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Borings and etchings in the Upper Bathonian-Lower Callovian oolite of the Paris Basin (France)

Bruno GRANIER [1]

Abstract: The oolite of the "Dalle Nacrée" Formation in the Paris Basin is made of marine calcareous ooids with, from base to top, radial (and therefore likely to have been calcite), concentric and micritic fabrics, each corresponding to a discrete stratigraphic unit. Several hardgrounds and oolitic pebble-cobble layers in the succession are encrusted and bored. Three main types of boring have been identified ranging in sizes from some tens of µm (sponge borings) to centimeters (bivalve borings), with an intermediate category (worm borings). Some worm borings have rough walls, where early marine fibrous cement is less corroded than the cortices of cemented ooids. The key to understanding this differential dissolution could be related to organic matter, present within the ooid cortices but lacking in the fibrous cement. Polychaete worms that use chemical means (enzymes or acids) to bore are probably responsible for these peculiar borings. A secondary conclusion is that partly or fully leached ooid cortices do not necessarily indicate an original aragonitic mineralogy of the dissolved parts.

Key Words: Calcareous ooids; oolite; dissolution; borings; polychaete; aragonite; calcite; organic matter.

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Résumé : ***Perforations et corrosion dans l'oolithe du Bathonien supérieur - Callovien inférieur du Bassin de Paris (France).-*** L'oolite de la Formation de la "Dalle Nacrée" du bassin de Paris est constituée d'ooïdes calcaires marins avec, de bas en haut, des textures radiaire (et par conséquent vraisemblablement calcitiques à l'origine), concentrique et micritique, correspondant chacune à une unité stratigraphique distincte. Plusieurs fonds durcis et niveaux à graviers et galets oolithiques observés dans la succession sont encroûtés et perforés. Les trois principaux types de perforation identifiés ont des dimensions allant de quelques dizaines de micromètres (perforations d'éponges) à quelques centimètres (perforations de pélécypodes), avec une catégorie intermédiaire (perforations de vers). Quelques perforations de vers ont des parois présentant des aspérités, là où le ciment précoce marin est moins corrodé que les cortex des ooïdes qu'il cimente. La clef pour comprendre cette dissolution différentielle pourrait être liée à la matière organique, présente dans les cortex oolithiques mais absente du ciment fibreux. Les vers polychètes qui utilisent des moyens chimiques (enzymes ou acides) pour perforer sont probablement responsables de ces perforations singulières. Une seconde conclusion est que la dissolution partielle ou complète de cortex oolithiques n'implique pas nécessairement qu'à l'origine ces parties dissoutes étaient aragonitiques.

Mots-clefs : Ooïdes calcaires ; oolithe ; dissolution ; perforation ; polychète ; calcite ; aragonite ; matière organique.

I - Introduction

Calcareous ooids are coated grains diverse in texture ("radial, concentric, micritic" *sensu* GRANIER, 1994a, et seq.), shape (superficial, cerebroid, eccentric, "broken" and regenerated, shrunken), polymorph mineralogy (aragonite, --high- and low-Mg -- calcite, and both), size (although by definition they should not exceed 2 mm in diameter), and as such they form one of the most fascinating category of calcareous grains. By definition, an oolitic sand is an unconsolidated sediment made of loose ooids and an oolite is a rock dominantly made of cemented ooids. Early submarine cementation, consisting commonly of isopachous fibrous cements and taking place toward the top of oolitic sand-bodies, leads to the formation of hardgrounds and lithoclasts (cobbles and pebbles) derived from the reworking of these cemented layers.

For some years, the author (GRANIER, 1994a, 1994b, 1994c, 1994d, 1995a; GRANIER & STAFFELBACH, 2009) --and his colleagues in TOTAL – Compagnie Française des Pétroles-- have investigated oolitic reservoirs of the "Dalle Nacrée" Formation, also known as "Pierre de Dijon-Corton" (for its lower part) and "Pierre de Ladoix" (for its upper part), latest Bathonian to Early Callovian in age, from oil exploration wells of the Paris Basin, as well as their outcrop analogues in Burgundy.

One purpose of this short paper is to document the borings observed in the "Dalle Nacrée" and to highlight an unusual morphology observed on the inner surface of some borings. This study is also part of a much broader project dealing with the ooids and their complex nature.

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[1] *Department of Ecology and Evolutionary Biology, The University of Kansas, 1200 Sunnyside Avenue, Lawrence, Kansas 66045 (USA)*
bgranier@ku.edu

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II - Material and methods

Though there are multiple hardgrounds and cobble layers in each quarry of Burgundy and in each cored well of the Paris Basin (GRANIER, 1994c, 1994d, 1995a; GRANIER & STAFFELBACH, 2009), only a limited set of figures are included in this paper. As in earlier publications, to maintain confidentiality the names of the wells and the sampling depths are not given. Intraclastic oolitic pebbles and cobbles as well as oolitic hardgrounds were selected for oriented petrographic thin-sections, usually circa 30 µm thick, including some stained with Alizarin Red S to discriminate between dolomite and calcite.

