

Reconstructing the History of Eastern and Central Florida Bay Using Mollusk-Shell Isotope Records

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ABSTRACT: Stable isotopic ratios of carbon and oxygen ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) from mollusk shells reflect the water quality characteristics of Florida Bay and can be used to characterize the great temporal variability of the bay. Values of $\delta^{18}\text{O}$ are directly influenced by temperature and evaporation and may be related to salinity. $\delta^{13}\text{C}$ values of $\delta^{13}\text{C}$ are sensitive to organic and inorganic sources of carbon and are influenced by productivity. Analyses of eight mollusk species from five short-core localities across Florida Bay show large ranges in the values of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, and reflect the variation of the bay over decades. Samples from southwestern Florida Bay have distinct $\delta^{13}\text{C}$ values relative to samples collected in northeastern Florida Bay, and intermediate localities have intermediate values. $\delta^{13}\text{C}$ values of $\delta^{13}\text{C}$ grade from marine in the southwest bay to more estuarine in the northeast. Long cores (> 1 m) with excellent chronologies were analyzed from central and eastern Florida Bay. Preliminary analyses of *Brachiodontes exustus* and *Transenella* spp. from the cores showed that both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ changed during the first part of the twentieth century. After a century of relative stability during the 1800s, $\delta^{13}\text{C}$ decreased between about 1910 and 1940, then stabilized at these new values for the next five decades. The magnitude of the reduction in $\delta^{13}\text{C}$ values increased toward the northeast. Using a carbon budget model, reduced $\delta^{13}\text{C}$ values are interpreted as resulting from decreased circulation in the bay, probably associated with decreased freshwater flow into the Bay. Mollusk shell $\delta^{18}\text{O}$ values display several negative excursions during the 1800s, suggesting that the bay was less evaporitic than during the twentieth century. The isotope records indicate a fundamental change took place in Florida Bay circulation early in the twentieth century. The timing of the change links it to railroad building and early drainage efforts in South Florida rather than to flood control and water management measures initiated after World War II.

Introduction

Algal blooms and seagrass mortality during the past decade raised concerns about water quality changes in Florida Bay (Fourqurean et al. 1999). These changes have been linked to hypersalinity, which may result from decreased freshwater flow into the estuary as a consequence of onshore water management practices (McIvor et al. 1994). Water quality monitoring, started in the late 1980s, is of insufficient duration to capture changes associated with either the major onshore drainage efforts of the early 1900s or flood control construction since World War II. The changes during the past decade may have their origins in alterations that occurred many decades ago. For example, hypersalinity has been a characteristic of the bay during periods of low rainfall since the late 1930s (Davis 1940, p. 348-351), but it is difficult to know if high salinity has been an intermittent feature of the bay prior to that time. We created a proxy record of water quality and variability during the past 200 yr based

on isotopic analyses of fossils from sediments in the bay. This paper reports initial results from three sites. Duplicate cores from these locations are being processed to verify and amplify the observations reported here.

Stable isotope ratios of carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) from aragonitic shell material are well established as tools for retrospective analyses of marine environments (e.g., Bosence and Allison 1995). Values of $\delta^{18}\text{O}$ have been used as measures of temperature and salinity (Barrera and Tevesz 1990; National Oceanic and Atmospheric Administration 1993). Values of $\delta^{13}\text{C}$ reflect the isotopic composition of dissolved inorganic carbon (DIC) in the water and, in combination with other measurements, may be a proxy for nutrient dynamics (National Oceanic and Atmospheric Administration 1993). Characteristics of marginal marine seas such as inputs from river discharge, upwelling, seasonal productivity, and stratification have been derived from isotopic study of mollusk shells (Krantz 1990; Jones and Allmon 1995; Purton and Brasier 1997).

Studies of mollusk shells in simple mixing estuaries have shown that linear relations exist between

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TABLE 1. Mean and standard deviation values for 435 stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopic measurements of National Bureau of Standards (NBS) standards analyzed at the United States Geological Survey (USGS) Stable Isotope Lab in Denver, Colorado, and expected NBS values. Standards included in the calculations of the USGS values were routinely analyzed among study samples from October 1995 to May 1997.

Standard	USGS Values		Expected NBS Values	
	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)
NBS 18 (n = 1210)	-4.94 ± 0.16	-22.79 ± 0.35	-5.00	-23.00
NBS 19 (n = 170)	1.87 ± 0.09	-2.20 ± 0.16	1.92	-2.19
NBS 20 (n = 146)	-1.12 ± 0.16	-4.21 ± 0.24	-1.06	-4.14

isotopic values and salinity (Mook 1971). Several observations suggest previous estuarine models may not be applicable to Florida Bay. First, significant portions of Florida Bay are dominated by evaporation and rainfall, not estuarine mixing, and evaporation greatly complicates the geographic distribution of $\delta^{18}\text{O}$ values in Florida Bay (Lloyd 1964). Second, dense benthic vegetation and a significant organic carbon fraction in the sediment suggest $\delta^{13}\text{C}$ values of DIC may likewise not be a simple function of mixing. Rather, the isotopic value of DIC is controlled, in part, by microbial oxidative decay of bottom sediments (Lloyd 1964; Patterson and Walter 1994a).

The retrospective approach used here is similar to that used by others working with annually banded coral skeletons (Swart 1983; McConnaughey 1989). We used mollusks for two reasons. First, long-lived corals do not occur in central and eastern Florida Bay, the areas most likely impacted by variable freshwater inflow. Second, most marine skeletal material is produced in disequilibrium with seawater (McConnaughey 1989), but disequilibrium in molluscan calcium carbonate is minimal (Epstein and Lowenstam 1953; Keith and Parker 1965). Bivalves lacking significant photosynthetic algae in their tissues precipitate skeletal carbonate that is close to equilibrium with respect to seawater (Mook and Vogel 1968), although the exact mechanisms of biocalcification remain unknown (Ad-dadi and Weiner 1997). We used $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of mollusks from well-dated sediment cores as a proxy for water from the interior of Florida Bay. Detailed studies of nearby corals in the Atlantic Ocean and western bay have been made (Halley et al. 1994; Swart et al. 1996). Florida Bay sediment cores lack the temporal resolution of coral skeletons, but their locations provide insight to time-averaged water quality changes in the bay over time scales that are impossible to document using other materials.

In addition to the immediate problem of ecosystem deterioration addressed by this volume, the isotopic values presented here will aid in the interpretation of ancient environments in geologic time. Isotopic studies of fossil mollusks are used to

determine the salinity of ancient marginal marine environments (Dodd and Stanton 1975; Hudson et al. 1995) and to document paleoceanographic processes cited above. The complexity of Florida Bay serves as a modern example that can be used to guide interpretations of isotopic values from fossil mollusks that are many millions of years old (Hendry and Kalin 1997).

