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Abstract

Animal-made bioturbational structures modify physio-chemical conditions and biota on the sediment surface and below. The behavior of the trace makers chiefly causes such changes by sediment irrigation, mucus lining, organic matter storage, microbial gardening etc. Such traces are preferential loci for accumulation of organic material that may foster syn- to post-bioturbational mineral authigenesis. Similar processes associated with plant roots have already been described and termed. In this study, accordingly, an analogous terminology is proposed for authigenic mineralization of and around animal traces in aquatic environments for which the general, subsuming term "ichnolith" (equivalent to "rhizolith") is suggested. Two types of ichnoliths are recognizable so far. (1) "Ichnopetrifications" are mineralized animal traces preserving their original morphology. (2) "Ichnocretions" are concretions, which preferentially developed around animal traces. These two categories supposedly do not cover all phenomena and thus, additional ones could be introduced in the future. Moreover, new terms "ichnostrome" and "ichnosax" are introduced for beds and irregular rock masses, respectively, which formed through early-diagenetic cementation along dense animal traces.

Ichnoliths form by cementation mostly close to the sediment surface. They are compaction-resistant and become not deformed or destructed by mechanical and chemical processes. Consequently, they may preserve primary sedimentary and bioturbational structures in detail. Thus, ichnoliths potentially store environmental data enabling more reliable and detailed reconstruction of depositional settings and ecological conditions than the surrounding sediment. In particular, carbonate cements are important archives of biogeochemical reactions and composition of fluids circulating shallow in sediment during or shortly after bioturbation.

Keywords: endobenthic activity, trace fossils, cementation, ichnocretion, ichnopetrification

1. Introduction

Ichnoliths, herein defined as mineralized animal traces, represent important documents of animal behavior and valuable archives of past environmental conditions. They form by precipitation of authigenic minerals during early diagenesis in or around bioturbational structures simultaneously to or shortly after animal activity. The formed authigenic mineral bodies are more resistant to mechanical and chemical processes, which commonly compact or even destroy not cemented animal traces and thus, obliterate these structures and hinder paleoenvironmental reconstruction. In fact, ichnoliths have a much higher preservation potential with respect to the original structure, texture, mineralogy as well as organic and geochemical properties than trace fossils not affected by early-diagenetic authigenesis.

Deciphering archives of paleoenvironmental data has significantly increased over past few decades due to a rapid progress in organic and inorganic geochemical analytical methods and their application to early-diagenetic authigenic mineral phases. Various types of early-diagenetic rocks, such as authigenic carbonates, have been investigated by numerous multiproxy analytical studies (see Loyd et al., 2023, and references therein) whereas ichnoliths have gained relatively little attention from the perspective of combined ichnological, petrographic, and geochemical approach so far. Thus, research on ichnoliths is lagging significantly behind other types of early-diagenetic rocks. Only recently, petrographic-geochemical investigations using methods applied to carbonate concretions already for 50 years have started to be reported (Wetzel and Bojanowski, 2022, 2025; Wetzel and Blouet, 2023; Bojanowski and Wetzel, 2026).

The purpose of this study is to (1) describe and illustrate different types of ichnoliths and their characteristics, (2) provide a terminology and classification for them while comparing them with rhizoliths, (3) define criteria for their identification, (4) address their formation mechanisms, and (5) evaluate their environmental significance while considering case studies.

2. Material and Methods

This study is chiefly based on a literature review supplemented with unpublished data obtained for carbonate ichnoliths collected by the authors over a few decades. These data have been obtained using various methods. Petrographic investigations were carried out on thin sections, polished sections, and rock chips using a polarizing microscope (in transmitted and reflected light), cathodoluminescence, and scanning electron microscopy combined with energy dispersive X-ray diffractometry (SEM-EDS). X-ray diffractometry was applied to powdered samples in order to determine the quantitative mineral composition. Organic and inorganic carbon content was measured with the use of an elemental analyzer. Stable C and O isotope measurements were performed with the use of standard isotope ratio mass spectrometry. Data for some of these samples have already been published in Wetzel and Bojanowski (2022, 2025) and Bojanowski and Wetzel (2026). Details of the methods listed above are given in these papers.

3. Arrangement of the Study

The main body of the paper is divided into five sections. After addressing terminology and classification of ichnoliths (Section 4), background information regarding the early-diagenetic setting is presented with particular focus on biogeochemical reactions and bioturbational structures fostering authigenesis close to the sediment-seawater interface (Section 5). Ichnoliths in marine sediments are dealt with in this section, since they represent the most common case in the rock record. Thereafter, more particular conditions and structures like freshwater settings and borings are considered with regard to potential ichnolith formation (Section 6). Identification criteria for each ichnolith type are outlined in Section 7. Selected case studies of each type of ichnoliths representing various environments and cement minerals are presented in sections 4–7. Finally, in Section 8 significance of ichnoliths in Earth sciences is addressed.

4. Terminology and classification

For root structures, Klappa (1980) proposed a terminology and classification, which has been accepted by the scientific community and is in common use (see, for instance, Craig et al., 2026, and references therein). For the sake of clarity and consistency, an analogous terminology and classification for structures associated with animal traces in aquatic environments is suggested here. Yet, certain differences between animal and root traces preclude a direct transfer of Klappa's (1980) terms and their definitions (Table 1) as outlined in the following paragraphs.

Ichnolith. This term is proposed for all animal bioturbational structures, which have been preferentially affected by cementation within or around them, which may subsequently undergo various secondary mineral transformations. Only two out of five types of rhizoliths defined by Klappa (1980) can be applied unambiguously to ichnoliths (Table 1; Fig. 1).

Ichnopetrification. It refers to animal traces, which have facilitated cementation to a degree that just the original morphology of the bioturbational structures is commonly preserved. If present, mucus and constructional lining (for definition see Bromley, 1996) can also be mineralized. This entity represents Zone 1 with respect to authigenesis (Figs. 1, 2).

Ichnocretion. It comprises concretion bodies precipitated preferentially around animal traces, which fostered cementation. With respect to authigenesis, the trace in the center represents Zone 1, surrounded by authigenic minerals impregnating Zone 2, and the enveloping concretion body constituting Zone 3 (Figs. 1, 3–5).

Tubular ichnocretion. It represents a subcategory for distinctively elongated ichnocretions having the causative burrow not cemented during early diagenesis but with a sediment and/or late-diagenetic cement fill, (Figs. 4B, F, G, 6D), equivalent to 'root tubules' of Klappa (1980).

The remaining two subtypes of rhizoliths, root casts and root moulds, have no analogs in the animal-trace record (Table 1).

The term “rhizolite” proposed by Klappa (1980) for a root rock, is not transferred here to animal traces by the new term *‘ichnolite’* (*trace rock*). Instead, to avoid confusion of ‘ichnolite’ with ‘ichnolith’, it is suggested to use the terms ***ichnostrome*** (from Gr. στρώμα = bed) for an early-diagenetic bed and ***ichnosax*** (from Lat. saxum = rock) for a complex authigenic rock mass if early diagenetic cementation was fostered by and occurred along dense bioturbational structures (Fig. 5). Ichnostromes and ichnosaxes must be primarily composed of early-diagenetic cements and show fabrics confirming preferential cementation in or around burrows. For example, an ichnostrome may have a positive relief on the bedding surface(s) in or around traces and early-diagenetic cements occupy a major proportion of the bed (Fig. 6A, B). An ichnosax represents a complex rock mass primarily composed of numerous interconnected ichnocretions (Fig. 6C, D). Depending on the actual concretion growth mechanism, concentric or pervasive (see Raiswell and Fisher, 2000), such ichnostromes and ichnosaxes form if adjacent ichnocretions coalesce. Alternatively, the spatial extent of oversaturation of cementing minerals is controlled by the burrows. The authors are aware of only rare examples of ichnostromes and ichnosaxes, for example in the Carpathians, along the Basque and NE Taiwanese coasts, but it is likely that more will be discovered.

5. Geochemical and ichnological background

In marine sediments, early diagenetic chemical reactions are directly or indirectly fueled by degradation of organic matter that becomes oxidized – according to the energy yield – from the sediment downward by oxygen, nitrate, manganese $^{IV–VII}$, iron ^{III}, sulfate and what is subsumed under the term methanogenesis (e.g., Froelich et al., 1979, Burdige, 2007; Fig. 7). A geochemically very reactive interface or zone develops where microbially mediated anaerobic oxidation of methane (AOM) takes place, at the sulfate methane interface (SMI) or within the sulfate methane transition (SMT) zone, methane migrating upward from the methanogenic zone while sulfate originates from the seawater.

The involved chemical reactions occur at increasing depth within sediment expressed by a geochemical stratification. The redox potential decreases from the sediment surface exposed to oxygenated seawater downwards: It decreases from Eh ~ +100 mV in the oxic/aerobic zone, over Eh ~ –100 mV in the organoclastic sulfate reduction (OSR) zone, to Eh ~ –200 mV in the methanogenesis zone (e.g., Schulz, 2006; Fig. 7). Oxygen becomes almost exhausted in the nitrate reduction zone, so that suboxic conditions occur in the Mn and Fe reduction zones, which are, however, relatively thin and usually of minor importance. The top of the OSR zone represents the redox potential boundary (RPD) below which the environment becomes anoxic. Since the cementing agents are mainly produced below the oxic/aerobic zone, suboxic and anoxic/anaerobic sediments are more prone to authigenesis than oxic ones. Organic matter degradation and associated microbial activity are especially enhanced around the RPD, where both aerobic and anaerobic microbes process the organics creating particularly favorable conditions for authigenesis.

