Carnets Geol. 21 (9)

E-ISSN 1634-0744
DOI 10.2110/carnets.2021.2109

The KALKOWSKY Project - Chapter I

Ooid - stromatoid relationship in a stromatolite from the Maiz Gordo Fm (Argentina)

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Abstract: The comparative study of oolites and stromatolites demonstrates striking similarities between KALKOWSKY's German Triassic material (drawn from the scientific literature) and our Argentinian Paleogene material. However, the latter better illustrates that ooids and stromatoids, hence oolites and stromatolites, which share the same dual (*i.e.*, organic and mineral) nature, are merely the end-members of a continuum of microbial carbonate structures.

Key-words:

- ooid;
- stromatoid;
- microbial carbonates;
- Salta;
- Argentina;
- Paleogene

Citation: GRANIER B.R.C. & LAPOINTE Ph. (2021).- The KALKOWSKY Project - Chapter I. Ooid - stromatoid relationship in a stromatolite from the Maiz Gordo Fm (Argentina).- *Carnets Geol.*, Madrid, vol. 21, no. 9, p. 193-201.

Résumé : *Le Projet KALKOWSKY - Chapitre I. La relation ooïde - stromatoïde dans un stromatolithe de la Formation Maiz Gordo (Argentine).-* L'étude comparative d'oolithes et de stromatolithes démontre des similitudes frappantes entre le matériel triasique allemand de KALKOWSKY (d'après des informations disponibles dans la littérature scientifique) et notre matériel paléogène argentin. Cependant, ce dernier est mieux à même d'illustrer qu'ooïdes et stromatoïdes, donc oolithes et stromatolithes, qui partagent la même nature duale, organique et minérale, ne sont que les membres extrêmes d'un ensemble de structures carbonatées d'origine microbienne.

Mots-clefs :

- ooïde ;
- stromatoïde ;
- carbonates microbiens ;
- Salta ;
- Argentine ;
- Paléogène

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Published online in final form (pdf) on June 14, 2021
[Editor: Michel MOULLADE; language editor: Phil SALVADOR; technical editor: Bruno R.C. GRANIER]

1. Introduction

The central idea behind the concept of the KALKOWSKY Project is that much on microbial carbonates can still be learned from the mere petrographic analysis of thin sections.

Most geologists are not familiar with the word "stromatoid", which was first introduced by KALKOWSKY (1908). As an oolite is made of ooids, a stromatolite is made of stromatoids. A stromatoid is merely one of the thin laminae, the accumulation of which creates a stromatolite (MONTY, 1977; KRUMBEIN, 1983; PAUL *et al.*, 2011), *i.e.*, the stromatoids are the building blocks of the stromatolites. The recent reinterpretation of the historical locality of KALKOWSKY, *i.e.*, Heeseberg (Helmstedt, Lower Saxony, Germany), by KÄSBOHRER and KUSS (2021) pushed us to write and publish this contribution in order to share a slightly different opinion on the topic. Although we could not directly study the Lower Triassic German material, a strikingly similar material from an Argentinian Paleogene series was available to us.

2. Material and general setting

The material studied was collected by one of us (P.L.) accompanied by three IFP colleagues (namely Bernard COLLETTA, Jean LETOUZEY, and Roland VIALY) on October 8, 1988. The section they measured crops out at 24°22'23.82"S 64°58' 30.56"W (Province of Jujuy, Argentina), on the eastern side (opposite side) of the junction of road 66 to San Salvador de Jujuy with road 34 from San Pedro de Jujuy to General Güemes and Salta (Fig. 1). This intersection is some 35 km ESE of San Salvador de Jujuy and some 65 km NE of Salta. It is located in the Salta Basin, in a corridor joining its southern Metán-Alemania subbasins to its eastern Lomas de Olmedo subbasin. Green to grey clays dominate the 7 meter thick interval studied, which is ascribed to the Maiz Gordo Fm (MORENO, 1970) of the Santa Barbara Subgroup, Thanetian-Ypresian [Late Paleocene – Early Eocene in age (*e.g.*, DEL PAPA, 1999)]. Since the 1988 field work, the road bank has become overgrown by vegetation and the few limestone beds are hardly visible today. Only two petrographic thin sections were prepared from a piece of rock labelled ARA 288 that comprises both oolitic and stromatolitic facies: The first thin section (ARA 288) is probably lost, the second thin section (AG 288 B) was prepared from an offcut of the first.

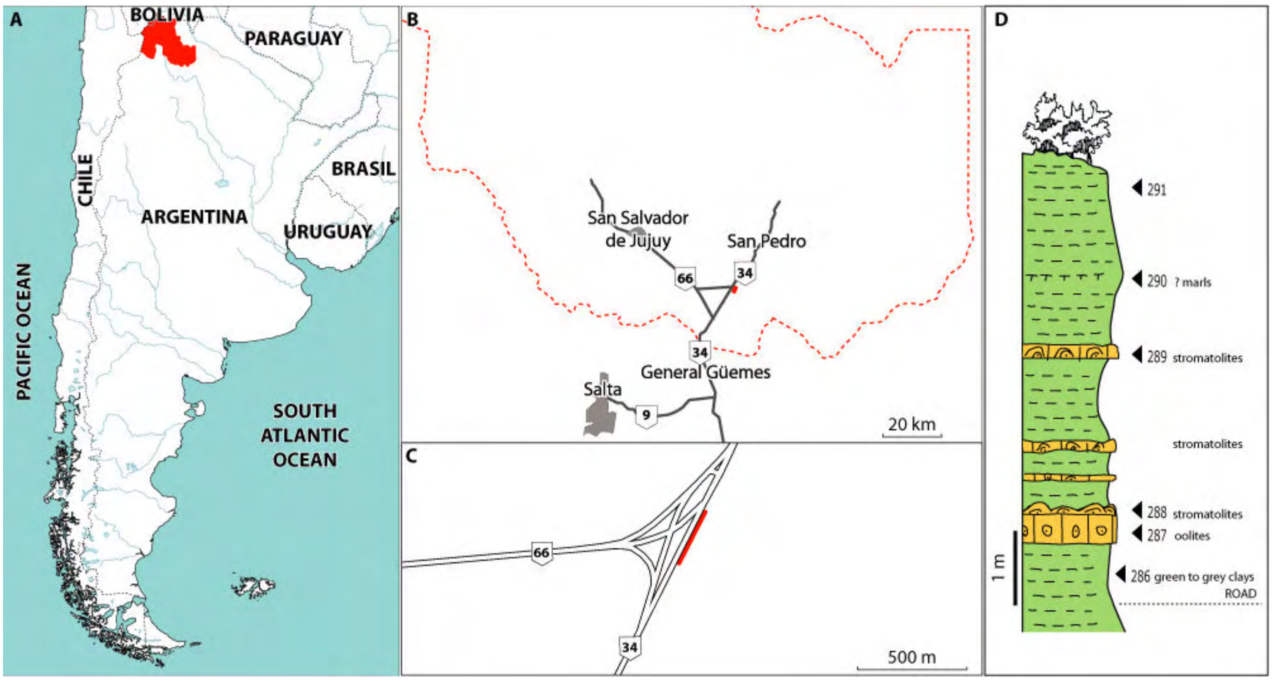

Figure 1: A) Location map of the Province of Jujuy, Argentina. **B)** Map of the southeastern corner of the Province of Jujuy. **C)** Location of the section at the junction of road 66 and road 34. **D)** Schematic lithologic log of the section with the location of the sampling points.

3. Description of ARA 288 and comparison with Kalkowsky's material

The microfacies observed in thin sections ARA 288 (Pl. 1) and AG 288 B are: 1) a grain-supported texture with radial-concentric ooids (="Ooid mit Lagenstruktur" *sensu* Kalkowsky, 1908, Pl. IV, fig. 1), in the lower parts of both thin sections, and 2) a microcolumnar stromatolitic architecture with mud-supported texture between the columns, in their upper parts. In both sections, one counts three columns and three interstitial spaces. This material presents some features similar with those illustrated by Kalkowsky (1908, Pl. IX and Pl. VII, fig. 2) as "Grenze zwischen Oolith und kompaktem Stromatolith mit Wurzeln (links)".

The lower part consists of an oolitic grainstone. Ooids are all about the same size, *i.e.*, 0.5-1.0 mm in diameter, which suggests some mechanical sorting. Most of them are connected by micritic bridges in the manner of some meniscus cements. Some ooids are broken ooids (Pl. 1, figs. l, t), not necessarily hemiooids *sensu* Kalkowsky (Pl. 1, fig. a). The broken ooids *sensu stricto* (Pl. 1, figs. j-k, n, p-q, u) display a fresh cut surface whereas Kalkowsky's hemiooids (1908, Pl. V, fig. 2) are broken ooids with "restoration" / rejuvenation phases. Contrary to Carozzi's (1961) opinion, we do not assume the ooid breakage is due to a mechanical cause. This last point, which is outside the scope of this paper, will be addressed in another publication. Some biooids (Pl. 1, figs. e, o, r-s), *i.e.*, ooids with two nuclei (= "Ooid mit (…) zwei Kernen" *sensu* Kalkowsky, 1908, Pl. IV, fig. 4), polyooids (Pl. 1, fig. v) and even botryoidal lumps (= "Ooidbeutels" *sensu* Kalkowsky, 1908, Pl. V, fig. 4) are also observed. In addition to the ooids, allochems also include a few calcium phosphate fish bones, small (1 to 2 mm in length) subrounded micritic extraclasts, including once-hollow extraclasts (Pl. 1, fig. x), or fibrous sparitic fragments of stromatolites (Pl. 1, fig. y), commonly with a superficial ooidal coating, and larger (commonly more than 1 cm in length) subangular flakes without coating, including mudstones with numerous desiccation cracks (a reworked piece of a ? paleosoil, Pl. 1, fig. w) and fragments of stromatolites. Within this grainy fabric, large drusy-cemented cavities commonly occur and are interpreted here as former keystone vugs (Pl. 1, figs. b-d). It is suggested here that this facies could mark the swash zone on a shore of the Salta giant lake.

The upper part consists of a bind- to bafflestone fabric with a silty and oolitic wackestone trapped in spaces between the microcolumns of the stromatolite. This pattern is quite similar to that illustrated by Kalkowsky (1908, Pl. VI, fig. 2) as "Zwei Äste von Stromatolith mit Lagenstruktur und mit Interstitium". However, there are some discrepancies because, for instance, our stromatolitic columns are made of relatively thick layers with spongiostromate [*], either micritic or spongious, fabrics alternating more or less regularly with thin fibrous sparitic crusts, each of which may pass laterally to a micritic layer. Both types of stromatoids, *i.e.*, the micritic layers and the fibrous sparitic crusts, locally jump from one column to the next and bind the wackestone of the common instertitial space, which makes it possible to evaluate the relative height of a column when the stromatolite was growing. The top of a column rarely exceeds more than 5 mm above the lowest point of its surrounding interstitial spaces. The growth of a column is determined by variation in volume of the spongious layers and, to a minor extend, by trapping of some formerly aragonitic bioclasts (? Gastropods) and fewer ooids.