Materials and Methods

During this study, 500 shell fragments from surface sediments and 2,000 from ^{210}Pb -dated sediment cores (Robbins et al. in press; Holmes et al. in press) were analyzed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values following the methods of O'Neil et al. (1969). Individual shells, or several portions of an individual, were crushed and heated in vacuo for 1 h at $200 \pm 10^\circ\text{C}$. Replicates of National Bureau of Standards isotopic standards NBS 18, NBS 19, and NBS 20 were analyzed to maintain standardization (Table 1). The accuracy of standard values was better than 0.06‰ for $\delta^{13}\text{C}$ values and 0.21‰ for $\delta^{18}\text{O}$ values and exhibited an average precision of $\pm 0.14\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.25\text{‰}$ for $\delta^{18}\text{O}$ (Table 1). All samples are reported in per mil notation (‰) relative to the University of Chicago standard PDB (Pee Dee Belemnite).

SURFACE SAMPLES—PILOT STUDY

To test our hypothesis that fossil mollusk shells can be used to reconstruct paleo-water chemistry and to determine which species were most suitable, we collected stable isotope data from shells of eight different species at five locations in the bay. Cores (10 cm diameter) were collected from Long Sound, Buttonwood Sound, Alligator Bay, Whipray Basin, and Old Dan Bank northwest of Long Key (Fig. 1). These locations range from strongly influenced by freshwater runoff (Long Sound) to dominantly Gulf of Mexico and Atlantic Ocean water (Long Key). The upper 10 cm of sediment, representing approximately 10–30 y of accumulation, was washed and separated into two size fractions: $425 \mu\text{m} - 1 \text{ mm}$ and $> 1 \text{ mm}$. Commonly occurring species of carbonate-shell-forming invertebrates were selected primarily from the $425 \mu\text{m} -$

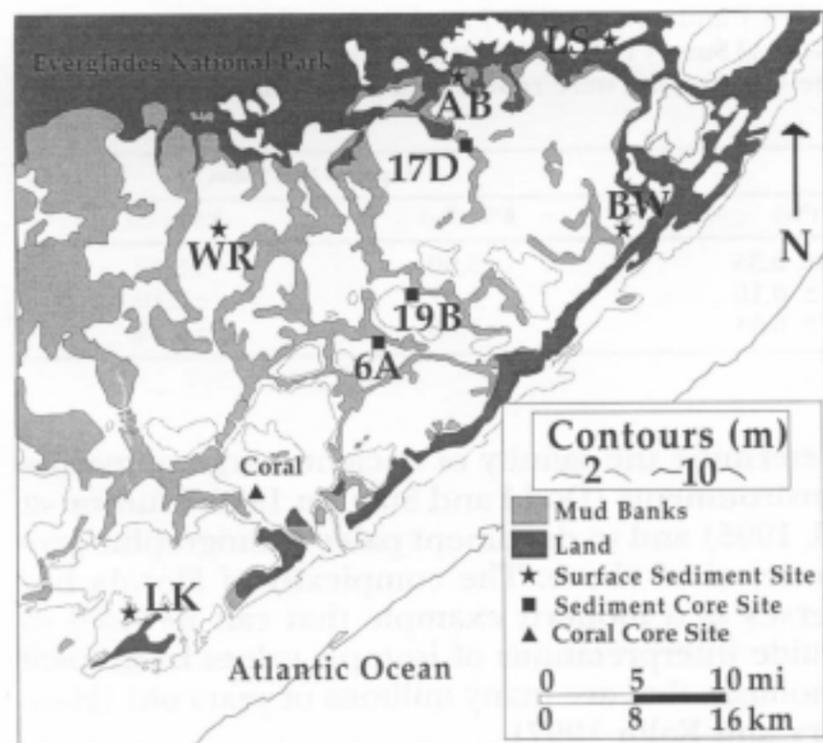


Fig. 1. Sample sites in Florida Bay. Surface samples (stars) in five sub-basins: LS—Long Sound, AB—Alligator Bay, BW—Buttonwood Sound, WR—Whipray Basin, LK—Long Key. Core sites (squares): 6A—Bob Allen Bank, 19B—Russell Bank, and 17D—Pass Key. Coral core site (triangle) is in Lignum Vitae Basin near the Peterson Keys (Swart et al. 1996).

1 mm fraction. Seven species of mollusks and a serpulid worm species were identified in most samples. On average, 15 individuals of each species were selected for analysis.

CORES

For reconstruction and dating, multiple piston cores (10 cm diameter and < 2 m in length) were

taken in May 1994 and February 1995 from sites on Bob Allen Bank (site 6), Russell Bank (site 19), and south of Pass Key (site 17). These localities form a southwest to northeast transect in the bay (Fig. 1). Although many more cores were taken throughout the bay, only these three sites yielded chronologies of sufficient length and reproducibility to be useful for this study (Holmes et al. In press). Sediments were processed as described in Wingard et al. (1995). Included in this paper are data from Bob Allen Bank (6A) and Russell Bank (19B) which were sampled at 2 cm intervals, representing about 2–5 yr accumulation, and data for Pass Key (17D). Intervals from core 17D that had less than 30 *B. exustus* were combined; these data may represent more than a decade. The Pass Key core record extends to about 1930, whereas core records from Russell Bank and Bob Allen Bank span the turn of the century and represent 120 yr and 200 yr of accumulation, respectively. Age assignments for core intervals were based on ^{210}Pb -dating methods. Ages were verified using anthropogenic Pb as a tracer described by Robbins et al. (In press) and Holmes et al. (In press).

Results

SURFACE SAMPLES

Results from analyses of surface samples were twofold. First, we recognized that of the eight species analyzed, *B. exustus* is common in all samples, showed the greatest range in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (Table 2), and was widely distributed in Florida Bay as shown in Fig. 2. Second, grouping data by location showed that each sub-basin had dis-

TABLE 2. Minimum (min) and maximum (max) isotope ratios for modern carbonate organisms collected from the surface sediments of five sub-basins in Florida Bay. Blanks indicate that a species was not found at that locality. LS—Long Sound, AB—Alligator Bay, BW—Buttonwood Sound, WR—Whipray Basin, LK—Long Key.

