

Hughes, G. B., and C. W. Thayer, Sclerosponges: Potential high-resolution recorders of marine paleotemperatures, 2001, in L. C. Gerhard, W. E. Harrison, and B. M. Hanson, eds., Geological perspectives of global climate change, p. 137–151.

## 7 | **Sclerosponges: Potential High-Resolution Recorders of Marine Paleotemperatures**

**Gary B. Hughes**

*Raytheon Infrared Operations  
Goleta, California, U.S.A.*

**Charles W. Thayer**

*Department of Earth and Environmental Science  
University of Pennsylvania  
Philadelphia, Pennsylvania, U.S.A.*

### **ABSTRACT**

Sclerosponges have great potential as seawater temperature recorders. These animals precipitate their skeletons in carbon and oxygen isotopic equilibrium with the surrounding seawater (Druffel and Benavides, 1986). Their skeletons also display chemical properties that vary directly with changes in environmental conditions. Lack of photosynthetic symbionts allows sclerosponges to live below the photic zone, providing the potential to investigate past marine conditions beyond the range of corals. Individual sponges live for several centuries, preserving archives of pre- and postindustrial seawater variations within single specimens (Hartman and Reiswig, 1980). Cross-correlation of successively older specimens could yield up to 2000 years of marine history. Extracting environmental information can be accomplished by determining elemental characteristics preserved in skeletal growth bands. A method is presented here that utilizes energy dispersive spectroscopy (EDS) to provide inexpensive assessment of magnesium (Mg): calcium (Ca) and

chlorine (Cl): calcium (Ca) ratios at high spatial resolution, yielding environmental data with correspondingly high temporal resolution. The relationship between environmental conditions and skeletal characteristics is defined by a spectral transfer function, which can then be applied to skeletal carbonate data from ancient sponges to reconstruct past environmental conditions. Accurate reconstruction of seawater temperature and salinity variations is demonstrated here at sub-monthly resolution. The technique's efficiency is ideal for documenting long, high-resolution records of marine paleoenvironments.

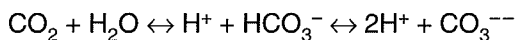
## SCLEROSPONGES AS POTENTIAL ENVIRONMENTAL RECORDERS

Instrument records of climatological conditions generally represent data gathered for short time spans over limited geographical extent. This is particularly true for the marine environment, in which continuous instrument records spanning more than a few tens of years are rare. The short time span of most instrumental records critically limits the conclusions that can be drawn from analyzing them. The limited spatial extent of instrumental recordings also raises issues with applying even narrow conclusions to larger geographical areas. Investigations focusing on regional and global climate patterns are hampered by this paucity of data. Thus, it is of great interest to pursue possible sources of paleoenvironmental data that complement and extend currently available instrument data and that offer the possibility of investigating longer-term (interdecadal to millennial) climate patterns at regional or global scales.

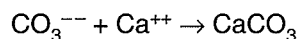
Biogeochemical records, such as marine sediments, represent rich potential archives of long-time-span paleoenvironmental data. Bottom sediments record important aspects of broad trends in marine environmental parameters such as seawater temperature and salinity. However, data derived from these sources are insufficient for many studies, due to coarse temporal resolution. Turbulence, mixing, and bioturbation tend to inhibit high-frequency environmental variability from being reflected in bottom-sediment characteristics. Annual or better resolution in sediment-derived environmental parameters is uncommon. Studies that rely on information about seasonal fluctuations in climate must search for other archives.

Fortunately, the sea offers some intriguing possibilities in the form of biogenic sedimentary structures such as coral reefs. The animals responsible for constructing coral reefs are influenced by environmental parameters, and studies have shown that environmental influence is discernible in the calcareous skeletal material left behind by the organisms. Similar to corals, sclerosponges (phylum Porifera) also deposit calcareous skeletons as they grow, and they offer some advantages over corals as paleoenvironmental archives (Swart et al., 1998). This study focuses on one potential archive of paleoenvironmental data, sclerosponges. One method of extracting high-resolution data from sclerosponges is presented here that shows the potential of these animals as environmental recorders.

Both corals and sclerosponges precipitate calcium-carbonate ( $\text{CaCO}_3$ ) from seawater to construct exoskeletons. As atmospheric carbon dioxide ( $\text{CO}_2$ ) dissolves into the oceans, bicarbonate and carbonate are formed, according to the equilibrium reactions



Dissolved calcium ions in seawater then combine with carbonate ions to form calcium carbonate, providing the raw material for sclerosponge skeletons:



In this way, dissolved atmospheric  $\text{CO}_2$  represents the source material for carbon atoms in coral and sclerosponge skeletal carbonate; specifically, the carbonate carbon atoms are the same

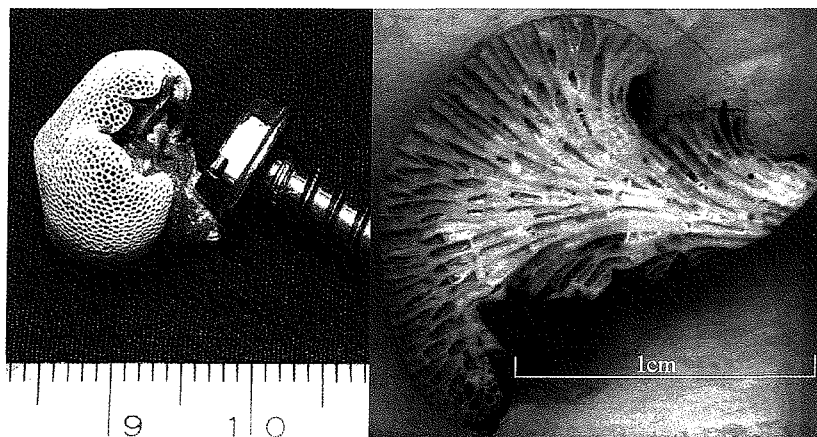
carbon atoms that came into the ocean as atmospheric carbon dioxide. As sclerosponges grow, successive growth bands are laid down on top of older layers of the skeleton. At each layer, the precipitated carbonate is drawn from the surrounding seawater. It is the hope of paleoenvironmentalists that some characteristics of the ambient seawater affect skeletal carbonate formation and that these characteristics are immutable after the carbonate has been deposited. That is, some lasting characteristic of the precipitated carbonate must vary directly with environmental conditions for these animals to represent a viable paleoenvironmental archive.

