

Sclerosponges as a new potential recorder of environmental changes: Lead in *Ceratoporella nicholsoni*

Claire E. Lazareth* Analytical Chemistry Department, Vrije Universiteit Brussel, B-1040 Brussels, Belgium

Philippe Willenz Department of Invertebrates, Royal Belgian Institute of Natural Sciences, B-1000 Brussels, Belgium

Jacques Navez Section of Petrography-Mineralogy-Geochemistry, Royal Museum for Central Africa, B-3080 Tervuren, Belgium

Eddy Keppens Geology Department, Vrije Universiteit Brussel, B-1040 Brussels, Belgium

Frank Dehairs Analytical Chemistry Department, Vrije Universiteit Brussel, B-1040 Brussels, Belgium

Luc André Section of Petrography-Mineralogy-Geochemistry, Royal Museum for Central Africa, B-3080 Tervuren, Belgium

ABSTRACT

Lead concentrations have been analyzed on a 223 yr profile through the aragonitic skeleton of the reef-building Caribbean sclerosponge *Ceratoporella nicholsoni* by using laser-ablation inductively coupled plasma-mass spectrometry. A parallel study of the $\delta^{13}\text{C}$ distribution in the skeleton validates the previously established mean annual growth rate of 230 $\mu\text{m}/\text{yr}$, at least for long-term important environmental changes. The Pb trend in the specimen displays a general increase from 0.30 ppm ca. A.D. 1760 to 2.15 ppm ca. A.D. 1984; a major threefold increase occurred after 1930. This Pb profile is analogous to results acquired from ice or coral cores and clearly highlights the potential of sclerosponges as a new proxy of environmental changes for time series extending over several centuries.

Keywords: coralline sponge, lead, global change, LA-ICP-MS, carbonate.

INTRODUCTION

It has been demonstrated that the skeleton of scleractinian corals can be used as a historical recorder of trace metal pollution and climatic variations in marine environments because elements and contaminants to which the corals are exposed are trapped within their skeleton during calcification (e.g., Shen and Boyle, 1987; Shen et al., 1992; Readman et al., 1996). However, the use of corals has four limiting factors. First, the relationship with environmental changes may be biased by physiological variables (McConnaughey, 1989) such as growth rate, calcification, and photosynthesis by symbiotic algae, influencing the incorporation of trace elements (e.g., de Villiers et al., 1995) or isotopes (e.g., Guzmán and Tudhope, 1998). Second, the rapid growth rate of corals ($\sim 0.2\text{--}5\text{ cm}/\text{yr}$) necessitates handling and analyzing several meters of core to obtain long time series (e.g., 5.5 m from one colony of *Pavona gigantea* to go back to A.D. 1600 [Dunbar et al., 1994]). Third, even the most massive corals generate a skeleton with variable densities, hampering continuous high-resolution analysis. Fourth, the indispensable symbiosis with photosynthetic algae involved in the skeletogenesis of scleractinian corals generally restricts their distribution to the euphotic layer (Wells, 1957a, 1957b).

Sclerosponges (or coralline sponges), a small assemblage of demersal sponge taxa secreting a massive basal calcareous skeleton, have recently attracted interest because of their potential to supplement data obtained from scleractinian corals (Swart et al., 1998). Sclerosponges feature several advantages over corals. First, these sponges are likely to secrete their massive calcareous skeletons in carbon and oxygen isotopic equilibrium with the surrounding seawater (Druffel and Benavides, 1986), as shown by the reproducibility of $\delta^{13}\text{C}$ patterns (Joachimski et al., 1995; Böhm et al., 1996; Moore et al., 1996; Swart et al., 1998; Wörheide, 1998). Second, the very slow growth rate of sclerosponges, ranging from 100 to 300 $\mu\text{m}/\text{yr}$ according to the species, implies that even relatively small specimens can be several centuries old (Dustan and Sacco, 1983; Willenz and Hartman, 1985, 1999; Benavides and Druffel, 1986; Wörheide, 1998). Third, the massive skeleton of some sclerosponges, such as *Ceratoporella nicholsoni*, is composed of con-

tinuous, closely packed fibrous tufts of aragonite, allowing high-resolution analysis. Fourth, because sclerosponges lack photosynthetic algal symbionts, they thrive in various dark habitats down to 300 m (Hartman and Goreau, 1970; Goreau and Land, 1974; Lang et al., 1975), extending the record of environmental changes deeper in the water column.