Organism	LS		AB		BW		WR		LK	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
$\delta^{13}\text{C}$ (‰)										
<i>Anomalocardia cuneimeris</i>	-4.92	-2.79	-3.50	-1.12	-2.44	0.65	-1.88	0.24		
<i>Brachiodontes exustus</i>	-4.68	-1.47	-2.86	0.27	-2.18	0.58	-1.72	1.00	0.35	3.30
<i>Bittium varium</i>	-4.31	-1.68	-2.70	-0.50	-1.89	-0.85	-1.64	1.51	-0.46	3.49
<i>Caecum</i> sp.	-2.77	-1.29			-1.42	-0.05				
<i>Chione cancellata</i>	-4.41	-2.20			-4.45	-1.62	-1.95	-1.18	-0.97	1.93
<i>Rissoina</i> sp.	-3.02	-1.29			-1.43	-0.18	-0.41	0.87	0.67	2.55
<i>Retusa</i> spp.	-4.74	-2.91	-2.61	-0.46	-2.60	-0.50			0.74	2.52
<i>Serpulina</i> sp.			-2.57	1.41	-2.30	1.09	-1.94	1.00	0.94	2.62
$\delta^{18}\text{O}$ (‰)										
<i>Anomalocardia cuneimeris</i>	-1.18	1.72	-0.80	2.05	-0.17	1.29	0.26	1.63		
<i>Brachiodontes exustus</i>	-1.53	2.79	1.07	3.04	0.25	2.38	0.80	2.20	-0.94	0.90
<i>Bittium varium</i>	-0.10	2.79	-0.22	1.89	0.36	2.10	-1.72	1.92	-0.99	1.26
<i>Caecum</i> sp.	0.85	2.29			-0.05	2.25				
<i>Chione cancellata</i>	-0.29	2.59			-1.54	2.23	-0.90	1.89	-1.70	0.84
<i>Rissoina</i> sp.	0.51	1.94			-0.73	1.66	0.12	1.57	-0.99	1.12
<i>Retusa</i> spp.	-0.41	1.49	-0.25	2.74	-0.61	2.31			-0.94	0.23
<i>Serpulina</i> sp.			0.35	2.57	-0.11	2.11	-0.38	2.40	-0.51	1.45

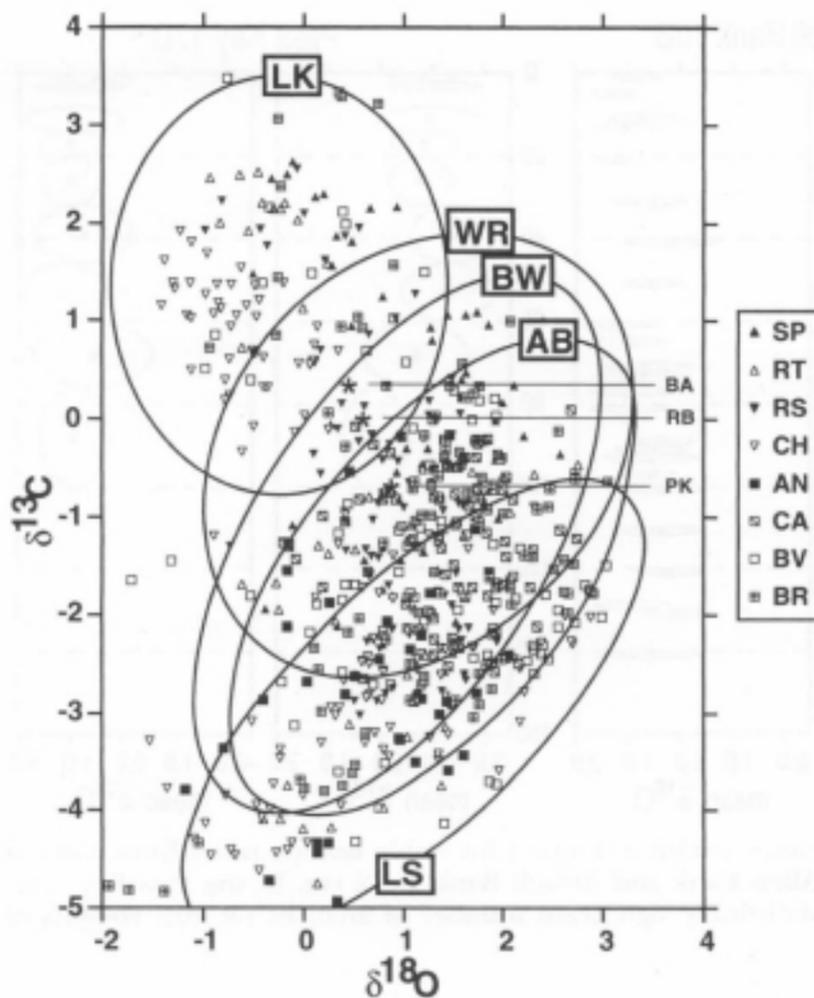


Fig. 2. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data for eight carbonate-secreting species from five surface samples (LS—Long Sound; AB—Alligator Bay; BW—Buttonwood Sound; WR—Whipray Basin; LK—Long Key) in Florida Bay. At each site, 15–20 individuals of each species were selected for analysis. SP—serpulid worm species, RT—*Retusa canaliculata*, RS—*Rissoina* sp., CH—*Chione cancellata*, AN—*Anomalocardia cuneimeris*, CA—*Caecum* sp., BV—*Bittium varium*, BR—*Brachiodontes exustus*. Ellipses enclose 96% (2σ) of the variation at each sample locality. Average values for analyzed cores are indicated by stars and identified along the right margin of the diagram (BA—Bob Allen Bank; RB—Russell Bank; PK—Pass Key).

tinctive characteristics (Fig. 2). Organisms from near Long Key and Long Sound have $\delta^{13}\text{C}$ values that represent end-members of a continuous distribution. Moving toward the interior of the bay there is overlap in $\delta^{18}\text{O}$ values of mollusks from various sub-basins, including Whipray Basin, Buttonwood Sound, Alligator Bay, and Long Sound, and these values are statistically different from the more normal marine values near Long Key. Each

location exhibits wide variation in both carbon and oxygen. Therefore we used a statistical approach to characterize *B. exustus* isotopic values from each core by averaging 30 values from each depth interval.