Modern analytical techniques have yielded results demonstrating that several skeletal characteristics of corals and other carbonate-secreting organisms do indeed vary directly with ambient seawater temperature. Mitsuguchi et al. (1996) report successful interpretation of Mg:Ca ratios in coral skeletal carbonate as an accurate paleothermometer. Seawater paleotemperatures have been investigated using Mg:Ca ratios in fossil ostracodes (Dwyer et al., 1995) and mussels (Klein, Lohman, and Thayer, 1996a), which both secrete carbonate exoskeletons. Other studies with corals indicate that trace elements such as strontium incorporated in skeletal carbonate during formation provide definitive environmental proxies (Beck, et al., 1992). Successful interpretation of isotopic data ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) as environmental indicators was reported in bivalves by Klein et al. (1996b) and in corals by Dunbar and Wellington (1981).

In addition to corals and other carbonate-secreting organisms, sclerosponges have also attracted attention as potential recorders of past marine conditions. It has been shown that isotopic composition ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) of sclerosponge skeletal carbonate is related to ambient seawater temperature (Druffel and Benavides, 1986; Swart et al., 1998, and references therein). Furthermore, the sensitivity of this recording mechanism is sufficient to allow investigation into marine and climatic variability. Sclerosponge skeletons collected in Jamaica and the Bahamas have recorded decreases in the isotopic signature of atmospheric carbon dioxide over the past century, a phenomenon called the carbon-13 Suess effect (Druffel and Benavides, 1986; Quay et al., 1992; Bohm et al., 1996; Swart et al., 1998).

Along with stable isotope analysis, trace-element chemistry shows promise as an environmental recorder in sclerosponge skeletons. In this study, the sponge *Acanthocaetetes wellsi* (Figure 1) is used. Hartman (1983) and Hartman and Reising (1980) describe their natural history. An explicit method is presented here for determining paleotemperature by measuring Mg:Ca ratios of skeletal carbonate in growth bands of *A. wellsi*. Furthermore, the same method is applied to the reconstruction of paleosalinity using Cl:Ca ratios. Although the measurement of chloride in skeletal carbonate has not yet gained wide acceptance as a salinity indicator, the data presented here hint at an intriguing connection. The method presented here to reconstruct past salinity variations could be exploited if future, more detailed studies validate the use of Cl:Ca ratios as a salinity indicator. Using an electron microprobe, Mg:Ca and Cl:Ca ratios are quickly measured at high spatial resolution in skeletal cross sections. Derived environmental data have correspondingly high temporal resolution. Biweekly records are obtained at measurement resolutions as coarse as  $50\mu\text{m}$  in *A. wellsi*. Data from extant sponges are calibrated with modern instrument records. In the method presented here, the modern relationship between elemental data and environmental conditions is defined by a system transfer function. The transfer function can then be applied to data from ancient sponges to reconstruct past environmental conditions.

The technique's efficiency is ideal for documenting a long, high-resolution record of these marine parameters. Furthermore, individual sponges typically live for several centuries. Living and dead specimens of *A. wellsi* are common from mean tide to at least 200 m depth throughout the western tropical Pacific. So sclerosponges offer the potential for both high-resolution and long time-span records over a large geographical region. These characteristics fit well with the requirements of many studies investigating long-term climate variability, such as El Niño/Southern Oscillation (ENSO).



**Figure 1** *Acanthoactetes wellsi* from Palau, harvested in July 1998. Sclerosponges do not depend on symbiotic algae as corals do. As a result, sclerosponges are outcompeted by corals in the photic zone. Sclerosponges are thus restricted to areas of reduced light where most corals cannot grow because of their dependence on algae. Sclerosponges are common in caves and along deep undersea cliffs beyond the penetration of light. This specimen began growing on top of a marker screw shortly after the screw was emplaced in July 1989 (approximate location of the screw is shown). Scale in centimeters. During this time, the sponge grew 1.21 cm, an average of 1.34 mm/yr. The specimen was cross-sectioned for elemental analysis.

## ENVIRONMENTAL RECONSTRUCTIONS

### Procedure for Analyzing Skeletal Carbonate in *Acanthoactetes wellsi*

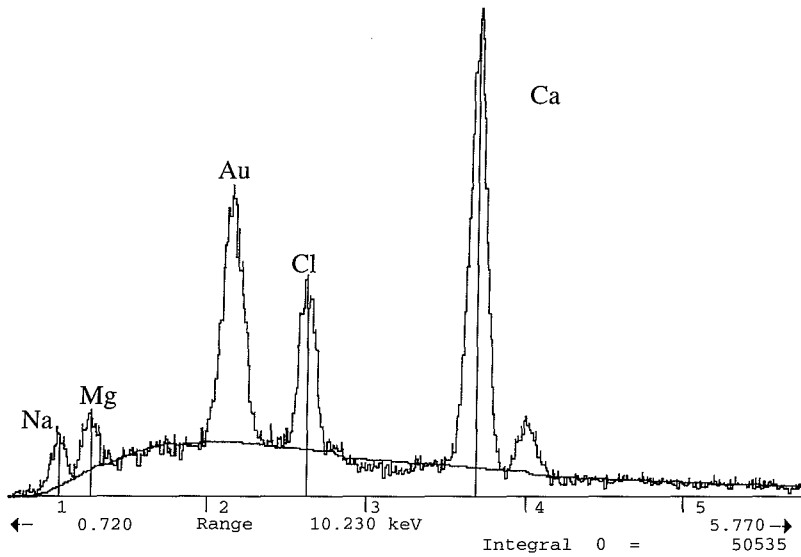
The objective of skeletal carbonate analysis is to obtain time-series data of isotopic and/or elemental ratios recorded across the growth bands. These skeletal characteristics presumably contain markers of environmental conditions that existed when each microlayer formed. That is, each layer deposited at a given point in time should contain approximately constant isotopic and elemental ratios determined by the environmental conditions present at that time. Achieving environmental proxies with a desirably high temporal resolution requires extraction of isotopic and elemental data with correspondingly high spatial resolution at known points along the growth axis of the skeleton. Precise determination of growth-layer boundaries is essential for determining an accurate time-series path over the cross-sectional area. Results presented here show that fast and inexpensive laboratory procedures can be exploited to attain this objective.

