L1	16.33	1999	-2.55	-9.52
FU90L1	16.80	1999	-0.49	-7.98
FU90L1	17.27	1999	-0.55	-6.48
FU90L1	17.73	1999	-1.62	-8.32
FU90L1	18.20	1999	-1.45	-8.61
FU90L2	0.00	1999	-0.83	-6.36
FU90L2	0.58	1999	-1.06	-6.49
FU90L2	1.16	1999	-1.07	-6.53
FU90L2	1.74	1999	-1.61	-7.33
FU90L2	2.32	1999	-2.71	-8.88
FU90L2	2.90	1999	-2.59	-8.91
FU90L2	3.48	1999	-1.21	-7.73
FU90L2	4.06	1999	0.36	-6.62
FU90L2	4.64	1999	0.25	-5.12
FU90L2	5.22	1999	0.02	-5.51
FU90L2	5.80	1999	-2.23	-8.33
FU90L2	6.38	1999	-2.34	-8.95
FU90L2	6.96	1999	-2.11	-8.80
FU90L2	7.54	1999	-0.10	-6.62
FU90L2	8.12	1999	0.68	-5.09
FU90L2	8.70	1999	-0.07	-5.17
FU90L2	9.28	1999	0.29	-5.54
FU90L2	9.86	1999	0.03	-6.28
FU90L2	10.44	1999	-0.75	-7.32
FU90L2	11.02	1999	-2.16	-8.44
FU90L2	11.60	1999	-1.38	-7.87
FU90L2	12.18	1999	-0.66	-7.58
FU90L2	12.76	1999	-0.46	-6.53
FU90L2	13.34	1999	-1.37	-8.21
FU90L3	0.00	1999	0.21	-5.34
FU90L3	0.52	1999	-0.30	-5.44
FU90L3	1.04	1999	-0.03	-5.61
FU90L3	1.56	1999	0.00	-6.00
FU90L3	2.08	1999	-0.11	-6.33
FU90L3	2.59	1999	-0.02	-5.86
FU90L3	3.11	1999	-1.10	-6.04
FU90L3	3.63	1999	-0.33	-5.93
FU90L3	4.15	1999	-0.12	-5.97
FU90L3	4.67	1999	-0.24	-5.94
FU90L3	5.19	1999	-0.72	-6.20
FU90L3	5.71	1999	-1.54	-7.28
FU90L3	6.22	1999	-1.76	-7.93
FU90L3	6.74	1999	-2.37	-8.46
FU90L3	7.26	1999	-3.29	-9.16
FU90L3	7.78	1999	-2.90	-8.89
FU90L3	8.30	1999	-2.80	-8.78
FU90L3	8.82	1999	-2.61	-8.65
FU90L3	9.34	1999	-2.69	-8.70
FU90L3	9.86	1999	-2.42	-8.51
FU90L3	10.38	1999	-2.38	-8.21
FU90L3	10.89	1999	-2.03	-8.19
FU90L3	11.41	1999	-2.14	-8.68

(continued on next page)

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
FU90L3	11.93	1999	-2.43	-8.75
FU90L3	12.45	1999	-0.62	-7.09
FU90L4	0.00	1999	0.06	-4.80
FU90L4	0.62	1999	0.02	-5.55
FU90L4	1.25	1999	-0.30	-5.47
FU90L4	1.87	1999	-0.43	-5.52
FU90L4	2.50	1999	-0.20	-5.61
FU90L4	3.12	1999	-0.03	-5.71
FU90L4	3.74	1999	-0.84	-6.85
FU90L4	4.37	1999	-2.46	-8.47
FU90L4	4.99	1999	-2.81	-9.17
FU90L4	5.62	1999	-2.53	-8.74
FU90L4	6.24	1999	-2.27	-8.56
FU90L4	6.86	1999	-2.45	-8.97
FU90L4	7.49	1999	-2.05	-8.24
FU90L4	8.11	1999	-1.53	-8.11
FU90L4	8.74	1999	-1.13	-8.07
FU90L4	9.36	1999	0.19	-6.65
FU90L4	9.98	1999	0.45	-6.50
FU90L4	10.61	1999	0.55	-5.42
FU90L4	11.23	1999	0.14	-6.07
FU90L4	11.86	1999	-2.34	-9.10
FU90L4	12.48	1999	-0.42	-7.47
FU90L4	13.10	1999	-0.79	-7.78
FU90L4	13.73	1999	-0.60	-7.43
FU90L4	14.35	1999	-0.72	-6.56
FU90L4	14.98	1999	-2.27	-9.05
FU90L4	15.60	1999	-1.87	-8.35
FU90L5	0.00	1999	-0.80	-6.62
FU90L5	0.61	1999	-0.72	-6.59
FU90L5	1.22	1999	-1.06	-7.61
FU90L5	1.83	1999	-1.03	-7.31
FU90L5	2.44	1999	-0.86	-6.77
FU90L5	3.04	1999	-1.25	-7.70
FU90L5	3.65	1999	-1.58	-8.09
FU90L5	4.26	1999	-1.75	-8.35
FU90L5	4.87	1999	-3.44	-9.57
FU90L5	5.48	1999	-3.28	-9.50
FU90L5	6.09	1999	-3.23	-9.19
FU90L5	6.70	1999	-3.23	-9.30
FU90L5	7.31	1999	-0.42	-7.18
FU90L5	7.92	1999	0.64	-6.92
FU90L5	8.53	1999	0.10	-6.89
FU90L5	9.13	1999	-0.02	-6.73
FU90L5	9.74	1999	0.74	-5.82
FU90L5	10.35	1999	0.40	-5.55
FU90L5	10.96	1999	-0.06	-5.62
FU90L5	11.57	1999	0.59	-5.39
FU90L5	12.18	1999	0.21	-5.46
FU90L5	12.79	1999	0.25	-5.64
FU90L5	13.40	1999	-0.05	-5.56
FU90L5	14.01	1999	0.33	-5.76
FU90L5	14.62	1999	-1.24	-7.30
FU90L5	15.22	1999	-2.33	-9.16
FU90L5	15.83	1999	-1.95	-8.56
FU90L5	16.44	1999	0.81	-5.48
FU90L5	17.05	1999	0.53	-5.68
FU90L5	17.66	1999	0.15	-6.34
FU90L5	18.27	1999	0.44	-6.01
FU90L5	18.88	1999	0.39	-6.67
FU90L5	19.49	1999	-1.10	-7.52
FU90L5	20.10	1999	-2.28	-9.37
FU90L5	20.71	1999	-0.18	-7.58