Burrowing animals can facilitate authigenesis because their traces, usually developed as open or sediment-filled tubes penetrating the sediment, can serve as fluid conduits or bioreactors. These functions of bioturbational structures represent endmembers while tubes having an organic-rich lining act as both and from a transitional stage.

(i) Conduits. Fluids can be circulated passively or actively by bioirrigation. The former occurs when waves or currents affect the sediment surface, in particular if the causative burrow has more than one opening on the seafloor (e.g., Vogel, 1994). Depending on the morphology of the causative burrow and the animal inhabiting it, in single tubes oxygenated water is transferred downward and/or fluids containing reducing compounds upward. In causative burrows having more than one opening on the seafloor, inflow of oxygenated and outflow of water containing reducing compounds can be simultaneous, like in U-tubes. Tube systems represent a special case since segments are intermittently bioirrigated: After oxygenated water has been pumped in, circulation is abandoned and, when tube water has become deoxygenated after some time, a next pumping cycle starts as it has been reported for some burrowing crustaceans (e.g., Forster and Graf, 1995). Fluid flow occurs at a reduced rate if parts of the burrow are filled with sediment having considerably higher permeability than the host sediment. In such a case, it is likely that reducing fluids are collected via such drainage systems, for instance in some *Chondrites* (e.g., Wetzel, 1981, 2008).

(ii) Bioreactors. Burrowing animals enrich organic matter in parts of their burrows directly or indirectly. In the first case, organic matter is collected on the seafloor or from suspension and stored deep in sediment, to be utilized during times of shortage of benthic food; these burrows are classified as *sequestrichnia* (Uchman and Wetzel, 2016, 2024). Indirect enrichment of organic matter is accomplished by fostering microbial growth within a burrow; these burrows are classified as *agrichnia* (resulting from gardening behavior; Bromley, 1990). Gaining of benthic food may also result in the enrichment of specific minerals, for instance, shells of planktonic organisms in sediments below the CCD (Wetzel, 1981; Wetzel and Unverricht, 2013) or heavy minerals forming the tests of benthic foraminifera (Kaminski and Wetzel, 2004).

(iii) Organic-rich tube lining. A mucus lining may stabilize the burrow wall, separate geochemical conditions inside and outside the burrow, and/or act as substrate for microbes. In particular, mucus along the tube wall can enhance its diagenetic potential. Similarly, constructional burrow lining composed of (selected) sediment particles and mucus may also facilitate early mineralization.

It needs to be mentioned that bioturbation may also prevent authigenesis. Bioirrigation and flushing of burrows with seawater may dilute the solutes in and supply oxygen to the pore water in and around the burrow. Both processes can hamper cementation by sustaining too low concentration of solutes and a too high oxygen level in the pore water (e.g. Bojanowski and Wetzel, 2026). In such cases, traces are not cemented and can be associated with a negative relief on the surface of early-diagenetic rocks (Fig. 8).

6. Limitations to ichnolith formation and special cases

Although ichnoliths are not limited to any specific cement mineralogy, they are predominantly composed of calcite, siderite, silica, pyrite, and iron oxides, all of which are reported in this contribution. Some ichnoliths are composed of two types of early-diagenetic cements, for example carbonate ichnocretions with silica- or pyrite-cemented tubes (Fig. 5B, E). So far, the present authors have not come across any primary dolomite ichnoliths, although dolomite concretions not related to trace fossils are rather common. This discrepancy may be related to the very shallow burrowing depth of endobenthic animals, at which ichnocretions form (up to a few meters), but dolomite supersaturation is difficult to attain due to the still relatively high sulfate concentration, insufficiently reducing conditions, and availability of Ca^{2+} cations favoring calcite precipitation (Curtis et al., 1986). Early-diagenetic formation of ichnoliths is indicated by two other pieces of evidence. (1) burrows in the ichnoliths are not deformed by compaction, and (2) septarian cracks, which form at shallow burial depths ranging from meters to tens of meters (Hesselbo and Palmer, 1992; Duck, 1995; Wetzel and Bojanowski, 2022), commonly postdate the ichnolith cements, including those precipitated in the central burrow (Fig. 5C).

The definition of ichnoliths proposed herein includes all kinds of animal traces mineralized during early diagenesis irrespective of the environment. However, based on own experiences and literature data, the authors are aware of ichnoliths associated only with burrows in marine sediments. Even if other ichnoliths exist, they appear to be very rare, which indicates that preferential cementation around traces and in continental settings is much less likely than around burrows in marine deposits. Potential reasons of this disparity are discussed below.

In continental settings, the pore fluid is usually meteoric water with little or no sulfate and thus, the sulfate reduction zone is absent or rather thin, as evidenced, for instance, by the scarcity of microbial pyrite (Berner, 1985). Furthermore, methane, if present, cannot be oxidized by sulfate, and anaerobic oxidation of methane (AOM) cannot operate. Indeed, methane-derived authigenic carbonates, the typical product of AOM in marine sediments, have not been reported from continental settings even in methane-rich deposits. Thus, oxygen-depleted pore-water conditions fostering authigenesis (e.g., Bojanowski et al., 2016) are less likely to develop in continental than in marine sediments. However, bioturbational structures have not yet been reported from such settings, to authors' knowledge. Still, authigenesis in and above the methanogenic zone is less likely than in marine settings, especially with regard to carbonates representing the most common ichnolith-forming authigenic minerals. Because methanogenesis releases large amounts of CO_2, which lowers pH and prevents carbonate precipitation unless buffered by a surplus alkalinity (Meister et al., 2011; Wallmann et al., 2008). Another limiting factor for mineral precipitation in continental settings (outside the evaporation-dominated zones) is the availability of cations in pore water. With respect to carbonates, concentration of Ca^{2+} and Mg^{2+} is usually lower in fresh than in marine water constraining precipitation of calcite and dolomite in the continental settings. Instead, authigenic carbonates in anoxic continental sediments are relatively more often composed of siderite, as Fe^{2+} dissolved in pore water is not bound in sulfides due to the absence or limited role of sulfate reduction.

Borings are entrenched in already hard substrate. Porosity and permeability in such rocks are much lower than in loose sediments. Therefore, the flow of fluids and diffusion of dissolved species are constrained in a hard substrate preventing abundant cementation. Also in case of hardgrounds, exposed to seawater, the probability is rather low that a geochemical gradient and deflected redox boundaries develop around borings. Although hardgrounds and exhumed concretions are often bored and affected by authigenesis, such as pyrite impregnations; these, however, not only occur along the borings but also along the rock surface and are, therefore, not preferentially associated with the bioturbational structures (e.g., Wetzel and Allia, 2000: fig. 4).

7. Identification of ichnoliths

To recognize an ichnolith as such requires the proof that cementation occurred preferentially in or around an animal trace during early diagenesis. For ichnolith identification are, therefore, both morphological and mineralogic-petrographical criteria essential. In addition, geochemical investigations can be useful, like stable isotope analysis, to elucidate if carbonate is of diagenetic origin. 3D preservation of the original burrow morphology is an important indicator of pre-compactional cementation occurring close to the sediment-water interface prior to significant compaction (see Wetzel, 1992; Raiswell and Fisher, 2000). However, burrows can become compressed to some degree already when buried by several meters of sediment (Fig. 4B, C), so compacted horizontal burrows do not exclude ichnolith identification.

Ichnopetrification. In the field, these preferentially cemented bioturbational structures are commonly harder and more resistant to weathering or stained differently than the surrounding rock and thus, more prominent features, which are relatively easy to identify (Fig. 2). Sediment-containing tubes are usually cemented by microcrystalline phases, whereas empty or only partly filled tubes commonly contain no or coarse-crystalline authigenic cement, respectively. On fresh surfaces or in drill cores, the identification of ichnopetrifications filled with sediment requires microscopic and/or geochemical investigations to detect preferential authigenic minerals therein.

Ichnocretion. The shape of ichnocretions is modulated or even controlled by the morphology of the trace inside (Figs. 3–5). In many instances, ichnocretions exhibit morphologies distinctly differing from early-diagenetic concretions not affected by burrows, commonly displaying regular, ellipsoidal, spherical, discoidal, or lenticular shapes reflecting the (an)isotropy of permeability of the host sediment (e.g., Seilacher, 2001). Ichnocretions are typically elongate bodies pre-conditioned by the course of a burrow, oriented parallel, oblique or perpendicular to bedding, the latter two cases being particularly diagnostic (Wetzel and Bojanowski, 2022). It is essential to consider that oblique to horizontal concretions embedded in mudrock became re-oriented (less inclined) during compaction (Wetzel and Blouet, 2023: fig. 12). Since permeability of the sediment is one of first-order factors influencing concretion morphology, the diameter of ichnocretions around more-or-less vertical tubes may vary reflecting the permeability of the host sediment. A steep porosity gradient present very close to the sediment-water interface (e.g., Bennett et al., 1991) or significant differences in grain size and/or sorting causing a strong permeability variation shallow in sediment are recoded by the shapes of ichnocretions resembling carrots, beetroots, radishes etc. (Figs. 3–5; Wetzel and Bojanowski, 2022).

