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Microstructural variation in oxygen isotopes and elemental calcium ratios in the coral skeleton of *Orbicella annularis*

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ABSTRACT

Corals have long been used as proxies for changes in the seawater environment. However, the existence of trace element and isotopic inconsistencies between different coral species and within different architectural elements of the same species grown simultaneously suggests that factors besides seawater temperature and its chemical composition contribute to coral geochemical records. Secondary Ion Mass Spectrometry (SIMS) analysis was conducted on the reef building coral *Orbicella annularis* from the Veracruz Reef System, in the Southern Gulf of Mexico in order to investigate variability in oxygen isotopes ($\delta^{18}O$) and elemental calcium ratios between the different architectural structures of this coral. The microstructures of *Orbicella* include thecae walls, septa, costae, exothecal dissepiments (ExDs), and endothecal dissepiments (EnDs). SIMS data showed that EnDs are isotopically heavier by 0.7‰ than other simultaneously grown structures. The elemental heterogeneity between architectural structures was observed by LA-ICP-MS: EnDs were found to become depleted in Mg/Ca, B/Ca and enriched in Ba/Ca, U/Ca relative to thecae. Elemental and isotopic spot profiles (with a 6.5 mm long sampling path) in the coral growth direction yielded weekly time resolution and demonstrated that factors other than temperature — including aragonite growth rate and modification of calcifying fluid chemistry — also affect elemental and isotopic ratios in corallite aragonite.

1. Introduction

Our understanding of climate change and oceanographic variability through time is largely derived from knowledge of oxygen isotopes ($\delta^{18}O$) (e.g. Fairbanks, 1979; Weil et al., 1981; Cole and Fairbanks, 1990; Leder et al., 1996; Wellington et al., 1996). Ratios of trace elements compared with calcium in coral skeletons have also been explored as potential paleothermometers (e.g. Weber, 1973; Smith et al., 1979; Beck et al., 1997; Wei et al., 2000; Cardinal et al., 2001; Watanabe et al., 2001; Quinn and Sampson, 2002; Cohen et al., 2004; Allison and Finch, 2007). However, the use of coral chemistry as a proxy for temperature has been complicated by inconsistencies between different temperature calibrations and temperature-independent heterogeneities of individual specimens (e.g. Land et al., 1975; Leder et al., 1996; Watanabe et al., 2002; Corrège, 2006; Giry et al., 2010; Gagan et al., 2012; DeLong et al., 2013; Sadler et al., 2014).

The complex microstructure of *Orbicella annularis* (previously known as *Montastraea annularis*) is formed by a few morphologically different units (architectural structures): thecae wall, septa, costae, exothecal dissepiments (ExDs), and endothecal dissepiments (EnDs) (Figs. 1–3). Detailed descriptions of the coral architecture are presented in Dávalos-Dehullu et al. (2008). The thecae are the vertical walls in which the coral polyps live. The septa are the vertical structures located between thecae walls. Costae are the bumps on the coral surface surrounding the entrance to the thecae where the polyp extrudes (i.e. extensions of septa outside of the thecae). The exothecal dissepiments (ExDs) are horizontal plates that connect one thecal wall to the thecal wall of an adjacent coral polyp. Endothecal dissepiments (EnDs) are horizontal plates the polyp builds under itself. In addition to differences in the position and orientation, it was suggested for *Orbicella* species that the formation of dissepiments is linked to lunar cycles (Dávalos-Dehullu et al., 2008).

Several studies have demonstrated isotopic heterogeneity in simultaneously grown aragonite from corallites. Leder et al. (1996) reported a stronger $\delta^{18}O$ response to temperature in thecal regions than in endothecal regions, which represents the mixture of different architectural structures of *O. annularis*. This temperature dependence caused a number of studies to conduct sampling along the thecal wall to avoid geochemical signals from endothecal regions (Swart et al., 2002; Smith et al., 2006; DeLong et al., 2011; Flannery and Poore, 2013). In most studies the difference between ExDs and EnDs was not specified. For example, Watanabe et al. (2002) observed differences in $\delta^{18}O$ between vertical (theca) and horizontal (dissepiment) structures in *Orbicella faveolata* and concluded that thecae are the most suitable structure for

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Low calcification rates and calcium carbonate production in *Porites panamensis* at its northernmost geographic distribution

