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CICLOS ISOTÓPICOS E TAXA DE CRESCIMENTO EM *Mussismilia hispida* (VERRILL, 1902): UM REGISTRO PARA O ATLÂNTICO SUL

Isabel Cristina Bezerra Sandes Silva

Orientador: Dr. Alexandre Liparini Campos

Coorientador: Dr. Natan Silva Pereira

DISSERTAÇÃO DE MESTRADO

Programa de Pós-Graduação em Geociências e Análise de Bacias

São Cristóvão-SE
2019

Isabel Cristina Bezerra Sandes Silva

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Dissertação apresentada ao Programa de Pós-Graduação em Geociências e Análise de Bacias da Universidade Federal de Sergipe, como requisito para obtenção do título de Mestre em Geociências.

Orientador: Dr. Alexandre Liparini Campos
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por:

Isabel Cristina Bezerra Sandes Silva
(Bióloga, Universidade Estadual da Bahia – 2016)

DISSERTAÇÃO DE MESTRADO

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BANCA EXAMINADORA:

______________ Dr. Alexandre Liparini Campos [Orientador – UFS]

______________ Dr. Adauto de Souza Ribeiro [Membro Externo – UFS]

______________ Dra. Bárbara Ramos Pinheiro [Membro Externo –UFBA]

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RESUMO

Esqueleto de corais escleractínios incorporam dados geoquímicos capazes de registrar com precisão mudanças ambientais, possibilitando a reconstrução climática da história dos oceanos tropicais, auxiliando na compreensão das atuais mudanças climáticas globais. Essas assinaturas geoquímicas (e.g. isótopos de carbono ($\delta^{13}C$) e oxigênio ($\delta^{18}O$) podem revelar informações sobre a temperatura da superfície do mar (TSM), salinidade, cobertura de nuvem, entre outras. O Atlântico Sul Tropical ainda possui uma carência de estudos paleoclimáticos utilizando arquivos com base em corais. Esta pesquisa objetiva estimar a taxa de crescimento e investigar as alterações dos $\delta^{13}C$ e $\delta^{18}O$ incorporados no esqueleto do coral *Mussismilia hispida* durante seu crescimento, na região do Atol das Rocas, além de verificar o potencial de uso desses dados como *proxy* no estudo de variações ambientais. Para tanto, foram utilizadas três colônias de *M. hispida* (MH1, MH2 e MH3), nas quais foram feitas amostragens a cada 5 mm com uma microfuradeira de dentista, o carbonato retirado foi armazenado e analisado no Laboratório de Isótopos Estáveis da Universidade Federal de Pernambuco por espectrometria de massa determinando os valores do $\delta^{13}C$ e $\delta^{18}O$. As médias obtidas para o $\delta^{13}C$ foram (0,91‰, 0,40‰ e 0,57‰) e $\delta^{18}O$ (-3,29‰, 4,09‰ e -4,27‰), para as colônias 13MH1, 13MH2 e 13MH3 respectivamente. Além disso, foram estimadas a taxas de crescimento médio (mm/ciclo) e o número de ciclos para: 13MH1 2.83 ±0.51; 13MH2 3.21±0.86; and 13MH3 3.71±0.82. Do ponto de vista para utilização de corais como arquivo climático a espécie possui uma taxa de crescimento suficiente para a obtenção de informações de alta resolução. A fim de consolidar essa espécie como um arquivo natural confiável é necessário expandir as investigações aqui realizadas para outras regiões do nordeste brasileiro.

Palavras-chave: Taxa de Extensão; Geoquímica Isotópica; Corais Hermatípicos.

ABSTRACT

Skeleton of scleratinian corals incorporates geochemical data capable of accurately recording environmental changes, enabling climatic reconstruction of the tropical oceans history, aiding in understanding current global climate change. Such geochemical signatures (e.g. carbon isotope ($\delta^{13}C$) and oxygen ($\delta^{18}O$) can reveal information about the sea surface temperature (SST), salinity, cloud cover, among others. The Tropical South Atlantic, still has a lack of paleoclimatic studies using files based on corals. This research aims to estimate the growth rate and to investigate the changes of the $\delta^{13}C$ and $\delta^{18}O$ incorporated in the coral skeleton *Mussismilia hispida* during its growth, in the Atol das Rocas region, besides verifying the potential of using this data as a proxy in environmental variations studies. For this, three *M. hispida* colonies (MH1, MH2 and MH3) were used, in which samples were taken every 5mm with a dental drill, the extracted carbonate was stored and analyzed in the Stable Isotopes Laboratory of the Federal University of Pernambuco by mass spectrometry determining the values of $\delta^{13}C$ and $\delta^{18}O$. The averages obtained for $\delta^{13}C$ were (0.91‰, 0.40‰ and 0.57‰) and $\delta^{18}O$ (-3.29‰, -4.09‰ and -4.27‰), for colonies 13MH1, 13MH2 and 13MH3 respectively. Furthermore, the average growth rates (mm/cycle) and the number of cycles were estimated for: 13MH1 2.83 ±0.51; 13MH2 3.21±0.86; and 13MH3 3.71±0.82. From the point of view of the use of coral as a climatic file, the species has a sufficient growth rate to obtain high resolution information. In order to consolidate this species as a reliable natural file it is necessary to expand the investigations carried out here for other regions of the Brazilian Northeast.

Keywords: Extension Rate; Isotopic Geochemistry; Hermatypics Corals

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CAPÍTULO I – INTRODUÇÃO

A reconstrução da história dos oceanos tropicais é fundamental para entender a mudança climática global passada e fornecer dados para projeção de prováveis cenários futuros (Cohen et al., 2002; Gagan et al., 2012). A região do oceano Atlântico Sul, ainda é bastante limitada de informações paleoceanográfica baseado em instrumentos, logo, se torna necessário a utilização de arquivos naturais como anéis de árvores, testemunhos de gelo, espeleotemas, colônias de corais, dentre outros, que já se apresentam como ótimas ferramentas.

Os corais escleractínios pertencentes ao filo Cnidaria, classe Anthozoa e são organismos hipercalcificadores, capazes de produzir grande quantidade de carbonato de cálcio ($CaCO_3$) para formar seu esqueleto de aragonita. Este grupo de corais vem sendo utilizado frequentemente para estudos climáticos após a descoberta realizada por Knutson et al. (1972), de que os mesmos apresentam um padrão de crescimento em forma de bandamentos. Por meio de radiografia é visível a formação de bandas claras e escuras de forma alternada e regular, resultando em variações cíclicas de densidade do material esquelético depositado. A descoberta da formação desses bandamentos serem quase sempre anuais, possibilitou contar os bandamentos, datar e correlacionar com fatores ambientais, tornando os corais importantes calendários e fonte de informações do ambiente no qual se desenvolvem.

Registros com base em isótopos estáveis incorporados ao esqueleto dos corais tem se mostrado uma técnica promissora para estudos climáticos. Através desse método podem ser reconstruídas muitas variáveis ambientais como a cobertura de nuvens, temperatura da superfície do mar (TSM), zonas de ressurgência e salinidade (Fairbanks et al., 1997; Grottoli, 2001). Além disso, estimativas de taxas de crescimento anual de uma colônia de coral, podem ser realizadas medindo-se os comprimentos dos ciclos isotópicos (Grottoli, 2001; Pereira et al., 2018).

Isótopos estáveis de carbono ($\delta^{13}C$) no esqueleto de coral, majoritariamente, mantém uma relação direta com a atividade fotossintética das zooxantelas dos corais, logo, depende dos níveis de luz ambiente, relacionada à profundidade e insolação (Weber & Woodhead, 1970; Fairbanks et al., 1979; McConnaughey, 1989). Os valores de $\delta^{13}C$ incorporados aos corais irão aumentar de acordo com a atividade fotossintética (zooxantelas) presente nos corais (Swart, 1983). Deste modo, acredita-se que a mudança na taxa fotossintética ao longo do ano, pode ser responsável por uma mudança cíclica de $\delta^{13}C$ no esqueleto (Swart et al., 1996). $\delta^{13}C$ vem ganhando credibilidade como um indicador de variação sazonal na cobertura de nuvens (Swart, 1983; Fallick et al., 1996).

Os isótopos de oxigênio vêm sendo utilizado para reconstruções climáticas durante décadas (Dunbar et al., 1994; Gagan et al., 1994; Wei et al., 2000; Moses & Swart, 2006; Chen et al., 2013). A partir da análise do $\delta^{18}O$ presente no esqueleto de corais escleractínios, é possível estimar a TSM na qual uma determinada colônia viveu, e consequentemente saber se os corais experimentaram condições climáticas anômalas (Mayal et al., 2009). O valor de $\delta^{18}O$ da água do mar e do esqueleto dos corais também diminui ao passo que a salinidade diminui, devido a precipitação, que é empobrecida em $\delta^{18}O$ (Cole and Fairbanks, 1990; Grottoli, 2001).

As limitadas informações paleoceanográficas proveniente de corais no oceano Atlântico Sul, chamam a atenção para a necessidade de estudos com esse escopo, uma vez, que em outras regiões já está comprovado a importante fonte de informação que são os corais (Moses and Swart, 2006; Pandolfi, 2011; Swart and Grottoli, 2003; Weber and Woodhead, 1972). Além disso, a espécie *Mussismilia hispida*, objeto dessa pesquisa, integra o grupo das espécies importantes na construção dos recifes da costa brasileira. Dessa forma, utilizar o conteúdo geoquímico de espécies que são endêmicas e importantes para a região, pode se tornar uma ferramenta promissora para se reconstruir e compreender as mudanças oceanográficas do Atlântico Sul.

O interesse em estudar corais, mais precisamente seu conteúdo isotópico, advém dos resultados promissores obtidos na graduação, na possibilidade de gerar dados confiáveis para o oceano Atlântico Sul e contribuir com o conhecimento acerca das condições ambientais que influenciam no desenvolvimento das espécies de corais da costa brasileira.

O artigo gerado a partir de todos os dados analisados foi submetido à revista Journal of South American Earth Sciences Intitulado " Assessing the growth rate of the South Atlantic coral species *Mussismilia hispida* (VERRILL, 1902) using carbon and oxygen stable isotopes*”*.