III - The ooids of the "Dalle Nacrée" oolite

From base to top of the Dalle Nacrée Formation, the ooids gradually change in fabric from radial (base) to concentric (middle part) and then to micritic, which corresponds to an increase of the number of radial layers and micritic interlayers in parallel with a decrease in thickness of the radial layers (GRANIER, 1994c, 1995a). Since the change in fabric is stratigraphically gradual it probably does not correspond to a change in mineralogy from one polymorph of calcium carbonate to another, such as aragonite to calcite, or from high to low magnesium calcite. The radial structure of these ooids is regarded as a primary feature and their original mineralogy is likely to have been calcite (see discussion in TUCKER, 1984, or STRASSER, 1986, inter alia), though we cannot definitively exclude a conversion from high to low magnesium calcite "without textural changes of the affected crystals" (STRASSER, 1986: p. 719, quoting STEHLI & HOWER, 1961, and GAVISH & FRIEDMAN, 1969).

GRANIER (1994a, 1994c, 1994d, 1995a) used the ooid fabrics: radial, concentric and micritic, to define lithostratigraphic units at the scale of the Villeperdue oil-field and beyond: respectively a lower unit with radial ooids, a middle unit with concentric ooids and an upper unit with micritic ooids. These units are bounded by hardgrounds with borings, layers of bored cobbles and pebbles, and erosional surfaces. Note that whether ooids should be ascribed to the radial or concentric types and the concentric or micritic types is in part influenced by the thickness of the thin-sections studied (they should always be circa 30 µm thick). However, the jump from one fabric to another is always visible if the thin-section was made from the hardground at the surface boundary (GRANIER, 1994c: Fig. 4.7-8; 1995a: Fig. 3.I-J).

IV - Early lithification and borings in the "Dalle Nacrée" oolite

In view of their small sizes and their relative mobility when forming a loose sand, individual ooids are only bored by microbes (cyanobacteria, fungi, …), which make their way inwards through the ooid cortices by chemical means. Other borers (only animals actually) require larger and more stable substrates, *e.g.*, ooid aggregates, oolitic hardgrounds or lithoclasts derived from them. Some borers, *e.g.*, foraminifers, clionid or phloeodictyid sponges, polychaete worms or bryozoans, use chemical processes while others, usually larger, *e.g.*, barnacles, gastropods, polychaete worms, sipunculid worms, bivalve molluscs and echinoids, use mechanical means instead, or a combination of both processes (ANSELL & NAIR, 1969; GLYNN, 1997, inter alia).

Among people studying the "Dalle Nacrée" (PURSER, 1969 *; LAVILLE *et al.*, 1989; BRIGAUD, 2009), the author was probably the one who paid the most attention to the micro- and macro- borings of the many hardgrounds and cobble layers exposed in the walls of the quarries in Burgundy and in the cores from the oil wells in the Paris Basin (GRANIER, 1994a: Figs. 2 & 5-6; 1994c: Figs. 3.2-7 & 4.7-8; 1995a: Figs. 3.A-F, 3.H-J & 4.C-F).

PURSER (1969) described some "inverted bored surfaces" in small submarine caves. However the author did not observe such structures and it may well be that the inverted borings are actually sited on the lower surface of rolled cobbles.

Below the hardground surface or inside the pebbles and cobbles, the microfacies is generally an oolitic grainstone with fibrous (likely high-Mg) calcite fringing cement. A secondary micrite, postdating this marine-phreatic isopachous cement, occurs within the remaining intergranular pores in a geopetal pattern or completely fills the pore space. There may be several generations of internal sedimentation as a boring can cross-cut an early internal deposit while a later deposit fills the boring itself. Borings and erosional contours (of the pebbles and cobbles) or surfaces (of the hardgrounds) cross-cut grains, the fibrous cement and internal sediments. They may eventually be encrusted by microbial (*Girvanella*) structures,

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* *Although PURSER (1969: Figs. 4.A, 7.A-B & 12.B) illustrated borings from Burgundy, he only identified one Lower Callovian bored surface, the one that marks the top of the "Dalle Nacrée" and therefore ends the Callovian cycle, to compare with the many surfaces reported by subsequent workers.*