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Abstract

Porites panamensis is a hermatypic coral present in the eastern Pacific Ocean. Skeletal growth parameters have been reported, but studies of the relationship between annual calcification rates and environmental controls are scarce. In this study, we investigated three aspects of the annual calcification rates of *P. panamensis*: growth parameters among three *P. panamensis* populations; the sea surface temperature as a calcification rate control spanning a latitudinal gradient; and calcium carbonate production among three sites. Growth parameters varied among the sites due to the colony growth form. Massive colonies in the north showed a higher calcification rate than encrusting colonies in the south (mean: 1.22–0.49 g $CaCO_3 \cdot cm^{-2} \cdot yr^{-1}$), where variations in calcification rates were related to growth rate (0.91–0.38 $cm \cdot yr^{-1}$) rather than to skeletal density differences (overall mean $\pm$ SD, 1.31 $\pm$ 0.04 g $CaCO_3 \cdot cm^{-3}$). Our results showed a positive linear relationship between annual calcification rates and sea surface temperatures within these *P. panamensis* populations. Differences were related to distinct oceanographic environments (within and at the entrance of the Gulf of California) with different sea surface temperature regimes and other chemical properties. Different populations calcified under different environmental conditions. Calcium carbonate production was dependent upon the calcification rate and coral cover and so carbonate production was higher in the north (coral cover 12%) than in the south (coral cover 3.5). Thus, the studied sites showed low calcium carbonate production (0.25–0.43 kg $CaCO_3 \cdot m^{-2} \cdot yr^{-1}$). Our results showed reduced calcification rates, regional temperature regime control over calcification rates, different growth forms, low coral cover and low calcium carbonate production rates in *P. panamensis*.

Introduction

Coral reefs provide goods and environmental services worth close to US$352 billion per ha annually and are valuable ecosystems (Costanza *et al.* 1998; de Groot *et al.* 2012). Coral reefs are highly diverse bioconstructions based on coral calcification. Hermatypic corals precipitate $CaCO_3$ through an organic matrix and chemical mediation

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Veracruz Reef System: a hermatypic coral community thriving in a sedimentary terrigenous environment

Guillermo Horta-Puga [1], José Luis Tello-Musi [2], Aurora Beltrán-Torres [3], Juan Pablo Carricart-Ganivet [4], José D. Carriquiry [5], Julio Villaescusa-Celaya [5]

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Abstract

In the Veracruz Reef System (VRS) general average of living coral cover and density are 19.1% and 1.0 col m-1. The dominant coral species, in terms of absolute reef bottom cover are: *Colpophyllia natans, Orbicella faveolata, Montastraea cavernosa, Pseudodiploria* spp., *Siderastrea siderea*, and *S. radians*. The community structure is different between western tropical Atlantic reefs and the VRS, which could be explained as a consequence of the differential effect on the performance of corals that thrive in the highly turbid environment of the VRS. Coral recruits density is low (2.6 Rec m^{-2}), which compromise the recovery of the coral community after natural and/or anthropogenic disturbances. The live coral cover has declined from ~33% in the 1960s to ~19% in the late 1980s, since then it has remained in a steady state (~20%).
Key words: Gulf of Mexico, coral reef, turbid environments.

Resumen

En el Sistema Arrecifal Veracruzano (SAV), la cobertura y densidad general promedio de coral vivo es 19.1% and 1.0 col m-1. Las especies dominantes en términos de cobertura absoluta del fondo arrecifal son: Colpo-

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Differences in Growth and Calcification Rates in the Reef-Building Coral *Porites lobata*: The Implications of Morphotype and Gender on Coral Growth

José de Jesús A. Tortolero-Langarica[1,2], *Amílcar L. Cupul-Magaña*[2], *Juan. P. Carricart-Ganivet*[3], *Anderson B. Mayfield*[4] and *Alma P. Rodríguez-Troncoso*[2]*

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Corals display different growth forms as an adaptive response to both local and global environmental conditions. Despite the importance of morphologic variability on corals, growth and calcification rates of different coral morphotypes have been poorly recorded in the Eastern Pacific. The purpose of this study was to compare annual extension rate (cm yr^{-1}), skeletal density (g cm^{-3}), calcification rate (g cm^{-2} yr^{-1}), and tissue thickness (mm) of males and females colonies in three different morphotypes of the common reef-building coral *Porites lobata*; columnar, massive, and free-living (corallith) forms. The results show significant differences in all four-growth parameters between morphotypes over a 6-year interval, and also differences between males and females in most morphotypes. Massive colonies presented 15–33% faster annual rates compared with columnar and free-living. Male colonies showed 30–40% faster annual rates than females for both columnar and corallith morphologies. These data exhibit the extensive plasticity of this species and highlight the fact that each morphotype × gender group produced a different physiological response to environmental conditions. Therefore, these information reveal that *P. lobata* from the Eastern Tropical Pacific develops different morphologies to allow it to maintain coral species population, characteristics that enhance the species possibility to further its distribution across the reef-framework.

