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Density banding pattern of the south western Atlantic coral *Mussismilia braziliensis*

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ABSTRACT

The South Atlantic Ocean is a region that lacks data regarding the long-term monitoring of oceanographic parameters. In addition, proxy indicators in this region are not yet well established. We evaluate the density-banding pattern of the coral *Mussismilia braziliensis* to calibrate it for use as a proxy of paleoceanographic parameters, such as temperature and light availability. Colonies of the coral were stained with alizarin red in the field and in an aquarium system to determine the periodicity and cyclicity of the skeletal density banding and to determine whether this coral species presents banding pattern characteristics useful as an environmental proxy. The results show that *M. braziliensis* forms annual density bands in nature that comprise a pair of high- and low-density bands (light and dark bands, respectively, in negative X-radiography). Furthermore, *M. braziliensis* forms high-density bands starting from October to November, when the average monthly temperature is between 25 °C and 25.5 °C, and low-density bands starting from May, when temperature is around 26.5 °C and 26 °C. In a time series (1997 to 2005) of *M. braziliensis* growth observed in core slabs and collected in Abrolhos, no significant difference in the widths of the low and high density bands was observed, although clear asymmetry was observed in the temperature seasonality. Thus, the resultant linear extension rate is lower during the warming period comparing with the cooling period. However, colonies of this species that were maintained for one year in a closed aquarium system at a constant temperature of 26 °C ± 0.2 °C and 12 h of illumination also formed a new and complete density cycle despite the absence of seasonality in temperature and photoperiod during the experiment. This result implies that the primary cue for density banding is endogenous, possibly the reproductive cycle, and that temperature plays a secondary role in fine-tuning the banding cycle. Thus, we conclude that this species can be used as an archive for environmental parameters. On the other hand, it can be used to evaluate environmental impacts induced by human action and/or by global climatic changes on the growth of corals in recent decades and centuries along the coast and the continental shelf of the tropical western Atlantic Ocean.

1. Introduction

The South Atlantic Ocean lacks an extensive oceanographic data time series. A database compiled by the Brazilian Navy and the National Meteorological Institute contains sea surface temperature records that date back to the 1970s and atmospheric data such as air temperature, rainfall and wind speeds along the coastline that date back only to the 1940s. In this scenario, paleoceanographic data based on proxies play an important role in reconstructing and modeling ocean and atmospheric dynamics. However, paleoceanographic records are also scarce, with the exception of data obtained by Druffel (1996) on the corals *Montastraea cavernosa* and *Mussismilia braziliensis* that provided archives of ^{14}C data. In addition to *M. cavernosa* and *M. braziliensis*, the coral *Siderastrea stellata* also has good potential for use in creating regional archives. *M. braziliensis* and *S. stellata* colonies can grow more than one meter high, and the length of time represented can be up to 150 and 300 years, respectively, based on the linear growth rate. *M. braziliensis*, despite its confinement south of the São Francisco river (approximately 10°30′S), occurs on the reefs of the Eastern Brazilian continental shelf along a distance of more than 1000 km. In the Abrolhos region (approximately 17°S to 19°20′S), this coral is the main builder of the shallower parts of the reefs, forming colonies that may reach a diameter of more than 1 m (Kikuchi et al., 2003); these colonies exhibit density banding that suggests an average growth rate of 8 mm per year (Leão, 1982).

Since Knutson et al. (1972) confirmed for the first time that the skeletons of massive corals are characterized by an annual density band pattern that is visible in negative images of X-rays, where light bands (high density) and dark bands (low density) represent coral growth during one year, several other authors have shown that other massive corals from various regions of the world exhibit similar annual banding growth patterns (Barnes and Devereux, 1988;

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Buddemeier et al., 1974; Hudson et al., 1976; Lough and Barnes, 1990). However, the period of band density formation varies, frequently depending on the geographic region (Carricart-Ganivet et al., 2000; Highsmith, 1979; Lough and Barnes, 1990). For example, *Mostrastrea annularis* forms high-density bands during summer (Leder et al., 1991; Mendes, 2004), fall (Carricart-Ganivet et al., 2000) and winter (Goreau, 1977) in regions of the Caribbean Sea. Other corals, such as species of *Porites*, evaluated in the Great Barrier Reef, Australia, generally form high-density bands during summer (Isdale, 1977, 1984; Weber et al., 1975), although it has been reported that species of this genera form high-density bands in winter in West Australia (Lough and Barnes, 1990; Schneider and Smith, 1982).

These bands, which are formed in the calcareous skeletons of corals, also yield information concerning the strategy of skeletal growth and the climate of past decades and centuries (Carricart-Ganivet and Merino, 2001; Knutson et al., 1972; Lough and Barnes, 1997). Furthermore, these bands yield information on the development of long-living corals and coral reefs, allowing for the identification and discrimination of natural environmental variability from non-natural environmental changes (Bessat and Buigues, 2001; Lough and Barnes, 1997).

