




First Record of Miocene Polychaete Cirratulids in the Atlantic Ocean from the Pirabas Formation of Brazil: A MicroCT Approach

Primeiro Registro de Cirratulídeos Poliquetas do Mioceno no Oceano Atlântico da Formação Pirabas do Brasil: uma Abordagem de MicroCT

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Abstract

A new record of the cirratulid polychaete *Diplochaetetes mexicanus* Wilson, 1986 from the of Miocene Pirabas Formation outcrops (Burdigalian to Langhian) is documented in the context of the paleodiversity of the equatorial margin of Brazil and represents the first record for the equatorial shelf of South America. *D. mexicanus*, previously known from the Oligocene–Miocene interface of the Pacific in Mexico and from the Miocene of the Pacific in Peru, shows an amphi-American paleodistribution (Eastern Pacific and Western Atlantic) and a wide tropical to subtropical latitudinal range. The stratigraphic fidelity observed in the two studied outcrops (Praia do Atalaia and Fazenda on Fortaleza Island in north Brazil) is indicative of the species' resilience under different paleoenvironmental conditions. MicroCT analyses and 3D reconstructions allowed for greater accuracy in the study of the colony.

Keywords: Biobuilders; Neogene; *Diplochaetetes*

Resumo

O novo registro do poliqueta cirratulídeo *Diplochaetetes mexicanus* Wilson, 1986 dos afloramentos da Formação Pirabas do Mioceno (Burdigaliano ao Langhiano) é documentado no contexto da paleodiversidade da margem equatorial do Brasil e representa o primeiro registro para a plataforma equatorial da América do Sul. *D. mexicanus* é conhecido da interface Oligoceno-Mioceno do Pacífico no México e do Mioceno do Pacífico no Peru, mostrando uma paleodistribuição anfiamericana (Pacífico Oriental e Atlântico Ocidental) e uma ampla faixa latitudinal tropical a subtropical. A fidelidade estratigráfica nos dois afloramentos estudados (Praia do Atalaia e Fazenda na Ilha de Fortaleza no Norte do Brasil) é indicativa da resiliência da espécie sob diferentes condições paleoambientais. Análises de microCT e reconstruções 3D permitiram maior precisão no estudo da colônia.

Palavras-chave: Bioconstrutores; Neógeno; *Diplochaetetes*

1 Introduction

The Pirabas Formation (Maury 1925) is well recognized through outcrops in the coastal plains of municipalities such as Maracanã, Salinópolis, and São João de Pirabas, as well as in the quarries of Capanema and Primavera, all located in the state of Pará, along the northeast Atlantic coast of Brazil. The Pirabas Formation is also documented in the subsurface of the equatorial platform in the Barreirinhas Basin, overlying the Ilha de Santana Formation (Pamplona 1969; Trosdorf Jr. *et al.* 2007). This unit represents a sequence of shallow-water carbonate–siliciclastic deposits (Rossetti *et al.* 2013; Aguilera *et al.* 2022; Teixeira *et al.* 2023) in the stratigraphic record from the late early Miocene to the late middle Miocene (Gomes *et al.* 2023).

The paleontology of the Pirabas Formation is notable for its limestone matrix, associated with a rich diversity of marine micro- and macrofossils, composed mainly of foraminifera, ostracods, sponges, mollusks, echinoids, ophiuroids, asteroids, crinoids, bryozoans, decapod crustaceans, fish, sirenian mammals, and ichnofossils (*e.g.*, Aguilera & Pães 2012; Aguilera *et al.* 2017; Ramalho *et al.* 2019; Lima *et al.* 2020a, b; Bencomo *et al.* 2021; De Araújo *et al.* 2021; Kerber & Moraes-Santos 2021; Lima *et al.* 2021; Aguilera *et al.* 2023). The paleoenvironmental context includes marginal zones and tidal flats in mangrove forests, surf zones, and shallow sandy bottoms (Aguilera *et al.* 2020a, b), and even areas of the inner to middle shelf influenced by high-energy tropical storms (Aguilera *et al.* 2023; Teixeira *et al.* 2023).