Este trabalho foi executado no Programa de Pós-Graduação em Geociências e Análises de Bacias (PGAB) da Universidade Federal de Sergipe (UFS), com apoio do

Laboratório de Pesquisas Integrativas em Biodiversidade (PIBi) da UFS, da Fundação de Apoio à Pesquisa e à Inovação Tecnológica do Estado de Sergipe (FAPITEC-SE) e a Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), com apoio do Laboratório de Estudos em Sedimentologia e Paleoclimatologia (NESP) da Universidade do Estado da Bahia (UNEB), Núcleo de Estudos Geoquímicos e Laboratório de Isótopos Estáveis (NEG-LABISE) da Universidade Federal de Pernambuco (UFPE) e Laboratório de Espectrometria de Massa e Mudanças Ambientais (HISPEC) da Universidade Nacional de Taiwan.

Objetivos

Este trabalho tem como objetivo estimar a taxa de crescimento e investigar as alterações dos $\delta^{13}C$ e $\delta^{18}O$ incorporados no esqueleto de três colônias do coral *Mussismilia hispida* durante seu crescimento, na região do Atol das Rocas, além de verificar o potencial de uso desses dados como *proxy* no estudo de variações ambientais. Como objetivos específicos:

1. Analisar o $\delta^{18}O$ e $\delta^{13}C$ das amostragens obtidas do exoesqueleto das colônias de *M. hispida;*
2. Determinar a idade de uma das colônias e em que ano iniciou seu desenvolvimento;
3. Averiguar o potencial das espécies de *M. hispida* para estudos climáticos históricos.

Área de Estudo

O Atol das Rocas (3°51´S, 33°49´W) está localizado a 266 km a nordeste da cidade de Natal-RN e 150 km a oeste do arquipélago de Fernando de Noronha (Figura 1). Se tratando de oscilações climáticas, Atol das Rocas vem se mostrando um local apropriado para tais investigações, uma vez que este não sofre influência humana e nem continental (Pereira et al., 2015).

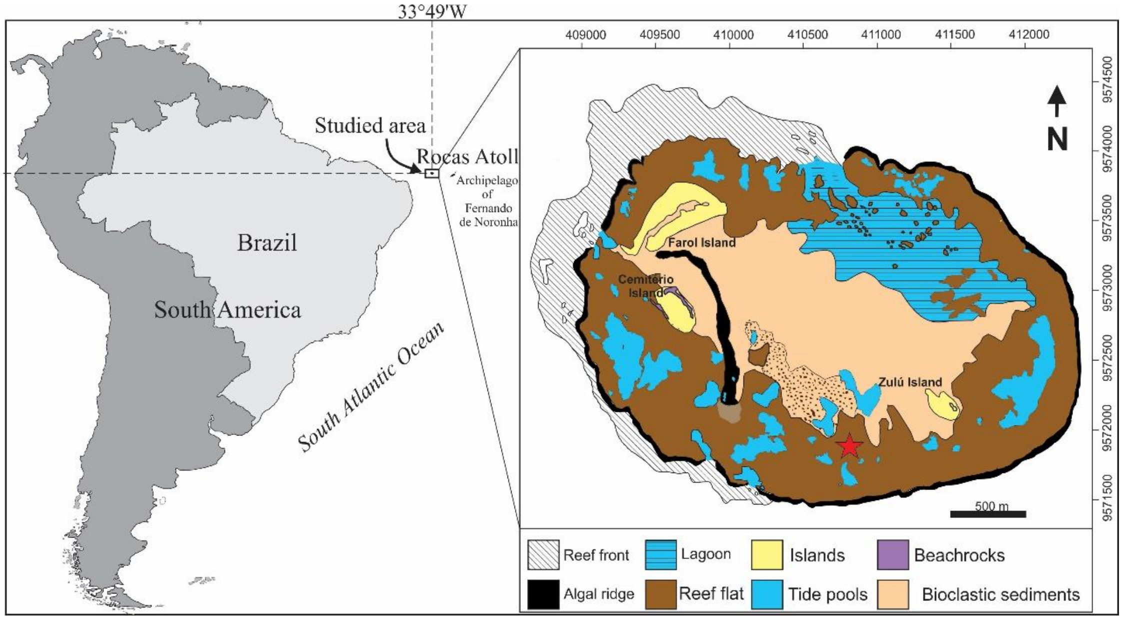

Figura 1 – Localização e mapa geomorfológico do Atol das Rocas. Fonte: Pereira et al., 2017.

Rocas apresenta uma forma elipsoide e está situado sobre um monte submarino com um topo achatado no Oceano Atlântico (*guyot)* (Kikuchi and Leão, 1997; Pereira et al., 2013). Tendo uma área de aproximadamente 6,56 km^2, com um perímetro de 11 km é considerado o menor atol do mundo comparado a outros, como o Atol Rangiroa, no arquipélago de Tuamotu, na Polinésia Francesa com 72x36 km^2 (Pereira et al., 2013).

Aspectos geomorfológicos do Atol das Rocas abrange uma frente recifal em duas formas diferentes: a barlavento até profundidade de 10 m, colonizado por algas sem esqueleto e coralinas, esponjas e corais e sotavento onde se cresce o contraforte recifal (pontões e reentrâncias) desde a borda até profundidades de ~18 m. O recife é formado principalmente por algas coralinas incrustantes e gastrópodes vermetídeos. O platô recifal é uma superfície plana, limitado pela borda externa, envolvendo o anel recifal que é descontínuo por dois canais (Barreta Grande e Barretinha). Além disso, há piscinas no platô recifal de 3 m de profundidades que são preenchidas por sedimentos arenosos. Em relação à sedimentologia, nas ilhas o sedimento é cascalho arenoso (superior a 60%) e na laguna é areia (cerca de 80%), os sedimentos são classificados como areias calcárias biogênicas, constituídas por algas coralinas e foraminíferos (Kikuchi, 2002).

Rocas é caracterizado por um clima tropical oceânico, tendo uma temperatura média de 26°C, e uma variabilidade interanual de 24°C a 30°C para os últimos 30 anos, apresentando chuvas de março a julho; período mais quente em agosto, e outubro o mais seco (Kikuchi and Leão, 1997). A temperatura da água possui variação sazonal com mínimo e máximo em setembro (26°C) e maio (28,3 °C), tendo uma média de 27°C. Se tratando da salinidade há uma variação de 36 psu a 37 psu (Hoflich, 1984).

Os organismos construtores do Atol das Rocas são as algas coralinas e macroalgas, gastrópodes vermetídeos, foraminíferos e espécies de corais: *Siderastrea stellata, Favia gravida, Mussismilia hispida, Agaricia* sp., *Montastrea cavernosa, Madracis decactis* e *Porites* sp. (Kikuchi, 2002).

Métodos de trabalho

Coleta de colônias de corais

As colônias utilizadas foram coletadas mortas na região do platô recifal na porção Sul do Atol das Rocas em julho de 2013. Cada colônia recebeu um código de referência (13MH1, 13MH2 e 13MH3) e foram colocadas em sacos plásticos individuais para transporte. O material foi armazenado no Laboratório de Isótopos Estáveis (LABISE) do Departamento de Geologia da Universidade Federal de Pernambuco - UFPE.

Corte das colônias e raio-X

As colônias foram cortadas em lâminas de 0,5 cm de espessura, por meio de uma serra de mesa lubrificada com água. Logo após, as lâminas foram encaminhadas e armazenadas no Laboratório de Geologia e Sedimentologia – LAGES da Universidade do Estado da Bahia - *Campus VIII*, para em seguida serem radiografadas. As radiografias das lâminas foram realizadas no Hospital Público Nair Alves de Souza, da cidade de Paulo Afonso-BA seguindo as seguintes configurações: aceleração de voltagem de 50 KV e amperagem de 320 mA, com tempo de exposição de 3,2 segundos e distância entre o equipamento e a lâmina do coral de 108 cm. As imagens digitais obtidas (Figura 2) foram utilizadas para a escolha de um melhor local para realizar as amostragens.

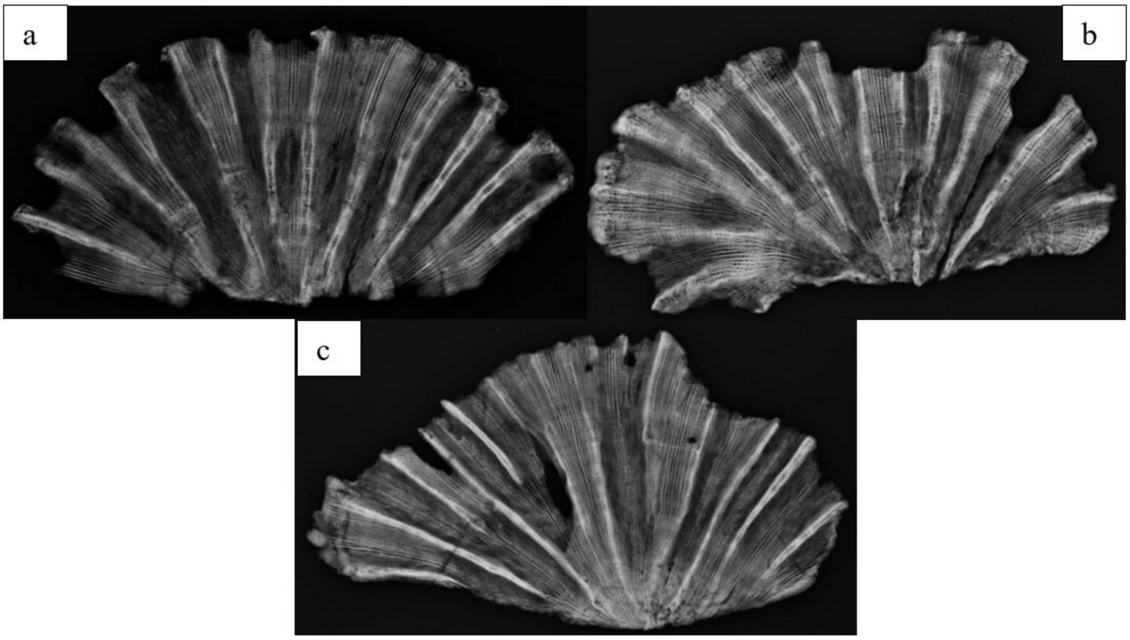

Figura 2. Imagem digital das lâminas das colônias de *M. hispida*, a 13MH1; b 13MH2; c 13MH3.

Amostragem para análise isotópica

As amostras foram extraídas ao longo do eixo de crescimento de cada lâmina dos corais (Figura 3. b - d) por meio de uma micro furadeira de dentista (Figura 3.a) com distanciamentos de 0,5 mm. Sendo, a amostragem da lâmina de 13MH1 realizada no Laboratório de Geologia e Sedimentologia – LAGES da Universidade do Estado da Bahia - *Campus VIII*. Já as lâminas de 13MH2 e 13MH3 foram realizadas no Instituto de Geociências – IGEO da Universidade Federal da Bahia, por meio de perfurações superficiais. Essas amostras foram todas encaminhadas para análise no LABISE – UFPE.

