

**Universidade Federal do Rio Grande - FURG**

**Instituto de Oceanografia**

Programa de Pós-Graduação em Oceanologia

**Considerações Icnotaxonômicas e  
Tafonômicas dos Icnofósseis Encontrados  
*Ex Situ* na Planície Costeira do Rio Grande  
do Sul, Quaternário do Brasil**

**Giovana Pedrol de Freitas**

Dissertação apresentada ao  
Programa de Pós-Graduação em  
Oceanologia, como parte dos  
requisitos para a obtenção do  
Título de Mestre.

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Rio Grande, RS, Brasil

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por

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ATA

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# Lista de Acrônimos e Abreviações

## D

**DRX** – Difractometria de Raios-X

## E

**EDS** – Espectroscopia de Raios-X por Dispersão em Energia (*Energy Dispersive X-ray Spectroscopy*)

## M

**MSL** – *Main Sea Level*

**MEV** – Microscopia Eletrônica de Varredura

## N

**NMM** – Nível médio do mar

## P

**PCRS** – Planície Costeira do Rio Grande do Sul

## R

**ROV** – *Remotely operated underwater vehicle*

**RSCP** – Rio Grande do Sul Coastal Plain

## S

**SEM** – *Scanning Electron Microscopy*

**SOT** – *Spongiomorpha, Ophiomorpha and Thalassinoides*

## X

**XRD** – *X-Ray Diffractometry*

# Resumo

A Planície Costeira do Rio Grande do Sul (PCRS) (Sul do Brasil) é composta por diversos depósitos fossilíferos tanto continentais, quanto marinhos que estão relacionados a, pelo menos, quatro sistemas deposicionais do tipo laguna-barreira pertencentes aos sedimentos Quaternários (Pleistoceno–Holoceno). Parte destes depósitos se encontram submersos atualmente e estão sujeitos à erosão devido à incidência de ondas, resultando em exumação de fósseis corporais de vertebrados e invertebrados e icnofósseis que são depositados na face de praia atual. Dentre eles, 253 fragmentos de tocas de crustáceos fósseis foram coletados e o estudo destes materiais é o objetivo deste trabalho. Diferentes análises foram realizadas com o intuito de descrever o registro destes traços na PCRS, como análise morfológica, que incluiu medições do diâmetro externo e interno, largura da parede (em seção transversal) e o diâmetro dos *pellets*, quando presentes. Análises químicas e de microestruturas obtidos pela Microscopia Eletrônica de Varredura (MEV), Difratomia de Raios-X (DRX), Espectroscopia de Raios-X por Dispersão em Energia (EDS) e lâminas petrográficas, além de análises tafonômicas e neoicnológicas. Duas icnoespécies de *Ophiomorpha* foram identificadas (*O. nodosa* e *O. puerilis*), mas grande parte do material foi designada ao grupo SOT (= *Spongeliomorpha*, *Ophiomorpha* e *Thalassinoides*) principalmente pela ausência de *pellets* na parede externa dos traços. Os processos tafonômicos (exumação, retrabalhamento e transporte) que agem nos depósitos submersos de origem da assembléia icnofossilífera *ex situ* pode ser uma das razões da ausência de *pellets*. Com isso, uma reconstituição tafonômica incluindo a dinâmica paleoambiental são apresentados com a finalidade de demonstrar como os processos afetam os traços coletados *ex situ*, desde sua construção, passando pela exumação e posterior transporte para a face de praia atual. Além disso, observações neoicnológicas das tocas de *Sergio mirim* indicaram que organismos maiores que o *S. mirim* foram os construtores do traço *O. nodosa* encontrado *ex situ*.

**Palavras-chaves:** Icnologia; *Ophiomorpha nodosa*; *Ophiomorpha puerilis*; *Spongeliomorpha*; *Thalassinoides*; *Sergio mirim*; Paleolinhas de costa.

# Abstract

The Rio Grande do Sul Coastal Plain (RSCP) (southern Brazil) is composed by extended marine and continental deposits related to at least four barrier-lagoon systems of Pleistocene-Holocene age. Part of these deposits is currently submerged and passing through erosion processes by waves. Vertebrate and invertebrate body and trace fossils are constantly exhumed from these deposits and redeposited on the modern beach face. Among them, a total of 253 fragments of crustacean burrows were collected and the study of these materials is the main goal of the present manuscript. Different analyses were performed in order to describe the record in the RSCP, such as morphological analysis, which included measurements of the external and internal diameter, wall width (in cross section) and pellet diameter, when possible. Chemical and microstructural analyzes obtained by Scanning Electron Microscopy (SEM), X-Ray Diffractometry (DRX), Energy Dispersion X-ray Spectroscopy (EDS) and petrographic thin-sections. Two ichnospecies of *Ophiomorpha* were recognized (*O. nodosa* and *O. puerilis*), but most of the materials can only be assigned to the SOT group (*Ophiomorpha*, *Spongeliomorpha* and *Thalassinoides*), mainly because of the lacking of a pelleted lining. The taphonomical processes (exhumation, reworking and transportation) that acted in the formation of this *ex situ* assemblage could be one of the reasons of the absence of pellets. The paleoenvironmental dynamics and a taphonomical reconstitution is presented to demonstrate how the processes affect the traces since its construction, through exhumation until its deposition. Furthermore, neoichnological observations led us to infer larger producers in comparison to the extant ghost shrimp *Sergio mirim*.

**Keywords:** Ichnology; *Ophiomorpha nodosa*; *Ophiomorpha puerilis*; *Spongeliomorpha*; *Thalassinoides*; *Sergio mirim*; Paleo shorelines.

## Capítulo I: Introdução

### 1.1. Introdução

Os icnogêneros *Spongiomorpha* de Saporta, 1887, *Ophiomorpha* Lundgren, 1891 e *Thalassinoides* Ehrenberg, 1944 compreendem tocas de crustáceos calianassídeos (Crustacea, Decapoda, Callianassidae) (Fig. 1) [Weimar & Hoyt 1964, Frey *et al.* 1978, 1984] com sistemas arquiteturais semelhantes, sendo agrupados no grupo SOT (= *Spongiomorpha*, *Ophiomorpha* e *Thalassinoides*) por Rindsberg [2018]. Os crustáceos construtores destas tocas, de acordo com Dworschak [2000], são animais bentônicos que habitam a zona intermareal.

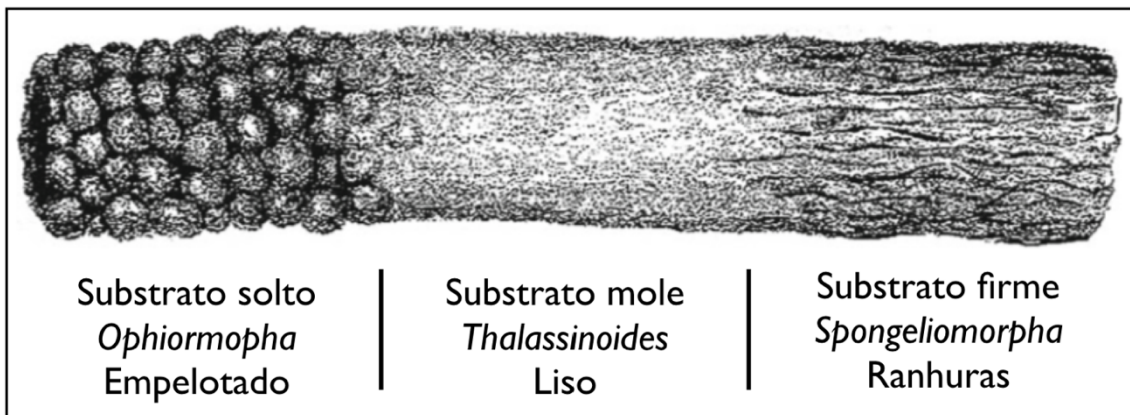


Figura 1. Icnogêneros pertencentes ao grupo SOT (*sensu* Rindsberg [2018]) e suas características morfológicas da parede externa. Retirado e modificado de Knaust [2017].

Atualmente são conhecidas aproximadamente 173 espécies de crustáceos da Família Callianassidae em todo mundo, dos quais 95% apresentam uma distribuição ao longo do assoalho oceânico, desde a zona de *swash* até 200 m de profundidade [Löwemark *et al.* 2016, Hernández-Ocaña *et al.* 2019]. Além disso, estes crustáceos são bioturbadores sedimentares eficientes (principalmente em substratos arenosos e lamosos), predominantemente marinhos e ocorrem em áreas tropicais e subtropicais (latitudes entre 60° norte e 60° sul) [Dworschak 2000, Hyžný & Klompmaker 2015].

Griffis & Suchanek [1991] e Hyžný & Klompmaker [2015] evidenciaram que esta família de crustáceos constrói suas tocas como resposta a uma sofisticada característica comportamental de permanecer permanentemente dentro das mesmas durante suas vidas, o que os torna importantes engenheiros do ecossistema local. Conseqüentemente, estas tocas possuem como funções principais prover refúgio contra predadores, espaço para reprodução, proteção



contra eventos de maior turbulência e conseqüentemente colapso e obtenção de alimento [Griffis & Suchanek 1991, Dworschak 2000, Löwemark *et al.* 2016].

Segundo Frey *et al.* [1978], *Ophiomorpha* é o icnofóssil mais conhecido ao redor do mundo, sendo suas principais características morfológicas o formato cilíndrico e o diâmetro homogêneo, com a presença de aglutinados de sedimento em forma de pelotas (*pellets*) com morfologia específica, distribuídos ao longo de sua estrutura (podendo ou não apresentar organização) (o único icnogênero do grupo SOT com presença de *pellets* na parede externa). Além disso, *Ophiomorpha* pode ocorrer como sistemas arquiteturais variados (desde simples túneis a sistemas complexos e extensos, que podem apresentar ramificações e bifurcações em formato de 'Y' e/ou 'T') e apresentar *turn-around points* que, de acordo com Kennedy & Sellwood [1970], são espaços arredondados e alargados utilizados pelos crustáceos para mudar sua direção dentro do túnel e conseguir se locomover.

Os icnogêneros *Spongiomorpha* e *Thalassinoides* diferem de *Ophiomorpha* devido à ausência de *pellets* em suas paredes externas, apresentando uma parede apenas com ranhuras ou completamente lisa, respectivamente (compreendendo os icnogêneros do grupo SOT sem *pellets* na parede externa; Fig. 1) [Goldring *et al.* 2007]. Os icnogêneros do grupo SOT são excelentes indicadores das condições ambientais, sedimentares e ecológicas para os estratos em que ocorrem, já que podem coexistir em um mesmo sistema de tocas, contudo em profundidades distintas, onde a percolação e compactação do sedimento refletirá na morfologia e estrutura de cada icnogênero [Goldring *et al.* 2007].

Uma vez que *Ophiomorpha* é um icnofóssil restrito a fácies de ambientes marinhos rasos, este icnogênero é um excelente indicador de linhas de praia pretéritas [Hyžný *et al.* 2018] e, conseqüentemente, da evolução do nível do mar. No Brasil, *Ophiomorpha* encontrados *in situ* foram reportados em depósitos Paleozoicos na sucessão Rio Bonito-Palermo (Grupo Guatá, Bacia do Paraná) localizado no Paraná [Tognoli & Netto 2003]; em depósitos indeterminados do Cretáceo médio, da Bacia de São Luis-Grajaú, localizada no Maranhão [Rossetti *et al.* 2000]; na Formação Barreiras (Mioceno da Bacia de Sergipe-Alagoas), localizada em Alagoas [Rossetti & Góes 2009]; na parte inferior da Formação Barreiras (Mioceno, também da Bacia São Luís-Grajaú) [Netto & Rossetti 2003]; na Formação Solimões (Mioceno médio), Rio Acre, na Amazônia (AC) [Gingras *et al.* 2002]; e em depósitos pleistocênicos da planície costeira de Pinheira, localizada em Santa Catarina (SC) [Martins *et al.* 2018].

No Rio Grande do Sul, as icnoespécies *Ophiomorpha nodosa* e *Ophiomorpha puerilis* ocorrem *in situ* nos depósitos emersos da Formação Chuí (Pleistoceno Superior) [Villwock & Tomazelli 1995, Gibert *et al.* 2006, Netto *et al.* 2012, Lopes 2013, Netto *et al.* 2017]. Contudo, alguns dos depósitos fossilíferos relacionados às paleolinhas de costa do Rio Grande do Sul [Corrêa 1996] encontram-se submersos e os fósseis e icnofósseis que nelas se encontram podem ser exumados de sua rocha matriz e transportados para a face de praia atual, assim estes fósseis são encontrados *ex situ* ao longo da Planície Costeira do Rio Grande do Sul (PCRS) (Fig. 2).

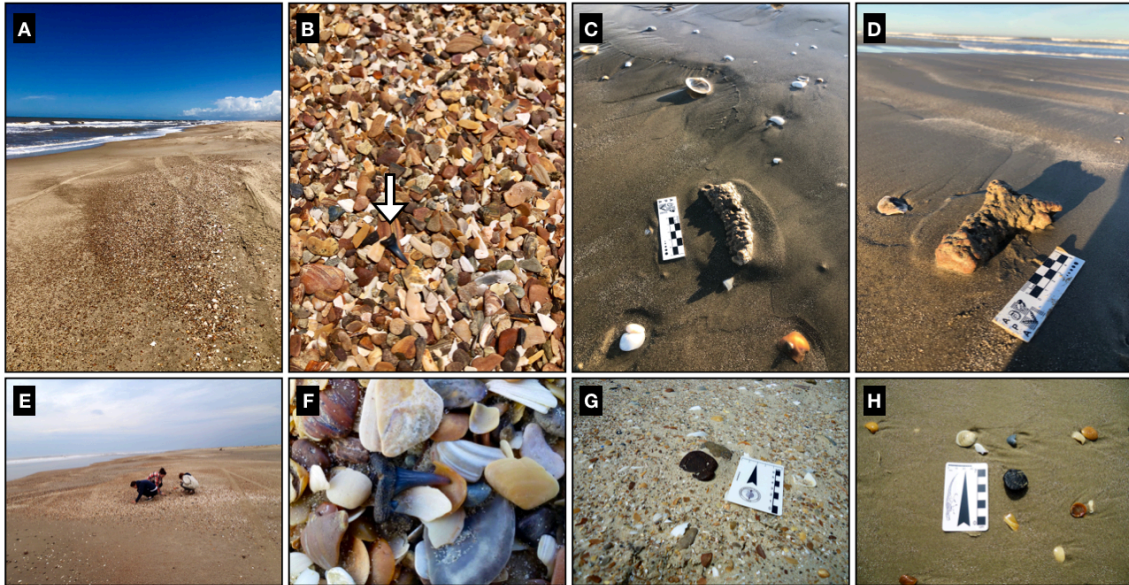


Figura 2. Depósito fossilífero *ex situ* encontrado na face de praia atual da Planície Costeira do Rio Grande do Sul. (A) Praia dos Concheiros, RS - Brasil. (B) Dente fóssil de tubarão em meio a fragmentos de conchas. (C–D) *Ophiomorpha*. (E) Coleta de fósseis e icnofósseis na Praia dos Concheiros, RS - Brasil. (F) Dente fóssil de tubarão. (G–H) Placas fósseis da carapaça de gliptodontes.

Atualmente, nas praias arenosas ao longo do litoral do Rio Grande do Sul, a única espécie de calianassídeo que constrói tocas com estruturas similares ao icnofóssil *Ophiomorpha* é *Sergio mirim* Rodrigues, 1971, popularmente conhecido como corrupto. O registro de icnofósseis ocorrendo *ex situ* em outras regiões do mundo é raro, uma vez que são estruturas sedimentares de origem biogênica e são facilmente destruídos quando fora de sua posição original nos estratos em que foram produzidos. Segundo Buatois & Mángano [2011], traços fósseis são raramente transportados, ou seja, em sua maioria são preservados no local de formação (*in situ*). Contudo, existem algumas exceções. Tocas com paredes reforçadas e bem estruturadas (como as de *Ophiomorpha*) podem resistir a processos destrutivos, que de acordo com Fernandez-Lopez [1991] incluem os principais processos tafonômicos, como

exposição superficial, transporte, intemperismo, abrasão, bioerosão e bioincrustação, e, assim, serem transportadas e depositadas em um local distinto de sua rocha matriz (*ex situ*).

No caso particular de depósitos fossilíferos submersos da costa do Rio Grande do Sul, após os traços serem exumados de sua rocha matriz, eles podem ser submetidos a processos tafonômicos (e.g., transporte, fragmentação, bioerosão, bioincrustação, dissolução, etc.) que, de acordo com Savrda [2007], são análogos aos que ocorrem com os somatofósseis, podendo modificar sua morfologia e composição ou mesmo destruí-los. Apesar de Andrews [1997] considerar que um fóssil em boas condições de preservação não deveria ter sido submetido a processos tafonômicos devido à sua destrutibilidade, alguns autores [e.g., Kindwell & Behrensmeyer 1988, Fernandez-Lopez 1991] ressaltam que tais processos podem gerar alterações tanto negativas quanto positivas e, assim, enriquecer a informação preservada em um determinado registro fóssil, auxiliando na reconstrução paleoambiental [Behrensmeyer *et al.* 2000].

## **1.2. Área de Estudo**

A área de estudo abrange a Planície Costeira do Rio Grande do Sul (PCRS) que está localizada no extremo Sul do Brasil e se estende por aproximadamente 620 km, desde o município de Torres, ao Norte, até o município de Chuí, ao Sul [Tomazelli & Dillenburg 2007]. Ao todo, quatro eventos glacio-eustáticos de regressão e transgressão do nível médio do mar

(NMM) ocorreram na região nos últimos 400 mil anos (Pleistoceno–Holoceno), dando origem a quatro respectivos sistemas deposicionais do tipo laguna-barreira (I–IV) [Villwock, 1984, Villwock & Tomazelli 1995, Corrêa 1996, Tomazelli & Villwock 2000, Dillenburg *et al.* 2004, Lowe & Walker 2015]. Segundo Villwock & Tomazzelli [1995] os três sistemas laguna-barreira mais antigos (I–III) possuem idade pleistocênica, enquanto o Sistema Laguna-Barreira IV iniciou sua formação a aproximadamente 7 mil anos atrás (Holoceno) e segue ativo na extremidade leste da costa gaúcha (Fig. 3).

Ao longo da evolução destes sistemas deposicionais formaram-se diversos depósitos fossilíferos. Dentre eles, destacam-se a Formação Santa Vitória, que dispõe de macrofósseis de vertebrados continentais [e.g., Lopes 2013] e a Formação Chuí que possui um registro fossilífero que inclui microfósseis (palinórfos) e icnofósseis [e.g., Lopes 2013, Netto *et al.* 2012, Netto *et al.* 2017], que, segundo Goldring *et al.* [2007], se encontram inseridas no contexto do Sistema Laguna-Barreira III (Pleistoceno). Os icnofósseis *Macaronichnus* isp., *Diplocraterion parallelum*, *Rosselia socialis*, *Ophiomorpha puerilis* e *Ophiomorpha nodosa* são encontrados *in situ* nos depósitos da Formação Chuí, nos municípios de Osório, São José do Norte, Santa Vitória do Palmar e Chuí [e.g., Netto *et al.* 2017]. Depósitos fossilíferos como os descritos também podem ocorrer abaixo do NMM atual, ou seja, em antigas linhas de praia que atualmente encontram-se submersas [Corrêa 1996] (Fig. 3 A).

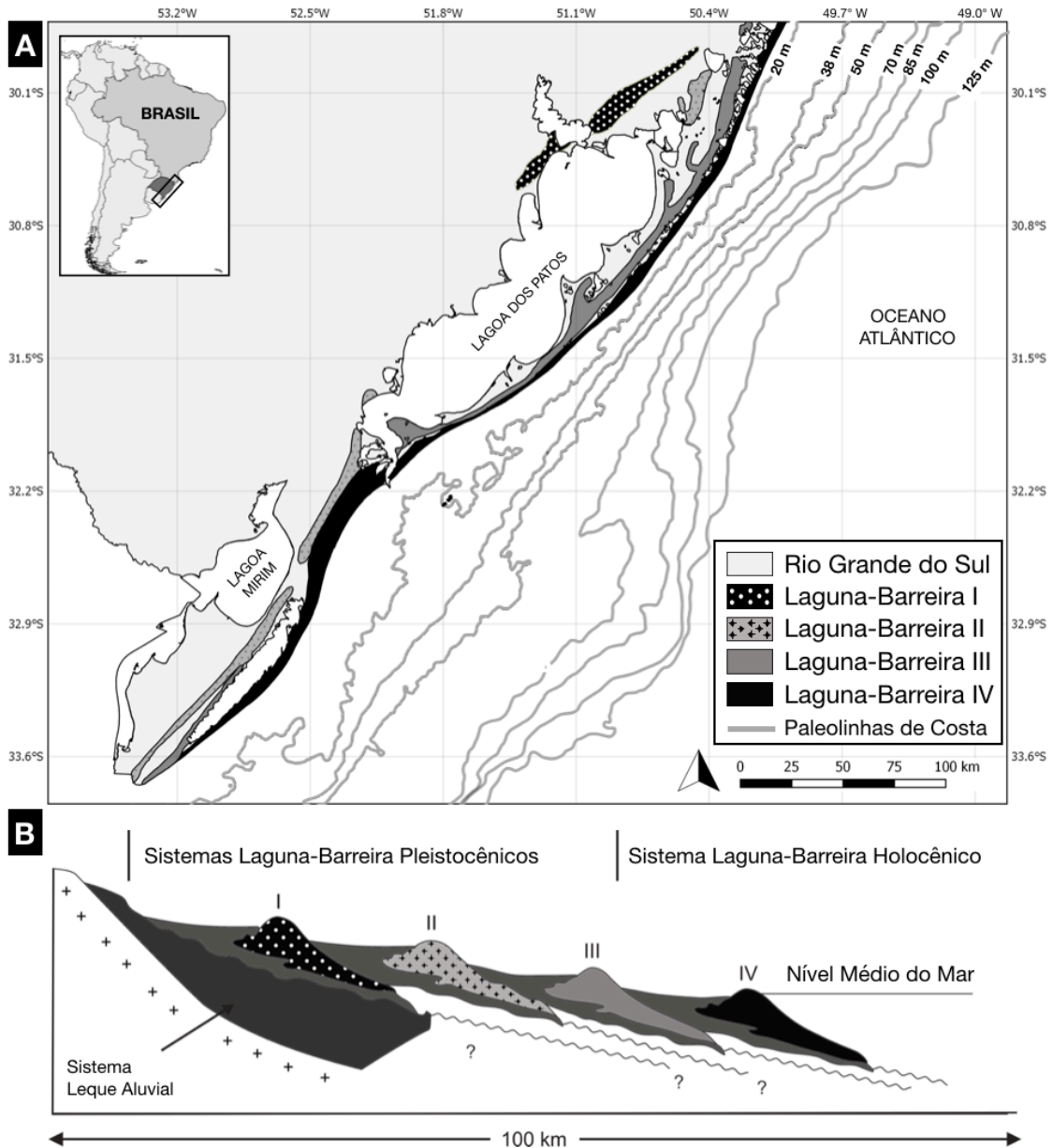


Figura 3. (A) Planície Costeira do Rio Grande do Sul (PCRS). (B) Sistemas Depositionais Laguna-Barreira I-IV. Modificado de Corrêa [1996] e Villwock e Tomazelli [1995].

