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EDITED BY
Linda Ivany,
Syracuse University, United States

REVIEWED BY
Andrew K. Rindsberg,
University of West Alabama,
United States
Franek Hasiuk,
University of Kansas, United States

*CORRESPONDENCE
Javier Dorador,
javidr@ugr.es

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The puzzling influence of *Ophiomorpha* (trace fossil) on reservoir porosity: X-ray microtomography analysis

Olmo Miguez-Salas[1], Jose Cabrera Ortiz[2], Javier Dorador[2]* and Francisco J. Rodríguez-Tovar[2]

[1]Department of Marine Zoology, Senckenberg Research Institute, Frankfurt, Germany, [2]Departamento de Estratigrafía y Paleontología, Universidad de Granada, Granada, Spain

Bioturbation can influence petrophysical properties (e.g., porosity, permeability) of sedimentary rocks and, in consequence, reservoir quality. The impact can be positive, negative, or neutral, requiring detailed ichnological analysis. *Ophiomorpha*, a branched cylindrical burrow with diagnostic peloidal wall, may be present in bioturbated reservoirs that exhibit properties of both super-permeability and reduced porosity/permeability. However, no mechanistic understanding of how *Ophiomorpha* positively or negatively impacts petrophysical properties has yet been established. This study presents high-resolution X-ray microtomographic analysis of how the features of *Ophiomorpha* (i.e., peloidal wall vs. burrow fill) influence porosity distribution in deep-water deposits (Neogene Tabernas Basin, SE Spain). The results show that the peloidal burrow wall exhibits the lowest porosity (up to six orders of magnitude lower than burrow fill or host sediment), while surrounding sediment shows variable values. Abrupt porosity changes within the fill material likely relate to burrow-associated diagenesis. A refined understanding of the features of *Ophiomorpha* and their associated porosity distribution help to constrain understanding of their diverse impacts on reservoir properties.

KEYWORDS

bioturbation, petrophysical properties, Micro-CT, reservoir quality, diagenesis

Introduction

Applied ichnology is used in tandem with sedimentologic, stratigraphic, diagenetic, and reservoir petrophysical characterization of sedimentary successions considered to have petroleum potential, interest for carbon capture, or representing valuable water resources (e.g., Dawson et al., 1977; MacEachern et al., 2007; Knaust and Bromley, 2012; Hose and Stumpp, 2019). Advances arise from the interest of the petroleum industry and water providers in understanding how bioturbation controls petrophysical properties (e.g., porosity and permeability). Studies have evaluated bioturbation's impacts on porosity and permeability in reservoir characterization (e.g., McDowell et al., 2001; Pemberton and Gingras, 2005, Cunningham et al., 2009, 2012; Gingras et al., 2012;

Knaust, 2013, Knaust et al., 2020; Baniak et al., 2014, 2015, 2022; Bednarz and McIlroy, 2015; Eltom et al., 2019; Dorador et al., 2021; Oliveira de Araújo et al., 2021; Rodríguez-Tovar et al., 2021; Miguez-Salas et al., 2022), showing that bioturbation can impart both positive or negative impacts on reservoir character. Usually, bioturbation lowers porosity and permeability since tracemakers tend to reduce sorting or introduce clay (e.g., Gingras et al., 2012; Alqubalee et al., 2022), but several studies have shown that bioturbation can enhance porosity and permeability (Pemberton and Gingras, 2005; Cunningham et al., 2009; Tonkin et al., 2010; Gingras et al., 2012; Baniak et al., 2022 for a recent review) or may exert no influence at all (Miguez-Salas et al., 2022). Ichnological features such as burrow morphology, architecture, and fill, and tracemaker behavior can combine with post-depositional chemical processes (cementation/dissolution) to modify pore structure and distribution and ultimately affect lateral and vertical fluid flow (Gingras et al., 2012; Knaust, 2013; Miguez-Salas et al., 2022).