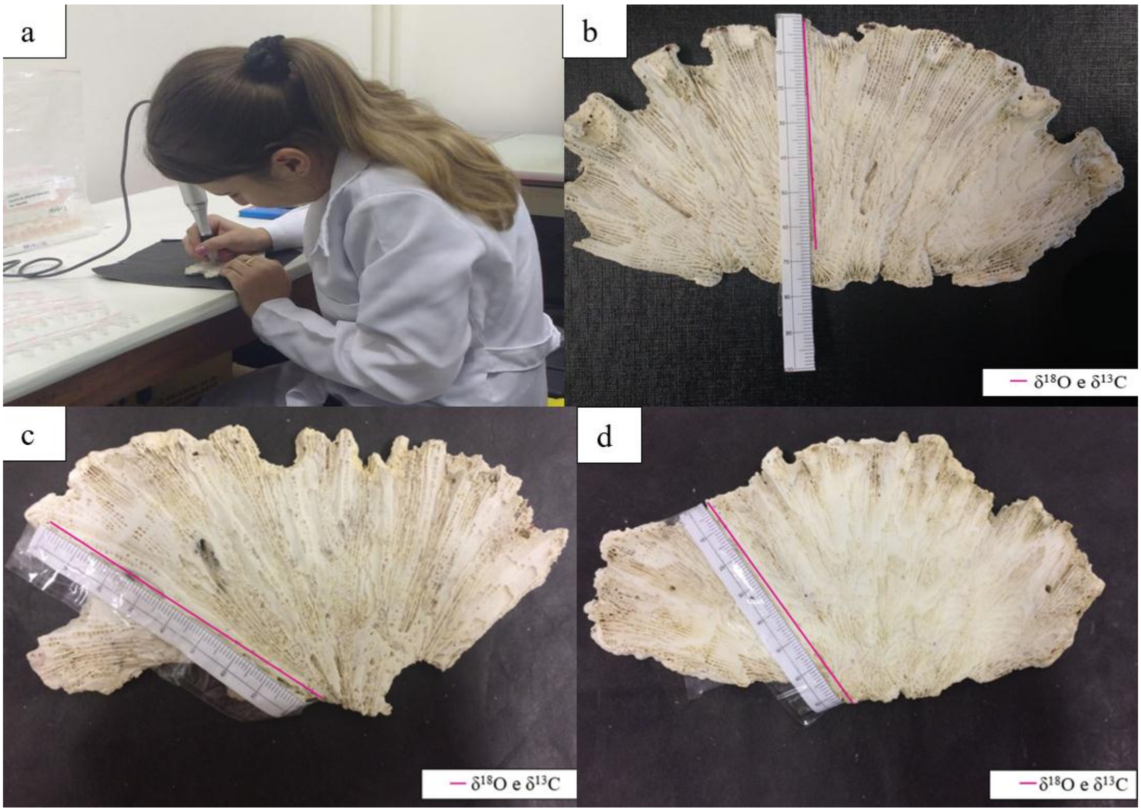

Figura 3. a Extração de carbonato (linha rosa) para análise isotópica por meio de micro furadeira de dentista; colônias amostradas b-13MH1, c-13MH2 e d-13MH3.

Análises geoquímicas de $\delta^{18}O$ e $\delta^{13}C$

Análises de $\delta^{18}O$ e $\delta^{13}C$ foram determinadas utilizando espectrômetro de massa Delta V Advantage com GasBench II acoplado do LABISE da UFPE. Para isso foram necessários cerca de 0,6 - 0,7 mg de carbonato que foram transferidos para frascos de vidro de borossilicato de 10 ml e selados com tampas com septos de borracha. Em cada rodada de análise foram processadas 72 amostras usando uma unidade de multifluxo dos quais 16 frascos contêm 4 réplicas de 4 padrões de referências, 2 internacionais (NBS-18 e NBS-19) e dois internos (REI e VICKS) para calibração.

Inicialmente, os frascos passaram por um *flush* de Hélio, que consiste em um jato de gás He por 240 segundos para remoção de gás atmosférico, especialmente CO_2 e H_2O. O gás é inserido por uma agulha introduzida através do septo de borracha na qual a mistura de gases será continuamente removida por um canal de escape aberto na agulha introduzida.

Após o *flush* de He, 90 mg (equivalente a ~50 µl) de ácido ortofosfórico anidro H_3PO_4 foram adicionados automaticamente em cada amostra para liberar o CO_2 do carbonato, através de uma agulha de aço movida por um braço robótico Comb Pal.

Depois da adição de H_3PO_4, as amostras reagiram por 90 minutos antes de serem analisadas. A mistura de He-CO_2 de cada amostra foi então transferida em um processo automático e mensurados contra uma mistura de gás de referência de He-CO_2. Os dados isotópicos de C e O (Apêndice A) foram expressos no padrão internacional VPDB (*Vienna Peedee Belemnite*).

Datação Urânio-Tório U/Th

A idade do coral fóssil *M. hispida* foi determinada por espectrometria de massa de ionização térmica U/Th realizado no HISPEC (*High-precision Mass Spectrometry and Environmental Change Laboratory*) do departamento de Geociências da Universidade Nacional de Taiwan (NTU), para isso foi retirada 2 amostras (2 gramas cada) em dois pontos denominadas de MHA (ápice) e MHB (base) (Figura 4) ao longo do eixo de crescimento da lâmina do coral 13MH1.

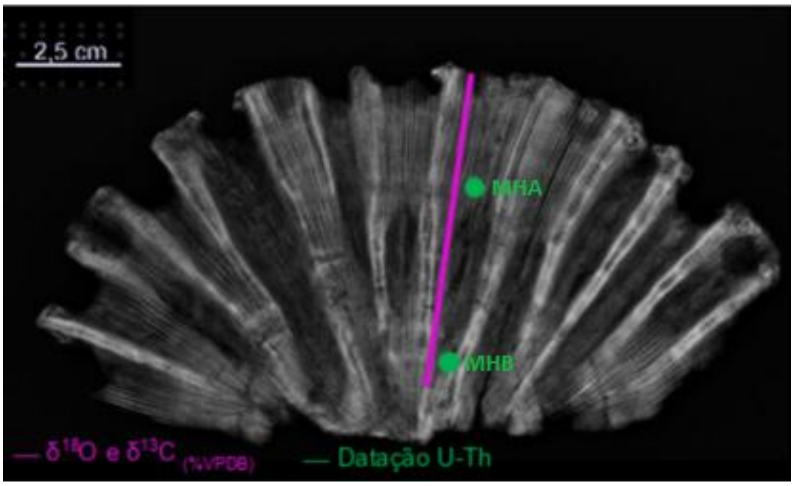

Figura 4 – Radiografia da colônia MH1 com identificação do local da amostragem para análise isotópica em rosa e em verde o local de amostragem para análise de Urânio-Tório em dois pontos MHA (ápice) e MHB (base).

Taxa de Crescimento

A taxa de crescimento foi determinada medindo a extensão (mm) entre os picos dos ciclos isotópicos de $\delta^{13}C$ ou a distância entre as cavas dos ciclos de $\delta^{18}O$, uma vez que esses ciclos são interpretados como anuais. A média do comprimento dos ciclos de cada colônia foi utilizada para determinar a taxa de crescimento anual média das colônias de corais, na qual, o primeiro e último ciclos de cada colônia foram excluídos devido a dubiedade se representariam ciclos completos ou não.

A colônia 13MH-1 também teve a taxa de crescimento estimada por meio da Datação U/Th, no qual a diferença entre as idades (ano) determinadas entre os dois pontos foi dividida pela distância (mm) entre os dois pontos de amostragem (Pereira et al., 2018).

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CAPÍTULO II– ARTIGO SUBMETIDO À REVISTA JOURNAL OF SOUTH AMERICAN EARTH SCIENCES:

Assessing the growth rate of the South Atlantic coral species *Mussismilia hispida* (VERRILL, 1902) using carbon and oxygen stable isotopes

I.C.B.S Silva[a], A Liparini[a], N.S Pereira[b,d*], B.L.S.S Braga[c], A.N, Sial[d], S.-C. Liu[e], C.-C. Shen[e,f], R.K.P. Kikuchi[c]

[a] Laboratório de Pesquisas Integrativas em Biodiversidade (PIBi-Lab), *Programa de Pós-Graduação em Geociências e Análise de Bacias (PGAB) – Universidade Federal de Sergipe, São Cristóvão, SE, 49100-000, Brazil*
[b]*NESP, Departamento de Biologia, Universidade do Estado da Bahia, Campus VIII, Paulo Afonso, 48608-240, Brazil*
[c]*RECOR, Departamento de Oceanografia, Universidade Federal da Bahia, Salvador 40210-340, Brazil*
[d]*NEG-LABISE, Universidade Federal de Pernambuco, C. P. 7852, Recife 50670-000, Brazil*
[e] *High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Roosevelt Rd., Taipei 10617, Taiwan, ROC*
[f]*Research Center for Future Earth, National Taiwan University, Roosevelt Rd., Taipei 10617, Taiwan, ROC*

Abstract

Scleractinian corals grow by the precipitation of $CaCO_3$ by a thin tissue layer at the top of the colony. The exoskeleton resulted from this biomineralization process usually presented density bands, which a pair of low and high-density is interpreted as annual bands. Such information is used to determine the growth rate of a colony and estimate chronology in calendar year. Nevertheless, some corals do not present density bands, making difficult to constrain a good chronology and assess growth rate pattern, demanding another approach. Carbon and oxygen stable isotope ratios ($\delta^{13}C$ and $\delta^{18}O$) are commonly used as proxies for cloud cover and sea surface temperature (SST), respectively. Thus, once these proxies have annual seasonality, the length and number of $\delta^{13}C$ and $\delta^{18}O$ cycles can be used to estimate growth rate and dating a coral record. Here we used $\delta^{13}C$ and $\delta^{18}O$ length cycles to estimate and report the growth rates data for three colonies of the coral *Mussismilia hispida* (VERRILL, 1902*)*, an endemic species of the South Atlantic Ocean. The studied colonies, 13MH-1, 13MH-2, and 13MH-3, demonstrated mean growth rates of 2.83±0.51, 3.21±0.86 and 3.71±0.82 mm/year respectively. U-Th dating of two samples from colony 13MH-1 indicated absolute ages of 61.5 ± 1.1 and 72.7 ±1.1 calendar years and a mean growth rate of 3.57±1.03 mm/year, similarly to the stable isotope results. Our results showed that the $\delta^{18}O$ and $\delta^{13}C$ records of *M. hispida* colonies at the Rocas Atoll are dominated by short and medium-term variations. The short-term variation seems to be governed by annual seasonality (i.e., SST and solar radiation levels) and were used to determine the extension rates of the three colonies, providing know insights for the use of the species *M. hispida*, a widely distributed species in the South Atlantic, as a good high-resolution environmental record.