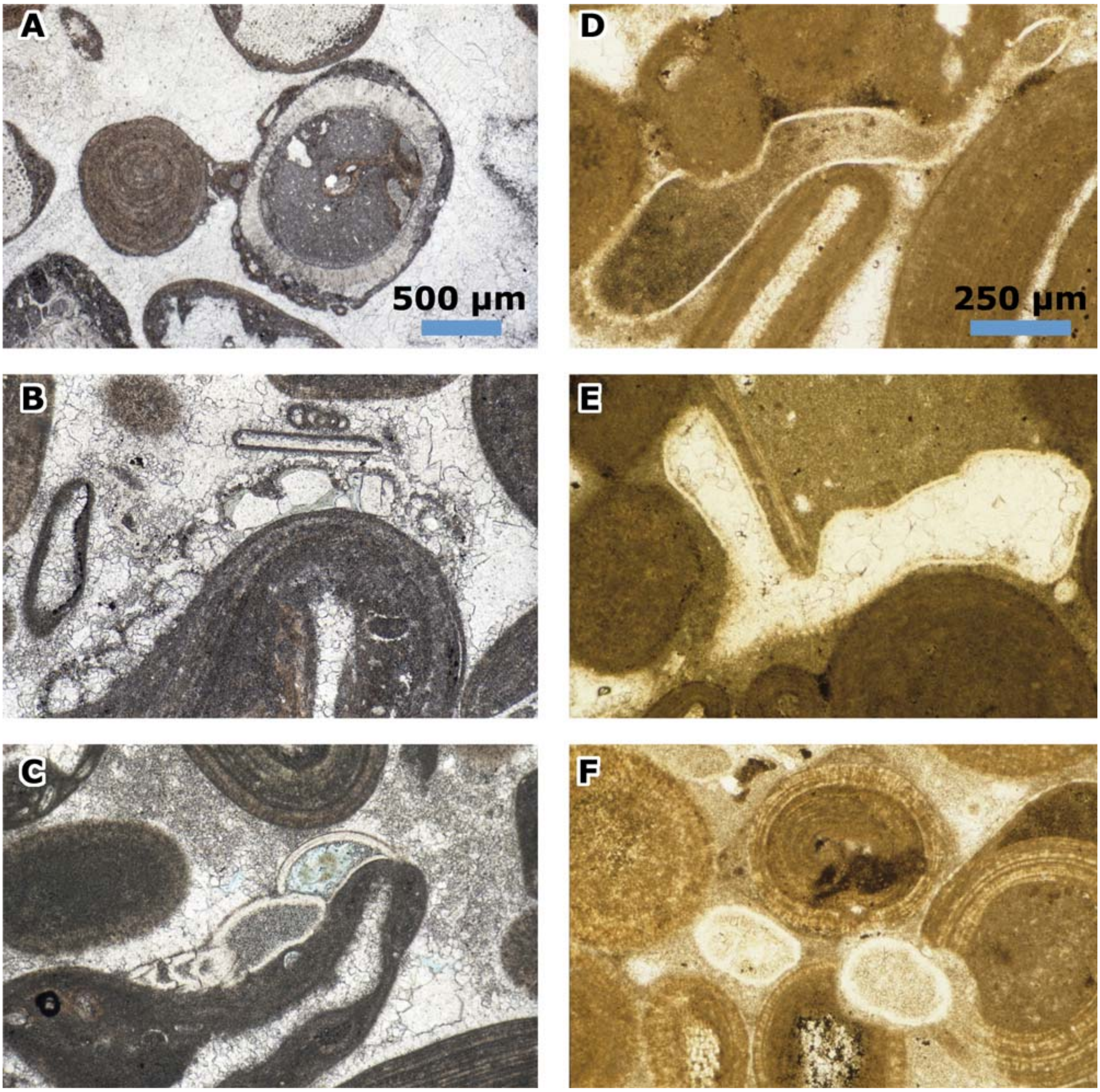


Figure 1: A. Foraminifers with a porcelaneous test (likely Nubecularids), aggregating calcareous grains. Middle unit with concentric ooids; B. Foraminifer with an agglutinated test. Middle unit with concentric ooids; C. Foraminifer with a hyaline test. Middle unit with concentric ooids; D. Microcave dweller foraminifer with a hyaline test; its shape perfectly fits in the intergranular network. Micritic ooid unit; E. Foraminifer with a hyaline test; its shape perfectly hugs those of neighbouring grains. Upper unit with micritric ooids; F. Foraminifer with a hyaline test; its shape perfectly fits in the mesoboring. Middle unit with concentric ooids [B-F: same scale].

foraminifers, bryozoans, serpulids and oysters. These encrusting organisms can in turn be perforated by a later generation of borers (see PALMER & FÜRSICH, 1974; GOLDRING & KAŹMIERCZAK, 1974; TAYLOR & WILSON, 2003, for examples of ecological assemblages).

In addition to the encrusting foraminifers with porcellaneous (Fig. 1.A), agglutinated (Fig. 1.B) or hyaline (Fig. 1.C) tests, other foraminifers of the hardground community are represented by micro-cave dwellers, the hyaline tests of which follow the shape of the intergranular pores (Fig. 1.D-E).

V - Practical typology (based on sizes) of the borings

a) Microborings (seen under a microscope)**:**

The smallest borings, which are locally tubular, less than 250 µm in cross-section, curved and branching, are ascribed to sponges (GRANIER, 1994c: Figs. 3.6 & 6.26; 1995a: Fig. 3.H), possibly by Clionidae, but not by Phloeodictyidae.