4. Ooid - stromatoid relationship

The historical locality of Kalkowsky, *i.e.*, Heeseberg in Germany, was recently revisited by Käsbohrer and Kuss (2021). Although much was expected from their study, it includes some interpretations that, in our opinion, could be erroneous. For instance, these authors (Käsbohrer & Kuss, 2021) state that their stromatolitic crusts (LFT2) were formed by "light sparite laminae" of abiotic origin. However, it looks like the fibrous sparitic crusts in their material (as in our material) are rarely hyaline but commonly slightly colored, as some ooid cortices are (Pl. 2, figs. m-q); hence they are not a palisadic fibrous cement. This feature suggests that organic matter is embedded in the calcite crystals and it points to a biological origin or influence (Granier, 2020). In the caption of their Figure 15.D, Käsbohrer and Kuss (2021) describe "Syntaxial overgrowths by fibrous calcite (...) on ooids with radially arranged cortices" (*op. cit.*). However, the corresponding photomicrograph shows a very narrow field of view of a zone affected by pressure-solution joints. In our opinion, their "syntaxial overgrowth" interpretation should be discarded because growth breaks in the concentric cortices of the ooids are also observed in the subsequent fibrous sparitic crusts. Actually, it is here assumed that such photomicrographs capture a genuine transition from ooids to stromatoids. In the same figure caption (Käsbohrer & Kuss, 2021, Fig. 15.E), these authors state that "Debris with (broken) ooids (...) and angular quartz grains (…) fill cavities (…) at the top of stromatolitic crusts" whereas, in our opinion, their so-called "broken ooids" are rather ooids with sutured boundaries and their alleged "cavity" is a thin dolomitic layer sandwiched between stylolitic joints.

[*] These are spongiostromate microstructures *sensu* Monty, 1981 (derived from the Spongiostromata Pia in Hirmer, 1927).

Back to KALKOWSKY (1908), he was the first to conceive the idea that the ooids result from the activity of organisms related to the stromatolites, *i.e.*, to microbes, an opinion that was not accepted by most (*e.g.*, CAROZZI, 1964) until recently (*e.g.*, BREHM *et al.*, 2004; O'REILLY *et al.*, 2017; DIAZ & EBERLI, 2019, and references therein). What he did not see in his material is a very small detail enlightening the true nature of the ooid - stromatoid relationship. For instance, it is possible that he interpreted as "Teil eines Ooidbeutels mit Fortwachsung des Ooide in der Beutelhülle", *i.e.*, botryoidal lumps (KALKOWSKY, 1908, Pl. V, fig. 3), what could be seen as the genuine transition from oolite to stromatolite, *i.e.*, from ooids to stromatoids. He also documents the transition from ooids to the fibrous sparitic crusts of a botryoidal lump (KALKOWSKY, 1908, Pl. V, fig. 4) and obviously the same reasoning can apply to the transition from ooids to the fibrous sparitic crusts of stromatoids. As already summarized by PAUL *et al.* (2011) and earlier by KRUMBEIN (1983), KALKOWSKY "regarded 'Ooids' and 'Stromatoids' as end members of a continuum, with 'poly-ooids' and 'Ooid bags' as intermediate stages".

As a matter of fact, in our Argentinian material, we do observe genuine cases of such a transition from ooids to stromatoids (Pl. 1, figs. f-i, m; Pl. 2, figs. m-q). Such features cannot be interpreted as "Syntaxial overgrowths by fibrous calcite (...) on ooids with radially arranged cortices" as suggested by KÄSBOHRER and KUSS (2021) because, contrary to their photomicrograph (*op. cit.*, Fig. 15.D), our fibrous sparitic stromatoids clearly extend laterally and occasionally change gradually into micritic stromatoids (Pl. 2, figs. m-r) as reported earlier.

5. Conclusion

Having both being deposited in giant paleolakes, KALKOWSKY's German Triassic material and our Argentinian Paleogene material present striking similarities. However, the continuum from ooids to biooids, polyooids, botryoidal lumps, and stromatoids is better documented by our Argentinian material. Amongst the discrete stromatoids, those forming fibrous sparitic laminae clearly extend laterally, where they eventually gradually change into micritic stromatoids. The continuum is working both ways, which implies that, as anticipated by KALKOWSKY (1908), both stromatoids and ooids inherently share the same dual nature, organic and mineral, and the same microbial origin.

Acknowledgements

The rock sample studied here was collected by one of us (P.L.) on the occasion of a joint mission of Total - Compagnie Française des Pétroles, and IFP - Institut Français du Pétrole from October 5 to November 3, 1988. The second author (P.L) acknowledges the support of his IFP colleagues, Bernard COLLETTA, Jean LETOUZEY, and Roland VIALY, for fieldwork. The first author (B.G.) would like to thank Phil SALVADOR for his appreciated help with the original (English) text. The manuscript also benefited from the constructive reviews of George PLEŞ and Pablo SUAREZ-GONZALEZ.

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Plates

Plate 1: Photomicrograph of thin section ARA 288 (probably lost) with enlargements of some details of interests. **a)** hemiooid with a broken ooid nucleus; **b-d)** keystone vugs; **e, o, r-s)** biooids; **f-i, m)** transition from an ooid to fibrous sparitic stromatoids; **j-k, n, p-q, u)** broken ooids; **l, t)** partly broken ooids; **v)** polyooids; **w)** detail of a large subangular mudstone flakes with numerous desiccation cracks; **x)** hollow micritic extraclast, possibly after the spongiostromate coating of an algal thallus or a small plant stem; **y)** fibrous sparitic fragment of stromatolitic crusts. Graphical scale bar of the photomicrograph = 5 mm; graphical scale bar for the details = 1 mm.

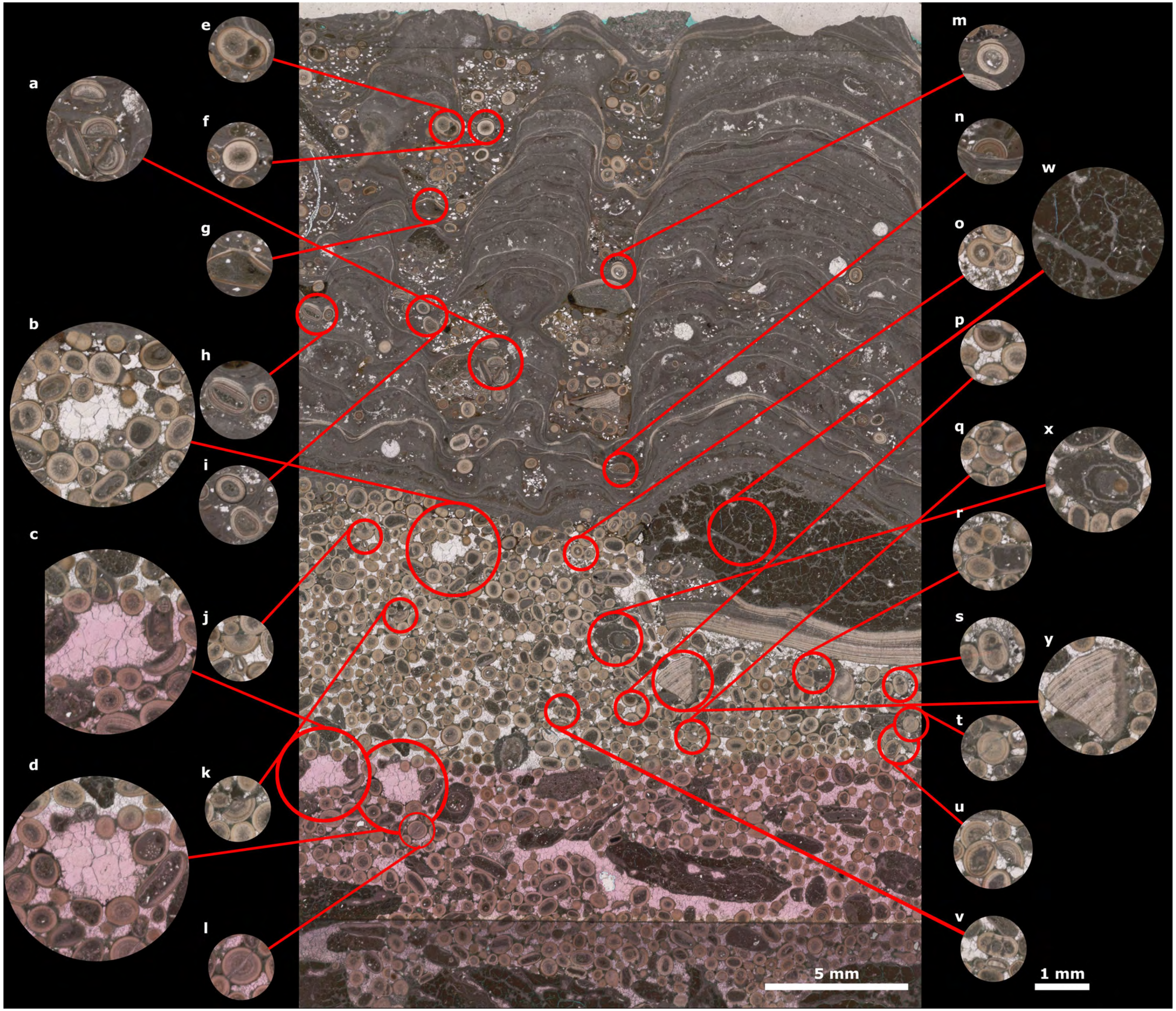
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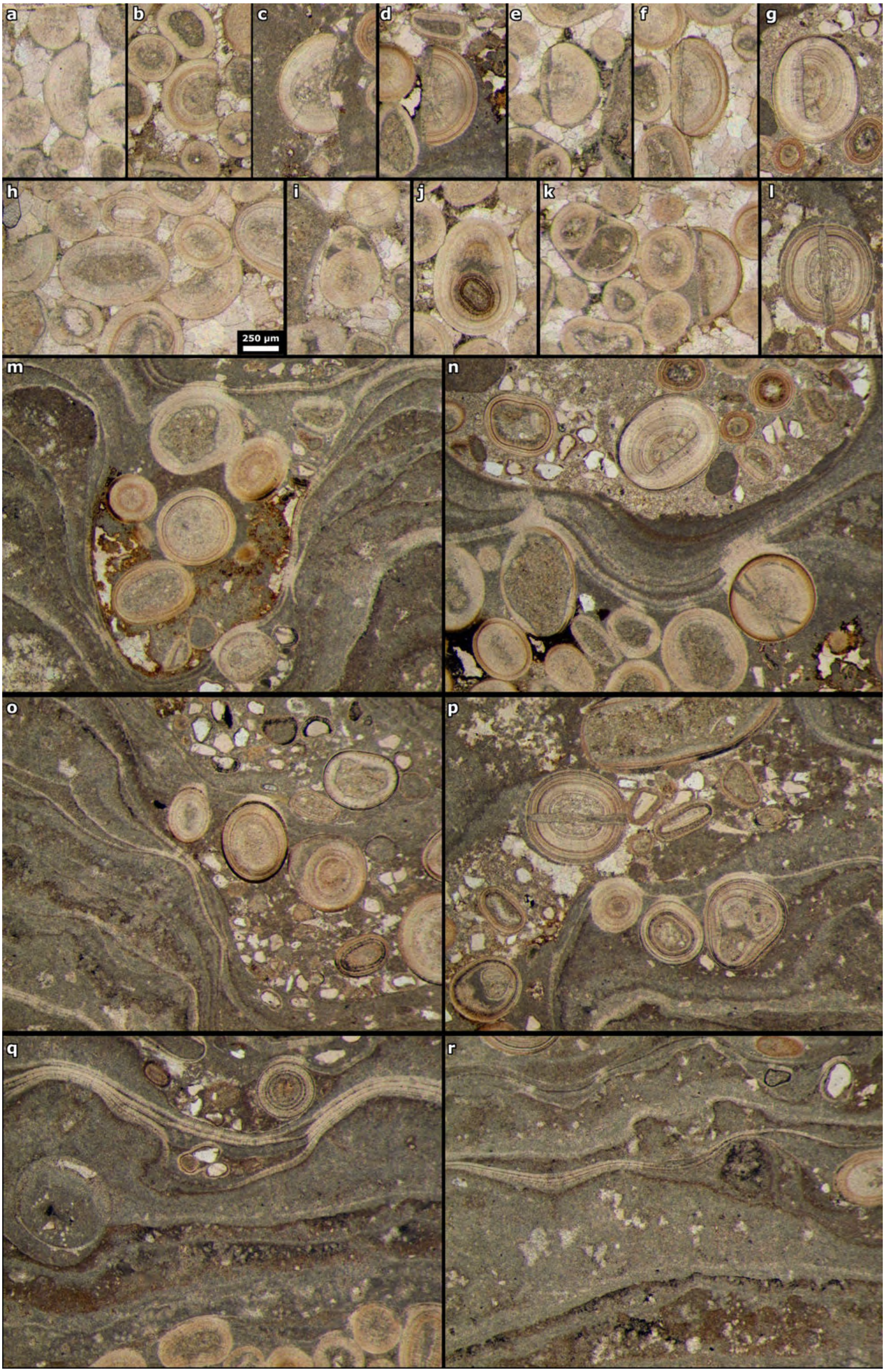
Plate 2: Photomicrographs of thin section AG 288 B. **a-c, h)** broken ooids; **d-f)** partly regenerated broken ooids; **g)** hemiooid (see fig. n); **i-j)** biooids; **k)** biooid with a lump of ooids; **l)** interrupted ooid breakage (see fig. p); **m-q)** transition from ooids to fibrous sparitic stromatoids. Note the gradual lateral change of the fibrous sparitic laminae to micritic stromatoids; **r)** combination of spongiostomate, micritic and spongious, fabrics with fibrous sparitic laminae. Graphical scale bar for all photomicrographs = 250 µm.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***Carnets Geol.* 22 (3)**