Keywords: coral morphology, gender growth rates, Eastern Tropical Pacific, massive corals, coral calcification

INTRODUCTION

Morpho-plasticity in colony structure is an adaptive strategy upon which some coral species rely to take advantage of changes in their environment (Foster, 1979; Muko et al., 2000; Smith et al., 2007; Todd, 2008; Forsman et al., 2009). Hermatypic corals can adopt branching, massive, encrusting, columnar, laminar, foliaceous, nodular, and free-living (corallith) forms (Veron, 2000). However, morphologic variation may be present within not only a single species, but even within a single colony; such phenomena are typically in response to local environmental conditions, which

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Skeletal extension, density and calcification rates of massive free-living coral *Porites lobata* Dana, 1846

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ABSTRACT

Hermatypic corals are an important sessile group in the benthic structure of tropical coral reef communities. Many organisms, in response to the environmental conditions, have developed different strategies of growth by modifying their morphologies and reproduction mode, as is the case of free-living colonies called coralliths. So far, important parameters such as calcification, growth rates and their relation with biotic and abiotic factors on coralliths have not been described. This study represents the first record of a corallith form of *Porites lobata* and provides information on its sclerochronology. Coral growth parameters of different coralliths were compared by measuring extension rate (cm y^{-1}), skeletal density (g cm^{-3}), calcification rate (g cm^{-2} y^{-1}), average age (yr) and sphericity (S). The influence of the environment on corallith growth was assessed using water temperature as an abiotic factor and bioturbation by fish as a biotic factor. Analysis of annual density bands using X-ray densitometry provided a mean extension rate of 0.47 ± 0.23 cm y^{-1}, skeletal density of 1.08 ± 0.14 g cm^{-3}, and calcification rate of 0.51 ± 0.26 g cm^{-2} y^{-1}. The results reveal differences in growth parameters between coralliths including a strong relationship of calcification rate with seawater temperature. In addition, direct and indirect bioturbations promoted the colony rotation resulting in a hemispherical form. Hence, the evidence suggests that scleractinian corals have developed an important growth strategy that allows the species to form new colonies and maintain successful coral reef communities through free-living corallith growth.

1. Introduction

Scleractinian corals grow as hard structured colonies with different forms and shapes depending on species and the environment (Grigg, 2006; Sheppard et al., 2009). At the community level, they determine the benthic substrata and complexity of the coral ecosystem. Factors such as environmental conditions, substrate availability, competition between groups and other local characteristics determine the different growth strategies which help the organism to survive successfully (Rodríguez-Martínez and Jordán-Dahlgren, 1999; Smith et al., 2007; Sheppard et al., 2009; Sorauf, 2010).

Coral growth (= Shape) is represented by branched, massive, encrusting, columnar, laminar, foliaceous and free-living forms or "coralliths" (Veron, 2000). Free-living (i.e., unattached) corals are less common, characterized by low diversity and abundance, and have been infrequently studied to date. Consequently their importance and contribution to coral reef communities is poorly known (Latypov, 2007). Free-living corals can disperse over small scales and, in turn, can colonize new spaces close to the main coral reef framework (Glynn, 1974; Scoffin et al., 1985; Roff, 2008).

Coralliths result from asexual fragmentation produced by fish erosion (Cortés, 1997), and "gemmae" fragmentation, a reproduction mode where single or groups of polyps detach from the parent colony, known as polyp bail out (Sammarco, 1982; Weil et al., 2000). The small fragments and polyps settle on small, unstable substrates such as coralline algae, shells, dead corals, and rocks and then form a new colony that develops into spherical, radial or globular shapes; such corals are commonly called "rolling stones" (Glynn, 1974; Harrison, 2011). This spherical shape results in the colonies being unattached and consequently, the colonies are subject to constant movement, stress and partial tissue death which are not optimal conditions. Thus they are relatively inconspicuous and uncommon in benthic communities (Fig. 1) (Kissling, 1973; Glynn, 1974; Scoffin et al., 1985; Sorauf and Harries, 2009). As a consequence of their instability, local environmental conditions such as currents, tides, waves and bioturbation produces and intensifies a direct factor that may have a positive effect on promoting their hemispheric growth, or it may have a negative effect of causing partial or total mortality (Glynn, 1974; Lewis, 1989; Sorauf and Harries, 2009).