Em consequência da dinâmica oceânica e da sedimentação da PCRS, diversos fósseis destes sistemas laguna-barreira submersos são exumados de sua matriz original, muitas vezes sendo transportados até a linha de praia atual. Dentre eles, podem ser encontrados restos de vertebrados marinhos e continentais [Lopes *et al.* 2008], invertebrados (Fig. 4) [Tâmega *et al.*, 2019] e

icnofósseis, sendo o icnogênero *Ophiomorpha* o mais abundante deles [Netto *et al.* 2012].

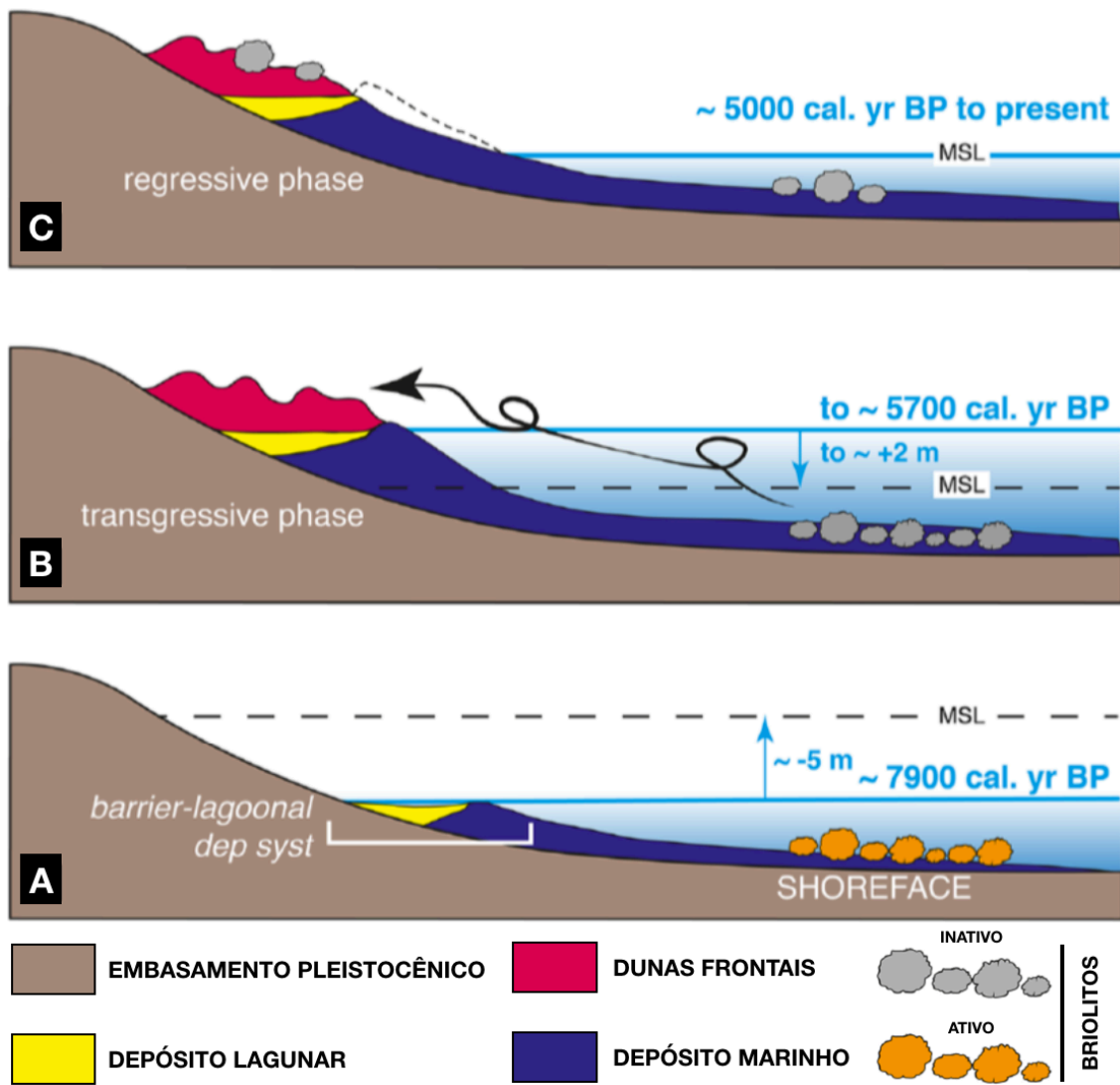


Figura 4. Modelo de preservação de briolitos (colônias móveis de briozoários) na Planície Costeira do Rio Grande do Sul. (A) Briolito ativo, sendo formado. (B) Briolito inativo, já fossilizado. (C) Briolito transportado e depositado nas duas frentes da face de praia atual. Retirado e modificado de Tâmega *et al.*, [2019].

Desta forma, a proposta deste trabalho é descrever os icnofósseis encontrados *ex situ* ao longo da PCRS (Laguna-Barreira IV), assim como compreender sua história tafonômica.

### 1.3. Objetivos

O objetivo geral deste estudo é caracterizar a morfologia e modos de preservação dos icnofósseis coletados *ex situ* na face de praia atual da Planície Costeira do Rio Grande do Sul, investigando os aspectos tafonômicos envolvidos em sua preservação e discutindo sua icnotaxonomia. Como objetivos específicos, este estudo pretende:

- (i) Descrever detalhadamente os espécimes de *Ophiomorpha* encontrados *ex situ* na faixa de praia atual do RS, com base em sua morfologia, padrão de organização e formato dos *pellets*, composição química e microestrutura;
- (ii) Classificar icnotaxonomicamente os materiais de *Ophiomorpha* encontrados *ex situ* e verificar se existem diferenças icnotaxonômicas quando comparados com os depósitos da Formação Chuí (materiais *in situ*; Pleistoceno);
- (iii) Comparar a morfologia dos icnofósseis *Ophiomorpha* encontrados *ex situ* com as tocas recentes do crustáceo decápode *Sergio mirim*, verificando se ocorreram mudanças morfológicas ou de tamanho no registro desde o Pleistoceno até o recente;



- (iv) Caracterizar as principais assinaturas tafonômicas (químicas e físicas) dos materiais encontrados *ex situ* e propor um modelo que explique sua história tafonômica.

## Capítulo II: Material e Métodos

### 2.1. Materiais

Os materiais analisados neste trabalho pertencem às coleções do Laboratório de Geologia e Paleontologia da Universidade Federal do Rio Grande (LGP-FURG) e do Museu de Ciências Naturais (MCN) da Fundação Zoobotânica do Rio Grande do Sul (FZB-RS). A coleção do LGP-FURG contém 204 espécimes, enquanto a da FZB-RS possui 49 espécimes, resultando em um número amostral total de 253 materiais.

Por outro lado, materiais coletados e observados *in situ*, foram utilizados como base de comparação e identificação. Estes espécimes pertencem a duas coleções e são provenientes da Formação Chuí (Pleistoceno Superior). Os materiais do LGP ( $n=3$ ) foram coletados na calha do Arroio Chuí (Santa Vitória do Palmar, RS) e em áreas de mineração de areia (Osório, RS), enquanto os materiais depositados na coleção do Laboratório de História da Vida e da Terra

(LAVIGEA) da Universidade do Vale do Rio dos Sinos (UNISINOS) ( $n=8$ ) foram coletados em duas jazidas (Jazida Gomes e Jazida Transareia) no município de Osório (RS).

Os materiais *ex situ* do LGP-FURG foram coletados ao longo da Planície Costeira do Rio Grande do Sul (PCRS). Tais coletas vêm sendo realizadas desde a década de 1990, mas foram intensificadas nos últimos dez anos. Nas coletas mais recentes, a partir de 2012, as localidades geográficas dos pontos de coleta foram anotadas com o auxílio de um GPS (Garmin Etrex Vista H; *datum* WGS 84). Após a coleta dos materiais, os mesmos foram levados ao LGP para serem devidamente preparados e catalogados, recebendo um registro de tombamento específico: LGP-H e um número arábico sucessivo conforme a ordem de coleta (e.g. LGP-H0154).

## **2.2. Métodos**

Com o intuito de descrever e caracterizar os materiais coletados *ex situ*, foram medidos seu diâmetro externo e interno e a largura da parede (em seção transversal; Fig. 5), com o auxílio de um paquímetro digital (graduado em milímetros) e do *software* Image J, seguindo a metodologia usada por Frey *et al.* [1978], Goldring *et al.* [2007], Uchman [2009] e Löwemark *et al.* [2016]. Com isso, histogramas de frequência de ocorrência de cada diâmetro obtido foram elaborados. Também foram calculados alguns parâmetros estatísticos básicos referentes a estes histogramas (e.g. média, mediana, moda, variância e desvio padrão) utilizando o *software* Past.

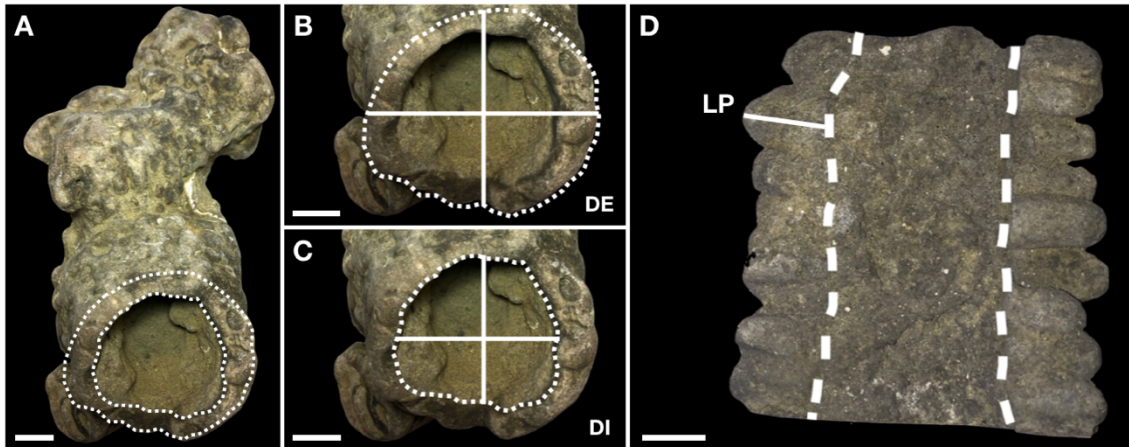


Figura 5. (A) Circunferência sinalizando os limites do diâmetro externo e interno da toca. (B) Diâmetro externo (DE) em seção transversal. (C) diâmetro interno (DI) em seção transversal. (D) Pontilhado demonstra o limite da parede da toca ressaltando até onde a medida da largura da parede (LP) é feita.

Além disso, quando possível, foram medidos os diâmetros dos *pellets*, onde cada valor apresentará uma frequência de repetição dos mesmos. Também foi analisada a morfologia dos *pellets* e sua composição sedimentar, sendo posteriormente descrito o tipo de organização dos mesmos, como *pellets* individuais, agrupadas em pares (de dois em dois) ou em forma de tijolo (*brick-like*) [*sensu* Frey *et al.* 1978, Goldring *et al.* 2007, Uchman 2009].

Foi observado se as amostras possuem alguma bifurcação (no formato de 'Y' e/ou 'T') e se as mesmas possuem *turn-around points*, sendo estas características atribuídas categoricamente (ausência ou presença) para ambos. O preenchimento das amostras também foi observado. Todas as informações e dados registrados do material *ex situ* foram organizados em um único banco de dados ( $n=253$  entradas) no *software* Microsoft Excel, que foi incluído no artigo derivado desta dissertação como material suplementar.

Análises químicas, como a Difractometria de Raios-X (DRX) e a Espectroscopia de Raios-X por Dispersão em Energia (EDS) também foram realizadas, a fim de verificar as composições mineralógica e elementar das amostras, tal como realizada por Löwemark *et al.* [2016]. Além disso, foram realizadas análises de Microscopia Eletrônica de Varredura (MEV), cuja finalidade foi o acesso a imagens de alta resolução, buscando-se encontrar estruturas não visíveis a olho nu, tal como realizado por Netto *et al.* [2017]. As análises de DRX foram realizadas pelo Laboratório de Difractometria de Raios-X do Instituto de Geociências da Universidade Federal do Rio Grande do Sul (IGeo-UFRGS). Para tal análise, dois espécimes (H0050; H0218) foram selecionados, e foi necessário que aproximadamente 3 g de cada amostra fossem pulverizados e submetidos a um difratômetro (Siemens® D-500) com goniômetro  $\theta$ - $\theta$ . Posteriormente, radiação  $K\alpha$  foi utilizada em tubos de cobre, sob 40 kV e 25 mA e, então, as análises foram interpretadas pelo *software* DIFFRAC PLUS®. As análises de MEV e de EDS, foram realizadas no Centro de Microscopia Eletrônica da Zona Sul (CEME-SUL) da Universidade Federal do Rio Grande (FURG), usando um microscópio eletrônico de varredura (JEOL JSN-6610LV). Para estas análises, *pellets* da parede externa de cinco espécimes (H0516; H0011; H0529; H0549; H0515) foram selecionados, dispostos em *stubs* de alumínio, secos em uma estufa a 40°C por 24 horas e posteriormente recobertos com ouro.

Também foram confeccionadas lâminas petrográficas pelo Núcleo de Estudos em Paleontologia e Estratigrafia (Nepale) da Universidade Federal de Pelotas (UFPel). Para tal análise foram selecionados dois espécimes (H0007; H0008), onde para a preparação das lâminas foram necessários quatro passos:

i) as amostras foram cortadas no sentido desejado (cortes transversal e longitudinal) e impregnadas em resina epóxi; ii) os materiais foram então lixados e colados com a mesma resina epóxi na lâmina de vidro; iii) a seguir, o excedente do material foi cortado e desbastado; e, por fim, iv) polido até atingir a espessura desejada. As lâminas petrográficas foram analisadas em um microscópio petrográfico (Olympus® BX51TF) do LGP da FURG e, então, imagens foram tomadas com uma câmera Canon® Rebel T6. As amostras enviadas para as análises químicas e mineralógicas foram escolhidas devido a um diferencial em sua composição e seu aspecto (e.g. presença de bioclastos, cores e tamanhos distintos e organização e formato dos *pellets*).

Feito isto, a análise icnotaxonômica dos materiais coletados *ex situ* se deu com base nos materiais e metodologia descritas nas principais referências bibliográficas [Kennedy & MacDougall 1969, Frey *et al.* 1978, Griffis & Suchanek 1991, Nickell & Atkinson 1995, Bromley & Edkale 1998, Bertling *et al.* 2006, Gibert *et al.* 2006, Uchman 2009, Netto *et al.* 2012, Angulo & Souza 2014, Netto *et al.* 2017, Martins *et al.* 2018, Rindsberg 2018], além de comparação com os materiais coletados *in situ* na Formação Chuí.

Adicionalmente, análises neoicnológicas com tocas de crustáceos calianassídeos atuais (*Sergio mirim*) (n=18) foram realizadas na praia do Cassino (município de Rio Grande-RS), com intuito de acessar a morfologia e o tamanho dessas tocas (*Ophiomorpha-like*) para, assim, comparar com o registro fóssil. Para isso, as tocas de *S. mirim* foram escavadas, medidas e fotografadas. A área da seção transversal das tocas foi utilizada para estimar a massa de seus produtores, seguindo a equação alométrica proposta por White

[2005]. Para fins de comparação, replicamos essa metodologia usando os *Ophiomorpha* isp. encontrados *ex situ*.

Para a investigação tafonômica, os materiais foram classificados segundo um sistema criado com cinco classes (A-E) onde, os critérios utilizados foram a presença, tipo de organização e preservação dos *pellets* na parede externa que, devido aos processos abrasivos que os espécimes estavam sujeitos após sua exumação, puderam ou não ter sofrido alterações morfológicas. As classes A (*pellets* presentes em >50% da área externa) e B (*pellets* presentes em <50% da área externa) incluem espécimes onde foi possível identificar o tipo de organização dos *pellets* presentes na parede. Já as classes C (*pellets* presentes em >50% da área externa) e D (*pellets* presentes em <50% da área externa) incluem materiais onde ainda é possível visualizar os *pellets*, no entanto, não é possível identificar seu tipo de organização. A Classe E inclui espécimes onde nenhum *pellet* pode ser visualizado ou identificado. Já para a bioerosão e bioincrustação, foram registrados presença ou ausência e, quando possível, identificados os organismos geradores.

### Capítulo III: Artigo Científico

Para a obtenção do título de Mestre pelo Programa de Pós-Graduação em Oceanologia, é requerido que o discente realize a submissão de pelo menos um artigo científico como primeiro autor em periódico com corpo indexado. Desse modo, os resultados da pesquisa desenvolvida durante o período de mestrado e a discussão dos resultados serão apresentados em forma de artigo neste Capítulo. O manuscrito, de autoria de Giovana Pedrol de Freitas, Heitor Francischini, Frederico Tapajós de Souza Tâmega, Paula Spotorno-Oliveira e Paula Dentzien-Dias, é intitulado “**On the *ex situ* ichnofossils from the Quaternary of the Rio Grande do Sul Coastal Plain (Brazil): taphonomic and paleoenvironmental remarks**” e foi submetido para publicação no periódico “*Journal of Paleontology*” (Qualis-CAPES B1 na área de Geociências).



# Journal of Paleontology



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**On the ex situ ichnofossils from the Quaternary of the Rio Grande do Sul Coastal Plain (Brazil): taphonomic and paleoenvironmental remarks**

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Broad Geologic Time:	Quaternary < Cenozoic
Detailed Geologic Time:	Holocene < Quaternary, Pleistocene < Quaternary
Subject area Geographic Location:	South America

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1 **On the *ex situ* ichnofossils from the Quaternary of the Rio**  
2 **Grande do Sul Coastal Plain (Brazil): taphonomic and**  
3 **paleoenvironmental remarks**

4  
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16  
17 **Running Header:** *Ex situ* fossil crustacean burrows from Quaternary of Brazil

18  
19 **Abstract.**—The Rio Grande do Sul Coastal Plain (southern Brazil) is composed by extended  
20 marine and continental deposits related to at least four barrier-lagoon systems of Pleistocene-  
21 Holocene age. Part of these deposits is currently submerged and passing through erosion  
22 processes by waves. Vertebrate and invertebrate body and trace fossils are constantly

23 exhumed from these deposits and redeposited on the modern beach face. Among them, a total  
24 of 253 fragments of crustacean burrows were collected and the study of these materials is the  
25 main goal of the present paper. Two ichnospecies of *Ophiomorpha* were recognized (*O.*  
26 *nodosa* and *O. puerilis*), but most of the materials can only be assigned to the SOT group  
27 (*Ophiomorpha*, *Spongiomorpha* and *Thalassinoides*), mainly because of the lacking of a  
28 pelleted lining. The absence of pellets and, by consequence the ichnotaxonomy of these  
29 specimens, is related to taphonomical processes (exhumation, reworking and transportation)  
30 that acted in the formation of this *ex situ* assemblage. The paleoenvironmental dynamics and  
31 a taphonomical model is presented to demonstrate how the processes affect the traces since  
32 its construction, through exhumation until its deposition. Neoichnological observations led us  
33 to infer larger producers in comparison to the extant ghost shrimp *Sergio mirim*.

## 35 **Introduction**

36  
37 Crustacean-made fossil burrow *Ophiomorpha* Lundgren, 1891 is one of the most well-known  
38 marine invertebrate ichnotaxon (Frey et al., 1978). These trace fossils are usually found *in*  
39 *situ* in foreshore and shoreface deposits since the Late Jurassic and are characterized by the  
40 following morphological features: a cylindrical format with homogenous diameter (ranging  
41 from 10 mm to 60 mm), the presence of simultaneous Y- and/or T-shaped branches and  
42 bifurcations (which give a maze or box-work appearance to the whole burrow system), the  
43 passive infilling, and the presence of the typical agglutinated pellets of sediment partially  
44 aligned throughout the walls of the tunnels and shafts (Kennedy and Sellwood, 1969;  
45 Bromley and Frey, 1974; Frey et al., 1978).

46 It differs from other ichnogenera of similar architectural designs, such as  
47 *Spongiomorpha* de Saporta, 1887 and *Thalassinoides* Ehrenberg, 1944, by the presence of

48 the pelleted (knobby) wall lining, being the organization and shape of these pellets important  
49 ichnotaxobases used on its classification at the ichnospecific level (Frey et al., 1978).  
50 Actually, the ichnogenera *Spongiomorpha*, *Ophiomorpha* and *Thalassinoides* (the SOT  
51 group; following Rindsberg, 2018 nomenclature) represent different expressions of  
52 callianassid crustacean burrow systems made in substrates of different consistencies, that is  
53 distinct grain sizes and percolation (Goldring et al., 2007). The SOT ichnotaxa are, therefore,  
54 considered substrate-controlled and coexistence between these three ichnogenera could occur  
55 within the same burrow system with increasingly vertical depth, depending on substrate  
56 consistency (Goldring et al., 2007). The SOT ichnotaxa are confidentially attributed to  
57 fossorial ghost shrimps (Crustacea: Decapoda: Callianassidae) (Weimer and Hoyt, 1964; Frey  
58 et al., 1978, 1984).

59 In this context, *Ophiomorpha* represents the expression of burrows produced in upper  
60 shoreface and foreshore environments, which are characterized by unconsolidated siliciclastic  
61 substrates (soft grounds) and high wave or current energy, typical of the *Skolithos*  
62 Ichnofacies or the proximal *Cruziana* Ichnofacies (MacEachern et al., 2007, 2012). The pellet  
63 lining function is to structure and reinforce the burrow wall, avoiding its collapse (Kennedy  
64 and Sellwood, 1969; Frey et al., 1978). According to Gibert et al. (2006), *Ophiomorpha*  
65 pellet composition consists of siliciclastic grains with size ranging from fine to medium sand,  
66 but bioclasts (such as mollusk shell fragments) and other type of debris can also be included  
67 in the pellet during the wall construction by the crustacean. Organization and shape of the  
68 pellets vary largely and are important ichnotaxobases for distinguish different *Ophiomorpha*  
69 ichnospecies (Frey et al., 1978; Miller and Curran, 2001).

70 As presented above, the SOT group is an excellent indicator of environmental and  
71 ecological conditions for the strata in which they occur. More particularly, *Ophiomorpha* is a  
72 direct index for paleo shorelines (Hyžný et al., 2018) and, consequently, of sea level

73 evolution. *In situ* *Ophiomorpha* have been reported to distinct geological units of Brazil  
74 (Rossetti et al., 2000; Gingras et al., 2002; Netto and Rossetti, 2003; Tognoli and Netto,  
75 2003; Rossetti and Góes, 2009; Martins et al., 2018). In the particular case of the Rio Grande  
76 do Sul coastal plain (RSCP), *Ophiomorpha nodosa* Lundgren, 1891 and *Ophiomorpha*  
77 *puerilis* Gibert, Netto, Tognoli and Grangeiro, 2006 occur *in situ* in the emerged deposits of  
78 the Upper Pleistocene Chuí Formation (Villwock and Tomazelli, 1995; Gibert et al., 2006;  
79 Netto et al., 2012, 2017; Lopes, 2013).

80 On the other hand, fragments of SOT burrows (*O. nodosa*, *O. puerilis* and other  
81 indeterminate specimens), exhumed from still indeterminate immersed deposits, are often  
82 found deposited on the current beach line of the southern littoral of Rio Grande do Sul,  
83 characterizing an uncommon case of *ex situ* fossil bioturbation assemblage. The main goal of  
84 this paper is to describe in detail, for the first time, the occurrence of *ex situ* callianassid  
85 burrows, comparing them to the *in situ* record of the Chuí Formation and to burrows made by  
86 the modern callianassid *Sergio mirim* (Rodrigues, 1971). The ichnotaxonomy of these  
87 materials is also discussed and a taphonomic model for explain this peculiar assemblage is  
88 proposed.