Keywords: Isotopic geochemistry; Hermatypic corals; Paleoclimatology.

*Corresponding author: Natan Silva Pereira e-mail: natansp_bio@hotmail.com

1. INTRODUCTION

Coral-based climate records have been used worldwide to generate high-resolution reconstructions of past environmental conditions in tropical regions (e.g., Swart & Grottoli 2003; Kilbourne et al. 2004; Saenger et al. 2008; Felis et al. 2015; Hetzinger et al. 2016; LaVigne et al. 2016; Rivera et al. 2018, among others). Reliable environmental reconstructions using Scleractinia coral skeletons requires, however, an understanding how different coral species grow and record environmental information, and how biological and environmental factors affect their growth (Lough & Barnes 1990; Cruz-Piñón et al. 2003). Many factors (e.g., temperature, dissolved nutrients, sedimentation rates, light availability, turbidity, and endogenous reproduction factors) have been pointed in previous works as environmental factors that could influence coral skeleton formation (Cruz-Piñón et al. 2003).

Corals are hypercalcifiers organisms capable of synthesizing large quantities of calcium carbonate to form their aragonite exoskeletons. Their growth patterns alternate between rapid thickening associated with slow extension (increasing skeletal density), and rapid extension with reduced thickening (reducing skeletal density). Those cyclic variations produce banding patterns in the skeletal structure of corals that are visible on x-ray radiographs (Knutson et al. 1972; Buddemeier et al. 1974; Macintyre & Smith 1974; Dodge & Vaisnys, 1975). Corals generally add a high- and low-density band annually (Knutson *et al*. 1972; Dodge & Thompson 1974; Hudson et al. 1976; Wellington & Glynn 1983). Similar to tree rings, coral growth bands can used as a calendar recording environmental events.

The measurement of density bands can reveal information concerning the growth rate and environmental factors that influence and limit coral development (Wellington & Glynn, 1983; Taylor et al., 1993; Lough & Barnes, 1997), such as temperature, dissolved nutrients, sedimentation rates, light availability, turbidity, and reproduction (Weber et al. 1975; Buddemier & Kinzie, 1975; Highsmith, 1979; Dodge & Vaisnys, 1980; Wellington & Glynn, 1983; Cruz-Piñón et al. 2003). However, not all corals produce the well-defined annual bands necessary for accurately evaluating their growth rates and ages.

Corals grow at rates that vary from millimeters to centimeters each year, continuously incorporating geochemical information (isotope and trace element ratios) in their exoskeletons (e.g., Weber & Woodhead 1970; Hart & Cohen 1996; Swart et al. 1996; Böhm et al. 2006; Giry et al. 2010; Saha et al. 2016). Carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope ratios have been widely used as proxies for a series of environmental conditions and physiological factors in hermatypic corals (Weber & Woodhead 1970; Weber 1973; Swart 1983; Swart et al. 1996; Grottoli 2001; Cohen & McConnaughey 2003; Swart & Grottoli 2003; Eakin & Grottoli 2006a).

Depending on local conditions, the $\delta^{18}O$ signatures incorporated into corals reflect sea surface temperatures (SST) (Fairbanks & Dodge, 1979; McConnaughey, 1989; Pätzold, 1984; Weber & Woodhead, 1970) and sea surface salinity (SSS) (Cole & Fairbanks, 1990). $^{18}O/^{16}O$ ratios change as a function of temperature (Swart 1983), with a proportional inverse correlation between temperature and coral $\delta^{18}O$ content; higher temperatures result in low $\delta^{18}O$ ratios and lower temperatures result in high $\delta^{18}O$ ratios (Weber and Woodhead 1972). Numerous authors have used the $\delta^{18}O$ of corals in recent decades to reconstruct paleotemperatures in tropical oceans (e.g., Kuhnert et al. 1999; Felis et al. 2000; Omata et al. 2006).

$\delta^{18}O$ data can also be used as a source of information concerning climatic events, such as the El Niño-Southern Oscillation – ENSO. The oceanic thermal anomalies associated with that event can become recorded in coral skeletons, allowing long-term reconstructions of El-Niño/La Niña events (Cole et al. 1993; Linsley et al. 2010; Soppa et al. 2011). Thermal stress situations can also influence the growth rates of corals (i.e., diminishing their linear extension rates), allowing us to determine if the corals have experienced anomalous climatic conditions (Rivera et al. 2018).

Carbon stable isotopes are still a matter of debate in terms of their application as proxies for climatic conditions due to the complex role of physiology on the control of carbon (Swart 1983). However, numerous workers have reported that annual variations in $\delta^{13}C$ in corals are directly related to light incident levels, which ultimately influence photosynthetic activity of symbiont host by corals call zooxanthellae. The lighter isotope (^{12}C) is preferentially used by the zooxanthellae during photosynthesis, leaving the calcification site, where coral exoskeleton is formed, enriched in ^{13}C and as consequence the aragonite produced has a higher $\delta^{13}C$ (Weber & Woodhead 1970; Rodrigues & Fauth 2013).

Therefore, thee $\delta^{13}C$ of corals can be used as a proxy for luminosity and cloud cover (Allison et al. 1996) although it is influenced by other factors beyond photosynthesis, such as pH, reproduction, water depth, and respiration (Swart, 1983; Swart et al. 1996). Several workers have shown that decadal- to centennial-scale variation in coral $\delta^{13}C$ can be used to track changes in surface dissolved inorganic carbon (DIC) (Swart et al. 2010; Al-Rousan & Felis 2013; Dassié et al. 2013; Pereira et al. 2018) long-term changes in coral $\delta^{13}C$ are associated with changes in atmospheric carbon isotopic compositions resulted from fossil fuel burning and known as Suess Effect (Keeling 1979).

As $\delta^{18}O$ and $\delta^{13}C$ short-term variations are dependent on seasonal environmental variables, C and O stable isotope cycles along the growth axis of coral exoskeletons can be used to evaluate their growth rates.

The western region of the tropical South Atlantic is characterized by a low diversity of coral species but high endemism (Leão et al. 2003, 2010). Many of those species have not been yet evaluated in terms of their potential as natural archives for environmental variables, and few workers are actively investigating them (Mayal et al. 2009; Kikuchi et al. 2013; Evangelista et al. 2015, 2018; Pereira et al. 2018b).

The Brazilian genera of hermatypic corals from the South Atlantic that have been studied to date include: *Porites* (e.g., Pereira et al. 2015, 2017), *Siderastrea* (e.g., Evangelista et al. 2018; Pereira et al. 2018), and *Mussismilia* (e.g. Evangelista et al. 2007; Kikuchi et al. 2013). Of the four species of *Mussismilia* (*M. hispida*, *M. braziliensis* , *M. hartti*, and *M. lepdophylla*), *M. hispida* has the widest geographic distribution, occurring in the states of Maranhão, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Bahia, Espírito Santo, Rio de Janeiro, and São Paulo; they are also found on more distant oceanic coral reefs such as the Rocas Atoll and on Fernando de Noronha Island (Leão et al. 2016).

The geographic distribution of *M. hispida* call the attention for the possibility of replicated studies that compare the same species in different regions - which would minimize any particular effects of species variations in relation to the incorporation of geochemical data. Here, we present the first data of $\delta^{18}O$ and $\delta^{13}C$ records for the species *M. hispida*, and growth rate of that important species in the equatorial South Atlantic.

2. STUDY AREA

The Rocas Atoll is located in the western part of the South Atlantic (3°51´S, 33°49´W), 266 km off the northeastern coast of Brazil (Fig. 1). It is an isolated oceanic atoll in an interesting location that allows corals to grow in a near-pristine environment with distinct oceanic and atmospheric processes.

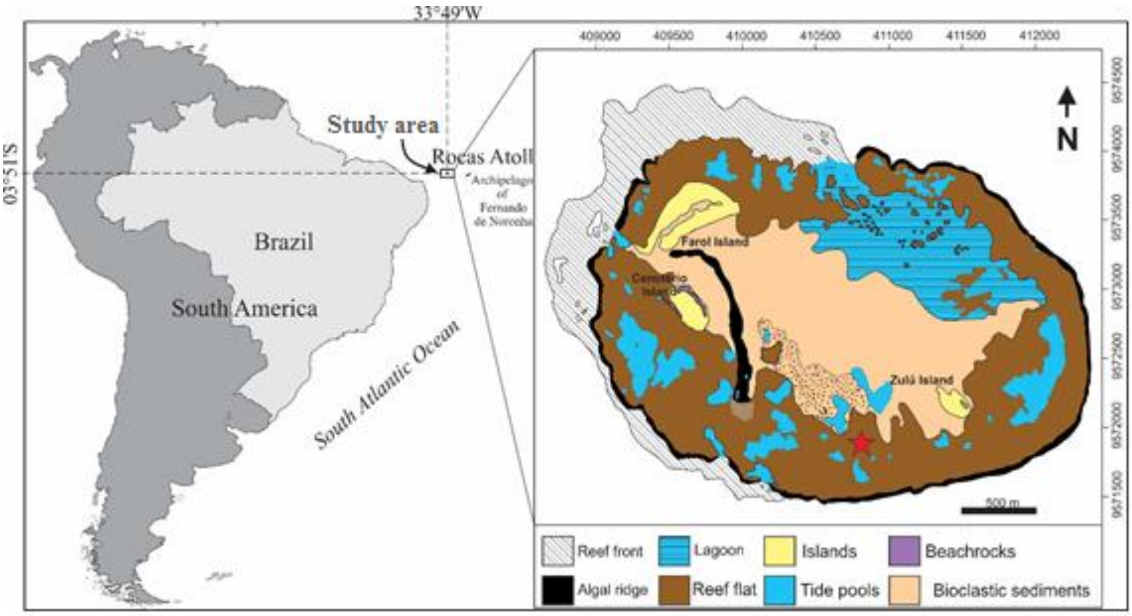

Figure 1 –Geomorphological map of the Rocas Atoll. The red star indicates the location on a flat reef where *M. hispida* colonies were studied and collected. Adapted from Pereira et al., 2017.