Recent preliminary trace element investigations in *Astrosclera willeyana* (Fallon et al., 1999) and in *C. nicholsoni* (Lazareth et al., 1999) as well as periods of low $\delta^{18}\text{O}$ recorded in *A. willeyana* that correlate with strong El Niño activities (Wörheide, 1998) are promising clues for using sclerosponges as paleoenvironmental recorders.

In order to highlight the potential of sclerosponges as a valuable paleoenvironmental proxy, this paper reports on (1) an indirect $\delta^{13}\text{C}$ control of the sponge growth and (2) a high-resolution Pb profile in the aragonitic skeleton from one of the most massive Caribbean sclerosponges, *C. nicholsoni*.

MATERIAL AND METHODS

Sample

A specimen of *Ceratoporella nicholsoni*, 14 cm in diameter (Fig. 1A), was collected in a reef crevice at a depth of 30 m on the fore-reef slope of Jamaica Bay (southern tip of Acklins Island), Bahamas, in August 1985. A diamond saw was used to cut a 5-mm-thick slab perpendicular to the surface of the specimen. A maximum age of 390 yr was assigned to the specimen (9 cm high along growth axis), based on a mean annual growth rate of $230 \pm 45\ \mu\text{m}/\text{yr}$, obtained from in situ labeling of 10 specimens with calcein over a 10 yr interval in Jamaica (Willenz and Hartman, 1999).

LA-ICP-MS

The Pb data were acquired by using laser-ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS), a microanalysis technique allowing high spatial and thus temporal resolution. The LA-ICP-MS analyses were made with a frequency-quadrupled ultraviolet-wavelength (266 nm) Nd-YAG (neodymium-doped yttrium aluminum garnet) Fisons-VG microprobe and a Fisons-VG PlasmaQuad II+ mass spectrometer. The laser was operated in the Q-switched mode at a power of 2 mJ and a frequency of 10 Hz with control of the crater size through the insertion of an aperture at the laser output. The ablation craters obtained were 60 μm in diameter without aperture (Fig. 1C) and 30 μm with use of the medium aperture. Considering a mean annual growth rate of 230 $\mu\text{m}/\text{yr}$, the largest craters correspond to three months of skeletal accretion, whereas the smallest ones correspond to 1.5 months. The preablation and acquisition times were both set at 20 s (for conditions, see Appendix 1). The instrumental instability and drift were corrected by using ^{43}Ca as an internal standard. For quantification, LA-ICP-MS data were compared to a sclerosponge external standard cut out from the ancient part of the specimen (Fig. 1A). The Pb concentration in this standard was established by ICP-MS measurements on eight dissolved microdrilled samples (1 mm in diameter). In this part of the specimen, the Pb is homogeneously distributed at 0.47 ppm ($\pm 0.06\text{ ppm}$; $2\ \sigma_x$).

For each transect, extending from about 30 μm below the edge of a pseudocalyx (skeletal tube containing the live material, Fig. 1B) toward the base of the skeleton, the laser beam was carefully targeted along the corre-

*E-mail: clazaret@vub.ac.be.

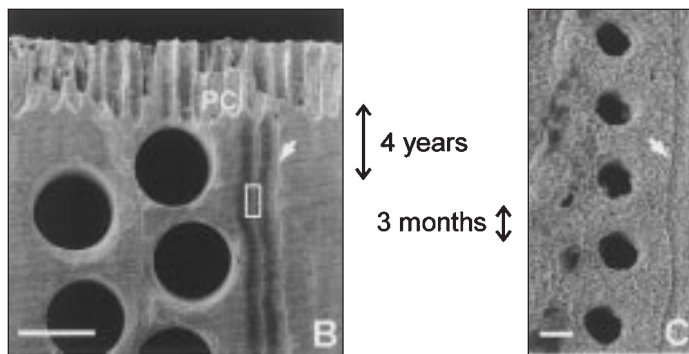
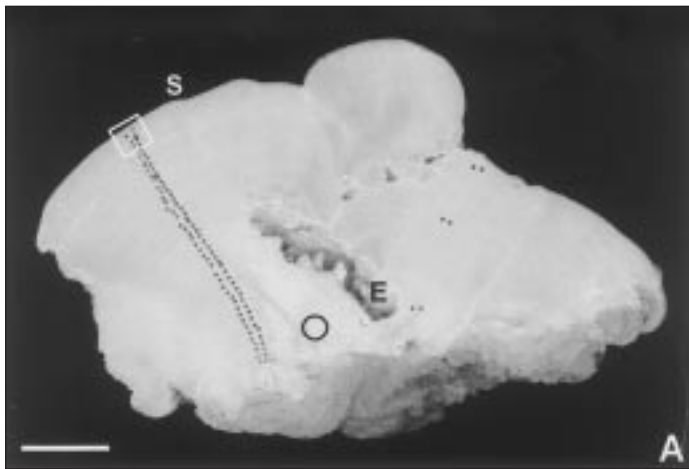