Given their uncertain influence on reservoir character, Knaust (2013), Knaust (2014) proposed a morphological classification of burrows related to bioturbation-influenced porosity based on particular ichnogenera. While this predictive model may provide accurate results, countless ichnogenera (e.g., *Macaronichnus*) have ambiguous effects on void space and results may depend on reservoir facies or some morphological trace-fossil features. These caveats hold true for *Ophiomorpha*, one of the commonest and most studied ichnogenera in potential reservoir strata. Gingras et al. (2012) stated that, "in the light of their branching morphology, deeply penetrative nature and passive fill, *Thalassinoides* and *Ophiomorpha* are likely the most important permeability-enhancing trace fossils." The positive effects appear clearly in several prominent examples. The Biscayne aquifer of southeastern Florida (United States) hosts a dense *Ophiomorpha* assemblage that establishes zones of superpermeability (Cunningham et al., 2009; Cunningham et al., 2012). The Upper Jurassic Ula Formation (Norwegian Central Graben) consists of an *Ophiomorpha*-dominated sandstone with enhanced permeability (Baniak et al., 2014; Baniak et al., 2015). However, *Ophiomorpha*-dominated strata can also show reduced porosity and permeability, and these clearly diminish reservoir quality (e.g., Tonkin et al., 2010; Knaust, 2013; La Croix et al., 2017; Alqubalee et al., 2022).

Thus, the influence of *Ophiomorpha* on porosity and permeability remains ambiguous. The diverse, three-dimensional morphology of *Ophiomorpha* and its pore distribution also remain poorly understood. This study reports a detailed, high-resolution analysis of pore distribution in samples hosting *Ophiomorpha* specimens, from deep-water deposits (Neogene Tabernas Basin, SE Spain), a facies associated with petroleum potential. The study uses digital X-ray axial microtomographic (Micro-CT) analysis to interpret pore density and distribution in terms of 1) burrow fill, 2) peloidal wall, and 3) host sediment. The analysis seeks to determine how *Ophiomorpha* burrow features control porosity distribution and burrow-associated diagenesis to ultimately influence reservoir petrophysical properties.

Regional geology, material and methods

The Neogene Tabernas Basin (Almeria, SE Spain) represents an elongate intramontane basin developed during and after an Alpine-aged collision between Iberia and North Africa (Sanz de Galdeano and Vera, 1992; Haughton, 2000). During the late Miocene, sediment gravity-flow deposits came to dominate the basin fill, which consists of muddy to sandy, high-density turbidites (Kleverlaan, 1989; Haughton, 2000; Postma et al., 2014). These deposits have been studied from different perspectives as sedimentology or tectonic (e.g., Kleverlaan, 1989; Hodgson and Haughton, 2004), but bioturbation has not been analyzed in detail and there are just a few contributions where it is even mentioned (e.g., Doyle, 1996; Hodgson, 2002). The ichnological assemblage in the turbiditic deposits from the study area is characterized by pre- and post-depositional associations. In general, the pre-depositional assemblage is mainly composed of graphoglyptids (e.g., *Paleodyction*, *Helminthoraphe*), and the post-depositional association is dominated by structures such as *Thalassinoides*, *Scolicia* and especially *Ophiomorpha* (De Matteis et al., 2016; Cabrera-Ortiz et al., 2022, research in progress). *Ophiomorpha* samples from sandy, clastic turbidites were collected based on their ichnological features (e.g., length, diameter, shape, wall). Then, over 40 *Ophiomorpha* specimens were collected from the freshest available material and studied in the laboratory through polished sections; special attention was paid to the fill, constructional lining, pellet shape, surrounding sediment, and internal textures (e.g., diagenetic halos), among other features. Some other architectural features, such as branching or orientation, that are usually considered in evaluation of reservoir quality of bioturbated deposits (Knaust, 2017 for a detailed review) were not considered, because they mainly affect permeability in a reservoir, instead of porosity. Micro-CT analysis was performed on 17 representative specimens of *Ophiomorpha* with well-preserved peloidal walls.