The Rocas Atoll is dominated by the South Equatorial Current (SEC), with a consistent westerly flow (Goes 2005). The mean velocity of the SEC at the 4°S parallel (which crosses Rocas Atoll) is 30 cm/s (Richardson & Walsh 1986). According to Gherardi & Bosence (2001), the tidal regime on the atoll is semi-diurnal and meso-tidal, and grid box salinity within the coordinates of Rocas (33.5W and 3.5S) varies between 35.8 and 36.3 annually (Antonov et al., 2010).

The reef grows on the western part of the flattened top of a submarine volcano (Guyot type) that rises up from depths of 4000 m (Kikuchi & Leão 1997; Pereira et al. 2013). The evolution of this complex reef included colonization of the guyot by coralline algae, scleractinian corals, mollusks, and crustaceans. The accumulation of marine carbonate provided the base for the ellipsoid reef ring now in existence (Gherardi and Bosence 2001). Coral skeletons at the bottom of an 11.69 m drill hole into the carbonate platform of the Rocas Atoll provided a maximum conventional ^{14}C radiometric age of 4.86 ± 0.21 ky BP at the depth of 11.2 m (Kikuchi and Leão 1997). That age may not correspond to the beginning of reef development, however, as no basement rock was recovered. Thus, it is assumed that the initiation of reef growth began before 4.86 ka, with a buildup rate of 1.5 to 3.2 m/kyr (Kikuchi and Leão 1997).

3. METHODOLOGY

3.1. Colony collections

Three dead *M. hispida* colonies (13MH-1, 13MH-2 and 13MH-3) were collected on the reef plateau in the southern portion of the Rocas Atoll (Fig. 2). While that species currently shows low representivity in terms of coral cover at the Rocas Atoll, there are expressive numbers of dead *M. hispida* colonies on the southern portion of that atoll (although the causes of that elevated mortality are still unknown). Two subsamples were removed at two locations, MHA (upper portion of the colony) and MHB (the lower portion of the colony) along the growth axis of the lamina of coral 13MH-1 (Fig. 2a) to determine its age using U-Th dating.

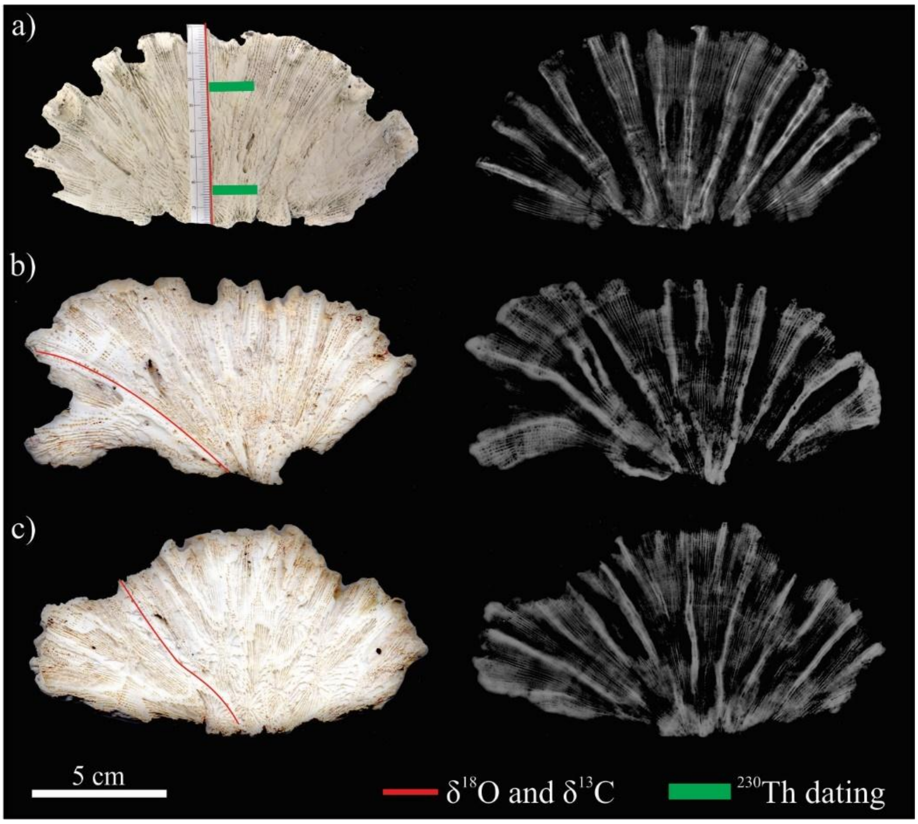

Figure 2. 5-mm-thick slices and respective radiographies of colonies 13MH-1 (a), 13MH-2 (b), and 13MH-3 (c). Density bands are not visible in these X-rays. High-resolution carbonate sampling for $\delta^{18}O$ and $\delta^{13}C$ analyses (red lines) was performed, following a single coralline wall. Two subsamples were collected for U-Th dating (green bars) of colony 13MH-1.

3.2. Sampling for isotopic analyses

The colonies studied were cut into 5-mm-thick slices along the principal growth axis. A slice was selected from each colony to be radiographed at 50 kVA, 320 mA, for 3.2 s, with the distance of 108 cm from the equipment to the coral slice. Micro-sampling was performed using a micro-drill to remove carbonate samples along one of the coralitte walls, with a resolution interval of 0.5 mm (Fig. 2).

3.3. Isotopic analyses of Carbon and Oxygen

Stable isotope ratios of carbon and oxygen were measured at the Federal University of Pernambuco using a Delta V Advantage coupled with a GasBench II device. Sets containing 56 coral samples were analyzed against 16 samples of 4 different standards, 2 international, NBS-18 and NBS-19 and 2 internal, REI and VICKS. The precision of the analysis was assessed by repeated measurements of the four standard and was better than 0.10‰ for $\delta^{13}C$ and $\delta^{18}O$. All coral $\delta^{13}C$ and $\delta^{18}O$ data are reported in per mill (‰) relative to Vienna Pee Dee Belemnite (VPDB).

3.4. Uranium-thorium (U/Th) dating

U-Th dating was conducted in a class-10.000 metal-free clean room with class-100 benches at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Geosciences Department, National Taiwan University (Shen et al., 2008). U-Th isotopic compositions and concentrations were determined on a multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) in the HISPEC (Shen et al., 2012). The half-lives of U-Th nuclides used for ^{230}Th age calculation are given in Cheng et al. (2013). Uncertainties in the U-Th isotopic data and ^{230}Th dates are calculated at the 2σ level (two standard deviations of the mean, $2\sigma_m$), unless otherwise noted.

3.5. Growth rate

Coral growth rates were determined by measuring the distances (mm) between the peaks of the isotopic cycles of $\delta^{13}C$, or the distances between the valleys of the $\delta^{18}O$ cycles, as those cycles are interpreted as being annual. The lengths of the cycles of each colony were used to determine their mean annual growth rates (excluding the first and last cycles of each colony due to uncertainty of whether they represent complete cycles).

The growth rate of colony 13MH-1 was also estimated by U/Th dating, in which the differences between the ages determined (in years) for two points were divided by the distance between them (in mm).

4. RESULTS

4.1. Stable isotopes

$\delta^{13}C$ data for the colonies of *M. hispida* varied between −0.38 and 2.40‰, with a mean value of 0.91±0.59‰ for colony 13MH-1, between −2.59 and 3.78‰, with a mean value of 0.40±1.0‰ for colony 13MH-2 and for colony 13MH-3 yielded values between −2.81‰ and 2.67‰, with a mean of 0.57±0.99‰ (Fig. 3).

The $\delta^{18}O$ values of colony 13MH-1 varied between −4.27 and −1.32‰, with a mean value of −3.29 ±0.42‰; colony 13MH-2 showed $\delta^{18}O$ values between −6.89 and

−1.58‰, with a mean of −4.09±1.00‰; colony 13MH-3 showed values between −6.18 and −1.58‰, with a mean of −4.27±1.00‰ (Fig. 3).

Medium to long-term oscillation on the isotopic record are observed. There was a sequence of isotopic cycles between ~30 and 43 mm in colony 13MH-1 demonstrating low carbon values (Fig. 3). Colony 13MH-3 demonstrated large temporal series of $\delta^{18}O$ values between 5 and 30.5 mm (cycle 1) and between 47.5 and 64.5 mm (cycle 2) (Figure 3) that were characterized by low ^{13}C contents.

Those anomalous temporal series of $\delta^{18}O$ and $\delta^{13}C$ values could indicate changes in the conditions of the coral environments, or artifacts reflecting different skeleton structures with different isotopic compositions, such as those identified by DeLong et al. (2013) and will not be discussed in this study, which will focuses on short-term variations.