E-ISSN 1634-0744
DOI 10.2110/carnets.2022.2203

The KALKOWSKY Project - Chapter II
Wobbly ooids in a stromatolite from the Yacoraite Formation (Argentina)

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Abstract: Eccentric ooids are described from a brackish Maastrichtian paleolake in NW Argentina. The first report of such atypical coated grains was from marine Upper Jurassic strata in SE Poland. Because their growth pattern is not likely to be confused with that of other "eccentric" ooids, such as asymmetric ooids, hiatus ooids, half-moon ooids, or "broken" ooids, it is suggested here to name them "wobbly ooids".

Key-words:

- ooid;
- microbial carbonates;
- Salta;
- Argentina;
- Maastrichtian

Citation: GRANIER B.R.C. & LAPOINTE Ph. (2022).- The KALKOWSKY Project - Chapter II. Wobbly ooids in a stromatolite from the Yacoraite Formation (Argentina).- *Carnets Geol.*, Madrid, vol. 22, no. 3, p. 111-117.

Résumé : *Le Projet KALKOWSKY - Chapitre II. Ooïdes bancals dans un stromatolithe de la Formation Yacoraite (Argentine).-* Nous décrivons des ooïdes excentriques formés dans un paléolac saumâtre d'âge maastrichtien du Nord-Ouest de l'Argentine. Des grains cortiqués de ce type avaient déjà été signalés dans des couches sédimentaires marines du Jurassique supérieur du Sud-Est de la Pologne. Parce que le mode de croissance de ces ooïdes argentins ne peut être confondu avec celui d'autres ooïdes excentriques, tels que les ooïdes asymétriques, les ooïdes hiatals, les ooïdes en demi-lune ou les ooïdes brisés, nous proposons ici de les dénommer "ooïdes bancals".

Mots-clefs :

- ooïde ;
- carbonates microbiens ;
- Salta ;
- Argentine ;
- Maastrichtien

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Published online in final form (pdf) on February 15, 2022
[Editor: Michel MOULLADE; language editor: Phil SALVADOR; technical editor: Bruno R.C. GRANIER]

1. Introduction

Mere petrographic analysis of thin sections shows that much can still be learned from microbial carbonates (GRANIER & LAPOINTE, 2021); this is the central idea behind the concept of the KALKOWSKY Project. The present paper documents a new case of eccentric ooids sensu GASIEWICZ (1984a, 1984b). The latter described similar atypical coated grains from the marine Upper Jurassic of SE Poland whereas the material presented here comes from the lacustrine Yacoraite Formation (Maastrichtian to Danian) of NW Argentina.

2. Material and general setting

The material studied was collected by one of us (P.L.) accompanied by three IFP colleagues (namely Bernard COLLETTA, Jean LETOUZEY, and Roland VIALY) on October 11, 1988, from a quarry site in Puesto Viejo (Province of Jujuy, Argentina). This quarry is today operated by Lafarge Holcim (Fig. 1). A short section of the Yacoraite Formation (Fig. 2) was measured and sampled at one quarry face (NW), ca. 24°30'36.8"S 64°56' 20.9"W (Fig. 2).

Figure 1: A) Location map of the Province of Jujuy, Argentina. **B)** Map of the southeastern corner of the Province of Jujuy. **C)** Location of the section in the Lafarge Holcim quarry at Puesto Viejo. **D)** Panoramic view of the lower quarry and its face in October 1988.

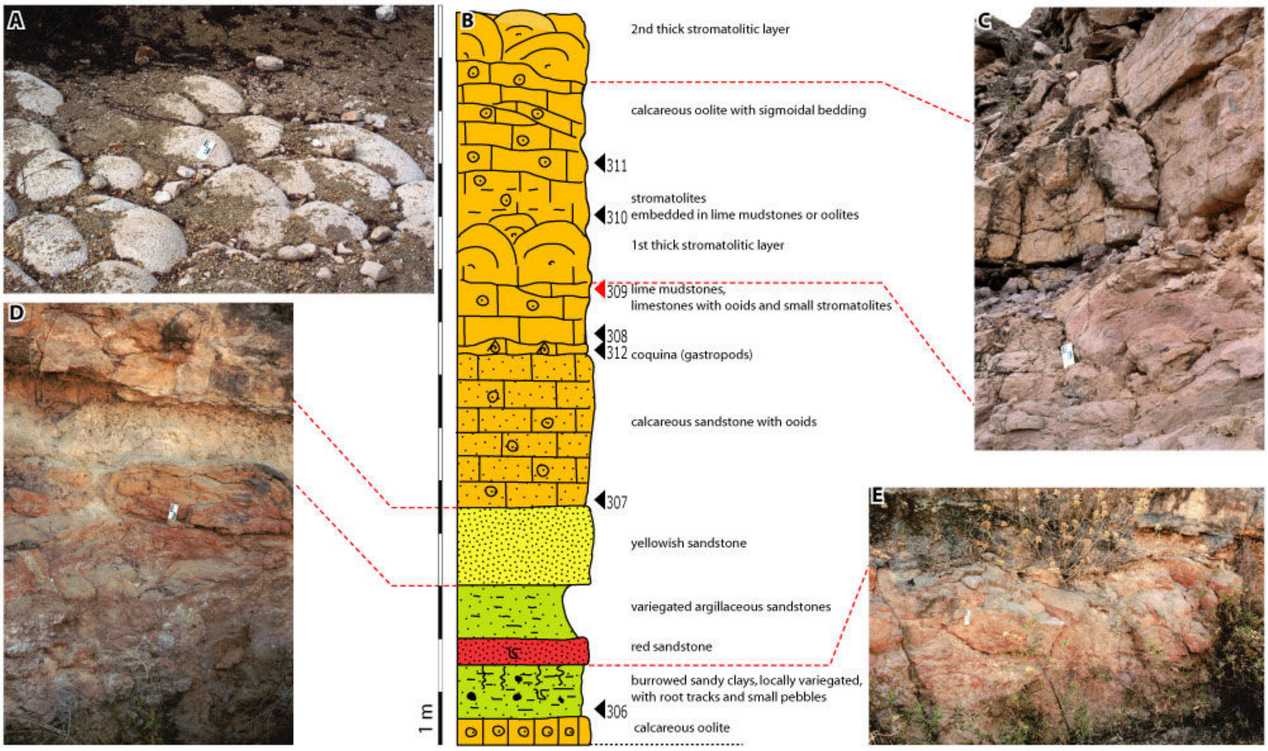

Figure 2: A) Stromatolitic domes capping the section; **B)** schematic lithologic log of the quarry section (Yacoraite Formation) with the location of the sampling points; **C)** first thick stromatolitic layer (8.5-10 m) overlain by oolitic facies; **D)** the yellowish sandstone (3-4.5 m) overlying a variegated argillaceous sandstone; **E)** the red sandstone (1.5-2 m) overlying variegated sandy clays.