Tomographic data were obtained using X-ray computerized axial microtomography (Micro-CT, Zeiss Xradia 510 Versa) conducted at the Center for Scientific Instrumentation (CIC) of the University of Granada. Instrumental settings for sample analysis were ×0.4 magnification and image bins of 1–2,334 images. Scanning parameter were adjusted for every single sample to get the best results. Voltages ranged from 80 to 140 kV, amperage from 72 to 87 µA and time from 4 to 50 s. Image reconstruction was performed using Reconstructor Scout and Scan™ software (Zeiss), a 0.5 Recon filter, and

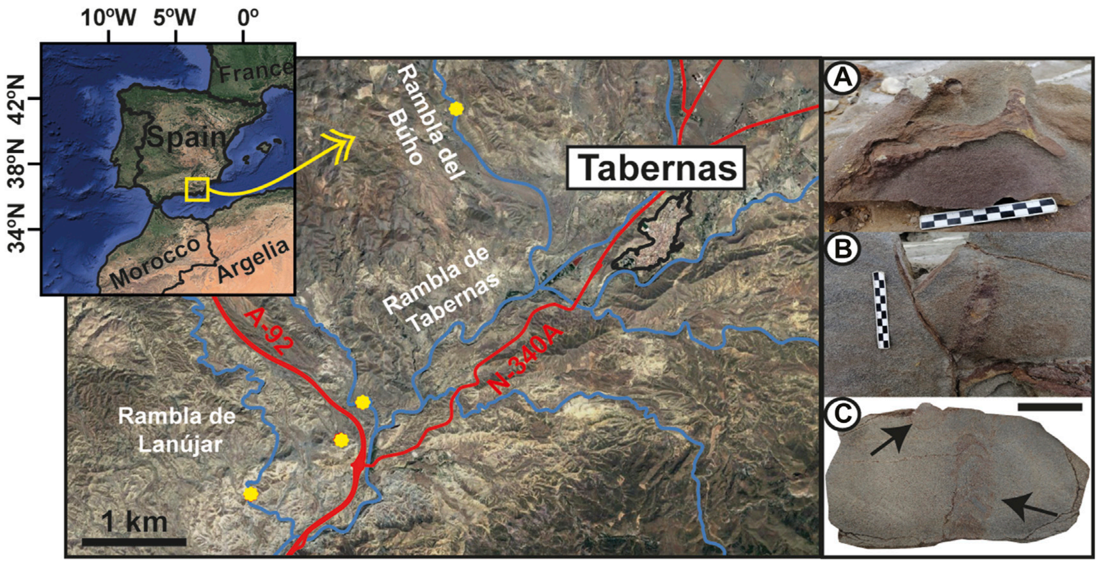

FIGURE 1
Location of the study area (sampled outcrops = yellow points). **(A,B)** Outcrop examples of *Ophiomorpha* specimens. **(C)** Polished section with *Ophiomorpha* specimens (black arrows) (specimen Op-7), scale bar = 2 cm.

3,201 projections. Dragonfly Pro™ (Object Research System) software was used for advanced post-processing analysis of 3D image porosity data. Processing of CT files by Dragonfly Pro™ allows generation of a porosity mesh (pore abundance visualization) in which higher color intensity (red) indicates higher pore density (see Miguez-Salas et al., 2022 for a detailed explanation). Quantitative pore analysis characterization was conducted using binary black and white CT still images with the open software Fiji (Schindelin et al., 2012). Each CT image was converted to an 8-bit grayscale image with a threshold defined to establish an appropriate differentiation range for black and white pixels, wherein black pixels indicate void space (Miguez-Salas et al., 2019). For each *Ophiomorpha* sample, at least 20 still images were generated and processed. Within the same image, multiple, random porosity measurements were conducted to evaluate the peloidal wall, fill, and host sediment. In total 1,626 values were considered, more than 500 measurements were obtained for each of these three parts (567 for the host sediment, 512 from walls and 547 values from burrow fill). Statistical analysis comparison of porosity data in the three parts included one-way ANOVA testing (alpha level of 0.05), and then *t*-Test: Two-Sample (assuming equal variances) was performed to address which parts had differences in means at the 0.05 confidence level.