A specimen of *A. wellsi* was collected from Palau (Micronesia). This specimen began growing on top of a marker-plate screw shortly after the screw was emplaced in July 1989. The sponge was harvested in July 1998 (**Figure 1**). During this time period, the specimen grew 1.21 cm, an average of 1.34 mm/yr. The specimen was cross-sectioned, and energy dispersive spectroscopy (EDS) was used to measure elemental ratios at discrete locations across growth bands. At each point, the atomic percentage of sodium (Na), Mg, Cl, and Ca was recorded (**Figure 2**). EDS gives semiquantitative atomic percentages, often with large associated errors. However, calibration studies with samples of known chemical composition confirm that *ratios* of EDS atomic percentages accurately and repeatably reflect atomic *proportions* in the sample. Repeatability studies of tooth carbonate on

**QUANTEX EDS STATISTICS**

ELEMENT	WEIGHT PERCENT	ATOMIC PERCENT*
Na	11.49	17.38
Mg	7.04	10.08
Cl	16.34	16.03
Ca	65.12	56.51
TOTAL	99.99	

\*NOTE: ATOMIC PERCENT is normalized to 100

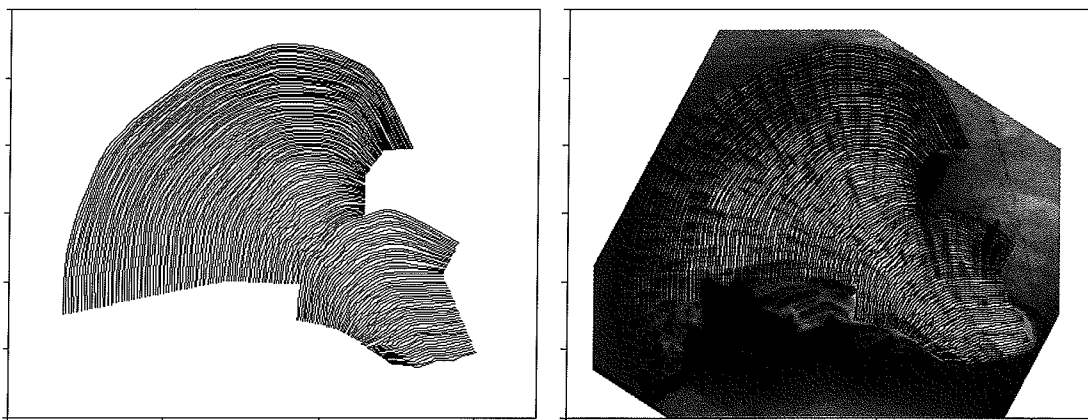


**Figure 2** Energy dispersive spectroscopy (EDS) is used to perform elemental analysis of skeletal carbonate. Atomic percentages of each element are derived from the measured energy spectrum and are semiquantitative. However, studies with carbonate samples of known composition verify that *ratios* of semiquantitative atomic percentages are accurate estimates of *elemental proportions* in the skeletal carbonate. On the machine where the current study was performed, EDS-derived elemental ratios are consistently within 3% relative error when both elements being measured comprise >1% of the substrate. Calcium (Ca) and magnesium (Mg) are components of skeletal carbonate. Sodium (Na) and chlorine (Cl) are believed to be incorporated into interstitial spaces of the carbonate crystal lattice, possibly as NaCl. The gold (Au) peak is introduced into the spectrum when the sample is prepared for EDS analysis. Gold is sputtered onto the surface of the cross section to allow excess charge to bleed away from the surface.

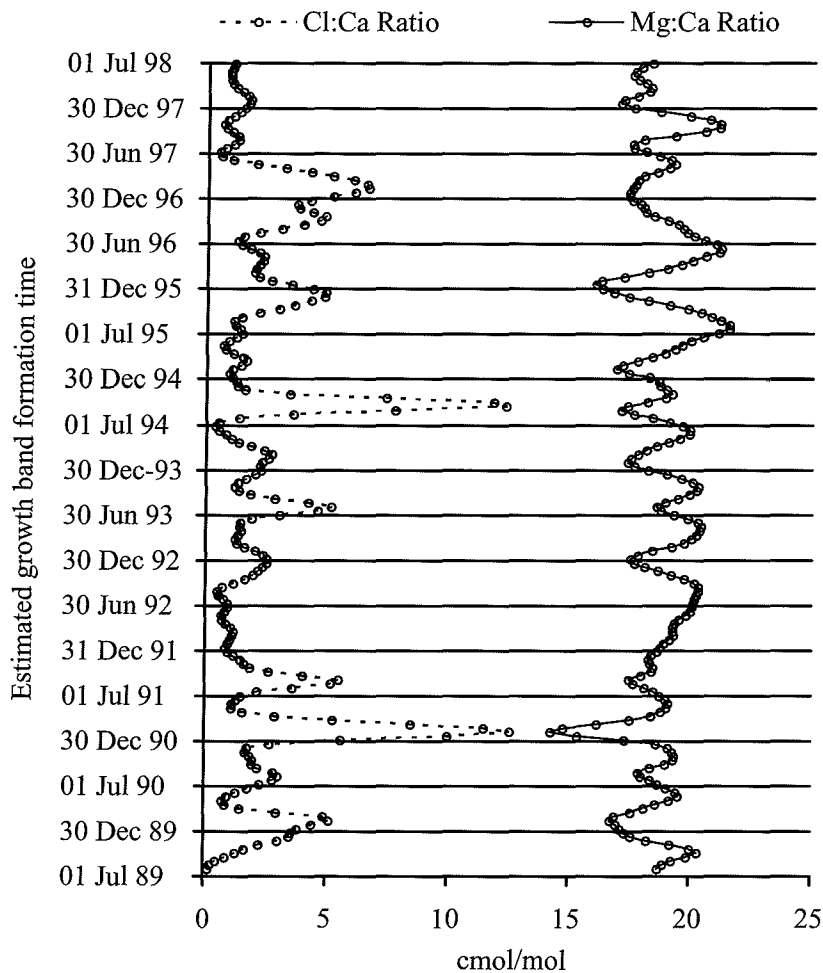
the machine where the current study was performed show that EDS-derived elemental ratios have a standard error of the mean (2 sigma) of 3% when both elements being measured comprise >1% of the substrate. It is this feature of EDS analysis that allows quantitative Mg:Ca and Cl:Ca ratios to be determined.

