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Thermal stress assessment using carbon and oxygen isotopes from Scleractinia, Rocas Atoll, northeastern Brazil

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More than 430 C and O isotope analyses were carried out on carbonates from six coral species collected during June 1995, July 1998 and February 1999 at Rocas atoll, offshore northeastern Brazil: *Siderastrea stellata* Verrill 1868, *Porites branneri* Rathbum 1887, *Porites astreoides* Lamarck 1816, *Mussismilia hispida* Verrill 1902, *Madracis decactis* Lyman 1859 and *Montastrea cavernosa* Linnaeus 1886. Samples were collected in pools within the ring of the atoll, at water depths from 1.0 to 7.0 m. Oxygen isotope chemistry demonstrated that the studied species experienced several periods of bleaching; calculated temperature for one species vary, suggesting important changes within the time scale of coral growth. The species *P. branneri, P. astreoides, M. cavernosa* and the Brazilian endemic species *M. hispida* registered temperature variations during coral growth more accurately than did *S. stellata* and *M. decactis*. Carbon isotope behaviour in coral skeletons of the species examined at this atoll seems to have maintained a close relationship between density and/or zooxanthelar productivity: the greater the algal density, the heavier the $\delta^{13}C$ values in skeletons.

Keywords: Scleractinia; C and O isotopes; Rocas atoll; bleaching; northeastern Brazil

Introduction

There is an increasing interest in understanding global climate change. A promising technique for this has been the compilation of proxy temperature records based on the stable isotopic signatures of Scleractinia coral skeletons (Gill *et al.* 1995). Corals have the capability of recording temperature variations of the water in which they grow, a valuable source of information on past climate oscillation. Knowing the oxygen isotope behaviour of a coral skeleton, it may be possible to monitor temperature changes that the coral skeletons may have undergone during anomalous climate warming. Carbon isotopes, in their turn, provide the algal density (zooxanthellae).

A prolonged temperature increase can be a stress factor for corals and if the temperature increase reaches anomalous levels, it may lead to bleaching. During a

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warming period, dinoflagellata that are found in the tissues of various reef dwellers (including corals), where they are found in their tissue, can leave the Scleractinia during this unfavourable period.

The El Niño/Southern-Oscillation (ENSO) phenomenon is the name given to a series of inter-annual episodes of abnormal climatic changes caused by the pressure oscillation of the atmosphere in the Indo-Pacific region. It refers to the movement from east to west of warmer water, carrying the thermoclina near the surface in the east and lowering it in the west, with typical, very long and slow movements that spread in the bottom up to the upper portion of the ocean (Carriquiry *et al.* 1994; NOAA 2001/2003). This causes warm water accumulation along the American coast to cross the cold Humboldt stream. This phenomenon led to environmental biochemical changes in South America.

The La Niña event on the other hand is due to temperature cooling in the equatorial Pacific Ocean (NOAA 2001/2003), leading to positive $\delta^{18}O$ values in corals. The conditions caused by these events may last for up to 2 years, but usually only for 9–12 months (NOAA 2001/2003). During neutral periods, which correspond to the regular cycle between hot (El Niño) and cold (La Niña) conditions, there is a complete interaction between the surface wind powers, which blow from the east along the Equator, and the tides and sub-surface temperature.

Bleaching of Brazilian corals was reported for the first time by Maÿal *et al.* (1991). The bleaching may be caused by thermal stress, but there are other factors as well. The bleaching causes stress in various reef inhabitants, many of which have dinoflagellate in their tissues, the symbiotic relationship with microalgae in the case of coral helps with growth. When these microalgae die, they either abandon the corals or reduce their metabolism, leading to bleaching (Maÿal *et al.* 1995). If the dinoflagellates become encysted, they do not contribute with $\delta^{13}C$ resulting from photosynthesis. According to Glynn (1990), the physiological and ecological effects of bleaching in corals include growth decrease, protein, lipids carbohydrates decline, gonad regression, tissue necrosis, etc.

Bleaching can be also due to pollution, high sedimentation rate, turbidity, fresh water input, incidence of ultraviolet light and illness, among other factors. Field and laboratory experiments have demonstrated that a high sedimentation rate kills the coral polyps by asphyxia, therefore recovery is not possible. Dead corals become a substrate for algae and these are a food source mainly for herbivorous fish and many equinoids, especially *Echinometra lucunter*. Hence, the destruction of the 'heads' of corals may occur by the process called bioerosion, hindering the organism which depends on them. Death of microalgae that live in coral tissues leads to a decrease in the primary productivity. Corals are very sensitive to environmental changes and bleaching is a response to the environment; it can be a very useful parameter of environmental impact, which in the longterm may be more damaging than expected (Maÿal *et al.* 1995, 1997).

In this study, only bleaching due to thermal stress is considered, and stress temperatures are those $\geqslant 30^{\circ}C$. An increase of $0.5^{\circ}C$ above the limit of temperature a coral can tolerate may be a factor leading to stress. Taking into account that temperature is recorded in the carbonates of the coral skeleton by the oxygen isotopes, one way to analyse the extension of the thermal stress phenomenon is to examine oxygen isotope composition of the skeletons. C and O isotope analyses have been used to describe the photosynthesis mechanism of algae, variations and

influence of the *in situ* temperature and past thermal events, providing information on unknown periods of thermal stress.

Urey (1947) suggested that fractionation of isotopes of C and O between water and shells of different organisms could be used to determine palaeotemperature of the waters of the oceans. The use of stable isotopes in studies of coral skeletons had its first step with the publication of an article by Keith and Weber (1965). Weber and Woodhead (1972) confirmed Urey's assumption on oxygen isotope fractionation during the formation of coral skeleton, demonstrating that the oxygen isotope composition of the calcium carbonate precipitated in isotopic equilibrium with ocean water is temperature dependent.

Oxygen isotope values in coral skeletons can demonstrate periods when, during coral growth, thermal stress took place. According to Swart (1983), positive $\delta^{13}C$ values are related to corals, and the greater the productivity (zooxanthellae) to corals, the higher will be $\delta^{13}C$ values. Rosenfeld *et al.* (2003) pointed out that all the above variables are directly influenced by the depth at which the coral is growing and consequently are bound to affect skeletal $\delta^{13}C$ composition. Suzuki *et al.* (2003) studied specimens of the genera *Porites* and also examined the bleaching using $\delta^{13}C$ and $\delta^{18}O$ of the skeleton (photosynthesis and skeletogenesis). They had verified in growth bands of bleached corals that had suffered stress that bands were irregular, less dense and associated with the discontinuous growth.

The scope of the present study is to evaluate thermal stress and organic productivity of corals in an environment devoid of anthropogenic influence using O and C isotope data from growth bands of coral species collected in the years 1995, 1998 and 1999 at the Rocas atoll, northeastern Brazil.

Materials and methods

Studied area

The oval Rocas atoll in the Atlantic Ocean, offshore northeastern Brazil (Figure 1), is 3.7 km long and 2.5 km wide, and is an area that suffers very little anthropogenic influence. This atoll has been built on top of a seamount that extends from the continental slope to the proximities of the 3°W longitude, in the continental platform, between 2° and 4°30′S latitude. This seamount is part of the Fernando de Noronha fracture zone (Gorini and Carvalho 1984; Palma 1979). The atoll is predominantly formed by calcareous algae, which shows a reasonable amount of vermetid (mollusc, gastropod). There is no true lagoon, but only a shallow tidal system that during low tide allows one to walk across the lagoon. In the northeastern portion of the atoll, the low water level allows one to often see shark cubs. Corals are found in shallow ponds formed at low tide, but they are more concentrated in the water pools within the atoll ring. In the shallow ponds, the coral species found here is the endemic Brazilian *S. stellata*, which occurs as small specimen representatives; in the deep water pools, this same species presents a larger development forming specimens up to 80 cm in diameter or more, and in some water pools, they construct mono-specific buildings.