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
FU90L5	21.31	1999	-1.07	-8.60
FU90L5	21.92	1999	-0.42	-6.81
FU90L5	22.53	1999	-0.29	-5.94
FU90L5	23.14	1999	-2.20	-8.63
FU90L5	23.75	1999	-1.68	-8.87
FU90L6	0.00	1999	-1.18	-7.11
FU90L6	0.64	1999	-1.98	-7.58
FU90L6	1.28	1999	-3.91	-9.64
FU90L6	1.91	1999	-3.51	-9.57
FU90L6	2.55	1999	-1.29	-7.78
FU90L6	3.19	1999	0.04	-7.02
FU90L6	3.83	1999	-0.12	-6.29
FU90L6	4.47	1999	0.68	-5.60
FU90L6	5.10	1999	0.02	-5.30
FU90L6	5.74	1999	0.69	-5.42
FU90L6	6.38	1999	0.00	-6.16
FU90L6	7.02	1999	-2.19	-9.05
FU90L6	7.65	1999	-1.04	-7.75
FU90L6	8.29	1999	0.65	-5.71
FU90L6	8.93	1999	-0.66	-7.95
Faka-Union subfossil shells				
FU90D13	0.00	1270	-1.46	-8.12
FU90D13	0.52	1270	-1.45	-7.73
FU90D13	1.04	1270	-1.48	-7.82
FU90D13	1.56	1270	-1.29	-7.72
FU90D13	2.08	1270	-1.07	-7.79
FU90D13	2.61	1270	-0.80	-7.21
FU90D13	3.13	1270	-0.62	-6.91
FU90D13	3.65	1270	-0.86	-7.55
FU90D13	4.17	1270	0.18	-6.82
FU90D13	4.69	1270	-0.22	-6.68
FU90D13	5.21	1270	-0.15	-6.93
FU90D13	5.73	1270	0.90	-5.96
FU90D13	6.25	1270	1.17	-5.38
FU90D13	6.77	1270	-0.31	-5.25
FU90D13	7.29	1270	0.50	-5.81
FU90D13	7.82	1270	0.33	-6.07
FU90D13	8.34	1270	0.68	-5.56
FU90D13	8.86	1270	0.58	-5.41
FU90D13	9.38	1270	0.36	-5.00
FU90D13	9.90	1270	-0.04	-6.02
FU90D13	10.42	1270	-0.74	-6.71
FU90D13	10.94	1270	-2.78	-9.11
FU90D13	11.46	1270	-2.97	-9.03
FU90D13	11.98	1270	-1.32	-7.91
FU90D13	12.50	1270	0.20	-6.74
FU90D13	13.03	1270	-0.24	-6.49
FU90D13	13.55	1270	0.16	-6.08
FU90D13	14.07	1270	0.51	-4.98
FU90D13	14.59	1270	1.17	-4.17
FU90D13	15.11	1270	0.49	-5.42
FU90D13	15.63	1270	0.07	-6.10
FU90D13	16.15	1270	-2.65	-9.12
FU90D13	16.67	1270	-2.36	-8.94
FU90D13	17.19	1270	0.30	-6.16
FU90D13	17.71	1270	1.08	-5.16
FU90D13	18.24	1270	0.86	-4.91
FU90D13	18.76	1270	0.76	-5.34
FU90D13	19.28	1270	-0.96	-7.83
FU90D13	19.80	1270	0.24	-6.95
FU90D13	20.32	1270	1.46	-4.69
FU90D3	0.00	1450	-0.82	-4.30

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
FU90D3	0.45	1450	-0.48	-4.49
FU90D3	0.90	1450	-0.26	-4.20
FU90D3	1.35	1450	-0.09	-4.04
FU90D3	1.80	1450	-0.15	-3.95
FU90D3	2.25	1450	0.21	-3.98
FU90D3	2.71	1450	0.36	-4.02
FU90D3	3.16	1450	-0.34	-4.58
FU90D3	3.61	1450	-0.80	-4.30
FU90D3	4.06	1450	-0.16	-4.05
FU90D3	4.51	1450	0.16	-4.78
FU90D3	4.96	1450	-0.15	-3.73
FU90D3	5.41	1450	0.16	-3.59
FU90D3	5.86	1450	0.19	-3.26
FU90D3	6.31	1450	-0.45	-3.86
FU90D3	6.76	1450	-0.87	-4.35
FU90D3	7.21	1450	-1.73	-5.22
FU90D3	7.66	1450	-1.51	-5.01
FU90D3	8.12	1450	0.51	-3.95
FU90D3	8.57	1450	1.16	-3.43
FU90D3	9.02	1450	0.16	-2.79
FU90D3	9.47	1450	0.42	-3.68
FU90D3	9.92	1450	-1.15	-5.96
FU90D3	10.37	1450	-0.11	-4.37
FU90D3	10.82	1450	-0.03	-4.48
FU90D10	0.00	1650	0.40	-4.88
FU90D10	0.54	1650	0.43	-4.91
FU90D10	1.09	1650	1.18	-4.62
FU90D10	1.63	1650	1.00	-4.88
FU90D10	2.18	1650	1.13	-4.95
FU90D10	2.72	1650	1.00	-4.84
FU90D10	3.27	1650	0.94	-4.89
FU90D10	3.81	1650	0.40	-5.28
FU90D10	4.36	1650	0.44	-4.84
FU90D10	4.90	1650	0.19	-5.08
FU90D10	5.45	1650	-0.10	-5.10
FU90D10	5.99	1650	-0.14	-4.97
FU90D10	6.54	1650	-0.45	-5.25
FU90D10	7.08	1650	-0.52	-5.34
FU90D10	7.62	1650	-0.49	-5.17
FU90D10	8.17	1650	-0.20	-5.76
FU90D10	8.71	1650	-0.14	-5.32
FU90D10	9.26	1650	0.18	-5.00
FU90D10	9.80	1650	-1.07	-5.63
FU90D10	10.35	1650	-2.23	-6.02
FU90D10	10.89	1650	-1.44	-5.51
FU90D10	11.44	1650	-3.95	-6.80
FU90D10	11.98	1650	-5.08	-7.52
FU90D10	12.53	1650	-4.24	-7.37
FU90D10	13.07	1650	-3.31	-7.20
FU90D10	13.62	1650	-3.38	-7.32
FU90D10	14.16	1650	-2.89	-7.17
FU90D10	14.70	1650	-2.94	-7.20
FU90D10	15.25	1650	-2.77	-7.07
FU90D10	15.79	1650	-2.93	-7.12
FU90D10	16.34	1650	-2.56	-7.22
FU90D10	16.88	1650	-2.57	-7.22
FU90D10	17.43	1650	-2.15	-7.26
FU90D10	17.97	1650	-2.04	-7.42
FU90D10	18.52	1650	-1.47	-7.39
FU90D10	19.06	1650	-0.97	-7.84
FU90D10	19.61	1650	-0.37	-7.91
FU90D10	20.15	1650	-0.27	-7.43
FU90D10	20.70	1650	-1.23	-8.78

