The Use of Proxy Chemical Records in Coral Skeletons to Ascertain Past Environmental Conditions in Florida Bay

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The Use of Proxy Chemical Records in Coral Skeletons to Ascertain Past Environmental Conditions in Florida Bay

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ABSTRACT: This paper will discuss the use of chemical proxies in coral skeletons to reconstruct the history of salinity (from the $\delta^{18}O$ of the skeleton) and nutrients in the water (from the $\delta^{13}C$) in Florida Bay between 1824 and 1994. Monthly salinity and water temperature data collected since 1989 were used to establish a correlation between salinity, temperature, and the $\delta^{18}O$ of the skeleton of the coral *Solenastrea bournoni* from Lignumvitae Basin in Florida Bay. This relationship explains over 50% of the variance in the $\delta^{18}O$ of the skeleton. Assuming that interannual variations in the temperature of the water are small, we have applied this relationship to the $\delta^{18}O$ measured in the coral skeleton collected from Lignumvitae Basin which has a record between 1824 and 1993. These data provide a revised estimate of salinity variation in Lignumvitae Basin for the period when historical records for salinity were not available, and show that the highest salinity events occurred in the past 30 yr. Using the relationships between the salinity in Lignumvitae Basin and other basins, obtained using a modern dataset, we are able to estimate ranges in salinity for other portions of Florida Bay. Skeletons of specimens of the coral species *Siderastrea radians* collected from other areas of Florida Bay show similar patterns in the $\delta^{18}O$ over the past 10 yr, indicating that corals in most portions of Florida Bay are recording salinity variations in their skeletons and therefore support the idea that salinity variations in different portions of Florida Bay can be related. Fluorescence analysis of the coral from Lignumvitae Basin shows a large change in the magnitude of the 10-yr signal coincident with the construction of the railway, confirming that this event had a significant impact upon Florida Bay. The $\delta^{13}C$ of the coral skeletons reveals a long-term history of the oxidation of organic material, fixation of carbon by photosynthesis (algal blooms), and the intrusion of marine water into the bay. Since the construction of the railway from Miami to Key West there has been a long-term decrease in the $\delta^{13}C$ of the coral skeleton from Lignumvitae Basin, suggesting the increased oxidation of organic material in this area. This decrease in $\delta^{13}C$ appears to have reached a minimum value around 1984 and has increased since this time in the western portions of Florida Bay. The increase may be related to the algal blooms prevalent in the area or alternatively could result from intrusion of more marine water. In the eastern areas, a small increase in the $\delta^{13}C$ between 1984 and 1988 was followed by further decline suggesting more oxidation of organic material. We have also attempted to use the concentration of barium in the coral skeleton as a proxy indicator of the nutrient status in Florida Bay.

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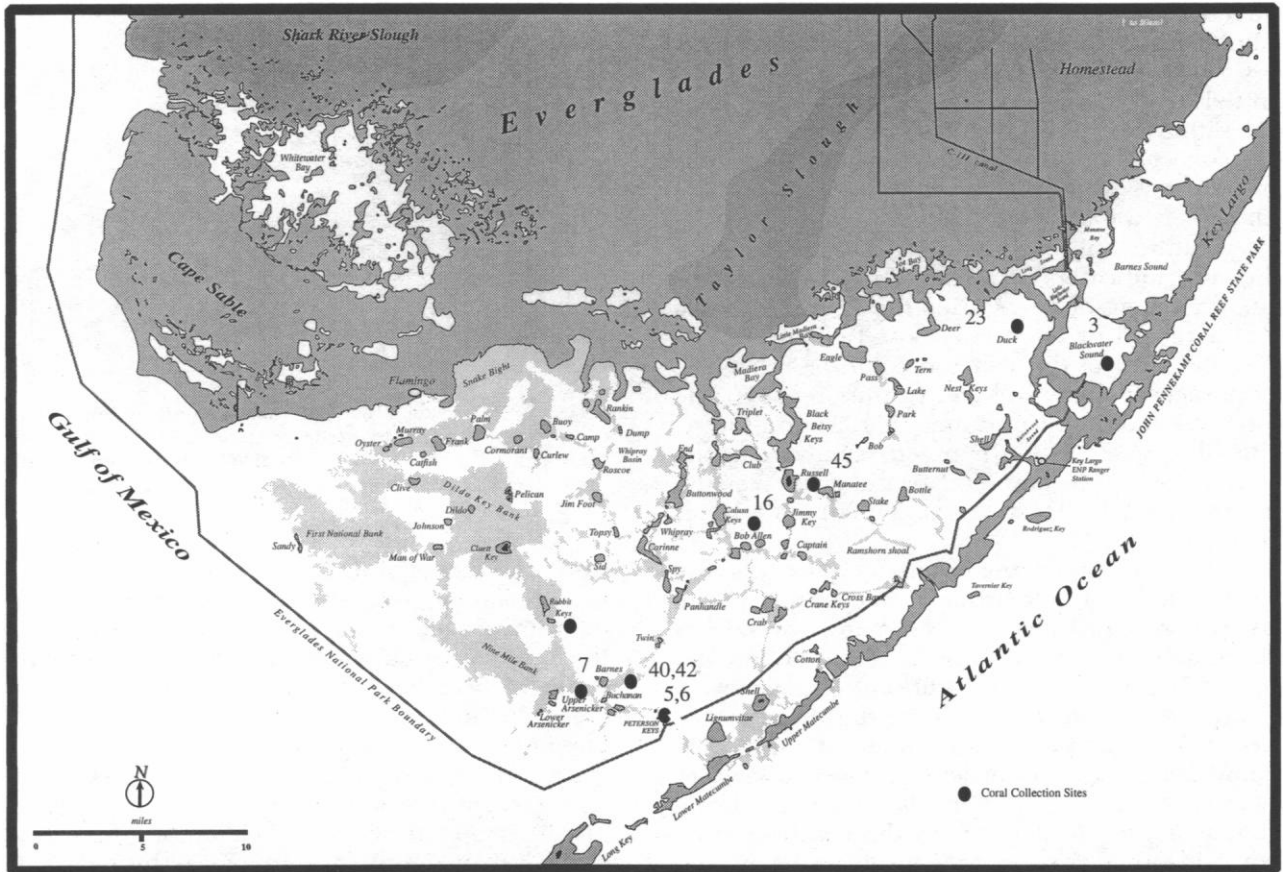
Fig. 1. Map of Florida Bay. Locations of corals are shown by solid dots. The numbers of the corals are positioned by the dot. The Overseas Railway followed the line of the Florida Keys. Construction of the railway between Miami and Key West filled in most of the area between Lower and Upper Matecumbe Keys and reduced the flow between Lower Matecumbe and Long Key.