There are two islets in the atoll: Farol and Cemitério. The land area of the two islets is 0.36 km^2 and the Farol accounts for almost two-thirds of the aggregate area (Almeida *et al.* 2000). These islets present low-standing vegetation that are used as nesting sites by marine birds that live there or others that are passing through, and among them are found: *Stermas foscata, Amius minutos, Amius stollus, Sula sula,*

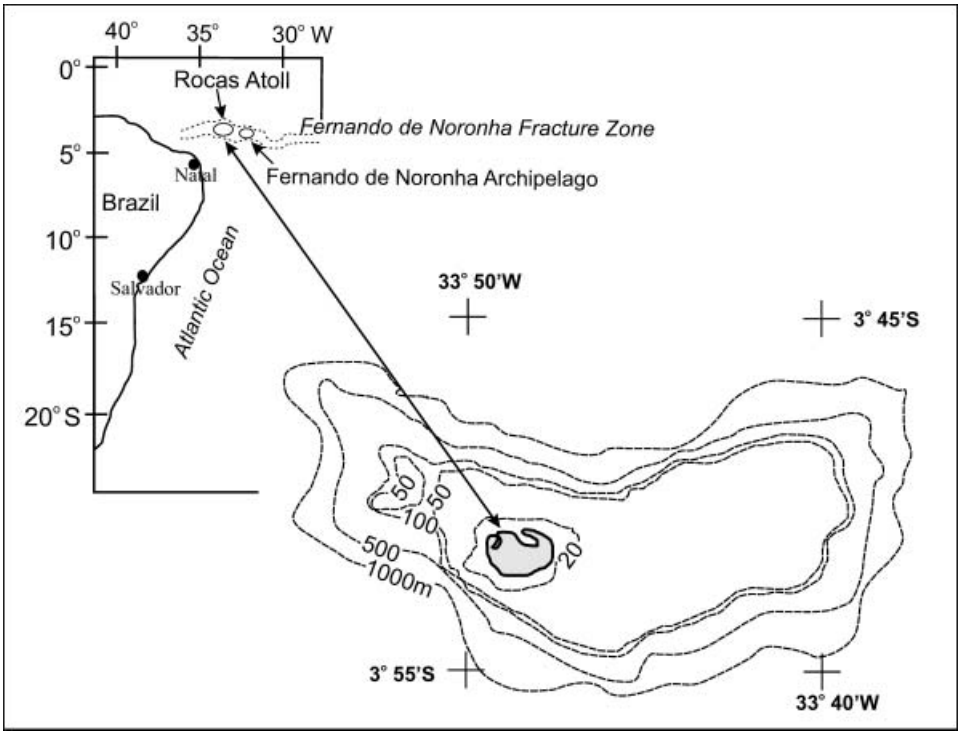

Figure 1. Location map of the Rocas atoll and the biological reserve limits (1000 m isobaths) (Kikuchi 2002).

Sula dactilata, Sula leucogaster and *Fragata magnificus.* The atoll is also a place where young turtles of the species *Chelonia midas* feed and, together with the species *Eretmochelys imbricate*, spawn (Maÿal and Bezerra 1994/1995). The climate in the atoll is warm equatorial, with winds blowing from the southeast, August being the warmest month. The rain season runs from March to July with more intense precipitation from April to May (about 250 mm); October is regarded as the driest month, with 6 mm precipitation (Feitosa and Passavante 2004). These authors determined a high amount of dissolved oxygen in the seawater next to the Rocas atoll, with saturation levels close to 100%, and alkaline pH, which are expected in an area with low anthropogenic influence. The inorganic nutrients, according to these authors, are not very abundant, as opposed to the organic ones, which are more abundant due to excrements of marine birds.

The following coral species are found in water pools of the Rocas atoll: M. *decactis*, *S. stellata*, *P. branneri*, *P. astreoides*, *Porites sp.*, *M. cavernosa*, *Favia gravida*, *M. hispida* and the hydrocoral *Stylaster roseus* (Maÿal and Bezerra 1994/1995).

Studied species

For this study, the coral species studied were *S. stellata*, *P. branneri*, *P. astreoides*, *M. hispida, M. decactis* and *M. cavernosa*. From these six species, two are endemic Brazilian.

The species *M. decactis* belongs to the Pocilloporidae Gray 1842 family. According to Wells (1956), this family is placoid, usually branchy, mostly

hermatypic and are made up by extratentacular budding. Septa rarely have more than two reduced cycles, have narrow laminae or striae; eventually, they have spines. Columella is styliform and vertically discontinued. The coenosteum is solid or vesicular. The genus *Madracis* Milne Edwards and Haime 1849, according to Wells (1956), can be branchy or solid. Septa are well developed with smooth margins; higher cycles reduced to spines, arranged in group of 8–10. Columella is prominent and styliform. This genus first appeared in the Cretaceous. Columnar-shaped specimens of the species *M. decatis* are found in the atoll.

The species *S. stellata*, common along the entire Brazilian coastal area from the northeast down to Rio de Janeiro, belongs to the Siderastreidae Vaughan and Wells, 1943 family. According to Wells (1956), the members of this family are colonial and rarely solitary; they are hermatypic colonies formed by intratentacular or extratentacular budding or synapticulothecate. Septa are composed of a fan system of small, simple or compound trabecular, laterally strongly granulated, with more or less porous margins beaded or dentate, laterally united by simple synapticulae. The columella is composed of one or more papillary trabeculae; it presents endothecal dissepiments. The genus *Siderastrea* Blainville 1830 is according to Wells (1956) solid, branchy or encrusting; cerioid, colonies are made up by extratentacular budding. Corallite has well-defined walls, made up by several synapticular rings. This genus has existed since the Cretaceous. The species *S. stellata* has the corallite with larger diameter, and the fifth cycle or septa is united to the four cycle (Maÿal *et al.* 2000) and samples from the atoll are similar to those of the continent. In the tidal pools of the atoll, the specimens are very small and in the pools they reach a larger size. In general, they are round or semi-hemispheric (incrusting shapes are also found).

The species *P. branneri* belongs to the Superfamily Poriticae Gray 1842, family Poritidae Gray 1842. According to Wells (1956), this is colonial hermatypic, and colony formation is extratentacular buds. Corallites are mostly closely united without coenosteum, limited by one or more synapticular rings. Septa are formed by 3–8 nearly vertical trabeculae, loosely united, with fairly regular perforations. The genus *Porites* according to Wells (1956) can be massive, ramose or incrusting. Corallites are small with two septal cycles. Septa are formed by 3–4 trabeculae. It is an important cosmopolitan hermatypic coral genus. This genus first appeared in the Eocene. The species *P. branneri* has corallites up to 1.5 mm in diameter, the septa are porous with the internal edge fused forming a central ring. This species does not show any columellae. Colonies were found incrusting and rounded massive, frequently with mamelonated polyps (Maÿal *et al.* 2000).

The species *P. astreoides* presents corallite with diameter between 10 and 14 mm and septa in number of 12. The columella is porous, well developed in some specimens. Specimens have been found with solid colonies, less dense, irregular, hemispheric, incrusting, frequently presenting protuberance, and almost always having a dense endofauna (Maÿal *et al.* 2000.).

The species *M. cavernosa* belongs to the Suborder Faviina Vaughan and Wells 1943, Superfamily Faviicae Gregory 1900, Family Faviidae Gregory 1900, Subfamily Montastreinae Vaughan and Wells 1943. According to Wells (1956), the subfamily is colonial hermatypic. Colony formation is by extratentacular budding, with a few exceptions. Septa are formed by one fan system of mostly simple trabeculae. This subfamily first appeared in the Jurassic.

The genus *Montastrea* Blainville 1830, according to Wells (1956), can be massive, incrusting, subfoliaceous and placoid. It is septhotecate, with septal margins

regularly dentate; the columella is trabecular. In the species *M. cavernosa* the corallite is tall, above the floor of the skeleton, reaching up to 8 mm in diameter. They show three complete cycles of septa and one incomplete cycle of septum. The complete cycles of septa are completely adhered to a long porous and deep columella, which stretches in the space between the corallites, are serrulated and number as many as 36. The teeth are small and triangular. The mounds are well defined with lateral walls, which are thick and high (Maÿal *et al.* 2000).

The species *M. hispida* belongs to the Mussidae family Ortmann 1890. According to Wells (1956), colony formation is by intratentacular budding, centres are linked by lamellae or trabeculae could be septhotecate or parathecate. The septum is enterocelic and made up by several fan systems of large, simple trabeculae, each fan system producing lobed teeth. The dissepiments are well developed and the columella is trabecular. The fossil record points to a Jurassic age for the first appearance of this family. The genus *Mussismilia* Ortmann 1890 has the septa with small teeth. This genus first appeared in the Quaternary. The species *M. hispida* presents wide corallites. In some specimens, the diameter of the corallites is up to 2.2 cm (Maÿal *et al.* 2000). These colonies generally found in the atoll are much more developed than the ones found in the continent. In the atoll, the encrusting shapes are more common than the hemispheric ones. The encrusting ones are found in the pinnacles and walls of the water pools.