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
FU90D10	21.24	1650	-1.71	-7.95
FU90D11	0.00	1760	-1.93	-8.00
FU90D11	0.51	1760	-2.22	-7.93
FU90D11	1.02	1760	-2.05	-7.71
FU90D11	1.53	1760	-2.45	-8.21
FU90D11	2.03	1760	-2.51	-8.44
FU90D11	2.54	1760	-2.18	-7.95
FU90D11	3.05	1760	-1.71	-7.78
FU90D11	3.56	1760	-1.02	-7.36
FU90D11	4.07	1760	-0.38	-6.91
FU90D11	4.58	1760	-0.12	-6.48
FU90D11	5.09	1760	-0.50	-6.34
FU90D11	5.59	1760	0.21	-6.15
FU90D11	6.10	1760	0.45	-5.95
FU90D11	7.12	1760	1.00	-6.13
FU90D11	7.63	1760	0.56	-5.81
FU90D11	8.14	1760	-0.05	-5.06
FU90D11	8.64	1760	0.26	-5.08
FU90D11	9.15	1760	0.93	-4.72
FU90D11	9.66	1760	1.17	-4.53
FU90D11	10.17	1760	0.75	-4.58
FU90D11	10.68	1760	0.07	-4.53
FU90D11	11.19	1760	-3.07	-7.46
FU90D11	11.70	1760	-2.78	-7.63
FU90D11	12.20	1760	-2.63	-8.03
FU90D11	12.71	1760	-2.32	-8.29
FU90D11	13.22	1760	-2.44	-8.20
FU90D11	13.73	1760	-2.62	-8.43
FU90D11	14.24	1760	-1.55	-7.53
FU90D11	14.75	1760	0.29	-5.76
FU90D11	15.26	1760	-0.45	-6.17
FU90D11	15.76	1760	-0.57	-5.70
FU90D11	16.27	1760	-0.43	-4.89
FU90D11	16.78	1760	-0.41	-5.20
FU90D11	17.29	1760	-0.40	-5.60
FU90D11	17.80	1760	-2.03	-6.31
FU90D11	18.31	1760	-2.38	-8.02
FU90D11	18.81	1760	-1.55	-7.88
FU90D11	19.32	1760	-0.23	-6.43
FU90D11	19.83	1760	0.25	-4.77
FU90D11	20.34	1760	0.35	-4.96
FU90D11	20.85	1760	0.46	-4.59
FU90D11	21.36	1760	0.05	-5.59
FU90D11	21.87	1760	-0.44	-5.90
FU90D11	22.37	1760	-0.87	-6.58
FU90D11	22.88	1760	-1.32	-7.36
FU90D11	23.39	1760	-0.96	-7.08
FU90D11	23.90	1760	-0.49	-6.04
FU90D9	0.00	1820	-1.04	-7.07
FU90D9	0.48	1820	-0.75	-7.07
FU90D9	0.96	1820	-0.58	-7.30
FU90D9	1.43	1820	-0.50	-6.70
FU90D9	1.91	1820	-0.64	-6.55
FU90D9	2.39	1820	-0.95	-6.82
FU90D9	2.87	1820	-1.84	-6.93
FU90D9	3.35	1820	-1.84	-6.41
FU90D9	3.83	1820	-1.38	-6.06
FU90D9	4.30	1820	-0.87	-5.38
FU90D9	4.78	1820	-0.40	-6.04
FU90D9	5.26	1820	0.25	-6.13
FU90D9	5.74	1820	0.36	-5.73
FU90D9	6.22	1820	0.40	-5.38

(continued on next page)

Table 4 (continued)

Sample No.	Distance from umbo (mm)	Year AD	$\delta^{18}\text{O}$ ‰ VPDB	$\delta^{13}\text{C}$ ‰ VPDB
FU90D9	6.70	1820	0.70	-5.12
FU90D9	7.17	1820	0.65	-4.96
FU90D9	7.65	1820	0.45	-5.59
FU90D9	8.13	1820	0.30	-5.77
FU90D9	8.61	1820	0.21	-4.88
FU90D9	9.09	1820	0.53	-4.42
FU90D9	9.56	1820	0.69	-4.46
FU90D9	10.04	1820	0.93	-4.39
FU90D9	10.52	1820	0.36	-4.70
FU90D9	11.00	1820	-0.30	-6.80
FU90D9	11.48	1820	-0.12	-7.15
FU90D9	11.96	1820	-0.39	-7.46
FU90D9	12.43	1820	-0.84	-7.48
FU90D9	12.91	1820	-0.99	-7.31
FU90D9	13.39	1820	-1.69	-6.92
FU90D9	13.87	1820	-2.21	-6.69
FU90D9	14.35	1820	-1.37	-6.59
FU90D9	14.83	1820	0.36	-5.28
FU90D9	15.30	1820	0.63	-4.76
FU90D9	15.78	1820	1.18	-4.79
FU90D9	16.26	1820	0.51	-4.90
FU90D8	0.00	1850	0.05	-6.55
FU90D8	0.52	1850	0.09	-6.68
FU90D8	1.05	1850	-0.02	-6.52
FU90D8	1.57	1850	0.01	-6.21
FU90D8	2.09	1850	-0.15	-6.37
FU90D8	2.62	1850	-0.40	-6.75
FU90D8	3.14	1850	-1.86	-7.29
FU90D8	3.66	1850	-2.50	-7.69
FU90D8	4.18	1850	-3.67	-7.68
FU90D8	4.71	1850	-2.50	-6.00
FU90D8	5.23	1850	-1.54	-5.51
FU90D8	5.75	1850	-0.70	-5.64
FU90D8	6.28	1850	0.07	-5.27
FU90D8	6.80	1850	0.06	-5.91
FU90D8	7.32	1850	0.19	-5.41
FU90D8	7.85	1850	0.88	-5.34
FU90D8	8.37	1850	1.43	-5.31
FU90D8	8.89	1850	1.24	-4.97
FU90D8	9.42	1850	0.84	-4.93
FU90D8	9.94	1850	0.77	-4.57
FU90D8	10.46	1850	0.95	-4.23
FU90D8	10.98	1850	0.92	-4.36
FU90D8	11.51	1850	0.47	-4.52
FU90D8	12.03	1850	0.74	-4.36
FU90D8	12.55	1850	0.40	-4.47
FU90D8	13.08	1850	1.18	-3.64
FU90D8	13.60	1850	0.95	-3.95
FU90D8	14.12	1850	1.29	-4.05
FU90D8	14.65	1850	0.40	-5.79
FU90D8	15.17	1850	0.47	-5.85
FU90D8	15.69	1850	-0.72	-7.00
FU90D8	16.22	1850	-0.34	-6.55
FU90D8	16.74	1850	-0.50	-6.72
FU90D8	17.26	1850	0.17	-6.09
FU90D8	17.78	1850	-0.37	-6.23
FU90D8	18.31	1850	0.09	-6.18
FU90D8	18.83	1850	-1.45	-6.04
FU90D8	19.35	1850	-0.51	-5.09
FU90D8	19.88	1850	-0.07	-5.42
FU90D8	20.40	1850	0.13	-5.83