CORES

Although *B. exustus* occurs in all surface samples, results from faunal analyses of the first core (Bob Allen 6A) revealed many intervals with insufficient samples for analyses. *Transenella* spp., however, was present in some intervals lacking *B. exustus* (Wingard et al. 1995). Based on studies of Florida Bay (Wingard personal communication), both species may be found in water ranging from 12‰ to 30‰. Others have documented even wider ranges. Turney and Perkins (1972), for example, found *B. exustus* between 22‰ and 52‰. Andrews (1971) lists *B. exustus* as euryhaline and estuarine with a range of 10–30‰. Although both mollusks are tolerant of a wide range of salinity, *B. exustus* is more suitable for this investigation because its epifaunal habitat keeps it in the water column, as opposed to the infaunal, filter feeding habit of *Transenella* spp., which occupies surface sediments. To determine if the habitats of *Transenella* spp. and *B. exustus* would affect interpretation, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ were determined from core intervals where both of these species were found. The results of unpaired *t*-tests conducted for three sample intervals in core 6A from Bob Allen Bank are summarized in Table 3. Based on these analyses we determined that *Transenella* spp. could be used in addition to *B. exustus* as needed to obtain a representative sample from each interval. Using both species, sufficient samples were available for almost half of the 2-cm core intervals. Fewer fossils were present in the Pass Key core and intervals were combined to obtain approximately 30 samples.

Statistical analyses of secular trends are shown in Fig. 3 and listed in Table 4. Whole-core averages of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are within the ranges predicted from their locations using the surface values plotted in Fig. 2 (Bob Allen Bank $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, respectively: ± 0.471 , and $+0.251$; Russell Bank: $+0.671$, and -0.061 ; Pass Key Bank: ± 0.851

TABLE 3. Summary statistics for unpaired *t*-tests using stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopic data for coexisting *Brachiodontes exustus* (B) and *Transenella* spp. (T) populations in core 6A from Bob Allen Bank. The number of analyses performed for *Brachiodontes exustus* and *Transenella* spp. are indicated by n_B and n_T as is the mean difference (mean difference). Taking into consideration analytical precision, *p*-values from *t*-tests were calculated using hypothesized mean differences of 0.14‰ for $\delta^{13}\text{C}$ and 0.251 for $\delta^{18}\text{O}$.

Interval	n_B	n_T	Mean $\delta^{13}\text{C}$ B	Mean $\delta^{13}\text{C}$ T	Mean diff.	<i>p</i> -values	Mean $\delta^{18}\text{O}$	Mean $\delta^{18}\text{O}$ T	Mean diff.	<i>p</i> -values
48–50	31	50	-0.06	-0.39	0.33	0.2726	0.65	0.74	-0.091	0.0423
68–70	15	16	-0.80	0.09	-0.89	0.0095	1.40	0.03	1.369	<0.0001
156–158	18	17	0.93	-0.06	0.99	0.0002	0.56	0.06	0.503	0.2032

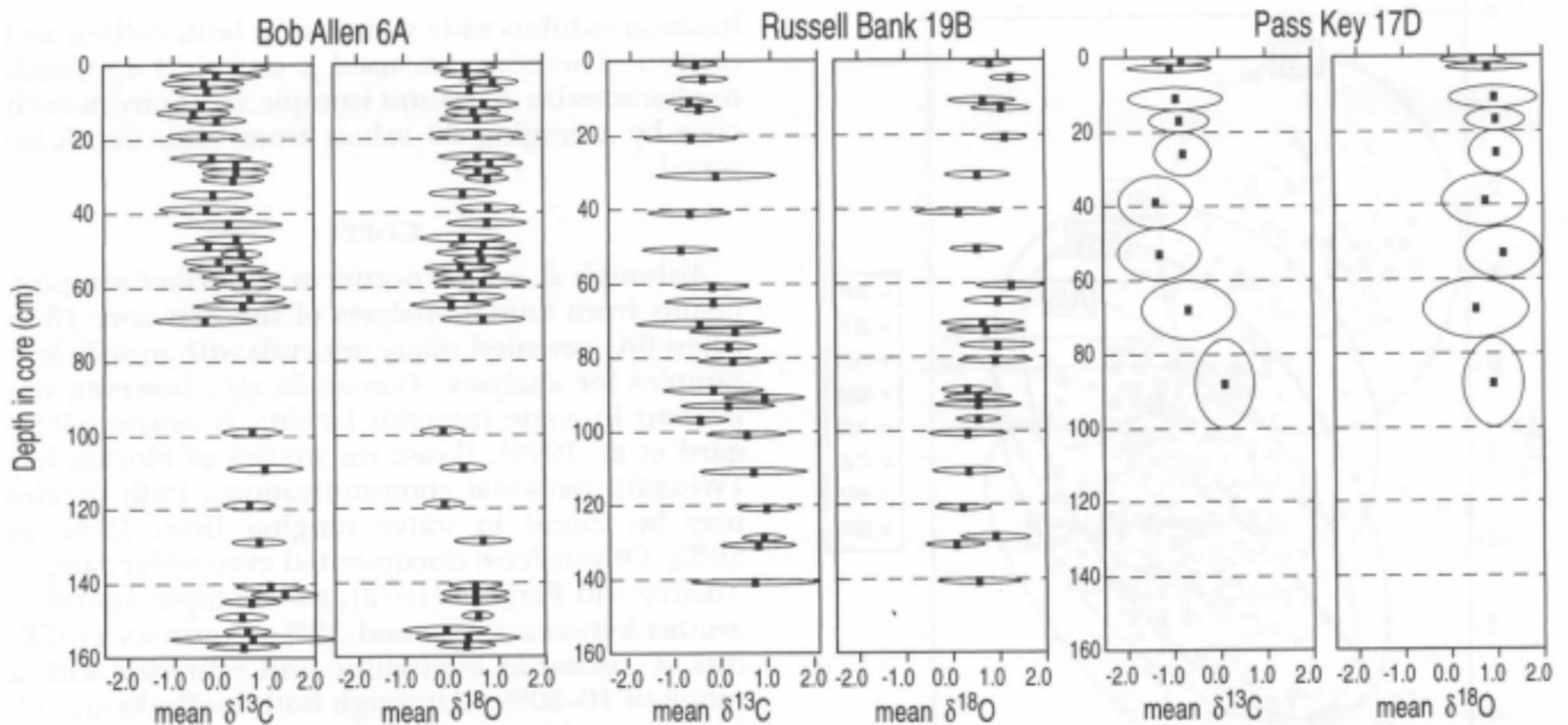


Fig. 3. Core isotope data showing the means (squares) and 1σ variance (width of ellipse) for stable isotope ratios from cores at Bob Allen Bank, Russell Bank, and Pass Key. All intervals from Bob Allen Bank and Russell Bank are 2 cm. In the Pass Key core, intervals with few *B. exustus* were combined in order to maintain a statistically significant number of analyses (≥ 20). Heights of ellipses represent sampled interval thickness.

and, -0.861). The core from Bob Allen Bank is most similar to the Long Key surface sample. The Russell Bank and Pass Key cores are progressively more like surface samples from Long Sound, increasing in $\delta^{18}\text{O}$ values and decreasing in $\delta^{13}\text{C}$ values toward the northeast bay. Given the surface variation among individual shells (Fig. 2), the long-term means exhibited by the 2-cm core intervals are surprisingly consistent. The ranges of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in 2-cm core sections from Bob Allen Bank and Russell Bank are large, 2‰ and 3‰ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ respectively, but 2-cm interval means vary generally less than 1‰ . Interval means reveal a stability in bay water values when time-averaged over periods of several years or more, the length of time represented by a 2-cm core section.