Results

Ophiomorpha specimens exhibit cylindrical burrows, which appear rectilinear or gently curved, and muddy peloidal walls. These burrows, whose diameters range from 1 to 3 cm, are part of tridimensional branching networks composed of horizontal mazes and vertical shafts. The peloidal walls consist of cylindrical or conical pellets with rounded edges (Figure 1). Pellet diameter typically spans ~0.5 cm but can reach 1 cm. Burrows show occasional branching (Figure 1A). No predominant orientation to the bedding planes is observed. Polished sections of the burrows reveal ferruginized halos in the boundary between the peloidal wall and the fill material for some samples. Fill is passive, commonly structureless but sometimes exhibiting textural heterogeneities (e.g., halos, lamination) reflecting differential cementation and/or mineral replacement.

Micro-CT analysis clearly shows different porosity intensities (pore abundance) for the three studied parts (i.e., host rock, peloidal wall and *Ophiomorpha* fill; Figures 2–4). Peloidal walls exhibit a low abundance of pores and poor connectivity between them, which evidently prevented network porosity (Figures 2, 3). Host sediment confers different degrees of porosity or give varying mesh estimates depending on the particular sample (Figures 2, 3). In some cases, even the same sample can give differing pore intensities that reflect heterogeneity in diagenetic cementation (Figures 2A, 3A). Different *Ophiomorpha* fill also give varied estimates of porosity and porosity mesh. In some cases, structureless fill without diagenetic textural heterogeneities give low to moderate intensity porosity mesh with a high degree of pore isolation (Figures 2B, 3B). In other cases, diagenetic precipitation (e.g., ferruginized halos; Figure 2A) and dissolution features generate zones with differing degrees of cementation (Figure 2C),