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Calcification and growth rate recovery of the reef-building *Pocillopora* species in the northeast tropical Pacific following an ENSO disturbance

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ABSTRACT

Pocilloporids are one of the major reef-building corals in the eastern tropical Pacific (ETP) and also the most affected by thermal stress events, mainly those associated with El Niño/Southern Oscillation (ENSO) periods. To date, coral growth parameters have been poorly reported in *Pocillopora* species in the northeastern region of the tropical Pacific. Monthly and annual growth rates of the three most abundant morphospecies (*P. cf. verrucosa*, *P. cf. capitata*, and *P. cf. damicornis*) were evaluated during two annual periods at a site on the Pacific coast of Mexico. The first annual period, 2010–2011 was considered a strong ENSO/La Niña period with cool sea surface temperatures, then followed by a non-ENSO period in 2012–2013. The linear extension rate, skeletal density, and calcification rate averaged (±SD) were 2.31 ± 0.11 cm yr^{-1}, 1.65 ± 0.18 g cm^{-3}, 5.03 ± 0.84 g cm^{-2} yr^{-1} respectively, during the strong ENSO event. In contrast, the respective non-ENSO values were 3.50 ± 0.64 cm yr^{-1}, 1.70 ± 0.18 g cm^{-3}, and 6.02 ± 1.36 g cm^{-2} yr^{-1}. This corresponds to 52% and 20% faster linear extension and calcification rates, respectively, during non-ENSO period. The evidence suggests that *Pocillopora* branching species responded positively with faster growth rates following thermal anomalies, which allow them to maintain coral communities in the region.

Subjects Environmental Sciences, Marine Biology

Keywords Coral density, Thermal stress, Extension rate, Annual calcification, Central Mexican Pacific

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INTRODUCTION

Coral growth is the key factor to building reef with calcareous hard structures that provide direct and indirect habitats for marine species and consequently maintain the growth (accretion) and structure of coral reef ecosystems (*Hubbard, Miller & Scaturo, 1990*; *Guzmán & Cortés, 1993*; *Sheppard, Davy & Pilling, 2010*). Despite the importance of coral growth, in the last decades calcification rate have been declining due to different threats including anthropogenic and natural factors (*Kleypas, McManus & Menez, 1999*;

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Historical insights on growth rates of the reef-building corals *Pavona gigantea* and *Porites panamensis* from the Northeastern tropical Pacific

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ABSTRACT

Historical coral growth assessed by sclerochronology records provides an environmental retrospective and future perspective on the maintenance of coral-reef ecosystems. Three growth parameters, extension rate, skeletal density, and calcification rate were evaluated over the past two decade's interval (1988–2013) in different gender of two massive corals *Pavona gigantea* and *Porites panamensis*. The species *P. gigantea* calcified two-times faster (0.84 ± 0.29 g cm^{-2} yr^{-1}) than *P. panamensis* (0.36 ± 0.15 g cm^{-2} yr^{-1}); and male colonies presents13-58% higher calcification rates than females. Annual growth parameters do not show significant trends over the period 1988–2013, but significant, growth disruption associated with ENSO events. The data presented here suggest that *P.gigantea* and *P.panamensis* from the area have developed phenotypic plasticity to a wide range of environmental condition; the life history of both species is reflected in their calcification rates during both optimal and non-optimal conditions over the last two decades. Massive species develop denser structures that provide a permanent habitat to many marine species and contributes to the long-term maintenance of coral reef communities in the eastern tropical Pacific.

1. Introduction

In coral reef there are many important biological processes such as production, calcification and dissolution (Sheppard et al., 2009). However, calcification is one of the most important active processes of construction of coral-reef ecosystems (Gattuso et al., 1999; Allemand et al., 2011). The deposition of calcium carbonate ($CaCO_3$) and the balance between accretion and erosion rates determine the maintenance of the coral reef-framework and habitat of many marine species (Hutchings, 1986; Glynn, 1997). Beside the ecological relevance, some massive reef-building coral species incorporate historical climate information into their skeletal structure, which allows determination of the environmental conditions during the organism's growth (Buddemeier, 1974; Barnes and Lough, 1989; Lough, 2010), and the influence of local conditions determining the formation of coral-band patterns (low density and high density), which are displayed in X-radiographs of massive species (Knutson et al., 1972). Both density bands (dark and light) reflect the growth at annual temporal scale and allows estimates of different coral growth parameters such as extension rate (cm yr^{-1}), skeletal density (g cm^{-3}) and the resultant mass of carbonate deposited (calcification rate = g cm^{-2} yr^{-1}) (Chalker et al., 1985; Carricart-Ganivet and Barnes, 2007).