The long-term stability of the bay is more apparent when the chronologies of the cores (Robbins et al. in press) are applied to the isotope data. In Fig. 4a the isotope data are plotted against time down the cores, rather than depth. Plotted against time, a number of similarities emerge between the cores which were not apparent in Fig. 3. An interpretation of the changes in interval means is shown in Fig. 4b. Values of $\delta^{13}\text{C}$ for each core decrease beginning about 1910 and ending between 1940 and 1960. The initiation of the change is best defined at Russell Bank; it is poorly defined by data from the Bob Allen core because of a lack of appropriate mollusks between 1880 and 1910. The initiation is not recorded in the Pass Key Bank core

because the core is short and the sedimentation rate higher than in the other cores. The cores from Bob Allen Bank and Russell Bank record the entire shift; Pass Key records only the last portion. The termination is best defined in the Bob Allen core at close to 1940; it is not as well constrained at Russell Bank at about 1940. The termination in the Pass Key core could be anywhere between 1940 and 1960 because the 10-cm intervals provide only coarse temporal resolution.

The $\delta^{13}\text{C}$ data from Bob Allen Bank and Russell Bank cores indicate that dissolved inorganic carbon (DIC) at those sites maintained a long-term average of about $+0.73\text{‰}$ and $+0.65\text{‰}$ respectively, for many decades, and perhaps a century prior to 1910 (Fig. 4b). For five decades since 1940, values have been about -0.12‰ and -0.59‰ (Fig. 4b). These data reveal that an unusual change took place in the DIC of the central and eastern bay during the first half of this century. The magnitude of the $\delta^{13}\text{C}$ shift appears to increase toward the northeast, from 0.85‰ at Bob Allen Bank to 1.24‰ at Russell Bank, and at least 1.12‰ at Pass Key where the base is not recorded.

The $\delta^{13}\text{C}$ values are crudely reflected in the plots of $\delta^{18}\text{O}$ values (Fig. 3). The mirror-like trend between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ exhibited in Figs. 3 and 4, while obvious, is not statistically significant. The $\delta^{13}\text{C}$ shift is statistically significant, but the down-core change in $\delta^{18}\text{O}$ means is not sufficiently great to be distinct from the overall variation in means.

TABLE 4. Descriptive statistics for stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotope analyses made for each sample interval from cores used for reconstruction. Listed in this table by core number and the beginning depth of each interval are mean values for core 6A (Bob Allen Bank), 19B (Russell Bank), and 17D (Pass Key) along with standard deviations (stdev), the number of *Brachiodontes exustus* analyzed (N_B), and the number of *Tranzenella* spp. (N_T).

Core; Interval	Mean $\delta^{13}\text{C}$	SD $\delta^{13}\text{C}$	Mean $\delta^{18}\text{O}$	SD $\delta^{18}\text{O}$	N_B	N_T
6A; 0	0.32	0.72	0.34	0.69	30	0
6A; 2	-0.10	0.97	0.36	0.54	30	0
6A; 4	-0.35	0.87	0.93	0.55	27	0
6A; 6	-0.28	0.69	0.42	0.74	31	0
6A; 10	-0.41	0.69	0.71	0.78	28	0
6A; 12	-0.57	0.77	0.50	0.58	38	0
6A; 14	-0.07	0.63	0.58	0.79	39	0
6A; 18	-0.34	0.79	0.57	1.00	23	9
6A; 24	-0.19	0.87	0.58	0.83	34	0
6A; 26	0.32	0.79	0.86	0.70	32	0
6A; 28	0.33	0.70	0.60	0.55	33	0
6A; 30	0.27	0.67	0.80	0.47	21	0
6A; 34	-0.17	0.87	0.26	0.72	35	0
6A; 38	-0.31	0.99	0.81	0.66	39	0
6A; 42	0.16	1.17	0.79	0.85	29	0
6A; 46	0.33	0.85	0.26	0.92	23	0
6A; 48	-0.26	0.77	0.71	0.72	31	50
6A; 50	0.46	0.44	0.62	0.90	21	0
6A; 52	-0.05	0.74	0.68	0.60	34	0
6A; 54	0.17	0.85	0.22	0.76	27	0
6A; 56	0.45	0.83	0.37	0.69	34	0
6A; 58	0.57	0.70	0.69	1.05	31	0
6A; 62	0.63	0.78	0.49	0.70	26	0
6A; 64	0.47	1.05	0.02	0.87	27	0
6A; 68	-0.34	1.11	0.69	0.90	15	16
6A; 98	0.66	0.65	-0.18	0.48	0	30
6A; 108	0.93	0.82	0.25	0.49	0	36
6A; 118	0.59	0.55	-0.16	0.45	0	34
6A; 128	0.80	0.58	0.67	0.61	0	35
6A; 140	1.04	0.74	0.51	0.57	19	0
6A; 142	1.34	0.71	0.51	0.72	20	0
6A; 144	0.63	0.64	0.50	0.73	32	0
6A; 148	0.42	0.57	0.56	0.33	0	16
6A; 152	0.53	0.50	-0.13	0.92	9	0
6A; 154	0.66	1.76	0.34	1.11	25	0
6A; 156	0.45	0.78	0.32	0.62	18	17
19B; 0	-0.61	0.48	0.83	0.46	28	0
19B; 4	-0.45	0.55	1.27	0.42	39	0
19B; 10	-0.75	0.52	0.67	0.72	31	0
19B; 12	-0.55	0.49	1.06	0.62	38	0
19B; 20	-0.72	1.01	1.14	0.49	31	0
19B; 30	-0.18	1.28	0.55	0.70	31	0
19B; 40	-0.75	0.89	0.14	0.92	30	0
19B; 50	-0.94	0.82	0.53	0.56	31	0
19B; 60	-0.26	0.77	1.26	0.72	21	0
19B; 64	-0.25	1.03	0.97	0.71	23	0
19B; 70	-0.55	1.36	0.64	0.88	26	0
19B; 72	0.22	0.98	0.73	0.84	28	12
19B; 76	0.08	0.61	0.96	0.79	36	0
19B; 80	0.18	0.76	0.92	0.80	45	0
19B; 88	-0.24	1.08	0.31	0.54	0	33
19B; 90	0.84	0.87	0.55	0.71	30	0
19B; 92	0.07	1.01	0.54	0.92	15	7
19B; 96	-0.55	0.63	0.55	0.48	6	12
19B; 100	0.45	0.86	0.32	0.83	18	11
19B; 110	0.59	1.15	0.33	0.77	3	4
19B; 120	0.87	0.62	0.21	0.60	7	0
19B; 128	0.81	0.47	0.90	0.75	31	0
19B; 130	0.69	0.81	0.06	0.64	7	0

TABLE 4. Continued.