An elongate concretion morphology itself is not diagnostic of an ichnocretion as it might have, for instance, been grown preferentially around a long body fossil or a fluid conduit of physical origin (then forming part of a seep plumbing systems, e.g., De Boever et al., 2006; Nyman et al., 2010; Cau et al., 2015). In the first case, the concretions' interior provides already conclusive information in the field (Bojanowski and Wetzel, 2026). In the latter case, it may be difficult to unequivocally decipher the biogenic origin of a tube. It appears that in – so far underestimated cases – methane-derived tubular concretions have formed along burrows, which pre-conditioned a seep plumbing system and hence, should be considered as ichnocretions (e.g., Wiese et al., 2015; Blouet et al., 2021b). Observations by the authors at several methane seep sites revealed that especially *Thalassinoides* and *Spongeliomorpha* burrows, both commonly produced by crustaceans, have a high potential to act as conduits for methane-charged fluids. In addition, *Balanoglossites* may act in a similar way (Knaust, 2021). This can be due to two reason, (i) the burrows form open tube systems (e.g., Knaust, 2017), and (ii) their producers can dig very deep, > 3 m (e.g., Pemberton and Buckley, 1976). These burrows are identified with certainty as such if typical Y-shape branching and enlarged chambers are present (Fig. 2A; Blouet et al., 2021a). Similarly, the trace fossil *Tisoa*, easily identified by the twisted U-tube (seen as paired tubes), has been reported encased in ichnocretions formed along the U-tube serving as a fluid conduit (Fig. 3A–C; Wetzel and Blouet, 2023). However, also the inverse case has been reported that animals burrowed into a substrate, already cemented to some degree by methane-derived carbonates (Wetzel, 2013; Giunti et al., 2024). In ichnocretions, burrows solely filled with detrital, not cemented material have rarely been observed; these structures are herein referred to as tubular ichnocretions (Fig. 4B, F, G). Commonly, the sediment-filled traces having fostered authigenesis are cemented by intergranular, microcrystalline cement; they are herein referred to as ichnopetrifications. If they are not or incompletely filled with sediment, coarse-crystalline cements usually fill the voids.

An additional diagnostic feature of the bioturbational structures, apart from their morphology, is the presence of a lining (= material applied to the burrow wall by the occupant but passively accumulated material may be included, which adhered to the wall while the burrow was open (Bromley, 1996)). Compared to the surrounding sediment, the lining is usually enriched in organic matter and thus, a preferred spot for microbial activity that fosters early, rapid, and abundant mineral impregnation along the tube wall. Such mineral impregnations commonly show diffuse, gradational margins. Depending on the degree of mineralization, impregnation can be limited to the tube walls or spread away from them into both the tube and into the ichnocretion body (Fig. 5D). Moreover, such impregnations may vary from disseminated fine crystals to a massive mineralization. A good example are carbonate ichnocretions with pyrite impregnating burrow walls, as iron sulfide precipitation due to microbial degradation of organic matter via sulfate reduction is particularly intensive along mucus-lined tube wall. These impregnations form by microbially-driven precipitation of metastable phases (e.g., greigite) that subsequently become stabilized to pyrite, which often preserves an original microbial fabric displaying, for instance, a framboidal morphology. Even if not impregnated, the material directly surrounding a tube may differ in color from that further away, which creates a halo around the tube. Two main reasons of such coloration may be invoked, although others can also occur. Enriched organic matter along the tube wall related to lining is related with a darker tint (Fig. 4D), whereas enhanced oxidation around the tube that served as a conduit for oxygenated seawater causes bleaching (Fig. 5B). If no features typical of traces are evident, the identification of tubular ichnocretions becomes challenging because cement precipitated at the margin of a burrow can obliterate the morphological details of the trace in particular if cementation continued for a long time. Thus, elongate concretions require detailed microscopic and geochemical investigation to decipher their true nature.

8. Significance of ichnoliths

Early-diagenetic mineral accumulations, such as concretions, form by precipitation of authigenic minerals in soft and still not compacted sediments. The abundant early cement produces a rigid, compaction-resistant framework that prevents mechanical and chemical destruction of primary features (Wetzel, 1992; Raiswell and Fisher, 2000). Therefore, such concretions preserve environmental data enabling more reliable and detailed reconstruction of the depositional setting than the surrounding sediments. In general, cements precipitate when the pore fluid contains sufficient concentrations of dissolved ions while the local redox conditions are sufficiently reducing and oxygen-deficient. Since only an insignificant amount of minerals can be precipitated from a given volume of supersaturated fluid, dense accumulation of early cements typically observed in concretions (usually > 60%) require a significant transport of solutes towards the sites of concretion formation. If accomplished by diffusion only, this process would take thousands to ten-thousands of years (Raiswell, 1971).

Ichnoliths are a specific type of early-diagenetic concretions, which usually form in response to bioirrigation of the sediment by animals for respiration or other purposes, which enhances fluid circulation. Such increased flux of fluids into the sediment interval penetrated by burrows may foster more rapid cementation and formation of ichnoliths. Due to the early and rapid cementation, physical and biogenic sedimentary structures, fossils, organic material etc. are well and much better preserved in ichnoliths than in the surrounding deposits in which they become obliterated by post-depositional processes. Therefore, ichnoliths, in particular ichnocretions, are quite reliable archives of the depositional setting.

The association of early-diagenetic cements and trace fossils provides additional advantages. On one hand, cements store geochemical data that is of use to elucidate environmental parameters, such as pore-water source, fluid circulation pathways, source of parent solutes, and biogeochemical processes taking place within the burrows and the surrounding sediments. These parameters may influence significantly benthic activity, but are usually not recorded in clastic deposits not affected by early-diagenetic cementation. On the other hand, bioturbational structures document the ecological preferences of their producers, which sensitively react on physical properties of the sediment, hydraulic energy of the depositional setting, food availability, redox conditions etc. (e.g., Uchman and Wetzel, 2011). Ichnoliths represent an intriguing research material preserving both types of proxies, which store much more information than trace fossils and early-diagenetic cements separately.

9. Conclusions

This study provides the first comprehensive framework for describing, classifying, and interpreting early-diagenetic mineralized animal traces – herein termed ichnoliths. By introducing and defining the concepts of ichnopetrifications, ichnocretions, as well as ichnostromes and ichnosaxes, a terminology parallel to root-related structures is proposed, while highlighting fundamental differences resulting from the nature of animal behavior and associated fluid circulation and sediment-water interactions. Ichnoliths form predominantly in shallow-marine sediments, where bioturbation strongly modifies pore-water chemistry, enhances microbial activity, and increases solute fluxes, all of which promote localized authigenesis in and around animal traces. Therefore, ichnoliths not only resist compaction and preserve the primary morphology of burrows, but also record geochemical signatures of early diagenetic processes during or shortly after bioturbation. Consequently, ichnoliths are invaluable archives for reconstructing past benthic behavior, sedimentary environments, and the biogeochemical conditions prevailing at or shallow below the sediment-water interface. Combining ichnological, petrographic, and geochemical methods offers a much more reliable and rich source of information about the previous environment than in the case of non-cemented, deformed bioturbational structures. Thus, ichnoliths deserve recognition as a distinct category of early-diagenetic rock features and should receive increased attention in future multiproxy studies aiming to unravel the complexity of ancient depositional systems.

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References

Bennett, R.H., O'Brien, N.R. and Hulbert, M.H., 1991. Determinants of clay and shale microfabric signatures: process and mechanisms. *In* Bennet, R.H., O'Brien, N.R., Hulbert, M.H. (eds.). Microstructure of Fine-Grained Sediments. Springer, Berlin, Heidelberg, New York, pp. 5–32.

Bernardini, S., Abbassi, A., Cipollari, P., Della Ventura, G., Saiz-Jimenez, C., Mugnaioli, E., Jovane, L., Sodo, A., Bellatreccia, F., Zaghloul, M.N., Cosentino, D., 2025. The *Tubotomaculum* enigma and the rise of benthic life during the opening of the Western Mediterranean Basin. Geobiology 23, article e70031. https://doi.org/10.1111/gbi.70031

Berner, R.A., 1985. Sulphate reduction, organic matter decomposition and pyrite formation. Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences, 315, 25–38.

Blouet, J.-P., Imbert, P., Ho, S., Wetzel, A., Foubert, A., 2021a. What makes seep carbonates ignore self-sealing and grow vertically: the role of burrowing decapod crustaceans. Solid Earth, 12, 2439–2466. https://doi.org/10.5194/se-12-2439-2021

Blouet, J.P., Wetzel, A., Ho, S., 2021b. Fluid conduits formed along burrows of giant bivalves at a cold seep site, Southern Taiwan. Marine and Petroleum Geology, 131, article 105123.

Bojanowski, M.J., Jaroszewicz, E., Košir, A., Łoziński, M., Marynowski, L., Wysocka, A., Derkowski, A., 2016. Root-related rhodochrosite and concretionary siderite formation in oxygen-deficient conditions induced by a ground-water table rise. Sedimentology, 63, 523–551.

Bojanowski, M.J., Wetzel, A., 2026. Sequestrichnial activity of endobenthic animals stowing food in anoxic sediments fostering growth of "gumiklyjza" concretions (Book Cliffs, Utah). Palaeogeography, Palaeoclimatology, Palaeoecology, in review.

Bromley, R.G., 1990. Trace Fossils: Biology and Taphonomy. Special Topics in Palaeontology, 3. London, Unwin Hyman, 280 p.

Bromley, R.G., 1996. Trace Fossils: Biology, Taphonomy and Applications. 2nd ed. London, Chapman and Hall, 361 p. https://doi.org/10.4324/9780203059890/

Burdige, D.J., 2007. Preservation of organic matter in marine sediments: controls, mechanisms, and an imbalance in sediment organic carbon budgets. Chemical Reviews, 107, 467–485.

Cau, S., Franchi, F., Roveri, M., and Taviani, M., 2015. The Pliocene-age Stirone river hydrocarbon chemoherm complex (northern Apennines, Italy). Marine and Petroleum Geology, 66, 582–595.