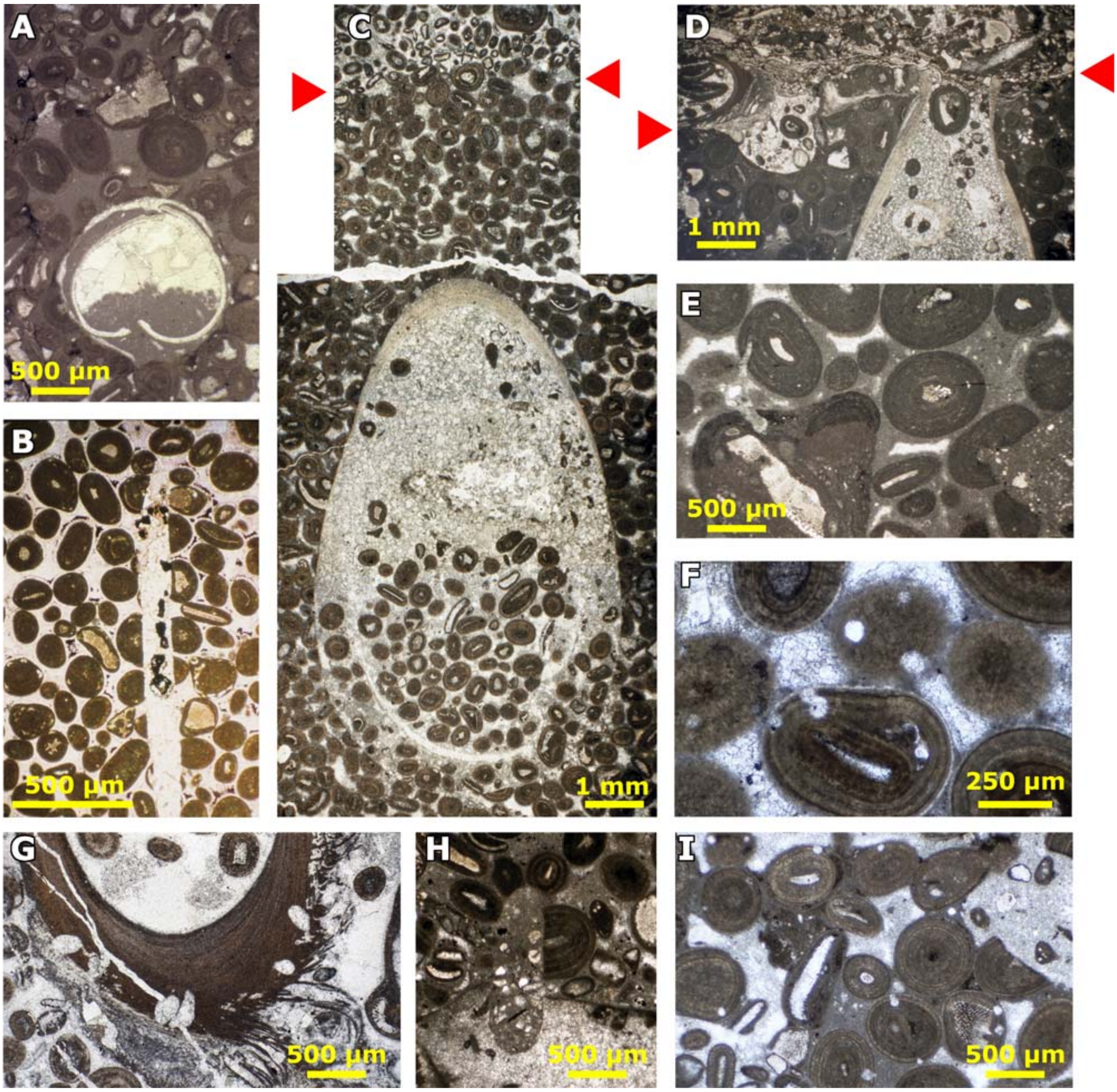
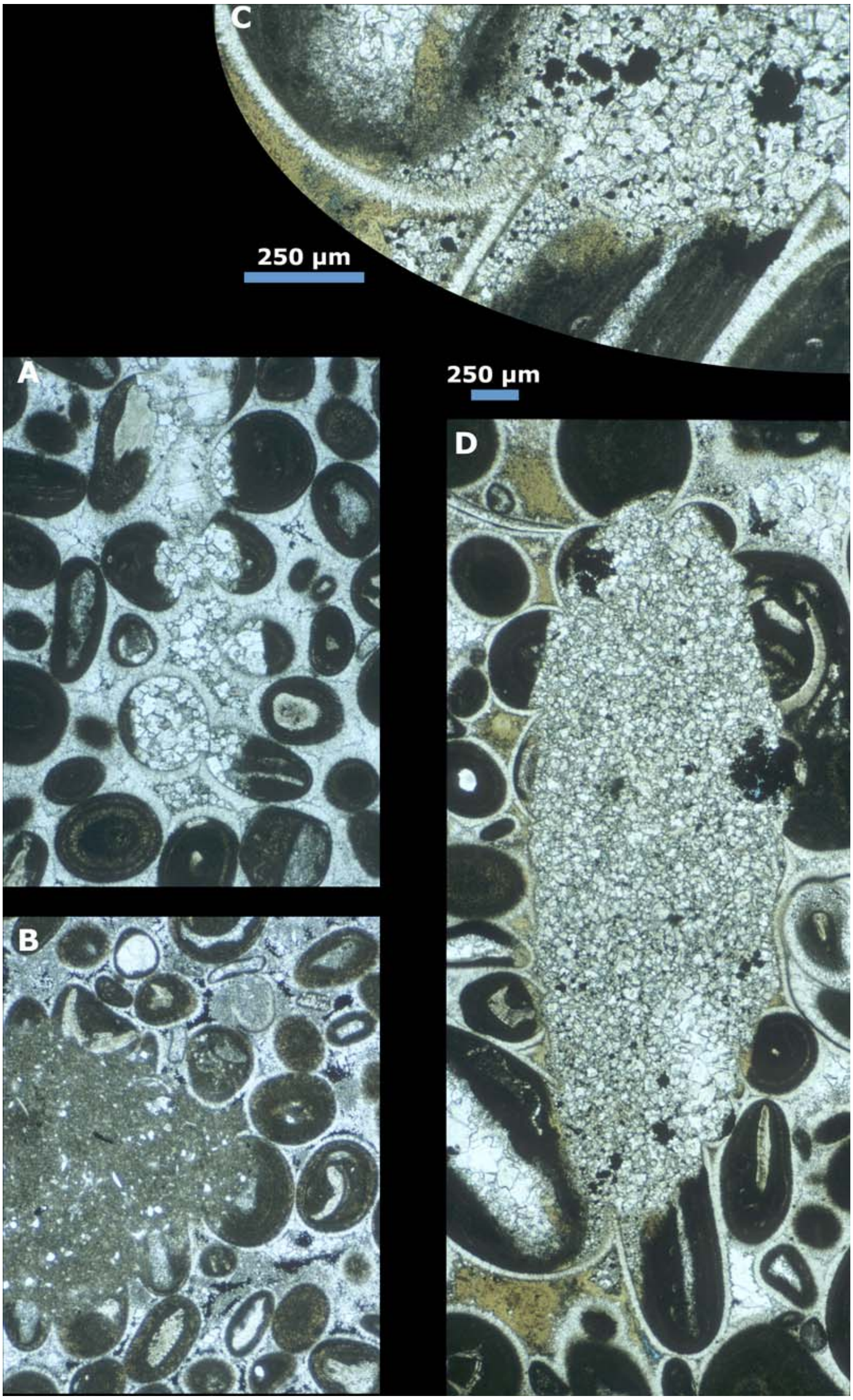