Electron-microprobe techniques allow data to be recorded at high spatial resolution. To translate this high spatial resolution into high temporal resolution, an accurate microspatial map of growth-band boundaries is produced. To accomplish this, the specimen is cross-sectioned and mounted in epoxy resin. High-resolution digital photos of the cross section are produced. Three datum points on the surface are chosen that are recognizable in both the digital image and the electron-microprobe image. The  $(x, y)$  locations of the microprobe stage at each datum point are recorded, and a datum plane is established from these values.

The EDS spectrum is recorded at successive points along continuous skeletal ridges exposed in the cross-sectional surface. EDS settings for this study were 10 kilovolts (kv) accelerating voltage,  $0^\circ$  beam angle, and 120-second exposure, at  $\sim 100\times$  magnification. The atomic percentage values returned by the EDS software give the estimated percentages (xx.xx%) of each element in the substrate. For a Mg value of mm.mm% and a Ca value of cc.cc%, the Mg:Ca ratios reported here are computed by  $(\text{mm.mm}/\text{cc.cc}) \times 100$ , giving cmol Mg/mol Ca. Each Mg:Ca ratio measurement also has an associated location within the datum plane, determined from the microprobe stage readings. Spatial data analysis, such as described by Dettman and Lohmann (1995), is used to create a map of growth-band microtopography over the digital image (**Figure 3**). Each of the lines in **Figure 3** represents an estimated contour of constant Mg:Ca ratio as calculated by spatial interpolation from EDS measurements. Once the microtopography is established, a time-series path of Mg:Ca ratios can be established. Elemental ratios are then estimated at equally spaced points along the time-series path, spatially interpolated from surrounding known data values (**Figure 4**). Further details of data extraction and analysis are presented in Hughes (1999). For the Palau



**Figure 3** Growth-band contours derived from energy dispersive spectroscopy (EDS) data and spatial data analysis techniques. The key to generating high temporal-resolution environmental reconstructions is obtaining high spatial-resolution elemental data and determining precise boundaries of growth-band layers. Each of the contours represents a line of constant Mg:Ca ratio as estimated by spatial interpolation from EDS measurements. A time-series path is always perpendicular to the growth bands and may follow a convoluted path through the cross section.



**Figure 4** Time series of elemental ratios as determined from energy dispersive spectroscopy (EDS). Spatial locations of the measurements are converted to carbonate formation times by assuming a constant, linear growth rate and by estimating the age of youngest and oldest carbonate. This specimen presumably began growing shortly after July 1989, on top of a marker-plate screw. Data represent one sample every 16.28 days over the period July 1989 through July 1998, when the specimen was harvested. The skeleton left behind by a growing sclerosponge animal is considered here as a biologically precipitated sedimentary structure. The conventional presentation of time-series data for sedimentary structures places the youngest portion of the column at the top, with age of the sedimentary component increasing downward along the vertical axis. The dependent variables (Mg:Ca and Cl:Ca ratios) are still considered to be functions of the independent time variable.

specimen, EDS data were recorded at approximately 50 micron ( $\mu\text{m}$ ) grid spacing. Using this method, 200 data values were produced over a 1.0 cm time-series path spanning approximately 8 years, 10 months, and 29 days (3256 days). Assuming linear growth of one band directly above the previous band, this translates to one measurement every 16.28 days across the growth bands.

## Syn depositional Environmental Data and Correlation with Skeletal Characteristics

The objective here is to compile a high-resolution temperature history from the elemental data. To accomplish this, ambient seawater parameters from the area where the sponge was growing are required. Data for this study were obtained from the Leetmaa Pacific Ocean Analysis (1998, see reference). This analysis uses various sources of environmental data to estimate monthly average seawater temperature and salinity in grid cells of  $1^\circ$  latitude by  $1.5^\circ$  longitude, and at various depths between 5 and 3126.5 m. A direct comparison between the environmental data and the elemental ratios can be made by using linear regression. The regression line then gives a crude mapping from Mg:Ca or Cl:Ca ratios to temperature or salinity, respectively. But variability in the regression will likely occur due to differences between local conditions at the islands of Palau and the grid average, especially for short-lived temperature or salinity spikes caused by upwelling, wind-driven mixing, or rainfall. It is also possible that some amount of difference will arise due to errors in the estimation of growth-band formation times that result in inaccurate mapping of the elemental ratios to the time axis. The growth bands contain calcium carbonate precipitated over a range of times, because a certain amount of “backfilling” occurs on the inner calicle walls, adding small errors to calibration of the time axis. Precise microspatial mapping of growth-band boundaries mitigates the magnitude of this error. In the case of the salinity curve, the relationship between skeletal Cl:Ca ratios and ambient conditions may be more complex than a simple linear dependence, because the Cl is believed to be incorporated into the interstitial spaces of the carbonate crystal. It remains to be determined why Cl:Ca ratios should vary directly with ambient seawater salinity. Data in **Figure 4** suggest some connection. The elemental ratios would likely explain more environmental variability if local ambient conditions were used in the regression.

## Spectral Transfer Function Approach

The linear regression approach is not necessarily the best tool to use for establishing a relationship between elemental ratios and environmental conditions. Since environmental conditions are cyclical, the concept of frequency content of the time-series measurements provides a more appropriate means of establishing relationships between elemental ratios and environmental conditions. Spectral techniques can provide powerful tools for investigating correlation between two cyclical variables such as Mg:Ca ratios and seawater temperature. The inaccuracies of regression models can be overcome by exploiting the concept of a spectral *system transfer function*. In linear regression, the model takes each value of the measured variable at a fixed point in the time domain and estimates the value of the predicted variable at the *same point in time*. However, viewing the time series data sets as quasi-periodic functions over finite domains, each signal can alternatively be described by its frequency content. A system transfer function is a model that operates on each frequency of the measured variable signal and estimates how the predicted variable signal will behave at the *same frequency* (see Weaver, 1983).