Figure 1. *Ceratoporella nicholsoni*. **A:** Section perpendicular to sample surface (S) with microdrilled samples aligned along major growth axis. E is bio-eroded zone. Circle indicates area from which calibration standard was cut out. Scale bar represents 2 cm. **B:** Scanning electron microscope (SEM) view of framed area from A showing microdrilled sample locations (large black holes) and alignment of laser-ablation inductively coupled plasma–mass spectrometry craters (very small dots extending through rectangle) in most recent part of skeleton, below pseudocalicles (PC). Scale bar represents 1 mm. **C:** SEM view of framed area from B showing craters left by laser ablation. Scale bar represents 60 μm . White arrows in B and C indicate groove marked with scalpel blade used to guide laser-ablation targeting.

sponding fascicular fibrous aragonite crystal columns, following a groove marked with a scalpel blade under a dissecting microscope. An initial series of 132 craters, 60 μm in diameter every 383 μm , was made, corresponding to one analysis for every 1.6 yr of growth. The slab being oblique to the growth axis next to the center of the specimen, a longer profile could not be obtained. The analytical reproducibility was measured as $2\sigma_x$ on successive analyses of the sclerosponge standard. The reproducibility on the sample was tested with additional shorter transects (40–60 craters) made next to the main one, in recent as well as in older regions of the slab, at a higher time resolution (craters 30 μm in diameter, every 60 μm , corresponding to an analysis for every three months of growth).

ICP-MS

Accuracy of the LA-ICP-MS analyses was controlled by measuring Pb distribution in the aragonitic skeleton by inductively coupled plasma–mass spectrometry (ICP-MS). Two interwoven series of 42 and 44 evenly spaced samples (approximately every 1.5 mm) were collected next to the LA-ICP-MS profile with a 1-mm-diameter drill parallel to the major growth direction of the sponge (Fig. 1A and 1B), corresponding to a measurement approximately every 6.5 yr for each series. The powders (~10 mg each) were dissolved in 10% suprapure HNO_3 and analyzed in a Fisons-VG PlasmaQuad II+ mass spectrometer (Appendix 1).

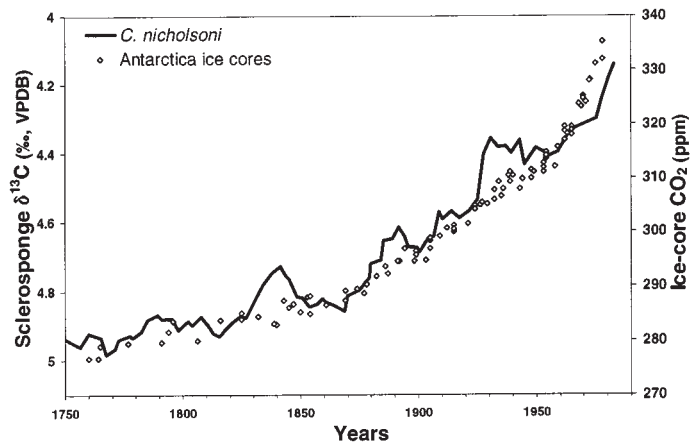


Figure 2. *Ceratoporella nicholsoni* $\delta^{13}\text{C}$ record compared with CO_2 content in ice-core air bubbles. Thick continuous line—*C. nicholsoni* three-point running-average $\delta^{13}\text{C}$ profile in delta notation relative to Vienna Pee Dee belemnite (VPDB) standard; open diamonds— CO_2 records from Antarctic ice cores (data from Etheridge et al., 1998; Neftel et al., 1985; Friedli et al., 1986).

