Shells as Recorders of Environmental Change—A Study in Florida Bay

Introduction

The South Florida region is currently undergoing a massive restoration effort guided by the Comprehensive Everglades Restoration Plan (CERP) written by a multi-agency group of Federal, State and local governments. One of the primary goals of the CERP is to restore the quantity, quality, and timing of freshwater delivery throughout South Florida to a more natural state. The natural flow of freshwater in the South Florida ecosystem was altered throughout the 20th century by the construction of a series of canals and water-control structures. These systems affected the estuaries of South Florida, including Florida Bay (located within Everglades National Park), by altering the natural seasonal mixing of fresh and saline waters. In addition, construction of the Flagler Railroad and, later, U.S. Highway 1 through the Florida Keys restricted the exchange of water between the Atlantic Ocean and Florida Bay. In order to establish realistic goals and performance measures for restoration, it is essential to first determine how the natural system functioned prior to significant human alteration. The goal of this research is to develop a method to identify historical patterns of salinity change throughout the bay, perhaps at the seasonal scale, from the remains of animals preserved in shallow-water sediment cores.

Setting

Florida Bay (fig. 1) is a very shallow, subtropical estuary that is subdivided by a complex mosaic of mudbanks and mangrove keys (islands) that constrain the movement of tides and currents. Variations in salinity and temperature within the bay are largely controlled by the annual cycle of wet and dry seasons. The cooler winter months of November to April constitute the dry season (average daily precipitation is approximately 0.075 inches). During the hot, wet summer months of May through October, precipitation increases three- to fourfold (average daily precipitation is 0.25 to 0.30 inches).

The natural precipitation cycle, though annually variable, drives the timing and amount of natural freshwater available to the South Florida ecosystem. Low regional rainfall during the winter reduces the freshwater input, both as direct rainfall and as reduced runoff from the terrestrial Everglades, into the bay. This decrease in freshwater raises the salinity in the bay, especially along the northern margin where terrestrial runoff from the Everglades enters the bay. During the wet season, the abundance of regional rainfall, both as direct precipitation into the bay and as increased outflow from the terrestrial Everglades, increases the freshwater input to the bay and decreases the salinity. The result of these seasonal changes is that salinity can vary significantly in northern and central Florida Bay. These changes create a rigorous environment in which only very adaptable organisms can survive.

Marine Animals as Data Recorders

Information on the regional variation and seasonal changes in the water chemistry of Florida Bay is reflected in the variations in the shell chemistry (trace elements and stable isotopes) of marine organisms. As the animals grow by adding sequential layers of calcium carbonate, they are recording information about the water in which they grow. By learning how to "read" the record contained in the shells, scientists can derive information about both modern and historical changes in salinity, temperature, and freshwater sources.

In order to interpret the shell chemistry data, the following questions must be answered: (1) What are the spatial and temporal patterns of the animal's growth and how are these patterns related to seasonal change? (2) Does the temporal growth record coincide with seasonal variations in salinity, temperature, or some other environmental variable? (3) Can the chemical variations of individual shell layers be accurately measured at a microscopic scale? (4) Are the variations in the trace-element concentration of the shell layers the response to a biological function of the animal that is independent of changes in the water mass, or are the variations representing changes in salinity and temperature while the shell is secreted? (5) If the trace-element variations of the shell correlate to salinity and temperature, then can these variations be calibrated and used as a proxy to represent changes in the water mass through time?

For this study, the marine bivalve *Chione cancellata* (commonly known as the Cross-barred Venus) was selected because it met these important criteria necessary to serve as a good "data recorder" of salinity change: (1) the species is widely distributed and locally abundant throughout Florida Bay; (2) although it prefers marine conditions, it is tolerant of a range of salinities from 20 to >40 parts per thousand (ppt); (3) it is comparatively long-lived (estimates of 5-7 years for the oldest specimens); and (4) its thick, ornamented shell facilitates specimen preparation, identification of seasonal growth, and accurate tracing of growth layers for geochemical analysis.

Once the basic questions have been answered from studies of living *Chione cancellata* in both Florida Bay and the laboratory setting, a calibration data set can be established that will be used to compare the animal's shell chemistry with the chemistry of the water in which it grew. The calibration data can then be applied to the analysis of shells taken from isotopically dated sediment cores collected in Florida Bay and other South Florida estuaries as part of the U.S. Geological Survey's Ecosystem History projects. The results will provide the regional and temporal patterns of change in salinity over the last 100 to 500 years, which is necessary to set realistic and obtainable performance measures for restoration.