The system transfer function method for establishing a relationship between elemental ratios and environmental conditions has several advantages for the task at hand. Small, random inaccuracies in the time estimates of the measured variables are effectively smoothed when transforming to the frequency domain, so skeletal growth-rate variations do not pose significant problems as in linear regression. Also, individual frequencies in the measured variable can be amplified or attenuated by the transfer function, allowing complex relationships between the measured and predicted variables. The transfer function can be estimated from basic principles of how Ca, Mg, and

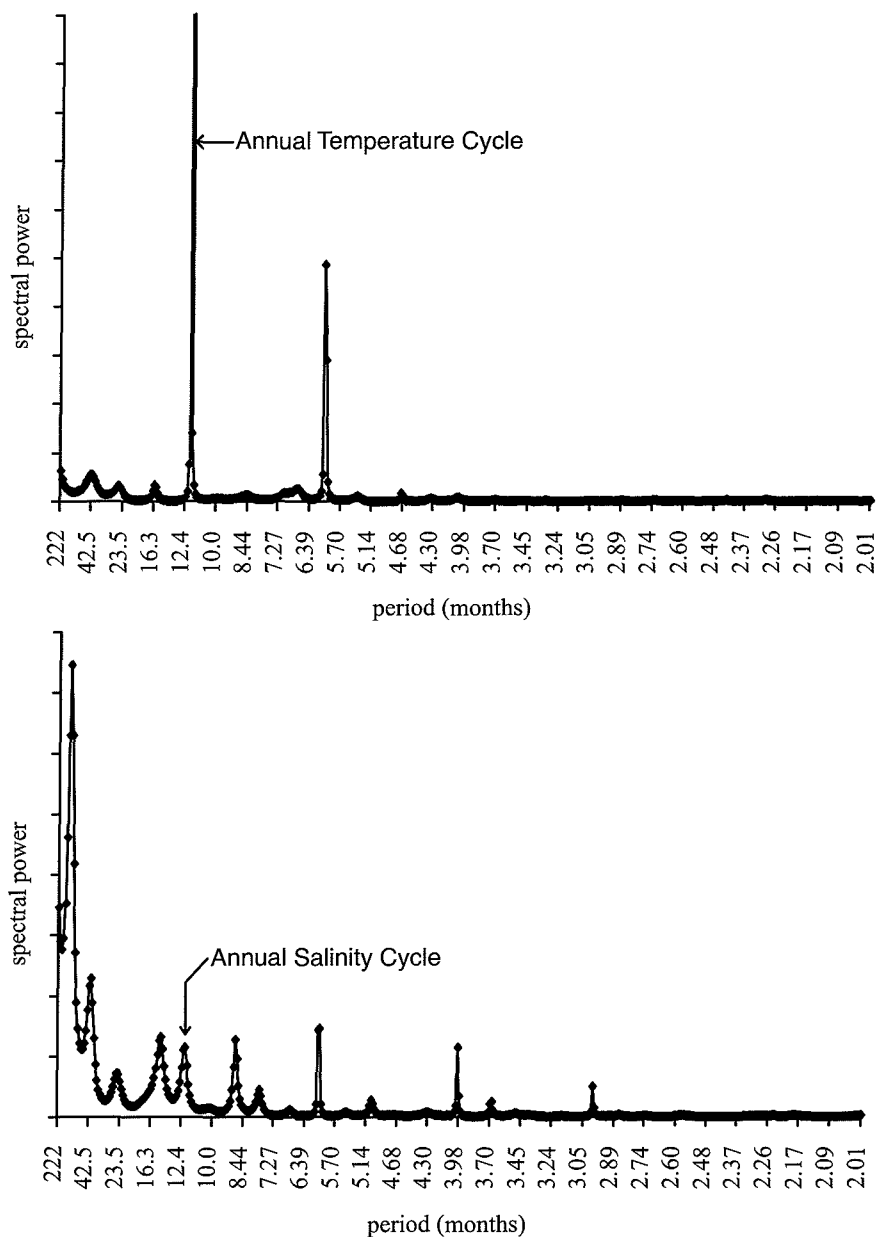


Cl are incorporated into the skeletal carbonate lattice and interstitial spaces, and from how the sampling technique alters the actual signal. Time lags in the response of skeletal carbonate properties to environmental fluctuations can be easily accounted for. Longer time-series data sets provide increasingly narrower constraints on the shape of the transfer function.

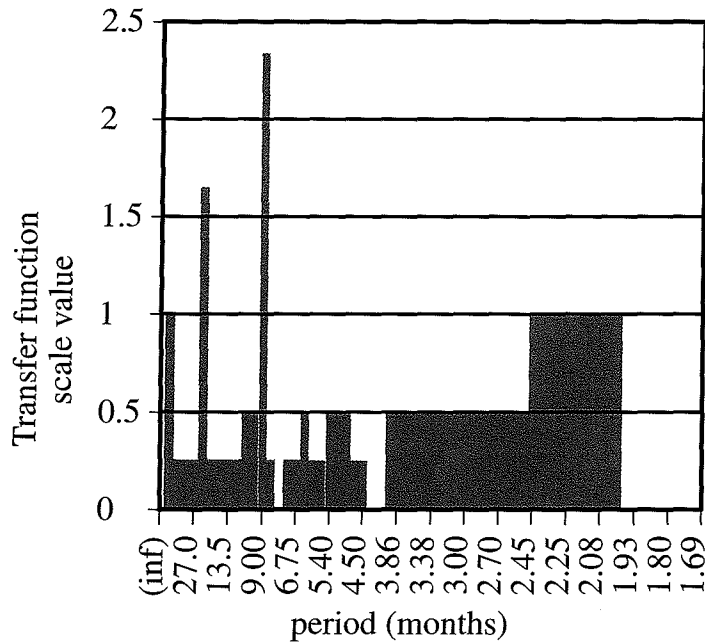
System transfer functions have been successfully applied to issues in mixing of abyssal sediments, where depositional characteristics are sought from measurements made on the sediments after mixing has altered the original signal (Schiffelbein, 1984; Goreau, 1980). This concept can also be used to establish the relationship between sclerosponge skeleton elemental ratios and ambient seawater conditions. If instrument records were available from *in situ* monitoring of temperature and salinity at the precise location where the sponge was growing, the transfer function would be constructed by taking the ratio, at each frequency, of power in the temperature data to power in the elemental data. In this case, when the transfer function is applied to the elemental data, the temperature curve would be reproduced exactly over the entire time span of measured data. Thus, the transfer function captures the precise relationship between ambient temperature and skeletal Mg:Ca ratios. Elemental data could then be measured in older sponges for which there is no available temperature information. The transfer function determined from the modern sponge could be applied to the older data to reconstruct ambient seawater temperatures.