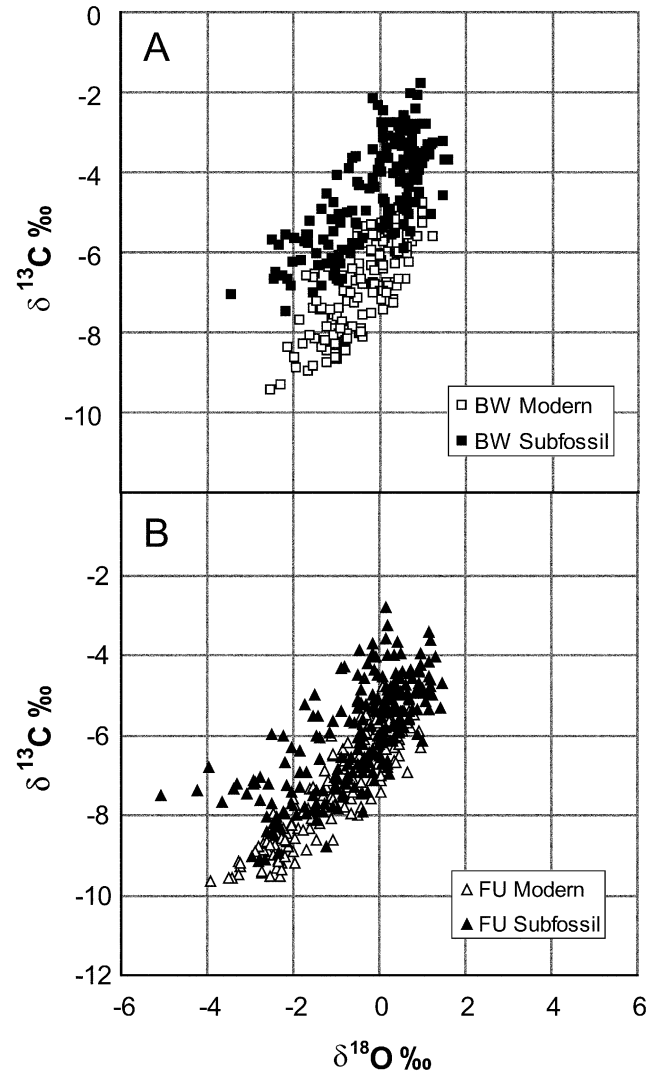


Fig. 4. Covariation of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of modern and subfossil shells from (A) Blackwater River and (B) Faka-Union Bay.

$\alpha$  is 0.05 in this case,  $k$  is the number of groups (shells),  $v$  is the degrees of freedom, and  $s$  is the standard error for each shell.

All shells are statistically indistinguishable with respect to mean  $\delta^{18}\text{O}$  (Fig. 5A). Distinct patterns are reflected in mean  $\delta^{13}\text{C}$  of shell carbonate (Fig. 5B). Mean values of  $\delta^{13}\text{C}$  from live-collected shells from both estuaries are statistically indistinguishable from each other. In contrast, all subfossil shells from Blackwater River are statistically different from four of the five shells (BW2, BW3, BW4, and BW5) that were collected live from that estuary (Fig. 5 and Table 5). Two of the subfossil shells (from years 1460 and 1860 AD) from Faka-Union Bay are statistically different from those collected live from the same site. The subfossil shell from year 1460 AD is statistically similar to subfossil shells from Blackwater River.

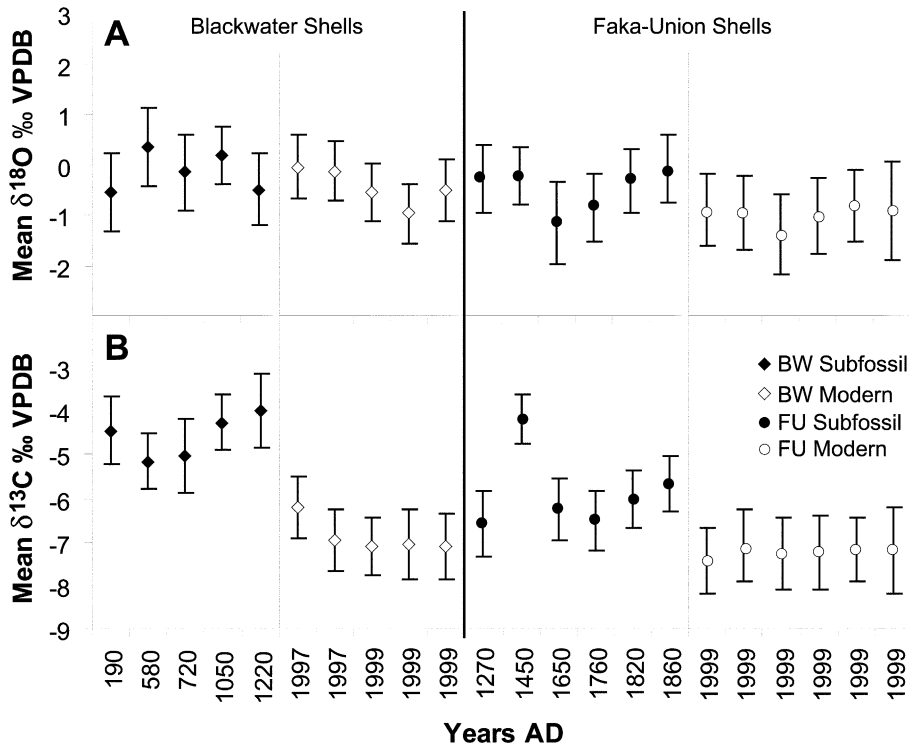


Fig. 5. Results of statistical comparison (GT2 method as modified by Gabriel (1978)) of mean (A)  $\delta^{18}\text{O}$  and (B)  $\delta^{13}\text{C}$  of individual shells. Bars through symbols indicate comparison limits at  $p = 0.05$ . Shells are statistically different from each other if and only if comparison limits do not overlap. Filled symbols represent subfossil shells, and open symbols represent modern shells. Shell numbers of subfossil shells indicate age in years AD.

Table 5  
Mean and standard error (SE) of oxygen and carbon isotope compositions of live-collected and subfossil oyster shells

Shells	Year AD	Mean $\delta^{18}\text{O}$	SE	Mean $\delta^{13}\text{C}$	SE
<i>Blackwater river</i>					
Live-collected					
BW1	1997	-0.05	0.15	-6.21	0.19
BW2	1997	-0.14	0.13	-6.96	0.19
BW3	1999	-0.54	0.13	-7.11	0.17
BW4	1999	-0.98	0.14	-7.07	0.25
BW5	1999	-0.51	0.14	-7.13	0.22
Subfossil					
BW20D6	190	-0.55	0.22	-4.44	0.24
BW20D2	580	0.35	0.22	-5.15	0.16
BW20D3	720	-0.16	0.21	-5.02	0.28
BW20D1	1050	0.20	0.13	-4.25	0.16
BW20D4	1220	-0.50	0.20	-3.98	0.27
<i>Faka-Union Bay</i>					
Live-collected					
FUL1	1999	-0.91	0.19	-7.44	0.22
FUL2	1999	-0.96	0.21	-7.09	0.26
FUL3	1999	-1.39	0.23	-7.28	0.27
FUL4	1999	-1.02	0.21	-7.24	0.28
FUL5	1999	-0.80	0.19	-7.19	0.21
FUL6	1999	-0.92	0.38	-7.20	0.38
Subfossil					
FU90D13	1270	-0.29	0.18	-6.59	0.21
FU90D3	1450	-0.23	0.13	-4.17	0.13
FU90D10	1650	-1.16	0.26	-6.24	0.19
FU90D11	1760	-0.86	0.18	-6.51	0.19
FU90D9	1820	-0.31	0.15	-6.03	0.17
FU90D8	1860	-0.09	0.18	-5.67	0.16

## 4. Discussion

### 4.1. Changes in carbon sources

Carbon isotope compositions of modern and subfossil shells from Blackwater River and Faka-Union Bay suggest an environmental change in the dominant sources of carbon (Fig. 5).  $\delta^{13}\text{C}_{\text{DIC}}$  of the water must have changed through time to result in a 1–2.5‰ offset, with subfossil shells more positive than modern shells (Fig. 5B). Three scenarios may explain this difference in  $\delta^{13}\text{C}_{\text{DIC}}$ : (1) change in freshwater input; (2) change in carbon source due to anthropogenic influence on the environment (e.g. sewage and nutrient runoff, burning of fossil fuels); or (3) change in vegetation structure. The first scenario does not seem plausible. If there was a change in the amount of rainfall, a concomitant shift in  $\delta^{18}\text{O}$  would be expected, which is not the case. The statistical similarity of  $\delta^{18}\text{O}$  among modern and subfossil samples and among estuaries is surprising given the difference in surface runoff patterns (sheet flow in Blackwater versus point flow in Faka-Union). This finding probably results from the lack of shell deposition during the summer rainy season (Surge et al., 2001). In other words, oysters inhabiting the 10 Thousand Islands may only record a very small portion of the rainy season in the late Fall and are not capturing the portion of the rainy season that occurs during summer months; thus,

differences between estuaries are not reflected in shell  $\delta^{18}\text{O}$ . We, therefore, considered the second scenario.