Field Work

In February 2001, scientists placed two habitat enclosures in Whipray Basin, an isolated basin in central Florida Bay (figs. 1, 2). The location was established because of the close proximity to an Everglades National Park water monitoring station that records daily temperature, salinity, and precipitation. One hundred *Chione cancellata* specimens, collected locally, were labeled, digitally photographed, and placed in each habitat.

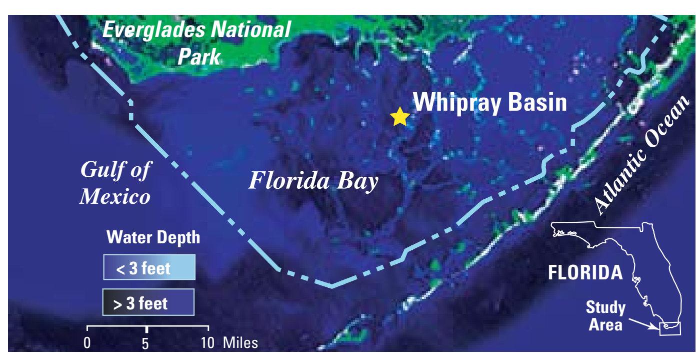

Figure 1. Satellite image of southernmost Florida showing Whipray Basin, where two growth habitats were placed in order to study *Chione cancellata*. Most of Florida Bay lies within Everglades National Park (blue dashed line). Image from Jones and others (2001).

Figure 2. Placement of specimens in Whipray Basin habitat.

Since February 2001, the specimens have been retrieved on a regular winter and summer schedule and have occasionally been retrieved in the spring and fall to provide additional data. Each specimen, whether dead or alive, was compared to its previous photograph to determine when and how much growth had occurred. All live specimens that exhibited growth were digitally rephotographed prior to their replacement in the field habitat. Dead and lost specimens were replaced with new labeled and photographed individuals to maintain a statistically significant population of approximately 100 individuals.

When do *Chione cancellata* grow?

Preliminary data from field growth studies indicate that *Chione cancellata* from Florida Bay can provide the necessary seasonal growth record over time for shell-chemistry analysis. Data analyzed over three years indicate that the habitat population grew in response to the seasonal water temperature cycle (fig. 3). The preliminary data indicate that during those months when the water mass is cool to cold (fall, winter, and early spring), over 80 percent (typically over 95 percent) of the population did not exhibit growth; however, data from the late spring and summer indicate that 40 to 47 percent of the individuals had measurable valve growth. During this period, both water temperature and salinity increased from the winter minimums to late spring and summer maximums.

Data also indicated that juvenile and young adult individuals represented the largest part of the population that exhibited growth (fig. 4). Image analysis of digital photographs of the specimens with confirmed growth indicated that juveniles accounted for 25 percent of the population and young adults accounted for 20 percent of the population; however, "old-age" individuals accounted for less than 1 percent of this population. In fact, some "old-age" specimens in the study did not grow for 2 to 3 years. In general, small specimens showed more continuous, sequential annual growth, while larger individuals grew more episodically in 2- to 3-year increments.

These combined data indicate that as Florida Bay water temperatures and salinities increase from winter minimums to late spring and summer maximums (fig. 5*B*), 40 to 50 percent of the *Chione cancellata* population of Florida Bay show growth. Of this population, a majority of juvenile and sub-adult individuals will secrete biogenic calcium carbonate, which records the physical and chemical changes in the water mass.

How do *Chione cancellata* grow?

Chione cancellata have a morphology similar to many other molluscan bivalves. The first and most obvious common feature is the two-part valve structure, which is characterized by a thin, relatively featureless inner layer of aragonite, and a thicker, outer prismatic layer of subparallel, anastomosing calcite crystals (fig. 6). The second common feature, which is more difficult to detect, is the presence of parallel laminae secreted at the shell margin, which represents incremental growth. The laminae are approximately 1 μm (micrometer) thick in the inner aragonite layer and thicken to 5 to 7 μm in the outer calcite layer.

Throughout the *Chione cancellata*'s life history, changes in the physical environment (seasonal temperature, salinity, food supply, and turbidity), together with the individual's age, affect the timing and rate of shell growth. The outer prismatic layers show successive cycles of growth in the form of groupings of laminae (fig. 6). These groups of laminae are set apart by both distinct and subtle punctuations, or "breaks," that represent cessation of calcium-carbonate secretion; therefore, a missing period of time in the shell's "data recorder" is created. Three different scales of cyclical groupings, or bundles of laminae, can be detected that probably represent daily, intraseasonal, and seasonal growth history.