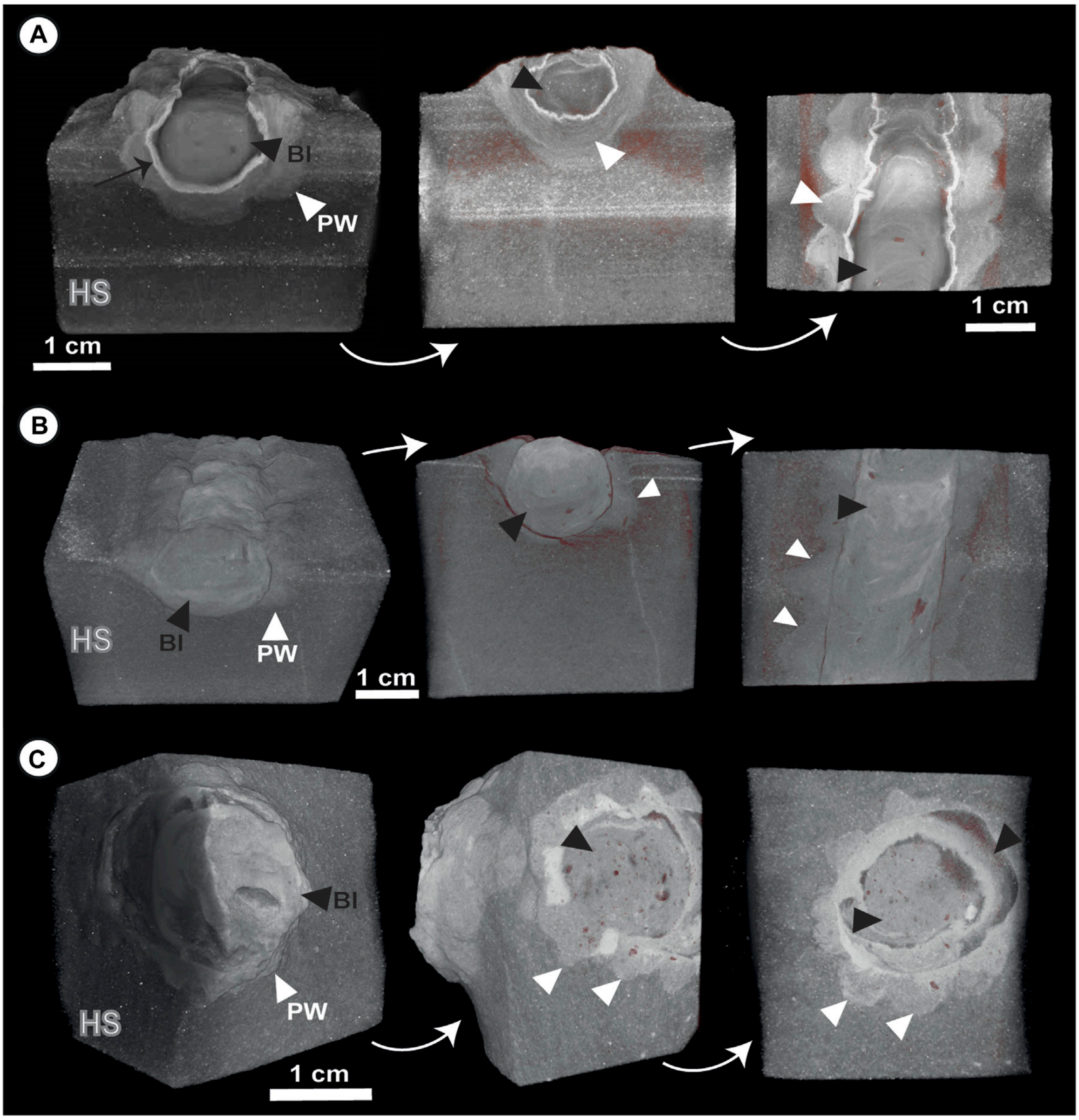

FIGURE 2
(A) Micro-CT images of *Ophiomorpha* with a ferruginized halo (black arrow) surrounding the fill (specimen Op-15). Note that the peloidal wall (white triangles) lacks porosity, while the fill exhibits (black triangles) porosity zonation (being higher in proximity to the ferruginized halo). **(B)** Micro-CT captions of *Ophiomorpha* with structureless and low porosity fill. Peloidal wall again shows near absence of porosity (specimen Op-24). **(C)** Micro-CT captions of *Ophiomorpha* with (specimen Op-17A). Note that the fill has areas of high porosity due to differing degrees of cementation. PW, Peloidal wall; BI, Burrow fill; HS, Host sediment.

yielding a range of different porosity mesh estimates according to diagenetic heterogeneities (Figures 2A,C).

Tomographic still images confirm that peloidal walls are associated with the lowest observed porosity values. Porosity shows reductions of up to six orders of magnitude in peloidal walls relative to values for fill and host sediment (Figures 4A,B). Peloidal walls shows an average porosity value of 0.54% while the fill and host sediment show 3.39% and 3.20% respectively. The median porosity values are 2.85% for the host sediment, 0.27% for the peloidal wall and 2.56% for the fill.

Binary images indicate differing degrees of diagenetic cementation within the fill of some specimens and show zones of notable porosity contrast (see right and left areas of the *Ophiomorpha* fill in Figure 4A). Statistical analysis demonstrates that fill and host sediment are associated with a wide range of porosity values (Figure 4B). One-way ANOVA