The species *M. hispida* is common in the entire Brazilian coastal area from northeastern Brazil down to São Paulo. The Brazilian endemic species *S. stellata* is similar to the ones found in the Caribbean Sea. This species perhaps correspond to Caribbean species; they appear with ecomorphs of the Brazilian species.

The most common species of the atoll, *S. stellatta*, made up a large number of the total collected specimens with fewer specimens from the other species. Since the Rocas atoll is a biological reserve, Brazilian federal regulations do not allow collecting specimens very often and therefore, in this study, we have only used the specimens we collected in 1995, 1998 and 1999.

Sample collection and analytical methods

Studied coral specimens were collected both by scuba and free diving during low tide, using chisel and hammer. Sampling depth was measured with a depth meter.

Seventeen specimens of the *S. stellata* species were collected at 1.5 m in the Farol water pool, at 2.0 m in the Cemitério, Âncoras and Tartarugas water pools, at 3.0 m in the Tartarugas, Âncoras and Salão water pools, at 3.5 m in the Salão water pool, at 4.0 m in the Salão water pool and at 7.0 m deep in the Salão water pool in the years 1995, 1998 and 1999 (Table 1). Three specimens from the *P. branneri* species were collected at 0.5, 1.0 and 2.5 m depth in the Cemitério water water pool in 1995, and one specimen was collected in 1998 at 1 m depth in the Tartarugas water pool (Table 2).

Three specimens from the *M. hispida* species were collected at 1.0 m depth at the Cemitério and Tartarugas water pools, and at 2.0 m depth in the Cemitério water pool, in 1995 (Table 3). The *M. decactis* species had eight specimens analysed, collected at 1 m depth in the Cemitério and Tartarugas water pools, at 1.5 m in the Tartarugas water pool and at 2 m depth in the Cemitério and Tartarugas water pools, in 1995 (Table 4). Seven specimens from the *M. cavernosa* species were collected in 1999 at 2.0 m depth in the Âncoras and Tartarugas water pools, and at 3.0 m depth in the Tartarugas water pool (Table 5). Specimens of the *P. astreoides*

Table 1. Carbon and oxygen isotopic values (‰V-PDB) for specimens of *S. stellata* collected in 1995, 1998 and 1999. Numbers within parentheses indicate the point corresponding to the year of sampling.

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
01	01	−0.1	−2.7	26.6	28.6	1.5	Farol
	02	+0.2	−2.4	25.1	29.2		
	03	−0.1	−2.8	26.7	28.5		
	04	−0.4	−3.3	29.1	27.4		
	05	+0.2	−2.7	26.7	28.5		
	06	−0.1	−3.5	30.5	26.8		
	07	+0.5	−2.6	26.1	28.8		
	08	+0.4	−3.0	28.0	27.9		
	09	−0.1	−2.8	26.7	28.5		
	10 (1995)	−0.2	−2.9	27.4	28.2		
02	01	−0.2	−2.7	26.4	28.7	1.5	Farol
	02	+0.5	−2.7	26.2	28.8		
	03	+0.4	−2.7	26.4	28.7		
	04	+0.4	−2.8	27.1	28.3		
	05	+0.8	−2.7	26.5	28.6		
	06	+1.1	−2.6	25.9	28.9		
	07	+0.5	−2.9	27.4	28.2		
	08 (1995)	0.0	−2.8	26.7	28.5		
03	01	+1.1	−2.2	24.0	29.8	1.5	Farol
	02	+1.5	−2.3	24.6	29.5		
	03	+1.5	−2.4	24.9	29.4		
	04	+1.1	−2.6	26.0	28.8		
	05	+1.3	−2.4	25.2	29.2		
	06	+0.9	−2.6	26.1	28.8		
	07	+0.4	−2.7	26.2	28.8		
	08	+0.4	−2.7	26.2	28.7		
	09 (1995)	+0.3	−2.7	26.2	28.7		
04	01	−0.9	−4.9	36.9	23.9	2.0	Cemitério
	02	−0.3	−3.9	32.1	26.1		
	03	−0.6	−3.6	30.9	26.6		
	04	−0.4	−3.7	31.2	26.5		
	05	−1.7	−6.0	42.4	21.5		
	06	−0.6	−3.8	31.7	26.2		
	07	−0.2	−3.6	30.9	26.6		
	08	−0.3	−3.5	30.4	26.8		
	09 (1995)	+0.2	−3.3	29.5	27.2		
05	01	−0.3	−3.7	31.0	26.6	2.0	Cemitério
	02	−0.1	−3.3	29.3	27.3		
	03	−0.2	−3.3	29.5	27.2		
	04	−0.3	−3.6	30.9	26.6		
	05	−0.5	−4.0	32.8	25.7		
	06	−0.2	−3.5	30.4	26.8		
	07	−0.7	−3.5	30.2	26.9		
	08 (1995)	−0.6	−3.5	30.2	26.9		
06	01	+0.2	−2.6	25.7	29.0	2.0	Cemitério
	02	+0.4	−3.5	30.4	26.9		
	03	−0.2	−4.5	30.0	24.8		
	04 (1995)	+0.8	−3.8	31.9	26.2		

Table 1. (*Continued.*)

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
07	01	+0.1	−3.5	30.0	27.0	2.0	Cemitério
	02	+0.4	−3.4	29.5	27.2		
	03	−0.5	−2.7	26.2	28.7		
	04	0.0	−3.7	31.2	26.5		
	05	+1.4	−2.4	24.9	29.3		
	06 (1995)	+0.1	−4.3	34.1	25.2		
08	01	−2.2	−3.1	29.3	27.8	3.0	Salão
	02	−1.6	−3.3	29.1	27.4		
	03	−1.8	−3.4	29.9	27.0		
	04	−1.6	−3.4	29.8	27.1		
	05	−1.7	−3.3	29.4	27.3		
	06	−1.8	−3.4	29.9	27.1		
	07	−1.7	−3.7	31.3	26.4		
	08	−1.2	−3.2	29.0	27.5		
	09 (1995)	−1.5	−3.3	29.1	27.5		
09	01	−0.2	−2.7	26.6	28.6	3.0	Tartarugas
	02 (1995)	−0.1	−3.2	28.7	27.6		
10	01	−2.1	−3.0	27.9	28.0	3.0	Tartarugas
	02	−0.6	−2.5	25.4	29.1		
	03	−1.3	−3.3	29.1	27.4		
	04	−2.4	−3.6	30.9	26.6		
	05	+0.2	−2.5	25.6	29.0		
	06	−0.7	−3.7	31.0	26.6		
	07	−1.5	−4.7	36.2	24.3		
	08	−0.4	−3.6	30.9	26.6		
	09	−0.6	−3.3	29.4	27.3		
	10	−0.3	−3.4	29.6	27.2		
	11 (1995)	−0.8	−3.3	29.4	27.3		
11	01	+1.4	−1.8	22.2	30.6	3.0	Tartarugas
	02	−1.4	−2.4	25.0	29.3		
	03	+2.1	−2.2	23.8	29.6		
	04 (1995)	+1.9	−2.3	24.7	29.4		
12	01	+1.1	−2.7	26.3	28.7	3.0	Tartarugas
	02	+0.9	−2.5	25.3	29.2		
	03	+1.3	−2.5	25.7	29.0		
	04	+1.3	−2.4	25.0	29.3		
	05	+1.3	−2.5	25.4	29.1		
	06	+0.9	−2.8	26.9	28.4		
	07	+0.6	−2.7	26.3	28.7		
	08	+0.8	−2.9	27.6	28.1		
	09	+1.1	−2.8	26.7	28.5		
	10	+1.3	−2.6	26.1	28.8		
	11 (1995)	+0.3	−2.9	27.4	28.2		
13	01	−0.6	−2.5	25.4	29.1	3.0	Salão
	02	−1.3	−3.3	29.1	27.4		
	03	−2.4	−3.6	30.9	26.6		
	04	+0.2	−2.5	25.6	29.0		
	05 (1995)	−0.7	−3.7	31.0	26.6		

Table 1. (*Continued.*)