Stable Carbon Isotope Analyses

Carbon isotope analysis was performed on a Finnigan Mat Delta E stable isotope-ratio mass spectrometer. Two parallel interwoven series of 45 microdrilled samples (1 mm in diameter, every 1 mm, corresponding to a value approximately every 4 yr for each series) were collected from a second slab of the *C. nicholsoni* studied, cut next to the one used for Pb determination. The 1–3 mg carbonate powders obtained were dissolved in $\geq 100\%$ orthophosphoric acid at 25 $^\circ\text{C}$ by using the procedure of Mc Crea (1950). Carbon isotope ratios are reported in the delta notation, expressed in per mil relative to the Vienna Pee Dee belemnite (VPDB) international standard, and corrected following procedures modified from Craig (1957). Reproducibility, determined by replicate analysis of NBS-19 and repeated analysis on randomly selected samples, was better than 0.05‰ at the 2σ level.

RESULTS

The $\delta^{13}\text{C}$ profile of this Bahamian specimen of *Ceratoporella nicholsoni* displays a general decrease from $+4.9\text{‰} \pm 0.05\text{‰}$ ca. 1750 to $+4.1\text{‰} \pm 0.05\text{‰}$ ca. 1980 with two distinct sections (Fig. 2). The oldest part (1750–1860) of the skeleton shows almost no decline in $\delta^{13}\text{C}$ (from $+4.9\text{‰}$ to $+4.8\text{‰}$ [–2%]), whereas in the more recent region of the skeleton (1860–1984) a more severe decrease is observed, from $+4.8\text{‰}$ to $+4.1\text{‰}$ (–15%).

The LA-ICP-MS Pb profile leads to a time series extending from 1760 to 1983 with a measurement for every 1.6 yr of growth (Fig. 3). The Pb concentration evolves from 0.30 ppm ca. 1760 to 2.15 ppm ca. 1984. The shorter transects confirmed these Pb concentrations and trends, and both analytical techniques used for Pb measurements (LA-ICP-MS and ICP-MS) gave very similar results (linear regression: LA-ICP-MS = 1.15 ICP-MS – 0.062, $r^2 = 0.9$). The Pb profile of *C. nicholsoni* can be subdivided into three periods: (1) from 1760 to 1860, a limited Pb increase and an average Pb level of 0.35 ± 0.1 ppm; (2) from 1860 to 1931, irregular fluctuations with an overall slight increase and a mean at 0.71 ± 0.2 ppm; and (3) from 1931 to 1983, a threefold increase, from 0.72 to 2.31 ppm.

DISCUSSION

Validation of Growth Rate

A $\delta^{13}\text{C}$ decrease over the past 200 yr has been reported for sclerosponges (Druffel and Benavides, 1986; Joachimski et al., 1995; Böhm et al., 1996; Wörheide, 1998). It has been related to the increase of fossil-fuel burning and deforestation since preindustrial time. Indeed, the resulting dramatic increase of atmospheric CO_2 has gone with a ^{13}C depletion (cf. review in

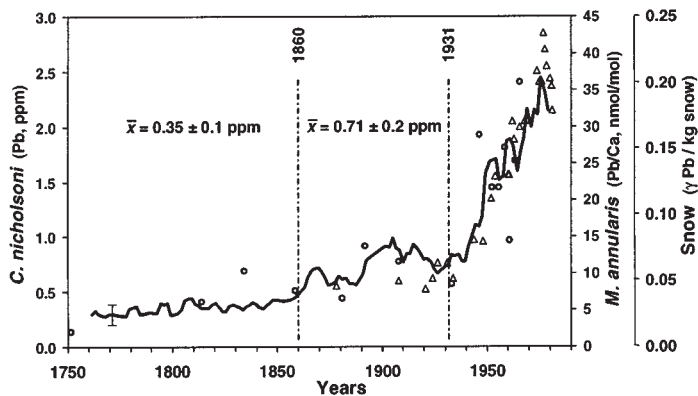


Figure 3. Evolution of Pb concentration in *Ceratoporella nicholsoni* from 1750 to 1990 compared with other Pb records. Solid line—*C. nicholsoni* three-point running-average laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) profile; circles—Greenland snow Pb concentration, data from Murozumi et al. (1969); triangles—Florida Keys *Montastrea annularis* (scleractinian coral) Pb/Ca ratio, data from Shen and Boyle (1987). For *C. nicholsoni*, values are means $\pm \sigma$ of Pb for selected periods. Bar—analytical reproducibility of LA-ICP-MS analyses, $\pm 2 \sigma_{\bar{x}}$.