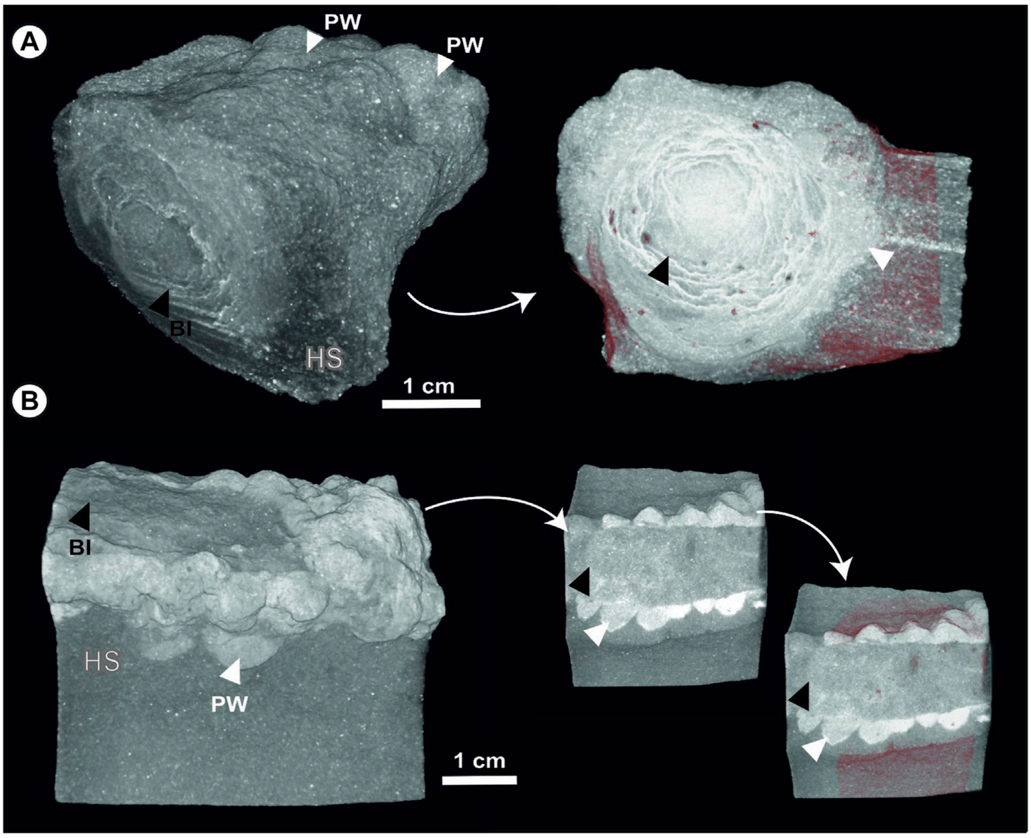

FIGURE 3
(A) Micro-CT images of *Ophiomorpha* with concentrical burrow-associated diagenesis in the fill (specimen Op-22). Peloidal wall and host sediment show near absence of porosity. **(B)** Micro-CT captions of *Ophiomorpha* with structureless and low porosity fill (specimen Op-18). Note that the peloidal wall lacks porosity. PW, Peloidal wall; BI, Burrow fill; HS, Host sediment.

tests showed that the three types of features gave significantly different porosity values [F(2,1623) = (313.4), $p < 0.01$]. Two sample *t*-Tests found that burrow fill/peloidal wall and host sediment/peloidal wall porosity values differed significantly ($p < 0.01$). However, the burrow fill/host sediment *t*-Test values gave t(1,112) = −1.23, p=0.1 indicating non-unique porosity distributions.

Discussion and implications

Burrowing organisms modify the sediment in several ways. Modification of the original sedimentary fabric and the subsequent influence on diagenetic processes can especially affect void space (Gingras et al., 2012). The tracemakers that create *Ophiomorpha*, probably callianassids (thalassinidean shrimp), usually create galleries that occupy more than the 50% of the rock volume (Gingras et al., 2012) and modify the host sediment fabric by incorporating constructional pellets into their burrow walls (e.g., Leaman et al., 2015; Netto et al., 2017). The embedment of pellets into burrow walls compacts the surrounding host sediment. Thus, as suggested by previous studies (Tonkin et al., 2010; Baniak et al., 2014; Quaye et al., 2019), peloidal material should show different porosity values than the host sediment. However, these studies were conducted in a limited number of samples and few quantitative measurements were done. Tonkin et al. (2010) based on blue epoxy resin methodology, showed that *Ophiomorpha* burrow walls create localized zones of porosity reduction, but no quantitative porosity data in relation to the burrow wall was reported. Then, Baniak et al. (2014) based on Micro-CT analysis revealed that greater X-ray attenuation occurred within the *Ophiomorpha* burrow wall linings, without quantitative porosity data. Recently, Quaye et al. (2019) based on a pressure decay porosimeter (point-counting mesh) made one quantitative porosity measurement of *Ophiomopha* peloidal walls, showing similar values for host sediment and burrow walls; this is not unexpected since this methodology offers limited results when addressing small features such as burrow walls (<1 cm). Thus, it has not yet been