Among the fossil assemblages, some groups have been considered miscellaneous and poorly studied. Cirratulid polychaetes (*Diplochaetetes* and *Dodecaceria*) that build calcareous colonies are among these groups; in the Pirabas Formation, such colonies of *Diplochaetetes* polychaeta have been confused with *Dendrophyllia* corals (see Lalor & Távora 2006). This misinterpretation was first introduced by Weissermel (1913) who described *Diplochaetetes longitubus* as a coral species from the Eocene of Namibia in Africa. Wilson (1986) attribute the polychaeta *Diplochaetetes mexicanus* as a demosponges, and later Fischer *et al.* (1989, 2000) recognized *Diplochaetetes* and *Dodecaceria* such as cirratulid polychaeta (Guido *et al.* 2024).

The fossil record of cirratulids, including the genus *Dodecaceria*, has so far been documented exclusively from

the late Oligocene Pacific Ocean of Baja California, Mexico (Fischer 1990; Fischer *et al.* 1989, 2000), from the early Miocene of Baja California (Fischer *et al.* 2000), from the Pliocene and Pleistocene of Oregon and California (Hove & Hurk 1993) in North America, and from the Miocene of Peru in South America (De Vries 2020; Kočí *et al.* 2020).

A systematic paleontological study of two colonies of cirratulid polychaetes from outcrops at Atalaia Beach and Fortaleza Island in Pará, Brazil, elucidates the paleoecological and paleoenvironmental interpretation of this new record in the context of the benthic invertebrate fauna of the Pirabas Formation and of the Neogene in tropical America.

2 Geological Setting

The Pirabas Formation (Maury 1925), from the North Brazilian carbonate platform (Soares Jr. *et al.* 2011), is exposed along the onshore coastal plain and is characterized by mixed siliciclastic–carbonate deposits (Rossetti *et al.* 2013). The Pirabas Formation is part of the Bragantina Platform, a sedimentary succession overlying the metasedimentary basement rocks of northern Brazil, and is considered the onshore extension of the Pará-Maranhão Basin (Rossetti & Góes 2004; Rossetti *et al.* 2013). The mixed siliciclastic–carbonate deposits of the Pirabas Formation (early–middle Miocene, Burdigalian/Langhian) were deposited in a complex system of interconnected shallow-water coastal environments on a wide and gently sloping shelf (Rossetti *et al.* 2013; Aguilera *et al.* 2020a, b).

The Praia do Atalaia outcrop (late middle Miocene) is composed of packstone- and wackestone-type carbonate rocks rich in siliciclastics. The paleoenvironment represents a succession of shallow water at the coastal plain interface (Aguilera *et al.* 2020a, 2022, 2023; Gomes *et al.* 2023; Teixeira *et al.* 2023).

The Fazenda outcrop (late early Miocene) is characterized by packstone containing red and green calcareous algae, small and large benthic foraminifera, numerous shell molds, echinoderms, corals, bryozoans, ostracods, barnacles, and *Thalassinoides* ichnofossils, with well-lithified burrow walls and an empty main channel. The paleoenvironment is interpreted as an open marine environment deposited under high-energy conditions, probably affected by storms (Aguilera *et al.* 2022, 2023; Gomes *et al.* 2023; Teixeira *et al.* 2023).

3 Material and Methods

Field trips to the Pirabas Formation were conducted on March 13, 2020, by O. Aguilera, K. Bencomo, and D. Lima during low tide at the outcrop in Atalaia Beach, municipality of Salinópolis (0° 35' 37" S, 47° 18' 54.4" W), and on February 06, 2023, by O. Aguilera and B. Teixeira to the Ilha de Fortaleza, Fazenda outcrop in the municipality of São João de Pirabas (0°42'43.79" S, 47° 9' 58.65" W), state of Pará, Brazil (Figures 1A-B). The stratigraphic sections with the fossil collections are presented in Figures 1C and 1D. The fossils were deposited in the paleontological collection of the Museu de Ciências da Terra, Serviço Geológico do Brasil, in Rio de Janeiro.