Trabalka and Reichle [1986] and in Siegenthaler and Sarmiento [1993]). In Figure 2, the $\delta^{13}\text{C}$ of *Ceratoporella nicholsoni* is compared to the CO_2 content in ice-core air bubbles reported by Murozumi et al. (1969). The strong similarity in the shapes of the two curves supports the choice of 230 $\mu\text{m}/\text{yr}$ as a value for average annual growth rate that is likely to have been steady, at least for the period examined. However, this conclusion must be considered with caution because growth rates are reported to fluctuate considerably. For example, Willenz and Hartman (1999) reported an annual growth rate as low as 124 $\mu\text{m}/\text{yr}$ in a population of young *C. nicholsoni*, indicating a physiological variability possibly related to the size of the individuals.

Pb Profile

The anthropogenic Pb input to the atmosphere over time has been studied by many authors, and different types of archives provide an overview of the atmospheric Pb evolution (e.g., snow strata and ice cores [Murozumi et al., 1969; Boutron and Lorius, 1979; reviewed in Boutron et al., 1994], as well as corals [Shen and Boyle, 1987]). The increase of environmental Pb concentrations began ca. 1750; there was a threefold augmentation during the second half of the eighteenth century, as reported from Greenland snows, followed by a twofold increase from 1815 to 1933 (Murozumi et al., 1969). The best-known anthropogenic Pb pollution is probably the threefold increase that occurred after 1930–1940, essentially related to leaded gasoline consumption (Murozumi et al., 1969; Schaule and Patterson, 1981). This rise was followed by a drop in the 1970s, linked to a decrease in the use of lead alkyl additives in gasoline, principally in the United States (Nriagu, 1989a; Boutron et al., 1991; Rosman et al., 1993). Natural input of Pb to the atmosphere is insignificant, relative to anthropogenic emission (e.g., Nriagu, 1989b), even if some huge volcanic emissions irregularly enhance global Pb fluxes (Hong et al., 1996). This atmospheric Pb is transferred to the open ocean by two vectors: (1) mostly wet deposition of aerosols and (2) river transport of particulate matter (Patterson et al., 1976; Schaule and Patterson, 1983; Elbaz-Poulichet et al., 1984).

The temporal evolution of Pb in the *Ceratoporella nicholsoni* specimen is characterized by a general increase, particularly pronounced after 1930, that can be related to the well-known gradual increase of anthropogenic Pb emissions. This profile is very similar to the one observed for Greenland snows (Murozumi et al., 1969) and for a Florida Keys coral (Shen and Boyle, 1987). In particular, it records the threefold input of anthropogenic Pb in the atmosphere after 1930 (Fig. 3). This observation has three major implications. First, it confirms the applied growth-rate value, at least for long-term measurements. Second, the similarity between our Pb profile and the one ob-

served in Greenland snows shows that most of the Pb found in surface waters around the Bahama Islands has been derived from the atmosphere. Third, the coincidence between *C. nicholsoni* and the coral record from Shen and Boyle (1987) suggests that Pb could be incorporated in the carbonate skeleton of these two reef-building animals, belonging to distinct phyla, following a similar biological process. Moreover, the results underline that the kinetics of Pb incorporation by the sclerosponge has been rather stable with time.

The higher Pb levels between the 1860s and 1930s in the *C. nicholsoni* record may be, at least in large part, related to the increased development of Pb smelting in the Northern Hemisphere at that time (Murozumi et al., 1969). The Pb fluctuations between 1860 and 1931 are similar in amplitude to the variations recorded in a Greenland ice core by Murozumi et al. (1969), who explained these features either by seasonal variations or by inconsistent locations in the collection of the samples. The 1860 to 1931 fluctuations in the *C. nicholsoni* record might be related to local seasonal variations, to regional fluctuations that could be linked with less polluted Southern Hemisphere water contributions brought by the Gulf Stream, or to global variations of Pb input in the atmosphere during that period.