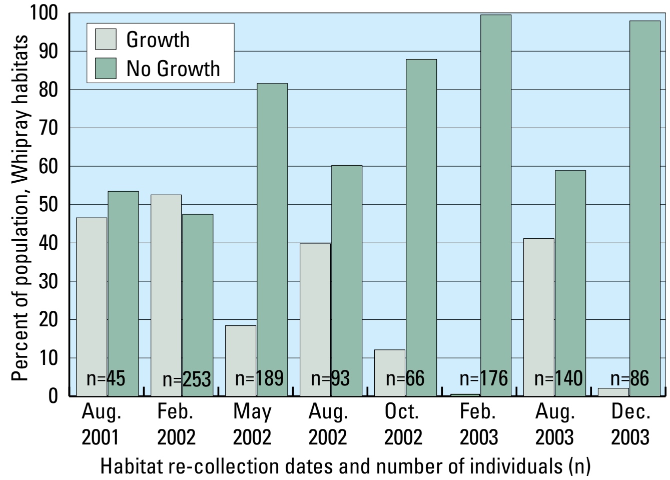

Figure 3. Histogram illustrating percentage of growth versus no growth in *Chione cancellata* populations in Whipray Basin habitats. The population shows a response to the seasonal climate cycle. Between 40 and 47 percent of the individuals retrieved during the summer showed measurable growth, compared to 1 to 12 percent during the fall and winter, with the exception of February 2002.

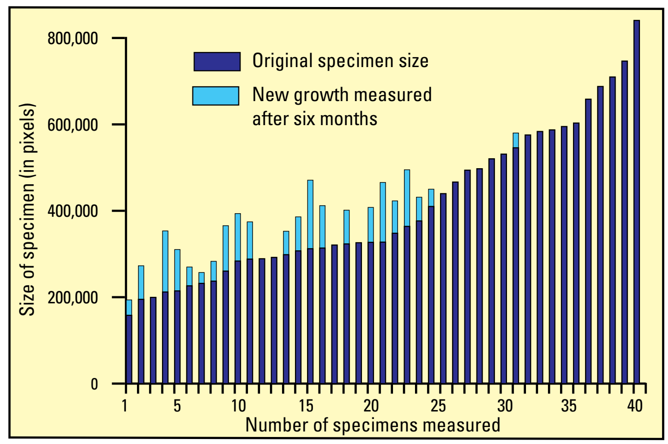

Figure 4. Histogram showing the preliminary growth analysis of *Chione cancellata* at Whipray Basin from February 2001 to August 2001. All specimens were digitally photographed at the same distance and magnification. The histogram shows the size distribution in pixels (determined from image-processing techniques) of 40 specimens photographed both before and after six months. New shell-margin growth principally occurs in smaller juvenile to young adult individuals, while very little growth is observed in the larger, mature to "old-age" individuals.

How do scientists detect change in shell layers?

Microbeam instruments, such as the electron microprobe (EM), are designed to measure the composition of extremely small amounts of material. The small probe diameter (10 μm) and close spatial sampling resolution (5-50 μm) of these instruments make them ideal for measuring the compositional changes at or near the micrometer-scale thickness of the shell-growth laminae. The EM performs both quantitative and semiquantitative analyses by detecting characteristic X-rays