89

## 90 **Study area**

91

92 The study area encompasses the region of the Rio Grande do Sul coastal plain of (RSCP),  
93 which is a long physiographic province located in the Rio Grande do Sul state of Brazil (Fig.  
94 **1.1**). The RSCP is extended for 620 km, is approximately 150 km wide, and represents the  
95 upper sedimentary package of the Pelotas Basin (Tomazelli and Dillenburg, 2007).

96 During the Quaternary, fluctuations on the main sea level (MSL) related to  
97 glacioeustatic cycles acted on the deposition of a sequence of Lagoon-Barrier Systems (Fig.

98 **1.2**; Villwock, 1984; Villwock and Tomazelli, 1995; Corrêa, 1996; Tomazelli and Villwock,  
99 2000; Dillenburg et al., 2004, Lowe and Walker, 2015). Specifically, four glacioeustatic  
100 events of MSL fluctuations occurred in the last 400 ka (Pleistocene–Holocene), giving rise to  
101 four respective Lagoon-Barrier depositional systems, named Lagoon-Barrier Systems I–IV  
102 (Villwock and Tomazelli, 1995) (Fig. 1). According to Dillenburg et al. (2009), the three  
103 oldest Lagoon-Barrier Systems (I–III) are Pleistocene in age, while the Lagoon-Barrier  
104 System IV began its formation approximately 7 ka (Holocene) and remains active at the  
105 eastern end of the coast of Rio Grande do Sul.

106 The MSL fluctuations during the Quaternary of Rio Grande do Sul are associated with  
107 the climatic changes, glacial and interglacial periods, derived from the Milankovitch cycle  
108 (Imbrie et al., 1984), as indicated by the oxygen isotopic curve and consequently the Marine  
109 Isotope Stages (MIS) (Villwock and Tomazelli, 1995). Each Lagoon-Barrier depositional  
110 systems of the RSCP has a representative MIS: MIS11 (Lagoon-Barrier System I;  $\pm$  400 ka),  
111 MIS9 (Lagoon-Barrier System II;  $\pm$  325 ka), MIS5 (Lagoon-Barrier System III;  $\pm$  120 ka)  
112 and MIS1 (Lagoon-Barrier System IV;  $\pm$  5–7 ka) (Imbrie et al., 1984; Villwock and  
113 Tomazelli 1995).

114 During the evolution of these depositional systems several fossiliferous deposits were  
115 formed. Among them, the Chuí Formation, inserted in the context of the Barrier-Lagoon  
116 System III, that has two main distinct sedimentary deposits: a lower marine unit and an upper  
117 continental (eolian) unit (Gibert et al., 2006; Netto et al., 2012). The ichnofossils  
118 *Cylindrichnus helix* Gibert, Netto, Tognoli and Grangeiro, 2006, *Macaronichnus* Clifton and  
119 Thompson, 1978, *Diplocraterion parallelum* Torell, 1870, *Rosselia socialis* Dahmer, 1937,  
120 *O. nodosa* and *O. puerilis* can be found *in situ* in the marine deposits of the Chuí Formation,  
121 indicating that this unit were deposited at a very shallow environment (Gibert et al., 2006;  
122 Netto et al., 2012, 2017).

123 Besides the emerged fossiliferous deposits, submerged deposits are accountable for  
124 the *ex situ* specimens encountered at the actual beach face where each submerged Paleo  
125 Shoreline has an estimated date of formation, 28 m = 8.000 years BP; 38 m = 9.000 years BP;  
126 50 m = 9.500 years BP; 70 m = 11.000 years BP; 85 m = 14.000 years BP; 100 m = 16.000  
127 years BP; and 125 m = 17.500 years BP (Corrêa, 1996) and represents immerse fossiliferous  
128 deposits (Fig. 1.1).

129

### 130 **Material and methods**

131

132 The material studied on this work (n=253) were collected along the extension of the modern  
133 beach face of the RSCP, southernmost coast of Brazil. These materials are housed on the  
134 Laboratório de Geologia e Paleontologia, Universidade Federal do Rio Grande (LGP-FURG;  
135 n=204) and Museu de Ciências Naturais, Fundação Zoobotânica do Rio Grande do Sul  
136 (MCN-FZBRS; n=49). A list of the acronyms and collection localities of each studied  
137 specimen is provided at Supplementary Table 1 (Supp. File 1).

138 In order to describe and characterize these *ex situ* materials, we performed a set of  
139 measurements, which included the external and internal diameters, the wall thickness (in  
140 cross section), and the pellet diameter (when they occur). The measurements were carried out  
141 by an electronic caliper and by the ImageJ software. Basic statistics was performed using the  
142 software PAST. Qualitative information, such as the pellet organization and shape (following  
143 Frey et al., 1978; Goldring et al., 2007; Uchman, 2009), the presence of bifurcation (in 'Y' or  
144 'T' shape), the occurrence of turn-around points, and the burrow filling, was also registered.

145 Samples of *ex situ* materials were also analyzed under the Scanning Electron  
146 Microscopy (SEM), X-Ray Diffractometry (DRX) and Energy Dispersive X-ray  
147 Spectroscopy (EDS), in order to verify their mineralogical and chemical compositions. The



148 SEM and EDS analyses were performed at Centro de Microscopia Eletrônica da Zona Sul of  
149 FURG (CEME-SUL), using a JEOL JSN-6610LV microscope. For these analyzes, pellets  
150 from the outer wall of five specimens (LGP H0516, LGP H0011, LGP H0529, LGP H0549,  
151 and LGP H0515) were assembled in aluminum stubs, dried in a stove at 40°C for 24 hours  
152 and then covered by gold. The DRX analysis was carried out by the Laboratório de  
153 Difractometria de Raios-X of the Universidade Federal do Rio Grande do Sul (LRX, UFRGS).  
154 For this analysis, two specimens were selected (LGP H0050 and LGP H0218), and 3 g of  
155 each sample were pulverized and submitted to a Siemens® D-500 diffractometer with  
156 goniometer  $\theta$ - $\theta$ . Subsequently, the  $K\alpha$  radiation was used in copper tubes under 40 kV and 25  
157 mA, and the results were interpreted by the software DIFFRAC PLUS®.

158 Furthermore, other two specimens (LGP H0007 and LGP H0008) were sectioned for  
159 petrographic analysis. Thin sections were made by the Núcleo de Estudos em Paleontologia e  
160 Estratigrafia of the Universidade Federal de Pelotas (NEPALE, UFPel), following standard  
161 techniques. The thin sections were analyzed by a petrographic microscope (Olympus®  
162 BX51TF) and an optical microscope at LGP-FURG.

163 The ichnotaxonomic identification of the *ex situ* specimens was accessed by  
164 comparison with other materials described in the bibliography (e.g., Kennedy and  
165 MacDougall, 1969; Frey et al., 1978; Griffis and Suchanek, 1991; Nickell and Atkinson,  
166 1995; Bromley and Edkale, 1998; Bertling et al., 2006; Gibert et al., 2006; Uchman, 2009;  
167 Netto et al., 2012; Angulo and Souza, 2014; Netto et al., 2017; Martins et al., 2018;  
168 Rindsberg, 2018), as well by direct comparison with the materials found *in situ* in the Chuí  
169 Formation (Barrier-Lagoon System III). The *in situ* traces used for comparison were analyzed  
170 directly from outcrops of the Chuí Formation at Osório, Santa Vitória do Palmar and Chuí  
171 municipalities (RS, Brazil). We also analyzed *O. nodosa* specimens housed in the

172 Laboratório de História da Vida e da Terra, Universidade do Vale do Rio dos Sinos  
173 (LAVIGEA-UNISINOS; n=8) and FURG (n=3), all of them from the Chuí Formation.

174 Additionally, neoichnological analysis were carried out at the Cassino beach (Rio  
175 Grande municipality; Fig. 1.1) for the purpose of access the morphology and size of modern  
176 *Ophiomorpha*-like burrows and to compare them to the fossil record (Fig. 2). For that, *S.*  
177 *mirim* burrows were excavated, measured and photographed (Fig. 2). The cross-section area  
178 of the burrows was used for estimate the mass of their producers, following the allometric  
179 equation proposed by White (2005). For comparison purposes, we replicate this methodology  
180 using the *Ophiomorpha* isp. found *ex situ*. All the data regarding this approach is in the  
181 Supplementary File 3.

182 In order to understand the taphonomic processes and modifications that occurred  
183 between the exhumation of the traces from the submerged paleo shorelines and their  
184 collection at the beach face, we classified the materials according to the degree of three  
185 taphonomic signatures: abrasion, bioerosion and bioincrustation (occurrence of sclerobionts  
186 along the internal and external surfaces). Five classes (A–E) were created using the presence,  
187 organization and preservation of pellets in the outer wall as a criterion. In classes A (pellets  
188 present in >50% of the external area) and B (pellets present in <50% of the external area) it  
189 was possible to identify the type of organization of the pellets present on the wall. In classes  
190 C (pellets present in >50% of the external area) and D (pellets present in <50% of the  
191 external area) it was still possible to visualize the pellets, however, the type of organization  
192 was unidentifiable. In spite of the unclear type of organization of Classes C–D, the pellet  
193 shape was preserved and their measurements were still viable in all four classes. The Class E  
194 comprises specimens where no pellet can be visualized or identified. For bioerosion and  
195 bioincrustation, presence or absence was recorded and, when possible, the bioerosion

196 ichnotaxon and the encrusting species were identified. Bioeroders and incrusters were  
197 identified to the generic or specific level.

198

199 *Repositories and institutional abbreviations.*—Laboratório de Geologia e Paleontologia  
200 (LGP), Instituto de Oceanografia (IO), Universidade Federal de Rio Grande (FURG), Rio  
201 Grande, Brazil; Museu de Ciências Naturais, Fundação Zoobotânica do Rio Grande do Sul  
202 (MCN-FZBRS), Porto Alegre, Brazil; Laboratório de História da Vida e da Terra  
203 (LAVIGEA), Universidade do Vale do Rio dos Sinos (UNISINOS), São Leopoldo, Brazil.

204

## 205 **Results**

206

207 *External morphology and ichnotaxonomy.*—Because all of the 253 specimens analyzed  
208 represent burrow fragments, some were not complete enough to allowing complete  
209 measurement. The burrow external diameter range is 6.82–75.72 mm (mean  $29.33 \pm 10.73$   
210 mm,  $n=193$ ) and the internal diameter ranges from 4.48 mm to 46.34 mm (mean  $16.9 \pm 8.36$   
211 mm,  $n=167$ ). The burrow wall thickness ranges from 2.18 mm to 16.41 mm (mean  $7.52 \pm$   
212  $2.75$  mm,  $n=216$ ).

213 Y- or T-shaped bifurcations are present in 59 specimens (Figs. **3.5–3.7**, **3.12**, **3.15–**  
214 **3.17**) and other 11 present turn-around points (Fig. **3.7**). Regarding the burrow filling, most  
215 ( $n=147$ ) of the analyzed burrows were filled by sand with bioclasts (mainly fragments of  
216 mollusk shells), but some are filled only by sand ( $n=52$ ), while others ( $n=54$ ) are unfilled.

217 For the burrows in which the pelleted outer wall is present (Classes A–D), the pellets  
218 diameter ranges from 2.3 mm to 13.77 mm (mean  $7.82 \pm 2.11$  mm). The pellet organization  
219 could be determined in 152 specimens (about 60%), being 97 of them organized individually,  
220 44 organized in a brick-like pattern, and 11 organized in pairs (Figs. **3.1–3.3**). The pellet

221 shape varies from cylindrical to ovoid, irregular, or rounded and are well distributed along  
222 the outer wall. SEM analysis (Supp. Figs. 5–9) shown that the shape of pellets varies between  
223 spherical, rounded and trapezoidal. Pellets are not evident in 101 specimens (Class E),  
224 representing about 40% of the total sample (Fig. 3.4). Microorganism remains (such as  
225 foraminiferans, diatoms, palynomorphs, etc.) were not found within the pellets. Thereby, the  
226 *ex situ* traces that presented pelleted outer wall (n=152) were identified as *O. nodosa*.

227 The external diameter of the *ex situ O. nodosa* presented a variation of 64 mm which  
228 represents a larger interval. Values of external diameter were not compared with specimens  
229 of *in situ O. nodosa* from Chuí Formation (Lagoon-Barrier III, RS, Brazil) (Gibert et al.,  
230 2006). However, the *in situ O. nodosa* from Pleistocene deposits at Pinheira coastal plain  
231 (Santa Catarina State, Brazil) presented a 32.82 mm maximum and 22.86 mm minimum  
232 external diameter (mean 27.84 mm) (Martins et al., 2018) which are occurrent values at the  
233 *ex situ O. nodosa* range but not as wide. Also, specimens of *in situ O. nodosa* from England  
234 presented 60 mm maximum diameter (Kennedy and Sellwood, 1969) which represents a 15.7  
235 mm smaller maximum external diameter when compared with the *ex situ O. nodosa*.

236 The internal diameter of the *ex situ O. nodosa* presented a variation of 41.3 mm while  
237 the *in situ O. nodosa* from Chuí Formation (Lagoon-Barrier III, RS, Brazil) presented a range  
238 of 20–50 mm (mean 32 mm) (Gibert et al., 2006). For the *ex situ O. nodosa*, the internal  
239 diameter minimum value is 15 mm smaller than the value described by Gibert et al., (2006)  
240 and 3.7 mm smaller than the maximum value (Table 1). The internal diameter has a directly  
241 relation to organisms size which reflects in burrow cross-sectional area (White, 2005; Wu et  
242 al., 2015).

243 The wall thicknesses of the *ex situ O. nodosa* presented a variation of 14.32 mm while  
244 the *in situ O. nodosa* from Chuí Formation (Lagoon-Barrier III, RS, Brazil) presented a range  
245 of 2.5–15 mm (mean 9 mm) (Gibert et al., 2006). For the *ex situ O. nodosa*, the maximum

246 value of wall thickness exceeded in 1.41 mm the maximum presented from Gibert et al.,  
247 (2006) while the minimum value is approximately the same (Table 1).

248 The pellets diameter of the *ex situ* *O. nodosa* have a variation of 11.47 mm while the  
249 *in situ* *O. nodosa* from Chuí Formation (Lagoon-Barrier III, RS, Brazil) have a range of 5–10  
250 mm (Goldring et al., 2007; Netto et al., 2017) which is inserted at the *ex situ* pellets diameter  
251 range but the maximum and minimum values are both smaller (Table 1).

252 Two specimens of *O. puerilis* (Fig. 4) were found into the walls of two distinct  
253 specimens of *O. nodosa* (LGP H0270 and LGP H0230). Due their size and poor preservation,  
254 the external and internal diameters could not be measured. The pellets diameter ranges from  
255 0.28 mm to 0.48 mm (mean 0.39 mm). The pellets presented a rod-shaped morphology which  
256 is one of the main diagnostic characteristic of *O. puerilis* (Gibert et al., 2006; Netto et al.,  
257 2017).

258 The identification was also made by comparison with *in situ* *O. puerilis* from the Chuí  
259 Formation (Supp. Fig. 11 at the Supp. File 2) and literature data. The burrow morphology  
260 measurements from the *in situ* *O. puerilis* from Chuí Formation (Lagoon-Barrier III, RS,  
261 Brazil) as the external diameter have a range of 1.36–12.9 mm (mean 4.47 mm) and the  
262 interval for internal diameter were 0.63–10.58 mm (mean 2.03 mm) while the pellets  
263 diameter of presented a range of 0.2–2.71 mm (mean 1.04 mm) (Netto et al., 2017). The *ex*  
264 *situ* *O. puerilis* have the maximum value pellets diameter much smaller when compared to  
265 the maximum diameter of the *in situ*.

266

267 *Mineralogical and chemical composition.*—The X-ray Diffractometry (XRD) indicated that  
268 the pellets of the analyzed specimens are composed mostly by quartz, representing 64% to  
269 70.8% of the mineralogical composition of the samples (Table 2). Other subordinate minerals  
270 include feldspars (microcline) and carbonates (calcite and dolomite).

271 The EDS results (Fig. 5) indicate relevant amounts of silicon, oxygen and calcium on  
272 the wall of the sampled materials, with minor amounts of aluminum, carbon, fluorine,  
273 sodium, magnesium, phosphorus, potassium, iron, nitrogen, sulfur, chlorine, titanium, copper  
274 and manganese (Supp. Table 2 in Supp. File 2). The presence of Si, O, C and Ca corroborates  
275 the XRD results, and indicate that the samples are composed mainly by quartz and calcium  
276 carbonates. Other elements can be potentially indicative of the presence of clay (Fe, Al and  
277 Mg), silt (Fe, Ti and Zr) and heavy minerals (such as kyanite, sillimanite, magnetite, augite  
278 and pyroxene) in the substrate used by the crustacean during the wall construction. All the  
279 mentioned minerals are common within the sediments of the RSCP (Corrêa et al., 2008).

280 Thin-sections indicated that the specimens are composed by well sorted, fine to very  
281 fine sand-sized grains of quartz and indeterminate opaque minerals cemented by calcium  
282 carbonate (Figs. 6–7). In both, burrow wall (pellets) and burrow filling, the grains are very  
283 compacted, but in the latter the grains can be coarser. Because the burrow wall and filling are  
284 very compacted, they are almost indistinguishable. A differentiation between them is only  
285 possible because changing in color (Fig. 6.3). Bioclastic fragments (mollusk shell remains)  
286 could be recognized within the pellets (Fig. 7.3) and the burrow infilling.

287

288 *Neoichnological analysis.*—The neoichnological observations regarding the *S. mirim*  
289 burrows at Cassino Beach reflected the local available beach sediments in their composition,  
290 as in burrows constituted by fine quartz sand and shell fragments in the pelleted outer wall  
291 such as in the smoothed inner wall, besides a thin layer of mud in its interior (Fig. 2). The  
292 pellets presented an elongated, spherical, oval-shaped morphology organized individually.  
293 The interior of the burrows was also filled with quartzose fine sand and shell fragments.

294 The external diameter ranges from 20.7mm to 49.8 mm (mean 31.77 mm; standard  
295 deviation 6.1 mm) while the internal diameter ranges between 12.3–31.2 mm (mean 19.4

296 mm; standard deviation 4.1 mm). Therefore, comparison between modern burrows and *ex*  
297 *situ* trace fossils shown that the fossil *O. nodosa* present a wider range of measurements,  
298 presenting higher maximum values and lower minimum values compared to the *S. mirim*  
299 burrows (Table 3). On the other hand, the mean values for both external and internal diameter  
300 are similar.

301 The estimated maximum mass inferred for the constructors of the *ex situ* *O. nodosa* is  
302 34.5 g greater than the same value obtained for *S. mirim* (Table 4). The mean mass inferred  
303 for both sample groups have a difference of only 1.4 g. Also, the minimum estimated mass  
304 value differentiates by 0.8 g, being the *ex situ* with the smallest value reported (Table 4).

305

306 *Taphonomic analysis.*—Regarding the *ex situ* traces, 152 specimens (60.7%) present pelleted  
307 outer wall, being classified within the classes A–D (Fig. 8). Class E (no pellet can be  
308 visualized or identified at the outer wall) (Fig. 8.5) represents 39.3% (n=101) of the total  
309 amount of burrows found *ex situ*.

310 Sclerobionts and their traces occur in some *ex situ* traces. Only one bioerosion trace  
311 was identified on the burrow walls: *Gastrochaenolites* Leymerie, 1842 which is a result of  
312 bivalve boring activity (Fig. 9.1). *Gastrochaenolites* occur in more than 55% (n=147) of the  
313 analyzed specimens and is randomly distributed along the burrow walls (Fig. 9.4).

314 In addition, 22% (n=56) of all *ex situ* burrows presented incrusting organisms  
315 colonizing the external and internal surfaces of the burrow walls (Fig. 9.5). Bryozoans  
316 (n=52), barnacles (n=3) and both (n=1) occurred randomly placed along the analyzed  
317 burrows (Fig. 9.2–9.3). The cheilostome bryozoan *Biflustra* aff. *holocenica* Vieira, Spotorno-  
318 Oliveira and Tâmega, 2019 (Tâmega et al., 2019) (Figs. 9.2, 10) and the barnacle  
319 *Amphibalanus* sp. were identified (Fig. 9.3).

320

## 321 **Discussion**

322

323 *Taphonomic processes and remarks on the non-pelleted specimens.*—Transportation,  
324 weathering, disarticulation, fragmentation, abrasion, dissolution, erosion (including  
325 bioerosion), and encrustation are among the main taphonomic processes that act on body  
326 fossils during the biostratinomic phase. The influence of these processes is directly related to  
327 the completeness, fidelity and quality of the fossil record. Some of these taphonomic process  
328 also acted on trace fossils, since their production until their final burial (period called  
329 ichnostratinomy, *sensu* Savrda, 2007), analogously influencing the quality of the trace fossil  
330 record.

331 One of the most striking differences concerning the way in which taphonomic  
332 processes act on body and trace fossils is transportation and reworking. It is widely accepted  
333 that bioturbation traces are unlike to be exhumed from their original matrix and then  
334 transported (Buatois and Mángano, 2011), representing obligatory *in situ* records of organism  
335 activities. Here we describe a peculiar case in which bioturbation traces (crustacean burrows)  
336 are exhumed and transported from their original context. Similar occurrences were already  
337 described on literature (Baird, 1978; Balson, 1980; Brett and Baird, 1991; Savrda et al.,  
338 2000).

339 The *ex situ* *O. nodosa* (Classes A–D) have distinct taphonomic evidences, such as the  
340 presence of encrusting organisms (*Biflustra* aff. *holocenica* and *Amphibalanus* sp.) and  
341 bioerosion traces (*Gastrochaenolites*), that indicate that burrows remained underwater after  
342 the exhumation. Also, the partial erosion of the pelleted outer wall present in burrows of  
343 Classes B and D is another evidence that they were subjected to erosional processes that  
344 directly affected their gross morphology. On the other hand, the traces belonging to Class E  
345 lacks completely the characteristic pelleted lining of *Ophiomorpha*.



346 We propose two non-excluding work hypotheses to explain this this lacking of pellets  
347 in the Class E specimens: i) the non-pelleted burrows found *ex situ* represent  
348 *Spongeliomorpha* and/or *Thalassinoides* (i.e., non-pelleted SOT) burrows, and/or ii) they  
349 represent *Ophiomorpha* specimens whose taphonomical processes acted to erode pellets.  
350 Below, we present arguments concerning both hypotheses.

351 The main difference between the SOT ichnogenera is related to the wall of the  
352 burrows. Differently to the pellet-lined *Ophiomorpha*, *Spongeliomorpha* and *Thalassinoides*  
353 lack the pelleted linings at their outer wall (Goldring et al., 2007). The main difference  
354 between *Thalassinoides* and *Spongeliomorpha* is the smoothness of the wall, which is  
355 scratched in this latter and completely smooth in the former (Goldring et al., 2007). Goldring  
356 et al. (2007) considered that the SOT ichnotaxa could be part of the same maze system in  
357 which the substrate cohesion and percolation combined with increasingly vertical depth  
358 induce the production of pellets by the crustacean, reflecting the sediment conditions at the  
359 burrow walls.