For the data extracted from the Palau sclerosponge specimen, the equivalent sampling rate was one measurement every 16.28 days. The highest Fourier frequency ( $f_c$ ) for these data is approximately 11.22 cycles per year, a period of 0.089 years (~1 month, 2 days). The data were collected over a time span equivalent to 8 years, 10 months, and 29 days (3256 days). This gives the lowest Fourier frequency as 1 cycle in 3256 days, or approximately 0.112 cycles per year, a period of 8 years, 10 months, and 29 days (~107 months). Spectral composition of the Leetmaa temperature and salinity series over the period January 1980 through December 1998 are shown in **Figure 5**. The annual cycle dominates the temperature spectrum. Some less significant cycles appear at longer and shorter periods. Longer period variability is likely due to ENSO, which displays broad-spectrum power at periods between 3 and 7 years (36 to 84 months). The large peak at a period of 6 months is the first harmonic of the annual cycle and represents deviations from an annual sinusoid. The fundamental cause of the 6-month peak is currently a matter of speculation. Spectral composition of the salinity series shows a small annual signal. The most significant salinity cycles are between periods of 3 to 7 years (36 to 84 months), likely driven by ENSO.

For this study, temperature and salinity data were used from the Leetmaa analysis grid. For the Leetmaa data and the Mg:Ca ratios measured in the Palau *A. wellsii* specimen, a system transfer function is shown in **Figure 6**. In this case, the shape of the transfer function is determined from conceptual rules designed to allow local variability to pass through the transfer, while at the same time capturing the overall cyclical elements seen in the grid. Frequencies in the Mg:Ca signal are scaled by the transfer function values shown in the graph. Periods shorter than 2 months are completely filtered, because they are near the Nyquist cutoff frequency. High-frequency fluctuations, represented by periods between 2 and about 3.5 months, can be left unchanged or filtered by the transfer function without significantly affecting the reconstructed signal (the latter choice would be somewhat smoother). Periods longer than 3.5 months are either filtered, attenuated, amplified, or left unchanged by the transfer function, depending on the empirical relationship between the two variables. In the transfer function shown in **Figure 6**, periods at 9 months are amplified because the absolute amplitude of the temperature signal is larger than the amplitude of the Mg:Ca signal at this frequency. This is analogous to the slope of a regression line, but the transfer function approach can use a different "regression slope" at each frequency,



**Figure 5** Spectral composition of the Leetmaa Pacific Ocean Analysis (1998) temperature (top) and salinity series for the  $1^\circ\text{lat}$  by  $1.5^\circ\text{long}$  grid cell centered at  $7^\circ\text{N}$ ,  $134.25^\circ\text{E}$  over the period January 1980 through December 1998, computed by Maximum Entropy Method. The islands of Palau are situated within this grid cell at  $7.5^\circ\text{N}$ ,  $134.5^\circ\text{E}$ . The Leetmaa reconstruction gives average conditions expected within the entire grid cell. Local conditions for sclerosponges growing in Palau may differ from the grid average due to local runoff and different mixing conditions. The annual cycle dominates the temperature spectrum, with some insignificant cycles at longer periods. The large peak in the temperature spectrum at six months is the first harmonic of the annual cycle and represents the majority of deviations from an annual sinusoid. The fundamental cause of the six-month peak is currently a matter of speculation. The salinity spectrum displays a small annual signal, but the most significant cycles are at periods of three to seven years (36 to 84 months), likely driven by ENSO.

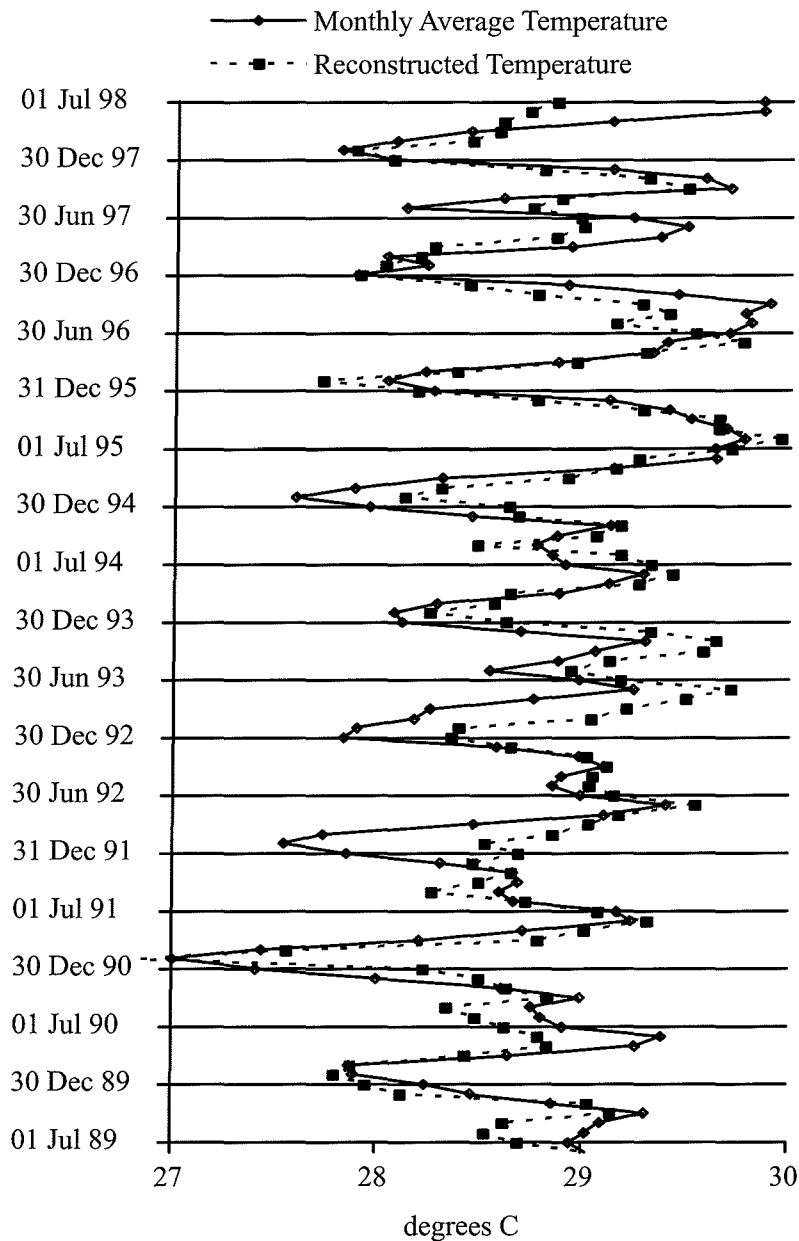


**Figure 6** An amplitude-only system transfer function for reconstructing ambient seawater temperature from skeletal carbonate Mg:Ca ratios based on the Palau specimen of *A. wellsi*. The system transfer function is determined from the Fourier spectra of (1) time-series elemental ratios in the cross section and (2) corresponding time-series of ambient conditions. The transfer function captures the spectral relationship between the two variables, and can be used to derive temperature if Mg:Ca ratios are known. The transfer function developed from modern data can thus be used to reconstruct paleotemperatures based on elemental data in ancient sponges.

resulting in better reconstructions. The reconstructed curves for temperature and salinity, determined by spectral system transfer functions, are shown in **Figure 7**. Again, the elemental ratios would likely be closer to environmental values if local ambient conditions were used in the analysis.