Most papers to date that address density banding formation have focused on the exogenous control of the thickening of the skeletal microstructure and have indicated that temperature and light are primary cues; however, nutrient availability, turbidity, sedimentation and wind stress have also been invoked as contributory factors (Barnes and Lough, 1993). Klein and Loya (1991) similarly noted that temperature and light are the main environmental factors controlling coral density banding. Furthermore, they noted that endogenous processes such as reproduction may be of relatively little importance. However, Wellington and Glynn (1983) interpret that banding in corals is a complex phenomenon that is governed by endogenous processes (e.g., the reallocation of energy from growth to reproduction), which may be mediated by exogenous factors (e.g., light and productivity), and that temperature plays a secondary role.

The purpose of the present study is to evaluate the density-banding pattern of the coral *M. braziliensis*. Specifically, we evaluated the cyclicity and seasonality of the banding, and the extent to which density and extension are directly related to water temperature. Our confirmation of an annual pattern of the density banding in *M. braziliensis* supports the use of this species as a natural archive of environmental parameters, thus filling the lack of high-resolution paleoceanographic archives in an ocean region where this type of data indicator has not been adequately studied. Coral growth characteristics, such as linear extension rates, skeletal density and calcification rates, are receiving increased attention from the scientific community because of the potential information they can provide regarding ocean acidification processes (Lough and Cooper, 2011). Thus, the study of coral growth through its density-banding pattern can also be an important approach to understanding the calcification potential of the southern Atlantic Ocean.

2. Materials and methods

2.1. Alizarin staining in the field

Three colonies of the coral *M. braziliensis* growing in the reefs of the Abrolhos Archipelago (Fig. 1), located approximately 70 km from the coast, at a depth of 5 m measuring approximately 25 cm in diameter were stained with alizarin red. Each colony was enveloped by a 1 m × 0.6 m plastic bag attached to the substrate. The bag contained a 10 mg/l solution of sodium alizarin and enclosed the colonies over a period of 24 h. This procedure was repeated for three days in December 2003, October 2004 and May 2005 (Table 1). A fourth colony was stained and cores were collected from the center of the first three colonies in May 2005. Each core measured approximately 5 cm in length by 5 cm in width. The fourth colony was collected in April 2006. In the laboratory, live coral tissue was removed from the collected samples using a Water-Pik.

2.2. Alizarin staining in the aquarium system

Six *M. braziliensis* colonies were collected in October 2005 from the coral reefs surrounding the island of Tinharé (Fig. 1) and transferred to the Coral Reef Studies Laboratory of the Institute of Geosciences at the Federal University of Bahia (IGEO–UFBA). The colonies were transferred to 15-l tanks in a closed aquarium system and stained with alizarin red (20 mg/l) for 30 h. After this period, the colonies were maintained for one year in a 430-l aquarium system under controlled physico-chemical conditions with the use of a skimmer, partial change of the water (15% of the total aquarium water volume) and addition of *kalkwasser*. The temperature was stable at 26 °C ± 0.2 °C, and the salinity was 35 PSU, in accordance with the descriptions given in Oliveira (2002) and Oliveira et al. (2008). Phosphate (PO_4) was held under 0.2 ppm, nitrite (NO_2^-) at zero and nitrate (NO_3^-) less than 2.5 ppm. The value of pH varied between 8.2 and 8.4, dissolved oxygen (DO) between 7.5 and 8.0 ppm, alkalinity at 2.8 meq/L, and calcium (Ca^{+2}) at 400 ppm. Water density was constant at 1022 kg/m^3.

The aquarium light system comprised HQI (metal halide) -type lamps (150 W, 10,000 K) and *Coralife*™ fluorescent blue (actinic blue — 03) and white tube lamps (40 W, 20,000 K), which were controlled by timers that maintained the colonies under a photoperiod regime of 12 hour light and 12 hour darkness during the entire period the corals remained in the aquarium.

2.3. Analysis of band density using X-radiographs

The coral cores collected in Abrolhos and the colonies sampled from the Tinharé reefs were cut along the growth axis in their central part using a rock saw into 1.5-cm-thick slabs. These slabs were X-rayed using the following settings: a) voltage acceleration of 50 kV and amperage of 320 mA, b) exposure time of 3.2 s and c) distance from the equipment to the cores or height from the object of 108 cm. Images were obtained from the slabs using FUJI HR-REGULAR 2 film, which was developed chemically. The positions of the alizarin staining were marked on the X-rays later. Overlaying digitized images of the stained core slabs with the corresponding X-ray images allowed us to evaluate the relationship between the stained horizons and the density bands.

The density banding was analyzed using Coral XDS software (Helmle et al., 2002) along three transects of the growth axis in each X-radiography image; this method provided the linear extension of the coral bands and the relative position of the stain line in the density graph. The limit of each band in the optical density graph was drawn using the half-range technique.

2.4. Sea surface water temperature

Sea temperature data were obtained from the National Oceanographic Database (BNDO) collected by the Directorate of Hydrography and Navigation (DHN) of the Brazilian Navy. Daily temperatures measured at 9:00 a.m. local time were used to calculate monthly averages from January 1998 to April 2001. Data for the period from March to December of 2000 were not available. From October 2004 to January 2006, a HOBO™ temperature logger was deployed at a depth of 4 m in the Abrolhos Archipelago to record water temperatures at 30-minute intervals. The values obtained at 9:00 a.m. in this series were used to calculate the monthly average water temperatures.

The data from May 2001 to September 2004 present a bias. To resolve this void in the data, we used the average daily air temperature