Chien, C.-W., Huang, C.-Y., Lee, H.-C., Yang, K.-M., 2013. Patterns and sizes of authigenic carbonate formation in the Pliocene foreland in southwestern Taiwan: implications of an ancient methane seep. Terrestrial, Atmospheric and Oceanic Sciences, 24, 971–984.

Craig, J.A., Davies, N.S., McMahon, N.S., 2026. An atlas of ancient vegetation-induced sedimentary structures (VISS): Their biogeomorphological, sedimentological and evolutionary significance. Earth-Science Reviews, 272, article 105326.

Curtis, C.D., Coleman, M.L., 1986. Controls on the precipitation of early diagenetic calcite, dolomite, and siderite concretions in complex depositional sequences. *In* Gautier, D.L. (ed.), Relationships of Organic Matter and Mineral Diagenesis. SEPM Special Publication, 38, 23–33.

De Boever, E., Swennen, R., and Dimitrov, L., 2006). Lower Eocene carbonate cemented chimneys (Varna, NE Bulgaria): Formation mechanisms and the (a) biological mediation of chimney growth? Sedimentary Geology, 185, 159–173.

Duck, R.W., 1995. Subaqueous shrinkage cracks and early sediment fabrics preserved in Pleistocene calcareous concretions. Journal of the Geological Society, 152, 151–156. https://doi.org/https://doi.org/10.1144/gsjgs.152.1.0151

Forster, S., Graf, G., 1995. Impact of irrigation on oxygen flux into the sediment: intermittent pumping by *Callianassa subterranea* and "piston-pumping" by *Lanice conchilega*. Marine Biology Research, 123, 335–346. https://doi.org/10.1007/BF00353625

Froelich P. N., Klinkhammer G. P. , Bender M. L., Luedtke N. A., Heath G. R., Cullen D., Dauphin P. , Hammond D., Hartman B., Maynard V., 1979. Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: suboxic diagenesis. Geochimica and Cosmochimica Acta, 43, 1075–1090.

Giunti, S., Gedl, P., Kędzior, A., Marynowski, L., Paszkowski, M., Wetzel, A., Bojanowski, M.J., 2024. Hydrocarbon-derived thrombolites from the Outer Carpathians (Lower Cretaceous, Poland). Sedimentology, 71, 2183–2209.

Haldimann, K., 2012. Fossile Wohnröhren. Schweizer Strahler, 2012, 39–40.

Hesselbo, S.P., Palmer, T.J., 1992. Reworked early diagenetic concretions and the bioerosional origin of a regional discontinuity within British Jurassic marine mudstones. Sedimentology, 39, 1045–1065.

Kaminski, M.A., Wetzel, A., 2004. A tubular protozoan predator: A burrow selectively filled with tubular agglutinated protozoans (Xenophyophorea, Foraminifera) in the abyssal South China Sea. *In* Bubik, M., Kaminski, M.A. (eds.), Proceedings of the Sixth International Workshop on Agglutinated Foraminifera, London, pp. 277–283.

Klappa, C.F., 1980. Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. Sedimentology, 27, 613–629.

Knaust, D., 2017. Atlas of Trace Fossils in Well Core. Springer, Cham. 209 p. https://doi.org/10.1007/978-3-319-49837-9

Knaust, D., 2021. *Balanoglossites*-burrowed firmgrounds – The most common ichnofabric on earth? Earth-Science Reviews 220, article 103747. https://doi.org/10.1016/j.earscirev.2021.103747

Lloyd, S.J., Sample, J., Tripati, R.E., Defliese, W.F., Brooks, K., HJovland, M., Torres, M., Malow, J., Hancock, L.G., Martin, R., Lyons, T., Tripati, A.E., 2016. Methane seep carbonates yield clumped isotope signatures out of equilibrium with formation temperatures. Nature Communications, 7, article 12274.

Meister, P., Gutjahr, M., Frank, M., Bernasconi, S.M., Vasconcelos, C., McKenzie, J.A., 2011. Dolomite formation within the methanogenic zone induced by tectonically driven fluids in the Peru accretionary prism. Geology, 39, 563–566.

Nyman, S.L., Nelson, C.S., and Campbell, K.A., 2010. Miocene tubular concretions in East Coast Basin, New Zealand: analogue for the subsurface plumbing of cold seeps. Marine Geology, 272, 319–336.

Pemberton, G.S., Buckley, D.E., 1976. Supershrimp: Deep bioturbation in the Strait of Canso, Nova Scotia. Science, 192, 790–791. https://doi.org/10.1126/science.192.4241.790

Raiswell R., 1971. The growth of Cambrian and Liassic concretions. Sedimentology, 17, 147–171.

Raiswell, R., Fisher, J., 2000. Mudrock-hosted carbonate concretions: a review of growth mechanisms and their influence on chemical and isotopic composition. Journal of the Geological Society, 157, 239–251.

Seilacher, A., 2001. Concretion morphologies reflecting diagenetic and epigenetic pathways. Sedimentary Geology, 143, 41–57.

Schulz, H.D., 2006. Quantification of early diagenesis: Dissolved constituents in pore water and signals in the solid phase. *In* Schulz, H.D., Zabel, M. (eds.), Marine Geochemistry, 2nd ed. Springer, Berlin, Heidelberg, New York, pp. 73–124. https://doi.org/10.1007/3-540-32144-6_3

Spadło, A., Sawłowicz, Z., Uchman, A., 2025. Mineralogy and geochemistry of some trace fossils filled or lined with fecal pellets from the Cenozoic of the Northern Apennines and the Tunisian Atlas. Marine and Petroleum Geology, 181, article 107433. https://doi.org/10.1016/j.marpetgeo.2025.107433

Uchman, A., Wetzel, A., 2011. Deep-sea ichnology: The relationships between depositional environment and endobenthic organisms. *In* Hüneke, H., Mulder, T. (eds.), Deep-Sea Sediments. Developments in Sedimentology, 60. Elsevier, Amsterdam, pp. 517–556. https://doi.org/10.1016/S0070-4571(11)63008-2

Uchman, A., Wetzel, A., 2016. Sequestrichnia – a new ethological category of trace fossils in oligotrophic deep-sea environments. *In* Baucon, A., Neto de Carvalho, C., Rodrigues, J. (eds.), Ichnia 2016 – Abstract Book. UNESCO Geopark Naturejo, International Ichnological Association, Castelo Branco, p. 190.

Uchman, A., Wetzel, A., 2024. Sequestrichnia – a new ethological category of marine trace fossils recording collecting and stowing nutritional material within burrows. Comptes Rendus Palevol, 23, 325–338.

Vogel, S., 1994. Life in Moving Fluids. The Physical Biology of Flow, 2nd ed. Princeton University Press, Princeton. 467 p. https://doi.org/10.2307/j.ctvzsmfc6

Wallmann, K., Aloisi, G., Haeckel, M., Tishchenko, P., Pavlova, G., Greinert, J., Kutterolf, S., Eisenhauer, A., 2008. Silicate weathering in anoxic marine sediments. Geochimica and Cosmochimica Acta, 72, 3067–3090.

Wetzel, A., 1981. Ökologische und stratigraphische Bedeutung biogener Gefüge in quartären Sedimenten am NW-afrikanischen Kontinentalrand. "Meteor" Forschungs-Ergebnisse, Reihe C, 34, 1–47.

Wetzel, A., 1992. An apparent concretionary paradox. Zentralblatt für Geologie und Paläontologie. Teil 1, Allgemeine, Angewandte, Regionale und Historische Geologie, 1991, 2823–2830.

Wetzel, A., 2008. Recent bioturbation in the deep South China Sea: A uniformitarian ichnologic approach. Palaios, 23, 601–615. https://doi.org/10.2110/palo.2007.p07-096r

Wetzel, A., 2013. Formation of methane-related authigenic carbonates within the bioturbated zone – an example from the upwelling area off Vietnam. Palaeogeography, Palaeoclimatology, Palaeoecology, 386, 23–33.

Wetzel, A., Allia, V., 2000. The significance of hiatus beds in shallow-water mudstones: an example from the Middle Jurassic of Switzerland. Journal of Sedimentary Research, 70, 170–180. https://doi.org/10.1306/2DC40908-0E47-11D7-8643000102C1865D

Wetzel, A., Blouet, J.P., 2023. The trace fossil *Tisoa siphonalis* in its type area – characteristics and environmental significance. Palaios, 38, 76–97.

Wetzel, A., Bojanowski, M.J., 2022. Radish concretions grown in mud during compaction. Sedimentology, 69, 750–774.

Wetzel, A., Bojanowski, M., 2025. 'Resurrected' concretions – resumed cementation after exhumation, transport, re-deposition and exploitation by producers of the trace fossil *Chondrites* when still being soft. Marine and Petroleum Geology, 182, article 107576.

Wetzel, A., Unverricht, D., 2013. A muddy megaturbidite in the deep central South China Sea deposited ~350 yrs BP. Marine Geology, 346, 91–100. https://doi.org/10.1016/j.margeo.2013.08.010

Wiese, F., Kiel, S., Pack, A., Walliser, E.O., Agirrezabala, L.M., 2015. The beast burrowed, the fluid followed – crustacean burrows as methane conduits. Marine and Petroleum Geology, 66, 631–640.