Coral growth and banding patterns are both controlled by extrinsic factors such as light irradiance, sea surface temperature (SST), hydraulic energy, water chemistry and organic and inorganic sediments (Wellington and Glynn, 1983; Lough and Barnes, 2000; Grigg, 2006; Smith et al., 2007; Lough and Cooper, 2011), and also by intrinsic factors including skeletal architecture, growth strategy and gender (Barnes and Lough, 1993; Carricart-Ganivet and Merino, 2001; Carricart-Ganivet et al., 2013; Cabral-Tena et al., 2013, 2015; Tortolero-Langarica et al., 2016a). So far, SST variation is considered one of most important abiotic factors that controls coral calcification rate and may have a different influence depending on the thermal sensibility and thermal history of the species (Carricart-Ganivet et al.,

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Did the community structure of a coral reef patch affected by a ship grounding recover after 15 years? Merging historical and recent data sets

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ABSTRACT

Shifts in dominance from coral to other benthic groups in coral reefs have raised concerns about the persistence of coral reefs and their ability to provide ecosystem services. Acute disturbances such as ship groundings offer the opportunity to examine the dynamics of successional processes in coral reefs, since understanding them is a prerequisite for their proper management. In this study, we investigated whether a ship grounding area in a reef located in a marine protected area in Cancún, Mexico, showed signs of recovery 15 years after the incident. We evaluated the reef's composition and structure by taking samples at three different scales (reef scale, 1 m^2, and 0.01 m^2). In these samples, we analysed coral density and recruitment, the abundance of five functional algal groups, and the abundance of the grazer sea urchin *Diadema antillarum*. If recovery had already occurred, we expected the impacted sector to have a community composition and structure similar to that of a contiguous, non-impacted sector. Using historical information, we found indications of a long-term phase shift, with *Porites astreoides* being the dominant coral species some time ago and at all scales of analysis; this species also showed intense recruitment. In agreement with previous studies of Caribbean reefs, architectural complexity was low. The algal cover was similar in impacted and non-impacted sectors though the density of sea urchins differed between them. Fifteen years after the ship grounding and despite the enforcement of the prohibition of tourism and fishing activities at the site, the impacted sector does not show signs of recovery. On the contrary, like other reefs in the Caribbean Sea, the non-impacted sector is becoming degraded due to the loss of reef builder key species and the increase of the algae-covered area, mirroring the path observed in the impacted sector.

1. Introduction

Around the globe, many coral reefs have lost their typical community structure and turned into a degraded condition. In the Caribbean, this situation has triggered the implementation of a number of strategies aimed at recovering the communities' original status (e.g., Jaap, 2000; Young et al., 2012). Common strategies include the establishment of marine protected areas (MPA), conceived as buffers against stressing factors and facilitators of coral recovery through the reestablishment of trophic cascade feedbacks (Mumby et al., 2006, 2007; but see Kramer and Heck,

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SHORT NOTES

Sex-related differences in the sclerochronology of the reef-building coral *Montastraea cavernosa*: the effect of the growth strategy

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Abstract
To investigate sex-related differences in the skeleton of the reef-building coral *Montastraea cavernosa*, a gonochoric broadcaster species with an annual cycle of gametogenesis, we collected six colonies during the reproductive season. Sex was determined by histological techniques and sclerochronological characteristics of digital X-ray images. Our results show, as previously reported for other gonochoric corals, differences in the sclerochronological characteristics between female and male colonies. Tissue thickness, density and calcification rate are significantly lower in females than in males, whereas there is no difference in extension rate between sexes. These are the first complete sclerochronological results reported for *M. cavernosa*, and for gonochoric species with solid skeletons. We conclude that sex differences in this coral arise by coupling energetic costs of reproduction and the growth strategy, and argue that it is important to consider how sclerochronological characteristics vary between sexes of gonochoric species when interpreting climate and environmental proxies from coral skeletons.

Introduction

Skeletal growth in massive scleractinian corals is the result of deposition of calcium carbonate, driven by the metabolic process of calcification that occurs in the thin layer of living tissue at the outer surface of the colony (Barnes and Lough 1993; Colombo-Pallota et al. 2010). X-radiographs of slices of coral skeletons show an alternating high- and low-density banding pattern, which represents the annual growth of the coral (Knutson et al. 1972). The discovery of this yearly density-banding pattern has made it possible to map and date skeletal growth, providing invaluable information about coral growth rates and the environmental conditions under which corals lived (Barnes and Lough 1996; Cohen et al. 2004; Lough 2010; Lough and Cantin 2014). Annual sclerochronological characteristics that can be recovered from the annual-banding pattern are skeletal density ($gCaCO_3\ cm^{-3}$), and linear extension ($cm\ year^{-1}$) and calcification ($gCaCO_3\ cm^{-2}\ year^{-1}$) rates. The density-banding pattern arises depending on the skeletal architecture, and follows two growth strategies: corals with porous skeletons invest calcification resources into linear extension of the colony, whereas corals with more solid skeletons use calcium carbonate to augment skeletal density (Carricart-Ganivet 2007; Lough and Cantin 2014).