Figure 2: A. Macroboring with the boring shell preserved *in situ* and a micritic geopetal fill. Middle unit with concentric ooids, near the concentric - micritic ooid boundary; B. Tubular mesoboring. Top of the upper unit with micritric ooids, uppermost discontinuity; C. Macroboring with a calcareous lining in its upper part and a grainy geopetal fill. The boring shell is preserved *in situ*. Red triangles point to the hardground surface. Middle unit with concentric ooids; D. Two macroborings, the right one with a calcareous lining. Red triangles point to the hardground surface encrusted by serpulids. Middle unit with concentric ooids; E. On the left side, a tortuous microboring cuts into both an ooid and a bothryoid. On the right side, a mesoboring. Upper unit with micritric ooids, uppermost discontinuity; F. Numerous microborings cut into the ooids and their thin fringing fibrous cement in a false-packstone (the micrite percolated into the intergranular porous network of the grainstone after the start of early cementation). Middle unit with concentric ooids; G. Microborings in a serpulid tube (not related to any hardground). Upper unit with micritric ooids; H. Tubular mesoboring cutting ooids and a micritre envelope cemented with drusy calcite. The original skeletal grain was still aragonitic at the time of the boring. Middle unit with concentric ooids, near the concentric - micritic ooid boundary; I.A set of macro- and microborings. Middle unit with concentric ooids [various scales].

b) "Mesoborings" (seen through a magnifying glass or under a microscope)**:**

Some larger borings, called herein "mesoborings", consist of wider (up to 0.2 cm in section), long (up to 10 cm in length) straight tubes, usually with a sharp boundary, and are ascribed to the ichnogenus *Trypanites* (see Bromley, 1972). The shape of these borings suggests that the animal responsible is likely to have been a polychaete or sipunculid worm.

In places a micro-cave dwelling foraminifer may colonize a mesoboring (Fig. 1.F).



◀ **Figure 3:** A. Tubular mesoboring. The ooid cortices next to the boring wall are partly leached. Cortical layers are cut obliquely; the intensity of dissolution decreases with distance from the boring. The fibrous cement fringing the ooids remains unaffected. Middle unit with concentric ooids, near the concentric - micritic ooid boundary; B. Micritic fill of a mesoboring. Some ooid cortices next to the boring wall are partly leached but the ooid nuclei and their fibrous cement remain almost unaffected. Top of the upper unit with micritric ooids, uppermost discontinuity; C-D. Dolomicrosparitic fill (probably a late replacement of an originally micritic fill) of a tubular mesoboring. Some ooid cortices next to the boring wall are partly leached but their fibrous cement remains unaffected. C is an enlarged view of the lower part of D. Middle unit with concentric ooids, near the concentric – micritic ooid boundary [A-B & D: same scale].

c) Macroborings (seen with naked eye):

The largest macroborings (1 cm in diameter in average, up to 2.5 cm in length) are clavate and therefore are ascribed to the ichnogenus *Gastrochaenolites*. Locally the pair of valves of the mollusc responsible for the boring is still preserved inside it (PURSER, 1969: Fig. 4.A-B; GRANIER, 1995a: Figs. 3.B & 3.E). Although it is known from the literature that the surface of some *Gastrochaenolites* ichnosp. displays scours and grooves (KELLY & BROMLEY, 1984, inter alia), which are the marks of mechanical abrasion, our claviform borings have rather smooth contours in thin-section, suggesting