Figure captions

Fig. 1. Schematic diagram illustrating the general structure of two main ichnolith types. An ichnopetrification is composed of a cemented tube (Zone 1), which may additionally be associated with a cemented lining. An ichnocretion comprises a cemented sediment around the tube as either authigenic mineral impregnation at the margin of the tube (Zone 2) or concretionary body around the tube (Zone 3). Note that the original morphology of the burrow tends to be preserved in ichnopetrifications, whereas it is commonly obscured in ichnocretions.

Fig. 2. Ichnopetrifications with well-preserved burrow morphology. All scale bars 1 cm. (**A**) Carbonate-cemented *Thalassinoides* slightly inclined to bedding (white broken lines) with the typical widening at the T-shape junction (yellow lines); the darker material in the lumen represents a passive fill surrounded by a lighter mantle, both carbonate-cemented (Marnes Bleues Fm., Aptian–Albian, Vocontian Basin, Gigors, France). (**B**) Siderite-cemented *Alcyonidiopsis* with a distinctive pellet lining; beach pebble from the Essaouira coast (Morocco) reworked from Oligo-Miocene rocks forming a cliff (see also Bernardini et al., 2025; Spadło et al., 2025). (**C**) Siderite-cemented *Ophiomorpha*; note

the small concretionary segment on the lining, which makes the specimen an intermediate element between ichnopetrification and ichnocretion. Beach pebble from Katharinenhof (isle of Fehmarn, Baltic Sea, Germany), reworked from submarine-outcropping Eocene Tarass Fm. (**D**) Siderite-cemented *Tasselia* composed of a central tube, feeding chamber, and outer burrow fill (Marina di Montechiaro, Pliocene, Sicily; see Haldimann, 2012).

Fig. 3. Carbonate-cemented ichnocretions with *Tisoa siphonalis*. (**A**) Large, radish-shaped ichnocretion (red dashed line), 100 cm high and < 70 cm wide; insert shows the double tube of *Tisoa siphonalis* (encircled) on a horizontal split surface (Fontaneilles section, Rivière-sûr-Tarn, Villeneuve Fm., Pliensbachian, Vocontian Basin, SE France). (**B**) Carrot-shape ichnocretion with the 2 *Tisoa* tubes extending above and below the ichnocretion (abandoned clay pit at La Glande, north of Lyon). (**C**) Two carrot-shaped ichnocretions from La Glande (left) and Fontaneilles (right). (**D**) Transverse (horizontal) split surface of an ichnocretion showing double tube of *Tisoa siphonalis*, Fontaneilles.

Fig. 4. Ichnocretions of various sizes and shapes. (**A**) Horizontal carbonate ichnocretion with curving *Thalassinoides* (dashed line). Note that the shape of the ichnocretion follows strictly the course of the burrow located in the center (Chiahsien section, Yenshuikeng Shale, Pliocene, Taiwan; for details see Chien et al., 2013). (**B, C**) Vertical sections through two horizontal carbonate ichnocretion with slightly compressed *Thalassinoides* tubes. Note, tube in (B) is filled with mud and represents a tubular ichnocretion, whereas tube in (C) has a cemented lumen enveloped by a muddy veneer (arrow) surrounded by a cemented mantle; (B) from the same locality as (A), (C) from Shicheng section, Pliocene Yenshuikeng Shale, (near Chiasien, Taiwan). In both sections, horizontal ichnocretions contain mostly not compressed *Thalassinoides* burrows indicating early-diagenetic cementation in otherwise compacted sediments. (**D**) Iron-oolite ichnocretion with *Skolithos* – entire specimen on the left and vertical section on the right; the darker tube

margin represents lining. Note that the tube is also iron-cemented. Minette open pit mine Lallingerbierg (abandoned) near Esch/Alzette (Luxembourg). (**E**) Roughly vertical broken surface of a silica-cemented ichnocretion with *Teichichnus*. Chert pebble from the beach at Hohenhain (northeast of Kiel, Germany), reworked from Weichselian moraine containing Cretaceous material eroded in Denmark or southern Sweden. (**F**) Tubular carbonate ichnocretion with *Thalassinoides* tube solely filled with white spar. (**G**) Tubular silica ichnocretion with *Thalassinoides* open tube originally filled with chalk (Cliff on Rügen Island, Germany). Scale bars in B–G are 1 cm long.

Fig. 5. Carbonate ichnocretions from the Middle Jurassic, Częstochowa region, Poland (**A–D**) and from the Naredi Fm., Eocene, Kutch Basin, W India (**E**). All scale bars 1 cm. (**A**) Vertical section through beetroot-shaped specimen with pyrite impregnation along the tube. (**B**) Horizontal section showing pyrite burrow infill (Zone 1) and impregnation (Zone 2) at the border between the tube and the surrounding ichnocretion body (Zone 3). Note the bleached halo around the impregnation. (**C**) *Chondrites* tubes dispersed in the ichnocretion body; their distribution is not related to the shape of the ichnocretion suggesting that calcite precipitation was not associated with *Chondrites* but with the central burrow (arrows). Note septarian cracks cutting through all traces and their infills. Yellow circles denote spots sampled for stable isotope analysis; low $\delta^{13}C$ values (-28 to -21‰) indicate early-diagenetic origin of carbonate cement. (**D**) Vertical section showing the central tube and associated with pyrite impregnation. The tube is also filled with reddish calcite spar (arrow), which indicates that the tube was void at least in a significant part. (**E**) Ichnocretion composed of silica-cemented burrow (Zone 1) and carbonate concretion body (Zone 3). Note, the carbonate concretion body enveloping the tube infill not completely results in a ‘hot-dog’-like morphology of the ichnocretion.

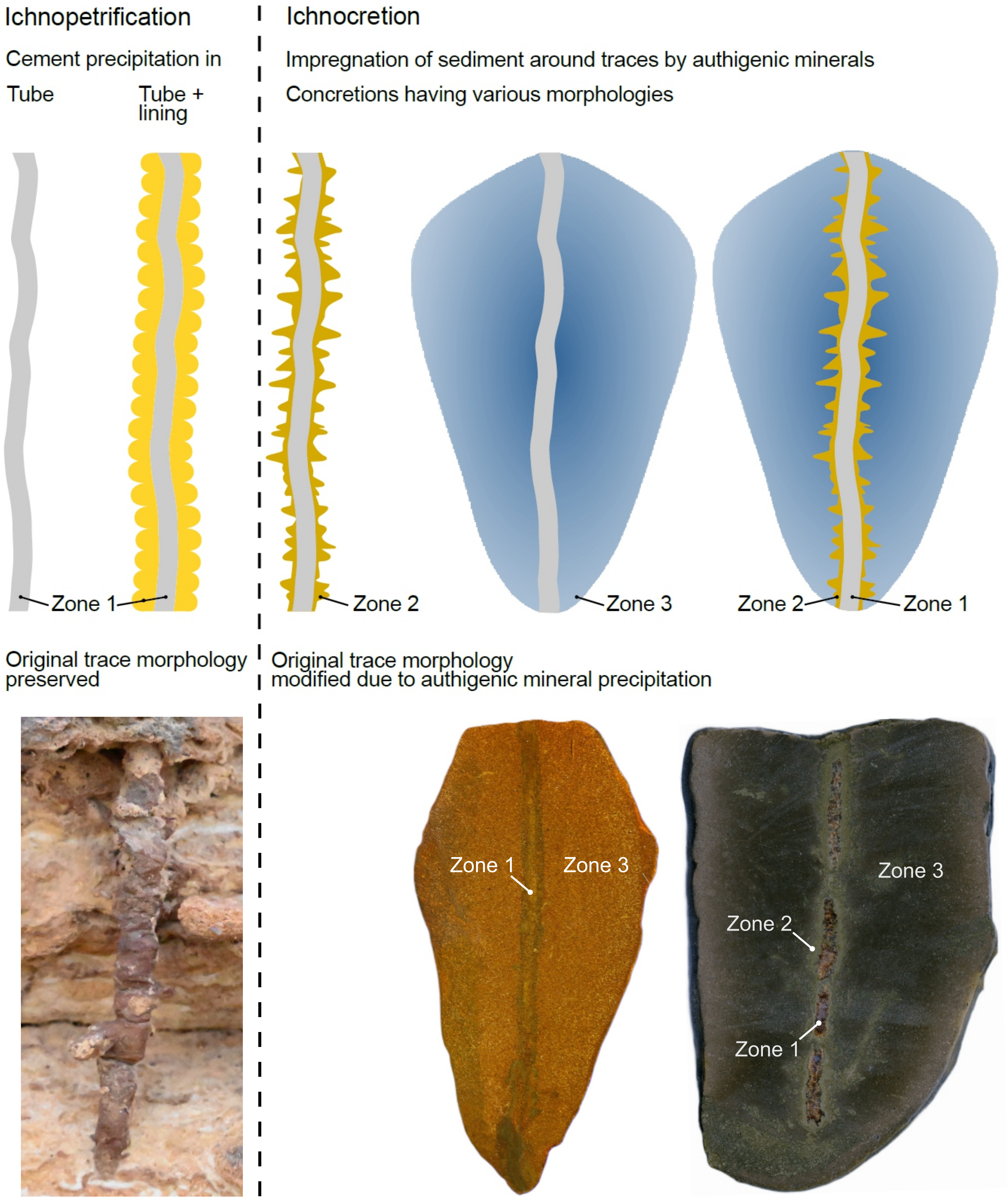
Fig. 6. Potential equivalents to “rhizolite” *sensu* Klappa (1980) for a “root rock”. (**A, B**) Carbonate ichnostrome from the Outer Carpathians, Oligocene, Skrzydlna quarry, S Poland. (**A**) Lower surface of a bed with distinctive conical protrusions having small tubes in their axial parts. (**B**) Vertical section of an ichnostrome (basal part) showing that the protrusions (on the lower surface) developed preferentially around burrows – small tubes partly filled with white calcite spar (some indicated with arrows). Early-diagenetic origin of carbonate cement in this rock is recorded by very low δ^{13}C values c. -21‰. (**C, D**) Carbonate ichnosax from the Basque-Cantabrian Basin (Kardala section, Albian, N Spain). (**C**) Irregular block with complex internal structure. (**D**) Closeup of the ichnosax showing that it is composed of numerous, variously oriented carbonate tubular ichnocretions (yellowish) developed around *Thalassinoides* burrows (some indicated with arrows).