Two petrographic thin sections were prepared from a piece of rock labelled ARA 309 that comprises a stromatolitic facies in its lower part and an oolitic to bothryoidal facies in its upper part. The first thin section (ARA 309: Fig. 3.A) is probably lost and the second thin section (AG 309 B) was prepared from an offcut of the first.

3. Description of ARA 309 and comparison with Gasiewicz's material

The microfacies observed in thin sections ARA 309 (Fig. 3) and AG 309 B (Fig. 4) are:

1) a bindstone fabric made of relatively thick layers with spongiostromate, either micritic or spongious, fabrics in the lower part (Fig. 3.A). The thin section was cut in a stromatolitic column the growth of which is determined by variation in volume of the spongious layers and, to a minor extend, by trapping of some allochems, mostly ooids;

2) a grain-supported texture with bothryoids floating in a grainstone matrix made of radial-concentric ooids in the upper part.

Small benthonic foraminifers (*e.g.*, Méndez & Viviers, 1973; Carignano, 2012), including some with milioline chamber arrangement (Figs. 3.E, 4.D-H), are commonly found as nuclei of small ooids. Other common microfossils are ostracods (*e.g.*, Méndez & Viviers, 1973; Carignano, 2012), which obviously cannot be taxonomically identified in thin sections. Locally present in the area, charophytes (*e.g.*, Musacchio, 1972, 2000; Carignano, 2012) were not observed in the studied sample, nor remains or dental plates of fossil fishes (*e.g.*, Cione *et al.*, 1985; Cónsole Gonella *et al.*, 2012). Largest macrofossils comprise gastropod (*e.g.*, Cónsole Gonella *et al.*, 2012; Fig. 4.F, .H) and mollusk shells. The fossiliferous assemblage, including the lack of echinoderm or bryozoan remains, and the architectural diversity of the coated grains do not point to hypersaline conditions in the Salta basin for this short time interval. Altogether, these features suggest that the environmental conditions were those of a paleolake with brackish water rather than those of a "carbonate shallow sea" (*e.g.*, Marquillas *et al.*, 2005). Fine angular quartz sand is locally common suggesting episodic terrigenous influx from wadis (ephemeral streams). It is worth highlighting that this environmental interpretation of a quiet-water Argentinian paleolake does not fit with the Bahamian setting that Gasiewicz (1984a, 1984b) conceived for his Upper Jurassic marine ooids, an environmental interpretation that one cannot agree upon either. This topic should not be discussed further without accessing the original Polish material studied, a goal that is out of the scope of this paper.

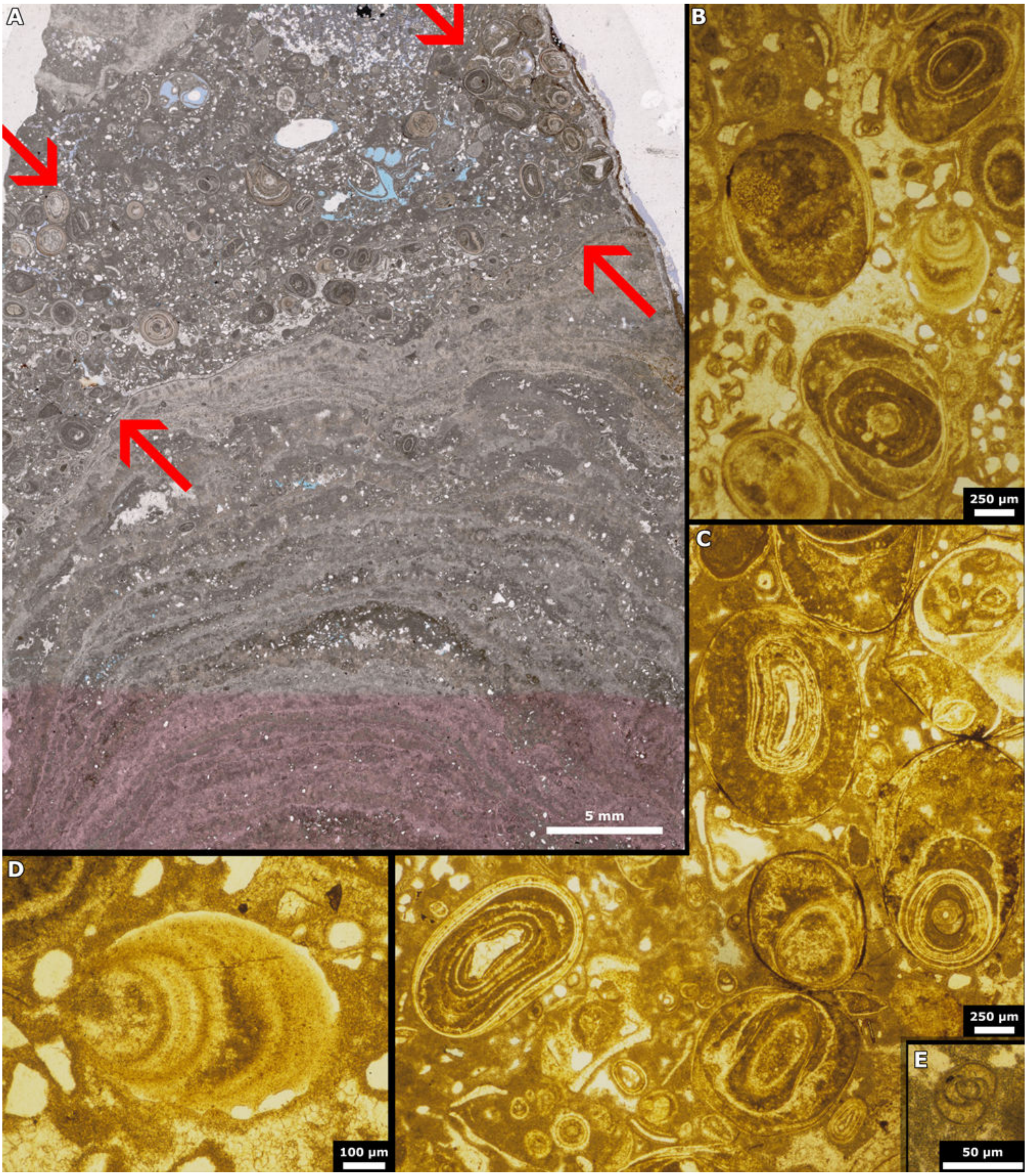

Figure 3: Thin section ARA 309 from the Maastrichtian of Puesto Viejo: **A)** scan of the petrographic thin section. The stromatolitic layers with eccentric ooids are framed by red arrows; **B-C)** various eccentric ooids; **D)** detail of B; **E)** small benthic foraminifer. Scale bars: **A)** 5 mm; **B-C)** 250 µm; **D)** 100 µm; **E)** 50 µm.

In sample ARA 309, ooids are confined to few stromatolitic layers at the top of a microbial column (Fig. 3.A). These ooids, ovoid in shape and matching the characteritics of the eccentric ooids as defined by GASIEWICZ (1984a, 1984b: "ekscentryczne ooidy"), commonly reach a maxImum length of 1 mm, which is almost twice the dimension given for GASIEWICZ's ooids. Similarly they consist of layers made either of yellowish "fibrite" (a neologism for "fibrous calcite", *i.e.*, "material with one large and two small dimensions" (FOLK, 1974)) or of dark micrite (= microcrystalline calcite). Micrite and fibrite layers are alternating more or less regularly within the ooid cortex. The fibrite forms roughly isopachous crusts of palisade crystals, whereas the micrite forms clearly anisopachous crusts, *i.e.*, genuine micritic bumps.

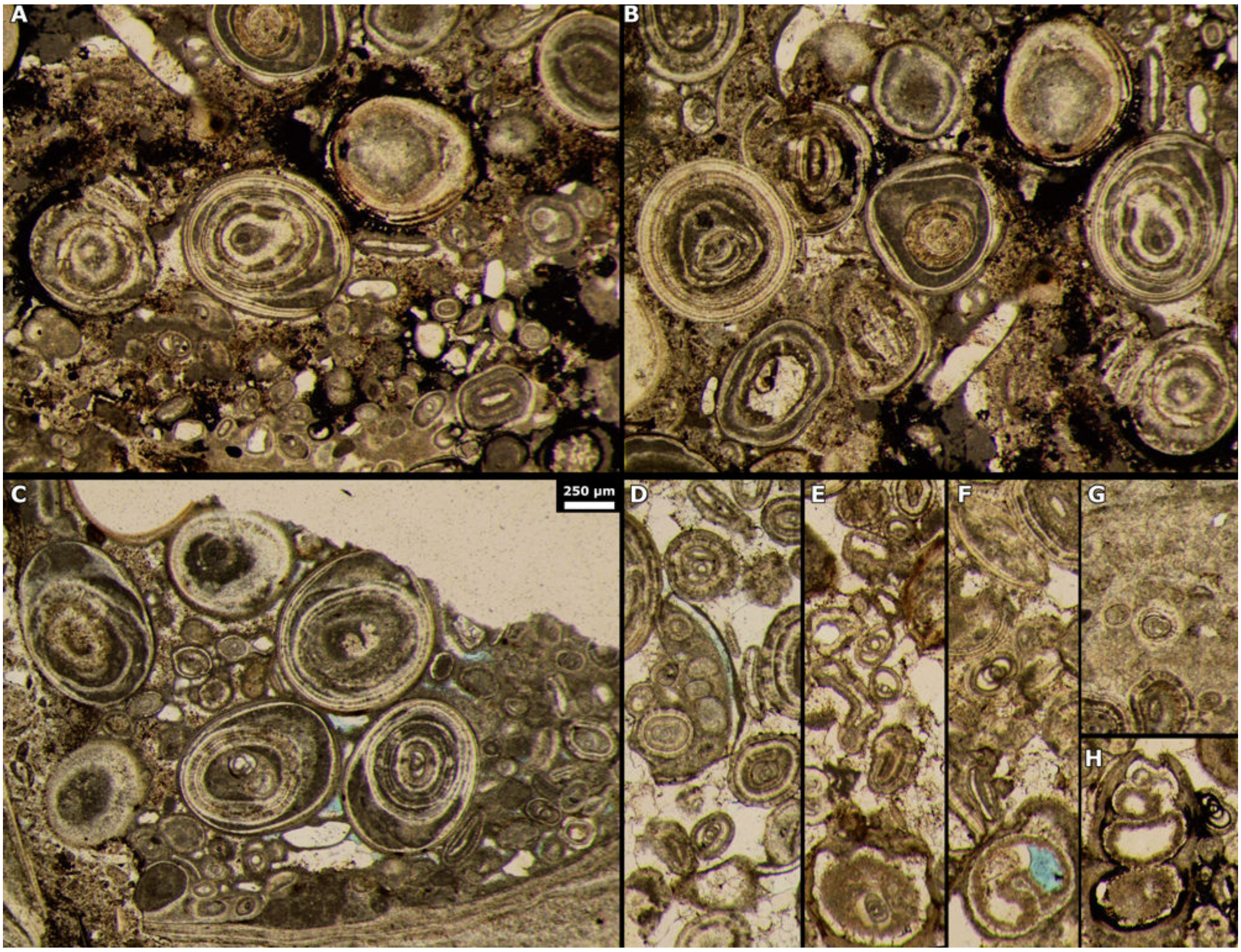

Figure 4: Thin section AG 309 B from the Maastrichtian of Puesto Viejo: **A-C)** various eccentric ooids; **D-H)** small benthic foraminifers with gastropods (in F and H). A single 250 µm scale bar is used for all photos.