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	*T* (°C)	S (‰)	Depth (m)	Water pool
	01	−1.7	−2.9	27.2	28.3		
	02	−1.9	−3.3	29.5	27.2		
	03	−2.5	−3.6	30.9	26.6		
	04	−2.1	−3.7	31.4	26.4		
	05	−1.8	−3.5	30.3	26.9		
14	06	−2.1	−3.6	30.7	26.7	3.5	Salão
	07	−2.1	−3.7	31.1	26.5		
	08	−2.7	−3.6	30.9	26.6		
	09	−2.2	−3.6	30.7	30.7		
	10	−2.4	−3.6	30.6	26.7		
	11 (1995)	−2.0	−3.4	29.5	27.2		
	01	−0.3	−3.1	28.4	27.7		
	02	+0.9	−2.5	25.3	29.1		
	03	+0.4	−3.0	27.9	28.0		
15	04	+0.3	−2.7	31.3	28.6	4.0	Salão
	05	+0.1	−3.0	28.1	28.0		
	06 (1995)	+0.3	−2.7	26.6	28.6		
	01	0.0	−2.8	27.1	28.3		
	02	−0.1	−3.4	29.8	27.1		
	03	−0.2	−3.1	28.5	27.7		
16	04	−0.2	−3.1	28.5	27.7	4.0	Salão
	05	−0.5	−3.2	29.0	27.5		
	06 (1995)	−2.2	−2.5	25.5	29.1		
	01	−2.2	−3.6	30.7	26.7		
17	02	+0.9	−4.3	34.0	25.2	7.0	Salão
	03 (1995)	+0.1	−3.5	30.1	27.0		
	01	−0.9	−4.9	36.9	23.9		
	02	−0.3	−3.9	32.1	26.1		
	03	−0.6	−3.6	30.9	26.6		
	04	−0.4	−3.7	31.2	26.5		
01	05	−1.7	−6.0	42.4	21.5	2.0	Âncoras
	06	−0.6	−3.8	31.7	26.2		
	07	−0.2	−3.6	30.9	26.6		
	08	−0.3	−3.5	30.4	27.2		
	09 (1998)	+0.2	−3.3	29.5	27.2		
	01	−0.6	−3.4	29.7	27.2		
	02	−0.8	−3.7	31.4	26.4		
	03	−0.3	−3.1	28.2	27.9		
	04	−2.6	−3.4	30.0	27.0		
	05	−0.5	−3.5	30.0	27.0		
02	06	−0.7	−3.4	29.9	27.1	2.0	Âncoras
	07	−0.1	−3.1	28.1	27.9		
	08	−0.6	−3.5	30.2	26.9		
	09	−0.6	−3.6	29.8	26.7		
	10 (1998)	−0.7	−3.4	29.8	27.1		
	01	−0.3	−3.7	31.5	26.5		
	02	−0.6	−3.8	31.5	26.3		
	03	−1.9	−6.0	42.5	21.5		
03	04	−0.7	−3.7	31.3	26.4	3.0	Âncoras
	05	−0.7	−3.6	30.8	26.6		
	06	−0.4	−3.8	31.6	26.3		
	07 (1998)	−0.3	−3.4	29.9	27.1		

Table 1. (*Continued.*)

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
	01	−0.2	−3.7	31.3	26.4		
	02	−0.2	−3.3	29.4	27.3		
	03	−0.4	−3.5	30.5	26.8		
04	04	−0.9	−4.0	32.6	25.9	3.0	Âncoras
	05	−0.8	−3.7	31.4	26.4		
	06	−0.5	−3.7	31.1	26.5		
	07 (1998)	−0.4	−3.5	30.3	26.9		
	01	−0.1	−3.5	30.2	26.9		
	02	−0.5	−3.5	30.5	26.8		
	03	−0.8	−3.7	31.3	26.4		
	04	−1.1	−3.8	31.8	26.2		
01	05	−1.0	−3.8	31.5	26.4	2.0	Âncoras
	06	−1.2	−3.8	31.8	26.2		
	07	−0.3	−3.4	30.0	27.0		
	08 (1999)	−0.3	−3.4	29.6	27.2		
	01	+0.1	−3.1	28.4	27.8		
	02	−0.7	−3.5	30.0	27.0		
	03	−0.6	−3.7	31.2	26.5		
02	04	−0.7	−3.9	32.2	26.0	2.0	Âncoras
	05	−0.5	−3.3	29.3	27.3		
	06	−0.6	−3.5	30.4	26.8		
	07 (1999)	−1.0	−3.6	30.8	26.7		
	01	+0.4	−3.2	29.0	27.7		
	02	+0.1	−3.3	29.4	27.3		
	03	+0.3	−3.2	28.6	27.7		
03	04	+0.3	−3.1	28.6	27.7	2.0	Âncoras
	05	+0.3	−3.3	29.1	27.4		
	06 (1999)	−0.6	−3.4	29.8	27.1		
	01	+0.2	−3.4	29.6	27.2		
	02	+0.5	−3.1	28.2	27.8		
	03	+0.2	−3.2	28.9	27.5		
	04	+0.4	−3.3	29.5	27.2		
04	05	+1.0	−3.1	28.4	27.8	2.0	Tartarugas
	06	+1.1	−3.3	29.5	27.3		
	07	+0.6	−3.3	29.2	27.4		
	08	−0.1	−3.4	30.0	27.0		
	09 (1999)	0.0	−3.2	28.7	27.6		
	01	−0.6	−2.6	25.9	28.9		
	02	+0.3	−3.5	30.3	26.9		
	03	+0.5	−3.2	28.7	27.6		
	04	+0.5	−3.6	30.9	26.6		
	05	0.0	−3.6	30.7	26.7		
	06	−0.2	−3.6	30.8	26.7		
05	07	+0.1	−3.7	31.0	26.6	2.0	Cemitério
	08	0.0	−3.5	30.4	26.8		
	09	+1.2	−3.5	30.2	26.9		
	10	+0.1	−3.6	30.6	26.8		
	11	−0.2	−3.5	30.3	26.9		
	12	−0.7	−4.7	36.0	24.4		
	13 (1999)	−0.7	−3.7	31.2	26.5		

Table 1. (*Continued.*)

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
06	01	−0.3	−3.4	30.0	27.1	2.0	Cemitério
	02	−0.4	−3.5	30.4	26.8		
	03	−0.4	−3.6	30.5	26.8		
	04	−0.4	−3.5	30.4	26.8		
	05	−0.2	−3.6	30.8	26.7		
	06	−0.1	−3.5	30.2	26.9		
	07	0.0	−3.4	29.9	27.1		
	08	−0.2	−3.6	30.9	26.6		
	09	−0.1	−3.4	29.6	27.2		
	10 (1999)	−0.3	−3.3	29.5	27.3		
07	01	−0.2	−3.1	28.4	27.7	3.0	Tartarugas
	02	−0.1	−3.2	28.7	27.6		
	03	−0.1	−3.4	30.0	27.0		
	04	−0.4	−3.4	29.8	27.1		
	05 (1999)	−0.4	−3.1	28.6	27.7		
08	01	+0.2	−2.5	25.6	29.0	3.0	Tartarugas
	02	+0.5	−3.0	27.8	28.0		
	03	+0.3	−2.7	26.5	28.6		
	04	−0.2	−2.8	27.1	28.3		
	05	−0.1	−2.8	27.0	28.4		
	06	+0.3	−2.8	26.8	28.5		
	07	+0.2	−3.2	28.6	27.6		
	08	+0.8	−3.2	28.6	27.6		
	09	+0.3	−3.0	28.1	27.9		
	10	−0.1	−3.2	29.0	27.5		
	11	0.0	−3.2	28.8	27.6		
	12	−0.1	−3.4	29.7	27.1		
	13	0.0	−3.3	29.2	27.4		
	14	−0.1	−3.3	29.3	27.3		
	15	+0.2	−3.2	29.0	27.5		
	16	+0.5	−3.3	29.5	27.2		
	17	+0.6	−3.2	28.6	27.5		
	18	+0.5	−3.2	29.0	27.5		
	19 (1999)	+0.1	−3.3	29.2	27.4		

species were collected in the years 1998 and 1999 at 3.0 m (Table 6) in the Âncoras and Tartarugas water pools.

The collected specimens were transported in plastic containers to the Nucleus of Study of Cnidaria (NEC), of the Department of Zoology, Federal University of Pernambuco. Samples were washed with tap water, placed in 15% hydrogen peroxide to remove any organic matter, rinsed with distilled water, and left to dry at room temperature.

Carbon and oxygen isotopes of carbonate (aragonite) skeletons of specimens from these species were analysed at the Stable Isotope Laboratory (LABISE), Federal University of Pernambuco, Brazil. Carbonate samples (20–40 mg) from coral skeletons were micro-drilled in each growth band, and placed to react with anhydrous phosphoric acid for 12 hours at 25°C following the method described by McCrea (1950). CO_2 gas released from this reaction was extracted in a high vacuum line, cryogenically cleaned and analysed in a dual inlet, triple collector mass spectrometer

Table 2. Carbon and oxygen isotopic values (‰V-PDB) for specimens of *P. branneri* collected in 1995 and 1998. Numbers within parentheses indicate the point corresponding to the year of sampling.