The interpretations of the microstructure of the cirratulid tubes in the colony follow the descriptions of Fischer (1990), Fischer *et al.* (1989, 2000), Vinn (2009), Taylor *et al.* (2010), and Kočí *et al.* (2020). Three-dimensional visualization and modeling were conducted via micro-CT using a V-Tomex|M (GE Measurement & Control Solutions, Wunstorf, Germany) at the Nuclear Instrumentation Laboratory of the Federal University of Rio de Janeiro. Three-dimensional reconstructions were performed using Phoenix Data software, applying section alignment, beam correction, and reduction of ring artifact effects, as well as a mathematical edge enhancement filter to achieve greater contrast between the rock matrix and the tubes. VG Studio Max v 3.0 software was used for 3D visualization. The micro-CT parameters for acquisition and porosity analysis followed the methods of De Araújo *et al.* (2018). The main channel volume models were performed with Avizo Fire Xlab Hydro (FEI Visual Sciences Group), which solves the Stokes equations using the finite volume method. External morphology images and digital representations were edited in Adobe Photoshop.

Classification follows Ehlers (1901), Weissermel (1913), Reish (1952), Wilson (1986), Fischer *et al.* (1989, 2000), Fischer (1990), Blake & Magalhaes (2019), and Kočí *et al.* (2020).

4 Systematic Palaeontology

Order Cirratulida Dales 1963
 Suborder Cirratuliformia Fauchald 1977
 Family Cirratulidae Ryckholt 1851
 Genus *Diplochaetetes* Weissermel 1913
Diplochaetetes mexicanus Wilson 1986
 (Figures 2–6)

Examined material – One specimen, MCT.I.7255, from the Praia do Atalaia outcrop of the Pirabas Formation (late middle Miocene), Salinópolis municipality; one specimen, MCT.I.7256, from the Ilha de Fortaleza, Fazenda outcrop of the Pirabas Formation (late early Miocene), São João de Pirabas municipality, Brazil.

Description – The colony from the Praia do Atalaia outcrop consists of an aggregation of elongate tubes with internal septum, ranging from straight to slightly undulating, arranged subparallel and adhering to one another. Some empty areas exhibit outlines of tubes around hollow spaces, likely representing entanglement with some organism not preserved in the fossil record, thus leaving open channels in the fossil colony (Figure 2). Coronal and sagittal microCT sections show a regular arrangement of empty tubes, mostly uniform in size and shape (rounded to oval in cross section). However, larger tubes are present in the central portion of the colony (Figure 3). This colony from Praia do Atalaia has a volume of 2258.7 mm³, with total porosity (empty tubes and vugs) reaching 46.7%. The frequency of structures per microCT slice indicates a dense conglomerate of tubes in the colony and a right-modal distribution per volume (Figures 4A–F). A comparison of sequential microCT views and 3D volumetric editing of individual tubes within the colony shows a clear spatial arrangement and high density (Figures 5A–D, S1_MicroCT Video). The external view of the colony from the Ponta da Fazenda outcrop exhibits a similar arrangement to the Atalaia colony. However, the solid attachment to the lithified carbonate rock suggests an overlap with a consolidated substrate (Figure 6).