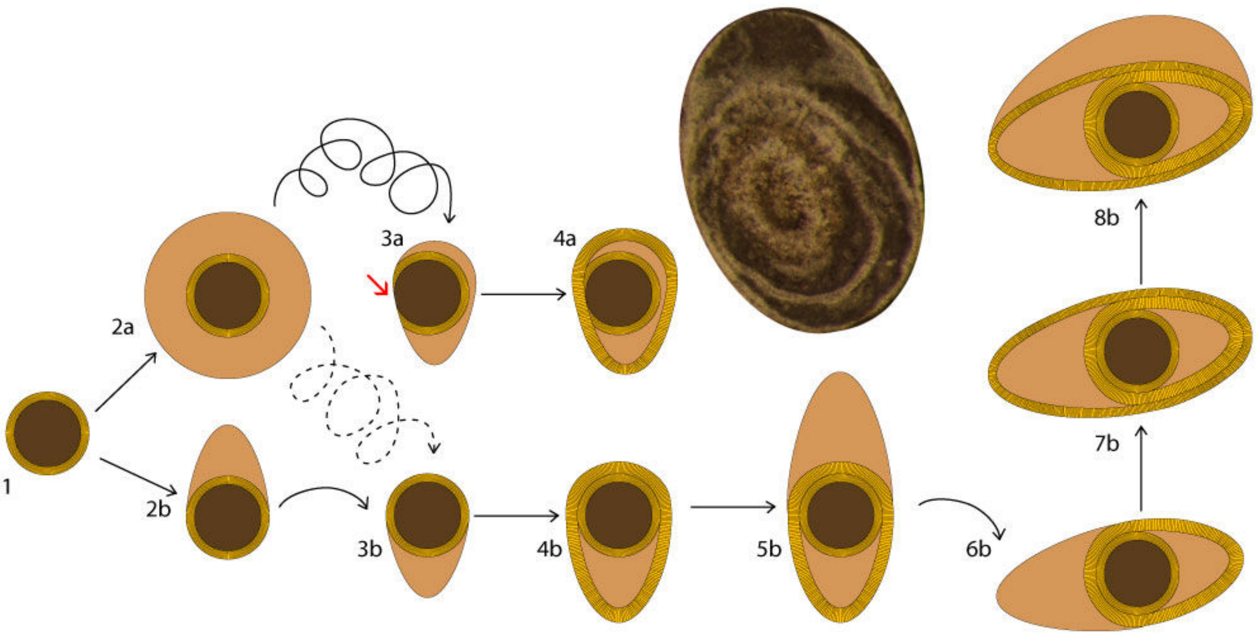

Figure 5: Tentative models for the growth of Argentinian eccentric ooids. 1) nucleus with an isopachous fibrite crust. Option a: 2a) thick isopachous micrite crust; 3a) partial abrasion of the micritic crust and the underlying fibrite crust (red arrow: truncation of the fibrite crust); 4a) new isopachous fibrite crust. The end product is a hiatus ooid *sensu* BERG (1944). Option b (our favorite model): 2b) micrite bump (anisopachous crust) growing in an upward direction; 3b) tilting of the ooid; 4b) new isopachous fibrite crust; 5b) new micrite bump growing in an upward direction; 6b) tilting of the ooid; 7b) new isopachous fibrite crust; 5b) new micrite bump growing in an upward direction. The shortcut transition with abrasion from 2a to 3b is highly improbable.

4. The wobbly ooid hypothesis

The maximum thickness of the micritic bumps always shifts from one bump to the next. Consequently, the center of mass of the ooid changed with each addition of a new micritic bump. Such coated grains should not be confused with other "eccentric" ooids, such as asymmetric ooids (*e.g.*, BERG, 1944, Fig. 26; FREEMAN, 1962, Fig. 6), hiatus ooids (*e.g.*, BERG, 1944, Fig. 27), half-moon ooids, or even "broken" ooids. Therefore, it is suggested here to call them "wobbly ooids". In Argentinian stromatoids described in a previous paper (GRANIER & LAPOINTE, 2021), "spongiostromate, either micritic or spongious, fabrics" are the key to the differential growth of the stromatolitic column whereas the contribution of thin fibrite crusts can be neglected. It is suggested here that the microbial consortium responsible for the micritic bumps comprises some phototrophic species. This hypothesis is taken into consideration in our favorite model (Fig. 5) to tentatively explain the growth of Argentinian eccentric ooids. Accordingly, the growth of each new micritic bump is assumed to have been in an upward direction. Contrary to GASIEWICZ's model (1984a, 1984b), our favorite model (Fig. 5) does not necessarily imply any significant abrasion, suspension, saltation, or traction. However, it should be noted that this model cannot explain all atypical features observed in the studied material (*e.g.*, Fig. 3.D).

The architecture of the wobbly ooids vaguely resembles that of some cave pearls recently documented by MELIM and SPILDE (2021: Figs. 7.B, 8.A) but they should not be confused with these because the latter are commonly larger (up to 14 mm) than the former. The dimensions of these cave pearls range within the pisolite category. Additionally, cave pearls are characterized by low-Mg calcite (MELIM & SPILDE, 2021), a mineralogy that is consistent with their concretionary growth in place during vadose diagenesis, whereas Argentinian ooids and bothryoids are primarily made of high-Mg calcite (GRANIER & LAPOINTE, 2021).

5. Conclusion

Both the peculiar ooids from the Maastrichtian Yacoraite Formation in NW Argentina and ooids described from the Upper Jurassic strata in SE Poland correspond to a distinct class of eccentric ooids: "wobbly ooids". They are not likely to be confused with asymmetric ooids, hiatus ooids, half-moon ooids, or "broken" ooids. Althought they are found in contrasting types of environments, lacustrine with brackish water for the first and marine with normal sea water for the second, these ooids are both markers of quiet water settings. It is assumed that transitions from fibrite cortical layers to micrite bumps probably correspond to changes in the microbial consortia. The eccentricity varied during growth due to repeated shifting of the center of mass of the ooids mostly related to the asymmetric growth of micrite bumps of their cortices.

Acknowledgements

The rock sample studied here was collected by the second author (P.L.) on the occasion of a joint mission of Total - Compagnie Française des Pétroles, and IFP - Institut Français du Pétrole from October 5 to November 3, 1988. He acknowledges the support of his IFP colleagues, Bernard COLLETTA, Jean LETOUZEY, and Roland VIALY, for fieldwork. They were granted permission to access and sample the section by representatives of the Cementos Minetti, now part of the Lafarge Holcim Group. The first author (B.G.) would like to thank Phil SALVADOR for his appreciated help with the original (English) text. The manuscript also benefited from some comments of three anonymous reviewers.

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E-ISSN 1634-0744
DOI 10.2110/carnets.2022.2205

The KALKOWSKY Project - Chapter III Significance of primary radial fabrics associated with ancient partly leached or recrystallized calcareous ooids

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Abstract: Calcitic ooids and bothryoids from the Yacoraite Formation in the provinces of Jujuy and Salta (Argentina) display radial fabrics pointing to their primarily high-Mg calcite (HMC) nature. The present publication documents some specimens that are partly or fully leached or recrystallized, which raises fundamental questions about the validity of some concepts, such as the very existence of the so-called "two-phase"/"bimineralic" ooids. It is assumed here that the organic content in the oolitic cortices (and, subsequently, its degree of oxidation) is the key to explaining some differential diagenetic alterations.

Key-words:

- high-Mg calcite;
- aragonite precursor;
- bimineralic ooids;
- radial fabrics;
- leaching;
- recrystallization;
- Argentina

Citation: GRANIER B.R.C. & LAPOINTE Ph. (2022).- The KALKOWSKY Project - Chapter III. Significance of primary radial fabrics associated with ancient partly leached or recrystallized calcareous ooids.- *Carnets Geol.*, Madrid, vol. 22, no. 5, p. 149-160.

Résumé : *Le Projet KALKOWSKY - Chapitre III. Importance des textures radiaires primaires associées aux anciens ooïdes calcaires partiellement dissouts ou recristallisés.-* Les ooïdes et les bothryoïdes calcitiques de la Formation Yacoraite dans les provinces de Jujuy et de Salta (Argentine) présentent des textures radiaires attestant qu'ils sont principalement constitués de calcite fortement magnésienne (HMC). Cet article rapporte l'existence de quelques spécimens partiellement ou totalement dissouts ou recristallisés, ce qui soulève des questions fondamentales sur la validité de certains concepts tels, par exemple, que celui suggérant l'existence d'ooïdes pouvant comporter deux phases minérales distinctes. Nous suggérons ici que le contenu organique du cortex oolithique (et, par la suite, son degré d'oxydation) permettrait d'expliquer certains phénomènes d'altérations diagénétiques différentielles.

Mots-clefs :

- calcite fortement magnésienne ;
- précurseur aragonitique ;
- ooïdes biminéraux ;
- texture radiaire ;
- lessivage ;
- recristallisation ;
- Argentine

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Published online in final form (pdf) on March 4, 2022
[Editor: Michel MOULLADE; language editor: Phil SALVADOR; technical editor: Bruno R.C. GRANIER]

1. Introduction

Although in the literature some earlier authors theorized that the radial oolitic structure is a secondary acquirement, *i.e.*, a result of diagenesis (*e.g.*, CAYEUX, 1931; SHEARMAN *et al.*, 1970), there is now a common agreement that the radial structure of either high-Mg calcite (**HMC**) or aragonite ooids is primary (*e.g.*, KAHLE, 1974; SANDBERG, 1975; TUCKER, 1984, amongst others).