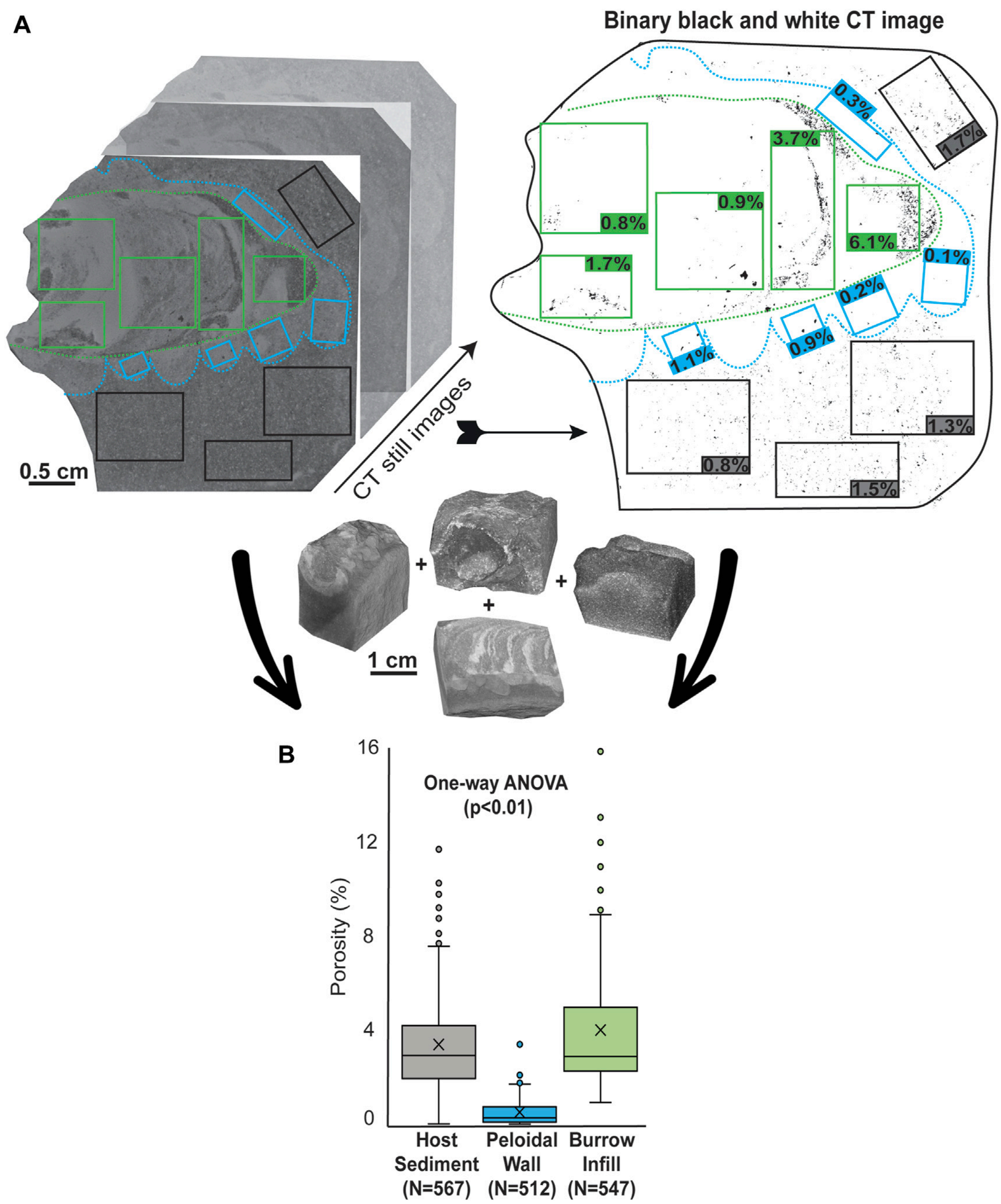

FIGURE 4
(A) Example of Micro-CT still images (left) with associated binary black and white image (right) from one *Ophiomorpha* sample (specimen Op-18). Note the Micro-CT binary image with random rectangles from which the porosity measurements were obtained for host sediment (grey rectangles), peloidal wall (blue rectangles), and burrow fill (green rectangles). **(B)** Box plots representing porosity values from the three measured parts of all *Ophiomorpha* specimens (17 specimens). Note the low porosity values for the peloidal wall and the highly variable porosity for the host sediment and burrow fill.

quantitatively verified how *Ophiomorpha* features may control porosity distribution.

Our research evidence (after doing more than 500 measurements on the peloidal wall and ANOVA One-way $p < 0.01$) that the peloidal wall can show a porosity reduction of up to six orders of magnitude (Figure 4B). These results carry significant implications for the reservoir potential of sediment hosting dense *Ophiomorpha* assemblages. The degree of contact between peloidal walls (i.e., the contact between different *Ophiomorpha* specimens) and the total volume of the peloidal wall with respect to the burrow fill volume can also influence reservoir quality.

Burrow-associated diagenesis, mainly dissolution and cementation processes, can affect petrophysical properties in both ways, but commonly results in improved porosity and permeability (Gingras et al., 2004). Strata hosting dense *Ophiomorpha* assemblages exhibit biogenic, vuggy macropores which have become superpermeability zones due to fabric-selective carbonate dissolution (Cunningham et al., 2012). However, trace fossils more commonly influence porosity by acting as loci of cementation and dissolution processes, which usually act in tandem during diagenesis (Gingras et al., 2012). Thus, biogenic modification and diagenesis can generate a range of sedimentary fabrics of varying petrophysical properties. Knaust (2017) reports that the nature of *Ophiomorpha* burrows can guide fluid flow and thereby localize precipitation of early diagenetic minerals. Afterward, *Ophiomorpha* fill can generate diagenetic heterogeneities through fluid dynamics and recrystallization. Our results support the idea that *Ophiomorpha* may have experienced differential fluid flow