Introduction

Over the past decade there has been mounting concern regarding increased salinity and nutrient concentrations in Florida Bay (McIvor et al. 1994). Salinity reached a maximum at the end of the 1980s, corresponding to a major period of drought in South Florida and coinciding with algal blooms and a major die-off of seagrasses. Concern had focused on whether these changes are of anthropogenic origin or whether they are a consequence of natural phenomenon such as climatic variation (Boesch et al. 1993). To answer these fundamental questions, proxy records of environmental conditions, such as those contained in undisturbed sediment records (Halley et al. 1999) and massive coral skeletons (Hudson et al. 1989; Smith et al. 1989; Swart et al. 1996a) are being used. Smith et al. (1989) examined the patterns of fluorescence in the skeleton of a specimen of the coral species *Solenastrea bournoni* (denoted FB-5) from Lignumvitae Basin as an indicator of freshwater input into the Bay. Fluorescence in coral skeletons has been

suggested to be a result of terrestrially derived humic material and hence is an indicator of the amount of freshwater delivered to the coral (Isdale 1984). The changes in fluorescence suggested a change in the freshwater delivery patterns prior to 1940, which Smith et al. (1989) interpreted as reflecting a change in water management practices in the Everglades. The work of Swart et al. (1996a) examined the $\delta^{13}C$ and $\delta^{18}O$ record in the skeleton of a second specimen of *Solenastrea bournoni* (denoted FB-6) in Lignumvitae Basin (Fig. 1) which has a record extending from 1824 to 1986. They concluded that significant changes in the $\delta^{13}C$ and $\delta^{18}O$ occurred in the coral skeleton coincident with the construction of the Florida Overseas Railway from Miami to Key West between 1907 and 1912. The interpretation of changes in $\delta^{18}O$ suggested that prior to the construction of the railway there appeared to be slightly lower, but much more variable salinity in this basin. After construction of the railway, Lignumvitae Basin became semi-isolated from the Florida Reef Tract, less exchange oc-

curred between these two water bodies, and the salinity became elevated. The large decrease in $\delta^{13}C$ observed by Swart et al. (1996a) can be interpreted as an increased oxidation of organic material within Lignumvitae Basin. Because this coral was collected prior to the major salinity crisis in Florida Bay, which occurred between 1989 and 1991, there was a paucity of continuous salinity and temperature data with which to correlate geochemical indicators of climate in the coral skeleton. The need was recognized for data of the most recent record of the coral (post 1986) such that $\delta^{13}C$ and $\delta^{18}O$ of the skeleton could be related to more recent salinity and temperature records. The coral was cored a second time in 1993 and the results of the correlation between salinity, temperature, and the $\delta^{13}C$ and $\delta^{18}O$ of the coral skeleton are reported by Healy et al. (1996) and Healy (1996).

This study applies the results of these correlations to the entire record presented by Swart et al. (1996a) and provides new estimates for salinity throughout Florida Bay prior to the start of regular monitoring of salinity. In addition to these new estimates we present new data on the fluorescence record from the same coral. In an attempt to examine the change in nutrients in Florida Bay over this time period, we present data on the concentration of barium and $\delta^{13}C$ in the coral skeleton, which in other areas of the world has been used both as a proxy indicator of nutrients (Lea et al. 1989) and riverine input (Shen and Sandford 1990; Anderegg et al. 1997). Finally, in order to test the applicability of our results to areas other than Lignumvitae Basin, we have analyzed the $\delta^{13}C$ and $\delta^{18}O$ records from specimens of *Siderastrea radians*, a species of coral growing up to 15 cm in diameter and found throughout Florida Bay.

Background

The $\delta^{18}O$ and $\delta^{13}C$ of coral skeletons has been widely used within the chronological framework of skeletal density bands to provide information on the salinity and temperature of the environment (see Swart and Leder 1996 and references therein). The $\delta^{18}O$ of coral skeletons has been determined for the species *Montastraea annularis* growing on the Florida reef tract (Leder et al. 1996) (Eqn. 1).

$$\delta w = \delta c - \frac{(5.33 - T)}{4.23} \qquad (1)$$

In this equation δw = isotopic composition of the water, δc = oxygen isotopic composition of the carbonate, and T = temperature. As there are three unknowns in this equation, knowledge of two variables are necessary to solve for the third. In the
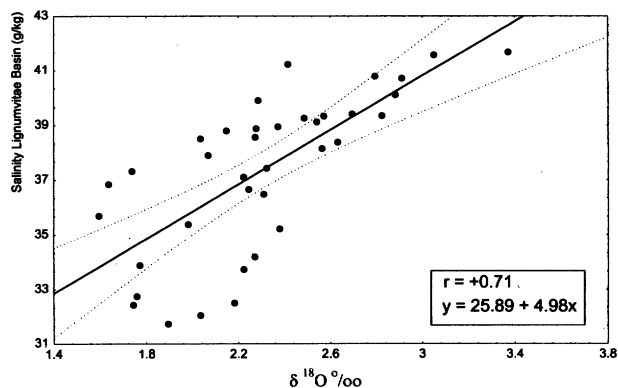

Fig. 2. Correlation between salinity and oxygen isotopic composition of *Solenastreas bournoni* growing in Lignumvitae Basin between 1991 and 1994 (Healy 1996). The dashed lines represent the 95% confidence limits of the regression line.

study of Swart et al. (1996a), it was assumed that a coarse sampling regime would effectively average out intra-annual variations in temperature and that the residual variations in the $\delta^{18}O$ would be the result of changes in the salinity of the environment. In studies in which higher resolution samples are taken, account must be made of both variations in temperature and salinity. In work on the most recent portion of the same coral, Healy (1996) sampled the coral skeleton at a high resolution (many samples within a given time period). As a result of the high resolution sampling and the availability of data on salinity and temperature, an equation was obtained relating the $\delta^{18}O$ of the coral skeleton to both temperature and salinity (Healy et al. 1996; Healy 1996).

This relationship between the $\delta^{18}O$ of the water (δw) and salinity is shown in Eqn. 2 and Fig. 2 (r = +0.71, n = 38, p > 0.05).

$$Salinity = 4.98\delta w + 25.89 \qquad (2)$$

Combining Eqns. (1) and (2), an expression (Eqn. 3) is derived expressing salinity in terms of the δc and T.

$$Salinity = 4.98\delta c + 1.18T + 19.62 \qquad (3)$$

The confirmation of a positive correlation between salinity and the $\delta^{18}O$ of the water (δw) seems to discount the notion that significant amounts of freshwater from Shark Slough, which is isotopically enriched in ^{18}O (Meyers et al. 1993), is influencing the salinity of Lignumvitae Basin. If this water were influencing the salinity of Lignumvitae Basin then either an inverse correlation or no correlation at all would be expected between δw and salinity.

The origin of the $\delta^{13}C$ of the coral skeleton is still uncertain but has been suggested to be related to annual variation in insolation (Fairbanks and

TABLE 1. Location and water depths of specimens of *Siderastrea radians* used in this study.

| ID	Location	Depth (m)
FB-3	Blackwater Sound	3
FB-7	Arsenicker Keys	2.5
FB-14	Rabbit Key	3.5
FB-16	Calusa Key	3
FB-23	The Boggies	3
FB-40	Lignumvitae Basin	2
FB-42	Lignumvitae Basin	2
FB-45	Manatee Key	2.5

Fig. 3. X-radiograph of a specimen of *Siderastrea radians* (FB-16). The contrast has been changed in an area in the center of the image to improve the recognition of the density bands.

Dodge 1979; Swart 1983; Swart and Leder 1996). Recent data suggest annual variations in the $\delta^{13}C$ of dissolved inorganic carbon (DIC) in seawater may be of considerable importance in directly controlling the skeletal isotopic composition and also in affecting the isotopic composition of the skeleton through the influence of the DIC on the food chain. Variations in the $\delta^{13}C$ of coral skeletons as a result of physiological processes were found to be small compared to the influence of $\delta^{13}C$ variations of the DIC (Swart et al. 1996b). In the analyses of the skeletal material of the Florida Bay corals, variations in the $\delta^{13}C$ have been interpreted as reflecting changes in the $\delta^{13}C$ of the DIC rather than physiological processes. This is because changes in the $\delta^{13}C$ of the DIC in excess of 2‰ have been documented in Lignumvitae Basin (Lutz et al. 1995). These variations were suggested to be a result of changes in the contributions of CO_2 derived from the oxidation of organic material.