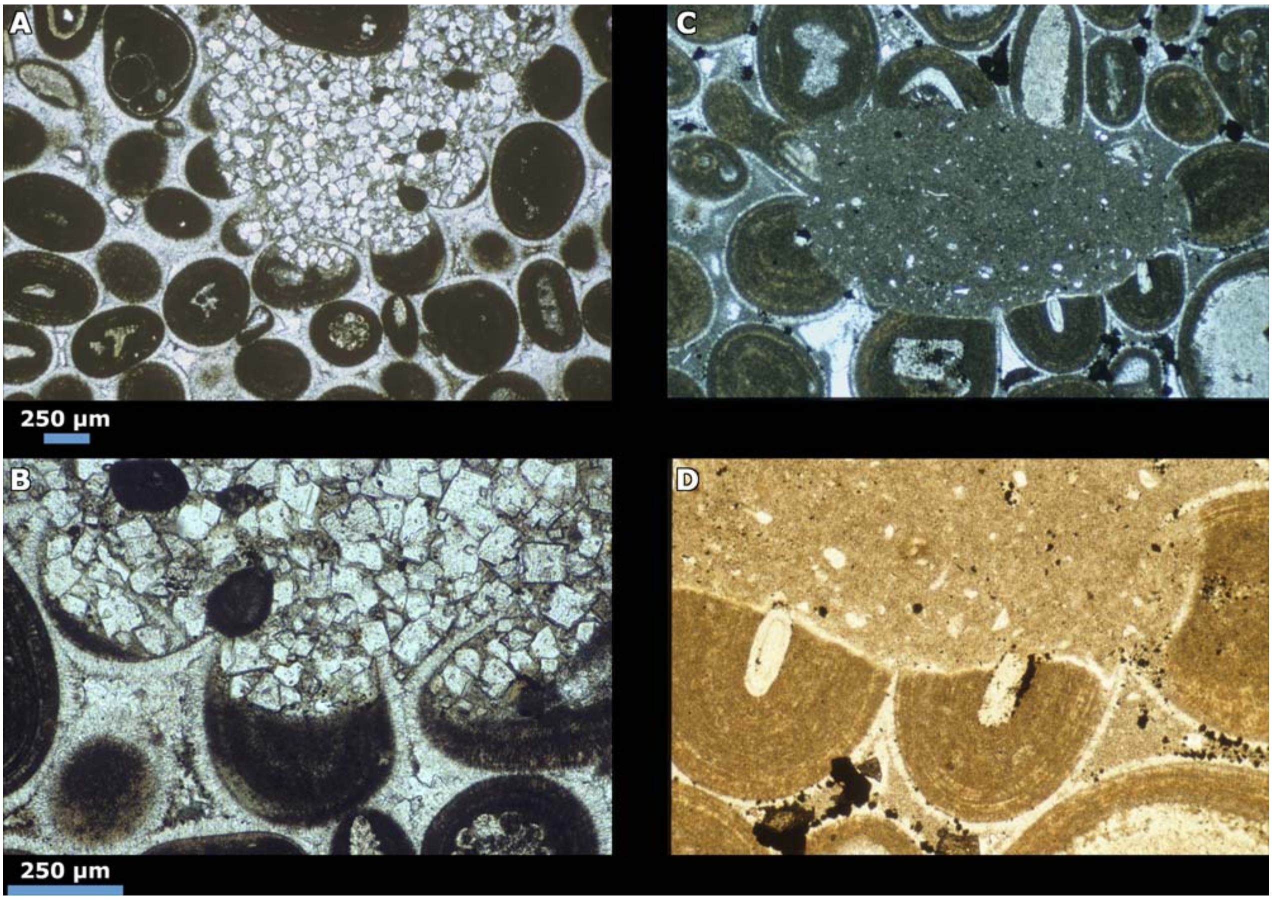


Figure 4: A-B. Dolomicrosparitic fill (probably a late replacement of an originally micritic fill) of a mesoboring. Some ooid cortices next to the boring wall are partly leached but their fibrous cement remains unaffected. B is an enlarged view of the right part of A. Middle unit with concentric ooids, near the concentric - micritic ooid boundary; C-D. Micritic fill of a tubular mesoboring. In places micrite percolated through the residual intergranular porous network of the oolitic grainstone. Some ooid cortices are slightly leached next to the boring wall, but the ooid nuclei and their early marine fibrous cement remain almost unaffected. D is an enlarged view of the lower right part of C. Top of the upper unit with micritric ooids, uppermost discontinuity [A & C: one scale; B & D: another scale].

that the bivalves responsible for them were secreting an acid mucus to chemically excavate the rock, similar to some living species of *Lithophaga* (YONGE, 1955: p. 399). As in the borings of the modern *Lithophaga plumula* (HANLEY, 1844) documented by YONGE (1955: Fig. 13, p. 395), we observed in some of our macroborings that "the outer half has a calcareous lining laid down by the animal" (Fig. 2.C-D).

All three types of boring (micro-, meso-, and macro-) can be found in any of the three units. They are illustrated here:

- microborings (Fig. 2.E-G, I),
- mesoborings (Figs. 1.F, 2.B, H, 3.A-D, 4.A-D, 5.A-D & 6.A-C),
- macroborings (Fig. 2.A, C-D, I).

VI - Discussion of some unconventional mesoborings

More attention was paid to the second category, *i.e.*, to the mesoborings. The worm responsible of these straight tubes did not slalom between the cemented grains, in the intergranular pore space, but drilled a straight tube "biting" the edges of the grains it encountered. Some tubes have sharp walls, but other tubes display rough, corroded walls, which suggests at least two ways of boring. Extant sipunculid worms bore by mechanical means, polychaete worms use either mechanical, chemical or a combination of both means. Thus it is likely that rather sharp tubes were cut using mostly mechanical means whereas rough tubes imply chemical means and the worm responsible for them should in this latter case have been a polychaete. The cutting is done by enzymes, acids or a combination of the two. The different response between the small calcite crystals of the ooid cortices and those of the early fringing cement is probably a reflection of the presence or absence of incorporated organic material. It is suggested that enzymes or acids first attack the organic part of the ooid cortices and in doing so favour the leaching of the small calcite crystals formerly embedded in this organic framework (see HUTCHINGS, 2008, who describes