CONCLUSIONS

The LA-ICP-MS technique proved to be particularly efficient for the determination of Pb concentrations in the skeleton of *Ceratoporella nicholsoni*. Because the $\delta^{13}\text{C}$ and Pb profiles match those from other archives independently dated, the use of a previously determined constant average growth rate of 230 $\mu\text{m}/\text{yr}$ appears sufficiently accurate to date long-term important environmental changes. This research confirms that sclerosponges with a massive aragonitic skeleton represent a new promising paleoclimate proxy that may potentially be used to supplement data obtained from scleractinian corals, on an advantageously longer time scale and on a wider range of water depths. However, it is apparent that further investigation on other trace elements is necessary to confirm the possibility of using sclerosponges to reconstruct more histories of the water column.

APPENDIX 1. OPERATING CONDITIONS OF INDUCTIVELY COUPLED PLASMA–MASS SPECTROMETRY (ICP-MS) AND LASER-ABLATION INDUCTIVELY COUPLED PLASMA–MASS SPECTROMETRY (LA-ICP-MS)

Liquid ICP-MS

External lens	1.61
Collector	7.87
Lens 1	7.70
Lens 2	6.19
Lens 3	6.17
Lens 4	5.01

Argon flow rate (L/min)

Carrier gas	0.80
Auxiliary gas	0.93
Cooling gas	13.57

Acquisition mode

Acquisition mode	Peak jumping
Points per peak	3
Dwell time (ms)	10.24

LA-ICP-MS

Laser Probe

Laser mode	Q-switched
Laser power (mJ)	2
Frequency (Hz)	10
Preablation time (s)	20

ICP-MS

Argon flow rate (L/min)

Carrier gas	1.1
Auxiliary gas	1.25
Cooling gas	13.53

Acquisition mode

Acquisition mode	Peak jumping
Points per peak	3
Dwell time (ms)	10.24
Acquisition time	20

ACKNOWLEDGMENTS

This work was supported by a European Grant under the Training and Mobility of Researchers (TMR) Program, contract FMBICT983440. André thanks the Lotto for its financial support in the acquisition of the LA-ICP-MS equipment. The specimen of *Ceratoporella nicholsoni* was collected by scuba diving during a cruise on the ORV *Cape Florida* to Acklins Island. We thank R. Colwell and D. Santavy for their invitation to Willenz to join the cruise while supported by National Science Foundation grant BSR-8317690 to W.D. Hartman, Yale University. We are also grateful to Hartman for helpful advice on the manuscript. We thank W. Dean and an anonymous reviewer for constructive comments and suggestions.