Anthropogenic modification of the environment is divided into two categories: (1) addition of sewage and nutrients; and (2) burning of fossil fuels. Both situations have been shown to be recorded in skeletal carbonate. Swart, Healy et al. (1996) examined a 160-year record of the stable isotopic composition of skeletal carbonate from a coral growing in Florida Bay. A sudden negative trend in  $\delta^{13}\text{C}$  values coincided with construction of the Florida East Coast Railway from Miami to Key West during the early 1900s. They suggested that construction of the railroad restricted the exchange of water between the Gulf of Mexico and the Florida reef tract, resulting in Florida Bay becoming more eutrophic and, hence, changing the isotopic composition of DIC and the  $\delta^{13}\text{C}$  of coral carbonate. (Primary productivity draws down the concentration of  $\text{CO}_2$  during photosynthesis and sequesters  $^{12}\text{C}$  in plant biomass leaving behind  $^{13}\text{C}$  in the carbon pool.) If there was a change in the nutrient and/or organic matter flux in Blackwater River and Faka-Union Bay, a difference in primary productivity would be expected between the two given their different histories of human disturbance. However, chlorophyll *a* data (a proxy for primary productivity) from Blackwater River (mean  $4.06 \pm 2.11 \mu\text{g/l}$ ) and Faka-Union Bay (mean  $5.19 \pm 2.61 \mu\text{g/l}$ ) do not support this hypothesis. Chlorophyll *a* from a nearby estuary with elevated sewage and nutrient runoff (Henderson Creek, Fig. 1) is as high as  $29.8 \mu\text{g/l}$  (L. Brand, M. Savarese and D. Surge, unpublished data), and live-collected oyster shells from Henderson Creek have much higher  $\delta^{13}\text{C}$  values (averaging approximately  $-4.5\text{‰}$ ) than those collected live from Blackwater River and Faka-Union Bay (D. Surge, unpublished data). Therefore, it is unlikely that a change in carbon sources due to nutrient and sewage inputs best explains the patterns observed in  $\delta^{13}\text{C}$  of modern and subfossil oyster shells from Blackwater River and Faka-Union Bay.

Burning of fossil fuels has affected the  $\delta^{13}\text{C}$  of the carbon pool by contributing isotopically light carbon ( $^{12}\text{C}$ ) to the atmosphere resulting in a  $1\text{--}1.5\text{‰}$  negative shift from pre-industrial values (the Suess effect) (Friedli, Löttscher, Oeschger, Siegenthaler, & Stauffer, 1986). This decline in  $\delta^{13}\text{C}$  is also reflected in marine surface water (Bacastow, Keeling, Lueker, & Wahlen, 1996; Sonnerup, Quay, & McNichol, 2000). However, the signal in marine surface water is dampened relative to the atmosphere due to disequilibrium between atmosphere–sea DIC and dilution of surface water by biologically altered subsurface water DIC (Böhm et al., 1996). Nonetheless, the Suess effect has been detected in  $\delta^{13}\text{C}$  of carbonate skeletons of corals, sponges, foraminifera, and clams (Aharon, 1991; Beveridge & Shackleton, 1994; Böhm et al., 2002; Böhm et al., 1996; Druffel & Benavides, 1986; Nozaki, Rye, Turekian, &

Dodge, 1978; Swart, Rubenstone, Charles, & Reitner, 1998). Therefore, the Suess effect may explain some, but not all, of the offset in the carbon isotope composition of modern and subfossil oysters shells from this study.

A change in vegetation structure can effect the isotopic composition of DIC. Dominant vegetation types in south Florida include mangrove forests, prairie grasslands, fresh and salt marshes, and aquatic seagrass beds (e.g. *Thalassia*). Decay of organic matter derived from these different plant types will contribute dissolved  $\text{CO}_2$  with distinctly different carbon isotope compositions to the DIC pool. For example, mangroves have the most negative  $\delta^{13}\text{C}$  averaging  $-27\text{‰}$  (Rodelli, Gearing, Gearing, Marshall, & Sasekumar, 1984). Terrestrial  $\text{C}_4$  plants, such as some grasses, average  $-12\text{‰}$  (Schlesinger, 1997). Lin, Banks, and Sternberg (1991) report that the carbon isotope composition of the seagrass *Thalassia testudinum* can range from  $-16.3$  to  $-7.3\text{‰}$ , depending on proximity to mangrove forests. Therefore, the negative shift of  $>1\text{‰}$  in  $\delta^{13}\text{C}$  from subfossil to modern oyster shells (Fig. 5) may reflect a change in the dominant carbon source, shifting from either  $\text{C}_4$  grasses or aquatic plants to mangrove forests.

In south Florida, the development of terrestrial plant communities that are supported by a freshwater wetland system of seasonal flooding and dominated by marshes and scattered tree islands (e.g. the Everglades and Big Cypress Swamp) began approximately 5000 years ago (Gleason & Stone, 1994). Along the Gulf coast and throughout Florida Bay transgressive sequences of marine–brackish sediments overlie freshwater sediments indicating that the early Everglades were considerably more extensive than present boundaries. The onset of transgressive conditions resulted in the landward retreat of Everglades wetlands and the development of saltwater-tolerant mangrove forests along coastal margins. Alternatively, aquatic plants may have dominated the carbon system in the past. *Thalassia* beds are common in the 10 Thousand Islands region. However, this habitat has suffered from human impact (e.g. damage by boat propellers, fluctuation in freshwater runoff) and may be less extensive today than they were in the past (Dawes, Andorfer, Rose, Uranowski, & Ehringer, 1997; Irlandi et al., 2002). Given the carbon isotope data from the oyster shells in this study, we cannot uniquely determine whether contributions of  $\delta^{13}\text{C}$  to the DIC pool were from terrestrial or aquatic plants. Future investigations that examine sediment cores from Blackwater River and Faka-Union Bay may provide the necessary information to distinguish between terrestrial versus aquatic plant contributions.