Following the preceding contributions (GRANIER & LAPOINTE, 2021, 2022), this new chapter of the KALKOWSKY Project chiefly concerns calcareous coated grains, more specifically calcite radial ooids, the cortices of which are made of HMC fibers perpendicularly orientated, and their diagenesis. Its purpose is to report and elaborate on special cases: 1) ooids with primarily HMC oolitic cortices partly or fully recrystallized to form low-Mg calcite (**LMC**) mosaics and 2) others with partly leached cortices, having generated oomoldic cavities that later were partly or fully filled by a LMC drusy cement.

2. Generalities on the mineralogies and the fabrics of calcareous ooids

As stated in the essentials of carbonate petrography summarized in FOLK's (1974) seminal paper the distinctive habits of $CaCO_3$ crystals can aid in the petrographical identification of their polymorphs. For instance, the fibrous crystal habit corresponds to HMC (FOLK, 1974, Fig. 4 left), whereas the blocky crystal habit is characteristic of LMC (FOLK, 1974, Fig. 4 right). In previous papers (GRANIER & LAPOINTE, 2021, 2022), the term "fibrite" was used to refer to the yellowish "fibrous calcite" that commonly forms the cortical layers of ooids - and that cannot be confused with "radiaxial fibrous calcite" -. On the basis of its crystal habit, it was then assumed that this cortical fibrite consists of HMC (*e.g.*, FOLK, 1974). The yellow tinge of radial HMC ooids for instance matches the yellow tinge of HMC echinoderm bioclasts (*e.g.*, GRANIER, 2019, 2020); thus the yellow tinge is a relict of a primary organic presence. Besides calcite (both low- and high-Mg calcites), aragonite is the other common polymorph with needle-like crystals; these needles are much thinner than fibers per definition, and commonly arranged in bundles. Spherulites and some ooids have radial fabrics that are directly related to the arrangement of calcite fibers or aragonite needles, the long axes of which are orientated perpendicular to the oolitic cortical layers, whereas the aragonite needles in Bahamian ooids (and in those from the Persian Gulf, as in Fig. 1) have their long axes tangentially orientated within the oolitic cortical layers.

In most calcitic ooids with radial-concentric fabrics, thin micrite layers delimit thicker fibrite growth bands. The thicknesses of these bands are responsible for the more or less visible radial pattern of the oolitic fabrics whereas the density of micrite layers (hence the number of fibrite interlayers) is responsible for their more or less visible concentric pattern. Because all transitional fabrics from a radial extreme to a concentric extreme may exist, making out their formal division into sub-categories is rather artificial. For instance, GRANIER (1994a, 1994b, 1994c, 1995a, 1996) describes an overall gradational sequence from calcitic "radial ooids" at the bottom of a Lower Callovian oolite in the Villeperdue oilfield (Paris Basin, France) passing to (radial-) "concentric ooids" in the median part and then to (concentric) "micritic ooids" at the top of the logged sections. Fortunately, in this case study, the occurrence of two short hiatuses in sedimentation permitted that author to sort these ooids into three subcategories, namely radial, concentric and micritic. For instance, in the case of the VPI-01 well (Infoterre), located 1.2 km S of Le Gault-Soigny (Marne), 100 km E of Paris, the radial/concentric and the concentric/micritic boundaries are respectively located at circa 1816 m and 1827 m core depths (Fig. 2). Note that the micritic ooids are not micritized ooids, but ooids with numerous micrite layers and very thin fibrite growth bands.

3. Material and general setting

Most ooids studied below display radial-concentric fabrics similar to the Paris Basin ooids. However, they are found associated with partly and fully replaced ooids, partly leached ooids, or both. Some calcite ooids (Fig. 2) from the Paris Basin (Villeperdue, at 48°48'19.0"N 3°35'42.0"E) and some aragonite ooids (Fig. 1) from the Abu Dhabi offshore (Abu Al Bukhoosh, circa 25°29'37.3"N 53°07'38.6"E) are also illustrated herein but only for comparison purpose.

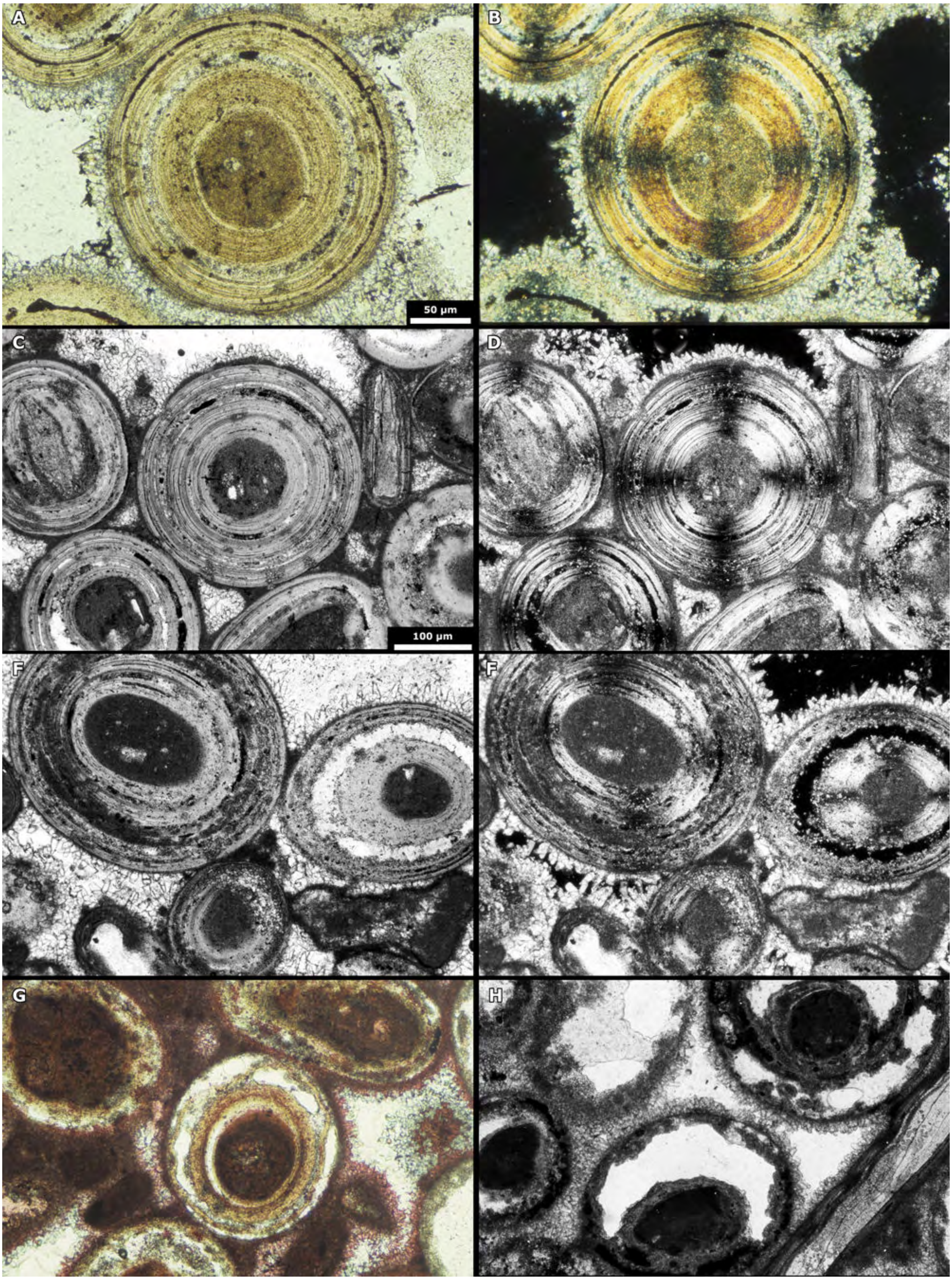

Figure 1: Aragonite ooids from ABK wells (Abu Al Bukhoosh oil field, Abu Dhabi offshore), Pleistocene: **A-D)** one cortical layer was oxidized and leached, ABK PP53, 25.25 m; **E-F)** two discrete cortical layers were oxidized and leached, ABK 51, 25 m; **G-H)** ABK 51, 24.5 m. In all cases, an intergranular "dog-tooth" calcite cementation precedes the aragonite leaching that affected a few cortical layers only. B, D, F) Crossed polarizers. Scale bars 100 µm (photos A-B) and 50 µm (photos C-H).

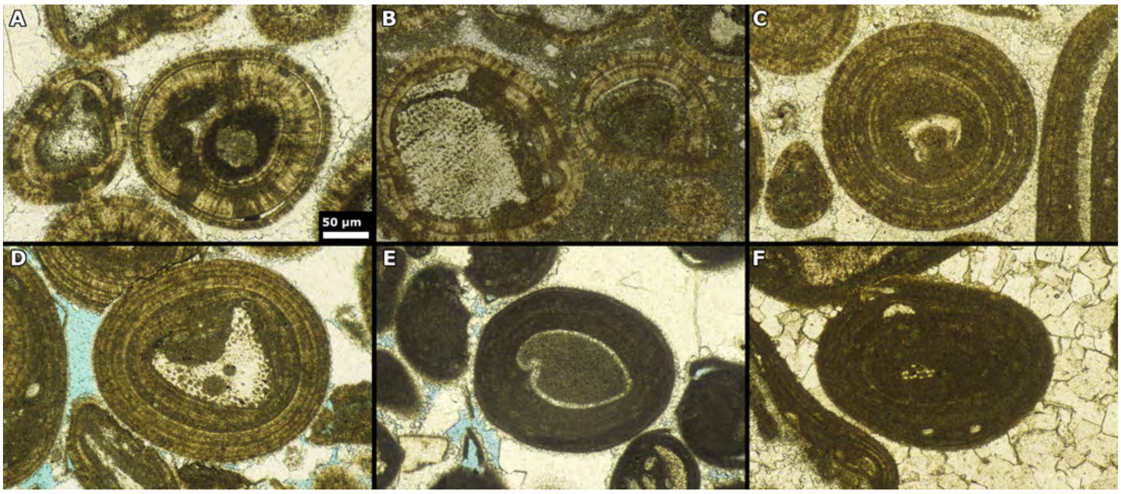

Figure 2: Calcite ooids from the VPI01 well (Villeperdue oil field, France), lower Callovian: "radial" ooids (A-B); "concentric" ooids (C-D); "micritic" ooids (E-F). **A)** 1828 m core depth, **B)** hiatus ooid on the right, 1827.75 m CD, **C)** 1836 m CD, **D)** 1816.75 m CD, **E)** 1811.10 m CD, **F)** 1806.75 m CD. Scale bar 50 µm (all photos).