The history of nutrient enrichment in calcareous organisms may be indicated by the trace elements cadmium, manganese, and barium (Shen 1986; Shen and Boyle 1988; Lea et al. 1989; Shen and Sanford 1990). Elements such as Cd and Ba are nutrient analogs (e.g., Boyle et al. 1981; Millero and Sohn 1992), exhibiting strong nutrient type depth profiles. These trace elements may be incorporated in the calcium carbonate lattice of coral skeletons by substitution for calcium (Shen and Boyle 1988; Shen and Sanford 1990). Cd and Ba in dated samples of coral skeletons have been shown to reflect former nutrient conditions, especially in regions marked by strong upwelling events (e.g., the Galapagos, Shen and Sanford 1990; the coast of southern Oman, Tudhope et al. 1996). Barium is also thought to be of value as a chemical tracer of freshwater delivered to the oceans by rivers (Boyle 1976; Hanor and Chan 1977; Edmond et al. 1978; Shen and Sanford 1990). It is not known how Ba might behave in an environment such as Florida Bay, but the expectation is that it can be used as a nutrient tracer and therefore derive information on the past history of
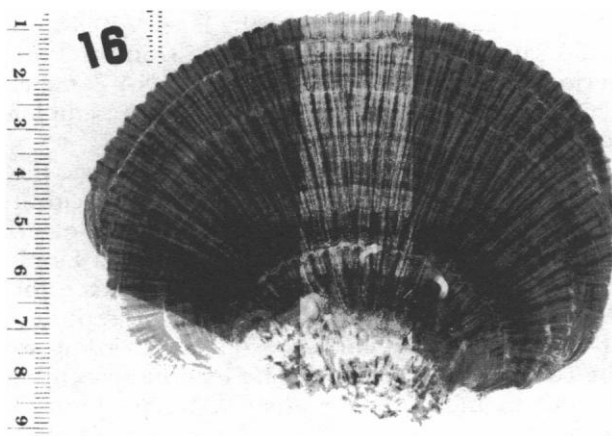
nutrient behavior (Lea et al. 1989) or it can be used as an indicator of the amount of freshwater input (Shen and Sanford 1990).

Methods

The location and water depths of the corals used in the study are shown in Fig. 1 and Table 1. The cores and corals were slabbed and subjected to X-radiography using standard methods (Hudson 1981; Dodge et al. 1984). Multiple slabs were made from all corals and the slab in which the corallites were orientated optimally was chosen for future analysis. Age assignments were made using the assumption that one couplet (a dense + less dense band) represented 1 yr. In the case of *Siderastrea radians*, the density bands are not always clear (Fig. 3). Therefore age assignment was carried out using a combination of annual variations in the stable C and O isotopic composition, in addition to similar variations in density and fluorescence.

In order to obtain samples for stable isotopic analyses, the slabs were mounted to glass slides and ground to a thickness of 1–2 mm. The slab surface was impregnated with resin and smoothed to provide a even sampling surface (minimal cavities). In this manner the powder resulting from the drilling of the skeleton was not lost into the coral. Replicate isotopic analyses revealed that the resin did not affect the stable isotopic composition of the sample. The data on the samples used for stable isotopic analyses of *Solenastrea bournoni* has been previously reported (Healy et al. 1996; Healy 1996; Swart et al. 1996a). In the original study (Swart et al. 1996a), a relatively crude technique was employed in which samples were drilled from discrete holes using a dental drill. Using this method only, between 3 and 12 samples were obtained within a

period of 12 mo. In the study by Healy (1996) up to 50 samples were obtained over a similar time period using a computer controlled X-Y-Z stage. This same method was used to obtain samples from specimens of *Siderastrea radians*.

The CO_2 for mass spectrometric analysis was obtained by reaction with orthophosphoric acid at 90°C using a common-acid device (Swart et al. 1991). The CO_2 was then analyzed using a Finnigan-MAT 251. The data have been corrected for the usual isobaric interferences and are reported as $\delta^{13}C$ and $\delta^{18}O$ relative to V-PDB, according to the conventional notation. The external precision for this method is better than 0.1‰ for both O and C.

Fluorescence was measured using the University of Miami's Laser Induced Fluorescence Analyzer (LIFA) (Milne and Swart, 1994). In this method a pulsed nitrogen laser induces fluorescence in a coral slab. The fluorescence is detected using a coupled fiber optic bundle and is passed through a monochromator (460 nm) into a photomultiplier. This signal and a normalizing signal are measured using a 100kHz 16 bit A-D converter, and the data over the first 200 ms is averaged over 100 pulses. The coral, which is positioned on a linear rail table, is moved a predetermined interval (100 μm) and the measurement process started again. This method produces a scan of relative amount of fluorescence and is not meant to be quantitative. The actual area being analyzed at a particular time is approximately 0.5 mm in diameter and therefore the method is very susceptible to surface irregularities.

Barium was measured by isotope dilution inductively coupled mass spectrometry (ICP/MS). Coral samples of approximately 0.1–1.5 g (0.5 g on average) were dissolved in distilled nitric acid, spiked with ^{135}Ba, and brought up to final volume (1.5 cm^3). From this, a calcium subsample was taken (50 μl) and independently analyzed by a flame atomic absorption spectrophotometer (AAS). The coral was sampled for Ba at 4 samples yr^{-1} from 1986 to 1945 and 2 samples yr^{-1} between 1850 and 1945.

A summary of the salinity data to derive relationships between the various different basins in Florida Bay is given by Boyer et al. (1999). The salinity records used for comparison to the specimens of *Siderastrea radians* have been obtained from the database assembled by Dr. M. Robblee (Swart et al. 1996a; Robblee et al. 1989).

In order to convert the samples to common time intervals, age assignment were made assuming that the dense band formed during the August of each yr. The chemical data were then interpolated to common time intervals using a rectangular inter-
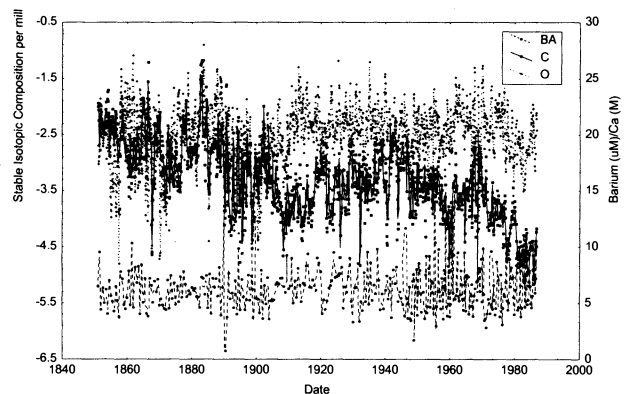

Fig. 4. Composite oxygen and carbon isotopic record (data from Swart et al. 1996a; Healy et al. 1996) and barium data (this study) from a specimen of *Solenastrea bournoni* (FB-6) collected in Lignumvitae Basin. Because of the lower growth rate for this coral prior to 1850, the Ba was only analyzed 1850–1986.

polation method. Single spectral statistical analysis was performed using a program supplied by Ed Cook of LDEO. Correlation between variables was determined using the Pearson correlation coefficient. The statistical significance of the data was determined using a two-tailed ANOVA.

Results

For the purpose of estimating salinity we have combined the datasets used in the Swart et al. (1996a) study with the data measured by Healy (1996) and calculated yearly means (Fig. 4). Annual $\delta^{18}O$ values from the *Siderastrea radians* specimens are shown as a function of age in Fig. 5a. These values (Table 2) range from −0.5‰ to −3.4‰. The highest values occur coincident with the highest reported salinities between 1989 and 1991.

The $\delta^{13}C$ data from Swart et al. (1996a) and Healy (1996) have been combined and are shown in Fig. 4. The carbon isotopic data from the specimens of *Siderastrea* are shown in Table 2 and Fig. 5b. These corals are isotopically negative with respect to the specimen of *Solenastrea bournoni* collected from Lignumvitae basin and range between −1.9‰ and −5.8‰. Based on the changes in the $\delta^{13}C$, the corals can be separated into two groups, those which show an increase in $\delta^{13}C$ after the drought period (FB16, FB14, FB5, FB40, FB42, and FB7) and those in which the $\delta^{13}C$ decreases (FB45, FB23, and FB3). The former group of corals occur in the eastern portion of the bay and the latter are located in the west.