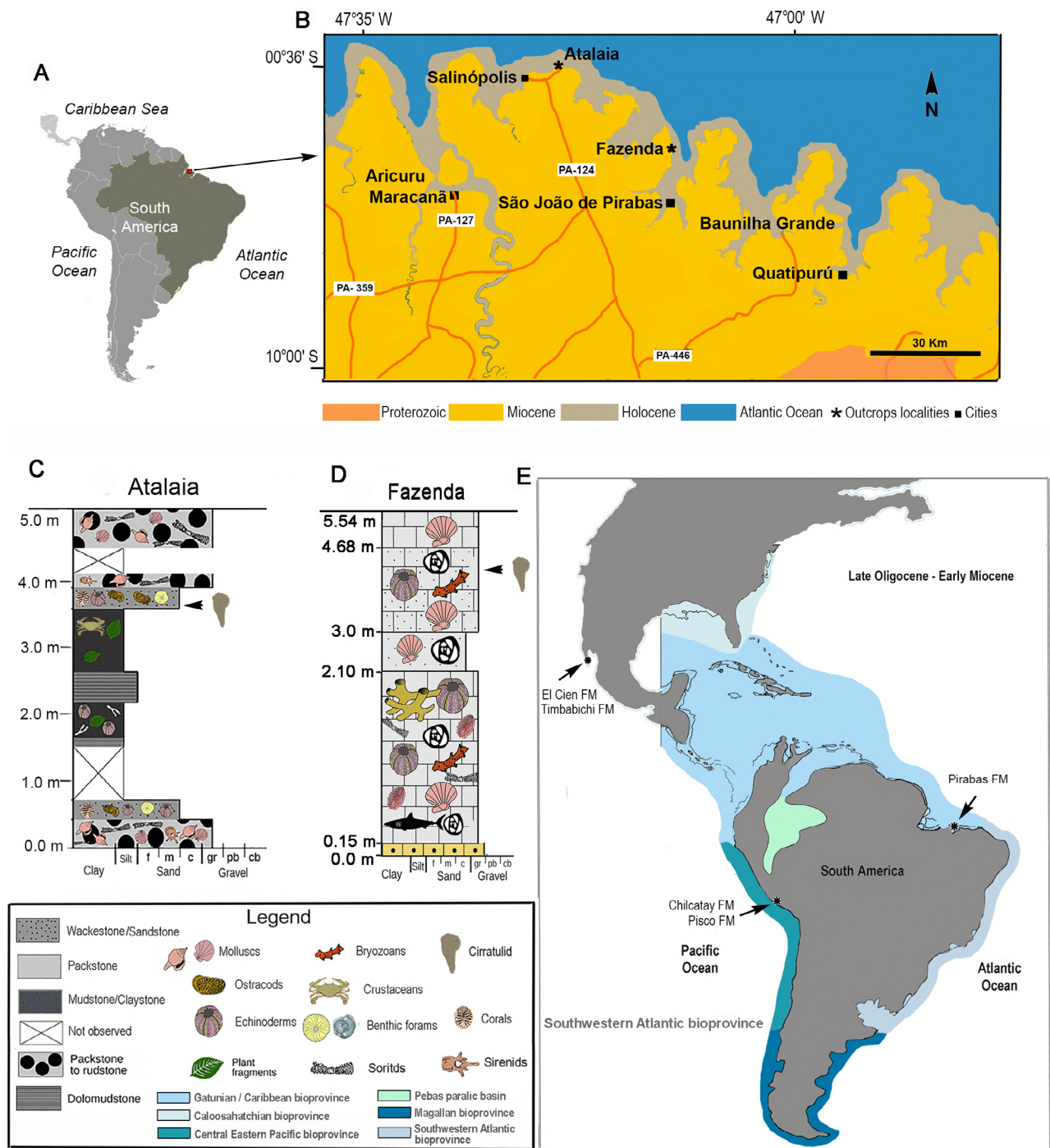


Figure 1. A. Map of South America; B. Outcrops and sampling localities locations (Praia do Atalaia and Fazenda); C. Praia do Atalaia stratigraphic section; D. Fazenda stratigraphic section; E. paleogeographic map showing the distribution of *Diplochaetetes mexicanus* Wilson, 1986 in the Americas. Adapted from Aguilera *et al.* (2020, 2022).

The observed structure of tubes is in agreement with the microstructure of tube-building cirratulidae, characterized by micritic peloidal lamellae, with intercalated lenses of calcite and fibrous aragonite investigated by Fischer (1990), Fischer *et al.* (1989, 2000), Vinn (2009), Taylor *et al.* (2010), Kočí *et al.* (2020), and Guido *et al.* (2024).