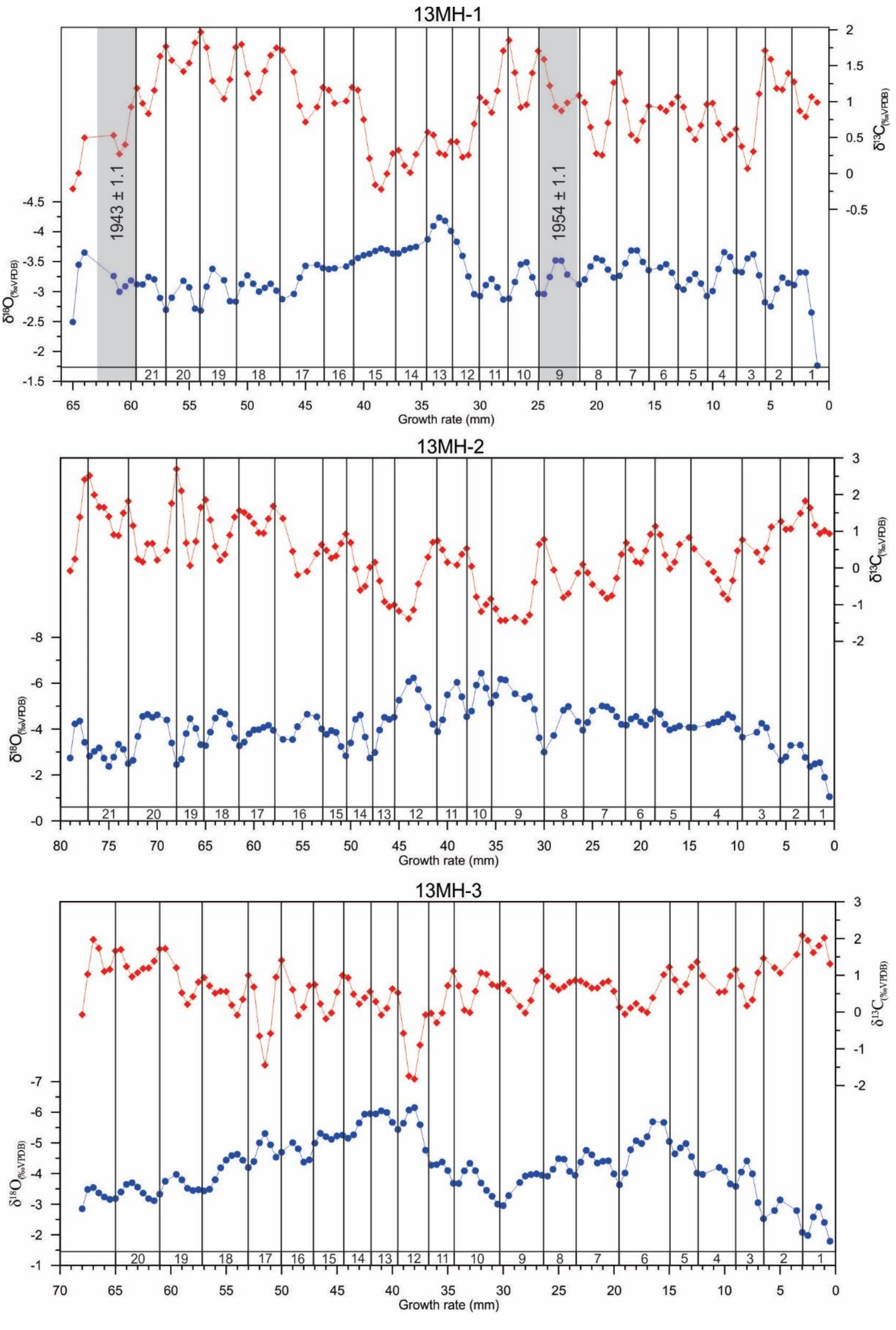

Figure 3 -Temporal series of $\delta^{18}O$ and $\delta^{13}C$ values obtained from sections of colonies 13MH11, 13MH-2, and 13MH-3 (the $\delta^{18}O$ axis is presented inverted).

4.2. U-Th Dating

The U-Th dating results for the two samples from colony 13MH-1 indicated absolute ages of 61.5 ± 1.1 and 72.7 ±1.1 years for samples MHA and MHB respectively (Table 1). These values approximately refers to the time interval between 1944 and 1955. The age difference between samples MHA and MHB was 11±2.2 years, equivalent to the age demonstrated by the numbers of annual isotopic cycles (13 for the same exoskeleton section) (Table 2).

Table 1 - Results of the U-Th dating technique using samples removed along the growth axis of the exoskeleton of *M. híspida*.

Sample ID	Weight g	^{238}U ppb^{a}	^{232}Th ppt	□^{234}U measured^{a}	[^{230}Th/^{232}Th] ppm^{c}	Non-corrected age	Corrected age^{d}	□^{234}U$_{initial}$ corrected^{b}
MH-A	0.17560	**2334.9 ± 2.2**	**160.5 ± 2.7**	**147.5 ± 1.7**	**159.2 ± 3.2**	**63.06 ± 0.71**	**61.5 ± 1.1**	**147.5 ± 1.7**
MH-B	0.23862	**2187.7 ± 2.1**	**138.5 ± 2.0**	**146.4 ± 1.5**	**203.1 ± 3.6**	**74.21 ± 0.78**	**72.7 ± 1.1**	**146.5 ± 1.5**

†Analytical errors are 2□ of the mean.
^{a}[^{238}U] = [^{235}U] x 137.77 (±0.11‰) (Hiess et al., 2012); □^{234}U = ([^{234}U/^{238}U]$_{activity}$ - 1) x 1000.
^{b}□^{234}U$_{initial}$ corrected was calculated based on the ^{230}Th age (T), i.e., □^{234}U$_{initial}$ = □^{234}U$_{measured}$ *X* e$^{□234*T}$, and T is the corrected age.
^{c}[^{230}Th/^{238}U]$_{activity}$ = 1 - e$^{-□230T}$ + (□^{234}U$_{measured}$/1000)[□$_{230}$/(□$_{230}$ - □$_{234}$)](1 - e$^{-(□230\ -\ □234)\ T}$), where *T* is the age. Decay constants are 9.1705 x 10^{-6} yr^{-1} for ^{230}Th, 2.8221 x 10^{-6} yr^{-1} for ^{234}U (Cheng et al., 2013), and 1.55125 x 10^{-10} yr^{-1} for ^{238}U (Jaffey et al., 1971).
^{d}The degree of detrital ^{230}Th contamination is indicated by the [^{230}Th/^{232}Th] atomic ratio instead of the activity ratio.
^{e}Age corrections, relative to the chemistry date on 1th, January, 2016 were calculated using an estimated atomic ^{230}Th/^{232}Th ratio of 4 ± 2 ppm (Shen et al., 2008)

4.3. Growth rate

The mean growth rate of colony 13MH-1 (Table 2), according to the U-Th dating, was 3.57±1.03 mm/year for the section between sample MHA and sample MHB, and 2.96±0.57 mm/year as determined by the stable isotopic cycles for the same section.

Table 2. a Growth rate and calendar years, calculated from October/2013. b Mean growth rate, estimated based on U-series ages for the total coral record.

Colony	Sample ID	Depth range (mm)	Age interval (U-series)	Growth rate (mm.y^{-1})	δ^{13}C cycles	Years (U-series)
13MH-1	MHA/MHB	25 to 65	1944-1955^{a}	3.57 (±1.03)^{b}	13	11 (±2.2)

By counting the isotopic cycles presented in the in colonies 13MH-1, 13MH-2, and 13MH-3, it was identified a total of 21, 21 and 20 cycles, respectively. Table 3 shows the mean growth rates as derived from measures of the isotopic cycles of all three colonies. Colony 13MH-1 demonstrated a minimum growth rate of 2.22 mm/year, a maximum of 3.79 mm/year, and a mean of 2.83±0.51 mm/year. Colony 13MH-2 demonstrated a minimum growth rate of 1.96 mm/year, a maximum rate of 4.71 mm/year, and mean of 3.21±0.86 mm/year; colony 13MH-3 demonstrated a minimum growth rate of 2.65 mm/year, a maximum rate of 5.29 mm/year, and a mean of 3.71±0.82 mm/year.

Table 3 – Growth rates evaluated according to cycle extensions (mm) for coral colonies 13MH-1, 13MH-2 and 13MH-3. Values from the first and last cycles were not included.

Isotopic Cycle	Extension (mm)		
	13MH-1	13MH-2	13MH-3
1	-	-	-
2	2.27	2.54	4.04
3	2.48	3.42	2.92
4	2.48	4.59	3.90
5	2.54	3.22	2.92
6	2.51	2.66	5.29
7	2.77	3.75	4.46
8	3.18	3.54	3.39
9	3.50	4.71	4.55
10	2.65	2.22	4.73
11	2.48	2.70	2.65
12	2.30	3.79	3.20
13	2.22	1.97	2.78
14	2.65	2.34	2.83
15	3.61	2.13	3.16
16	2.54	4.31	3.34
17	3.79	3.22	3.43
18	3.73	3.14	4.78
19	3.15	2.46	4.41
20	2.91	4.31	-
21	-	-	
Mean	2.83±0.51	3.21±0.86	3.71±0.82

5. DISCUSSION

5.1. Growth rate

The colonies of *M. hispida* analyzed here displayed well-defined annual stable isotopic cycles in most of their records, which could be used to measure their extension rates (which varied from 2.83 to 3.71 mm/year). Colony 13MH-1 growth rates were the most constant among the three colonies (Fig. 4). Coral colonies may present different growth strategies even within the same species living in the same region under similar environmental conditions (Rogers 1979).

Growth rate variations along the life of a coral colony can occur for numerous reasons, including the effects of climatic oscillation events such as the EL Niño Southern Oscillation (ENSO) (Dodge & Vaisnys, 1980; Wellington & Glynn, 1983; Cruz-Piñón et al. 2003 among others).

Analyses of the bands of the coral *M. leptophylla* at Abrolhos (off the Brazilian coast) under favorable conditions (abundant light) made by Evangelista et al. (2007), showed that coral growth during ENSO events decreased in contrast to normal conditions in the region due to greater sediment deposition.

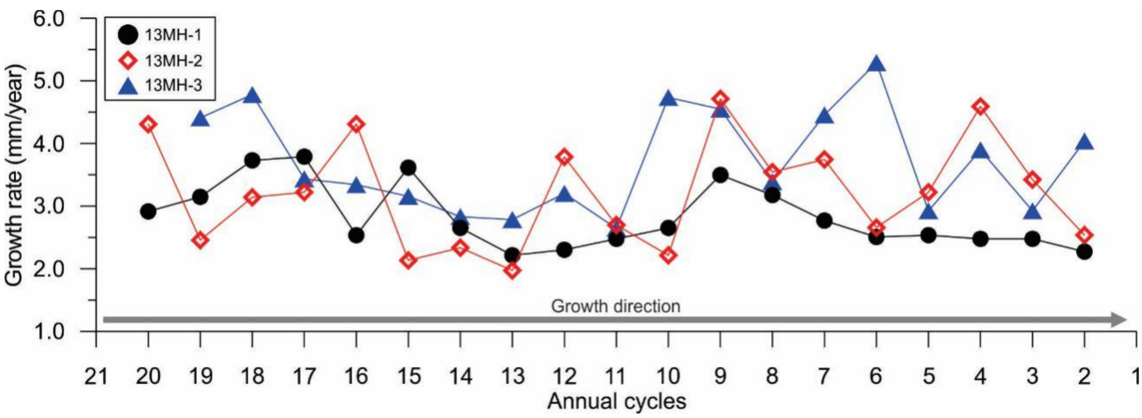

Figure 4. Growth rate through time of colonies 13MH-1 (black circle), 13MH-2 (red diamonds), and 13MH-3 (blue triangles).

Other species of the genus *Mussismilia* presented distinct growth rates from the ones reported here. Kikuchi et al. (2013) reported mean growth rate of 9.2 mm/year for a colony of *M. braziliensis*, measured using CoralXDS software (which allows measurements of linear extension, density, and calcification using coral exoskeleton radiographs). Suggett et al. (2012) reported a mean growth rate of ~6 mm/year for three colonies of *M. braziliensis*, and a mean value of ~2 mm/year for three colonies of *M.*

hartti. Leão et al. (2003) reported a mean growth rate of 8 mm/year for *M. braziliensis* (X-ray measurements). All of the abovementioned measurements were obtained from colonies collected at Abrolhos, in Bahia State. Comparisons of those published growth rates with those obtained here, demonstrates that *M. hispida* has a mean growth rate closer to *M. hartti* than to *M. braziliensis*.