The record of relative fluorescence for FB-6 is shown in Fig. 6. The age assignments of this record are based on the density record used in previous studies (Swart et al. 1996a). These data show a de-
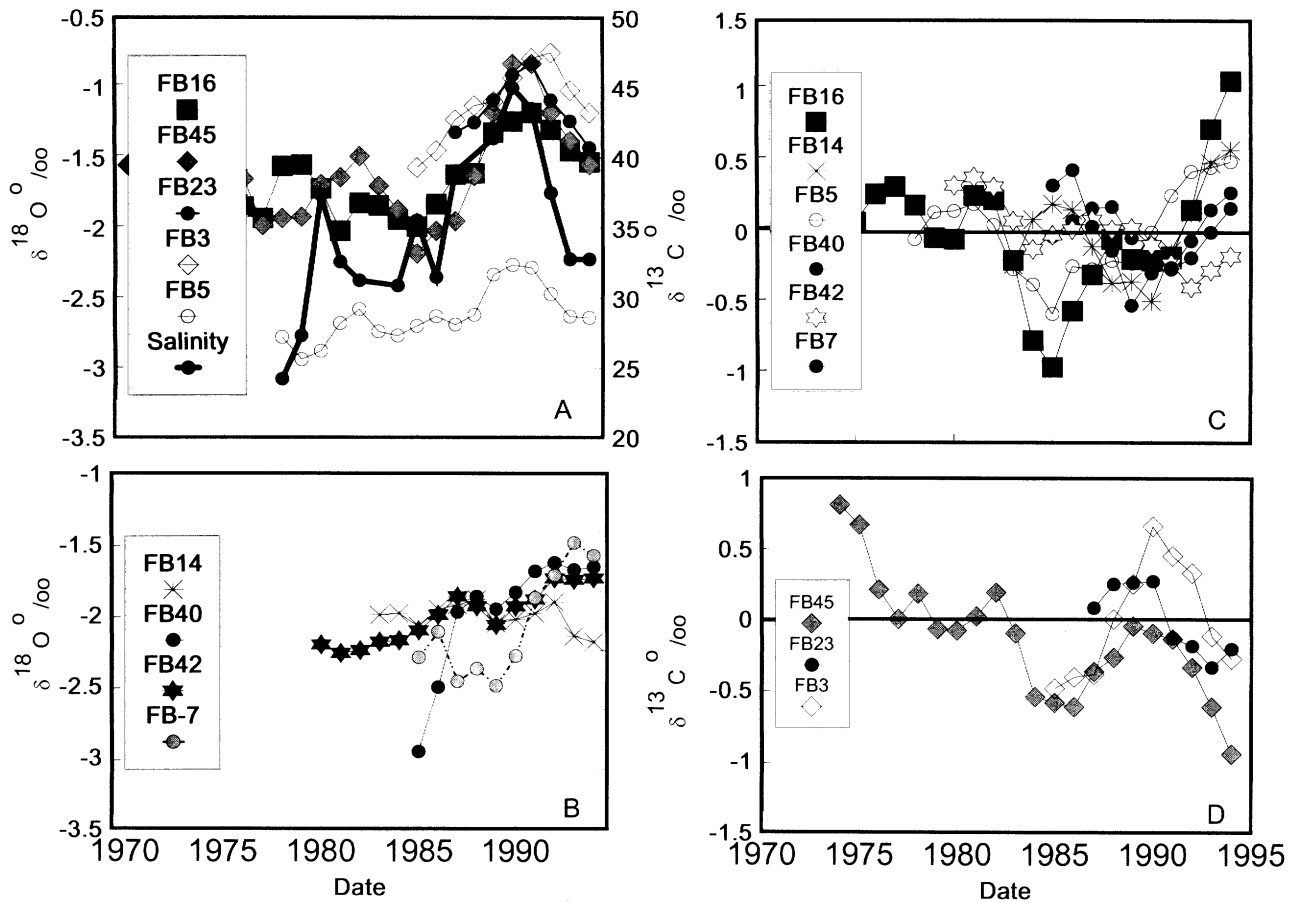
Fig. 5.   Three year moving averages of the C and O stable isotopic composition of corals: (a) Oxygen isotopic composition of *Siderastrea radians* from four localities (see Fig. 1) compared to the salinity and the $\delta^{18}O$ of the coral from Lignumvitae Basin. These corals show a positive correlation with salinity over the same time period and are all located in the northeastern portion of Florida Bay. (b) The oxygen isotopic composition of corals from the southwestern portion of Florida Bay. These corals do not exhibit any decrease in the oxygen isotopic composition after 1990. (c) The carbon isotopic composition of corals from different environments in Florida Bay (Fig. 1). Basins in the northeast portion of Florida Bay show a decrease in carbon isotopic composition since 1990. (d) In contrast to basins in the northeast portion of Florida Bay, basins in the southwest show an increase in the carbon isotopic composition, suggesting either the influence of algal blooms or increased intrusion of marine water and less influence from terrestrial sources.

crease in the amplitude of fluorescence coincident with the railway construction.

The results for barium are shown in Figs. 4 and 7. Raw data for Ba and salinity had a negative regression coefficient of r = −0.61 (n = 50; p > 0.001) over the 15-yr period 1973–1987. Ba increases when salinity decreases (as a result of precipitation, inundation by marine waters, or run-off from the Everglades).

Discussion

SALINITY ESTIMATES

Using the correlation between the salinity measured throughout Florida Bay from 1991 to the present, we established relationships between the different basins in Florida Bay and Lignumvitae Ba-

sin (Table 3). These relationships, although similar to those obtained by Swart et al. (1996a) employing the historical dataset assembled by Robblee et al. (1989), are more reliable as they are based on samples collected at monthly intervals between 1991 and 1996. The degree of correlation between the salinity in Lignumvitae Basin and other sampling sites in Florida Bay is shown in Fig. 8a,b. Figure 8a shows a contour map of the amount of variance explained between Lignumvitae Basin and other basins for the wet season in South Florida (May–October); Fig. 8b is a similar map for the dry season. These figures indicate the differing influences controlling salinity in Florida Bay. During the summer wet season the highest correlation coefficients exist between the salinity in Lignumvitae

TABLE 2. Mean annual C and O isotopic composition of *Siderastrea radians*.