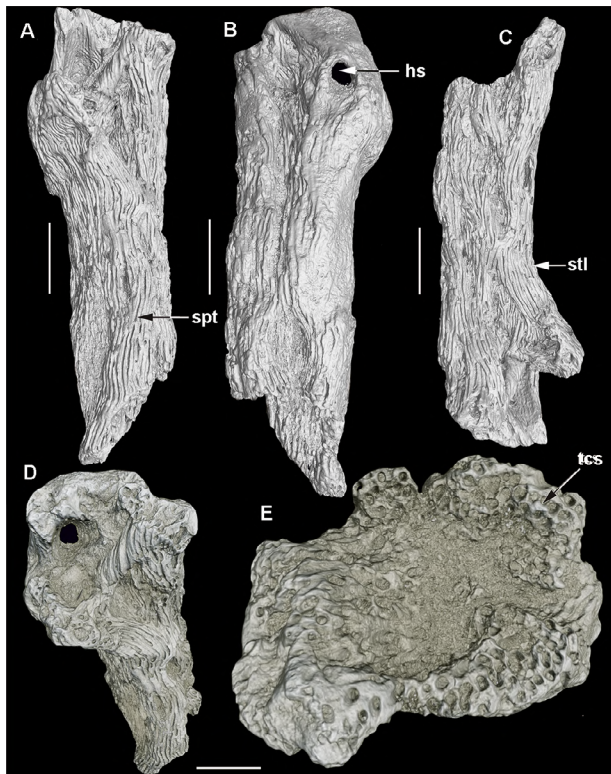


Figure 2. Colony of *Diplochaetetes mexicanus*, MCT.I.7255, Pirabas Formation, Praia do Atalaia, Salinópolis, Pará, Brazil: A–E. microCT external 3D reconstructions of the colony in rotate views. Abbreviations: tcs, tubes in cross section; spt, subparallel tubes; stl, septa inside the tubes lumina; hs, hollow spaces. Scale bar A–C: 15 mm, D–E: 5 mm.

Remarks – The discovery of cirratulid specimens referable to *Diplochaetetes mexicanus* in the Miocene (Burdigalian/Langhian strata) of northeastern Brazil suggests additional considerations regarding the paleobiogeographic distribution of this extinct polychaete species. The geologically oldest record of *D. mexicanus* is from the southern tip of the Baja California peninsula (Pacific of Mexico). The type horizon of *D. mexicanus*, which occurs in the El Cien Formation, was regarded by Wilson (1986) as upper Oligocene or lower Miocene, whereas Fischer *et al.* (1989) considered it upper Oligocene, near the Oligocene–Miocene boundary. Later, Grimm (2000) reported the occurrence of *D. mexicanus* in deposits belonging to the Oligocene–Miocene Timbabiichi

Formation, as well as in the upper portion of the El Cien Formation, which includes lower Miocene strata (Applegate 1986; Carreño 1992). The record from the northeastern part of South America in the Pacific Ocean (Peru) derives from the Chilcatay and Pisco formations (Kočí *et al.* 2020) (Figure 1E).



Figure 3 Colony of *Diplochaetetes mexicanus*, MCT.I.7255, Pirabas Formation, Praia do Atalaia, Salinópolis, Pará, Brazil: A,C. microCT sections in coronal views showing aggregated tubes in cross section, with numerous septa visible inside them. B, D, microCT sections in sagittal views of subparallel tubes along a longitudinal cut showing a pipe organ-like arrangement. Scale bar A: 5 mm, B: 15 mm, C: 7.5 mm, D: 10 mm.

The extensive and gradual exhumation of the Panamanian Isthmus between the late middle Miocene and the late Miocene (Coates & Obando 1996) ultimately closed the Central American Seaway (CAS) around ~10 Ma (Coates *et al.* 2004; Montes *et al.* 2012, 2015; Jaramillo 2018). Consequently, the strong eastward marine currents carrying waters from the Pacific Ocean into the Atlantic ceased after the CAS closed (Bartoli *et al.* 2005; Schneider & Schmitter 2006; Jaramillo 2018; Khon *et al.* 2023; Vallejo-Hincapié 2024). However, other seaway segments persisted until the total isolation of the Eastern Central Atlantic and the Western Central Pacific (Collins *et al.* 1996, O’Dea *et al.* 2016).