Core; Interval	Mean $\delta^{13}\text{C}$	SD $\delta^{13}\text{C}$	Mean $\delta^{18}\text{O}$	SD $\delta^{18}\text{O}$	N_B	N_T
19B; 140	0.62	1.38	0.55	0.90	12	0
17D; 0-2	-0.81	0.63	0.52	0.71	40	0
17D; 2-4	-1.07	0.91	0.81	0.87	39	0
17D; 8-14	-0.94	1.02	0.95	0.95	26	0
17D; 14-20	-0.85	0.65	0.99	0.65	33	0
17D; 20-32	-0.78	0.61	1.00	0.57	32	0
17D; 32-46	-1.37	0.80	0.75	0.92	33	0
17D; 46-60	-1.30	0.89	1.14	0.82	33	0
17D; 60-76	-0.68	1.00	0.55	1.14	37	0
17D; 76-100	0.10	0.64	0.92	0.65	32	0

It is evident from Fig. 4 that there is a bias for more positive $\delta^{18}\text{O}$ in the twentieth century than in the nineteenth century. This bias is driven by several negative excursions of $\delta^{18}\text{O}$ values to about 0.00‰ prior to 1920.

Discussion

Lloyd (1964) and Patterson and Walter (1994a, b) documented the wide range of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in water of Florida Bay, about 4‰ for $\delta^{18}\text{O}$ and 7‰ for $\delta^{13}\text{C}$. Figure 2 indicates that the baywide ranges estimated from the surface samples are even greater. *B. exustus* from the five sample sites exhibits a $\delta^{18}\text{O}$ range of 5‰ and a $\delta^{13}\text{C}$ range of 8‰. It is probable that these species have limited growth tolerances and do not record the entire range of conditions in the bay. The range suggests the potential for great variation in the bay when records spanning centuries are constructed. Figure 4 shows extremely limited variation on the scale of decades. The data implies long-term (decades) stability of the bay despite great short-term (seasonal to interannual) variability.

$\delta^{13}\text{C}$

The change in $\delta^{13}\text{C}$ values of DIC is interpreted to reflect biological and physical controls on carbon cycling in the bay. Water circulation is one of the most important factors controlling carbon flux. Mud banks restrict tidal circulation in Florida Bay and compartmentalize the bay into more than 40 shallow sub-basins (Ginsburg 1956; McCallum and Stockman 1964; Smith 1997). The effectiveness of the banks as barriers to flow is often indicated by abrupt changes of salinity and turbidity between adjacent sub-basins. Those familiar with the bay refer to the sub-basins as "lakes," a term common in the Florida Bay literature until the 1980s (e.g., Porpoise Lake of Hudson et al. 1970, now Panhandle Basin). The analogy between lakes and sub-basins may go well beyond the obvious physiographic similarities. Lakes have their own geochemical characteristics (Gonfiantini 1986), so too do the sub-