Specimens	Analysed point	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
	01	−0.2	−3.7	31.2	26.5		
	02	−0.2	−4.3	34.3	25.1		
	03	−0.5	−4.7	36.0	24.3		
01	04	−0.1	−4.3	34.1	25.2	0.5	Cemitério
	05	−0.2	−4.1	33.3	25.5		
	06	−0.2	−4.1	33.1	25.6		
	07 (1995)	−1.1	−5.6	40.4	22.4		
	01	−0.3	−4.1	33.3	25.5		
	02	+0.1	−3.8	31.8	26.2		
02	03	−0.9	−3.9	32.3	26.0	1.0	Cemitério
	04	−0.2	−3.8	31.5	26.3		
	05	−0.2	−3.4	30.0	27.0		
	06 (1995)	−1.3	−3.7	31.0	26.5		
	01	−1.3	−3.4	29.7	27.2		
	02	−0.3	−3.6	30.5	26.8		
	03	−0.9	−3.8	31.6	26.3		
03	04	−1.4	−3.8	31.8	26.2	2.5	Cemitério
	05	−0.8	−4.1	33.3	25.5		
	06	+0.8	−3.5	30.4	26.8		
	07 (1995)	+1.2	−3.5	30.1	27.0		
	01	−1.2	−3.9	32.4	26.0		
	02	−0.1	−3.7	31.4	26.4		
	03	−0.8	−4.2	33.4	25.5		
	04	−0.5	−4.0	32.7	25.8		
01	05	−0.9	−4.2	33.5	25.5	1.0	Tartarugas
	06	−0.9	−4.2	33.8	25.3		
	07	−0.4	−4.2	33.5	25.5		
	08 (1998)	−2.1	−6.8	46.7	19.7		

(SIRA II), using an internal standard, the Borborema skarn calcite (BSC), as reference gas. Precision, based on multiple standard measurements of NBS-19, was better than 0.1‰ for carbon and oxygen, and results are expressed in the international V-PDB (Vienna Peedee Belemite) scale, after Craig's (1957) corrections.

The temperature of isotopic equilibration with seawater was estimated using $\delta^{18}O_{PDB}$ values assuming that the $\delta^{18}O$ value of seawater is zero, using Horibe and Oba's (1972) equation for aragonite. Palaeosalinity in ‰ was calculated using the equation of Craig and Gordon (1965). In this study, only bleaching due to thermal stress is evaluated, with temperature $\geqslant 30^{\circ}C$ considered as the stress temperature.

Results

The following isotopic fluctuations have been recorded in specimens of the *S. stellata* species in the year of 1995 (Figure 2): values of $\delta^{13}C$ varied from −2.2 to +1.8‰, $\delta^{18}O$ values from −4.3 to −2.3‰$_{PDB}$, and calculated temperatures from 24.7 to 34.1°C. Bleaching temperatures have been observed in five cases. The calculated palaeosalinity varies from 25.1 to 29.4‰.

Table 3. Carbon and oxygen isotopic values (‰V-PDB) for specimens of *M. hispida* collected in 1995. Numbers within parentheses indicate the point corresponding to the year of sampling.

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
01	01	−0.6	−3.7	31.1	26.5	2.0	Cemitério
	02	−0.1	−3.6	30.9	26.6		
	03	+0.4	−3.5	30.5	26.8		
	04	+0.7	−3.5	30.1	27.0		
	05	+1.4	−3.4	29.9	27.1		
	06	+1.8	−3.3	35.6	24.5		
	07 (1995)	+1.3	−3.4	29.9	27.1		
02	01	+0.4	−4.0	32.5	25.9	1.0	Cemitério
	02	+0.6	−4.2	33.5	35.8		
	03	+1.1	−3.5	30,1	26.9		
	04	+0.5	−4.0	32.6	25.9		
	05	+2.2	−3.7	31.3	26.4		
	06 (1995)	+1.8	−3.3	29.1	27.4		
03	01	+0.4	−4.6	35.8	24.4	1.0	Tartarugas
	02	+0.3	−3.9	32.4	25.9		
	03	−0.6	−4.0	32.8	25.8		
	04	−0.9	−4.6	35.5	24.6		
	05	+0.7	−3.6	30.6	26.7		
	06	+1.8	−3.4	29.8	27.1		
	07	+1.9	−3.8	31.8	26.2		
	08	+2.1	−3.9	32.4	25.9		
	09	+1.2	−4.2	33.9	25.3		
	10 (1995)	+2.1	−3.8	31.5	26.3		

Carbon and O isotope analyses along the carbonate skeletons of these specimens present $\delta^{13}C$ values varying from −2.7 to +2.1‰, $\delta^{18}O$ values from −6.0 to −1.8‰$_{PDB}$, calculated temperature from 22.2 to 42.4°C and calculated palaeosalinity from 21.5 to 30.7‰.

These data suggest that the growth of the analysed specimens did not happen under anomalous temperatures, except for three samples that display more than three records of thermal stress. Two of them were collected at 2 m depth, in the Cemitério water pool, and one sample, at 3.5 m depth, in the Salão water pool.

The following isotopic fluctuation has been recorded in the specimens of this species in the year of 1998 (Figure 2): $\delta^{13}C$ values varied from −0.6 to +0.2‰$_{PDB}$, $\delta^{18}O$ values from −3.5 to −3.3‰$_{PDB}$, calculated temperatures from 29.5 to 30.3°C and calculated palaeosalinity from 26.7 to 27.2‰. Along skeletons, $\delta^{13}C$ values of the specimens varied from −1.9 to +0.8‰$_{PDB}$, $\delta^{18}O$ values from −6.0 to −3.0‰$_{PDB}$, calculated temperatures from 28.1 to 42.5°C and calculated palaeosalinity from 21.5 to 27.8‰.

Eight specimens of the *S. stellata* species collected in 1999 at 2.0 and 3.0 m deep present the following isotopic values (Figure 2): $\delta^{13}C$ values varied from −1.0 to +0.1‰, $\delta^{18}O$ values from −3.7 to −3.1‰$_{PDB}$, calculated temperatures varied from 28.5 to 31.2°C and calculated palaeosalinity from 26.4 to 27.7‰. Carbon and O isotope analyses along the carbonate skeletons of these specimens indicate $\delta^{13}C$ values varying from −1.2 to +1.2‰, $\delta^{18}O$ values from −4.7 to −2.5‰$_{PDB}$, calculated temperature from 25.6 to 36.0°C and calculated palaeosalinity from 24.4 to 29.0‰.

Table 4. Carbon and oxygen isotopic values (‰V-PDB) for specimens of *M. decactis* collected in 1995. Numbers within parentheses indicate the point corresponding to the year of sampling.

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
01	01	−1.5	−2.0	23.3	30.1	1.0	Cemitério
	02	−2.3	−3.0	27.7	28.1		
	03	−1.9	−2.8	27.0	28.4		
	04	−1.7	−2.9	27.4	28.2		
	05	−1.6	−2.8	27.0	28.4		
	06	−1.6	−2.8	26.9	28.4		
	07	−1.8	−2.9	27.3	28.2		
	08	−1.8	−2.8	27.0	28.4		
	09 (1995)	−2.0	−2.7	26.6	28.5		
02	01	−2.1	−3.6	30.7	26.7	2.0	Tartarugas
	02	−1.9	−3.4	29.7	27.2		
	03	−1.9	−3.3	29.5	27.3		
	04	−2.5	−4.5	35.1	24.7		
	05	−3.0	−5.5	40.2	22.5		
	06	−1.7	−3.2	28.8	27.5		
	07	−1.9	−3.3	29.2	27.4		
	08	−1.9	−3.3	29.4	27.3		
	09	−2.9	−5.2	38.3	23.3		
	10	−1.1	−2.7	26.3	28.7		
	11	−1.0	−3.9	32.1	26.1		
	12 (1995)	−0.3	−2.1	23.8	29.9		
03	01	−1.6	−2.5	25.6	29.0	1.0	Cemitério
	02	−1.3	−2.5	25.3	29.2		
	03	−1.4	−2.6	26.1	28.8		
	04	−1.6	−2.7	26.6	28.5		
	05	−1.6	−3.1	28.3	27.8		
	06	−2.2	−3.4	29.7	27.1		
	07	−1.4	−2.9	27.6	28.1		
	08	−5.5	−3.1	28.6	27.7		
	09	−1.5	−3.0	27.7	28.1		
	10	−1.4	−2.9	27.5	28.1		
	11	−1.2	−2.8	26.9	28.4		
	12 (1995)	−1.3	−2.7	26.4	28.7		
04	01	−2.5	−3.0	27.7	28.0	1.5	Tartarugas
	02	−2.0	−3.2	28.8	27.6		
	03	−2.2	−3.2	28.6	27.7		
	04	−1.9	−3.0	27.7	28.1		
	05	−1.9	−2.9	27.6	28.1		
	06	−1.8	−3.0	27.7	28.0		
	07	−1.8	−3.0	27.9	28.0		
	08	−1.8	−3.0	27.7	28.1		
	09	−2.0	−3.2	29.0	27.5		
	10 (1995)	−2.5	−3.2	29.0	27.5		
05	01	−2.1	−3.7	31.3	26.4	1.5	Tartarugas
	02	−1.4	−3.4	29.9	27.1		
	03	−1.2	−3.3	29.3	27.3		
	04	−1.3	−3.2	28.8	27.6		
	05	−2.1	−3.8	31.9	26.1		
	06	−1.5	−3.1	28.1	27.9		
	07 (1995)	−1.9	−3.7	31.1	26.5		