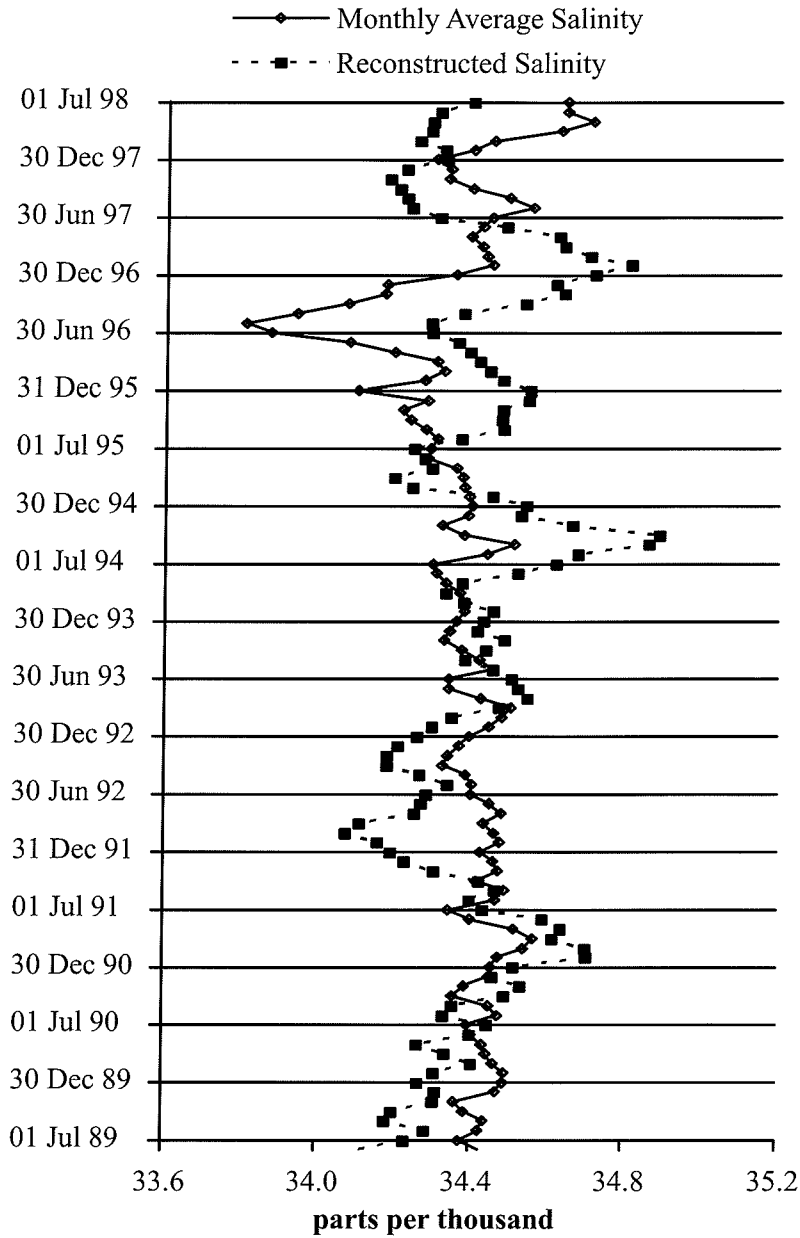
## CONCLUSIONS AND OUTLOOK FOR GLOBAL ENVIRONMENTAL STUDIES

The system transfer function is developed with modern instrument records of temperature and salinity, and with skeletal-carbonate elemental ratios from modern sclerosponges. As with any environmental proxy, the assumption is that the response of modern specimens to environmental fluctuations is similar to the response of ancient specimens. If this assumption holds, then the system transfer function developed with modern records is also applicable to ancient specimens. A long modern instrument record would serve to constrain the system transfer function. Then, by applying the system transfer function to skeletal-carbonate elemental ratios from ancient specimens, the history of temperature and salinity at the location where each specimen grew is estimated. Both living and dead specimens of *A. wellsi* are common in caves and cavities throughout the tropical Pacific. Radiometric age dating of sclerosponge skeletal carbonate has been accomplished with high



(a)

**Figure 7** Temperature (a) and salinity (b) signals reconstructed from skeletal carbonate elemental ratios using amplitude-only empirical system transfer functions. The reconstructed curves are compared with estimated monthly average values at 5-m depth in the  $1^{\circ}\text{lat}-1.5^{\circ}\text{long}$  grid cell centered at  $7^{\circ}\text{N}$ ,  $134.25^{\circ}\text{E}$  (data from Leetmaa Pacific Ocean Analysis, 1998). Departures between estimated and reconstructed curves likely reflect differences between local conditions where the sclerosponge was growing and the grid average. In any case, the reconstruction confirms that the goal of monthly-average resolution is attainable with these animals. Individual sponges live for several centuries, and as a species range over an extended area throughout the tropical Pacific. Therefore, accurate, high-resolution Pacific Ocean seawater temperature and salinity reconstructions over the past 2000 years are possible by using these archives.



(b)

Figure 7(b)

accuracy (Benavides and Druffel, 1986; Rubenstone et al., 1996), and these methods can be used to constrain the time axis for ancient sponges. Cross-correlation of successively older specimens could yield very long records, possibly up to 2000 years or more.