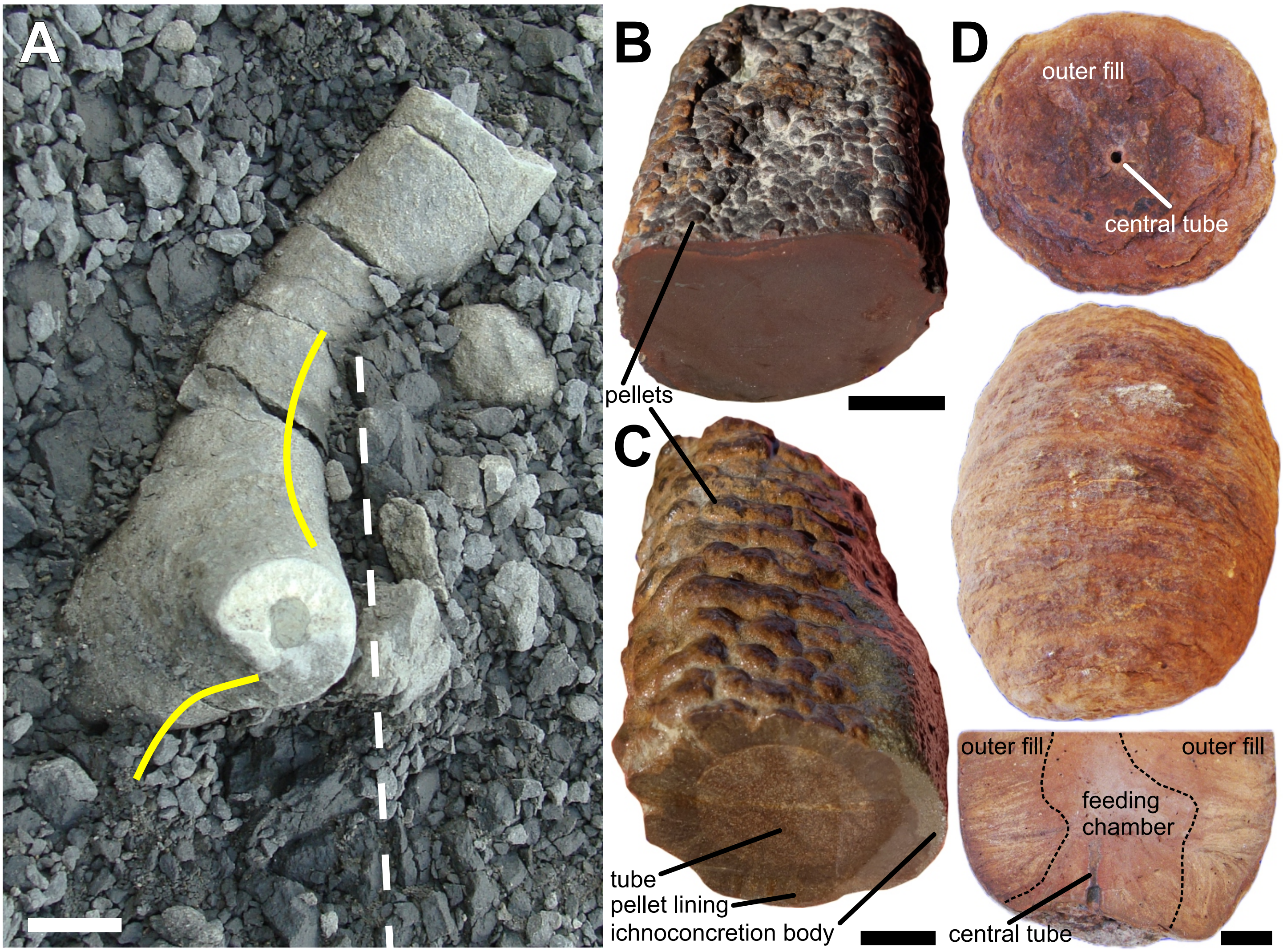
Fig. 7. Geochemical zonation in marine sediments (compiled from Froelich et al., 1979 and Schulz, 2006; simplified). s* – suboxic, RPD – redox potential discontinuity. Ichnoliths are preferentially formed in the anoxic/anaerobic zone (for details see text).

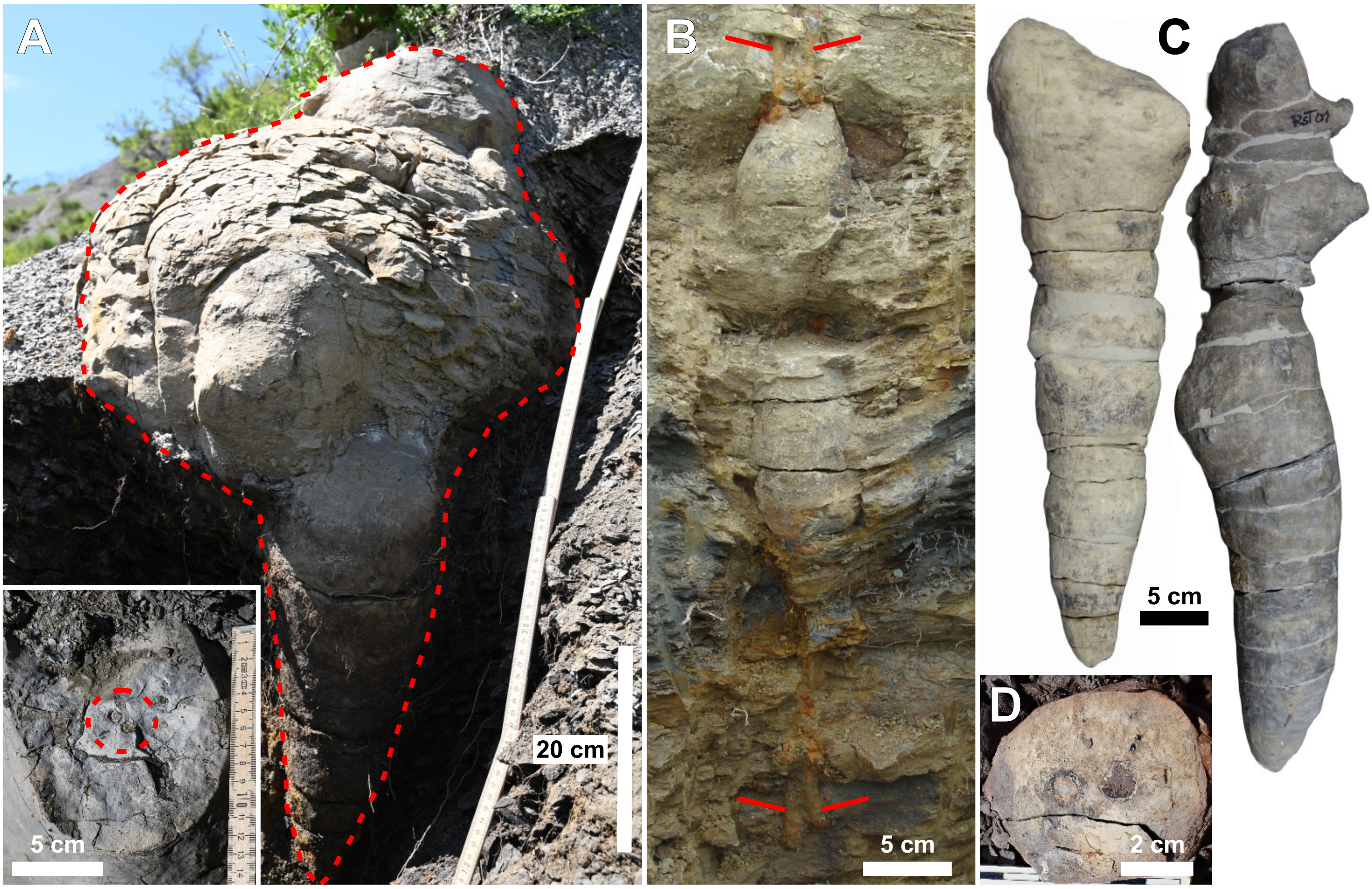
Fig. 8. Sediment-filled, not cemented burrows causing a negative relief on the surface of early-diagenetic carbonate rocks. (**A**) Bulbous morphology of a lower surface of seep carbonate (gray) with sand-filled burrows (brownish), Ubidepea section, Basque-Cantabrian Basin, Albian, N Spain. (**B**) Closeup of the bed in (A) showing that the burrows are not cemented and are associated with depressions in the seep carbonate (gray). (**C**) Carbonate “gumiklyjza” concretion (see Bojanowski and Wetzel, 2026) with a depression formed along a sequestrichnia tube. Western Interior Seaway, Turonian, Tununk Shale Mb., Mancos Shale Fm., San Rafael Swell, Utah, USA.