Recently, it has been reported that the sclerochronological characteristics may differ between female and male gonochoric corals, and this has been attributed to differences in energetic needs to produce gametes between sexes, i.e., there is a higher energetic cost to produce eggs by females, than sperm by males (Cabral-Tena et al. 2013; Carricart-Ganivet et al. 2013; Tortolero-Langarica et al. 2016). These studies

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To the memory of Pedro M. Alcolado, scientist, teacher and friend.

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BASE DE DATOS DE ALMACENES DE CARBONATO DE CALCIO EN ARRECIFES CORALINOS DE MEXICO

DATABASE OF CALCIUM CARBONATE STOCKS IN CORAL REEFS OF MEXICO

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RESUMEN

Los arrecifes coralinos son almacenes de carbono en el medio marino. México cuenta con estos valiosos ecosistemas en ambos litorales, pero las características fisiográficas, extensión espacial y composición de especies son muy distintas; por ejemplo, entre los que se encuentran en el Golfo de México y Mar Caribe (GM-MC) y, los del Pacífico (OP). En esta base de datos se compilaron datos de parámetros de crecimiento, como la extensión lineal, densidad esqueletal, tasa de calcificación y producción potencial de 11 especies de corales escleractíneos del GM-MC y 9 especies del OP. Se encontraron diferentes estudios con parámetros de crecimiento (20 artículos indizados, nueve bases de datos inéditas y dos tesis de posgrado). Se encontraron más estudios sobre los arrecifes coralinos del Golfo de México y Mar Caribe (17) que del Pacífico (12). Con el fin de tener una idea de la cantidad de carbono (en forma de carbonato de calcio), se estimó el área de 14 arrecifes del GM-MC (668 km^2) y 15 en el OP (3.5 km^2).

Palabras clave: *carbonato de calcio; tasa de crecimiento; tasa de calcificación; densidad esqueletal; producción potencial de carbonato.*

ABSTRACT

Coral reefs are carbon stock in the marine realm. Mexico harbours this valuable ecosystem on both littorals, but the physiography, spatial extension and species composition are sharply different between those in the Gulf of Mexico and the Caribbean (GM-MC) and those in the Pacific littoral (OP). We compiled a database from published and unpublished sources of coral growth rate, skeletal density, calcification rate and potential production of 11 species of scleractinian corals from the GM-MC and nine species from the Pacific. We found different studies (20 articles, nine unpublished databases and two graduate theses). There are more studies of coral reefs in the GM-MC (17) than in the Pacific (12). To have a gross idea of how much carbon is stored (as calcium carbonate), we estimated the area of 14 coral reefs from the GM-MC (668 km^2) and 15 from the OP (3.5 km^2).

Keywords: *Calcium carbonate; growth rate; calcification rate; skeletal density; carbonate potential production.*

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Coral Li/Mg thermometry: Caveats and constraints

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ABSTRACT

The coral Li/Mg temperature proxy is revisited through an in-depth trace element analysis of scleractinians collected live from tropical to polar environments. The dataset consists of Li/Ca, Mg/Ca, Sr/Ca and Li/Mg ratios from 64 coral specimens belonging to 8 different taxa, including both reef-building zooxanthellate and cold-water non-zooxanthellate species, from a wide range of water temperature (−1 to 29.5 °C), salinity (34.71 to 38.61), and depth (3 to 670 m).

Our results showed that the reliability of the Li/Mg temperature proxy is strongly limited by the organic matter associated with the coral skeleton, which is most evident within the green bands observed in tropical corals. Organic-rich bands can double the Mg content otherwise present in the skeleton, which may ultimately lead to a temperature overestimation exceeding 15 °C. We found that this bias can be overcome by the treatment of coral skeletons with a specific oxidizing cleaning protocol. We also detected the presence of calcite deposits within the aragonite skeleton of some Antarctic living coral specimens, which strongly affects the robustness of the Li/Mg proxy given its temperature sensitivity of ~1.5 °C/1% calcite. Therefore, to obtain reliable reconstructions a correction needs to be applied when organic matter and/or calcite contamination is present, which requires the scrupulous assessment of the integrity of the aragonite prior to geochemical analyses. Given that some species entrap more organic matter than others, and that some are more prone to calcite contamination, a taxon-related effect is apparent. Here we show that the tropical species *Porites* spp., *Pseudodiploria strigosa* and *Orbicella annularis*, and the cold-water species *Madrepora oculata*, *Caryophyllia antarctica* and *Flabellum impensum*, are all suitable candidates for reconstructing seawater temperatures.