The potential scope of information that could be gleaned from these animals is extremely tantalizing. Sclerosponges range over most of the tropical Pacific, and are found from the surface to at

least 200 m depth. Individual sponges live for several centuries, and specimens that have been dead for many years can be found clinging to cave walls and buried in cave sediments, perhaps representing several thousand years of history. Sclerosponges apparently preserve faithful and sensitive records of paleotemperature and possibly paleosalinity levels at the site where they grew. Efficient and inexpensive laboratory techniques described in this study can be used to reconstruct ambient conditions with submonthly resolution by measuring elemental data in skeletal carbonate growth bands. For ENSO research and other global climate studies, this potential is both rich and unprecedented. By collecting and analyzing many sclerosponges, both living and ancient, a marine climatological history of the tropical Pacific spanning the Medieval Warm Phase could be documented in great detail. This history would represent a critical aspect of studies seeking to understand global change and how ENSO cycles might be affected by ongoing global warming. Such extensive hindsight would undoubtedly lead to a deeper understanding of the fundamental nature of ENSO and other climatological phenomena.

## ACKNOWLEDGMENTS

Financial support for isotopic and elemental analysis was provided by Geological Society of America Research Grant No. 6054-97. The Mellon Foundation and the University of Pennsylvania Research Foundation provided financial support for field research in Palau and for isotopic and elemental analysis. Assistance with all aspects of field research from Robin Aiello, Great Adventures Company, Cairns, Australia, is gratefully acknowledged. Assistance with collection and interpretation of isotopic and elemental data from K. C. Lohmann and Lora Wingate, both of the University of Michigan Stable Isotope Laboratory, and from Jerry Harrison, University of Pennsylvania School of Dentistry, is also gratefully acknowledged.

## REFERENCES CITED

- Beck, J. W., R. L. Edwards, E. Ito, F. W. Taylor, J. Recy, F. Rougerie, P. Joannot, and C. Henin, 1992. Sea-surface temperature from coral skeletal strontium/calcium ratios. *Science*, vol. 257, 31 Jul 1992, p. 644.
- Benavides, L. M., and E. R. M. Druffel, 1986. Sclerosponge growth rate as determined by  $^{210}\text{Pb}$  and  $\Delta^{14}\text{C}$  chronologies. *Coral Reefs*, vol. 4, p. 221–224.
- Bohm, F., M. M. Joachimski, H. Lehnert, G. Morgenroth, W. Kretschmer, J. Vacelet, and W. C. Dullo, 1996. Carbon isotope records from extant Caribbean and South Pacific sponges: Evolution of  $\delta^{13}\text{C}$  in surface water DIC. *Earth and Planetary Science Letters*, vol. 139, p. 291–303.
- Dettman, D. L., and K. C. Lohmann, 1995. Microsampling carbonates for stable-isotope and minor element analysis: physical separation of samples on a 20 micrometer scale: *Journal of Sedimentary Research A*, vol. 65, no. 3, p. 566.
- Druffel, E. R. M., and L. M. Benavides, 1986. Input of Excess  $\text{CO}_2$  to the surface ocean based on  $^{13}\text{C}/^{12}\text{C}$  ratios in a banded Jamaican sclerosponge. *Nature*, vol. 321, p. 58–61.
- Dunbar, R. B. and G. M. Wellington, 1981. Stable isotopes in a branching coral monitor seasonal temperature variation. *Nature*, vol. 293, p. 453–455.
- Dwyer, G. S., T. M. Cronin, P. A. Baker, M. E. Raymo, J. S. Buzas, and T. Correge, 1995. North Atlantic temperature change during late Pliocene and late Quaternary climate cycles. *Science*, vol. 270, 1347.
- Goreau, T. J., 1980. Frequency sensitivity of the deep-sea climatic record. *Nature*, vol. 287, 16 October 1980, p. 620–622.
- Hartman, W. D., 1983. Modern and ancient Sclerospongiae. *In* Sponges and spongiomorphs: Notes for a short course organized by J. K. Rigby and C. W. Stearn, T. W. Broadhead, ed., University of Tennessee, Department of Geological Sciences, Studies in Geology 7, ISBN-0-910249-06-7.

- Hartman, W. D., and H. M. Reiswig, 1980. Morphological and ecological studies of sponges in Pacific reef caves. National Geographic Society Research Reports, vol. 12, p. 339–346.
- Hughes, G. B., 1999. Atmospheric carbon dioxide and land-surface air temperatures in geologic and modern-instrument records: Identifying patterns and formulating alternative hypotheses through spectral analysis. Ph.D. dissertation, University of Pennsylvania, Philadelphia, 1999.
- Klein, R. T., K. C. Lohman, and C. W. Thayer, 1996a. Sr/Ca and  $^{13}\text{C}/^{12}\text{C}$  ratios in skeletal calcite of *Mytilus trossulus*: Proxies of metabolic rate, salinity and carbon isotopic composition of seawater. *Geochimica et Cosmochimica Acta* 60(21):4207–4221.
- Klein, R. T., K. C. Lohman, and C. W. Thayer, 1996b. Bivalve skeletons record sea-surface temperature and salinity via Mg:Ca and  $^{18}\text{O}/^{16}\text{O}$  ratios. *Geology*, vol. 24, p. 415–418.
- Leetmaa Pacific Ocean Analysis data obtained from the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Website at <http://www.cdc.noaa.gov/>, accessed in November 1998.
- Mitsuguchi, T., E. Matsumoto, O. Abe, T. Uchida, and P. J. Isdale, 1996. Mg:Ca thermometry in coral skeletons. *Science*, vol. 274, 8 November 1996, p. 961.
- Quay, P. D., B. Tilbrook, and C. S. Wong, 1992. Oceanic uptake of fossil fuel CO<sub>2</sub>: Carbon-13 evidence. *Science*, vol. 256, p. 74–79.
- Rubenstein, J. L., M. D. Moore, C. D. Charles, and R. G. Fairbanks, 1996. High precision Th/U TIMS dating of young sclerosponges from the equatorial Pacific Ocean, EOS, supplement to vol. 77, no. 46, F384.
- Schiffelbein, P., 1984. Effect of benthic mixing on the information content of deep-sea stratigraphical signals. *Nature*, vol. 311, 18 October 1984, p. 651–653.
- Swart, P. K., J. L. Rubenstein, C. Charles, and J. Reitner, ed., 1998. Sclerosponges: A new proxy indicator of climate. NOAA Climate and Global Change Program, Special Report No. 12, Report from the workshop on the use of Sclerosponges as proxy indicators of climate, 22–24 March 1998, Miami, Florida.
- Weaver, H. J., 1983. Applications of discrete and continuous Fourier analysis. John Wiley & Sons, New York, 1983, 375 p.