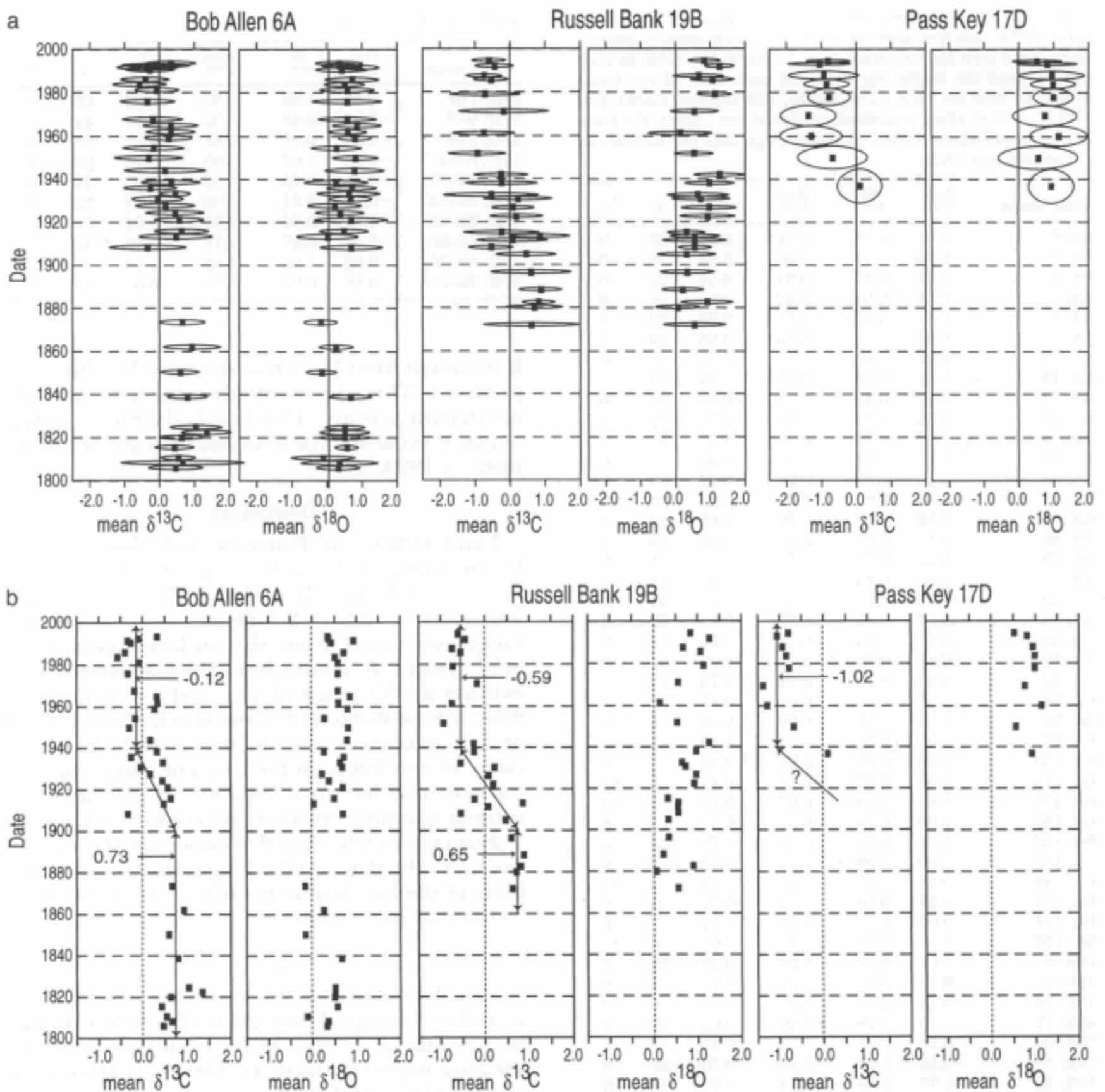


Fig. 4. (a). Core isotope data from Fig. 3 plotted versus time using ^{210}Pb -derived chronologies. Note the weak tendency for $\delta^{13}\text{C}$ to vary inversely with $\delta^{18}\text{O}$, resulting in a mirror-like reflection between the datasets. The most striking change occurs in the $\delta^{13}\text{C}$ record between about 1910 and 1940. (b) Core isotope data from Fig. 3 illustrating means without variance ellipses. Arrows indicate long-term averages and the 1910–1940 shift in $\delta^{13}\text{C}$ values discussed in text. A shift in $\delta^{18}\text{O}$ values in the opposite direction is suggested by the $\delta^{18}\text{O}$ data from Bob Allen Bank and Russell Bank, but it is not statistically significant.

basins in Florida Bay, as evidenced by the differences in $\delta^{13}\text{C}$ found in surface samples and cores of this study.

Continuing the analogy, a simplified carbon budget for a Florida Bay sub-basin can be based on that for a lake, here modified from Wachniew and Rozanski (1997) and illustrated in Fig. 5. The mod-

el describes the exchange of carbon among various reservoirs affecting the sub-basin. Carbon inputs come from flow into the lake (I), dark respiration of seagrass and macroalgae (D), and microbial oxidative decay of organic matter and dissolution of carbonate sediment (R). Carbon exits the lake through outflow (O), carbonate skeletal precipi-

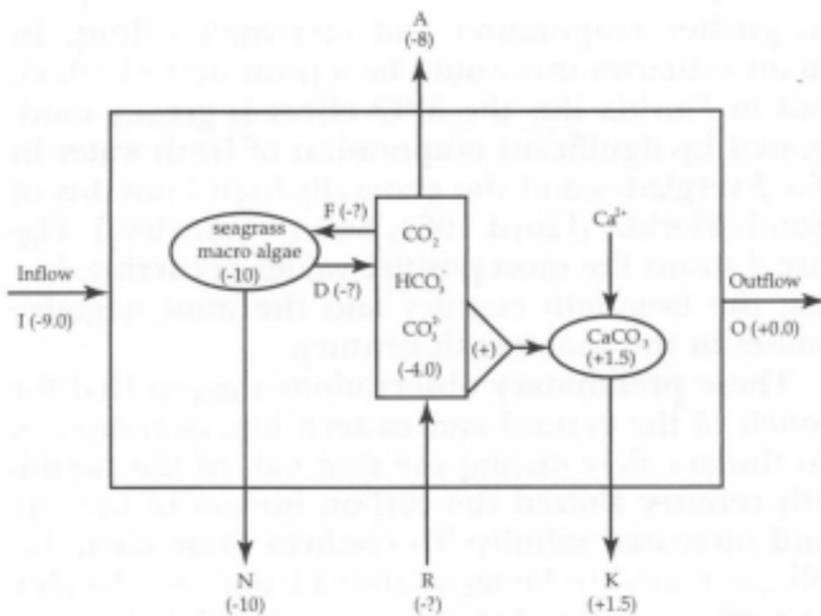


Fig. 5. Schematic for a long-term carbon budget for sub-basins (lakes) in Florida Bay (adapted from Wachniew and Rozanski 1997). The signs (+ or -) in parentheses indicate a positive or negative shift in the DIC reservoir induced by the process indicated by lettered arrows. $\delta^{13}\text{C}$ values for reservoirs are indicated in parenthesis if known and queried (?) if unknown.

tation and permanent deposition into sediments (K), particulate organic carbon sedimentation (N), and escape of CO_2 to the atmosphere (A).

For the time scales being considered here, the lake is a net producer of particulate organic and carbonate carbon, although dissolution may be recycling significant amounts of carbonate carbon (Patterson and Walter 1994b). Bosence (1989) estimates biogenic carbonate production to be between $128 \text{ g m}^{-2} \text{ yr}^{-1}$ and $347 \text{ g m}^{-2} \text{ yr}^{-1}$ at Upper Cross Bank in the northeastern bay. Net production of carbonate implies that the lake is a net producer of CO_2 (Garrells and Christ 1965) to the atmosphere (A).

The difference between carbon uptake by photosynthesis (P) and release during plant respiration (D) is the net production of organic carbon to sediment (N). Note that in this model we assume that recent algal blooms are an unprecedented phenomenon and that bay vegetation has been dominated by benthic species during the last two centuries.

The isotopic values are known for most of the reservoirs in Fig. 5 and values for others are being actively determined as part of the overall Florida Bay research program. Inorganic carbon species (CO_2 , HCO_3^{-1} , and CO_3^{-2}) can be determined using the fractionation factors of Deines et al. (1974). Modern DIC values have been measured by Sackett et al. (1997), Patterson (personal communication), and Holmes (1992) and average about -4‰ for the eastern/central bay. Seagrass and macroalgae reservoirs have been described by Fry et al. (1988) and Durako (1991) and average

about -10‰ . Particulate organic carbon in 30 samples from our cores ranges between -10‰ and -11‰ . We determined bulk carbonate sediment from Florida Bay to be $+1.5\text{‰}$, which reflects the positive influence of codiacian carbonate ($+2\text{‰}$ to $+4\text{‰}$; Milliman 1974).

The direction of changes in $\delta^{13}\text{C}$ values associated with most of the processes in the model is known, but the magnitudes of the fluxes have yet to be determined. From the direction of model processes, five processes might cause the observed negative shift in DIC after the turn of the century. The processes are 1) increased inflow of water with low $\delta^{13}\text{C}$ DIC values; 2) increased microbial decay of organic carbon; 3) increased carbonate production and accumulation; 4) increased vegetative respiration; and 5) increased residence time (decreased circulation) of water in the lake, resulting in greater influence of all in situ processes.