#### 4.2. Environmental archives in modern oyster shells

Modern climate in southwest Florida can be characterized in terms of relative precipitation. The dry season

occurs during the winter and spring and the wet season lasts from mid summer through the fall. The effect of seasonal change in rainfall is reflected in seasonal variation of salinity (Fig. 6; see Surge & Lohmann, 2002 for details). Based on the calibration study of modern *C. virginica* collected from RBNERR (Surge et al., 2001), the most positive  $\delta^{18}\text{O}$  values of shell carbonate correspond to the winter dry season where temperature is the dominant factor controlling  $\delta^{18}\text{O}_{\text{SHELL}}$ , whereas the most negative values correspond to the early fall rainy season where both temperature and mixing between fresh and marine water effect  $\delta^{18}\text{O}_{\text{SHELL}}$ . Because water temperature in this region rises above the optimal temperature for shell growth ( $\sim 30^\circ\text{C}$ ), the hottest months of the year are not represented in the shell.  $\delta^{13}\text{C}_{\text{SHELL}}$  tracks  $\delta^{13}\text{C}_{\text{DIC}}$  which in turn tracks salinity (most negative values correspond to low salinity and most positive values represent marine conditions) although a vital effect of  $\sim 0.75\text{‰}$  is evident during winter months (Surge & Lohmann, 2002). Therefore, the isotopic composition of oyster shells can be related to the temperature and salinity of the water in which they grew through most of the year.

To directly estimate temperature and salinity from shell data, covariance of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  of shell carbonate was compared to calculated lines of equal temper-

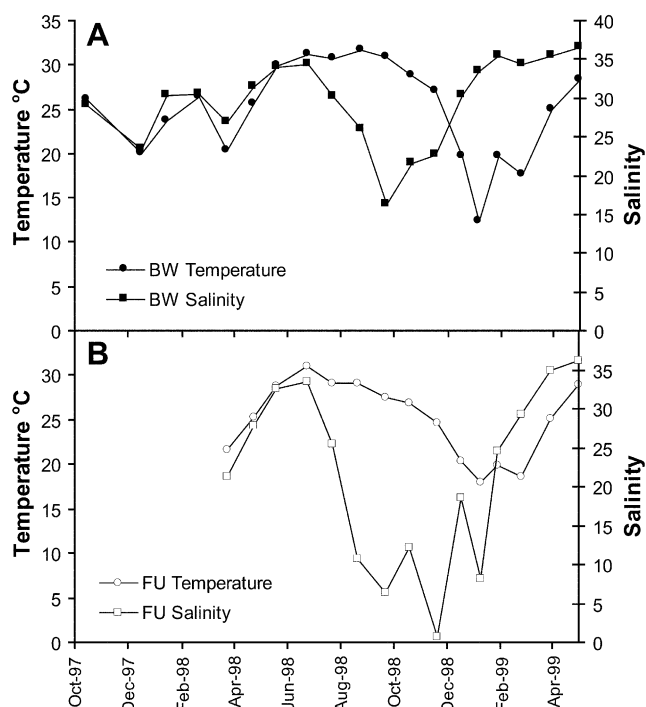


Fig. 6. Time series of monthly temperature and salinity measured at the reef localities in Blackwater River and Faka-Union Bay. (A) Temperature (black circles) and salinity (black squares) measured in Blackwater River; (B) temperature (white circles) and salinity (white squares) measured in Faka-Union Bay.

ature (isotherms) and salinity (isohalines) (Fig. 7). Isotherms and isohalines were calculated as described in Surge et al. (2001), using water property data (mixing relations between  $\delta^{13}\text{C}_{\text{DIC}}$ -salinity and  $\delta^{18}\text{O}_{\text{WATER}}$ -salinity, temperature, concentration of DIC) from Blackwater River (Surge & Lohmann, 2002), and the calcite-water fractionation factor modified from Tarutani, Clayton, and Mayeda (1969) where the term

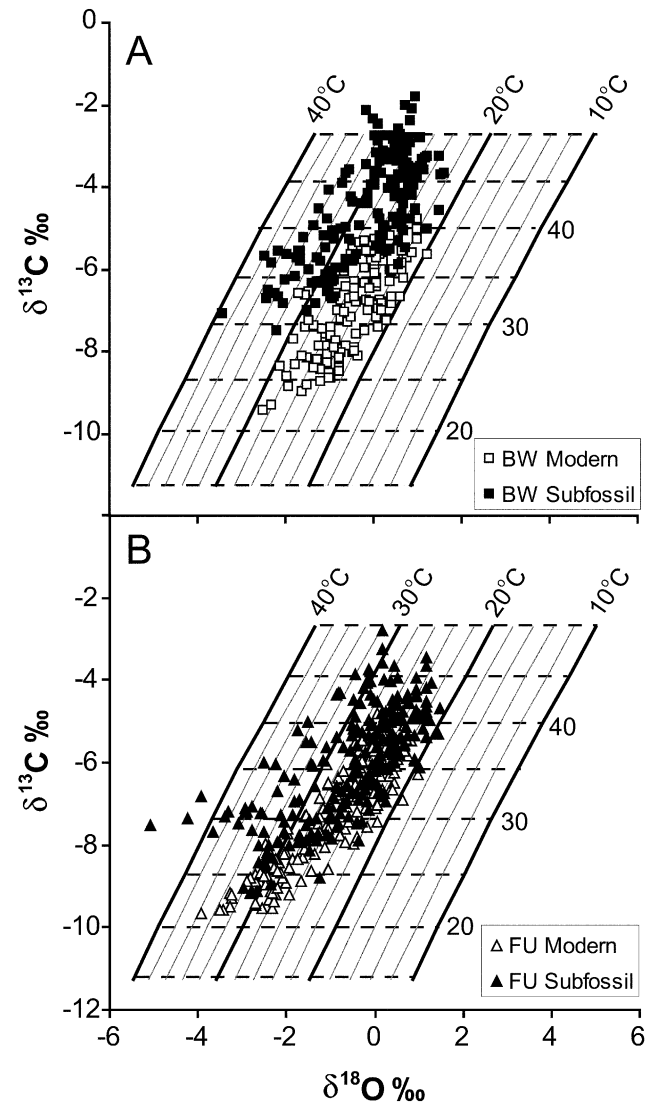


Fig. 7. Covariation of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of modern and subfossil shells relative to isotherms and isohalines. Solid lines represent lines of equal temperature (isotherms) at  $2^\circ\text{C}$  intervals from  $10$ – $40^\circ\text{C}$ . Dashed lines represent lines of equal salinity (isohalines) at intervals of five from  $15$ – $50$  units. Isotherms were calculated using water measurements from Blackwater River ( $\delta^{18}\text{O}_{\text{WATER}}$ -salinity relation and temperature) reported by Surge et al. (2001) and Surge and Lohmann (2002), and the calcite-water fractionation factor modified from Tarutani et al. (1969). Isohalines were calculated using the mixing relation between  $\delta^{13}\text{C}_{\text{DIC}}$  (dissolved inorganic carbon) and salinity (reported in Surge & Lohmann, 2002), and assuming that  $\delta^{13}\text{C}_{\text{DIC}}$  closely estimates  $\delta^{13}\text{C}_{\text{SHELL}}$  (Surge et al., 2001).

mol percent  $\text{MgCO}_3$  was omitted because its effect is negligible given that oyster shells are low in Mg calcite. Proportional mixing of two solutions having different isotopic compositions but similar concentrations of DIC as reported by Surge and Lohmann (2002) was assumed (e.g. 10% freshwater plus 90% seawater, etc.). The following parameters in the model were used: salinity range at the reef is from 0–40; freshwater  $\delta^{13}\text{C}_{\text{DIC}} = -15.5\text{‰}$ ; saltwater  $\delta^{13}\text{C}_{\text{DIC}} = -5.0\text{‰}$ ; freshwater DIC concentration =  $2400 \mu\text{mol/kg}$ ; saltwater DIC concentration =  $2700 \mu\text{mol/kg}$  (see Surge and Lohmann (2002) for details on the water chemistry). Pursuant to the calibration study of *C. virginica* by Surge et al. (2001), the assumption was made that  $\delta^{13}\text{C}_{\text{SHELL}}$  is similar to  $\delta^{13}\text{C}_{\text{DIC}}$ . It should be noted, however, that the calculations used to construct the isohalines do not take into account the  $\sim 0.75\text{‰}$  positive deviation from equilibrium observed in shell  $\delta^{13}\text{C}$  during winter months due to vital effects (Surge et al., 2001). Calculated isotherms and isohalines are more or less linear because fresh- and saltwater end members have similar concentrations of DIC. If the fresh- and saltwater end members had different concentrations of DIC, mixing lines would follow a hyperbolic (curved) mixing trend.