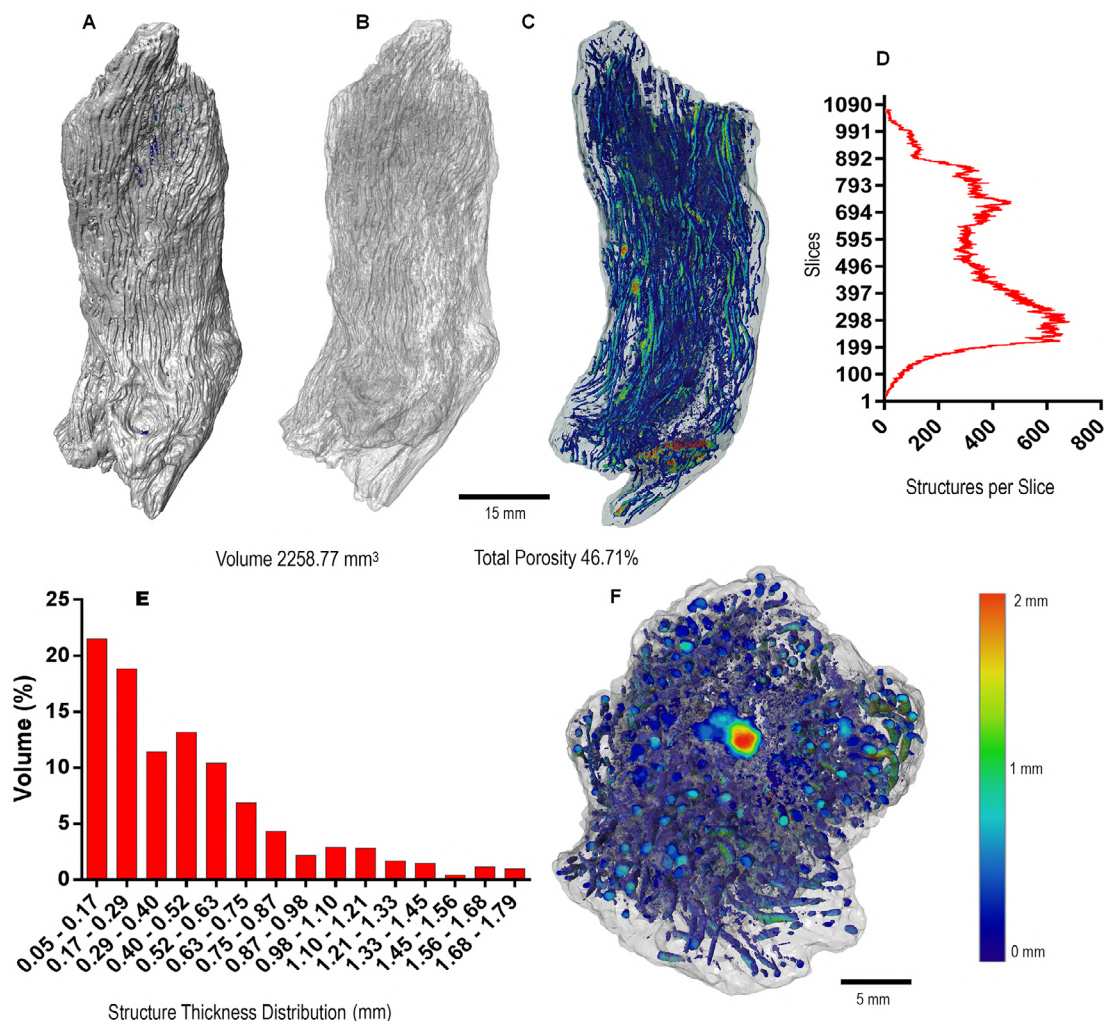


Figure 4. Colony of *Diplochaetetes mexicanus*, MCT.I.7255, Pirabas Formation, Praia do Atalaia, Salinópolis, Pará, Brazil: A–C. MicroCT reconstructions of the colony in external and internal views and mapping of internal tubes; D. Distribution of tubular structures per slide; E. percentage of tubes volume and distribution of diameters in the colony; F. Representation of tubes diameters in the colony.