360 Furthermore, if the Class E specimens do confidentially represent non-pelleted SOT  
361 burrows, the traces must have been exhumated from more distal (deep) marine environments,  
362 represented by *Cruziana*, *Nereites*, *Zoophycos* or *Glossifungites* Ichnofacies (MacEachern et  
363 al., 2007, 2012).

364 On the other hand, some of the *ex situ* *O. nodosa* inserted at Classes A–D show clear  
365 evidences of pellet erosion. This loss of part of the pelleted lining is solid evidence that the *O.*  
366 *nodosa* burrows were morphologically affected by underwater reworking. This observation  
367 leads us to deduce that the Class E burrows also passed by destructive processes that could  
368 have affected their morphology. Therefore, it is also plausible that the lack of pellets in Class  
369 E burrows is a taphonomic-derived feature.

370 Even though both hypotheses found support in different arguments, it is not possible  
371 to test them with the currently known data. The exact location of the deposit(s) in which these  
372 burrows are being exhumed and the effect of the ocean dynamics in their taphonomic history  
373 remain completely unknown.

374

375 *Neoichnological observations.*—According to White (2005) and Wu et al. (2015) there is a  
376 direct relation between animal size and burrow cross-sectional area. In addition, Twitchett  
377 and Barras (2004) stated that for ichnology standard burrow diameter is a proxy for body size  
378 and, consequently for the organism response of the surrounding environmental conditions.

379 The *ex situ* *O. nodosa* sample group presented a wider range calculated mass (0.05–  
380 49.2 g) when compared with *S. mirim* burrows (0.85–14.7 g; Table 2) and assuming that *O.*  
381 *nodosa* from Chuí Formation (Lagoon-Barrier III) have a high probability to derive from the  
382 fossilization of *S. mirim* burrows (Netto et al., 2017). The wide range of variation between  
383 the minimum and maximum estimated mass for the *ex situ* constructors could be explained  
384 by four distinct hypotheses:

- 385 (1) A monospecific contemporary crustacean population is represented by the *ex situ* *O.*  
386 *nodosa* assemblage and these crustaceans had a wider size range when compared with  
387 the modern *S. mirim* population;
- 388 (2) The *ex situ* assemblage represents multiple, but contemporanean crustacean  
389 populations of different species (with different size ranges);
- 390 (3) The *ex situ* assemblage represents different non-contemporanean monospecific  
391 crustacean populations and the size of these animals varied during the Quaternary;
- 392 (4) Different species of crustaceans of different mean sizes existed during the Quaternary  
393 and the *ex situ* burrow assemblage represent these variations.

394 Hypotheses (1) and (2) represent a time specific group sample unlike the hypotheses  
395 (3) and (4), that support a time-averaged *ex situ* sample considering that during the  
396 Quaternary the MSL fluctuates due to glacioeustatic changes (Villwock, 1984; Villwock and  
397 Tomazelli, 1995; Corrêa, 1996; Tomazelli and Villwock, 2000; Dillenburg et al., 2004; Lowe  
398 and Walker, 2015) and distinct immersed paleo shorelines (Corrêa, 1996) are currently being  
399 reworked resulting in ichnofossils exhumation and deposition at the actual beach face.  
400 However, only with dated material is plausible to confirm the exactly date of the traces initial  
401 burrowing.

402 Therefore, the exactly age of the *ex situ* *O. nodosa* collected along the foredunes and  
403 foreshore remains unknown, inferring the range as Pleistocene to Holocene. Tâmega et al.  
404 (2019) found shoreface Holocene bryoliths (free-living coated nodules by the bryozoans  
405 *Biflustra holocenica*) scattered in the foredunes of the RSCP. The bryolith radiocarbon  
406 datings (7910–7600 years BP), compositional and morphological features (Tâmega et al.,  
407 2019), were used to assess the paleoenvironmental dynamics in the region.

408  
409 *Paleoenvironmental dynamics and a taphonomic model for the ex situ traces occurrence.*—  
410 The *ex situ* traces were exhumed from their original strata, reworked and transported to the  
411 modern beach face of the RSCP (Fig. 11). As such, to better understand and visualize how  
412 the *ex situ* burrows were deposited at the modern beach face, a model for their taphonomic  
413 history is proposed (Fig. 12). Complex maze burrows were produced by ghost shrimps at the  
414 upper shoreface of a sandy beach at a stable coast line (Fig. 12.1). As presented earlier,  
415 during the Quaternary, the RSCP passed through transgressional and regressional fluctuation  
416 events that resulted in different coastal deposits. Nowadays, these deposits (and the  
417 respective trace fossil record) occur either emerged (i.e., the Chuí Formation) and submerged  
418 by the modern MSL.

419 Due MSL transgressions (Villwock and Tomazelli, 1995; Tomazelli and Villwock,  
420 2000; Dillenburg et al., 2004) the anterior coast line that were inhabited by crustaceans  
421 becomes submerged (Fig. **12.2**) and the burrow system is buried and may or may not be filled  
422 with the surrounding available sediment (Frey et al., 1978; Gibert et al., 2006). Regardless of  
423 whether the burrow is filled or not, after a sea level rise event, the burrow become  
424 inhospitable and the ghost shrimp is no longer part of the maze system, unless the soft bodied  
425 is rapidly buried to be further fossilized, which is rare (Hyžný and Klompaker, 2015).  
426 Following burial process, the crustacean burrow pass through fossilization and become  
427 lithified.

428 Because of ocean dynamics, as high energy wave incidence (i.e., storm waves), the  
429 now lithified burrow gallery is exposed at the surface of the ocean floor and fragments of the  
430 gallery are exhumated (Fig. **12.3**). The exhumation process is accompanied by the  
431 oceanographic and atmospheric events that interfere directly at the sediment rework and  
432 transportation, both towards inshore and offshore where these processes is mutually  
433 migrating according to the MSL variation.

434 After exhumation, the burrow fragments could be either buried again, transported or  
435 even destroyed. If the fragment outcome destruction, during the transportation the reworking  
436 processes took place, and abrasion, bioerosion and bioincrustation processes occur (Fig.  
437 **12.3**). The residence time of the fossilized burrow fragment at the ocean floor after  
438 exhumation is still unknown due to the lack of dated specimens which could range thousands  
439 of years, which also corroborates with a time-averaged sample. The taphonomic evidences  
440 observed on the outer wall of the ichnofossils may represent an estimative of that time,  
441 however, with the information retrieved it is not viable to quantify that exactly time due the  
442 extent time interval that is proposed for the creation origin leading to great errors as  
443 underestimating or overestimating the values.

444 Finally, when a meteorological high energy event occurs, pieces of the fragmented  
445 exhumated burrow are transported to the beach face (Fig. 12.4), along the foredunes or  
446 foreshore where the collection happened.

447

## 448 **Conclusions**

449

450 *Ex situ* crustacean burrows found along modern beaches of Rio Grande do Sul (southern  
451 Brazil) were described. Among them, pellet-walled materials could be assigned to *O. nodosa*  
452 (n=152) and *O. puerilis* (n=2). Other non-pelleted specimens (n=101) also occur, but their  
453 ichnotaxonomy is still perplexing because they can represent *Ophiomorpha* burrows with  
454 eroded pellets; *Spongeliomorpha* and/or *Thalassinoides* burrows; or both cases. Evidences of  
455 abrasion, bioerosion and bioincrustation demonstrate that this *ex situ* burrow assemblage  
456 passed through an intricate taphonomic history, in which exhumation, reworking and  
457 transportation played important roles on the composition and preservation of the assemblage.

458 Comparison with modern crustacean (*S. mirim*) burrows indicated that the size range  
459 of the *ex situ* burrows is wider than the modern analogues, leading us to consider that, during  
460 Quaternary, the size and mass of crustaceans varied. For now, we do not have conclusive  
461 evidences that suggest if the burrows were produced by different species of callianassids or if  
462 the modern *S. mirim* reached larger sizes in the past.

463 In spite of the lack of information regarding the age of this *ex situ* assemblage and the  
464 presence and scale of the time-averaging, this paper brings some new information regarding  
465 *ex situ* bioturbation assemblages. Due the difficulties in access submerged fossiliferous  
466 deposits, the description of this transported ichnofossils demonstrate to be useful for  
467 characterize the ecological and environmental processes that occurred on the RSCP during  
468 the Quaternary.

469

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471

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483

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648

## 649 **Figure captions**

650 **Figure 1.** The RSCP, southern Brazil. (1) Main locations for *ex situ* ichnofossils collection  
651 are: (1) – Hermenegildo Beach; (2) – Concheiros do Albardão; (3) – Verga Lighthouse; (4) –  
652 Sarita Lighthouse; (5) – Cassino Beach; (6) – Conceição Lighthouse; (7) – Bujuru; (8) –  
653 Balneário Lagamarzinho; and (9) – Lagoa do Peixe. Datum (WGS 84). (2) Lagoon-Barrier  
654 depositional systems I–IV from RSCP. (Adapted from Corrêa, 1996 and Tomazelli and  
655 Villwock, 2000)

656 **Figure 2.** (1) Cassino beach (Rio Grande municipality), where the *Sergio mirim* burrows (2–  
657 7) were sampled. (2) Main opening of the *S. mirim* burrow gallery. (3) *S. mirim* burrow  
658 pelleted wall exposed at the beachface. (4–5, 7) Fragments of *S. mirim* galleries. (6) Cross  
659 section view of a *S. mirim* burrow where the burrow wall and the burrow filling can be  
660 distinguished (white squares). Scale bars in centimeters.

661 **Figure 3.** *Ex situ* burrow fragments collected at the modern beach face of Rio Grande do Sul,  
 662 Brazil (1–17). (1) LGP H0011 with pellets organized in a brick-like pattern. (2) LGP H0513  
 663 with pellets organized individually. (3) LGP H0073 with pellets organized in pairs. (4) LGP  
 664 H0514, indeterminate burrow with no pellets on the outer wall. (5) LGP H0512 with  
 665 branches and bifurcations. (6) LGP H0232, with a Y-shaped bifurcation. (7) LGP H0049 and  
 666 LGP H0051, with turn-around points. (8) LGP H0586, with pellets organized in a brick-like  
 667 pattern. (9) LGP H0056, specimen composed by two burrows associated. (10) LGP H0038  
 668 with pellets organized individually. (11) LGP H0522 with pellets organized individually. (12)  
 669 LGP H0078 with a T-shaped bifurcation. (13) LGP H0016, evidencing the wall width. (14)  
 670 LGP H0011 with pellets organized in a brick-like pattern. (15) LGP H0078, with a Y-shaped.  
 671 (16) LGP H0089, with multiple tunnels connectors. (17) PI1670 with pellets organized in a  
 672 brick-like pattern. With the exception of LGP H0514 (4), all materials are assigned to *O.*  
 673 *nodosa*. Scale bars: 1 cm.

674 **Figure 4.** *O. puerilis* found emplaced on the walls of two *O. nodosa* (LGP H0270 and LGP  
 675 H0230) specimens (1–5). (1) and (2) distal image of *O. puerilis* that are cemented at an *O.*  
 676 *nodosa*. (3) and (4) emphasize the rod-shaped - ovoid pellets that are present at the *O. nodosa*  
 677 burrow wall. (5) emphasize the cemented *O. puerilis* (arrows) but it is not possible to  
 678 distinguish the pellets shape. Scale bars: 1 cm (1–2 and 5) and 1 mm (3–4).

679 **Figure 5.** SEM imagery and EDS graphics of outer wall pellets of an *ex situ* *O. nodosa*. (1)  
 680 Overview of the specimen LGP H0516. (2) SEM image of spherical, rounded pellets. (3)  
 681 Magnified SEM image of one of the pellets. (4–6) EDS graphic showing with specific  
 682 elementary compositions at different point. Scale bars: 1 cm (1), 2 mm (2) and 200  $\mu$ m (3).

683 **Figure 6.** Thin section of *O. nodosa* (LGP H0007). (1) Burrow in cross section view. (2)  
 684 Thin section under stereomicroscope. (3–4) Thin section under petrographic microscope. (3)  
 685 The red line indicates the border that divide the sediment of the burrow wall (BW) and the

686 burrow filling (BF), notice the difference of the arrangement, compaction and grains size. (4)  
687 The red arrows indicate larger quartz grains of the BW that differ from the other minerals or  
688 heavy minerals. Scale bar: 1 cm (1–2) and 1 mm (3–4).

689 **Figure 7.** Thin section of *O. nodosa* (LGP H0008). (1) Burrow in cross section view. (2)  
690 Thin section under stereomicroscope. (3) Shell fragment that is incorporated in the  
691 sedimentation of the burrow wall (BW) of the trace. (4) The red arrows indicate bigger bright  
692 quartz grains in the sediment composition of the BW. Scale bar: 1 cm (1–2) and 1 mm (3–4).

693 **Figure 8.** Classification of the burrows found *ex situ* according the presence and organization  
694 of pellets. (1) Class A. (2) Class B. (3) Class C. (4) Class D. (5) Class E. Scale bar represents  
695 1 cm. (6) Percentage representation of each Class (A–E).

696 **Figure 9.** Bioerosion and bioincrustation in the *ex situ* *O. nodosa*. (1) LGP H0482, with  
697 *Gastrochaenolites* isp. (2) PI 1732 with a bryozoan colony (*B. aff. holocenica*). (3) LGP  
698 H0068 with barnacles (*Amphibalanus* sp.). Scale bars: 1 cm (1–3). (4) Percentage of presence  
699 and absence of bioerosion on *ex situ* *O. nodosa*. (5) Percentage of presence and absence of  
700 bioincrustation on *ex situ* *O. nodosa*.

701 **Figure 10.** SEM images of zooidal bryozoan skeleton *B. aff. holocenica* incrustated in the  
702 outer wall of one *ex situ* *O. nodosa* (PI 1732). (1) Frontal surface of the *B. aff. holocenica*  
703 colony. (2) Magnified view of the *B. aff. holocenica* autozooids. Scale bars: 500  $\mu\text{m}$  (1) and  
704 100  $\mu\text{m}$  (2).

705 **Figure 11.** Diagram of taphonomic processes in which traces of *Ophiomorpha* collected *ex*  
706 *situ* along the RSCP may have been exposed from the moment of its construction to its  
707 collection in the current beach face.

708 **Figure 12.** Reconstruction of the paleoenvironmental dynamics since the construction of the  
709 crustacean burrow in a paleoshoreline until the deposition of the reworked fragmented  
710 *Ophiomorpha* in the current beach face of RSCP, southern Brazil. (1) The decapod

711 crustacean engineered the burrow at soft substrate in the upper shoreface (Quaternary). (2)  
712 The MSL rise (transgression phase) submerged the shoreface (paleoshoreline) and the  
713 crustacean burrow go through fossilization (*Ophiomorpha*). (3) The trace fossil is exhumated  
714 from its original bedrock at the paleoshoreline and fragments of the burrow are exposed to  
715 taphonomic process as (1) abrasion, (2) bioerosion and (3) bioincrustation, until (4) its  
716 deposition in the current beach face. Not to scale.

717

## 718 **Table captions**

719 **Table 1.** Maximum (Max.) and minimum (Min.) values in millimeter of the external diameter  
720 (ED), internal diameter (ID), wall thickness (WT) and pellets diameter (PD) for the *ex situ*  
721 and *in situ* (from the Chuí Formation) *O. nodosa*. *In situ* material data source: Gibert et al.  
722 (2006), Goldring et al. (2007) and Netto et al. (2017).

723 **Table 2.** Mineral composition of two *ex situ Ophiomorpha* (LGP H0050 and LGP H0218)  
724 obtained by X-ray Diffractometry (XRD). Values in weight (%): Cal: Calcite, Dol: Dolomite,  
725 Mc: Microcline, Qtz: Quartz.

726 **Table 3.** Maximum, minimum and mean values of the external diameter (ED) and internal  
727 (ID) diameters (mm) for the *ex situ O. nodosa* and the *S. mirim* burrows (n=18).

728 **Table 4.** Maximum, minimum and mean values of the estimated mass (g) for the producers  
729 of *ex situ O. nodosa* (n=111) and the extant *S. mirim* (n=18). Extended data are provided in  
730 the Supplementary Table 2.

731

## 732 **Supplementary file captions**

733 **Supplementary File 1.** Summary of all acronyms and localities for each analyzed specimen.

734 **Supplementary File 2.** Additional tables and figures with information regarding basic  
735 statistics, EDS, SEM, XRD and comparative morphological analyzes.



736 **Supplementary File 3.** Inferred mass (g) of *Ophiomorpha nodosa* producers and *Sergio*  
737 *mirim* based on internal burrow diameters (mm).

For Review Only

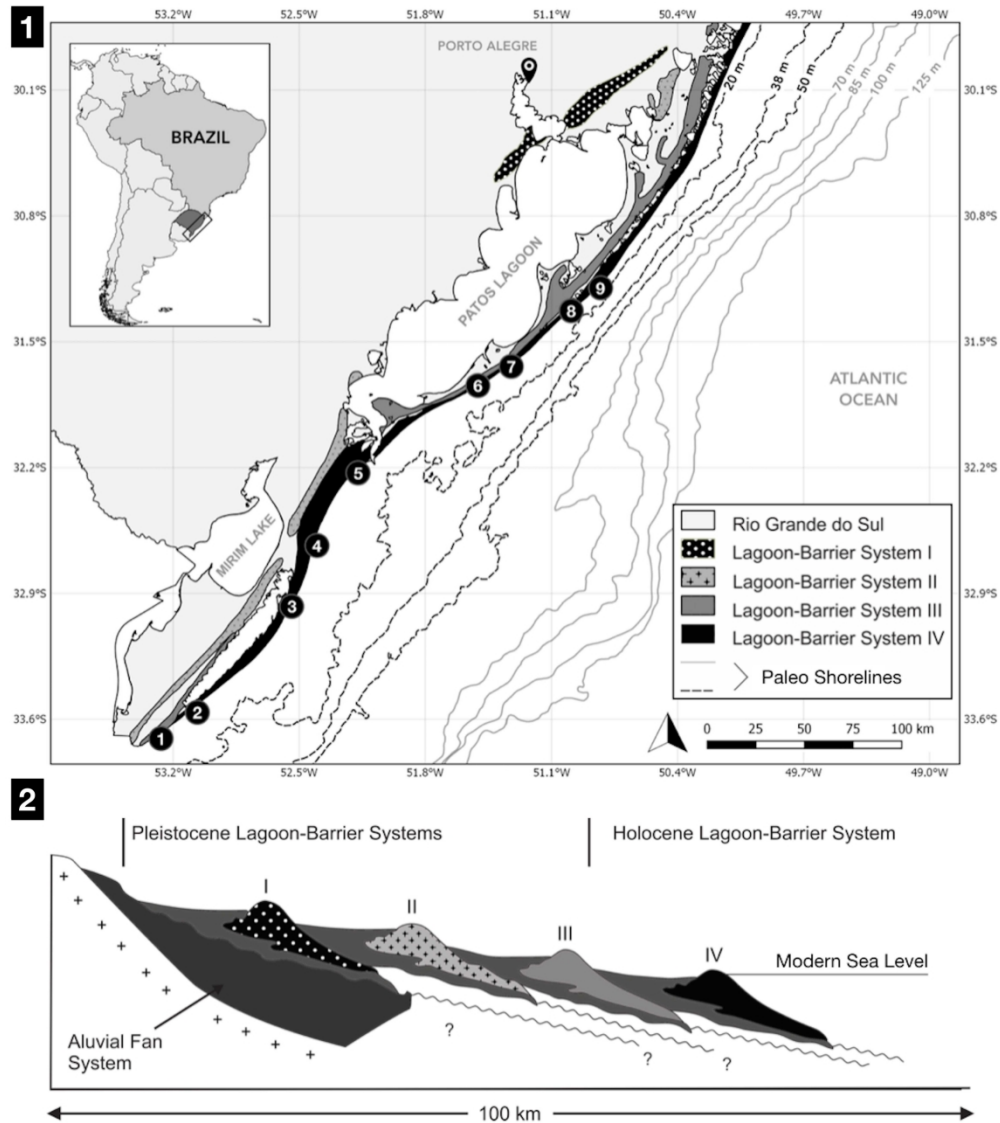


Figure 1. The RSCP, southern Brazil. (1) Main locations for ex situ ichnofossils collection are: (1) – Hermenegildo Beach; (2) – Concheiros do Albardão; (3) – Verga Lighthouse; (4) – Sarita Lighthouse; (5) – Cassino Beach; (6) – Conceição Lighthouse; (7) – Bujuru; (8) – Balneário Lagamarzinho; and (9) – Lagoa do Peixe. Datum (WGS 84). (2) Lagoon-Barrier depositional systems I–IV from RSCP. (Adapted from Corrêa, 1996 and Tomazelli and Villwock, 2000)

199x225mm (300 x 300 DPI)

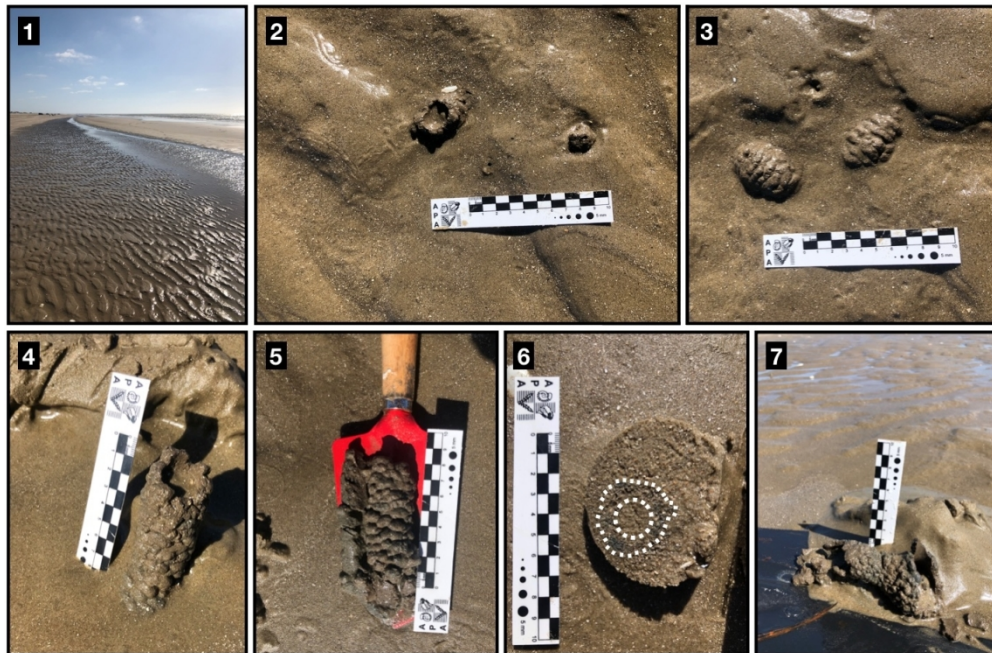


Figure 2. (1) Cassino beach (Rio Grande municipality), where the Sergio mirim burrows (2–7) were sampled. (2) Main opening of the *S. mirim* burrow gallery. (3) *S. mirim* burrow pelleted wall exposed at the beachface. (4–5, 7) Fragments of *S. mirim* galleries. (6) Cross section view of a *S. mirim* burrow where the burrow wall and the burrow filling can be distinguished (white squares). Scale bars in centimeters.