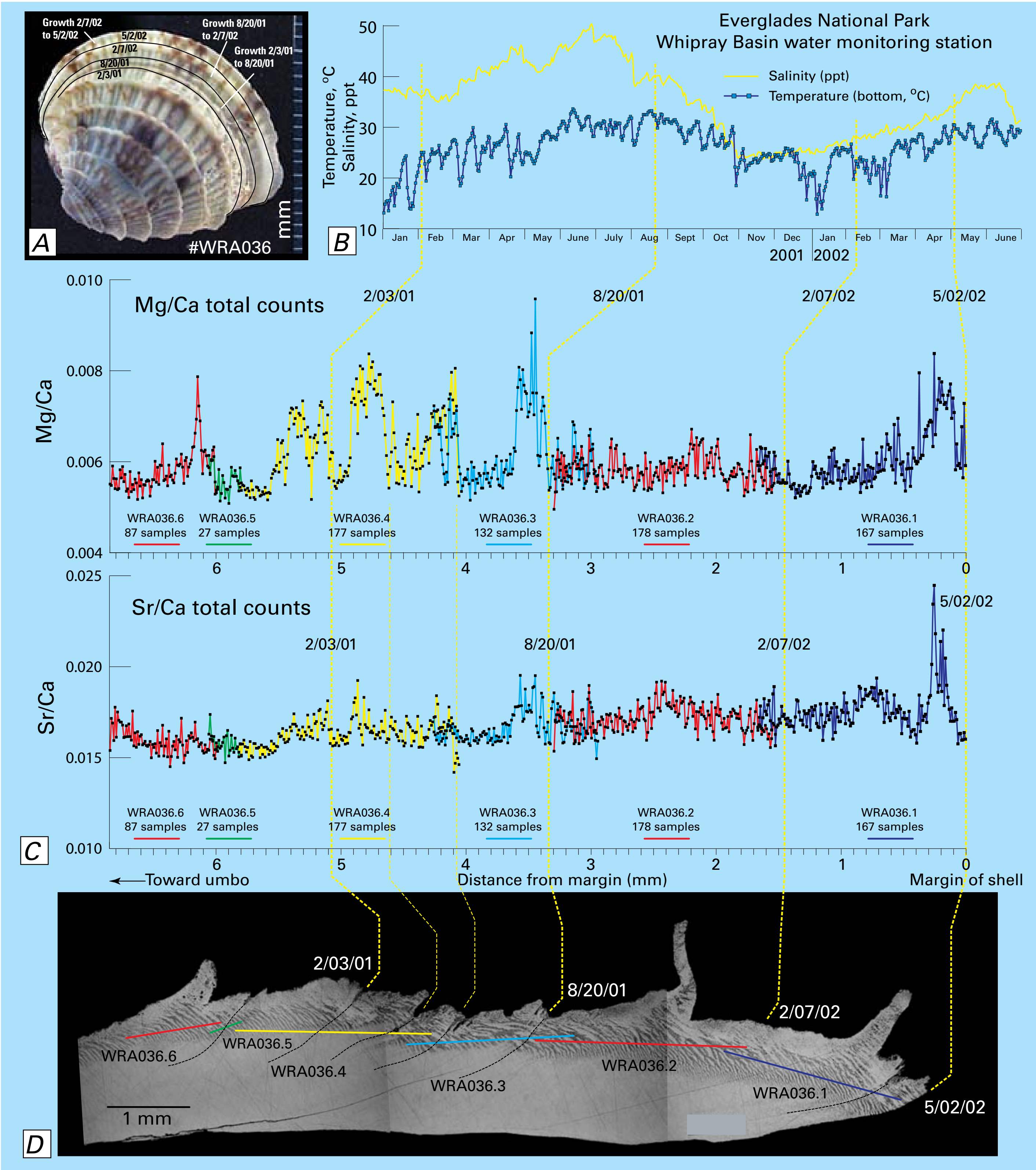

Figure 5. *A*, Digital photograph of *Chione cancellata* specimen #WRA036 showing growth record of the valve from February 3, 2001, to May 2, 2002. *B*, Graph showing Whipray Basin water-monitoring record of temperature and salinity for dates of growth. *C*, Electron-microprobe (EM) trace-element analysis of this specimen; top graph plots ratio of magnesium to calcium; lower graph plots the ratio of strontium to calcium. *D*, Photograph of longitudinal section through the specimen showing valve morphology and EM line transects. The 10-μm sample spacing provides a high-resolution record of trace-element variation through sequential growth record of the specimen. The Mg/Ca counts, and to a lesser extent Sr/Ca, show significant variations in concentration related to shell morphology. From February to August 2001, both episodic shell growth and cyclical variability of Mg/Ca appear to correspond to intraseasonal water temperature and salinity cyclicity as water mass moves from winter minimums to late spring and summer maximums. Between August 2001 and February 2002 (fall and winter), when water temperatures and salinity are declining to minimums, trace-element variation and shell morphology show little variability. However, as water temperatures and salinity again increase through late winter and spring of 2002 (February to May), trace-element concentration also increases.

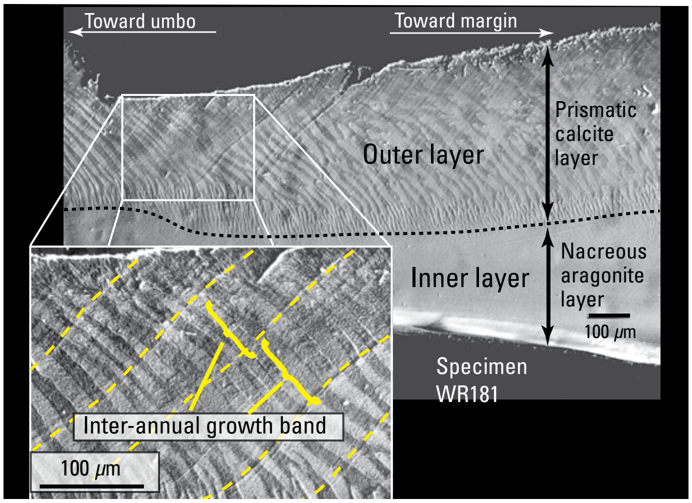

Figure 6. Scanning-electron microscope photograph of a cross section of an etched *Chione cancellata* valve (specimen WR181) illustrating the two-part calcium-carbonate shell structure and the more subtle growth laminae sequentially secreted through time. In the outer layer, wavy calcite prisms are secreted perpendicular to parallel, nominal ~5-μm-thick growth laminae; the laminae form 10- to 20-μm-thick couplets, which in turn form variably thick, light to dark, 60- to 120-μm-thick inter-annual growth bands.