Other coral genera from the same region on the Rocas Atoll have likewise been evaluated. Pereira et al. (2017) reported that the growth rate of *Porites astreoides* varied from 6.5 to 13.0 mm/year, with a mean of 8.62±1.82 mm/year. Pereira et al. (2018) reported that different *Siderastrea stellata* colonies had mean growth rates of 2.90, 2.76 and 3.46 mm/year. Evangelista et al. (2018) reported values of 6.01±1.08 mm/year for the same species by counting density bands. Pinheiro et al. (2017) reported a much larger growth rate (6.8±0.7 mm/year) in *S. stellata* using coralXDS software.

Coral species demonstrating high growth rates (between 3-15 mm/year) can provide high resolution climate data, while slow-growing species, such as *Siderastrea radians* (~1.3 mm/year), present more difficulty in interpreting climatic data due to the low resolution of their geochemical records, which could lead to erroneous interpretations (Moses & Swart, 2006). Thus, the colonies of *M. hispida* reported here are suitable for high-resolution climate archive.

5.2. Seasonal isotopic variability and environmental records

Fourier spectral analyses of the $\delta^{13}C$ data revealed weak peaks at the frequencies of 3.21 mm and 3.94 mm near the annual growth rates determined for colonies 13MH-1 and 13MH-2 respectively. Period peaks that could be interpreted as annual were not observed in colony 13MH-3. The dominant peaks in $\delta^{13}C$ data are at the frequencies of 26.88, 72.55 and 72.38 mm for colonies 13MH-1, 13MH-2 and 13MH-3, respectively, in which, the last two corals (13MH-2 and 13MH-3), the frequencies correspond to the approximately interval of 20 year, whereas colony 13MH-1 has frequency close to 10 years interval.

The $\delta^{18}O$ records showed dominant peaks at the frequencies of 26.66, 75.11 and 28.94 for colonies 13MH-1, 13MH-2 and 13MH-3, respectively. Frequencies at interval of approximately 20 years are present at the three colonies studied here and might be tracking interannual long-term trends in SST (table 4).

Table 4. Fourier transformation analyses of the $\delta^{18}O$ and $\delta^{13}C$ records of colonies 13MH-1, 13MH-2 and 13MH-3.

13MH-1 ($\delta^{13}C$) Period		13MH-2 ($\delta^{13}C$) Period		13MH-3 ($\delta^{13}C$) Period	
mm/wave	Years/wave	mm/wave)	Years/wave	mm/wave)	Years/wave
26.88	9.5	72.55	23.3	72.38	19.5
38.59	13.6	11.95	3.8	1.61	0.4
14.79	5.2	9.24	3.0	0.99	0.3
3.21	1.1	3.94	1.3	1.93	0.5
13MH-1 ($\delta^{18}O$) Period		13MH-2 ($\delta^{18}O$) Period		13MH-3 ($\delta^{18}O$) Period	
mm/wave)	Years/wave	mm/wave	Years/wave	mm/wave	Years/wave
26.66	9.4	75.11	24.1	28.94	7.8
55.29	19.5	25.88	8.3	72.38	19.5
15.66	5.5	9.05	2.9	21.55	5.8
8.67	3.1	11.35	3.6	15.05	4.1

The median and long-term frequencies observed in the $\delta^{18}O$ records of the three colonies could be explained by the equatorial location of the Rocas Atoll, where the climate is characterized by a strong interannual variability compared to seasonal variability. Multiple factors, such as the Intertropical Convergence Zone (ITCZ) and the ocean surface meridional temperature gradient (which is associated with changes in wind direction), influence climatic variability in the tropics (Mélice & Servain, 2003).

6. CONCLUSION

$\delta^{18}O$ and $\delta^{13}C$ coral-based records for the species *M. hispida* from the Rocas Atoll revealed time-series dominated by short and long-term variations. The short-term variations were governed by annual seasonality (i.e., SST and solar radiation levels) and could be used to determine the annual extension rates of the three colonies, revealing growth rates varying between 1.99 and 5.29 mm/year, with an overall mean of 3.21 ±0.87 mm/year – similar to the estimation obtained by using U-Th dating (3.57±1.03 mm/year). Due to its wide geographical distribution, *M. hispida* seems to be an important natural archive which may provide high-resolution climate and environmental records throughout the eastern coast of South America and composite-records using living and fossil colonies at multiple sites might generate longer records to assess climate variability at the tropical Southern Atlantic Ocean.

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CAPÍTULO III – CONCLUSÃO

Este estudo trouxe o primeiro registro a respeito da taxa de crescimento, bem como de dados isotópicos de *M. hispida*. A taxa de crescimento para essa espécie mostrou-se menor, comparada com outras espécies do mesmo gênero (*M. braziliensis* e *M. hartti*). Porém, esta taxa de *M. hispida* é suficiente para se obter informações de alta resolução, do ponto de vista para utilização de corais como arquivo climático e permite armazenar uma grande quantidade de informações por comprimento, no entanto, torna-se necessária a calibração de um paleotermômetro para a espécie estudada para consolida-la como arquivo paleoclimático.

O padrão das séries temporais das três colônias mostrou semelhança, como grandes sequências de ~15 mm e quantidade de ciclos ao longo dos 80 mm. A datação de U-Th mostrou coerência com os ciclos isotópicos da 13MH1, o que, demostra a capacidade da espécie *Mussismilia hispida* para estudos com resolução anual, o que permite o entendimento sobre as variações ambientais, por meio de seu amplo registro acerca do local em que cresceu.

Corais apresentam respostas diferentes para cada localidade, o que torna necessário expandir as investigações aqui realizadas para outras regiões do nordeste brasileiro. Sabendo que *M. hispida* integra o grupo das espécies importantes na construção dos recifes da costa brasileira e apresenta grande distribuição, a utilização dessa espécie endêmica e importante para a região, pode tornar seu conteúdo geoquímico uma ferramenta promissora para se reconstruir e compreender as mudanças oceanográficas do oceano Atlântico Sul.

ANEXO I

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AUTHOR INFORMATION PACK

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ANEXO II

Comprovante de submissão do artigo

Manuscript Details

Manuscript number	SAMES_2019_220
Title	Assessing the growth rate of the South Atlantic coral species Mussismilia hispida (VERRILL, 1902) using carbon and oxygen stable isotopes
Article type	Research Paper

Abstract

Scleractinian corals grow by the precipitation of $CaCO3$ by a thin tissue layer at the top of the colony. The exoskeleton resulted from this biomineralization process usually presented density bands, which a pair of low and high-density is interpreted as annual bands. Such information is used to determine the growth rate of a colony and estimate chronology in calendar year. Nevertheless, some corals do not present density bands, making difficult to constrain a good chronology and assess growth rate pattern, demanding another approach. Carbon and oxygen stable isotope ratios (δ13C and δ18O) are commonly used as proxies for cloud cover and sea surface temperature (SST), respectively. Thus, once these proxies have annual seasonality, the length and number of δ13C and δ18O cycles can be used to estimate growth rate and dating a coral record. Here we used δ13C and δ18O length cycles to estimate and report the growth rates data for three colonies of the coral Mussismilia hispida (VERRILL, 1902), an endemic species of the South Atlantic Ocean. The studied colonies, 13MH-1, 13MH-2, and 13MH-3, demonstrated mean growth rates of 2.83 ± 0.51, 3.21 ± 0.86 and 3.71 ± 0.82 mm/year respectively. U-Th dating of two samples from colony 13MH-1 indicated absolute ages of 61.5 ± 1.1 and 72.7 ± 1.1 calendar years and a mean growth rate of 3.57 ± 1.03 mm/year, similarly to the stable isotope results. Our results showed that the δ18O and δ13C records of M. hispida colonies at the Rocas Atoll are dominated by short and medium-term variations. The short-term variation seems to be governed by annual seasonality (i.e., SST and solar radiation levels) and were used to determine the extension rates of the three colonies, providing know insights for the use of the species M. hispida, a widely distributed species in the South Atlantic, as a good high-resolution environmental record.

Keywords	Isotopic geochemistry; Hermatypic corals; Paleoclimatology.
Taxonomy	Elemental Geochemistry, Radiogenic Isotope Geochemistry
Corresponding Author	Natan Pereira
Corresponding Author's Institution	State University of Bahia
Order of Authors	Isabel Silva, Alexandre Liparini, Natan Pereira, Brenda Braga, Alcides Sial, Sze-Chieh Liu, Chuan-Chou Shen, Ruy Kikuchi
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ANEXO III

Justificativa de coautorias

Em acordo à resolução 01/2018 do colegiado do PGAB, segue a justificativa da participação dos coautores nos artigos aqui propostos (outros autores além do aluno do programa, seu orientador e coorientador):

Brenda Lorena Soares da Silva Braga: a coautora contribuiu no tratamento e interpretação dos dados, edição de figuras e discussões.

Alcides Nobrega Sial: o coautor contribuiu com o apoio para a realização das análises geoquímicas, parte crucial deste estudo, uma vez que sem esta analise não seria possível chegar aos resultados e assim alcançar os objetivos.

Ruy Kenji Papa de Kikuchi: o coautor contribuiu com o equipamento necessário e com o auxílio para a realização das amostragens das colônias, além do seu riquíssimo domínio sobre a área de estudo e o conteúdo dessa pesquisa, o que foi de extrema importância, pois favoreceu para uma melhor construção deste trabalho.

Chuan-Chou Shen e Liu Sze-Chieh: os coautores contribuíram com a realização da datação de Urânio-Tório U/Th bem como com a interpretação destes dados, o que corroborou de forma significativa com este estudo, uma vez que por meio deste método obtivemos a idade precisa da espécie estudada, possibilitando um melhor esclarecimento dos resultados obtidos, além de contribuírem na elaboração do texto.

APÊNDICE A – Resultados das análises de isótopos estáveis de C e O nas colônias de M. hispida.