Throughout the Miocene, most of present-day tropical America constituted a single biogeographic district—namely, the Gatunian Province—which extended from the western U.S. coast down to Peru and eastward across the Caribbean region and along the Brazilian coast in the Atlantic Ocean (e.g., Petuch 1982; Vermeij 2005). However, the early records of *D. mexicanus* along the eastern-central Pacific coast of the Americas suggest a Pacific origin, followed by its subsequent invasion of the western-central Atlantic via the Central America Seaway, prior to the complete closure of the Panamanian Isthmus at 2.8 Ma (O’Dea et al. 2016). *D. longitubulus* Weissermel (1913) and *D. (L.) vermicularis* Weissermel, 1926 from Namibia (south-eastern Atlantic in Africa) suggest an alternative Atlantic invasion from the Indo-Pacific during the Eocene-Oligocene.

Other fossil cirratulids, belonging to the genus *Dodecaceria*, were reported by Fischer et al. (2000) from younger sediments of the same area (the early Miocene of the Baja Formation of California), and from Pliocene-Pleistocene deposits of Oregon and California (Hove and Hurk 1993).

D. mexicanus has dozens of large tubes than differ from *Filograna* Berkeley, 1835 and *Salmacina* Claparède, 1870 bundles that they have smaller and thin tubes in the fossil records (see Kočí et al. 2017). Furthermore, these large tubes of *D. mexicanus* differs from sabellids tube-worms that they attached on coral see Zuschin & Gebhardt (2009). The palaeoenvironment from the Praia do Atalaia outcrop (middle to late Miocene) is characterized by coastal lagoons with mangrove forests under the influence of a tidal regime and shallow inner platform (Aguilera et al., 2020b;