| Year	FB-16 C	FB-16 O	FB-45 C	FB-45 O	FB-14 C	FB-14 O	FB-23 C	FB-23 O	FB-3 C	FB-3 O	FB-40 C	FB-40 O	FB-42 C	FB-42 O	FB-7 C	FB-7 O
1970	-3.75	-1.67														
1971	-3.93	-1.46														
1972	-3.56	-1.63														
1973	-4.44	-2.15														
1974	-2.83	-1.86	-4.48	-2.31												
1975	-3.75	-1.55	-4.09	-1.44												
1976	-4.85	-1.85	-4.65	-2.11												
1977	-4.22	-1.55	-3.87	-2.00												
1978	-4.39	-2.54	-3.94	-1.69												
1979	-4.30	-1.71	-5.03	-0.98												
1980	-4.99	-1.52	-4.58	-1.99									-2.53	-1.99		
1981	-4.40	-1.84	-3.97	-2.18									-1.91	-2.42		
1982	-4.00	-1.55	-4.08	-1.88									-2.03	-2.39		
1983	-4.48	-1.09	-4.68	-1.40	-4.55	-2.03							-2.73	-1.93		
1984	-5.26	-2.45	-5.26	-2.23	-4.37	-1.97							-2.65	-2.27		
1985	-5.37	-2.06	-5.80	-2.20	-3.51	-1.98			-4.50	-1.73	-3.52	-3.40	-2.62	-2.35	-2.93	-1.78
1986	-4.59	-2.02	-5.24	-1.55	-4.21	-2.30			-4.24	-1.42	-3.05	-2.52	-2.42	-1.70	-2.94	-2.82
1987	-5.35	-1.96	-4.07	-1.73	-4.50	-1.61	-3.80	-1.32	-4.13	-1.21	-2.97	-1.61	-2.55	-1.96	-2.59	-1.76
1988	-4.61	-1.87	-5.00	-1.59	-4.27	-1.87	-3.88	-1.32	-4.45	-1.07	-3.22	-1.82	-2.41	-1.94	-4.12	-2.84
1989	-4.29	-1.07	-4.50	-1.50	-4.99	-2.19	-3.33	-1.11	-3.06	-1.10	-3.05	-2.18	-2.63	-1.93	-3.45	-2.53
1990	-4.69	-0.59	-4.48	-0.87	-4.49	-2.11	-3.80	-0.84	-3.37	-1.14	-3.60	-1.89	-2.52	-2.35	-3.76	-2.14
1991	-4.76	-0.84	-5.03	-1.35	-4.68	-1.78	-3.84	-0.78	-3.24	-0.54	-3.36	-1.47	-2.76	-1.56	-3.44	-2.18
1992	-4.43	-1.05	-4.42	-1.31	-3.91	-2.08	-4.53	-0.86	-3.67	-0.71	-3.59	-1.73	-3.02	-1.76	-3.35	-1.32
1993	-5.28	-1.64	-3.49	-1.24	-3.68	-1.88	-3.96	-1.62	-3.72	-1.00	-3.37	-1.69	-3.02	-1.91	-3.19	-1.65
1994	-5.59	-1.46	-3.31	-1.81	-4.23	-2.50	-4.31	-1.24	-4.60	-1.36	-2.81	-1.63	-2.42	-1.58	-2.77	-1.52
Mean	-4.48	-1.64	-4.47	-1.68	-4.23	-2.02	-3.93	-1.14	-3.90	-1.13	-3.25	-1.99	-2.55	-2.00	-3.25	-2.05
SD	0.63	0.46	0.60	0.40	0.44	0.23	0.34	0.27	0.53	0.32	0.26	0.55	0.29	0.28	0.44	0.51
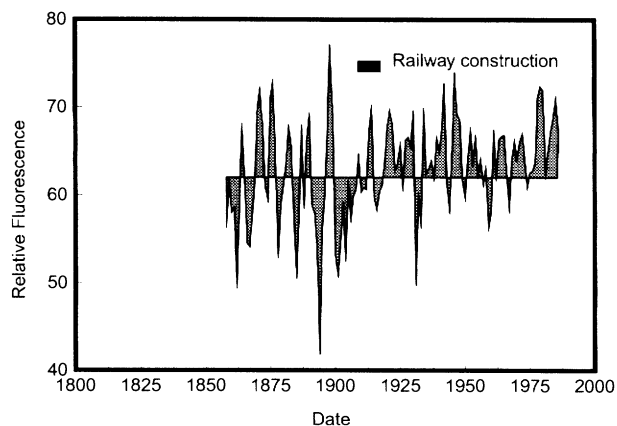
Fig. 6. Fluorescence analysis from FB-6. The LIFA reports the data as relative fluorescence units and therefore simply gives a qualitative impression as to whether there is less or more fluorescence and the magnitude of the variation. Note that the variation in the fluorescence prior to railway construction was much larger than after railway construction.

Basin and salinity in the majority of Florida Bay, with r^2 values decreasing rapidly towards the northeast. In contrast, during the winter the correlations are also good within all portions of Florida Bay, with r^2 values decreasing rapidly towards the west into the Gulf of Mexico.

Using the equations relating the salinity between various basins (Table 3), Eqns. (1) and (2) can be used to calculate long-term changes in salinity throughout Florida Bay (Fig. 9) using the data of Swart et al. (1996a) and Healy (1996). Because these data have been averaged into yearly samples the intraannual variations in water temperature have been effectively removed and an annual mean value for water temperature can be used in Eqn. 1. The use of such an approach implies that interannual variations in temperature or long-term trends in water temperature have not been accounted for. Interannual changes in temperature are small and the residual variations in the $\delta^{18}O$ can be related to changes in salinity. For example, based on continuous water temperature data from Lignumvitae Basin over the past 5 yr, the influence of annual changes in water temperature on the annual $\delta^{18}O$ signal in the coral would be less than 0.1‰, equivalent to an apparent salinity change of 0.5 (Eqn. 3). Using the longer historical dataset (Robblee et al. 1989), the variation in the annual mean water temperature from a selection of basins across Florida Bay is only 1.5°C, corresponding to an uncertainty of 1.5. If longer temperature records from more open oceanic sites are considered, the potential influence of temperature is
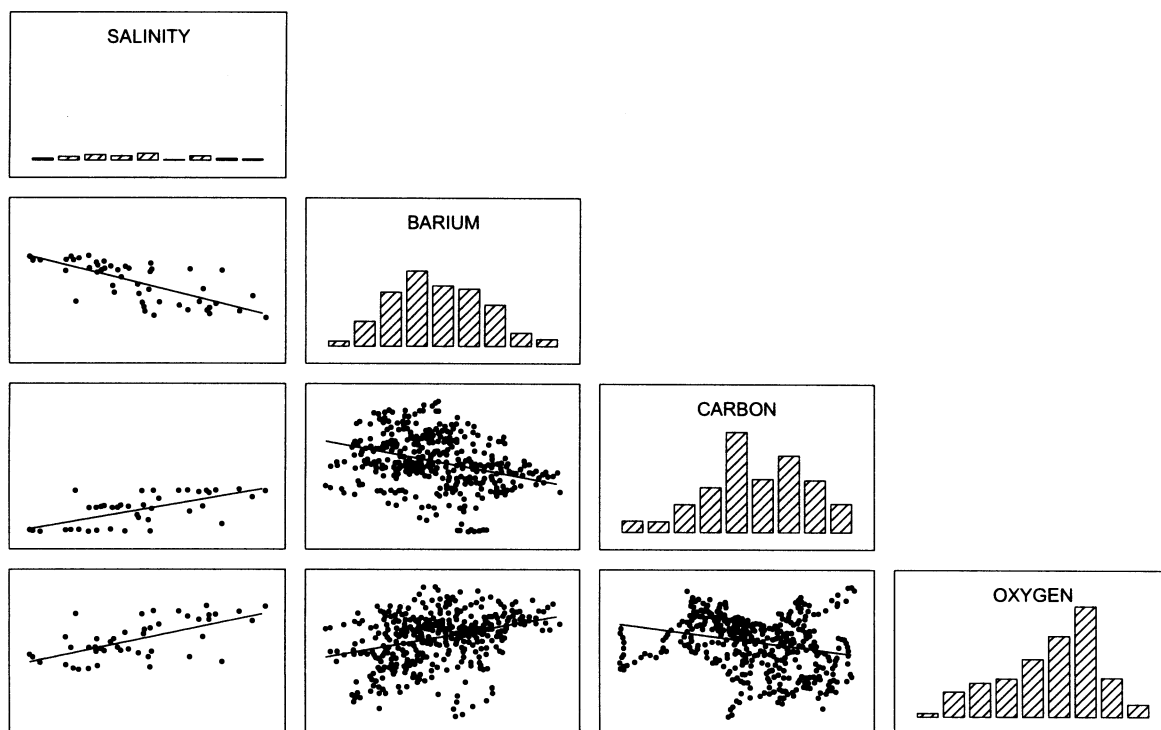

Fig. 7. Casement diagram showing correlation between Ba, C, O, and salinity in Florida Bay. The salinity data used are from the Robblee et al. (1989) dataset between 1973 and 1987. The histograms show the frequency distribution of the data. For scales see Fig. 5.