252x166mm (144 x 144 DPI)



Figure 3. Ex situ burrow fragments collected at the modern beach face of Rio Grande do Sul, Brazil (1–17). (1) LGP H0011 with pellets organized in a brick-like pattern. (2) LGP H0513 with pellets organized individually. (3) LGP H0073 with pellets organized in pairs. (4) LGP H0514, indeterminate burrow with no pellets on the outer wall. (5) LGP H0512 with branches and bifurcations. (6) LGP H0232, with a Y-shaped bifurcation. (7) LGP H0049 and LGP H0051, with turn-around points. (8) LGP H0586, with pellets organized in a brick-like pattern. (9) LGP H0056, specimen composed by two burrows associated. (10) LGP H0038 with pellets organized individually. (11) LGP H0522 with pellets organized individually. (12) LGP H0078 with a T-shaped bifurcation. (13) LGP H0016, evidencing the wall width. (14) LGP H0011 with pellets organized in a brick-like pattern. (15) LGP H0078, with a Y-shaped. (16) LGP H0089, with multiple tunnels connectors. (17) PI1670 with pellets organized in a brick-like pattern. With the exception of LGP H0514 (4), all materials are assigned to *O. nodosa*. Scale bars: 1 cm.

183x204mm (144 x 144 DPI)

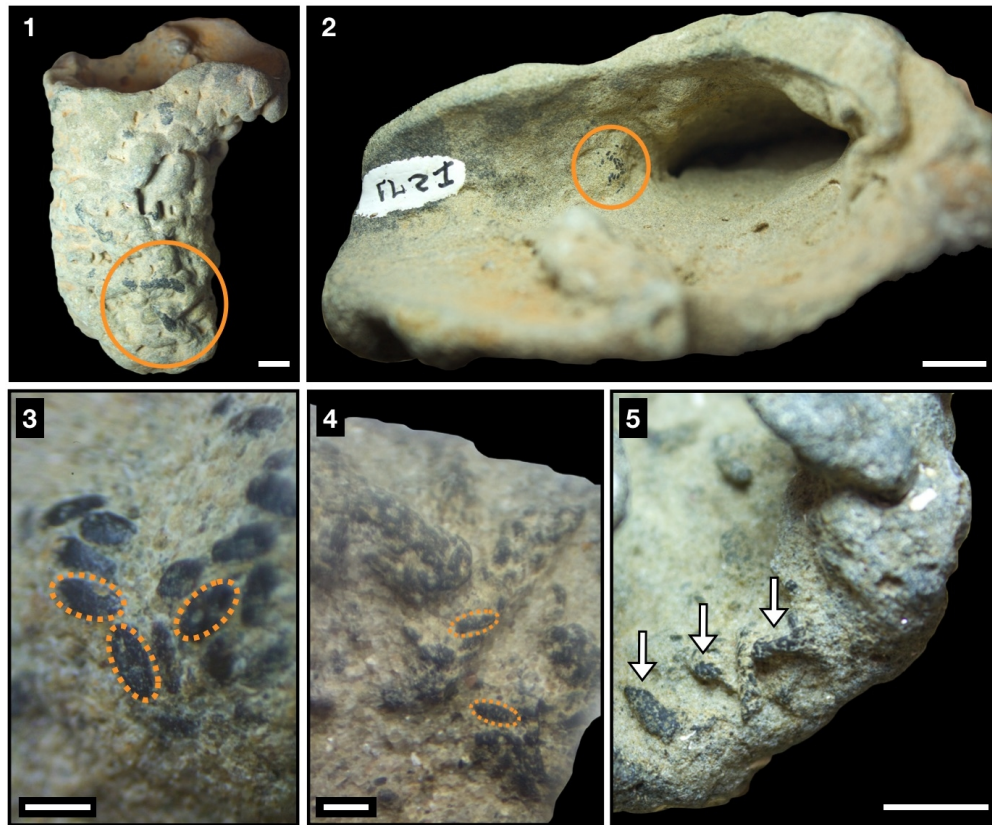


Figure 4. *O. puerilis* found emplaced on the walls of two *O. nodosa* (LGP H0270 and LGP H0230) specimens (1–5). (1) and (2) distal image of *O. puerilis* that are cemented at an *O. nodosa*. (3) and (4) emphasize the rod-shaped - ovoid pellets that are present at the *O. nodosa* burrow wall. (5) emphasize the cemented *O. puerilis* (arrows) but it is not possible to distinguish the pellets shape. Scale bars: 1 cm (1–2 and 5) and 1 mm (3–4).

243x200mm (144 x 144 DPI)

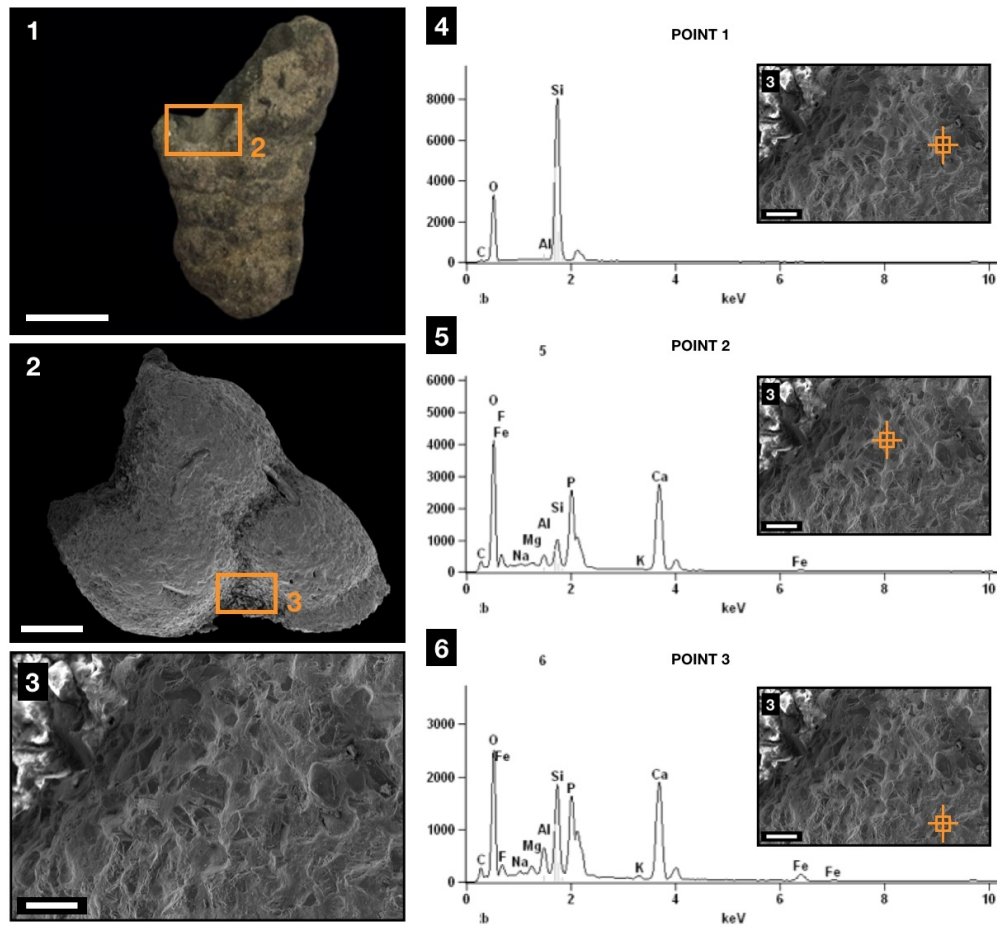


Figure 5. SEM imagery and EDS graphics of outer wall pellets of an ex situ *O. nodosa*. (1) Overview of the specimen LGP H0516. (2) SEM image of spherical, rounded pellets. (3) Magnified SEM image of one of the pellets. (4–6) EDS graphic showing with specific elementary compositions at different point. Scale bars: 1 cm (1), 2 mm (2) and 200  $\mu\text{m}$  (3).

213x196mm (144 x 144 DPI)

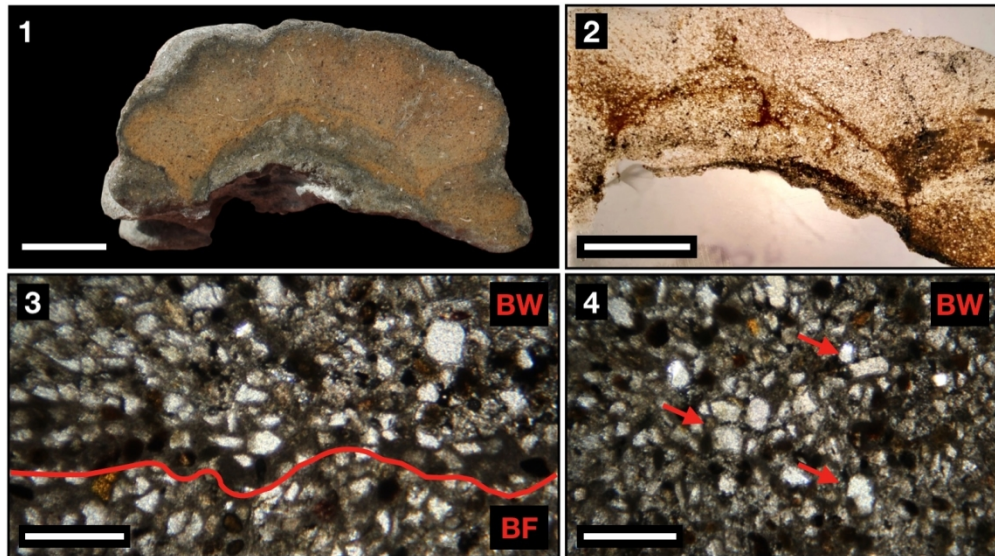


Figure 6. Thin section of *O. nodosa* (LGP H0007). (1) Burrow in cross section view. (2) Thin section under stereomicroscope. (3–4) Thin section under petrographic microscope. (3) The red line indicates the border that divide the sediment of the burrow wall (BW) and the burrow filling (BF), notice the difference of the arrangement, compaction and grains size. (4) The red arrows indicate larger quartz grains of the BW that differ from the other minerals or heavy minerals. Scale bar: 1 cm (1–2) and 1 mm (3–4).

280x156mm (144 x 144 DPI)

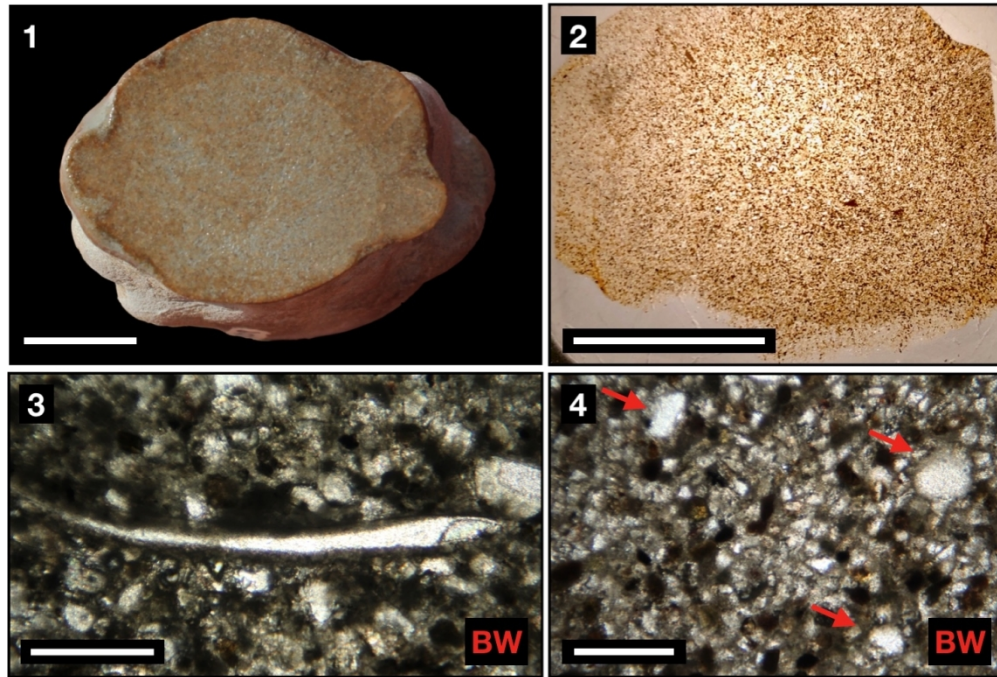


Figure 7. Thin section of *O. nodosa* (LGP H0008). (1) Burrow in cross section view. (2) Thin section under stereomicroscope. (3) Shell fragment that is incorporated in the sedimentation of the burrow wall (BW) of the trace. (4) The red arrows indicate bigger bright quartz grains in the sediment composition of the BW. Scale bar: 1 cm (1–2) and 1 mm (3–4).

259x176mm (144 x 144 DPI)



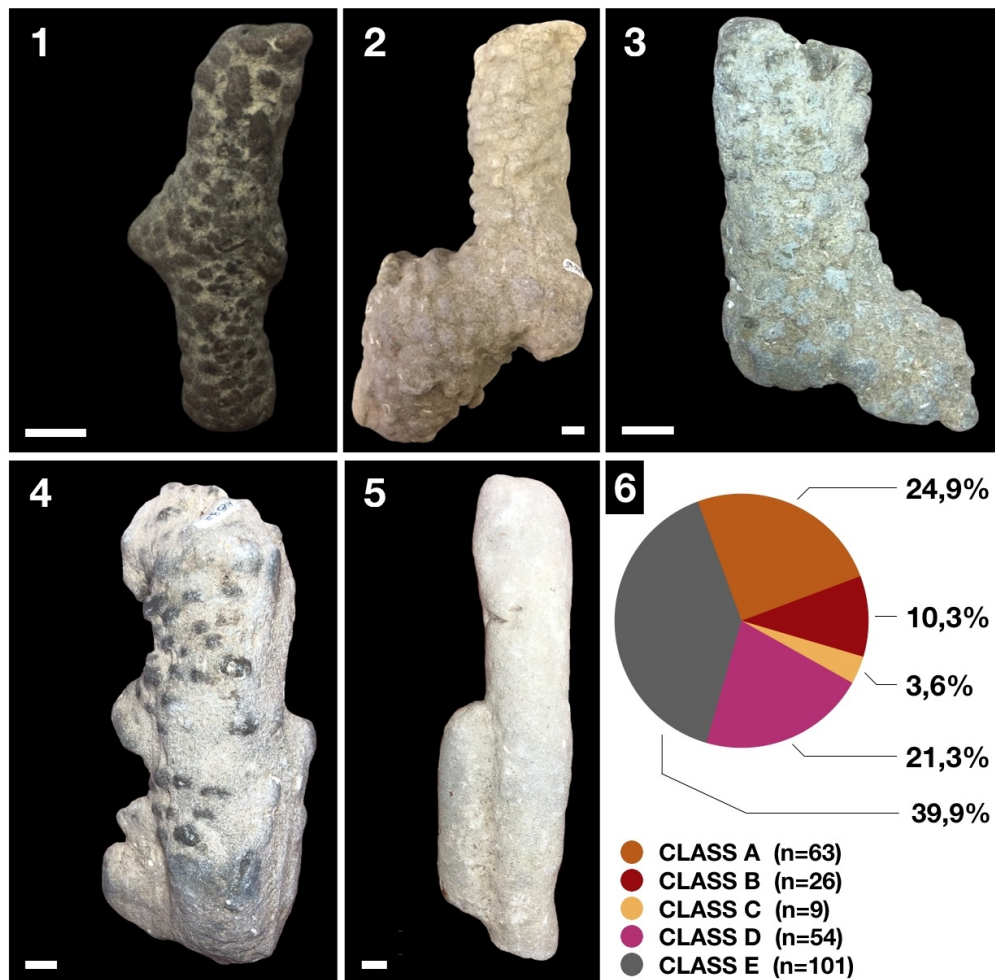


Figure 8. Classification of the burrows found ex situ according to the presence and organization of pellets. (1) Class A. (2) Class B. (3) Class C. (4) Class D. (5) Class E. Scale bar represents 1 cm. (6) Percentage representation of each Class (A–E).

216x212mm (144 x 144 DPI)

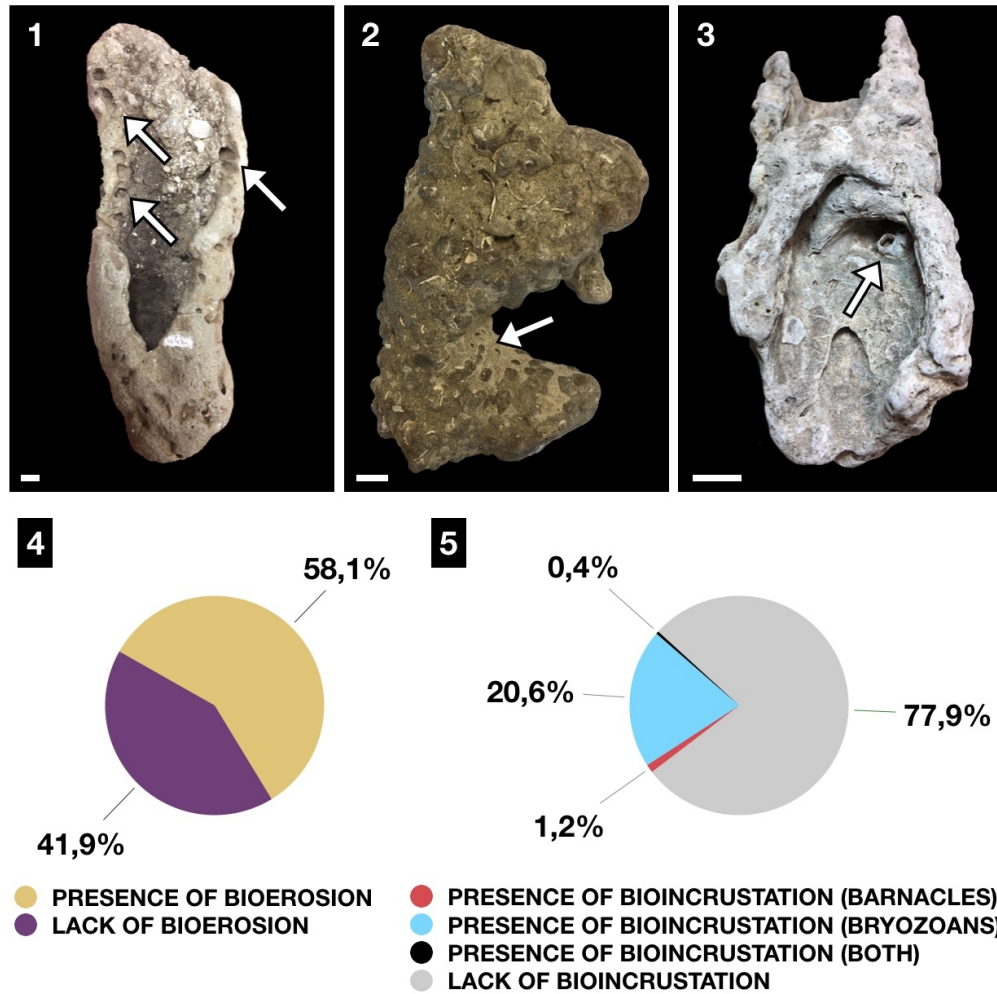


Figure 9. Bioerosion and bioincrustation in the ex situ *O. nodosa*. (1) LGP H0482, with *Gastrochaenolites* isp. (2) PI 1732 with a bryozoan colony (*B. aff. holocenica*). (3) LGP H0068 with barnacles (*Amphibalanus* sp.). Scale bars: 1 cm (1–3). (4) Percentage of presence and absence of bioerosion on ex situ *O. nodosa*. (5) Percentage of presence and absence of bioincrustation on ex situ *O. nodosa*.

216x216mm (144 x 144 DPI)

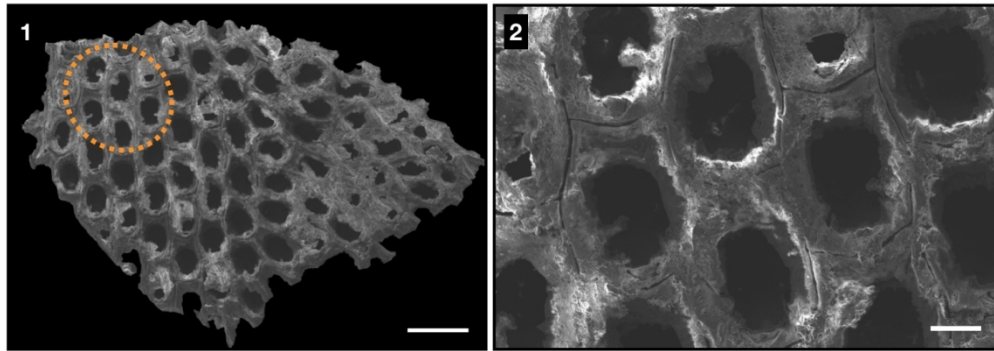


Figure 10. SEM images of zooidal bryozoan skeleton *B. aff. holocenica* incrusting the outer wall of one ex situ *O. nodosa* (PI 1732). (1) Frontal surface of the *B. aff. holocenica* colony. (2) Magnified view of the *B. aff. holocenica* autozooids. Scale bars: 500  $\mu\text{m}$  (1) and 100  $\mu\text{m}$  (2).

271x95mm (144 x 144 DPI)

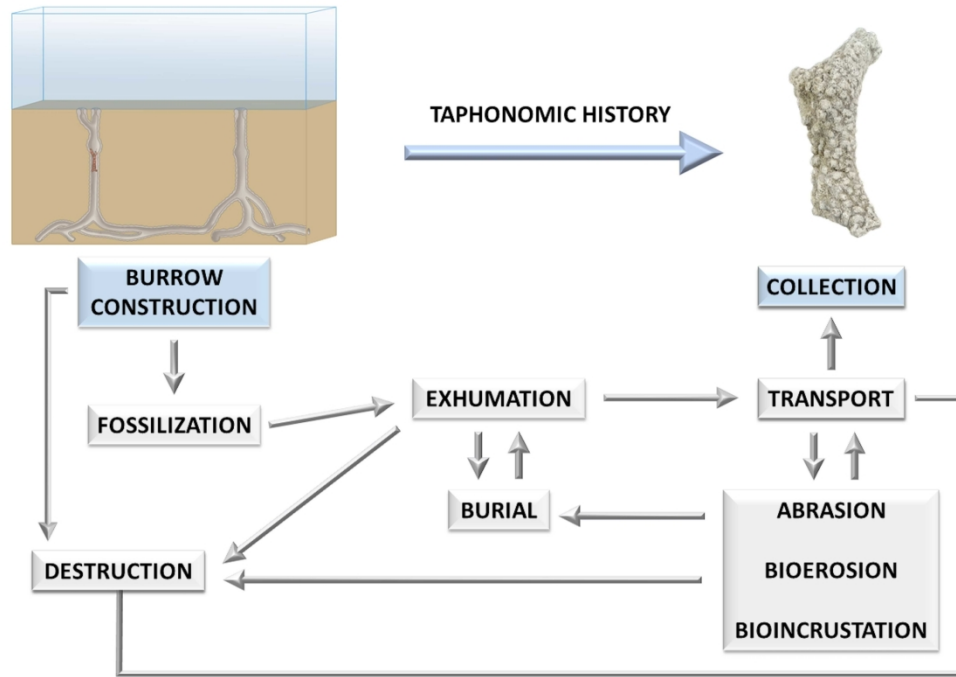


Figure 11. Diagram of taphonomic processes in which traces of Ophiomorpha collected ex situ along the RSCP may have been exposed from the moment of its construction to its collection in the current beach face.