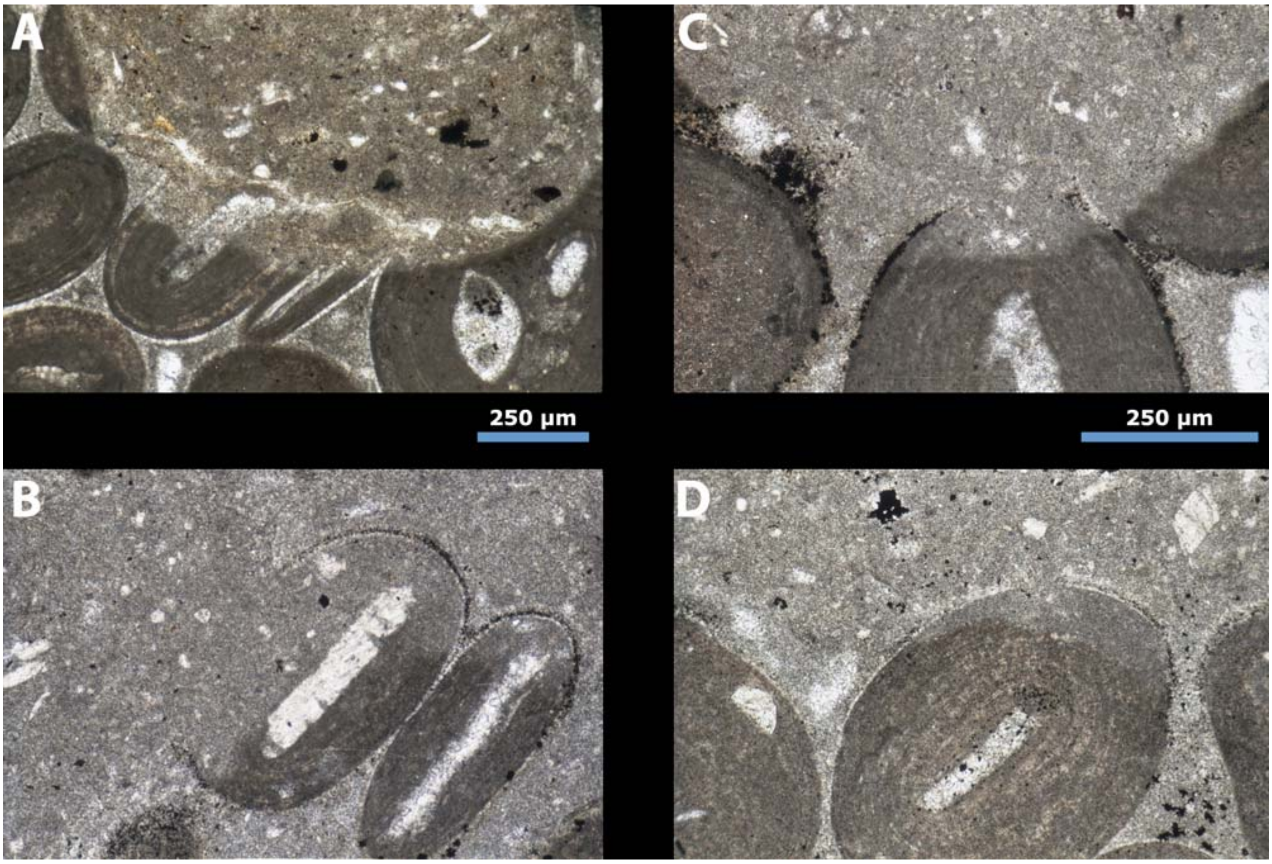


Figure 5: A-D. Mesoboring in a false packstone, *i.e.*, a grainstone. The micrite percolated into its intergranular porous network after the start of early cementation. The ooid cortices next to the boring wall are partly leached but the ooid nuclei and their fibrous cement remain unaffected. Top of the upper unit with micritric ooids, uppermost discontinuity [B-D: same scale].

a very similar process of bioerosion in coral substrates). The leaching away of ooid cortices from the worm tube is "collateral damage" due to enzyme or acid outflow.

VII - Conclusions

The marine ooids of the "Dalle Nacrée" Formation, whether they have a radial, concentric or micritic fabric (*sensu* GRANIER, 1994a, et seq.), were all originally calcitic. The hardgrounds and pebble-cobble layers resulting from their dismantling correspond to special biotopes within the oolitic shoals, with encrusters, borers and microcave dwellers. Borings can be classified according to their shapes, their measurements, the occurrence or absence of linings, the mechanical or chemical processes involved, and possibly the remains of the borers. The practical classification used herein retains three categories based on overall dimensions: micro-, meso- and macroborings. They correspond respectively to sponge, worm and bivalvia borings.

Some worm borings, *i.e.*, polychaete borings, are created through chemical processes. Since some borings show a differential response between the ooid cortices and the early marine fibrous cement, it is suggested that the organic matter of the cortices played a key role. As highlighted some twenty years ago (GRANIER, 1995b) "fringing cements are mainly inorganic" whereas "ooid cortices have a dual composition: inorganic and organic". Partly leached ooid cortices do not necessarily point to an original aragonitic mineralogy of the dissolved parts. Therefore the statement that aragonitic ooids are commonly dissolved does not imply the converse, *i.e.*, that dissolved ooids were originally aragonitic.