Live-collected shells from the oyster reef in Blackwater River record seasonal temperature ranging from 19–30 °C and salinity ranging from 20–39 units (Fig. 7A). Temperature estimates are reasonable given the temperature range measured at the oyster reef (Fig. 6A) and considering that the warmest temperatures are not recorded in the shell (Surge et al., 2001). The salinity range recorded in live-collected shells is also reasonable based on salinity measurements at the reef (Fig. 6A) and given that the lowest salinities are not represented in the shell (Surge et al., 2001). There is a slight overestimation of salinity during the dry season by four units due to the influence of a vital effect on  $\delta^{13}\text{C}_{\text{SHELL}}$  in winter months (Surge et al., 2001).

Shells collected live from the oyster reef in Faka-Union Bay perform well as recorders of temperature ( $\sim 19$  °C) and salinity ( $\sim 38$  units) during the dry, winter months (Figs. 6B and 7B). However, the most negative isotopic compositions appear to overestimate temperature and underestimate salinity. Moreover, unlike the cloud of data points from the live-collected shells from Blackwater River (Fig. 7A), the cloud of points of shells from Faka-Union Bay has a slightly curved (concave) pattern suggesting hyperbolic mixing. Isotherms and isohalines based on water property data from Blackwater River likely do not accurately reflect isotherms and isohalines characteristic of Faka-Union Bay. Without sufficient data on  $\delta^{13}\text{C}_{\text{DIC}}$  and the concentration of DIC from Faka-Union Bay, we estimated these parameters using ecological information (temperature of summer cessation:  $\sim 28$  °C; Kirby et al., 1998; Surge et al., 2001) that provided limits on reasonable isotherms

and isohalines which in turn might better represent patterns observed in shells from Faka-Union estuary. This approach is a working hypothesis that requires further testing.

Hydrologically, Faka-Union estuary is very different than Blackwater estuary because of the construction of extensive canal systems that have redirected surface flow (Delate & Haner, 1994). The effect of this extreme modification of the drainage basin would likely influence the  $\delta^{13}\text{C}_{\text{DIC}}$  of the water. Some of the surrounding vegetation within the Faka-Union drainage basin is comprised of prairie grassland communities which could effect the local  $\delta^{13}\text{C}_{\text{DIC}}$ . Based on one data point obtained from Faka-Union Bay near the oyster reef (Faka-Union at salinity = 17.0,  $\delta^{13}\text{C}_{\text{DIC}} = -8.96\text{‰}$ ; in comparison, Blackwater at salinity = 16.2,  $\delta^{13}\text{C}_{\text{DIC}} = -11.46\text{‰}$ ), we hypothesize that the freshwater end member in Faka-Union Canal is more positive than the freshwater end member in Blackwater River.

We also hypothesize that the DIC concentration between freshwater and saltwater end members in Faka-Union Canal and Bay are unequal, and that it is higher in Faka-Union Bay compared to Blackwater River. One data point from the same water sample mentioned above is consistent with this hypothesis (Faka-Union at salinity = 17.0,  $\Sigma\text{CO}_2 = 3593 \mu\text{mol/kg}$ ; Blackwater at salinity = 16.2,  $\Sigma\text{CO}_2 = 2566 \mu\text{mol/kg}$ ). This difference in  $\Sigma\text{CO}_2$  may result from variation in primary productivity. M. Savarese, L. Brand, and D. Surge (unpublished data) observe slightly lower chlorophyll *a* concentrations in Faka-Union Bay (mean  $4.06 \pm 2.11 \mu\text{g/l}$ ) than those measured in Blackwater River (mean  $5.19 \pm 2.61 \mu\text{g/l}$ ). Alternatively, given the complicated structure of the surficial aquifer system (Edwards et al., 1998), increased concentrations of DIC may be derived from dissolution of underlying Plio-Pleistocene limestones by groundwater.

By altering the DIC concentration of the freshwater end member, isotherms become curved due to hyperbolic mixing of two solutions having different compositions. If we assume that the DIC concentration of the freshwater end member in Faka-Union Canal is  $\sim 2$  times greater than that of saltwater and that  $\delta^{13}\text{C}_{\text{DIC}}$  of the freshwater end member is  $\sim 5\text{‰}$  more positive than what is observed in Blackwater River, and invoke ecological constraints (temperature of growth cessation; Kirby et al., 1998; Surge et al., 2001), the isotherms and isohalines provide a more reasonable estimation of the temperature and salinity conditions observed at the oyster reef in Faka-Union Bay and recorded in shells (Fig. 8). Given this assumption, seasonal temperature recorded in the live-collected shells ranges from 19–30 °C and seasonal salinity ranges from  $\sim 10$  units during the wet season to 38 units (probably a slight overestimation) during the dry season.

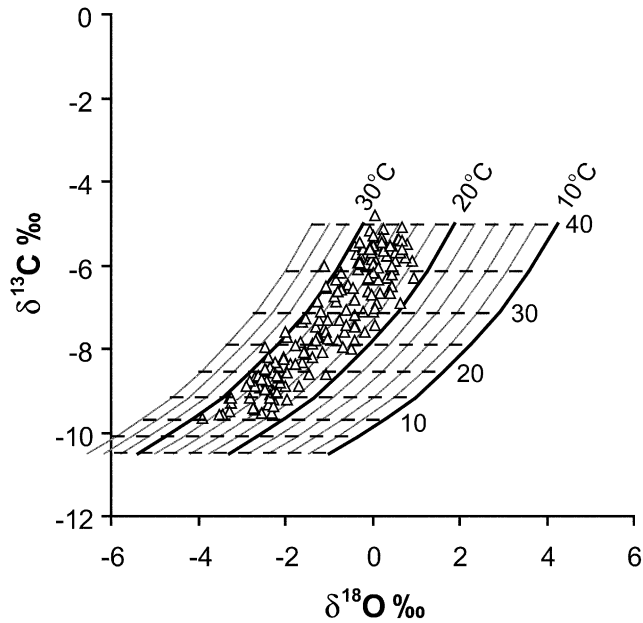


Fig. 8. Covariation of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of modern shells collected live from Faka-Union Bay. Solid lines are isotherms calculated using a proportional mixing model which assumes the concentration of DIC is  $\sim 2$  times higher than that of saltwater and assumes the  $\delta^{13}\text{C}_{\text{DIC}}$  of the freshwater end member in Faka-Union Canal is 5‰ more positive than the freshwater end member of Blackwater River. Intervals of isotherms and isohalines are as described in Fig. 7.