TABLE 3. Relationships between salinity at locations sampled by Florida International University and the salinity in Lignumvitae Basin between March 1991 and March 1997 (n = 73). Relationships expressed by the variance (r^2) are significant at greater than the 99.9% confidence limits.

K(Constant)	M(Slope)	r^2	Latitude	Longitude	Station Name
−6.38	1.01	0.82	−80.3746	25.2735	Card Sound Bridge
−5.17	0.89	0.64	−80.3950	25.2850	Middle Key
−16.40	1.17	0.54	−80.4152	25.2510	Manatee Bay
−16.05	1.24	0.75	−80.3883	25.2217	Barnes Sound
−24.06	1.47	0.78	−80.4231	25.1741	Blackwater Sound
−29.88	1.42	0.57	−80.4404	25.2067	Blackwater Sound
−20.10	0.80	0.29	−80.4442	25.2536	Highway Creek
−27.19	1.23	0.48	−80.4617	25.2274	Long Sound
−35.39	1.78	0.76	−80.4916	25.1771	Duck Key
−36.24	1.35	0.45	−80.5366	25.2245	Joe Bay
−42.07	1.83	0.71	−80.6269	25.1752	Merdin Bay
−37.59	1.97	0.78	−80.7161	25.1404	Terrapin Bay
−22.27	1.60	0.85	−80.7628	25.0879	Whipray Basin
−23.67	1.59	0.62	−80.8040	25.1183	Garfield Bight
−18.86	1.47	0.72	−80.8065	25.1454	Rankin Lake
2.18	0.90	0.82	−80.9396	25.1183	Murray Key
2.80	0.89	0.81	−80.9153	25.0447	Jimmy Key Basin
6.92	0.78	0.86	−80.8953	25.0016	Rabbit Key Basin
−2.83	1.07	0.92	−80.7535	24.9777	Twin Keys Basin
			−80.7287	24.9111	Peterson Keys
−17.29	1.46	0.94	−80.6957	25.0071	Porpoise Lake
−27.34	1.68	0.89	−80.6211	25.0366	Captain's Key
−35.88	1.77	0.80	−80.5997	25.1180	Park Key
−36.45	1.83	0.83	−80.5314	25.1018	Buttenwood Key
6.82	0.78	0.82	−81.0806	25.0837	East Cape
1.70	0.64	0.80	−81.0013	24.9827	Oxfoot Bank
16.38	0.51	0.70	−80.9263	24.9151	Sprigger Bank
15.24	0.55	0.76	−80.8522	24.8638	Old Dan Bank

Salinity (Basin) = M × (Salinity Lignumvitae) + K.

even less. While it is acknowledged that there is some uncertainty in the calculation of the salinity by assuming minimal changes in the annual temperature, these changes are small and do not alter the interpretations in this paper. The calculated salinity variations (Fig. 9) confirm the interpretations of Swart et al. (1996a) that there have been no long-term major changes in salinity, only a slight increase associated with railway construction between 1907 and 1912. In contrast to the study by Swart et al. (1996a), the range of salinities calculated within Lignumvitae Basin and other basins in this study is significantly greater as a result of the improved correlation between the $\delta^{18}O$ of the coral skeleton and salinity arising from the studies of Healy (1996). The increased range is particularly evident in the salinities calculated for Duck Key Basin where previously (Swart et al. 1996a) the lowest calculated salinity was approximately 25. This compares to 10 in the new calibration (Fig. 9). The high salinity events can be clearly seen in the new calculated salinity record. In addition to the high salinity in the late 1980s, the coral record reveals high salinity events in the 1970s and 1960s. These events represent the highest oxygen compositions throughout the entire coral record (Fig. 9). Although this study does not address the cause of the

salinity variations, a superficial comparison between precipitation from the lower east, coastal region of South Florida appears to indicate that periods of lowest rainfall relate to times when the salinity was the highest. For example, the time of the most severe salinity extremes during the late 1980s corresponds to a period of prolonged rainfall deficit. Other periods of high calculated salinity also relate to an extended period of below average rainfall between 1968 and 1978 (Fig. 9). A more rigorous correlation between rainfall and the $\delta^{18}O$ of the coral skeleton, however, reveals no statistically significant correlation and only a weakly significant negative correlation (r = −0.28, n = 80, p > 0.05) when precipitation during the winter months is considered. The reasons for the absence of such a correlation may be a result of slight imperfections in the stratigraphy of the coral skeleton (See Swart 1996a for discussion) and/or the absence of a good precipitation record for Lignumvitae Basin.

Single spectral analysis of the calculated salinity data show three important statistically significant signals in the time series, at 4–7 yr, 28 yr, and 12–14 yr (Fig. 10). These frequencies respectively account for 22%, 13%, and 9% of the variance in the data. The most significant periodicity, which ac-
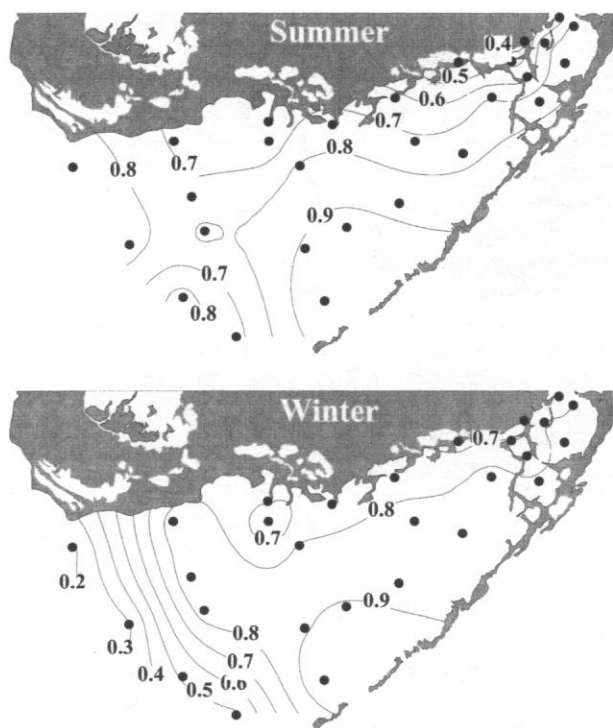
Fig. 8. Amount of variance (r²) explained by the correlation between the salinity in Lignumvitae Basin and Florida Bay locations sampled by Florida International University between 1991 and 1996 (n = 73) for the (a) wet season (May–October) and the (b) dry season (November–June). Values for r² greater than 0.16 are statistically significant at the 99.9% confidence limits.
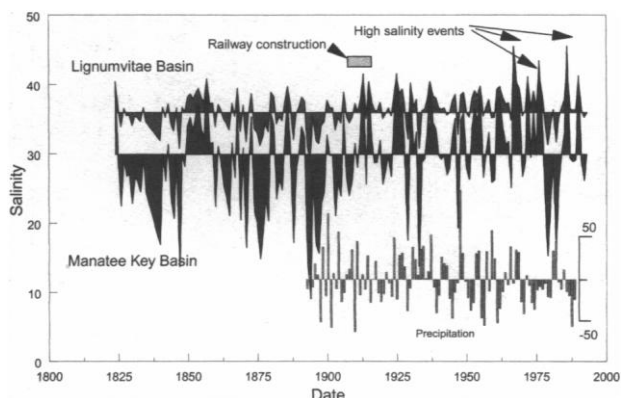

Fig. 9. Calculated salinity in Lignumvitae and Duck Key Basins using data from Swart et al. (1996) and relationships based on Eqns. 1 and 2. The precipitation data from South Florida (Swart et al. 1996a) is shown as deviations from the mean. Note that years of high salinity correspond to periods of low rainfall and vice versa.

counts for over 20% of the variance, is one of between 4 yr and 7 yr, a frequency which may be related to ENSO linked precipitation.