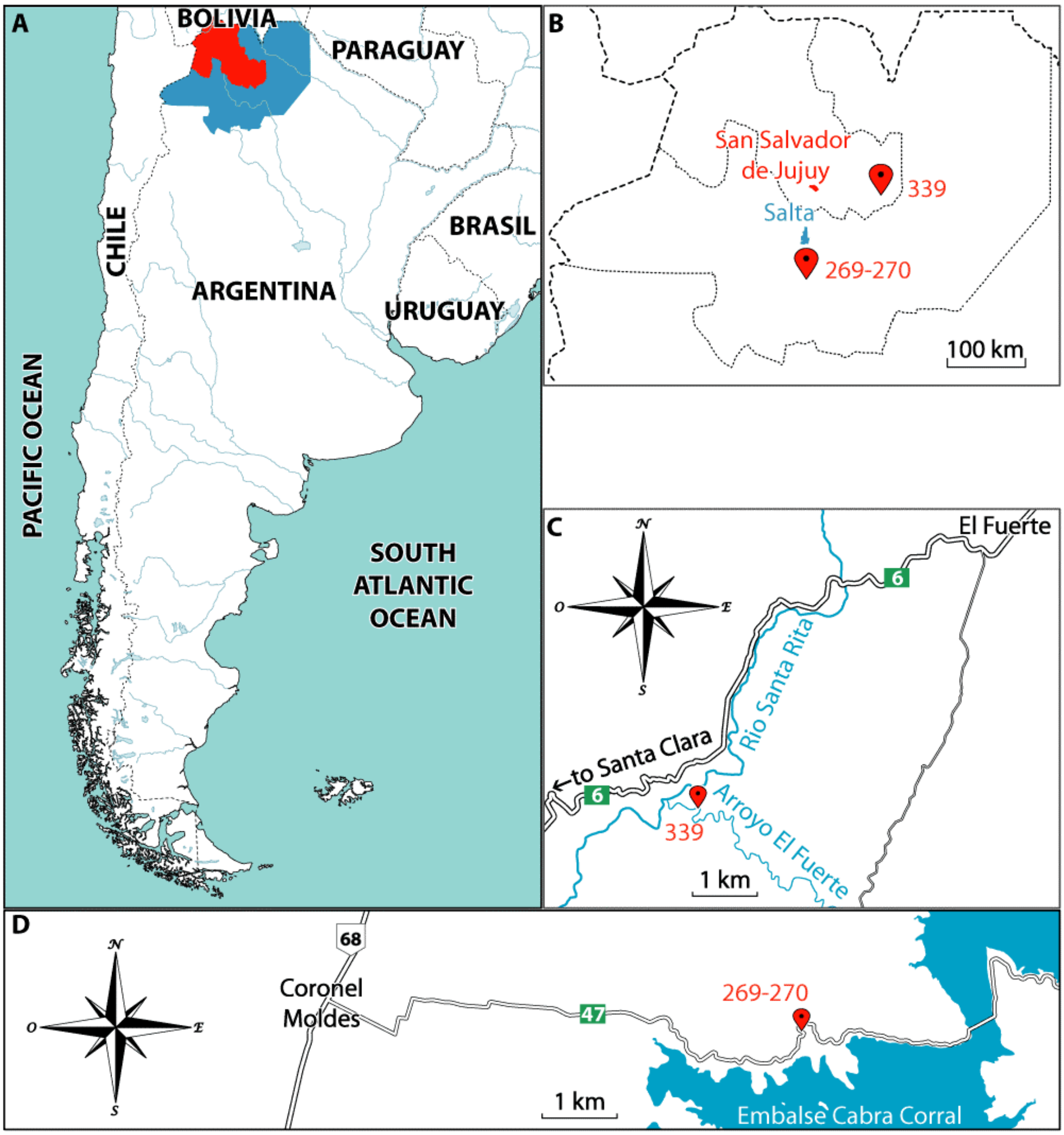

Figure 3: A) Location map of the provinces of Jujuy (red) and Salta (blue), N Argentina; **B)** location map of the studied sections in N Argentina; **C)** location of sampling 339 (Jujuy); **D)** location of samplings 269-270 (Salta).

The Argentinian material shown here was collected by one of us (P.L.) accompanied by three IFP colleagues (namely Bernard COLLETTA, Jean LETOUZEY, and Roland VIALY) at two discrete localities (Fig. 3):

1) on October 6, 1988. The first section measured (Figs. 4 - 5) crops out some 60 km south of Salta, more precisely at 25°17'04.4"S 65°24'-56.1"W (Province of Salta, Argentina), on the northern side (left hand side) of the road 47 from Coronel Moldes to Puente Dique Cabra Corral (Fig. 3.B, .D), on a bend with a view to the "embalse" (dam) Cabra Corral. It is located in the Metán subbasin of the Salta Basin. Although in the initial (unpublished) report it was ascribed to the Maiz Gordo Formation (MORENO, 1970), Thanetian-Ypresian in age [Late Paleocene - Early Eocene in age (*e.g.*, DEL PAPA, 1999)], this section, appears in a recent contribution of FREIRE (2012) as "Afloramento Viñuales" of the "Sequência Balbuena IV" (*op.cit.*, Figs. 5.1, 5.10, 8.7) of the Yacoraite Formation and is currently reascribed a Danian age. Four petrographic thin sections were prepared from two pieces of rock labelled ARA 269 and ARA 270. They were picked at the top of the logged section: The two first thin sections (ARA 269 and ARA 270) are probably lost; the two second thin sections (AG 269 and AG 270) were prepared from offcuts of the first two;

2) on October 13, 1988. The second section was measured (Fig. 6) in Arroyo El Fuerte. It crops out 6 km south of El Fuerte, some 45 km SSW of Palma Sola andsome 85 km east of San Salvador de Jujuy (Fig. 3.B-C), circa 24°17' 55.0"S 64°27'42.7"W (Province of Jujuy, Argentina). It is located in the Lomas de Olmedo subbasin of the Salta Basin. It spans the boundary of the Lecho and Yacoraite formations and comprises strata that are ascribed Campanian-Maastrichtian ages. Two petrographic thin sections were prepared from one piece of rock labelled ARA 339. It was picked near the bottom of the logged section: The first thin section (ARA 339) is probably lost, the second thin section (AG 339) was prepared from an offcut of the first one.

4. Description of the thin sections prepared from samples ARA 269-270 (Salta) and ARA 339 (Jujuy)

1) The Salta microfacies (ARA 269-270): The microfacies of thin section AG 269 corresponds to a floatstone of bothryoids (Fig. 7.N) and large cerebroid ooids (Fig. 7.F) with a wackestone silty matrix. In addition to the siliciclastic silt, the matrix yields smaller ooids and fish teeth. Ostracod shells are also present, commonly as nuclei of coated grains. One third of the thin section AG 270 exhibits the same facies; its remaining two thirds displays a mudstone texture.

2) The Jujuy microfacies (ARA 339): The microfacies of thin section AG 339 corresponds to an oolitic grainstone. Besides the ooids, allochems comprise few micritic extraclasts. Ostracod shells are common, mostly as oolitic nuclei.

5. Interpretation of some oolitic features from samples ARA 269-270 (Salta) and ARA 339 (Jujuy)

The mineralogy of the ooids and bothryoids of ARA 269-270 (Salta) and that of the inner cortices of the ooids of ARA 339 (Jujuy) are largely, if not exclusively, HMC. Locally, the two formers show evidence of recrystallisation whereas the latter was partly affected by recrystallisation but also by leaching and cementing.

1) Salta ooids and bothryoids (ARA 269-270, Fig. 8): In thin section (hence in two-dimensional view), some oolitic cortices yield scattered or amalgamated (*i.e.*, forming an idiotopic mosaic) polygonal sections of calcite crystals up to 50 µm in width. At first sight they could be confused with transverse sections of the "clubs" described by HALLEY (1977, Fig. 3.c-d) from the Great Salt Lake aragonite ooids, but whatever the ooid section is, tangential or deep (hence in reconstructed three-dimensional view), the crystal shape remains blocky, not pillaroid. These crystals still retain a yellowish color related to the original organic content. They correspond to the recrystallisation of fibrous HMC into blocky LMC.

2) Jujuy ooids (ARA 339, Fig. 9): Most calcite ooids from thin sections ARA 339 and AG 339 comprise two parts: 1) an outer part, *i.e.*, the outer cortex, and 2) an inner part consisting of the inner cortex and the nucleus, *e.g.*, quartz grain. When preparing the thin sections the inner parts of some ooids were ripped off but when they are preserved they commonly consist of an ooid with a radial-concentric fabric (Fig. 9). Again the inner cortex is probably made of HMC coalescent fibers, the brownish color of which contrasts with the overall yellowish color of the outer cortex. The outer cortex displays a concentric fabric with relicts of growth bands and an alternation of yellowish layers and hyaline layers.