The integrated results across a wide temperature range, from extreme cold to tropical shallow waters, yield an overall precision for the Li/Mg-temperature proxy of ± 1.0 °C, as quantified by the standard error of estimates. If

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Capítulo 7

ARRECIFES Y COMUNIDADES CORALINAS

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INTRODUCCIÓN

El ciclo del carbono es un proceso bioquímico de gran importancia a nivel ecosistémico tanto en ambientes terrestres como acuáticos, ya que se transfieren recursos energéticos entre rutas especificas atmósfera-océanos, y su equilibrio (ingresos, reservorios y pérdidas) son elementales para el funcionamiento y el balance de los ecosistemas, ya que generalmente controlan el aumento de dióxido de carbono atmosférico ($CO_{2\ gas}$) que afectan el clima de la tierra y los océanos.

Los arrecifes coralinos son ecosistemas marinos constituidos por grandes acreciones de carbonato de calcio ($CaCO_3$), que forman estructuras bentónicas tridimensionales de gran complejidad, las cuales son construidas por diversos organismos que tienen la capacidad de formar su exoesqueleto, y en conjunto al arrecife. Estos ambientes figuran como un elemento importante dentro del ciclo del carbono en los ecosistemas costeros, debido a que producen una gran cantidad de carbono en forma de materia orgánica, la cual es transferida a distintos niveles dentro de la red trófica, promoviendo su transporte dentro y fuera de estos ecosistemas (Reyes-Bonilla *et al*., 2014b). Además, son ecosistemas con una alta riqueza biológica y son considerados prestadores de bienes y servicios ambientales (Veron, 2000; Reyes-Bonilla *et al.*, 2014b), entre los cuales se incluyen su importancia en ciclos biogeoquímicos a escala global, crianza de peces, protección de la costa, provisión de material para la formación de playas, entre otros (Moberg y Folk, 1999; Barbier *et al.*, 2011; Reyes-Bonilla *et al*., 2014b).

En los arrecifes coralinos, la comunidad de organismos calcificadores extraen cantidades masivas de carbono de la columna de agua para formar sus esqueletos de $CaCO_3$ (Figura 1; Calderón-Aguilera *et al.*, 2007; Álvarez-Filip *et al*., 2013; Norzagaray *et al*., 2015), y producen cerca del 50% del $CaCO_3$ de aguas superficiales, con una producción global (Pg = 10^{12}kg) alrededor de 0.8 Pg·año^{-1} (Vecsei, 2004). Por lo tanto, los arrecifes coralinos son producto del crecimiento continuo de la comunidad calcificadora, las cuales mantienen las tasas de acreción mayores a las tasas de disolución y bioerosión (Chave *et al*., 1972). De manera general, la ecuación propuesta para la calcificación indica que este proceso metabólico produce $CO_{2\ gas}$ (Smith, 2013):

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Uncertainty and variability of extension rate, density and calcification rate of a hermatypic coral (*Orbicella faveolata*)

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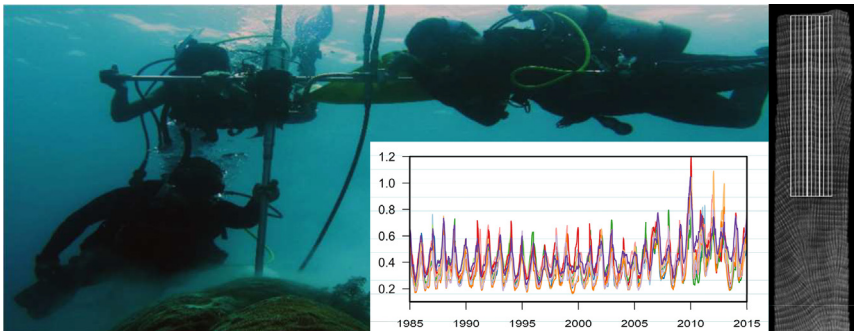
HIGHLIGHTS

- Hermatypic corals are widely used to reconstruct past environmental conditions.
- Uncertainties of all measurements were considered to calculate growth variables.
- The measurement uncertainty was small (<2%).
- Band variability was half of the overall variability (~30%).
- Coral growth variability must be considered for environmental reconstructions.