Table 4. (*Continued.*)

Specimen	Analysed points	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
06	01	−1.9	−3.0	28.1	27.9	1.5	Tartarugas
	02	−1.4	−2.9	27.3	28.3		
	03	−1.7	−3.4	29.8	27.1		
	04	−2.0	−3.8	31.6	26.3		
	05	−2.0	−3.8	31.7	26.3		
	06	−1.7	−3.8	31.7	26.2		
	07	−1.8	−3.5	30.1	27.0		
	08 (1995)	−2.1	−3.9	32.3	26.0		
07	01	−1.8	−2.3	24.5	29.5	2.0	Tartarugas
	02	−0.9	−2.1	23.5	30.0		
	03	−1.4	−2.7	26.2	28.7		
	04	−1.3	−2.6	26.0	28.9		
	05	−1.8	−2.8	26.8	28.5		
	06	−1.8	−3.0	28.1	27.9		
	07 (1995)	−0.8	−2.3	24.7	29.4		
08	01	−1.9	−3.1	28.5	27.7	2.0	Cemitério
	02	−1.9	−3.4	29.6	27.2		
	03	−1.9	−3.1	28.4	27.7		
	04	−1.9	−3.3	29.3	27.3		
	05	−2.0	−3.4	29.8	27.1		
	06	−1.8	−3.4	29.6	27.2		
	07	−1.8	−3.2	28.9	27.5		
	08	−1.9	−3.3	29.3	27.4		
	09	−1.7	−3.3	29.2	27.4		
	10 (1995)	−2.1	−3.0	28.0	28.0		

The collected specimens of the *P. branneri* species present $\delta^{13}C$ values varying from −1.3 to +1.2‰, $\delta^{18}O$ values from −5.6 to −3.5‰$_{PDB}$, calculated temperatures from 30.1 to 40.4°C and calculated palaeosalinity from 22.4 to 27.0‰. The analyses along the carbonate skeletons of these specimens indicate $\delta^{13}C$ values varying from −1.4 to +1.2‰, $\delta^{18}O$ values from −5.6 to −3.4‰$_{PDB}$, calculated temperatures from 29.7 to 40.4°C and calculated palaeosalinity from 22.4 to 27.2‰. These data show that all specimens record anomalous calculated temperatures in the year of 1995 as recorded by the outer points of the analysed specimens (Figure 3).

The analysed specimen of the *P. branneri* species collected in 1998 at 1.0 m depth showed $\delta^{13}C$ value of −2.1 ‰$_{PDB}$ and $\delta^{18}O$ value of −6.8‰; high calculated temperature of 46.7°C and calculated palaeosalinity of 19.7‰ (Table 2). There are only two positive values among 20 analyses for specimens collected in 1995, and among 130 analyses (specimens collected in 1995, 1998 and 1999) there are only 18 positive $\delta^{13}C$ values. The values of $\delta^{13}C$ along skeletons varied from −2.1 to −0.4‰, $\delta^{18}O$ from −6.8 to −3.7‰$_{PDB}$, calculated temperatures from 31.4 to 46.7°C and calculated palaeosalinity from 19.7 to 26.4‰. All calculated temperatures along the skeletons are anomalous, suggesting that the species have grown under thermal stress.

All specimens of *P. astreoides* species recorded anomalous temperature in the year 1998 and 1999 (Table 6). The following isotopic fluctuation was recorded in these specimens for the year of 1998 (Figure 4): $\delta^{13}C$ values varied from −0.5 to −0.4‰,

Table 5. Carbon and oxygen isotopic values (‰V-PDB) for specimens of *M. cavernosa* collected in 1999. Numbers within parentheses indicate the point corresponding to the year of sampling.

Specimens	Analysed point	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
	01	−1.1	−4.8	33.7	24.1		
	02	−1.0	−4.7	34.8	24.4		
01	03	−1.1	−4.8	36.5	24.0	2.0	Âncoras
	04	−0.9	−4.7	35.8	24.3		
	05 (1999)	−1.2	−4.6	35.6	24.5		
	01	−1.0	−4.2	33.7	25.3		
	02	−1.1	−4.4	34.8	24.8		
02	03	−1.3	−4.8	36.5	24.1	2.0	Âncoras
	04	−1.2	−4.6	35.8	24.4		
	05 (1999)	−0.9	−4.2	33.4	25.5		
	01	−0.4	−4.0	32.7	25.8		
	02	−0.7	−4.3	34.2	25.1		
	03	−0.6	−4.3	34.1	25.2		
03	04	−1.2	−4.9	37.0	23.9	2.0	Âncoras
	05	−0.4	−4.2	33.9	25.3		
	06 (1999)	−1.0	−4.3	34.3	25.1		
	01	−1.6	−4.3	33.9	25.3		
	02	−1.9	−4.8	36.4	24.2		
04	03	−2.2	−4.8	36.4	24.1	2.0	Âncoras
	04	−2.2	−4.6	35.7	24.5		
	05 (1999)	−1.8	−4.5	35.2	24.7		
	01	−0.8	−4.5	35.2	24.7		
	02	−0.9	−4.3	34.2	25.1		
	03	−1.1	−4.4	34.7	24.9		
05	04	−1.0	−4.7	36.0	24.3	2.0	Tartarugas
	05	−0.7	−4.6	35.5	24.6		
	06 (1999)	−0.4	−4.3	34.3	25.1		
	01	+0.1	−3.7	31.1	26.5		
	02	−0.3	−4.0	32.7	25.8		
	03	−0.1	−4.0	32.6	25.8		
06	04	−0.2	−4.3	34.2	25.1	3.0	Tartarugas
	05	−0.8	−4.3	34.4	25.1		
	06	−1.0	−4.2	33.8	25.3		
	07 (1999)	−0.9	−4.3	34.0	25.2		
	01	−0.4	−3.8	31.7	26.2		
	02	+0.7	−4.1	33.3	25.5		
	03	−0.5	−3.9	32.4	25.9		
07	04	−0.9	−4.1	33.4	25.5	3.0	Tartarugas
	05	−1.1	−4.4	34.6	25.0		
	06	−0.9	−4.3	34.3	25.1		
	07 (1999)	−0.8	−4.3	34.3	25.1		

$\delta^{18}O$ values from −4.1 to −4.0 $‰_{PDB}$, calculated temperatures from 32.6 to 33.3°C and calculated palaeosalinity from 25.5 to 25.9$‰_{PDB}$. Along skeletons $\delta^{13}C$ values varied from −1.6 to +0.6‰, $\delta^{18}O$ values from −4.3 to −3.8$‰_{PDB}$, calculated temperatures from 31.7 to 34.1°C and calculated palaeosalinity from 25.2 to 26.3‰.

Outer points of the three specimens collected in 1999 at depth of 3.0 m (Figure 4) showed $\delta^{13}C$ values varying from −1.4 to −0.6‰, $\delta^{18}O$ values from −4.3 to

Table 6. Carbon and oxygen isotopic values (‰V-PDB) for specimens of *P. astreoides* collected in 1998 and 1999. Numbers within parentheses indicate the point corresponding to the year of sampling.