with respect to the host sediment. Comparison of porosity between burrow fill and host sediment, and assuming the absence of primary porosity in peloidal walls, reveals similar but unequal values ($p = 0.052$). Varying porosity distributions between fill and host sediment may arise from fluid flow through *Ophiomorpha*, which results in contrasting dissolution and precipitation in fill zones. The diagenetic histories of the *Ophiomorpha* specimens analyzed here appears highly variable. The varying degrees of precipitation/dissolution observed suggests that a relatively limited volume of sediment with burrow structures can become a complex mosaic of cement and void space (Figures 2C, 3, 4).

The analysis presented here identifies several features of *Ophiomorpha* that appear to influence reservoir porosity strongly. These include the thickness of the peloidal wall, which usually decrease porosity, and the relative volume occupied by every burrow part (i.e., fill and wall), as the fill usually presents higher porosity values. Overlapping between burrows can also influence porosity. The balance between dissolution and precipitation that occurs as part of burrow-associated diagenesis of the fill also determines the structure and volume of void space. The results reported here demonstrate the importance of burrow-associated diagenesis which, in association with other burrow features (i.e., orientation, architecture, shape, etc.), can guide or hinder fluid flow. In sum, primary sediment fabric, sediment composition, tracemaker behavior, burrow morphology, and diagenetic processes can all significantly influence porosity and permeability. Thus, each of the aforementioned parameters requires rigorous and systematic analysis at different scales when evaluating their impact on reservoir quality. Future research in applied ichnology should seek to further establish precise and accurate paradigms of how bioturbation impacts reservoir properties.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

All the authors performed fieldwork and sampling. OM-S coordinated the project, and conducted the Micro-CT processing and quantitative analysis. All the authors discussed the results and collaborated in writing the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.1010729/full#supplementary-material

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