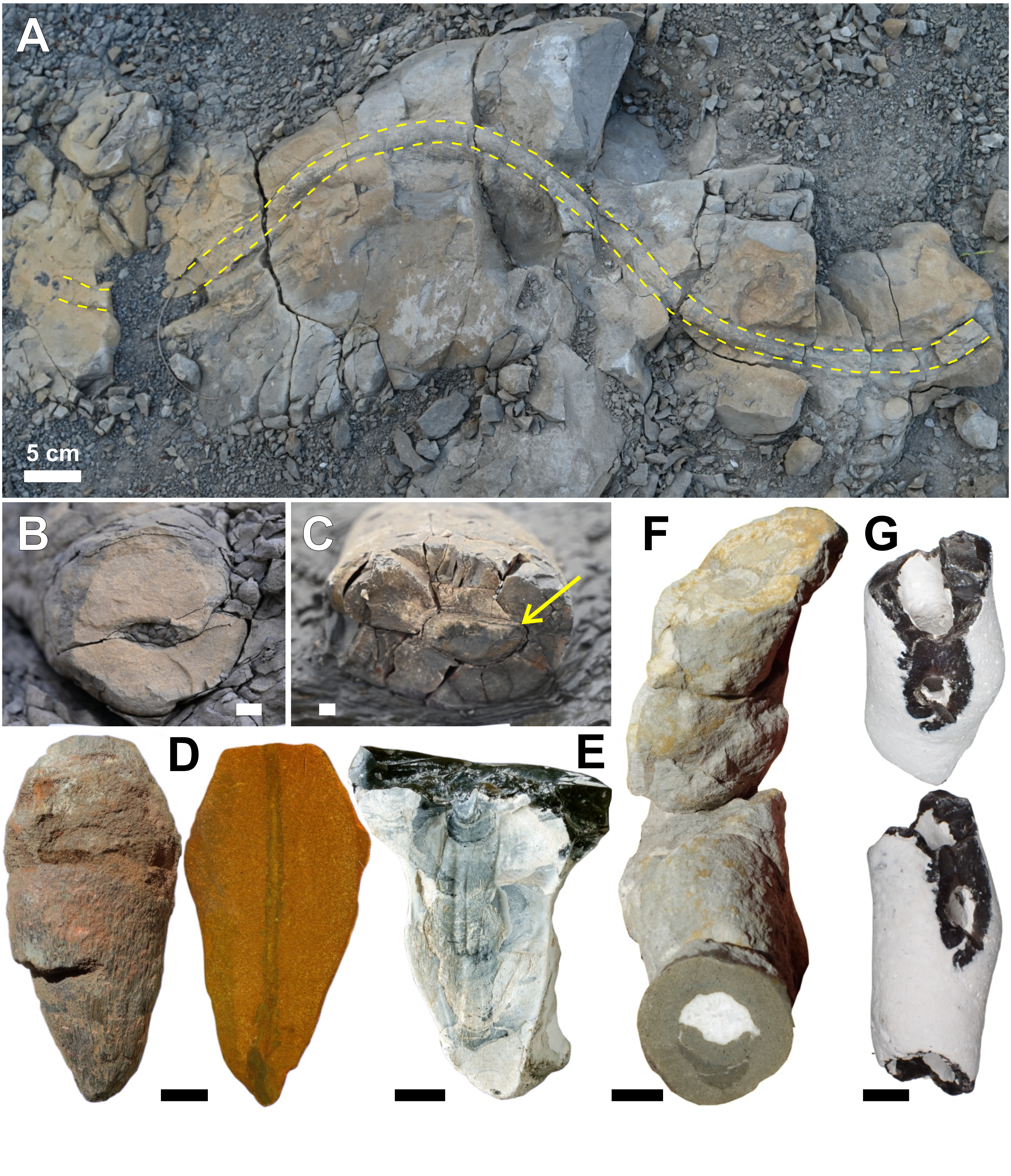
Table 1. Rhizolites and their possible equivalents in the animal-trace record – a critical evaluation

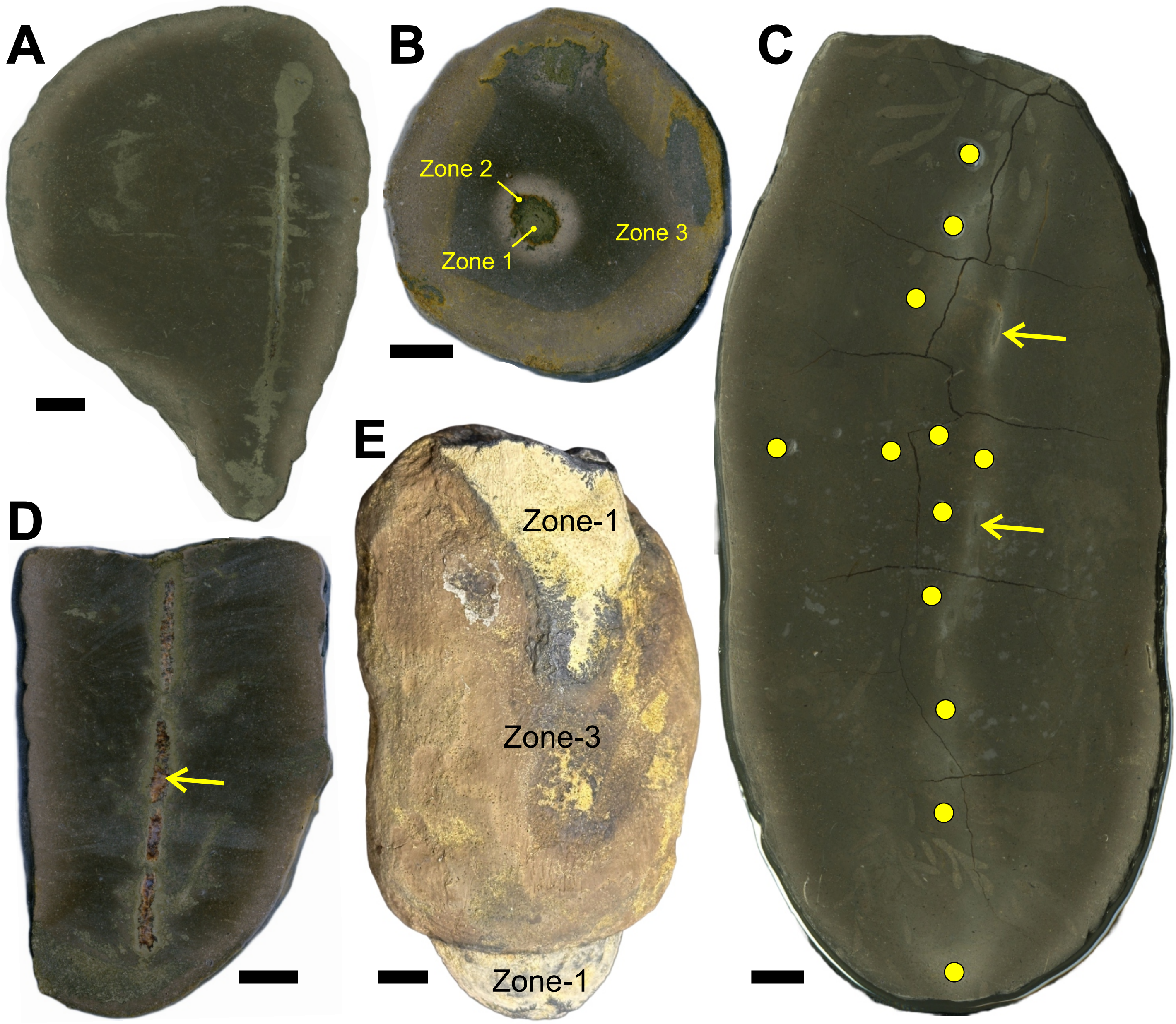
Rhizoliths (Klappa, 1980, except 7.)	**Ichnoliths (this work)**
1. Root moulds [root material decayed]	No evident equivalents in the animal-trace record *Questionable equivalents: empty tubes entrenched into stiff, firm or hard substrate*
2. Root casts [root moulds cast by sediment or cement]	No evident equivalents in the animal-trace record *Questionable equivalents: empty tubes entrenched into stiff, firm or hard substrate later filled by sediment or cement*
3. Root tubules [cylinders cemented around root]	Tubular ichnocretions [cylinders cemented around animal traces] *Questionable equivalents: mucus lining or wall structures that are actively segregated or constructed by the animals (see 7.)*
4. Rhizocretions [pedodiagenetic mineral accumulations around root moulds]	Ichnocretions [early-diagenetic mineral accumulations around animal traces] *So far, ichnocretions have only been observed in marine deposits*
5. Root petrifactions [mineral impregnations or replacements of <root> organic matter]	Ichnopetrifications [early-diagenetic mineral accumulation of animal traces] *Actively or passively filled burrows should be grouped into this category only if cemented during early diagenesis (see 2.)*
6. There are no equivalents in the root-trace record. Roots cannot sort sediment or select particles and form pellets	Trace fossils with actively constructed wall structure consisting of reworked material around a lined tube like *Tasselia* or mud pellets reinforcing *Ophiomorpha* tubes. *Such structures have a high potential to become cemented during early diagenesis and thus be termed ichnoliths, because the wall material is glued by mucus.*