Specimens	Analysed point	$\delta^{13}C$	$\delta^{18}O$	T (°C)	S (‰)	Depth (m)	Water pool
01	01	−1.6	−3.8	31.7	26.3	3.0	Âncoras
	02	−0.4	−4.1	33.0	25.7		
	03	−0.7	−4.1	33.0	25.7		
	04	−0.8	−4.1	33.0	25.7		
	05	−0.6	−4.1	33.0	25.7		
	06 (1998)	−0.4	−4.0	32.6	25.9		
02	01	−0.1	−4.1	33.2	25.6	3.0	Âncoras
	02	−0.2	−4.0	32.6	25.8		
	03	+0.6	−4.0	32.4	25.9		
	04	+0.1	−4.2	33.6	25.4		
	05	−0.5	−4.2	33.6	25.4		
	06	−0.3	−4.1	33.2	25.6		
	07	−0.7	−4.2	33.7	25.3		
	08	−0.7	−4.2	33.8	25.3		
	09	+0.1	−4.3	34.1	25.2		
	10	−0.3	−4.2	33.7	25.4		
	11	−0.4	−4.2	33.7	25.3		
	12	−0.3	−4.2	33.4	25.5		
	13	−0.2	−4.2	33.5	25.4		
	14 (1998)	−0.5	−4.1	33.3	25.5		
01	01	−0.8	−4.0	32.8	25.8	3.0	Tartarugas
	02	−0.4	−3.9	32.1	26.1		
	03	−0.4	−4.1	33.1	33.7		
	04	−0.4	−3.9	32.0	26.1		
	05 (1999)	−1.4	−4.2	33.6	25.4		
02	01	−1.7	−3.8	31.9	26.2	3.0	Tartarugas
	02	−1.1	−4.3	34.0	25.2		
	03	−1.0	−4.4	34.6	25.0		
	04	−0.7	−4.3	34.2	25.1		
	05	−0.4	−4.2	33.5	25.4		
	06	−0.7	−4.2	33.8	25.3		
	07 (1999)	−0.6	−4.2	33.8	25.3		
03	01	−0.7	−4.2	33.6	25.4	3.0	Tartarugas
	02	−1.0	−4.3	34.3	25.1		
	03	−1.0	−4.3	34.4	25.1		
	04	−0.8	−4.4	34.5	25.0		
	05	−0.8	−4.4	34.6	25.0		
	06	−1.0	−4.2	33.8	25.3		
	07	−0.9	−4.4	34.4	25.1		
	08	−1.3	−4.3	34.1	25.2		
	09	−0.9	−4.2	33.6	25.4		
	10 (1999)	−0.9	−4.3	34.0	25.2		

−4.2‰$_{PDB}$, calculated temperatures from 33.6 to 34.0°C and calculated paleosalinity from 25.2 to 25.4‰$_{PDB}$. Along skeletons $\delta^{13}C$ values varied from −1.7 to −0.4‰, $\delta^{18}O$ values from −4.4 to −3.8‰$_{PDB}$, calculated temperatures from 31.9 to 34.6°C and calculated palaeosalinity from 25.0 to 33.7‰.

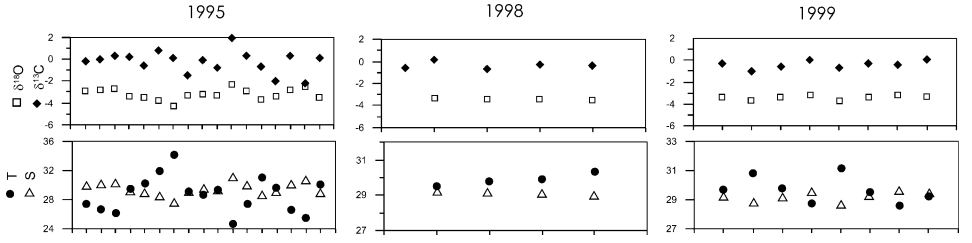

Figure 2. C and O isotopes (‰PDB), temperature (°C) and salinity (‰) variations for specimens of *S. stellata* species collected in 1995, 1998 and 1999.

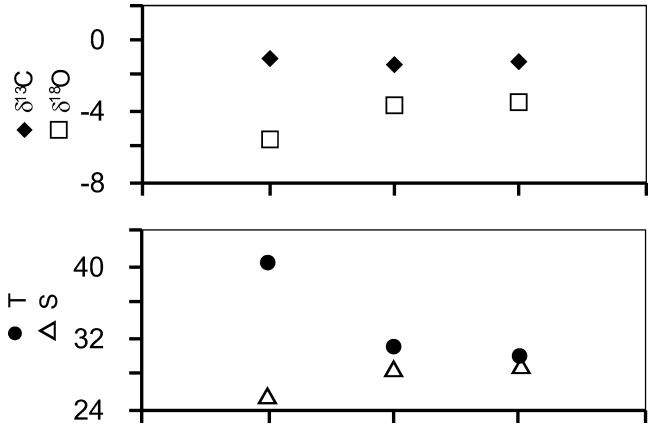

Figure 3. C and O isotopes (‰PDB), temperature (°C) and salinity (‰) variations for specimens of *P. branneri* species collected in 1995.

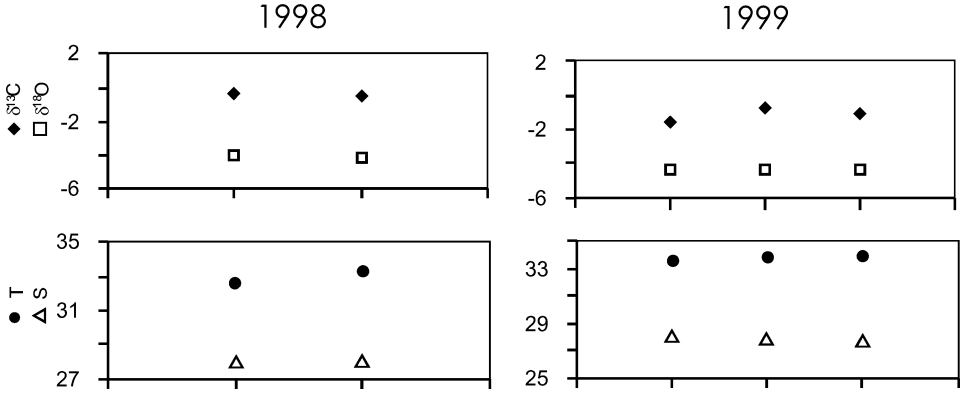

Figure 4. C and O isotopes (‰PDB), temperature (°C) and salinity (‰) variations for specimens of *P. astreoides* species collected in 1998 and 1999.

The specimens of the *M. hispida* species collected in 1995 (Figure 5) showed mostly positive $\delta^{13}C$ values varying from +1.3 to +2.1‰, $\delta^{18}O$ values from −3.8 to −3.3‰$_{PDB}$, calculated temperatures from 29.1 to 31.5°C and calculated palaeosalinity from 26.3 to 27.4‰. Along the skeletons of the three analysed specimens $\delta^{13}C$

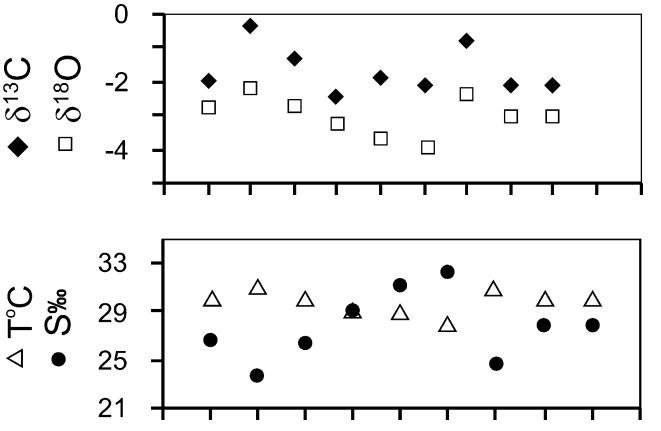

Figure 5. C and O isotopes (‰PDB), temperature (°C) and salinity (‰) variations for specimens of *M. hispida* species collected in 1995.

values varied from −0.9 to +2.2‰, $\delta^{18}O$ values from −4.6 to −3.3‰$_{PDB}$, calculated temperatures from 29.1 to 35.8°C and calculated palaeosalinity from 24.4 to 35.8‰.