Of these possibilities, it seems highly unlikely that freshwater flow with low $\delta^{13}\text{C}$ DIC values has increased during this century (McIvor et al. 1994). Much of the focus of the ecosystem restoration effort in South Florida is to return adequate freshwater flow to the Everglades and Florida Bay. Equally unlikely is an increase in microbial decay that is largely temperature dependent. There is no evidence that temperature changed significantly between 1910 and 1940 (Hanson and Maul 1993).

Carbonate production, calculated by Bosence (1989) as $1.3\text{--}3.5$ moles of carbonate carbon $\text{m}^{-2} \text{ yr}^{-1}$, is insufficient to affect $\delta^{13}\text{C}$ values. From alkalinity and total carbonate data (Patterson and Walter 1994b; Patterson personal communication), $1\text{--}3$ moles of carbon (as dissolved inorganic carbon) is contained in 2 m^3 of bay water. The impact of carbonate precipitation on the water depends on the rate of water transport through the bay. Given the net transport from the Gulf of Mexico to the Atlantic Ocean measured by Smith (1994), seawater transport is significant and the impact of carbonate precipitation on the lake reservoir of carbon is small.

Zieman et al. (1994) speculated about a long-term change in the benthic vegetation of the bay. From historical and anecdotal evidence, they suggested a continuing alteration, over decades, from a mixed habitat to an increasingly monospecific seagrass community. This alteration might have induced a change in the $\delta^{13}\text{C}$ value of DIC, depending on the amounts of respiration and photosynthesis of seagrass. Greater seagrass productivity might also lead to increased organic carbon accumulation in sediments. Widespread growth of seagrass resulting from decreased freshwater flow could have led to a positive feedback produced by increased bottom friction in channels and

across banktops. Seagrass is a very effective barrier to flow (Fonseca and Fisher 1986; Prager in press), and this may have further reduced circulation in the bay.

Decreased circulation would have the effect of increasing residence times of bay water in the lakes. Longer residence times allow for a greater flux of lower $\delta^{13}\text{C}$ DIC from microbial decay. Pending a test with a hydrodynamic circulation model, it seems likely that circulation would be diminished by infilling between the Florida Keys during railroad construction (1908–1912), by increasing seagrass cover on the mud banks and in channels, and/or by decreasing freshwater flow from the mainland.

The larger shifts in $\delta^{13}\text{C}$ values toward the northeast may be a critical observation for determination of the influence of freshwater flow on bay carbon. The observation is corroborated by coral records. Swart et al. (1996) determined a coral isotope record for the southwestern bay (Fig. 1), which exhibits an abrupt negative $\delta^{13}\text{C}$ shift between 1905 and 1912. From 1912 to 1946 there is a slight increase in $\delta^{13}\text{C}$ values, and then a decrease of about 1‰ between 1946 and 1986. The event just after the turn of the century is attributed to railroad construction that constrained flow between Florida Bay and the Atlantic Ocean. Filling the channels decreased circulation and increased residence time, with the result that lower $\delta^{13}\text{C}$ DIC was retained in the bay. Long-term variations after 1912 are attributed to changes in hurricane frequencies between 1912 and 1986. The absence from the coral record of a decrease between 1910 and 1940 is consistent with a decrease in the effect to the southwest and suggests causes for the decrease were negligible near the Peterson Keys. The coral site is strongly influenced by marine waters from the Atlantic Ocean and the Gulf of Mexico as evidenced by the much smaller range of salinity recorded near the Peterson Keys than in the northeastern bay (Swart et al. 1996). The greater shift in $\delta^{13}\text{C}$ values to the northeast is consistent with decreasing freshwater flow that primarily enters the bay from the northeast. The suggested mechanism would be that decreased freshwater flow increased residence time, allowing for bacterial oxidation to introduce lower value $\delta^{13}\text{C}$ DIC from organic detritus in the sediments.

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

The record of $\delta^{18}\text{O}$ values from these cores exhibits less pronounced historical change than $\delta^{13}\text{C}$ values but suggests higher values in the twentieth century compared to those of the nineteenth century. This inference is consistent with decreased circulation and increased residence time resulting

in greater evaporation and increased salinity. In many estuaries this would be a pronounced effect, but in Florida Bay the $\delta^{18}\text{O}$ effect is greatly moderated by significant evaporation of fresh water in the Everglades and the generally high humidity of South Florida (Lloyd 1964; Swart et al. 1989). Figure 4 shows the most positive values occurring during the twentieth century and the most negative values in the nineteenth century.

These preliminary observations suggest that for much of the central and eastern bay, decreases in freshwater flow during the first half of the twentieth century altered the carbon budget of the bay and increased salinity. To confirm these data, duplicate cores are being analyzed from each locality to verify existing observations and to further constrain the timing of the $\delta^{13}\text{C}$ shift. Interpretation of the observed carbon changes is enhanced with the use of a carbon budget. Some carbon reservoirs and fluxes must yet be established to complete a carbon budget for the bay. A quantified carbon budget coupled with a circulation model, and coral and mollusk isotope records will provide the basis for understanding the carbon history of the bay and potentially provide a means for quantifying the changes of historical freshwater flow into the estuary.

Conclusions

Carbon and oxygen isotopic characteristics of Florida Bay water are recorded in the shells of mollusks living in the bay. We surveyed eight species and found the mussel *B. exustus* to be geographically widespread and particularly tolerant of the widely ranging conditions in the estuary. Using this species, and in its absence, *Transenella* spp., past conditions were reconstructed from well-dated cores. Similar records of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ occurred at three locations in the central and northeastern bay. Oxygen isotope ratios suggest the bay has been more saline since 1900. $\delta^{18}\text{O}$ is not a very sensitive indicator of salinity because it primarily tracks evaporation, and Everglades fresh water is highly evaporated when it enters the bay. Nevertheless, the mollusk records indicate Florida Bay was less dominated by evaporation in the 1800s than it has been since 1910.

Carbon isotope records indicate a significant shift in the bay during the first half of the twentieth century. In the nineteenth century, DIC was significantly heavier than it has been during the past five decades. The most likely cause was a decrease in bay circulation and an increase in residence time, possibly associated with increased vegetative bottom cover and decreased freshwater inflow. Verification of these relationships requires verification of the preliminary results reported here, hydro-

dynamic circulation modeling, and the development of a carbon budget for Florida Bay.

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