REFERENCES CITED

- Benavides, L.M., and Druffel, E.R.M., 1986, Sclerosponge growth rate as determined by ^{210}Pb and $\Delta^{14}\text{C}$ chronologies: Coral Reefs, v. 4, p. 221–224.
- Böhm, F., Joachimski, M.M., Lehnert, H., Morgenroth, G., Kretschmer, W., Vacelet, J., and Dullo, W.-C., 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, v. 139, p. 291–303.
- Boutron, C.F., and Lorius, C., 1979, Trace metals in Antarctic snows since 1914: Nature, v. 277, p. 551–554.
- Boutron, C.F., Görlach, U., Candelone, J.-P., Bolshov, M.A., and Delmas, R.J., 1991, Decrease in anthropogenic lead, cadmium and zinc in Greenland snows since the late 1960s: Nature, v. 353, p. 153–156.
- Boutron, C.F., Candelone, J.-P., and Hong, S., 1994, Past and recent changes in the large-scale tropospheric cycles of lead and other heavy metals as documented in Antarctic and Greenland snow and ice: A review: Geochimica et Cosmochimica Acta, v. 58, p. 3217–3225.
- Craig, H., 1957, Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide: Geochimica et Cosmochimica Acta, v. 12, p. 133–149.
- de Villiers, S., Nelson, B.K., and Chivas, A.R., 1995, Biological controls on coral Sr/Ca and $\delta^{18}\text{O}$ reconstructions of sea surface temperatures: Science, v. 269, p. 1247–1249.
- Druffel, E.R.M., and Benavides, L.M., 1986, Input of excess CO_2 to the surface ocean based on $^{13}\text{C}/^{12}\text{C}$ ratios in a banded Jamaican sclerosponge: Nature, v. 321, p. 58–61.
- Dunbar, R.B., Wellington, G.M., Colgan, M.W., and Glynn, P.W., 1994, Eastern Pacific sea surface temperature since 1600 A.D.: The $\delta^{18}\text{O}$ record of climate variability in Galápagos corals: Paleoceanography, v. 9, p. 291–315.
- Dustan, P., and Sacco, W.K., 1983, Hidden reef builders: The sclerosponges of Chalet Caribe Reef: Discovery, v. 16, no. 2, p. 13–17.
- Elbaz-Poulichet, F., Holliger, P., Huang, W.W., and Martin, J.-M., 1984, Lead cycling in estuaries, illustrated by the Gironde estuary, France: Nature, v. 308, p. 409–414.
- Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola, J.-M., and Morgan, V.I., 1998, Historical CO_2 records from the Law Dome DE08, DE08-2, and DSS ice cores, in Trends: A compendium of data on global change: Oak Ridge, Tennessee, Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, <http://cdiac.esd.ornl.gov/trends/co2/lawdome.html>.
- Fallon, S.J., McCulloch, M.T., and Hooper, J.N.A., 1999, Trace element and stable isotope profiles from the coralline sponge (*Astroclera willeyana*), in Hooper, J.N.A., ed., Proceedings of the 5th International Sponge Symposium "Origin and Outlook": Queensland Museum Memoirs, v. 44, p. 174.
- Friedli, H., Löttscher, H., Oeschger, H., Siegenthaler, U., and Stauffer, B., 1986, Ice core record of the $^{13}\text{C}/^{12}\text{C}$ ratio of atmospheric CO_2 in the past two centuries: Nature, v. 324, p. 237–238.
- Goreau, T.F., and Land, L.S., 1974, Fore-reef morphology and depositional processes, north Jamaica, in Laporte, L.F., ed., Reefs in time and space: Selected examples from the recent and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 18, p. 77–89.
- Guzmán, H.M., and Tudhope, A.W., 1998, Seasonal variation in skeletal extension rate and stable isotopic ($^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$) composition in response to several environmental variables in the Caribbean reef coral *Siderastrea siderea*: Marine Ecology Progress Series, v. 166, p. 109–118.
- Hartman, W.D., and Goreau, T.F., 1970, Jamaican coralline sponges: Their morphology, ecology and fossil relatives: Zoological Society of London Symposia, no. 25, p. 205–243.
- Hong, S., Candelone, J.-P., and Boutron, C.F., 1996, Deposition of atmospheric heavy metals to the Greenland ice sheet from the 1783–1784 volcanic eruption of Laki, Iceland: Earth and Planetary Science Letters, v. 144, p. 605–610.
- Joachimski, M.M., Böhm, F., and Lehnert, H., 1995, Long-term isotopic trends from Caribbean demosponges: Evidence for isotopic disequilibrium between surface waters and atmosphere, in Lathuilière, B., and Geister, J., eds., Proceedings of the 2nd European Regional Meeting of the International Society for Reef Studies: Publication du Service Géologique du Luxembourg, v. 29, p. 141–147.
- Lang, J.C., Hartman, W.D., and Land, L.S., 1975, Sclerosponges: Primary framework constructors on the Jamaican deep fore-reef: Journal of Marine Research, v. 33, p. 223–231.