199x137mm (300 x 300 DPI)

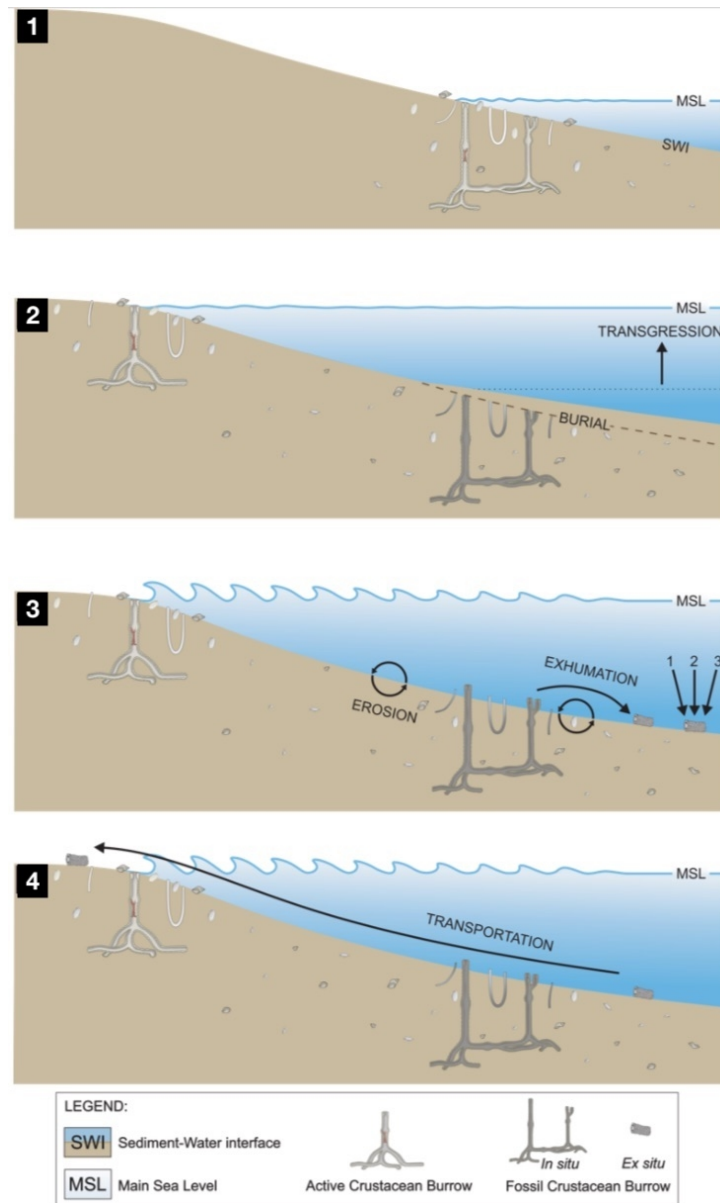


Figure 12. Reconstruction of the paleoenvironmental dynamics since the construction of the crustacean burrow in a paleoshoreline until the deposition of the reworked fragmented *Ophiomorpha* in the current beach face of RSCP, southern Brazil. (1) The decapod crustacean engineered the burrow at soft substrate in the upper shoreface (Quaternary). (2) The MSL rise (transgression phase) submerged the shoreface (paleoshoreline) and the crustacean burrow go through fossilization (*Ophiomorpha*). (3) The trace fossil is exhumated from its original bedrock at the paleoshoreline and fragments of the burrow are exposed to taphonomic process as (1) abrasion, (2) bioerosion and (3) bioincrustation, until (4) its deposition in the current beach face. Not to scale.

129x214mm (144 x 144 DPI)

1 **Table 1.** Maximum (Max.) and minimum (Min.) values in millimeter of the external diameter  
 2 (ED), internal diameter (ID), wall thickness (WT) and pellets diameter (PD) for the *ex situ*  
 3 and *in situ* (from the Chuí Formation) *O. nodosa*. *In situ* material data source: Gibert et al.  
 4 (2006), Goldring et al. (2007) and Netto et al. (2017).

	<b>Max.ED</b>	<b>Min.ED</b>	<b>Max.ID</b>	<b>Min.ID</b>	<b>Max.WT</b>	<b>Min.WT</b>	<b>Max.PD</b>	<b>Min.PD</b>
<i>Ex situ</i>	75.7	11.7	46.3	5	16.41	2.18	13.77	2.3
<i>In situ</i>	-	-	50	20	2.5	15	5	10

5

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- 1 **Table 2.** Mineral composition of two *ex situ* *Ophiomorpha* (LGP H0050 and LGP H0218)  
 2 obtained by X-ray Diffractometry (XRD). Values in weight (%). Cal: Calcite. Dol: Dolomite,  
 3 Mc: Microcline. Qtz: Quartz.

	<b>Qtz</b>	<b>Mc</b>	<b>Cal</b>	<b>Dol</b>
<b>LGP H0050</b>	70.8	29.2	-	-
<b>LGP H0218</b>	64.0	-	28.7	7.3

4

For Review Only

- 1 **Table 3.** Maximum, minimum and mean values of the external diameter (ED) and internal  
 2 (ID) diameters (mm) for the *ex situ* *O. nodosa* and the *S. mirim* burrows (n=18).

	<b>Maximum ED</b>	<b>Minimum ED</b>	<b>Mean ED</b>	<b>Maximum ID</b>	<b>Minimum ID</b>	<b>Mean ID</b>
<i>Ex situ O. nodosa</i>	75.7	11.7	31.2	46.3	5.0	18.5
<i>S. mirim</i> burrows	49.8	20.7	31.7	31.2	12.3	19.4

3

For Review Only



1 **Table 4.** Maximum, minimum and mean values of the estimated mass (g) for the producers  
 2 of *ex situ* *O. nodosa* (n=111) and the extant *S. mirim* (n=18). Extended data are provided in  
 3 the Supplementary Table 2.

	<b>Maximum mass</b>	<b>Minimum mass</b>	<b>Mean mass</b>
<i>Ex situ</i> <i>O. nodosa</i>	49.2	0.05	5.3
producers			
<i>S. mirim</i>	14.7	0.85	3.9

4

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## Capítulo IV: Síntese dos resultados e discussão

No total foram analisados 253 traços fósseis que foram coletados *ex situ* ao longo da PCRS. Além de representarem fragmentos de uma complexa estrutura construída por crustáceos estes icnofósseis apresentam evidência de uma série de processos tafonômicos os quais passaram durante o momento em que foram retrabalhados no oceano após sua exumação (tempo de residência na água).

Do total de traços coletados, 152 foram identificados como pertencentes à icnoespécie *Ophiomorpha nodosa*, os quais apresentaram parede externa revestida por *pellets* (Classes A–D). Além disso, foram identificados dois espécimes de *O. puerilis* aderidos a dois espécimes de *O. nodosa* (LGP-H0270 e LGP-H0230). Já os traços que não apresentaram parede externa revestida por *pellets* (n=101; Classe E) foram atribuídos ao grupo SOT [*sensu* Rindsberg 2018], o qual engloba os icnogêneros *Spongiomorpha*, *Ophiomorpha* e *Thalassinoides*.

Como não é possível identificar a qual icnogênero do grupo SOT pertencem os traços que não apresentaram *pellets* em sua parede externa, duas hipóteses não mutuamente excludentes foram levantadas, onde i) as tocas poderiam pertencer aos icnogêneros *Spongeliomorpha* e/ou *Thalassinoides* (i.e., tocas com parede externa lisa, sem *pellets*), e/ou ii) os espécimes representariam tocas do icnogênero *Ophiomorpha* em que processos tafonômicos teriam agido diretamente na erosão dos *pellets* que, uma vez, estiveram presentes na parede externa. Dessa forma o papel que a dinâmica oceânica tem sob os processos tafonômicos que agem diretamente sob os traços são ainda desconhecidos.

Além disso, a comparação entre as tocas atuais de *S. mirim* com as tocas de *O. nodosa* encontradas *ex situ* levou à formulação de quatro hipóteses quando comparada a massa calculada dos produtores:

- (1) A assembleia de icnofósseis *ex situ* estaria representada por uma população monoespecífica e contemporânea de crustáceos que apresentavam uma maior amplitude de tamanho corporal quando comparados com a população atual do crustáceo *S. mirim*;
- (2) A assembleia representaria múltiplas populações de crustáceos de diferentes espécies (com amplitudes de tamanho maiores que a de *S. mirim*), porém contemporâneas;
- (3) A assembleia representaria uma população monoespecífica, mas não contemporânea de crustáceos, sendo que o tamanho destes organismos variou durante o Quaternário;

(4) Diferentes espécies de crustáceos de diferentes tamanhos teriam existido ao longo do Quaternário e a assembleia está representada por essa variação.

Considerando as possibilidades, é importante ressaltar que as hipóteses (1) e (2) implicam em organismos contemporâneos entre si, representando então uma assembleia de fósseis provenientes de um intervalo de tempo específico (mas ainda assim desconhecido). Por outro lado, as hipóteses (3) e (4) representariam uma assembleia caracterizada por mistura temporal. Além disso, as oscilações glacioeustáticas do nível médio do mar (transgressão e regressão marinha) durante o Quaternário que deram origem às paleolinhas de costa que estão atualmente submersas e sendo erodidas (resultando na exumação dos icnofósseis, seu retrabalhamento e posterior transporte para a linha de praia atual) corroboram para que a assembleia possa ser considerada temporalmente misturada (hipóteses 3 e 4). Entretanto, como a idade exata dos traços coletados *ex situ* ainda é desconhecida, o intervalo de construção dessas tocas pode ter ocorrido tanto no Pleistoceno como durante o Holoceno.

Por fim, a reconstituição tafonômica proposta para os traços coletados *ex situ* caracteriza os principais aspectos envolvidos desde a exumação até a coleta destes icnofósseis e apresenta a alta variabilidade do ambiente em que os mesmos são expostos. Esta variabilidade nos aspectos oceanográficos, tanto físicos, químicos, biológicos quanto geológicos podem alterar a morfologia original dos traços, o que irá refletir em sua icnoidentificação como no seu tempo de residência na água pós exumação. Além disso, o modelo tafonômico proposto também servirá para outros fósseis que são exumados dos estratos originais, retrabalhados e depositados na linha de praia atual.

## Capítulo V: Perspectivas Futuras

Tendo em vista que os traços de bioturbação são habitualmente observados *in situ* e sua ocorrência fora dos estratos em que foram produzidos é excepcional, o estudo de icnofósseis coletados *ex situ*, é essencial. Além disso, é fundamental entendermos quais são os fatores tafonômicos (bióticos e abióticos) que moldam as alterações na morfologia original destes traços e quais consequências essas modificações infligem em sua icnotaxonomia, por exemplo. Especificamente, os traços que são retrabalhados no oceano, oferecem informações tanto bióticas, quanto abióticas, o que pode refletir em um tempo específico de residência neste meio.

Além disso, para o melhor desenvolvimento do trabalho com materiais provenientes de paleolinhas de costa que estão atualmente submersas, seria essencial o conhecimento de sua exata localização. Com esta informação,

seria possível adquirir uma melhor inferência a respeito de sua idade e dos fatores bióticos e abióticos que atuam sobre os fósseis delas exumados. Dessa forma, sugere-se que haja um esforço de prospecção por estes depósitos, se possível, com mergulhos e/ou ROV (*remotely operated underwater vehicle*) nas paleolinhas de praia submersas e nos parcéis da PCRS.

Com base na experiência em caracterizar os traços *ex situ* da PCRS, ressalta-se a necessidade que mais estudos sobre icnofósseis que ocorrem fora de sua rocha matriz original sejam realizados ao redor do mundo, para que conclusões mais acuradas sejam atingidas, como, por exemplo, como a dinâmica ambiental e as mudanças climáticas agem diretamente nas interações tafonômicas entre o icnofóssil e o meio a que ele foi exposto.

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## **ANEXOS**

**Anexo 1.** Material suplementar submetido juntamente com o manuscrito (Artigo do Cap. III). A formatação segue os padrões exigidos pela revista.

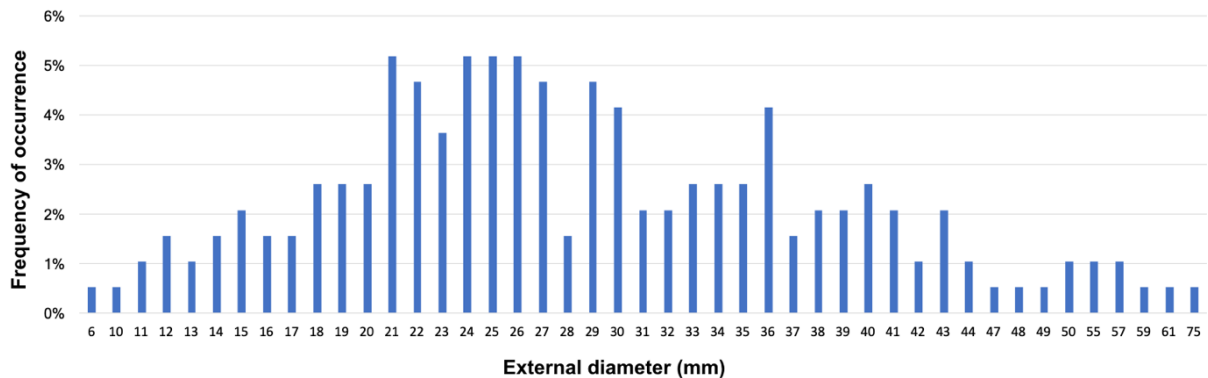
Supplementary Material for:

## On the *ex situ* ichnofossils from the Quaternary of the Rio Grande do Sul Coastal Plain (Brazil): taphonomic and paleoenvironmental remarks

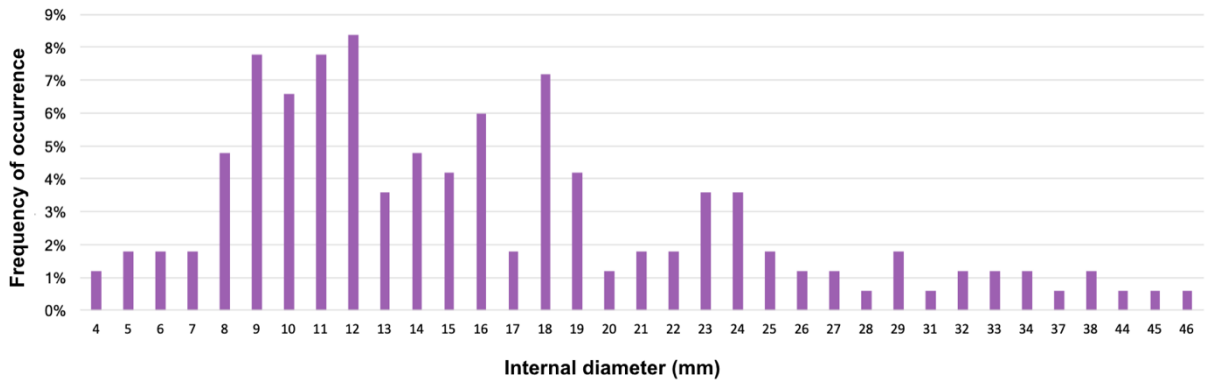
Giovana Pedrol de Freitas, Heitor Francischini, Frederico Tapajós de Souza Tâmega, Paula Spotorno-Oliveira and Paula Dentzien-Dias

**Supplementary table 1.** Statistical properties, in millimeters, of the morphological measurements of the *ex situ* burrows. Morphological characteristics: external diameter (ED), internal diameter (ID), wall thickness (WT) and pellets diameter (PD).

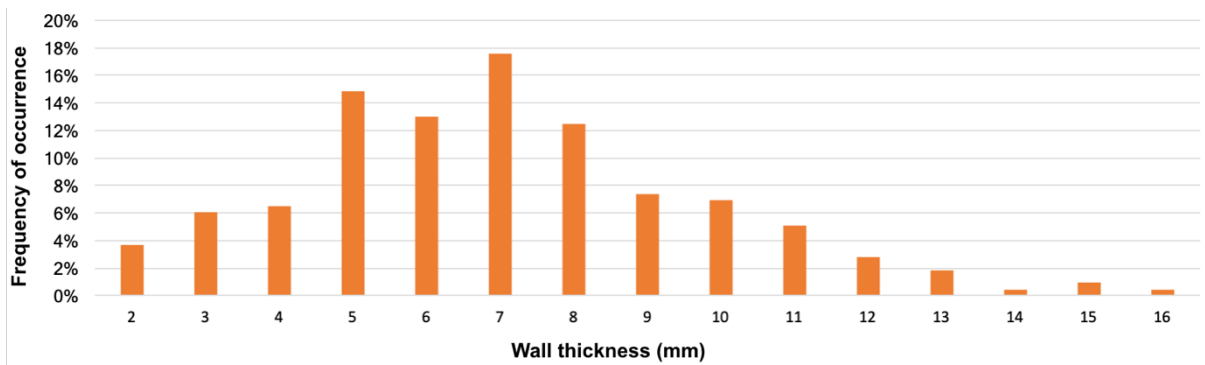
	Ex situ burrows	Mean	Median	Mode	Variance	Standard Deviation
<b>ED</b>	193	28.87	27	24	114.64	10.73
<b>ID</b>	167	16.42	14	12	69.4	8.33
<b>WT</b>	216	7.03	7	7	7.6	2.75
<b>PD</b>	152	7.32	7	8	4.48	2.11



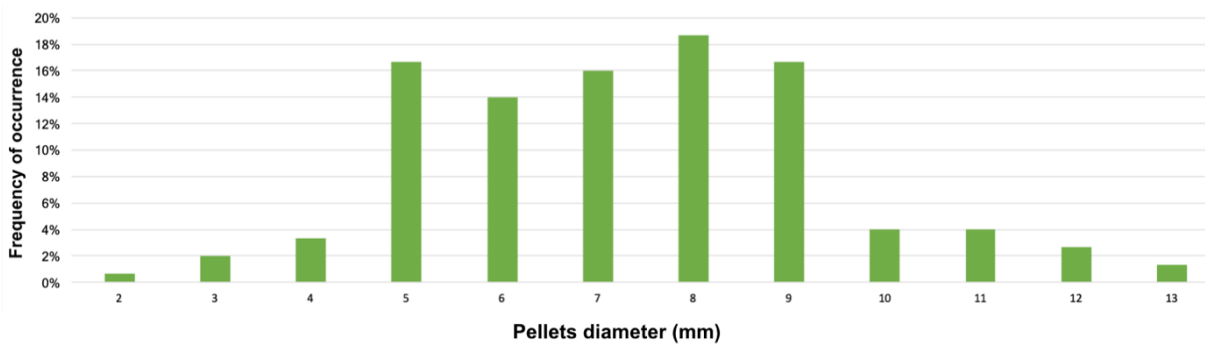
**Supplementary figure 1.** Frequency of occurrence histogram of the external diameter (ED) of 193 *ex situ* burrows in cross section.



**Supplementary figure 2.** Frequency of occurrence histogram of the internal diameter (ID) (main tunnel) of 167 ex situ burrows.



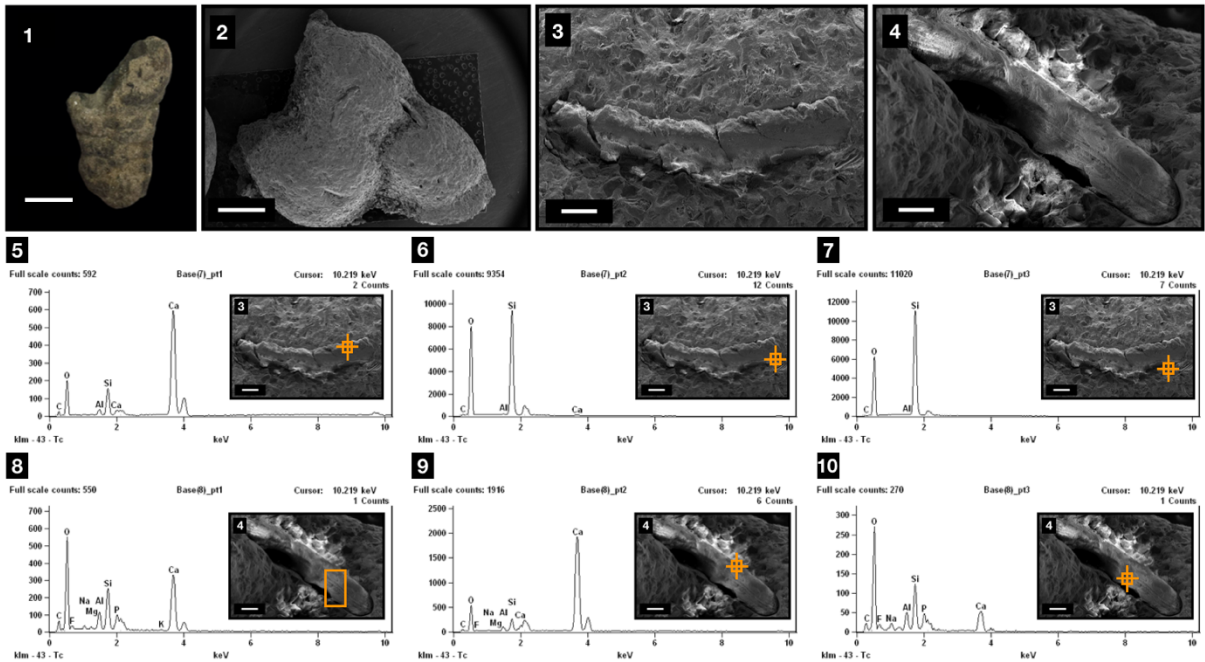
**Supplementary figure 3.** Frequency of occurrence histogram of the wall thickness (WT) of 216 ex situ burrows.



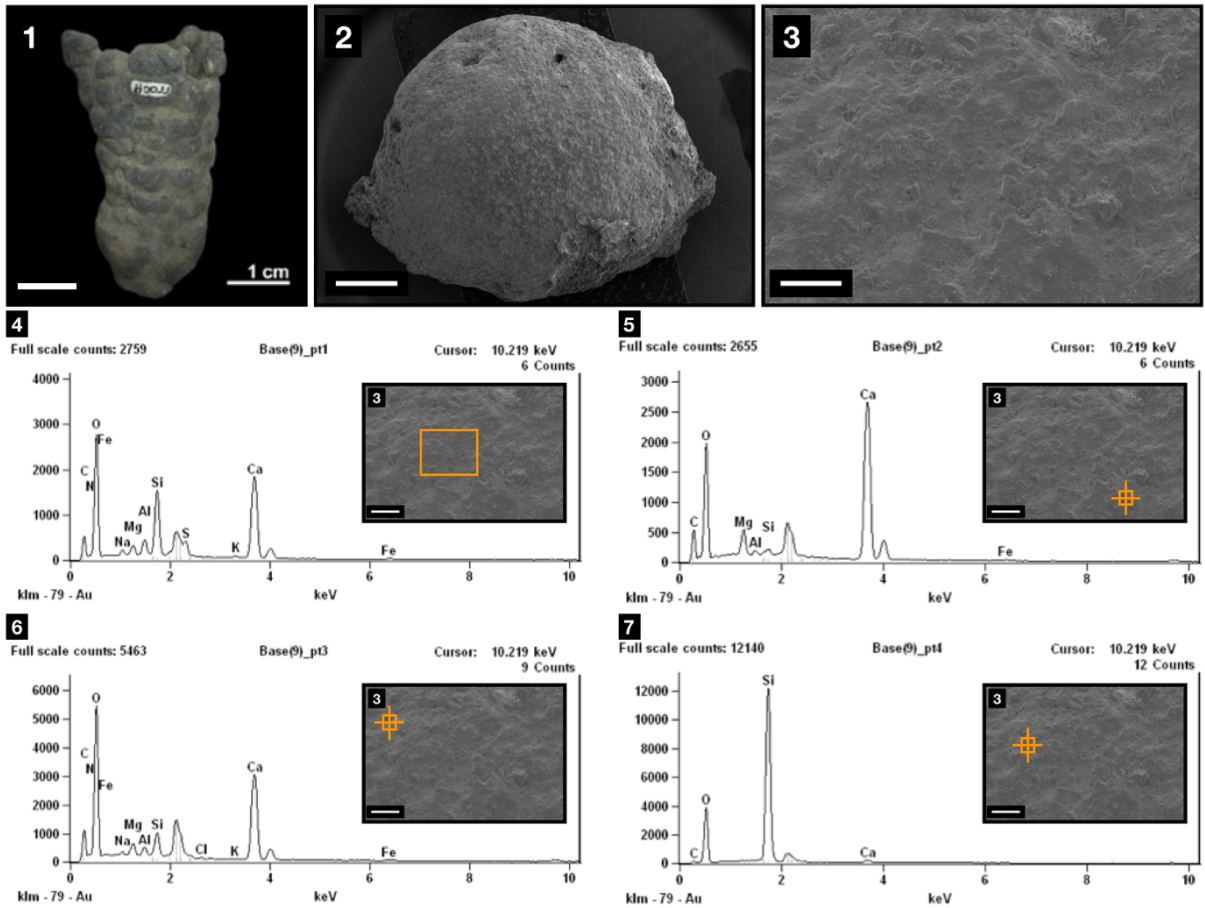
**Supplementary figure 4.** Frequency of occurrence histogram of the pellets diameter (PD) of 152 ex situ *Ophiomorpha* burrows.