CAN THE RAILWAY BE BLAMED FOR BAY WIDE CHANGES IN WATER QUALITY?

While it is not inconceivable that the reduction of the exchange of water between Lignumvitae Basin and the Florida reef tract can be held responsible for changes in Lignumvitae Basin, it is perhaps more difficult to extend these changes to the other more remote portions of Florida Bay. A major effect of the restriction would be to reduce the flow from the Gulf of Mexico and also to reduce the tidal amplitude within Lignumvitae Basin. This basin is one of the largest in Florida Bay in terms of area and volume and interfaces with a large number of adjacent basins, therefore the reduction in tidal range would result in less water flow from these basins into Lignumvitae Basin, causing wider ranges in salinity throughout Florida Bay. This reduction in the salinity range is evident in the coral record.

ERRORS ON THE ESTIMATES OF SALINITY USING THE OXYGEN ISOTOPIC RECORD OF THE CORAL

Although it is clear that the $\delta^{18}O$ of the coral skeleton is controlled by salinity, the question arises as to how accurate Eqn. 3 is in predicting past salinity variations. At least two sources of uncertainty are present in relating $\delta^{18}O$ to salinity. First, the correlation between salinity- and temperature-corrected $\delta^{18}O$ in the calibration period, although good (r = +0.71, n = 38, p > 0.05), is not perfect and only explains approximately 50% of the variation of the $\delta^{18}O$ in the coral skeleton. The residual variation is probably caused by variation in the isotopic composition of the water related to evaporation and uncertainties in the sampling of the coral skeleton. Second, the correlation between the salinity in Lignumvitae Basin and other basins is not perfect (Table 3) further increasing uncer-
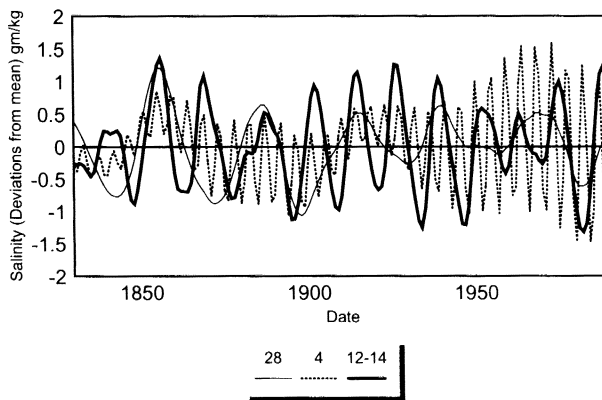

Fig. 10. Results of a single spectral analysis of the calculated salinity data from Lignumvitae Basin. The principal variations coincide with peaks at 4–7 yr, 28 yr, and 12–14 yr.
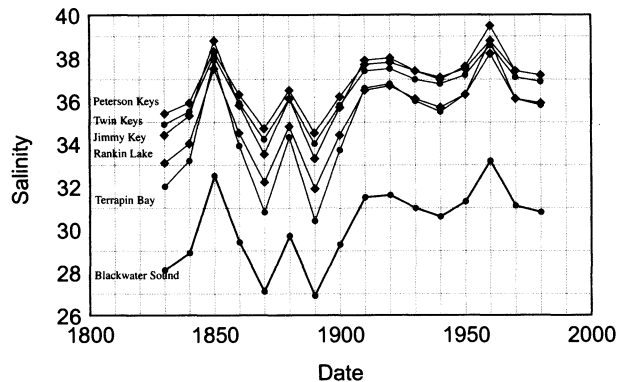
Fig. 11. Estimate of decadal mean salinities for eight basins: Peterson Basin (diamonds), Twin Key Basin (solid circles), Jimmy Key Basin (Stars), Rankin Lake (diamonds), Terrapin Bay (solid circles), and Blackwater Sound (solid circles). The data point for salinity is plotted at the termination of the decade for which the salinity is calculated (i.e., the decade of 1950–1960 is plotted at 1960).

tainty in the estimation of salinity. Estimating the combined uncertainty of these effects is difficult. Therefore, the best way to look at this reconstruction is to examine the record and derive a qualitative impression of whether salinity was higher or lower during specific time periods. This is the approach used in Fig. 11, in which decadal salinity averages are presented for six regions in Florida Bay. This figure confirms the notion that there was a change in the salinity patterns at the start of the twentieth century, which may be related to railway construction. Prior to 1900 there were large variations in salinity between decades, while in the twentieth century the changes were more gradual, with a maximum salinity occurring between 1950 and 1960.

BARIUM

The origin of variation in the concentration of barium in coral skeletons from Florida Bay is enigmatic as the concentration of Ba in the skeleton increases while salinity decreases. If Ba were an indicator of the concentration of nutrients, these data would imply lower concentrations of nutrients during the recent salinity crisis (McIvor et al. 1994). The inverse correlation between Ba and salinity seems to indicate that either increases in skeletal Ba are associated with freshwater runoff or that changes in the concentration of Ba are indirectly correlated to salinity through another parameter, such as variations in the input of organic material to Florida Bay. This might be the explanation for the statistically significant correlation ($r = -0.44$, $n = 50$, $p > 0.05$) between Ba and $\delta^{13}C$ in the coral skeleton. The trends in the smoothed record of the $\delta^{13}C$ are very similar to those observed in the smoothed barium record (Swart et al. 1996a). The $\delta^{13}C$ pattern in the FB-6 coral has been subdivided into four portions, and a linear trend was identified for each portion. Barium and $\delta^{13}C$ trends were averaged over each time segment. First there was a major decrease in the $\delta^{13}C$ and increase in Ba associated with the railway construction. The second portion was marked by a long and steady increase in the $\delta^{13}C$ and a decrease in the Ba concentration between 1910 and 1948. This increase in $\delta^{13}C$ was interpreted as being related to increases in hurricane frequency during this time interval (Swart et al. 1996a). During the next time period (1948–1986), a decrease in the number of hurricanes was accompanied by a $\delta^{13}C$ decrease and an increase in barium. This trend continued until 1986, with only a short punctuation by the occurrence of three hurricanes between 1959 and 1964.

A second possibility for the relationship between the skeletal barium and salinity, is that the Ba is present in freshwater delivered through the Everglades. Although there are no measurements of barium concentrations in Florida Bay waters or the Everglades, there are various workers who have suggested that Ba (Boyle 1976; Hanor and Chan 1977; Edmond et al. 1978; Shen and Sanford 1990) is delivered to the oceans by rivers. In the case of Florida Bay, Ba could be provided from the Gulf of Mexico, the relative contribution of which would increase during times of reduced input of freshwater from the Everglades (Boyer et al. in press). Whatever the control of the concentration of Ba in corals in restricted situations such as Florida Bay, it is clear that open oceanic controls are not necessarily applicable and more research will be necessary to understand the Ba cycling in this environment.

FLUORESCENCE

Fluorescence has been used by previous investigators to study in the input of humic material derived from riverine sources (Isdale 1984; Smith et al. 1989). The study of Smith et al. (1989) on the coral FB-5 from Lignumvitae Basin noted a decrease in the amplitude of the fluorescence signal prior to 1940 and suggested that this was a result of decreased freshwater input through Shark Slough. In this study we found a change in the variability of the fluorescence signal coincident (Fig. 6) with the railway construction, similar to that described by Swart et al. (1996a) for the $\delta^{18}O$. Prior to railway construction there was a considerable amount of interannual variability in the fluorescent signal, while after the construction this variability was reduced. It appears that the amount of fluorescence in the skeleton increases coinci-

dent with railway construction. Such an increase is unusual because if the amount of fluorescence is associated with freshwater, as has been suggested in the literature (Isdale 1984), an increase would imply a lower salinity and a greater influence of freshwater after railway construction. However, information based on the $\delta^{18}O$ of the coral skeletons suggests higher salinity after the railway was built. In the case of Florida Bay, higher amounts of fluorescence material may be associated with higher salinity. In such a case the fluorescence signal may be derived from the breakdown of organic material in the sediments. Such an explanation is supported by the $\delta^{13}C$ and barium data.