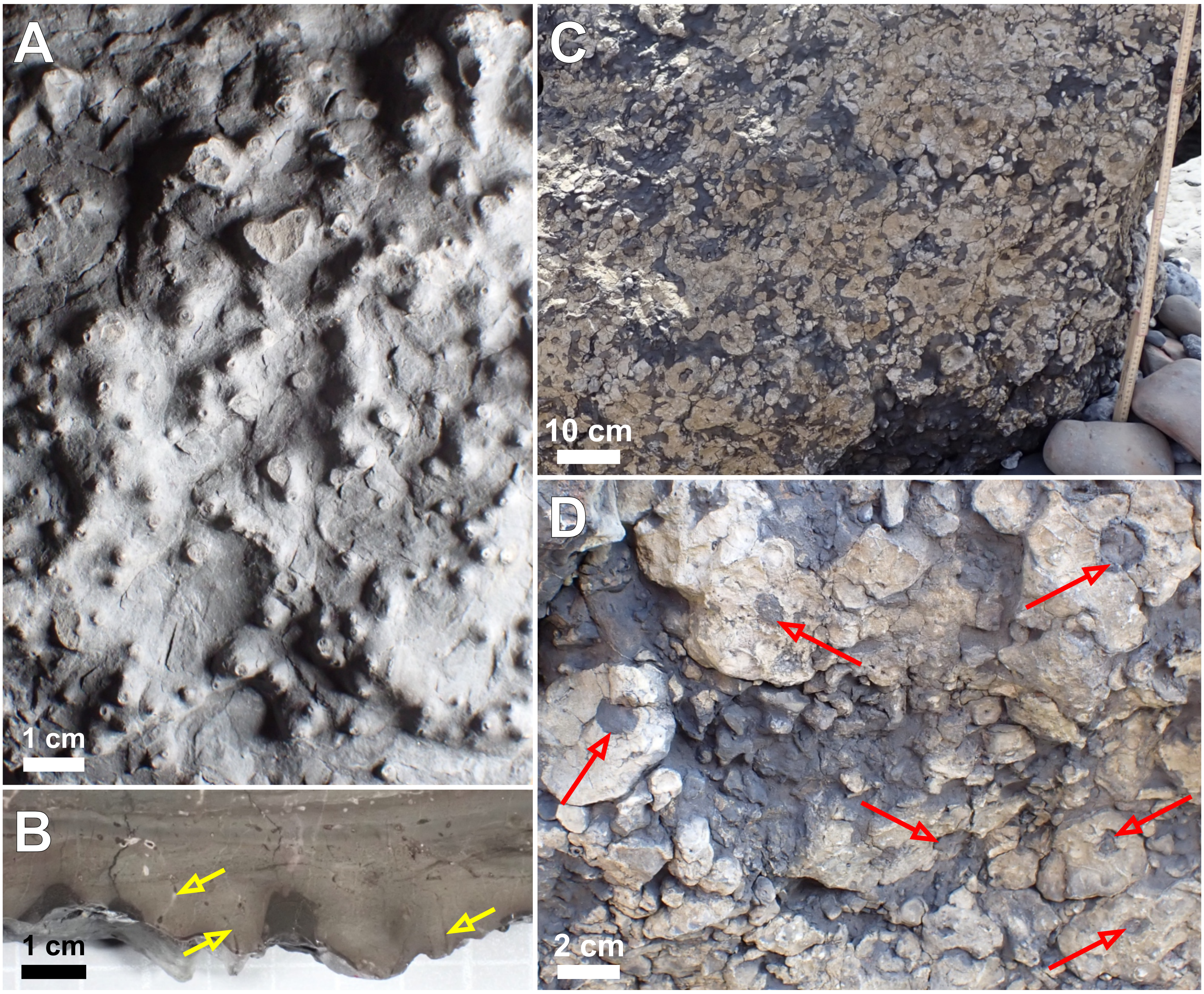

Ichnopetrification
Cement precipitation in
Tube
Tube + lining
Zone 1
Original trace morphology preserved
Ichnocretion
Impregnation of sediment around traces by authigenic minerals
Concretions having various morphologies
Zone 2
Zone 3
Zone 2
Zone 1
Original trace morphology modified due to authigenic mineral precipitation
Zone 1
Zone 3
Zone 3
Zone 2
Zone 1

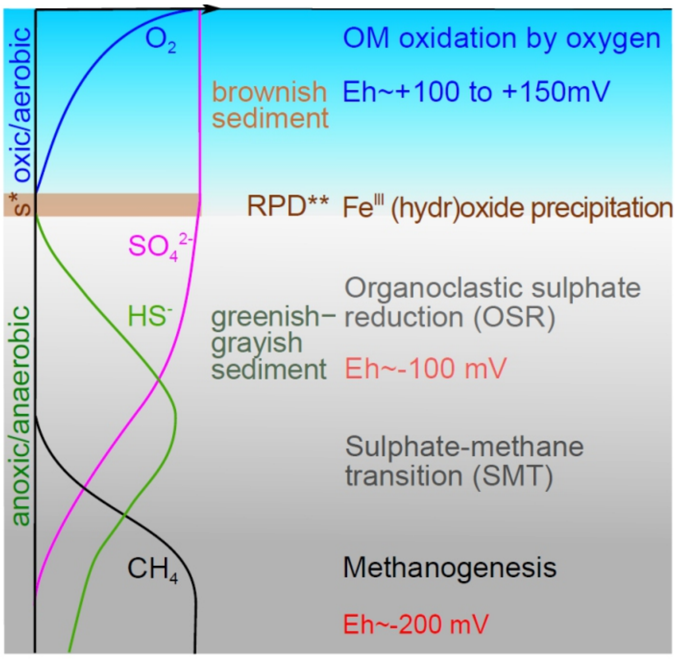

A
B
C
D
pellets
outer fill
central tube
tube
pellet lining
ichnoconcretion body
outer fill
outer fill
feeding
chamber
central tube


A
20 cm
5 cm
B
5 cm
C
5 cm
D
2 cm

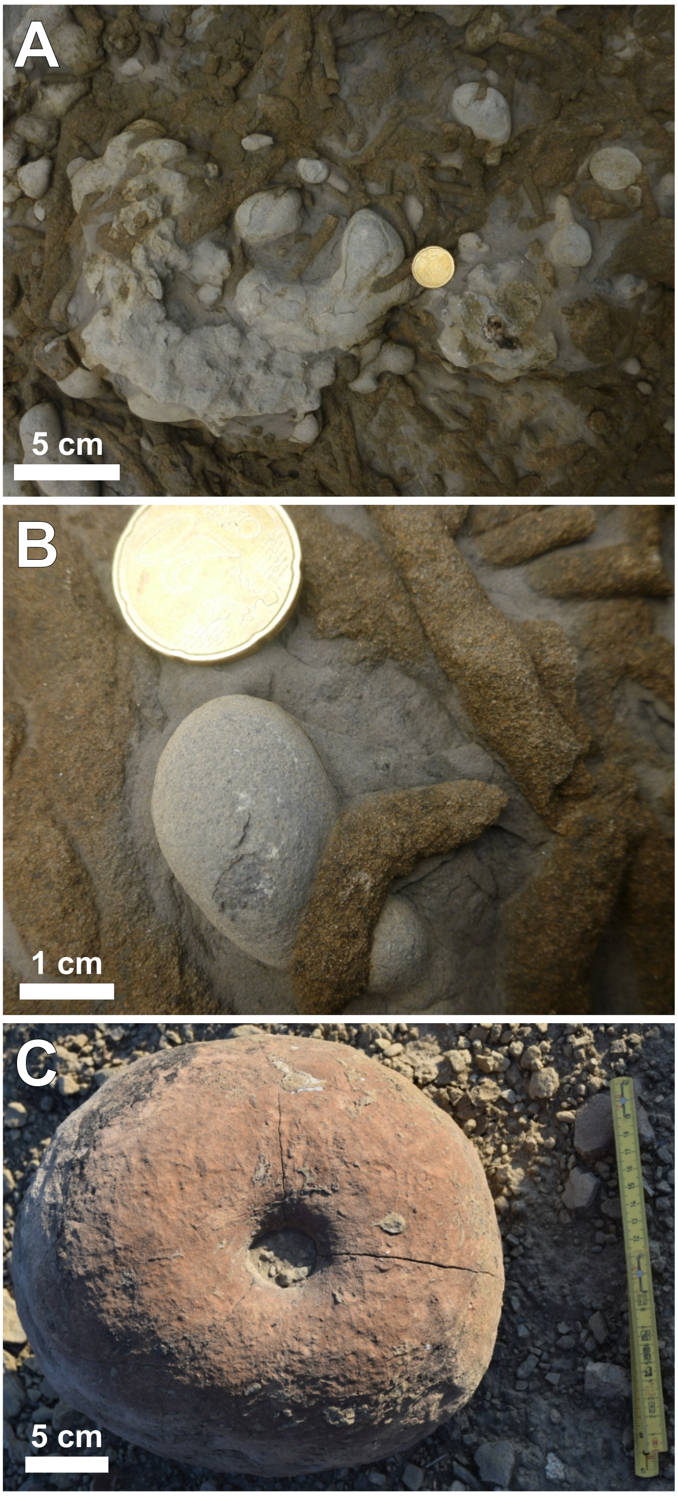

A
5 cm
B
C
D
E
F
G


A
B
C
D
E
Zone 2
Zone 1
Zone 3
Zone-1
Zone-3
Zone-1


A
1 cm
B
1 cm
C
10 cm
D
2 cm



oxic/aerobic
s*
anoxic/anaerobic
O2
SO4 2-
HS-
CH4
brownish
sediment
RPD**
greenish–
grayish
sediment
OM oxidation by oxygen
Eh~+100 to +150mV
Fe III (hydr)oxide precipitation
Organoclastic sulphate
reduction (OSR)
Eh~-100 mV
Sulphate-methane
transition (SMT)
Methanogenesis
Eh~-200 mV


A
5 cm
B
1 cm
C
5 cm