	MH1		MH2		MH3	
Distância (mm)	$\delta^{13}C_{cor}‰_{(VPDB)}$	$\delta^{18}O_{cor}‰_{(VPDB)}$	$\delta^{13}C_{cor}‰_{(VPDB)}$	$\delta^{18}O_{cor}‰_{(VPDB)}$	$\delta^{13}C_{cor}‰_{(VPDB)}$	$\delta^{18}O_{cor}‰_{(VPDB)}$
0,5	0,82	-2,98	1,07	-2,14	1,23	-3,58
1	1,03	-3,06	1,11	-1,69	2,09	-1,74
1,5	1,21	-2,18	1,02	-2,22	2,07	-2,59
2	0,81	-3,32	0,97	-2,35	0,99	-3,16
2,5	0,62	-3,31	1,62	-3,08	2,53	-1,58
3	1,47	-3,20	2,00	-2,30	1,92	-2,30
3,5	1,38	-3,09	1,28	-3,12	1,36	-2,67
4	1,23	-3,19			0,13	
4,5	0,95	-3,21	1,69	-3,38		
5	1,69	-2,49	-0,27	-3,49	1,38	-3,00
5,5	2,04	-2,98	2,64	-1,57	0,77	-3,38
6	0,55	-3,37				
6,5	0,64	-3,43	0,68	-3,84	2,16	-1,70
7	0,06	-3,54	0,01	-3,95	0,27	-3,51
7,5	0,33	-3,50	0,83	-4,33	0,83	-4,18
8	0,54	-3,28	0,14	-3,78	0,06	-4,04
8,5	0,61	-3,49			0,72	-3,96
9	0,55	-3,64			1,15	-4,02
9,5	0,57	-3,51	0,81	-3,50	0,67	-3,54
10	0,92	-3,09	0,57	-4,12	1,27	-3,68
10,5	1,30	-2,48	-0,65	-4,82	-0,08	-4,58
11	0,23	-3,63	-0,58	-4,21	2,62	
11,5	0,68	-3,08	-0,64	-4,40	-2,61	
12	0,82	-3,17	-0,43	-4,58	1,09	-3,98
12,5	0,46	-3,14	-0,50	-4,60	1,44	-3,97
13	1,45	-2,90	0,78	-3,29	1,55	-4,20
13,5	0,81	-3,58	3,78		0,13	-5,48
14	0,95	-3,25			0,82	-4,76
14,5	0,74	-3,47	0,38	-4,58	1,15	-4,18

15	0,64	-3,55	0,29	-4,45	1,01	-5,60
15,5	1,19	-3,26			0,80	-5,44
16	0,52	-3,74	1,23	-3,49	2,67	
16,5	0,54	-3,50	-0,15	-4,27	0,55	-5,59
17	0,63	-3,56	0,35	-3,92	0,46	-5,27
17,5	0,77	-3,79	-0,24	-4,55	-0,84	-5,31
18	1,59	-3,09	1,38	-4,15	1,01	-4,35
18,5	1,33	-3,17	0,83	-5,00	-0,59	-5,39
19	0,41	-3,49	1,43	-4,42	1,05	-3,98
19,5	0,51	-3,43	-0,13	-4,25	-1,25	-3,26
20	0,23	-3,70	0,08	-4,16	1,37	-4,13
20,5	0,54	-3,24	0,99	-4,72	0,96	-4,75
21	1,15	-3,22	-0,09	-3,99	0,45	-4,04
21,5	0,84	-3,35	0,32	-5,06	0,48	-4,25
22	0,24	-4,08	1,15	-3,30	1,05	-5,06
22,5	1,31	-2,97	-0,66	-4,92	0,84	-4,36
23	0,57	-3,71	-0,68	-4,92	0,38	-4,48
23,5	1,13	-3,47	-1,07	-4,83	0,93	-4,18
24	1,08	-3,23	-0,44	-5,18	1,39	-3,49
24,5	1,69	-2,95			0,11	-5,17
25	1,71	-3,06	-0,24	-4,41	0,62	-4,07
25,5	1,23	-3,05	-0,62	-4,72	1,09	-4,10
26	1,27	-3,64	0,38	-3,92	0,58	-4,11
26,5	0,51	-3,47	-0,15	-3,93	1,45	-3,89
27	1,75	-3,03	-0,81		0,53	-3,98
27,5	1,88	-2,92	-0,79	-5,41	0,37	-3,86
28	1,15	-3,02	-0,54	-4,58	0,35	-4,03
28,5	1,92	-2,80	2,03		-0,24	-3,77
29	0,41	-3,51	-0,52	-3,83	1,45	
29,5	0,95	-2,85	1,52		0,44	-3,20
30	1,20	-3,00	0,98	-3,09	1,48	-2,71
30,5	0,77	-3,13	1,03	-3,12	-0,19	-3,57
31	0,06	-3,05	-0,92	-5,58	1,69	-2,73

31,5	0,27	-3,52	-1,16	-4,99	-0,06	-3,63
32	0,55	-4,14	-1,43	-5,32	2,00	-3,81
32,5	0,42	-3,81	-0,62	,	0,40	-3,92
33	0,00	-4,18	-0,94	-5,53	-0,67	-4,41
33,5	0,74	-4,18	-2,59	,	0,74	-4,00
34	0,23	-4,27	-2,16	-6,59	0,63	-4,02
34,5	0,41	-3,91	-1,10	-5,48	0,97	-3,00
35	0,05	-4,11	-0,77	-5,82	0,34	-4,79
35,5	0,74	-3,35	-1,52	-5,35	0,70	-4,18
36	-0,16	-4,04	-0,39	-5,46	-0,31	-3,83
36,5	-0,38	-3,90	-1,49	-6,19	-1,23	-5,04
37	1,07	-3,14	-1,07	-6,81	1,47	-4,15
37,5	-0,09	-3,87	0,93	-3,89	-1,54	-5,92
38	-0,09	-3,79	-0,45	-4,92	-2,25	-5,98
38,5	-0,07	-3,65	1,00	-5,17	-1,18	-6,16
39	-0,23	-3,62	-0,52	-6,89	-0,50	-5,64
39,5	0,33	-3,53	-1,77		-0,07	-5,43
40	0,66	-3,94	1,28	-4,09	1,21	-5,56
40,5	0,98	-3,33	-0,91	-5,43	-0,21	-6,18
41	1,52	-3,41	1,65	-3,72	-0,05	-5,97
41,5	0,92	-3,52	0,47	-4,12	0,56	-5,83
42	0,88	-3,40	0,31	-4,63	0,11	-6,09
42,5	0,84	-3,56			0,61	-5,99
43	1,20	-3,06	-0,37	-6,15	0,36	-5,46
43,5	1,18	-3,55	-1,62	-6,34	0,43	-5,26
44	1,33	-3,44	-0,62	-5,60	0,50	-5,58
44,5	0,96	-3,45			1,57	-4,58
45	0,00	-3,51	-1,51	-5,40	0,45	-5,70
45,5	1,31	-3,05	-1,37	-4,78	-0,28	-5,07
46	1,64	-3,06	-0,55	-4,28	-0,28	-4,98
46,5	2,40	-2,57	-1,15	-4,47	0,81	-5,52
47	1,41	-2,89	-0,13	-3,72	0,40	-4,84
47,5	1,71	-3,04	-0,23	-3,45	0,23	-4,73

48	1,71	-3,02	0,10	-2,70	1,24	-3,78
48,5	1,73	-3,09	0,04	-3,16	-1,32	-5,67
49	0,70	-3,10	-1,27	-4,72	1,65	-4,22
49,5	1,13	-3,14	0,18	-5,33		
50	1,59	-3,00	0,77	-2,14	0,91	-4,93
50,5	1,73	-3,42	0,94	-3,47	0,44	-5,03
51	1,63	-2,80	0,72	-3,12	0,78	-4,10
51,5	1,27	-2,76	-0,05	-4,28	-2,74	-5,92
52	1,38	-2,99	0,59	-2,97	-0,02	-4,69
52,5	1,75	-1,32	0,67	-4,74	0,37	-4,71
53	0,95	-3,83	0,29	-3,32	1,37	-3,85
53,5	1,76	-2,85	0,21	-5,20	0,33	-4,44
54	2,24	-2,47	0,66		-0,79	-4,99
54,5	1,52	-3,00	0,47	-3,89	0,94	-4,38
55	1,77	-3,06	0,32		0,64	-4,21
55,5	1,09	-3,12	-0,43	-4,59	-0,03	-4,41
56	1,47	-3,14	0,29	-3,55	0,59	-3,98
56,5	2,12	-2,67			1,24	-3,24
57	1,16	-3,05	1,25	-3,39	0,70	-3,23
57,5	1,97	-2,83			0,39	-4,00
58	1,21	-3,02	2,30	-3,85	0,93	-3,03
58,5	0,65	-3,23	0,77	-4,46	-0,09	-3,74
59	0,93	-3,42	1,00	-3,94	1,08	-3,76
59,5	1,48	-2,90	1,17	-3,81	0,30	-3,43
60	0,69	-3,19	1,15	-4,25	-2,81	
60,5	0,37	-2,99	1,33	-3,57	2,12	-5,02
61	0,39	-3,25	1,53	-3,58	2,33	-2,18
61,5	0,61	-3,27	1,54	-3,14	0,63	-3,05
62	0,51	-3,51	1,61	-3,62	0,88	-4,31
62,5	0,32	-3,45	0,49	-4,42	2,53	-2,30
63	0,30	-3,51	0,64	-4,49	-0,19	-4,02
63,5	0,32	-3,65	0,42	-4,24	1,43	-3,31
64	0,25	-3,26	-0,16	-5,95	1,25	-4,30

64,5	0,08	-3,51	2,17	-2,14	1,79	-2,91
65	0,04	-3,45	1,38	-4,16	1,29	-3,26
65,5			1,76	-3,45	1,71	-2,98
66			0,50	-3,82	0,47	-3,83
66,5			0,59	-4,02	2,35	-2,88
67			0,20	-4,47	1,58	-3,46
67,5			2,32	-2,55	1,07	-3,50
68			2,40	-2,04	0,11	-3,88
68,5			2,39	-3,82		
69			-0,11	-4,11		
69,5						
70			0,28	-4,99		
70,5			0,98	-4,08		
71			0,42	-4,89		
71,5			0,22	-4,34		
72			0,14	-4,29		
72,5			1,42	-1,58		
73			1,37	-3,51		
73,5			2,09	-2,56		
74			0,44	-3,44		
74,5			0,79	-2,93	0,17	-4,61
75			1,94	-2,06	-0,23	-4,89
75,5			1,34	-3,08	0,47	-5,84
76			1,49	-2,98	0,40	-3,18
76,5			2,16	-2,99	0,20	-5,39
77			2,64	-2,92	0,40	-5,35
77,5			2,47	-3,53	0,48	-6,17
78			0,81	-4,00	0,03	-5,32
78,5			0,80	-4,41	-0,94	-5,43
79			-0,01	-3,28	-0,21	-4,24
79,5					-0,34	-4,38
80					-0,86	-5,05