emitted from selected elements of interest in the shell material. As the concentration of an element increases in the shell layer, a proportional number (or count) of X-rays also increases.

The middle and lowest graphs on figure 5 illustrate the results of six EM line analyses of a highly polished longitudinal section of *Chione cancellata* specimen #WRA036 (fig. 5*A*) from Whipray Basin. The transects, which parallel the axis of growth, have a spatial sampling resolution of 10 μm and a 10-μm probe diameter, which provides 100 compositional analyses per millimeter. This sampling resolution allows scientists to derive seasonal and intraseasonal patterns of compositional change from the shell.

What do scientists measure in the shell?

All living organisms either actively or passively sequester trace elements from their environment. Marine organisms, like *Chione cancellata*, incorporate trace elements from the water in which they live into the calcium-carbonate structure of the shell. Magnesium (Mg) and strontium (Sr) have many physical properties in common with calcium (Ca), and thus can easily substitute for calcium in the shell structure.

The concentration of magnesium and strontium in the world's oceans has remained stable for thousands of years. Both elements also are stable relative to the calcium that is a component of sea salt (CaCl); therefore, as the amount of salt in the water varies, the amount of magnesium and strontium varies. Previous studies (Dwyer and Cronin, 2001, and references therein) have demonstrated that the ratios of Mg/Ca and Sr/Ca in organisms with calcium-carbonate shells can be used to calculate the salinity of the water in which they grew. In this study, those ratios were measured in the EM transects across the shell as shown in figure 5*C*. Considerable questions still exist about the effect of water temperature and biological processes on the uptake and secretion of magnesium, calcium, and other elements. These questions still need to be answered.

What do we know so far?

The following points summarize the results to date:

1. Marine organisms (such as *Chione cancellata*) that secrete biogenic calcium-carbonate record information about the water in which they live.
2. Close to 50 percent of the *Chione cancellata* population of Florida Bay exhibits measurable growth during the spring and summer seasons, which also is the period when salinity and temperature increase from winter minimums to summer maximums.
3. Juvenile and sub-adult *Chione cancellata* generally exhibit both the greatest amount and the most continuous rates of shell growth.
4. Sequentially secreted growth laminae of the *Chione cancellata* shell are punctuated by discontinuities due to cessation in growth during seasonal and intraseasonal cool to cold water temperatures, which means information is missing from the shell "data recorder."
5. High resolution electron-microprobe analyses of *Chione cancellata* shells, which have documented growth during specific time periods, produce accurate "maps" of changes in trace-element concentrations over a given period of time.
6. The highly variable ratios of magnesium to calcium, and more subtly of strontium to calcium, appear to record both a first- and a second-order temporal cycle of seasonal and intraseasonal changes in water mass related to salinity and (or) temperature.

Will shell analyses be a useful tool for restoration?

Although additional investigation is needed, shell-chemistry analyses of *Chione cancellata* can be used to extract information about its environment; however, several cautions are in order. First, *Chione cancellata* do not grow continuously throughout the year; therefore, although they are not recording a complete annual history, the preliminary studies indicate that at least 50 percent will show growth during the summer maximums in salinity and temperature. Second, if only 50 percent show growth at any one time, either the results will need to be statistically averaged when analyzing specimens from cores, or some other method of dealing with the potential lack of growth during a given time period must be determined. Third, analyses should be limited to juveniles and sub-adult individuals, or to the juvenile and sub-adult portions of the shells of the older specimens.

Whether temperature or salinity is the controlling factor on trace-element uptake is a question that still needs to be answered; however, for South Florida, this issue is not critical because increases and decreases in temperature and salinity generally parallel each other and this relationship can be demonstrated statistically. Hence, the cautious analysis of *Chione cancellata* specimens from isotopically dated sediment cores from Florida Bay and other South Florida estuaries will provide information about historical changes in the environment. The results of this study potentially could be applied to other species of *Chione* and possibly to other genera of the Veneridae family.

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