#### 4.3. Environmental archives in subfossil oyster shells

To interpret the isotopic records contained in subfossil shells, we compared the covariance of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  of shell carbonate to the isotherms and isohalines constructed based on modern conditions measured at the oyster reef in Blackwater River (Fig. 7). Comparison of data points from both Blackwater and Faka-Union subfossils with modern isotherms and isohalines results in an overestimation of both temperature and salinity. It is unlikely that salinity was 10 units higher in the past during the dry season. It is also unlikely that oysters grew at much higher temperatures relative to their present temperature of summer cessation (Surge et al., 2001). Given that the mean  $\delta^{13}\text{C}$  of shell carbonate is more positive in the past than that of modern samples (Fig. 5), we increased the carbon isotope parameter in our calculated isotherms and isohalines comparable to the offset observed in the data. Thus, we increased the freshwater and saltwater end members by 2.5 and 1‰ for the Blackwater and Faka-Union models, respectively (Fig. 9).

By modifying the isotherms and isohalines to account for the 2.5‰ offset in  $\delta^{13}\text{C}_{\text{SHELL}}$ , ranges of oxygen and carbon isotope compositions of subfossil shells from Blackwater reflect reasonable growth temperatures ( $< 30^\circ\text{C}$ ) and seasonal salinity range (18–40 units) (Fig. 9A). However, temperature during winter months

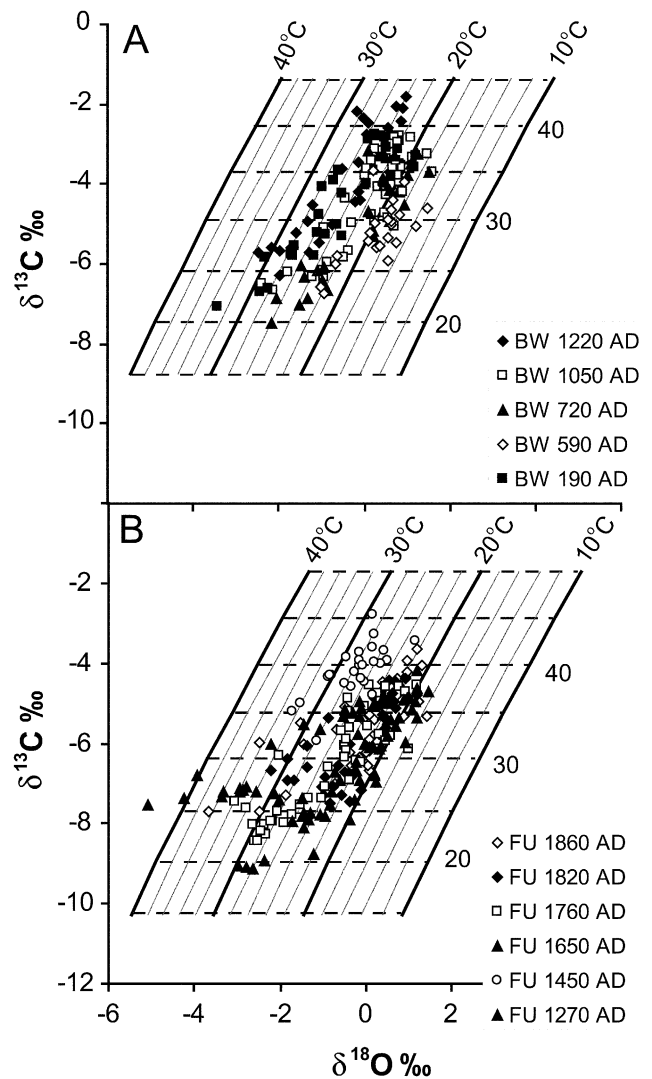


Fig. 9. Covariation of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of individual subfossil shells from (A) Blackwater River and (B) Faka-Union Bay with recalculated isotherms and isohalines to better represent past conditions. Isotherms and isohalines were recalculated using the offset in  $\delta^{13}\text{C}$  between fossil and modern shells as reflected in Fig. 7 ( $\delta^{13}\text{C}$ -Blackwater of freshwater and saltwater end members increased by 2.5‰;  $\delta^{13}\text{C}$ -Faka-Union of freshwater and saltwater end members increased by 1‰).

appears to be 1–5 °C colder as recorded in shells from years 190, 590, 720, and 1050 AD than winter temperatures recorded in modern shells. This result may reflect a change in climate. Alternatively, colder temperatures may indicate natural, year-to-year variation in winter temperatures as observed in modern air temperature records. Winter low air temperature (averaged monthly) can vary by as much as 5–6 °C from year to year based on temperature records (1892–2000) measured at Fort Myers, Florida by the National Oceanographic and Atmospheric Administration (<http://www.ncdc.noaa.gov>).

Correcting the isotherms and isohalines for Faka-Union to account for the +1‰ offset of  $\delta^{13}\text{C}_{\text{SHELL}}$  between modern and subfossil shells does not produce satisfying results (Fig. 9B). Salinity and summer temperatures are still unreasonably high. This may reflect a complex hydrology and water chemistry of this estuary and its watershed. It also emphasizes the need for developing independent elemental proxies for temperature and salinity (e.g. Mg/Ca as a paleothermometer).

## 5. Summary and conclusions

Stable isotope sclerochronology as a tool for reconstructing estuarine conditions is hampered by the simultaneous effects of temperature and salinity (mixing of fresh and saltwater) on the oxygen isotope composition of skeletal carbonates from organisms that inhabit this dynamic environment. Despite this complication, we present a new approach that involves an understanding of present isotopic characteristics of estuarine water to model what we expect to observe in oyster shells growing in estuaries of the 10 Thousand Islands. By comparing subfossil shells that were alive within the last few centuries to live-collected shells and water chemistry, estuarine environmental conditions from the recent past can be reconstructed and applied to watershed restoration and management studies. A radiocarbon-calibrated amino acid geochronology was established to date old shells that grew before channelization of the Faka-Union watershed. We determined that the regional marine reservoir age is 130 ( $\pm 18$ ) years greater than the typical worldwide value.

Live-collected shells record seasonal temperature and salinity measured at the oyster reefs in Blackwater River and Faka-Union Bay; although the warmest temperatures and lowest salinities are not represented in the shell due to summer growth cessation. Subfossil shells from Blackwater River record temperature and salinities during warm months similar to present, but four of the five subfossil shells record winter temperatures that are 1–5 °C colder than modern winter temperature. This may reflect a long-term change in climate or merely the natural variability in seasonal weather patterns from year to year. Analysis of more shells are required to better interpret the variation in past winter temperature. Estuarine conditions recorded in subfossil shells from Faka-Union Bay are difficult to interpret based on isotopic composition alone. Development of elemental proxies of temperature may provide more useful environmental information of past estuarine conditions. Despite these complications, carbon isotope compositions of skeletal carbonate suggest a change in the dominant carbon source from more  $\text{C}_4$  grasses (terrestrial or aquatic) to more mangrove forests ( $\text{C}_3$  plants) of today. The data set from this study cannot uniquely

discriminate between terrestrial versus aquatic grass contributions, but future information from sediment cores may distinguish between these two sources.

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