CORALS IN OTHER AREAS OF FLORIDA BAY

The two largest corals (FB-5 and FB-6 *Solenastrea bournoni*), we have encountered during many years of searching in Florida Bay are located in Lignumvitae Basin. Although we have failed to find similar size corals in other areas, there are abundant specimens of *Siderastrea radians* located in most areas of Florida Bay. For this study we analyzed eight individuals, the distribution of which is shown in Fig. 1. The O and C stable isotopic analyses of some of these corals show several similarities to the specimens of *Solenastrea bournoni* from Lignumvitae Basin. First, the O isotopic composition of four of the corals show very strong correlations with each other, suggesting these areas all have similar increases in salinity (Fig. 5a). The corals having similarities in their $\delta^{18}O$ records are from Manatee Key Basin (FB45), Duck Key Basin (FB23), Bob Allen Key Basin (FB16), and Lignumvitae Basin (FB-5 and FB-6). In contrast other corals show different patterns in the $\delta^{18}O$ record. Typically, the other corals all show more positive $\delta^{18}O$ values and do not exhibit a decrease from the high salinity values associated with the drought between 1989 and 1990. These corals are situated in the western portion of Florida Bay, near the Arsenicker Keys (FB-7), Rabbit Key Basin (FB-14) and Lignumvitae Basin (FB-40, 42) (Fig. 5b). These small corals may not have a decrease in $\delta^{18}O$ because they are affected by a layer of saline water near the bottom of the bay. This layer may be present in the western portion of Florida Bay where the water is deeper compared to the eastern bay where the water is shallow and well mixed.

CARBON

The $\delta^{13}C$ of the skeletons of *Siderastrea radians* also show many similarities to the coral skeletons from Lignumvitae Basin and can be separated into two groups (Fig. 5c,d). The first group, which is represented by the majority of the corals, shows an enrichment in $\delta^{13}C$ from approximately 1989 to

1993. In contrast, the second group shows a depletion over the same time period. Both groups show maximum depletion in $\delta^{13}C$ around 1984. This maximum depletion was also present in the record from FB-6 which reflects the lowest values in a decline in $\delta^{13}C$ which started with railway construction between 1907 and 1912. Some of the corals show a difference in the timing of the carbon depletion (Fig. 5c). This difference is probably a result of some problems in assigning age in these small corals. Changes in the patterns of $\delta^{13}C$ in the coral skeletons relate to four principal processes: (1) the oxidation of organic material releasing isotopically light CO_2, (2) the utilization of CO_2 in photosynthesis by benthic and plankton algae causing the residual $\delta^{13}C$ of the DIC to become isotopically more positive, (3) increased influence of marine waters with isotopically positive carbon, and (4) the increased input of freshwater with isotopically negative carbon. The increase in the $\delta^{13}C$ of the coral skeletons could be interpreted as either reflecting a relative decrease in the influence of carbon derived from oxidation of organic material and hence increasing influence of carbon derived from marine sources, or an increase in photosynthesis such as is associated with algal blooms. All these sites are known to have been affected by algal blooms since the late 1980s. In contrast, the three sites that all show a decrease in the $\delta^{13}C$ since 1989 are located in the same portion of Florida Bay. They must be influenced by increased input of organically derived CO_2 produced locally or associated with freshwater input from the Everglades. Salinities have decreased in all areas of Florida Bay between 1990 and 1994, therefore it is unlikely that the decrease in the $\delta^{13}C$ in only one portion of the bay resulted from an increased input of freshwater. The most probable cause is increased oxidation of organic material in the northeastern portion of Florida Bay and an increase in algal blooms in the western part of the bay. Physiological effects related to variations in salinity and temperatures might produce small variations in the $\delta^{13}C$ of the coral skeletons. As a result of the large documented changes in the $\delta^{13}C$ of the DIC in Florida Bay (Patterson and Walters 1994; Lutz et al. 1995; Lutz 1998) we believe that these are more important in controlling the $\delta^{13}C$ of the coral skeletons from this type of environment.

The mean of the $\delta^{13}C$ and $\delta^{18}O$ of the small corals show a relationship with the coral's position relative to the open marine environment (Fig. 12). The corals which tend to be most influenced by marine waters have relatively heavier $\delta^{13}C$ isotopic compositions. In contrast the corals situated in the more restricted environments have more positive $\delta^{18}O$ and more negative $\delta^{13}C$ values.
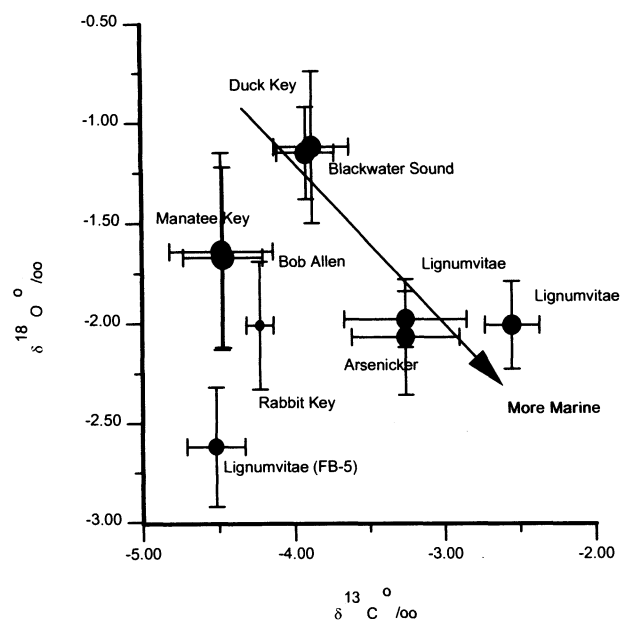
Fig. 12. Summary of the carbon isotopic compositions of *Siderastrea radians* and *Solenastrea bournoni.* Corals influenced by marine waters have isotopically heavier carbon isotopic compositions.

Summary and Conclusions

A revised relationship equating water temperature, salinity, and the $\delta^{18}O$ data of the skeleton of the coral species *Solenastrea bournoni* (Healy 1996) has allowed us to reinterpret the $\delta^{18}O$ record presented by Swart et al. (1996a) and Healy (1996). Using this equation, a wider range of salinities have been calculated for both Lignumvitae Basin and other basins in Florida Bay than were previously estimated (Swart et al. 1996a). The new $\delta^{18}O$ data presented for the portions of the skeleton produced after 1986 show that highest salinity episodes over the entire record (1824–1993) occurred between 1989 and 1990. High salinity episodes have also occurred at other times in the past 30 yr. The concentration of barium in the skeleton also shows an inverse correlation with historical salinity records and the $\delta^{18}O$ of the coral from Lignumvitae Basin. The inverse nature of the correlation suggests the source of the Ba is associated with freshwater. Although the precise mechanism of supply is not clear, it is probable that the Ba is associated with organic material supplied from the Everglades. The concentration of Ba and $\delta^{13}C$ show inverse historical trends since 1910, probably reflecting the changing magnitudes of the exchanges between Everglades, Florida Bay, and the Atlantic Ocean.

Most of the skeletons of the small coral *Siderastrea radians* collected from throughout Florida Bay

show similar patterns in the $\delta^{18}O$ composition during the past decade, indicating the patterns of salinity can be correlated from basin to basin. In contrast, the $\delta^{13}C$ of these small corals can be separated into two distinct patterns. The first pattern shows a decline in the $\delta^{13}C$ of the skeleton over the past 5 yr, reflecting increased oxidation of organic material. The second pattern shows an enrichment over the same period. The enrichment could reflect either increased marine influence or the presence of algal blooms.

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