**Supplementary table 2.** Semiquantitative proportions (in %) of the main elements of each ex situ *Ophiomorpha* (LGP H0515, H0011, H0529, H0549 and H0515) obtained by Energy Scattering X-ray Spectroscopy (EDS).

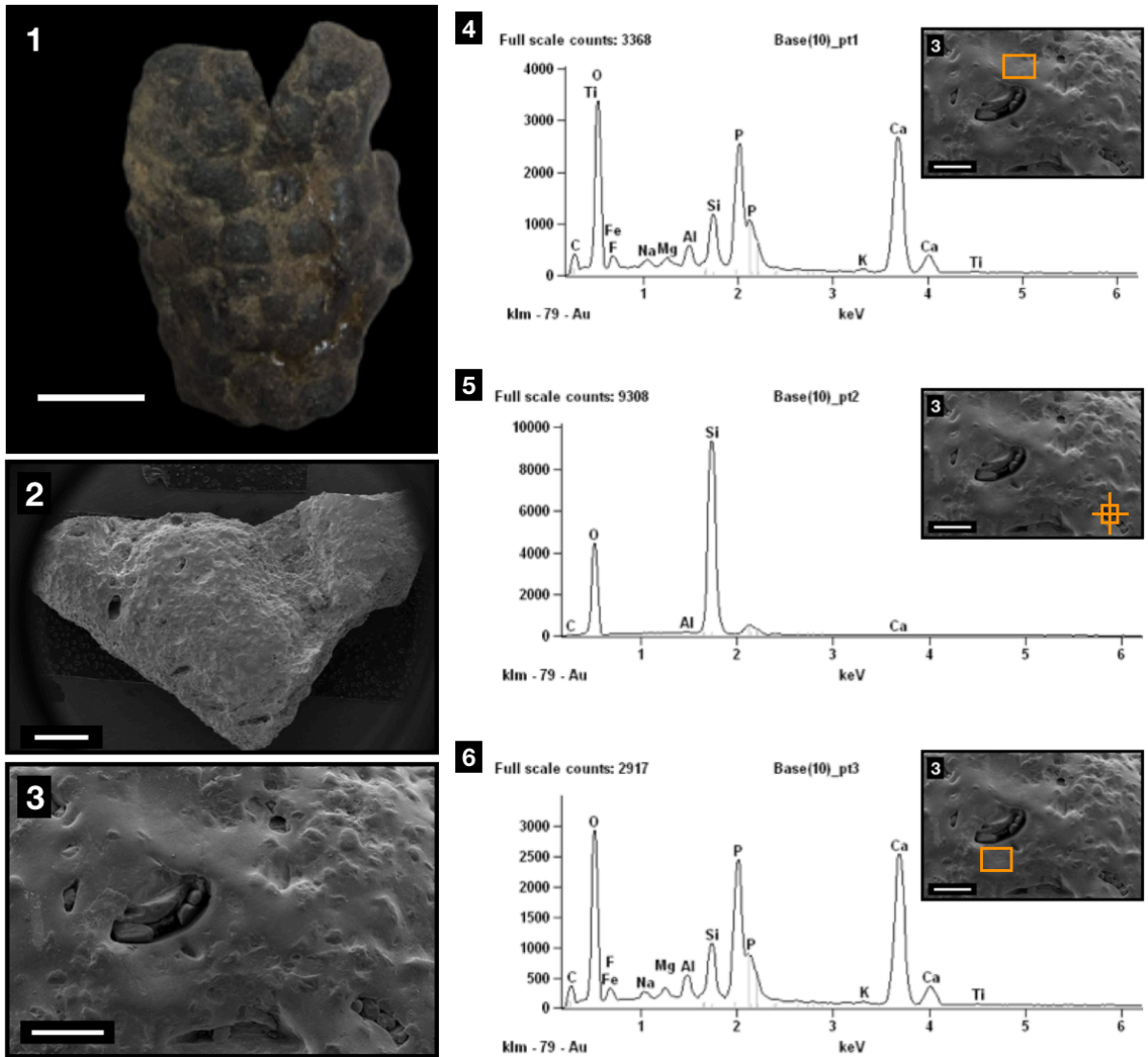
	EDS Base	Si	O	Ca	Al	C	F	Na	Mg	P	K	Fe	N	S	Cl	Ti	Cu	Mn
H516	B(6)_pt1	53.53	45.17	-	0.20	1.09	-	-	-	-	-	-	-	-	-	-	-	-
	B(6)_pt2	3.57	48.60	26.47	1.18	2.22	6.24	0.38	0.56	8.36	0.31	2.10	-	-	-	-	-	-
	B(6)_pt3	9.90	42.31	24.96	2.55	3.00	2.21	0.42	1.11	6.23	0.58	6.72	-	-	-	-	-	-
	B(7)_pt1	6.01	37.18	54.81	1.02	0.98	-	-	-	-	-	-	-	-	-	-	-	-
	B(7)_pt2	40.07	58.33	0.50	0.26	0.83	-	-	-	-	-	-	-	-	-	-	-	-
	B(7)_pt3	47.86	51.46	-	0.13	0.55	-	-	-	-	-	-	-	-	-	-	-	-
	B(8)_pt1	8.36	53.08	26.97	3.11	3.10	2.34	0.70	0.37	1.58	0.39	-	-	-	-	-	-	-
	B(8)_pt2	3.01	33.74	60.14	0.92	0.67	0.98	0.41	0.13	-	-	-	-	-	-	-	-	-
	B(8)_pt3	12.03	55.31	14.10	4.24	4.31	5.31	1.78	-	2.92	-	-	-	-	-	-	-	-
H011	B(9)_pt1	8.73	51.17	24.50	1.80	4.94	-	0.84	1.22	-	0.40	1.72	4.16	0.53	-	-	-	-
	B(9)_pt2	0.92	50.01	41.49	0.23	3.63	-	-	2.95	-	-	0.78	-	-	-	-	-	-
	B(9)_pt3	3.33	57.60	24.72	0.91	4.73	-	0.57	1.58	-	0.13	1.48	4.80	-	0.15	-	-	-
	B(9)_pt4	55.85	41.22	1.72	-	1.20	-	-	-	-	-	-	-	-	-	-	-	-
H529	B(10)_pt1	4.22	45.91	26.71	1.43	3.22	4.26	0.85	0.84	8.93	0.35	2.33	-	-	-	0.92	-	-
	B(10)_pt2	50.59	48.27	0.23	0.24	0.67	-	-	-	-	-	-	-	-	-	-	-	-
	B(10)_pt3	4.12	45.02	28.21	1.53	3.22	3.44	0.75	0.81	9.67	0.26	2.57	-	-	-	0.41	-	-
H549	B(11)_pt1	15.79	45.47	19.21	4.10	2.66	0.46	1.10	1.08	2.13	1.69	5.89	-	-	0.41	-	-	-
	B(11)_pt2	24.50	37.59	5.46	8.55	2.10	-	1.18	2.44	-	2.21	12.26	-	-	0.29	2.81	0.61	-
	B(11)_pt3	25.78	30.52	5.56	11.46	1.24	-	4.64	-	-	0.26	-	-	-	-	-	-	-
H515	B(12)_pt1	15.80	30.81	14.74	5.59	3.81	-	0.73	0.49	-	5.77	1.09	3.57	-	-	-	-	1.18
	B(12)_pt2	39.68	34.49	0.57	1.78	3.43	-	0.53	0.41	-	0.72	2.57	-	-	-	-	-	-



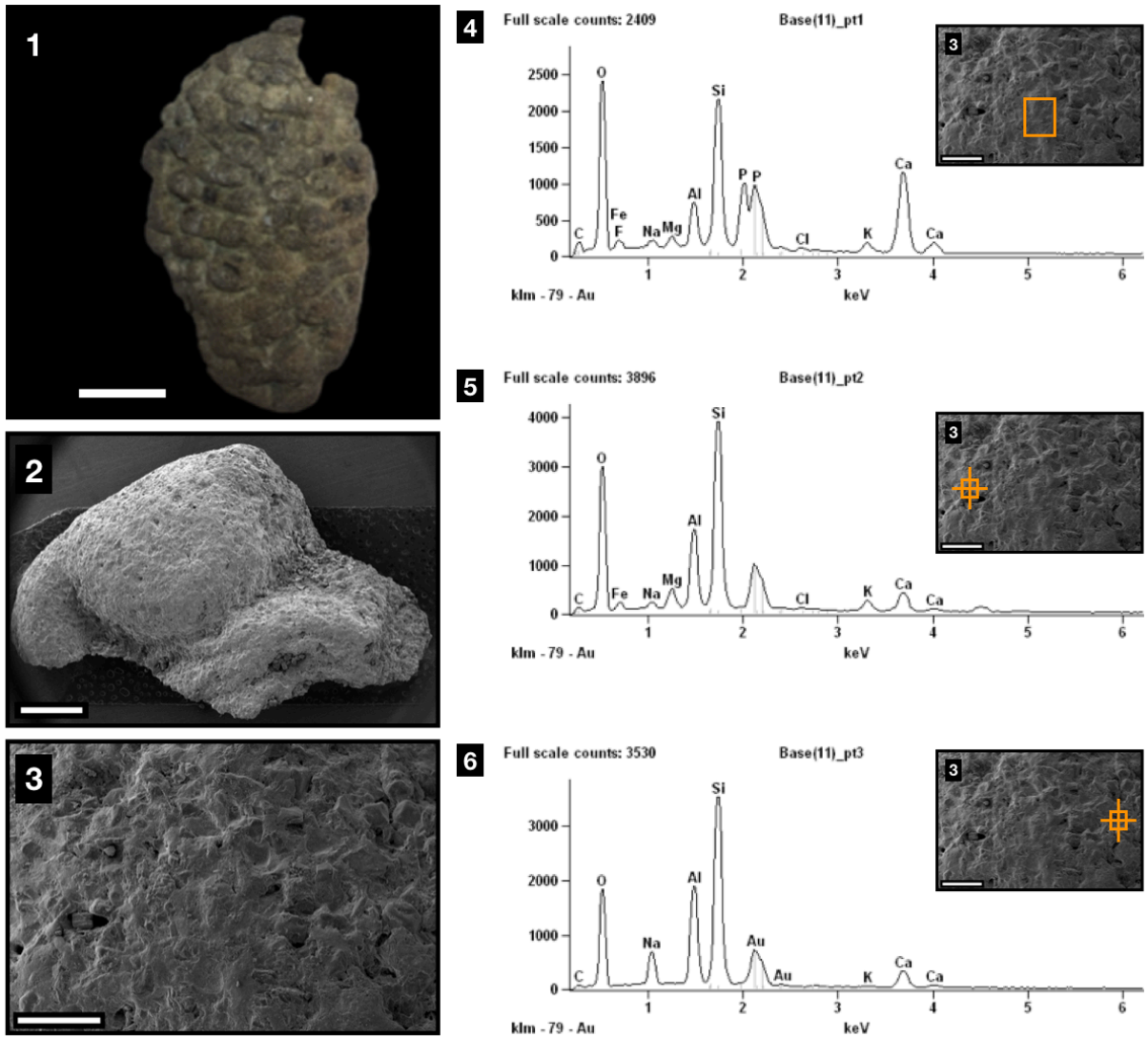
**Supplementary figure 5.** (1) Ex situ *Ophiomorpha nodosa* LGP H0516. Scale bar represents 1 cm. (2) SEM image of three spherical, rounded pellets. Scale bar represents 2 mm. (3) – (4) Magnified SEM image of the cemented pellet. Scale bar represents 200 μm. (5) - (10) EDS graphics of selected points with each specific elementary composition (H516 Base(7)\_pt1 (5); Base(7)\_pt2 (6) and Base(7)\_pt3 (7); H516 Base(8)\_pt1 (8); Base(8)\_pt2 (9) and Base(8)\_pt3 (10)).



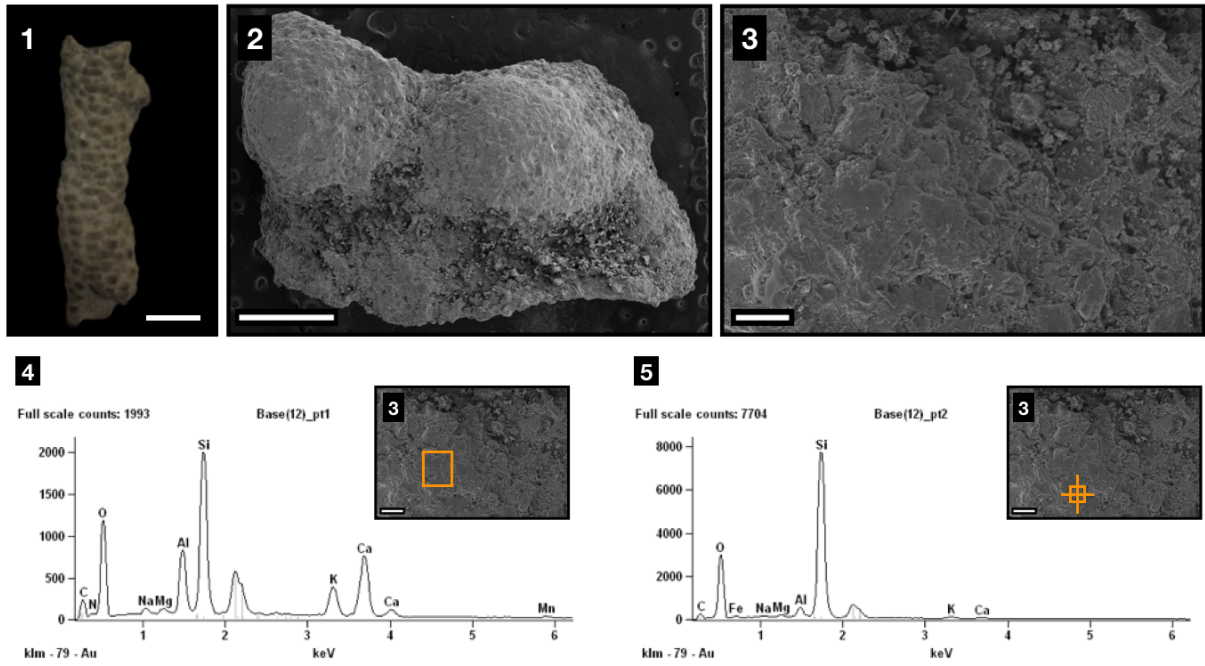
**Supplementary figure 6.** (1) Ex situ *Ophiomorpha nodosa* LGP H0011. Scale bar represents 1 cm. (2) SEM image of a spherical, rounded pellet. Scale bar represents 2 mm. (3) Magnified SEM image of the cemented pellet. Scale bar represents 200 μm. (4) - (7) EDS graphics of selected points with each specific elementary composition (H011 Base(9)\_pt1 (4); Base(9)\_pt2 (5); Base(9)\_pt3 (6) and Base(9)\_pt4 (7)).



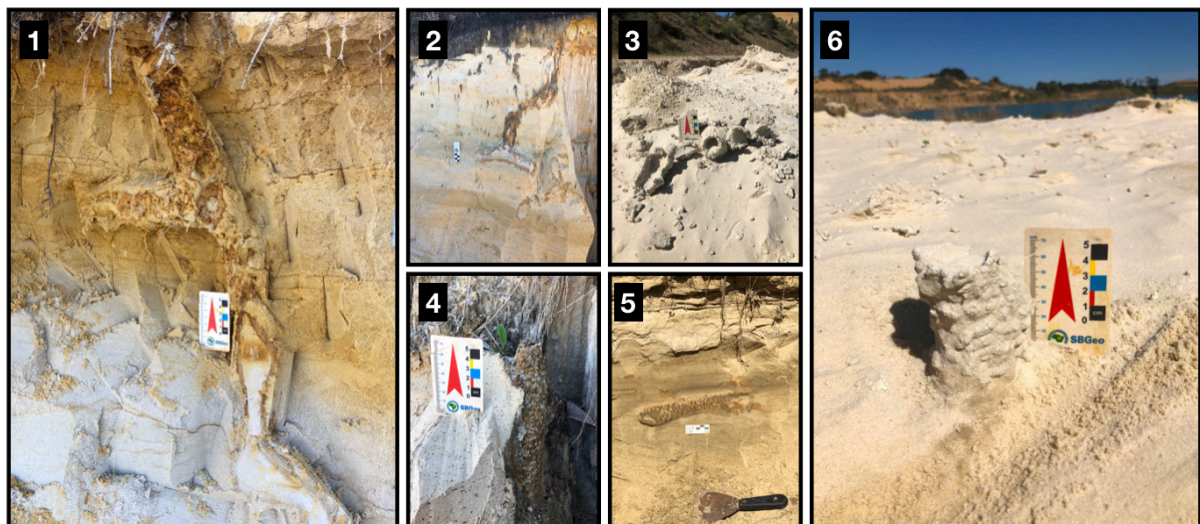
**Supplementary figure 7.** (1) Ex situ *Ophiomorpha nodosa* LGP H0529. Scale bar represents 1 cm. (2) SEM image of the spherical, rounded pellet. Scale bar represents 2 mm. (3) Magnified SEM image of the cemented pellet. Scale bar represents 500  $\mu\text{m}$ . (4) - (6) EDS graphics of selected points with each specific elementary composition (H529 Base(10)\_pt1 (4); Base(10)\_pt2 (5) and Base(10)\_pt3 (6)).



**Supplementary figure 8.** (1) Ex situ *Ophiomorpha nodosa* LGP H0549. Scale bar represents 1 cm. (2) SEM image of a spherical, rounded pellet. Scale bar represents 2 mm. (3) Magnified SEM image of the cemented pellet. Scale bar represents 500  $\mu\text{m}$ . (4) - (6) EDS graphics of selected points with each specific elementary composition (H549 Base(11)\_pt1 (4); Base(11)\_pt2 (5) and Base(11)\_pt3 (6)).

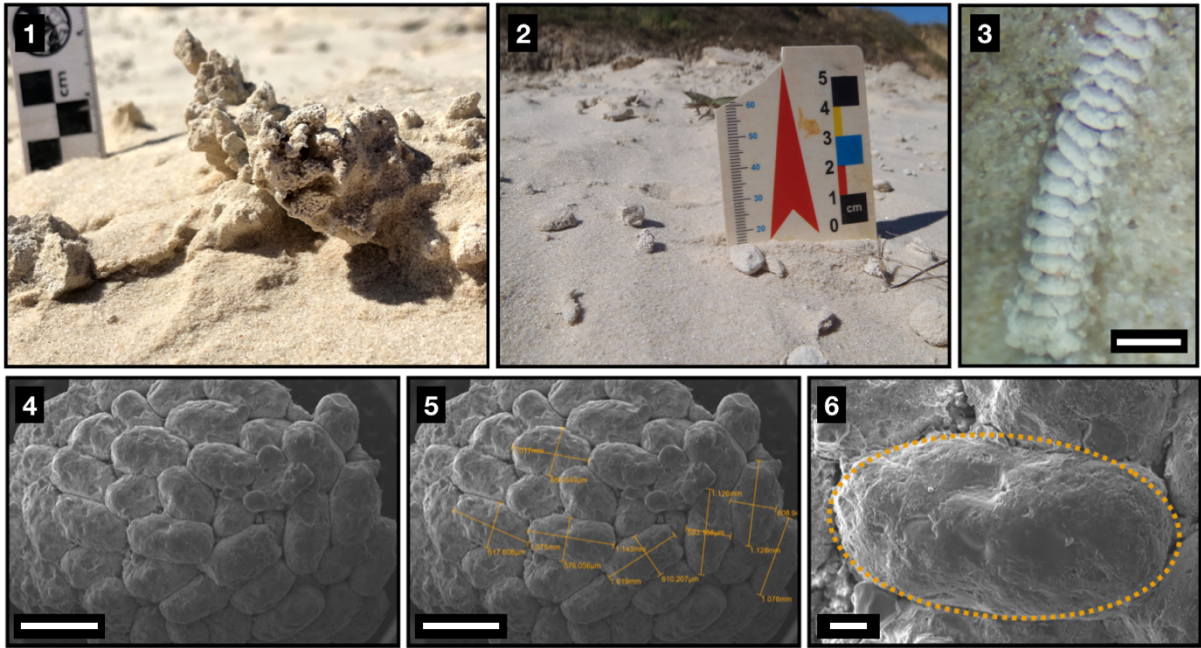


**Supplementary figure 9.** (1) Ex situ *Ophiomorpha nodosa* LGP H0515. Scale bar represents 1 cm. (2) SEM image of spherical, rounded pellets. Scale bar represents 1 mm. (3) Magnified SEM image of the cemented pellet. Scale bar represents 100 µm. (4) - (5) EDS graphics of selected points with each specific elementary composition (H515 Base(12)\_pt1 (4) and Base(12)\_pt2 (5)).



**Supplementary figure 10.** (1 – 6) - *Ophiomorpha nodosa* collected in situ by the LGP at depositional system Barrier-Lagoon III (Pleistocene), Osório – RS. at the Chui Formation where its shape and morphology were used as base for comparison porpoises with the ex situ burrows.





**Supplementary figure 11.** (1 – 3) - *Ophiomorpha puerilis* collected in situ by the LGP at depositional system Barrier-Lagoon III (Pleistocene). Osório – RS. (3) Scale bar represents 1 mm. at the Chui Formation where its shape and morphology were used as base for comparison porpoises with the ex situ burrows. (4) – Scanning Electron Microscopy (SEM) image of the ichnofossil *Ophiomorpha puerilis* used as guidance for the identification process of the ichnological material collect ex situ. Scale bar represents 1mm. (5) – SEM photo of the main size of the pellets that compose the burrow wall. Scale bar represents 1 mm. (6) – elongated, rod-shaped - ovoid pellet of the burrow wall. Scale bar represents 100 μm.