The outer points of the analysed specimens of the *M. decactis* species show negative $\delta^{13}C$ values varying from −2.5 to −0.3‰, $\delta^{18}O$ values from −3.9 to −2.2‰$_{PDB}$, calculated temperatures from 23.8 to 32.3°C and calculated palaeosalinity from 26.0 to 29.9‰ (Figure 6). Along skeletons $\delta^{13}C$ values varied from −5.5 to −0.3‰, $\delta^{18}O$ values from −5.5 to −2.0‰$_{PDB}$, calculated temperatures from 23.3 to 40.2°C and calculated palaeosalinity from 22.5 to 30.1‰.

The outer bands of the analysed *M. cavernosa* species collected in 1999 (Figure 7) recorded $\delta^{13}C$ values varying from −1.8 to −0.4‰, $\delta^{18}O$ values from −4.6 to −4.2‰$_{PDB}$, calculated temperatures are all high, from 33.4 to 35.6°C and calculated palaeosalinity from 24.5 to 25.5‰. Along skeletons $\delta^{13}C$ values varied from −2.2 to +0.7‰, $\delta^{18}O$ values from −4.9 to −3.7‰$_{PDB}$, calculated temperatures from 31.1 to 37.0°C and calculated palaeosalinity from 23.9 to 26.5‰.

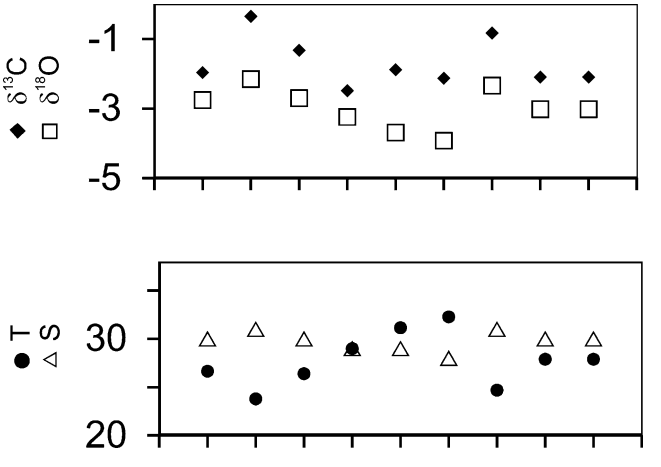

Figure 6. C and O isotopes (‰PDB), temperature (°C) and salinity (‰) variations for specimens of *M. decactis* species collected in 1995.

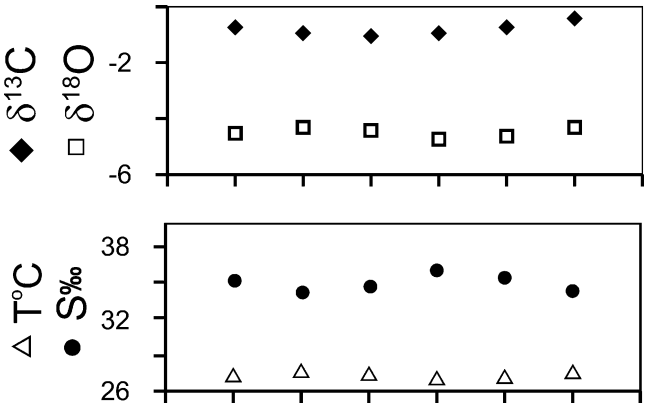

Figure 7. C and O isotopes (‰PDB), temperature (°C) and salinity (‰) variations for specimens of *M. cavernosa* species sampled in 1998.

Discussion and conclusions

The isotope data generated in this study show no systematic co-variation between C and O isotope values and, therefore, these isotope values are near-primary values. Specimens of the *S. stellata* species collected at 1.5 m depth at the Farol water pool have not recorded thermal stress. This water pool is located facing the open sea, and has a large communication with the external portion, of the atoll. On the other hand, specimens collected in the Cemitério water pool at 2 and 3 m depths have recorded bleaching calculated temperatures. This is a large, relatively shallow water pool, with depths around 2 m, occasionally up to 3 m. It is possible that this water pool has been subjected to warming temperatures, concomitantly to the ENSO phenomenon, which can explain the higher temperature records.

Specimens collected at the Tartarugas water pool, at 3 m depth, have not recorded bleaching temperatures. This is a large water pool with depths up to 5 m. The six specimens collected at the Salão water pool, at depths of 3.0, 3.5, 4.5 and 7.0 m, have not recorded stress calculated temperatures except for two specimens collected at 3 and 7 m depths. The Salão is a deeper water pool, located at the margin of the atoll ring and can reach, at some points, depths of 12 m. The communication with the external portion of the atoll is kept open all the time and characterized by turbulent water.

The endemic *S. stellata* species was the one for which the largest number of isotopic analyses have been performed. Among 17 analysed specimens of the *S. stellata* species, five recorded calculated temperatures >29°C, and only one was significant (34.1°C), for a sample collected at the Cemitério water pool. At this place, the water pool is rather shallow and this result should be interpreted with caution. It is worth mentioning that specimens of the *S. stellata* collected at 3 m depth at the Tartaruga water pool have not recorded anomalous temperatures, but at depths of 1. 5m *M. decactis* species revealed temperatures of stress.

Thermal stress has been recorded in growth bands of specimens collected in 1995 at 3 and 7 m depths at the Salão water pool. However, between 3 and 7 m depths, no thermal anomaly (>29°C) was observed. This picture probably resulted from thermal stratification in this water pool that is subjected to the inflow from the open sea of lower temperature water current than that prevailing near the surface of the water pool. This cautions us on the use of corals in determining thermal anomaly

regimes when specimens are collected in open-water pools such as the Salão. The oxygen isotope data available for this Brazilian species is still very limited. The only available data are found in Azevedo *et al.* (1992) and Ferreira *et al.* (1998) and therefore, any further statement about the behaviour of oxygen isotopes in this species cannot be made.

The *P. branneri* species present, at the Cemitério water pool, stress temperatures; the *M. decactis* species on the other hand have not recorded stress temperatures at this water pool.

The studied species *P. branneri* recorded a temperature of 46.7°C in this year, while the species *P. astreoides* recorded a temperature of 32 and 33°C. Records of temperature of the species *M. cavernosa*, 33–35°C, indicate that in 1999 the temperature in the atoll was still very high, although in this year corals have already begun to recover.

According to Glynn (1993), corals which show great sensitivity to an increase in water temperature present a great number of bleached colonies worldwide. Differences of tolerance to bleaching among species can be due to the environment in the tissues of the coral. Done (1999) suggests that some species may present tolerance, and it may be assumed that the coral and another symbiotic organism may be acclimatized in the exchange of saturated aragonite and in SST, and exchange with communities of the reef, and so this tolerance must be genetic. The most tolerant species should little by little take the place of the species most susceptible to temperature fluctuations.

The present investigation leads to the following conclusions:

(1) The *S. stellata* and *M. decactis* species demonstrated that they are not able to keep the original thermal fluctuation record during growth, while the species *P.branneri*, *P. astreoides*, *M. cavernosa* and the Brazilian endemic *M. hispida* seem to be those that better register temperature variation during growth.

(2) Different coral species collected from the same place (e.g. water pools in the ring of the atoll) may yield divergent temperature records. Specimens of a single species collected at the same period in the same site may yield different temperatures. This implies in that in some coral species, aragonite may not precipitate in isotopic equilibrium with seawater, or that in some species, oxygen isotopes are susceptible to further isotopic re-equilibrium.

(3) One could assume that dry micro-drilling of samples could possibly lead to mineralogical inversion (aragonite to calcite) presumably due to sample heating localized at the drill tip. This would imply a measurable isotopic change as pointed out by Gill *et al.* (1995) and that the system must be open to atmospheric exchange during the inversion process. However, the possibility of inversion and open system is discarded here by the fact that shifts in the oxygen isotopic ratios are not consistent. Therefore, changes due to micro-drilling, if any, might have been minor.

(4) Our data indicate that the stress registered in the atoll corals was due to the phenomenon called the El Niño Southern-Oscillation (ENSO).

These data show the importance of investigating which coral species actually have aragonite precipitated in isotopic equilibrium with seawater and keeps its original isotope record. There is no obvious correlation between bleaching temperatures recorded in some of the studied coral specimens and C isotope behaviour. The

specimens that present stress temperature and consequently lower $\delta^{13}C$ attest to a low productivity by zooxanthella. However, there is such a correlation in the *Porites* genus, which is used by palaeoclimatologists from the USA and France, among other countries, as temperature proxies (e.g. Urban *et al.* 2000).

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