Acknowledgments

From 1991 to 1993, the author was in charge of "carbonate sedimentology" studies for the Paris Basin at the Scientific and Technical Center of TOTAL – Compagnie Française des Pétroles, sited in Pessac, then in Saint-Rémy-lès-Chevreuse. During this short period, he and his colleagues in the company studied or revisited in detail 32 wells (namely BNV 1D, BVE 1, BYE 1, CBS 1, CFX 1, CGY 1, CPN 1, Fontaine au Bron: FAB 5 and FABE 1, Hautefeuille: HFE 1D, HFE 2D and HFE 7D, LES 1D, LFS 1, MAP 1, RCQ 1, SAU 2, SLP 1, Sancy lès Provins: SYP 1, SYP 2D and SYP 3D, VNY 1, Villeperdue: VP F52, VP H55, VP I01, VP I53, VP R09H, VP R52, VP S54, VP U01, VP W03 and VP X52). Today, almost ten years after having left this company to join the university, he takes the opportunity of this short paper to thank his former "calcareous" colleagues, the late Philippe BOUSQUET, Robert BOICHARD, Hervé CADILLAC, and Guy GOY, for their unwavering support. He also acknowledges the constructive reviews of Maurice E. TUCKER, André STRASSER and Mark A. WILSON, and the assistance of Phil SALVADOR, the Language Editor, in revising the English text of the final version.

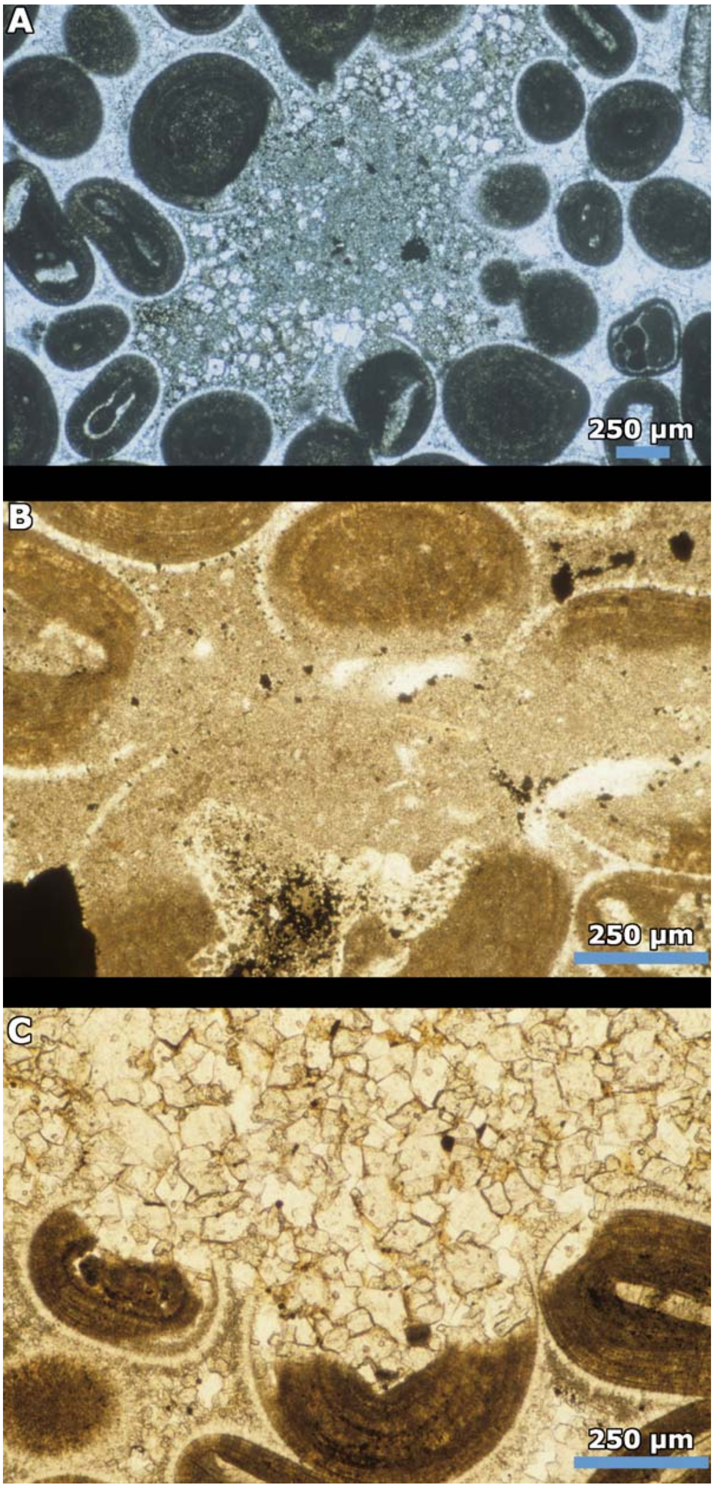


Figure 6: A. Some ooid cortices next to the wall of this tubular mesoboring are slightly leached. Middle unit with concentric ooids, near the concentric – micritic ooid boundary; B. Mesoborings in a false packstone. The ooid nuclei (for example here, an echinoid ossicle) and their fibrous cement remain unaffected. Upper unit with micritric ooids; C. Dolomicrosparitic fill (probably a late replacement of an original micritic fill) of a mesoboring. Some ooid cortices next to the boring wall are partly leached but their early fibrous cement remains unaffected. Middle unit with concentric ooids [B-C: same scale].

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