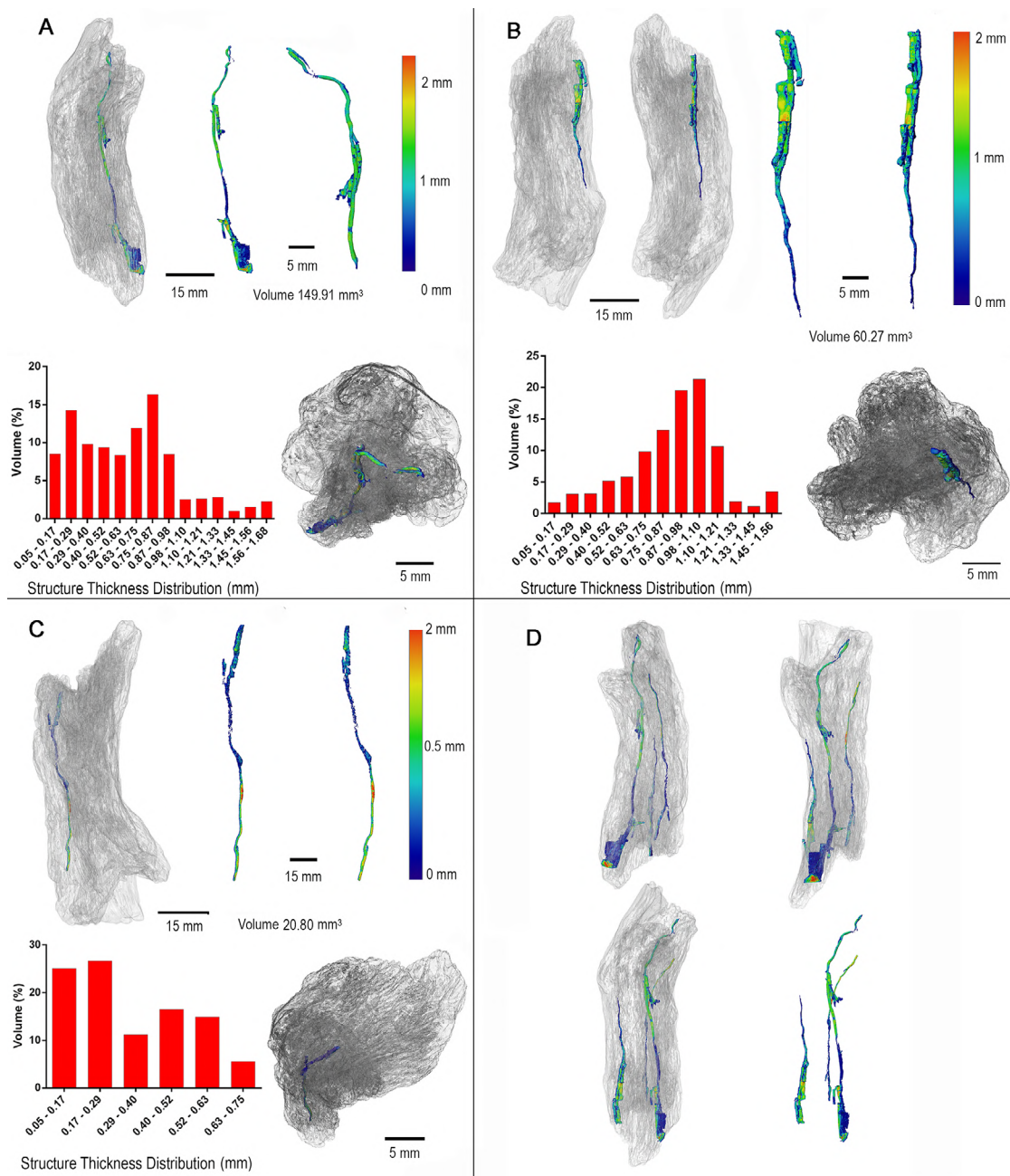


Figure 5. Colony of *Diplochaetetes mexicanus*, MCT.I.7255: A–C. Sequence of digital sections on the colony highlighting the individuals tubules, the volume, diameters of tubes in cross section and thickness distribution in the colony; D. Example of 3D reconstruction of tubes showing the regular arrangements.

Gomes *et al.*, 2023), and the Paleoenvironment from the Fazenda outcrop (late early-Miocene age) reveals high-energy and multiple Miocene tropical storms (Aguilera *et al.* 2023; Gomes *et al.* 2023). The facies analysis from both outcrops recognizes bioclastics–dominated distal

inner-platform and siliciclastics–dominated proximal inner platform (Aguilera *et al.* 2022). The polychaeta Cirratulidae recorded here are in agreement with extant tropical and subtropical species distribution that inhabit shallow water (Blake 1996; Kočí *et al.* 2020; Guido *et al.* 2024).





Figure 6. A-B. Colony of *Diplochaetetes mexicanus*, MCT.I.7256, Pirabas Formation, Fortaleza Island, outcrop of Fazenda, São João de Pirabas, Brazil.

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Supplementary material

S1_MicroCT Video. *Diplochaetetes mexicanus*, MCT.I.7255, Pirabas Formation, Praia do Atalaia, Salinópolis, Pará, Brazil (virtual sections).

Author contributions

Orangel Aguilera: writing-original draft; conceptualization; formal analysis; methodology; validation; writing – review and editing; supervision. **Tomáš Kočí:** conceptualization; formal analysis; methodology; writing – review and editing; validation. **Olga de Araújo:** conceptualization; formal analysis; methodology; writing – review and editing; validation. **Ricardo Lopes:** conceptualization; formal analysis; methodology; validation; writing – review and editing; supervision. **Jamille de Sousa da Silva:** writing-original draft; writing – review and editing. **Beatriz Teixeira Guimarães:** writing-original draft; writing – review and editing.

Conflict of interest

The authors declare no conflict of interest.

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All data included in this study are publicly available in the literature.

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