GRAPHICAL ABSTRACT



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ABSTRACT

Skeleton growth variables of hermatypic corals, such as extension rate, density and calcification rate, are widely used to study coral response to environmental stressors, establish chronological age models and reconstruct the evolution of key climate variables. In this work, we addressed methodological aspects of the measurement of coral growth variables and the implications of their variability. A core of *Orbicella faveolata* was collected from the Puerto Morelos coral reef, in the Mexican Caribbean, and we measured and analysed 10 parallel transects of a core slab, covering 30 years. Density calibration was performed by measuring a high-quality and well-characterised wedge of *Tridacna maxima*, and the interval of interest was adjusted to the measured coral optical densities. The measurement uncertainties of extension rate, density and calcification rate were 0.011%, 1.1% and 1.6%, respectively. However, for density and calcification rate, overall variability was 29% and 33%, respectively, of which about half was attributed to intra-band growth variability. The intra-band variability of extension rate was only 0.68%, indicating the suitability of extension rate as a precise environmental proxy. These results likely differ by coral species, environments and experimental conditions, such as the exact location of the core within the colony and the method used to determine density. Uncertainties of coral growth variables should be carefully considered when reconstructing past environmental conditions.

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ORIGINAL PAPER

Sensitivity of calcification to thermal history differs between sexes in the gonochoric reef-building corals *Dichocoenia stokesi* and *Dendrogyra cylindrus*

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Abstract

Calcification and sexual reproduction in corals are energy consuming metabolic processes. In symbiotic corals, calcification is a daily process and depends on the ability of the coral colony to produce energy, through the photosynthesis of symbiotic algae or heterotrophy, while sexual reproduction in several broadcast spawning species is carried out once a year and depends on the amount of energy stored as lipids within the coral tissue. Calcification and reproduction are influenced by environmental parameters, such as light irradiance and sea surface temperature (SST). Reproduction may be inhibited by thermal stress and coral calcification rate decreases as SST increases above a certain threshold. However, it is unknown if there is a sex-related response of calcification rate to thermal history. Here, we test the differential sensitivities of calcification rates to thermal history by examining its recent historical variation in females and males of two common Caribbean gonochoric reef-building coral species, *Dichocoenia stokesi* and *Dendrogyra cylindrus*. Colony sex was determined by histological techniques, and sclerochronology was measured using densitometry from digitized X-ray images. Calcification rates were higher in male colonies than in females of both species, as previously reported in other gonochoric corals, and can be explained in terms of disparity in energy availability for calcification among sexes due to the differential energetic costs of eggs and sperm. Calcification rates of both species were negatively related to SST when data of both sexes were pooled together. When data were analyzed separately by sex, only female colonies, of both species, showed a significant dependence of calcification rate to SST. The fact that SST differentially affects coral calcification in female and male colonies, will have repercussions on population dynamics of the studied coral species in a global warming scenario.

Introduction

The metabolic process of calcification, which occurs in the millimetric layer of living tissue at the outer surface of the colony, drives the deposition of calcium carbonate resulting in the skeletal growth in massive scleractinian corals (Barnes and Lough 1993; Colombo-Pallotta et al. 2010). Knutson et al. (1972) discovered that when coral skeletons

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Plutonium in coral archives: A good primary marker for an Anthropocene type section

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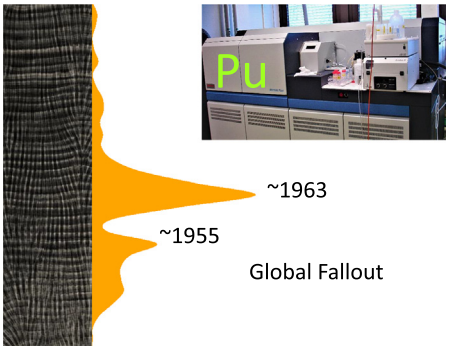
HIGHLIGHTS

- A new record of plutonium in a Caribbean coral is compared to seven records worldwide.
- The plutonium maxima in banded corals are asynchronous.
- The plutonium onsets in corals distant to nuclear detonation grounds are synchronous.
- Massive corals from Caribbean reefs are suitable to host an Anthropocene golden spike.

GRAPHICAL ABSTRACT



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ABSTRACT

While we officially live in the Holocene epoch, global warming and many other impacts of global change have led to the proposal and wide adoption of the Anthropocene to define the present geological epoch. The Anthropocene Working Group (AWG) established that it should be treated as a formal stratigraphic unit, demonstrated by a reference level commonly known as "golden spike", still under discussion. Here we show that the onset of bomb-derived plutonium recorded in two banded massive corals from the Caribbean Sea is consistent (1955–1956 CE), so sites far from nuclear testing grounds are potentially suitable to host a type section of the Anthropocene. Coastal coral demonstration sites are feasible, could foster economic development, and may serve as focal points for scientific dissemination and environmental education.

1. Introduction

The Quaternary period (2.6 Myr) is characterized by oscillations of the earth's climate between glacial and interglacial conditions. The Holocene epoch (11.7 kyr) is the present warm interglacial interval after

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