## **Anexo 2.**

**Título:** INVENTÁRIO DO ICNOFÓSSIL *OPHIOMORPHA* ISP. NA COLEÇÃO DO LABORATÓRIO DE GEOLOGIA E PALEONTOLOGIA (LGP) – IO/FURG

**Autores:** G. PEDROL-FREITAS, D. DINIZ, H. FRANCISCHINI, P. DENTZIEN-DIAS

**Apresentado em:** PALEO RS, Rio Grande – RS, Brasil, 2017

## INVENTÁRIO DO ICNOFÓSSIL *OPHIOMORPHA* ISP. NA COLEÇÃO DO LABORATÓRIO DE GEOLOGIA E PALEONTOLOGIA (LGP) – IO/FURG

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A coleção de fósseis do Laboratório de Geologia e Paleontologia (LGP) da Universidade Federal do Rio Grande (FURG) é composta por mais de 10.600 exemplares, sendo 560 icnofósseis, como coprólitos, tocas e pegadas. O icnofóssil *Ophiomorpha* é uma toca de crustáceo (Crustacea, Decapoda) construída de material sedimentar, ao longo de linhas de praias arenosas, onde sua ocorrência está concentrada na região intermareal. Este icnofóssil apresenta diversos sistemas arquiteturais: desde simples à complexos túneis dispostos vertical e horizontalmente ao longo do estrato sedimentar, com ramificações em formato de ‘Y’ e ‘T’. Além disso, *Ophiomorpha* possui características morfológicas singulares, apresentando formato cilíndrico mantendo seu diâmetro constante ao longo do túnel, variando entre 10 e 60 mm (exceto nos *turn-around points*, espaços cuja função é a troca de posição do crustáceo ao longo da galeria) e com aglutinados de sedimento compactado em formato de *pellets* dispostos na sua parede externa. Os *Ophiomorpha* isp. do LGP são coletados *ex situ* e são fragmentos do conjunto arquitetônico original. Após a coleta, os materiais foram lavados, tombados e posteriormente armazenados. As coletas de *Ophiomorpha* isp. iniciaram-se no ano de 1998, envolvendo saídas de campo (onde as buscas são realizadas desde a base das dunas costeiras até a zona de estirâncio) e doações via terceiros. Atualmente, a coleção é composta por 197 espécimes de *Ophiomorpha* isp., com diâmetro externo variando de 6 a 75 mm, diâmetro interno variando entre 4 e 46 mm e a largura da parede variando de 2 a 16 mm. Grande parte da coleção (n=147) não teve seu local de coleta especificado (coletados antes de 2012). As localidades em que foram coletados materiais após 2012 são: Lagoa do Peixe; Balneário Lagamarzinho, Bujuru, Farol da Conceição, Praia do Cassino, Farol Sarita, Farol da Verga, Concheiros do Albardão e Praia do Hermenegildo. Do total, 75 *Ophiomorpha* possuem a parede externa erodida, devido ao retrabalhamento pela ação das ondas antes de serem redepositados na face de praia. Com estas informações e continuidade nas coletas, a coleção do LGP se tornará cada vez mais completa e dará maior embasamento científico e auxílio a estudos futuros.

### **Anexo 3.**

**Título:** EXPANDINDO O CONHECIMENTO PALEONTOLÓGICO NA COMUNIDADE CIENTÍFICA E NO MUNICÍPIO DE RIO GRANDE - RS

**Autores:** G. PEDROL-FREITAS, D. DINIZ, D. MACHADO, K. MARINI, S. MEDEIROS, E. FONTOURA, C. MOZON, C. BENITES, N. SIEFERT, M. ANZAE, P. DENTZIEN-DIAS

**Apresentado em:** PALEO RS, Rio Grande – RS, Brasil, 2017

## **EXPANDINDO O CONHECIMENTO PALEONTOLÓGICO NA COMUNIDADE CIENTÍFICA E NO MUNICÍPIO DE RIO GRANDE - RS**

G. PEDROL-FREITAS<sup>1,2</sup>, D. DINIZ<sup>1</sup>, D. MACHADO<sup>1</sup>, K. MARINI<sup>1</sup>, S. MEDEIROS<sup>1</sup>, E. FONTOURA<sup>1</sup>, C. MOZON<sup>1</sup>, C. BENITES<sup>1</sup>, N. SIEFERT<sup>1</sup>, M. ANZAE<sup>1</sup>, P. DENTZIEN-DIAS<sup>1</sup>

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O Laboratório de Geologia e Paleontologia (LGP) da Universidade Federal do Rio Grande (FURG) possui uma extensa coleção de fósseis de animais da megafauna, em sua maioria já extintos, que habitaram o estado do Rio Grande do Sul durante o Quaternário. Além da importância nas pesquisas científicas envolvendo alunos de graduação, pós-graduação, técnicos e docentes, a coleção pode ser empregada com o objetivo de promover ações e eventos voltados para práticas educacionais de ensino fundamental, médio e extensionistas, despertando o interesse de crianças, jovens e adultos da comunidade riograndina. O LGP tem se envolvido repetidamente em ações oferecidas à comunidade e à academia, desde 2014, com finalidade de expandir o conhecimento sobre a grande diversidade ecológica e biológica que existiu ao longo do tempo, despertando curiosidade e interesse de toda a comunidade. Assim, os eventos se iniciaram com o projeto Ciência na escola: paleontologia da região costeira do Rio Grande do Sul, que se estendeu de 2014 – 2016. O projeto Confecção de material didático e científico para a Paleontologia foi criado em 2015 e se estendeu até 2016 com o intuito de disponibilizar material palpável de forma barata e acessível, já que a maioria dos fósseis são sensíveis e podem se fragmentar no manuseio. Onde, dentro destes projetos as principais ações foram: a criação do Kit com réplicas fósseis e fichas explicativas para escolas; e o Minicurso de Réplicas de Fósseis, ministrado na FURG, para toda comunidade com o enfoque em replicar os fósseis de forma acessível. Além disso, foram feitas Palestras e exposições entre os anos de 2016 e 2017, no Partage Shopping Rio Grande e na Semana da popularização da ciência – FURG. Assim como a Criação da Exposição Permanente (IO/FURG) sobre Fósseis, Rochas e Minerais, com ênfase no Rio Grande do Sul. Com a realização destas ações alcançou-se um grande público de diferentes faixas etárias com alta diversidade educacional e social. Sempre com o intuito de enfatizar sua importância científica, histórica e preservacional.

## **Anexo 4.**

**Título:** TAPHONOMIC HISTORY OF THE ICHNOFOSSIL *OPHIOMORPHA* ISP. OF THE COASTAL PLAIN OF RIO GRANDE DO SUL (QUATERNARY)

**Autores:** G. PEDROL-FREITAS, H. FRANCISCHINI, P. DENTZIEN-DIAS

**Apresentado em:** SPSAS (São Paulo School of Advanced Science on Ocean Interdisciplinary Research and Governance), São Paulo – SP, Brasil, 2018

# TAPHONOMIC HISTORY OF THE ICHNOFOSSIL *OPHIOMORPHA* ISP. OF THE COASTAL PLAIN OF RIO GRANDE DO SUL (QUATERNARY)

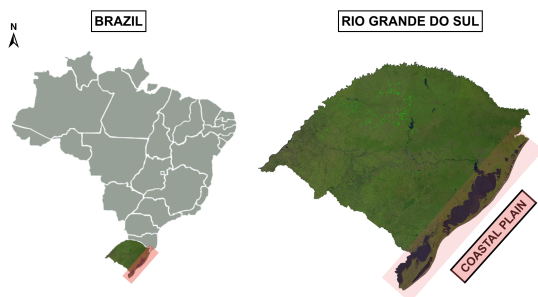
GIOVANA PEDROL DE FREITAS

UNIVERSIDADE FEDERAL DE RIO GRANDE - FURG

## RESEARCH OBJECTIVE

The aim of this masters research is to accomplish paleontological studies, with an ichnological focus, of the ichnofossil *Ophiomorpha* isp., crustacean decapod burrow (Decapoda: Thalassinidea: Callianassidae), collected ex situ (beach face) and in situ (ichnofossil outcrop) in the Coastal Plain of Rio Grande do Sul (CPRS), in the Quaternary Period.

## STUDY SITE



## RESEARCH DESIGN

### Morphological Analyses

- ◆ Measurements of the external (A) and internal (B) diameter, wall width (in cross section) (C) and pellets diameter (D) and organization (Figure 1).
- ◆ Petrographic Blades.
- ◆ Scanning Electron Microscopy (SEM).

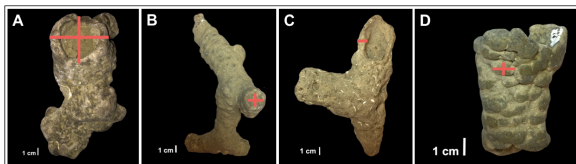


Figure 1. Measurements taken from the *Ophiomorpha* trace fossil collected ex situ by LGP along the Coastal Plain of Rio Grande do Sul (CPRS). (A) - external diameter; (B) - internal diameter; (C) - wall width; (D) - pellets diameter.

### Chemical Analyses

- ◆ X-ray Diffraction (XRD).
- ◆ Energy Scattering X-ray Spectroscopy (EDS).

### Dating Analyses

- ◆ Thermoluminescence (TL).
- ◆ Optically Stimulated Luminescence (OSL).

## EXPECTED CONTRIBUTIONS

- ◆ Confirm the ichnotaxonomy of the trace fossils *Ophiomorpha* isp. collected ex situ and in situ (at least the best preserved specimens).
- ◆ Understand the taphonomic stages of *Ophiomorpha* found ex situ, since their construction to its deposition on the current beach face, through the stages of fossilization, diagenesis and reworking.
- ◆ Provide an absolute dating for selected specimens of *Ophiomorpha* isp. Found ex situ.
- ◆ Compare qualitatively the *Sergio mirim* burrows (Figure 2) with the *Ophiomorpha* of the CPRS, verifying possible compatibilities of morphology, size and pellet organization (Figure 3).

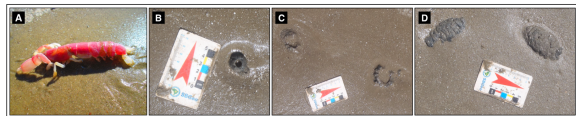


Figure 2. Decapod crustacean responsible for building burrows morphologically similar to *Ophiomorpha* on the coast of RS and its current burrow; (A) - *Sergio mirim* (Rodrigues, 1966) modified from Alcântara (2015); (B) - burrow entrance in plant; (C) - burrow in cross section; (D) - plan view of horizontal tunnels showing the pellets organization.

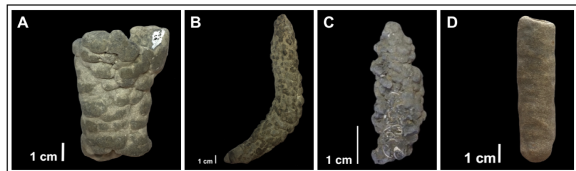


Figure 3. *Ophiomorpha* collected ex situ by the LGP along the Coastal Plain of Rio Grande do Sul (CPRS), where the types of pellets organization are evidenced. (A) - brick-like pellets; (B) - individual pellets organization; (C) - pellets organized two by two; (D) - eroded pellets.

- ◆ Also, it is expected to verify if there are variations between recent burrows (*Sergio mirim*) and Pleistocene trace fossils (in situ and ex situ) and if there is a relationship between this variation along with climate and sea level fluctuations which occurred in the Quaternary Period in the CPRS.

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## **Anexo 5.**

**Título:** GRAUS DE ABRASÃO NOS ICNOFÓSSEIS COLETADOS *EX SITU* NA PLANÍCIE COSTEIRA DO RIO GRANDE DO SUL E SUA IMPORTÂNCIA ICNOTAXONÔMICA

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**Apresentado em:** PALEO RS, São Leopoldo – RS, Brasil, 2018



## GRAUS DE ABRASÃO NOS ICNOFÓSSEIS COLETADOS *EX SITU* NA PLANÍCIE COSTEIRA DO RIO GRANDE DO SUL E SUA IMPORTÂNCIA ICNOTAXONÔMICA

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A ocorrência de *Ophiomorpha* nas faces de praias atuais da região Planície Costeira do Rio Grande do Sul é um dos raros exemplos de erosão diferencial e retrabalhamento de icnofósseis. Estas escavações foram produzidas por crustáceos calianassídeos e uma de suas principais características diagnósticas é a presença de paredes constituídas por *pellets*. Após sua fossilização, estes materiais são exumados, sendo retrabalhados pela ação das ondas e, posteriormente, soterrados, destruídos ou transportados. Outros processos tafonômicos, como abrasão, bioerosão e incrustação, podem ocorrer no período entre a exumação dos traços fósseis e sua coleta. Aqui, apresentamos os dados relativos à quantificação do dano causado pela abrasão e sua importância taxonômica. Para isso, um sistema de classificação foi criado, onde o principal critério é o grau de preservação dos *pellets*. Ao todo, foram analisados 229 espécimes encontrados *ex situ* e cinco classes foram reconhecidas (A–E). As classes A e B reúnem os espécimes melhores preservados, onde é possível identificar o tipo de organização dos *pellets* na parede, sendo que na Classe A ( $n=63$ ) os *pellets* ocorrem em mais de 50% do espécime, enquanto na Classe B ( $n=26$ ) menos de 50% da área do espécime apresenta *pellets*. As classes C e D agrupam os espécimes menos preservados, onde ainda é possível a visualização dos *pellets*, contudo, não é possível identificar seu tipo de organização. Na Classe C ( $n=10$ ) os *pellets* abrangem uma área >50%, enquanto que na Classe D ( $n=55$ ), os *pellets* estão presentes em uma área <50%. Já a Classe E ( $n=75$ ) agrupa os materiais mais abradidos, onde não é possível visualizar nenhum *pellet*. A caracterização e identificação de *pellets* na parede externa de *Ophiomorpha* é extremamente importante, pois é o principal caractere icnotaxonômico deste icnogênero. Outros traços semelhantes, mas que não apresentam *pellets* são *Spongiomorpha* e *Thalassinoides*. Desta forma, a classificação das tocas de crustáceos da Classe E como *Ophiomorpha* é dúbia, visto que a ausência de *pellets* não permite uma diagnose segura. Mais estudos sobre a história tafonômica destes icnofósseis estão sendo realizados para melhor compreender sua origem e implicações paleoecológicas, paleoambientais, tafonômicas e icnotaxonômicas. [CNPq]

## **Anexo 6.**

**Título:** MORPHOLOGICAL ASSESSMENT AND ANALYSIS OF *EX SITU* *OPHIOMORPHA* FROM THE COASTAL PLAIN OF RIO GRANDE DO SUL, BRAZIL

**Autores:** **Giovana Pedrol de Freitas**; Heitor Francischini; Paula Dentzien Dias

**Apresentado em:** SLIC (IV Simposio Latinoamericano de Icnología), Santa Marta, Colômbia, 2018

# MORPHOLOGICAL ASSESSMENT AND ANALYSIS OF *EX SITU* OPHIOMORPHA FROM THE COASTAL PLAIN OF RIO GRANDE DO SUL, BRAZIL

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*Ophiomorpha* is a decapod crustacean burrow that has been observed *in situ* along outcrops of the Lagoon-Barrier System III (Pleistocene) at Rio Grande do Sul state, southern Brazil. Besides those materials found *in situ*, fragments of *Ophiomorpha* also occur in the current sandy beach face along the Coastal Plain of Rio Grande do Sul (CPRS) (Fig. 1). These *ex situ* specimens were originated from paleoshorelines which are currently submerged and have passed through the burial and early stages of lithification, being after exhumed, reworked and transported to the beach face. The main destructive processes in which these specimens experienced include: abrasion, bioerosion and bioincrustation. These changes allow a better understanding of how these taphonomic processes work in the interval between the final exhumation and the collecting. Although the processes of reworking and abrasion alter their morphology, some of these ichnofossils present characteristics that allow their ichnotaxonomic identification, such as the presence of pellets in their outer wall (main diagnostic characteristic), Y- or T-shaped bifurcations, and turn-around points (Fig. 2). In order to identify at the level of ichnogenus or even ichnospecies, and observe the different processes that affect and change the morphology, 229 traces collected *ex situ* by the LGP were individually analyzed. For the abrasion analyzes, the specimens were characterized by different stages of preservation and a system was created where five classes were recognized (A-E) and the main criterion standardized were the preservation of pellets in the outer wall. For the classes A ( $n=63$ ) (pellets present in >50% of the area) and B ( $n=26$ ) (pellets present in <50% of the area) the well-preserved specimens were selected where it is possible to identify the type of organization of the pellets present on the wall. In classes C ( $n=10$ ) (pellets present in >50% of the area) and D ( $n=55$ ) (pellets present in <50% of the area) the less preserved specimens were selected where it is still possible to visualize the pellets, however, it is not possible to identify their type of organization. While Class E ( $n=75$ ) is composed by the most abraded specimens, where no pellet can be visualized or identified which can make the identification of the ichnofossil *Ophiomorpha* inaccurate since the lack of pellets in their outer wall make them similar to *Spongiomorpha* and *Thalassinoides*. Furthermore, it was observed that 138 specimens out of the total presented bioerosion traces (e.g., *Gastrochaenolites*) (Fig. 3A), mostly caused by bivalves. In addition, 47 specimens presented bioincrustation by bryozoans (Fig. 3B); three by barnacles (Fig. 3C); and just one specimen presents both. The analyses of all characteristics found in a trace, even if it is *ex situ*, can indicate for how long the specimen was exposed and even from each submerged paleoshoreline the trace was formed and thus the paleoecological and paleoenvironmental main characteristics.

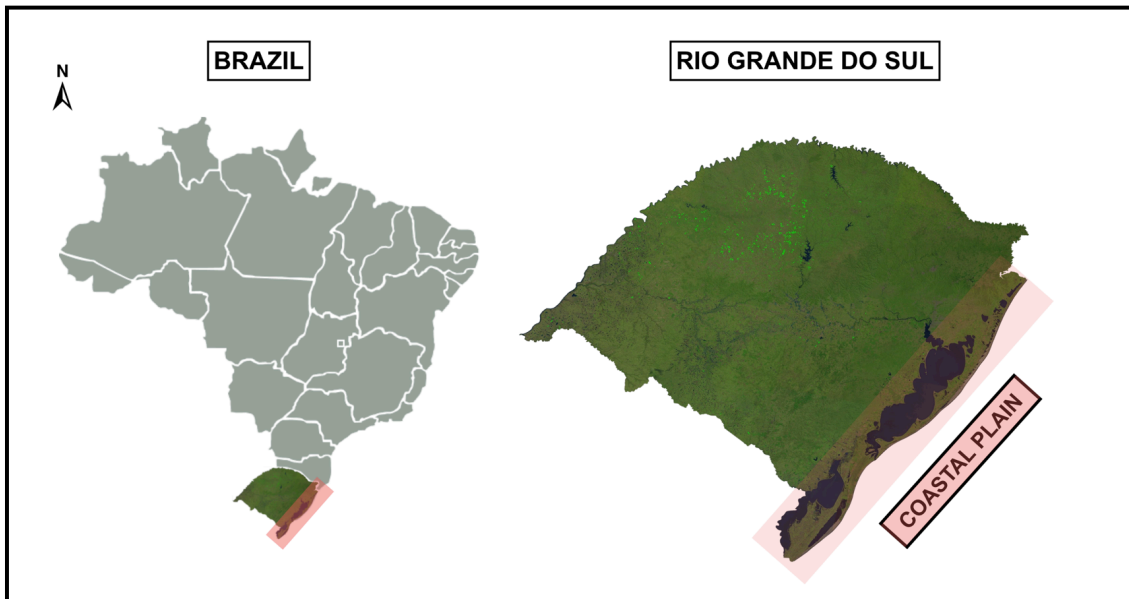


Fig 1. Coastal Plain of Rio Grande do Sul (CPRS) localized at southern Brazil.

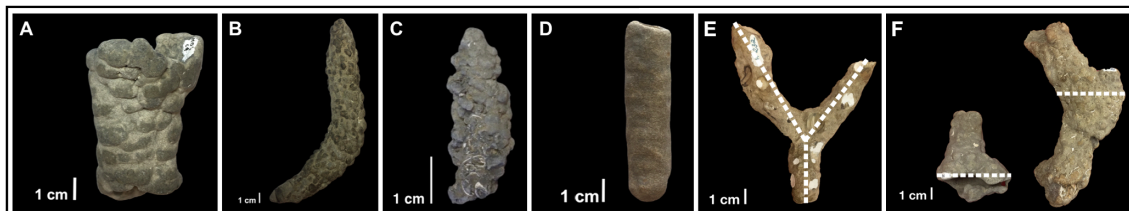


Fig 2. Main ichnotaxonomic characteristics of *Ophiomorpha* collected *ex situ* by the LGP along the Coastal Plain of Rio Grande do Sul (CPRS), where the types of pellets organization are evidenced as (A) - brick-like; (B) - individual; and (C) - two by two. The effect of abrasion in the outer wall is evidenced in (D) - eroded pellets. Also, there are other characteristics as (E) - Y-shaped bifurcation; and (F) - turn-around points.

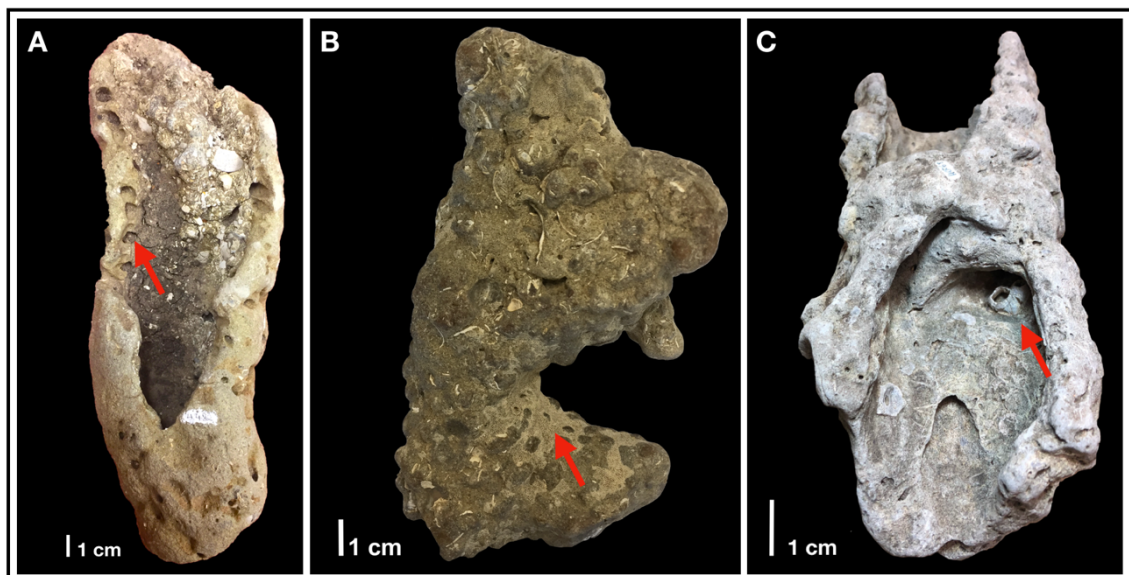


Fig 3. Morphological assessment on *Ophiomorpha* represented by (A) - *Gastrochaenolites*; (B) - bioincrustation by bryozoans; and (C) - bioincrustation by barnacles.