- Lazareth, C.E., Willenz, P., Dehairs, F., and André, L., 1999, Calcification rate and high-resolution trace element distributions (ICP-MS and LA-ICP-MS) in the Caribbean coralline sponge *Ceratoporella nicholsoni*: European Union of Geosciences 10, Journal of Conference Abstracts, v. 4, no. 1, p. 212–213.
- Mc Crea, J.M., 1950, On the isotopic chemistry of carbonates and a paleotemperature scale: Journal of Chemical Physics, v. 18, p. 849–857.
- McConnaughey, T., 1989, ^{13}C and ^{18}O isotopic disequilibrium in biological carbonates: I. Patterns: Geochimica et Cosmochimica Acta, v. 53, p. 151–162.
- Moore, M.D., Charles, C.D., and Rubenstone, J.L., 1996, Stable isotope records of tropical climate variability from U/Th dated sclerosponges: Eos (Transactions, American Geophysical Union), v. 77, p. F291.
- Murozumi, M., Chow, T.J., and Patterson, C., 1969, Chemical concentrations of pollutant lead aerosols, terrestrial dusts and sea salts in Greenland and Antarctic snow strata: Geochimica et Cosmochimica Acta, v. 33, p. 1247–1294.
- Neftel, A., Moor, E., Oeschger, H., and Stauffer, B., 1985, Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries: Nature, v. 315, p. 45–47.
- Nriagu, J.O., 1989a, History of leaded gasoline, in Vernet, J.-P., ed., Heavy metals in the environment, Volume 2: Edinburgh, CEP Consultants, p. 361–366.
- Nriagu, J.O., 1989b, A global assessment of natural sources of atmospheric trace metals: Nature, v. 338, p. 47–49.
- Patterson, C.C., Settle, D.M., and Glover, B., 1976, Analysis of lead in polluted coastal seawater: Marine Chemistry, v. 4, p. 305–319.
- Readman, J.W., Tolosa, I., Law, A.T., Bartocci, J., Azemard, S., Hamilton, T., Mee, L.D., Wagener, A., Le Tissier, M., Roberts, C., Downing, N., and Price, A.R.G., 1996, Discrete bands of petroleum hydrocarbons and molecular organic markers identified within massive coral skeletons: Marine Pollution Bulletin, v. 32, p. 437–443.
- Rosman, K.J.R., Chisholm, W., Boutron, C.F., Candelone, J.P., and Görlach, U., 1993, Isotopic evidence for the source of lead in Greenland snows since the late 1960s: Nature, v. 362, p. 333–335.
- Schaule, B.K., and Patterson, C.C., 1981, Lead concentrations in the northeast Pacific: Evidence for global anthropogenic perturbations: Earth and Planetary Science Letters, v. 54, p. 97–116.
- Schaule, B.K., and Patterson, C.C., 1983, Perturbations of the natural lead depth profile in the Sargasso Sea by industrial lead, in Wong, C.S., et al., eds., Trace metals in sea water: New York, Plenum Press, p. 487–503.
- Shen, G.T., and Boyle, E.A., 1987, Lead in corals: Reconstruction of historical industrial fluxes to the surface ocean: Earth and Planetary Science Letters, v. 82, p. 289–304.
- Shen, G.T., Cole, J.E., Lea, D.W., Linn, L.J., McConnaughey, T.A., and Fairbanks, R.G., 1992, Surface ocean variability at Galápagos from 1936–1982: Calibration of geochemical tracers in corals: Paleoceanography, v. 7, p. 563–588.
- Siegenthaler, U., and Sarmiento, J.L., 1993, Atmospheric carbon dioxide and the ocean: Nature, v. 365, p. 119–125.
- Swart, P.K., Moore, M., Charles, C., and Böhm, F., 1998, Sclerosponges may hold new keys to marine paleoclimate: Eos (Transactions, American Geophysical Union), v. 79, p. 635–636.
- Trabalka, J.R., and Reichle, D.E., eds., 1986, The changing carbon cycle—A global analysis: New York, Springer-Verlag, 592 p.
- Wells, J.W., 1957a, Coral reefs, in Hedgpeth, J.W., ed., Treatise on marine ecology and paleoecology. Volume 1. Ecology: Geological Society of America Memoir 67, p. 609–631.
- Wells, J.W., 1957b, Corals, in Hedgpeth, J.W., ed., Treatise on marine ecology and paleoecology. Volume 1. Ecology: Geological Society of America Memoir 67, p. 1087–1104.
- Willenz, P., and Hartman, W.D., 1985, Calcification rate of *Ceratoporella nicholsoni* (Porifera: Sclerospongiae): An in situ study with calcein, in Delesalle, B., et al., eds., Proceedings of the Fifth International Coral Reef Congress, Tahiti: Moorea, French Polynesia, Antenne Museum-Ecole Pratique des Hautes Etudes, p. 113–118.
- Willenz, P., and Hartman, W.D., 1999, Growth and regeneration rates of the calcareous skeleton of the Caribbean coralline sponge *Ceratoporella nicholsoni*: A long term survey, in Hooper, J.N.A., ed., Proceedings of the 5th International Sponge Symposium "Origin and Outlook": Queensland Museum Memoirs, v. 44, p. 675–685.
- Wörheide, G., 1998, The reef cave dwelling ultraconservative coralline demersal sponge *Astroclera willeyana* Lister 1900 from the Indo-Pacific: Facies, v. 38, p. 1–88.

Manuscript received October 29, 1999

Revised manuscript received March 9, 2000

Manuscript accepted March 17, 2000