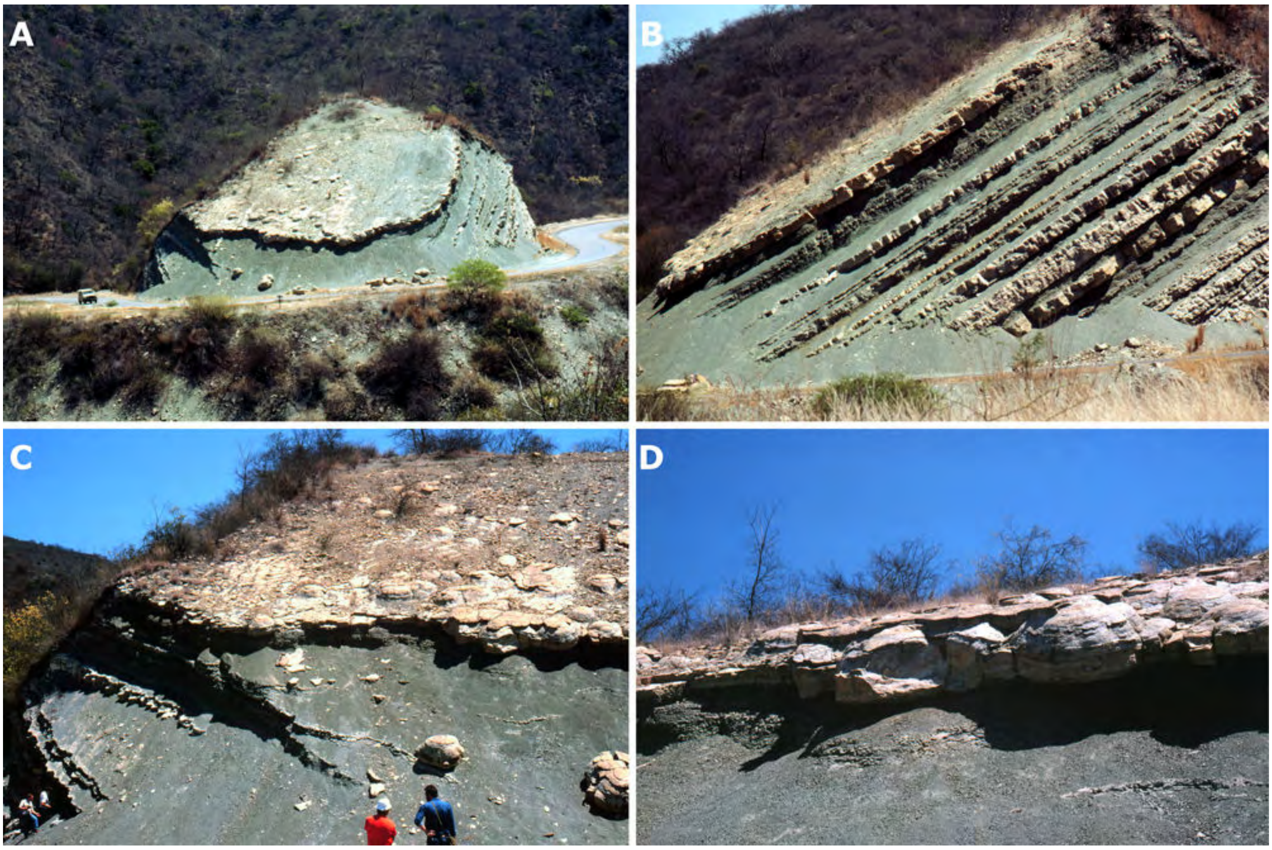

Figure 4: Cabra Corral outcrop. **A)** View from the South; **B)** view from the East; C) structural surface with the uppermost stromatolites; **D)** close-up on the uppermost stromatolites.

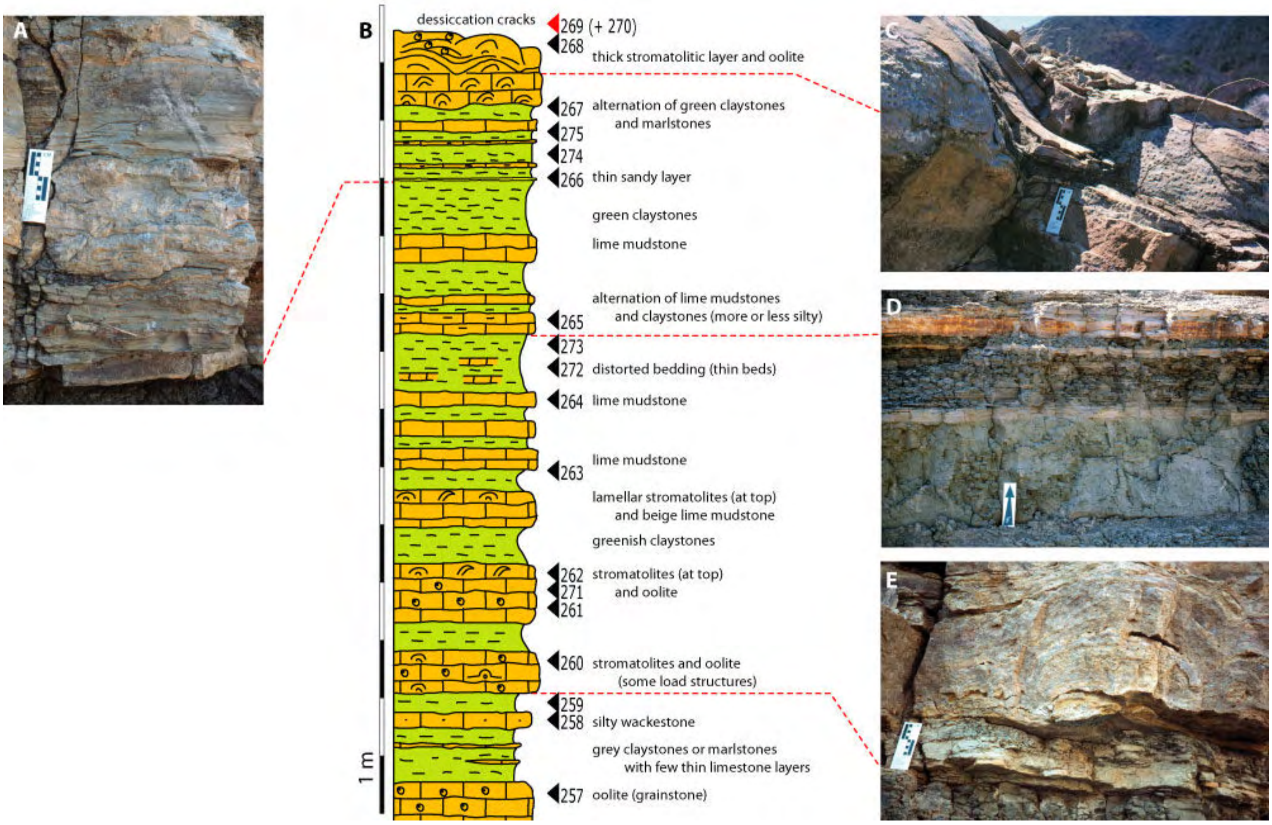

Figure 5: Cabra Corral section. **A)** alternation of green claystones and marlstones; **B)** schematic drawing of the Salta section (Cabra Corral) with location of samples 269 and 270; **C)** uppermost stromatolites; **D)** alternation of lime mudstones and claystones (more or less silty); **E)** lowermost stromatolites.

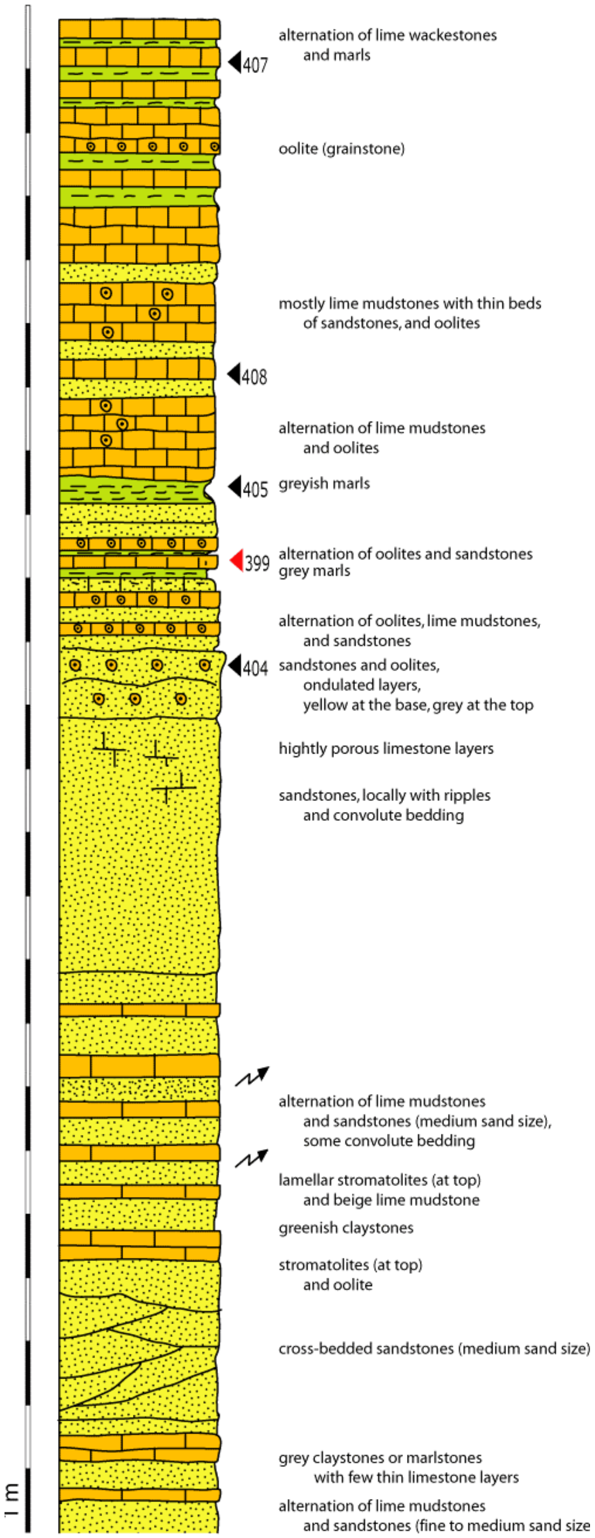

Figure 6: Schematic drawing of the Jujuy section (El Fuerte) with location of sample 339.

Tangential sections, which per definition do not reach the ooid inner part, are the most suitable to document the morphology of the LMC crystals of the outer cortex. Yellowish crystals, blocky in shape and almost equidimensional, form an hypidiotopic mosaic as a result of recrystallisation of some outer cortical layers. When the recrystallized layers are relatively thick, their fabric may be similar to the "brick-like texture" of some Italian Triassic pisolites described by Assereto and Folk (1976). On the other hand, hyaline crystals correspond to the drusy cementation of voids left by leaching after some other outer cortical layers. The typical arrangement of the drusy cement with crystals sizes increasing centripetally is better seen when the cavities are relatively large. Some crystals are both colored and hyaline (as is also the case with an echinoderm remain and its syntaxial cement, *e.g.*, Granier, 2020, Fig. 1.A-B) at the transition from replaced areas to cemented areas. That suggests that part of the cement crystals represents syntaxial overgrowths of replacement crystals.

6. Extended discussion on the Jujuy ooids (ARA 339)

According to generally accepted -but commonly erroneous- views, it is claimed that most recrystallized or leached ooids suggest an aragonite precursor in their oolitic cortices [*] whereas those with partly replaced or leached cortices are interpreted as "two-phase" or "bimineralic" (Buczynski & Wilkinson, 1982; Tucker, 1984; Chow & James, 1987; Heydari & Moore, 1994; Algeo & Watson, 1995). Probably because common bioclats such as originally HMC echinoid remains do not show obvious signs of recrystallization or leaching, the earlier authors did not really imagine the option that fully or partly recrystallized or leached ooids could have originally been "monomineralic", *i.e.*, made mostly of HMC. This was appreciated by Granier (2014) who

[*] *Cantrell D.L. (2006).- Cortical fabrics of Upper Jurassic ooids, Arab Formation, Saudi Arabia: Implications for original carbonate mineralogy.-* Sedimentary Geology, *vol. 186, no. 3-4, p. 157-170.*

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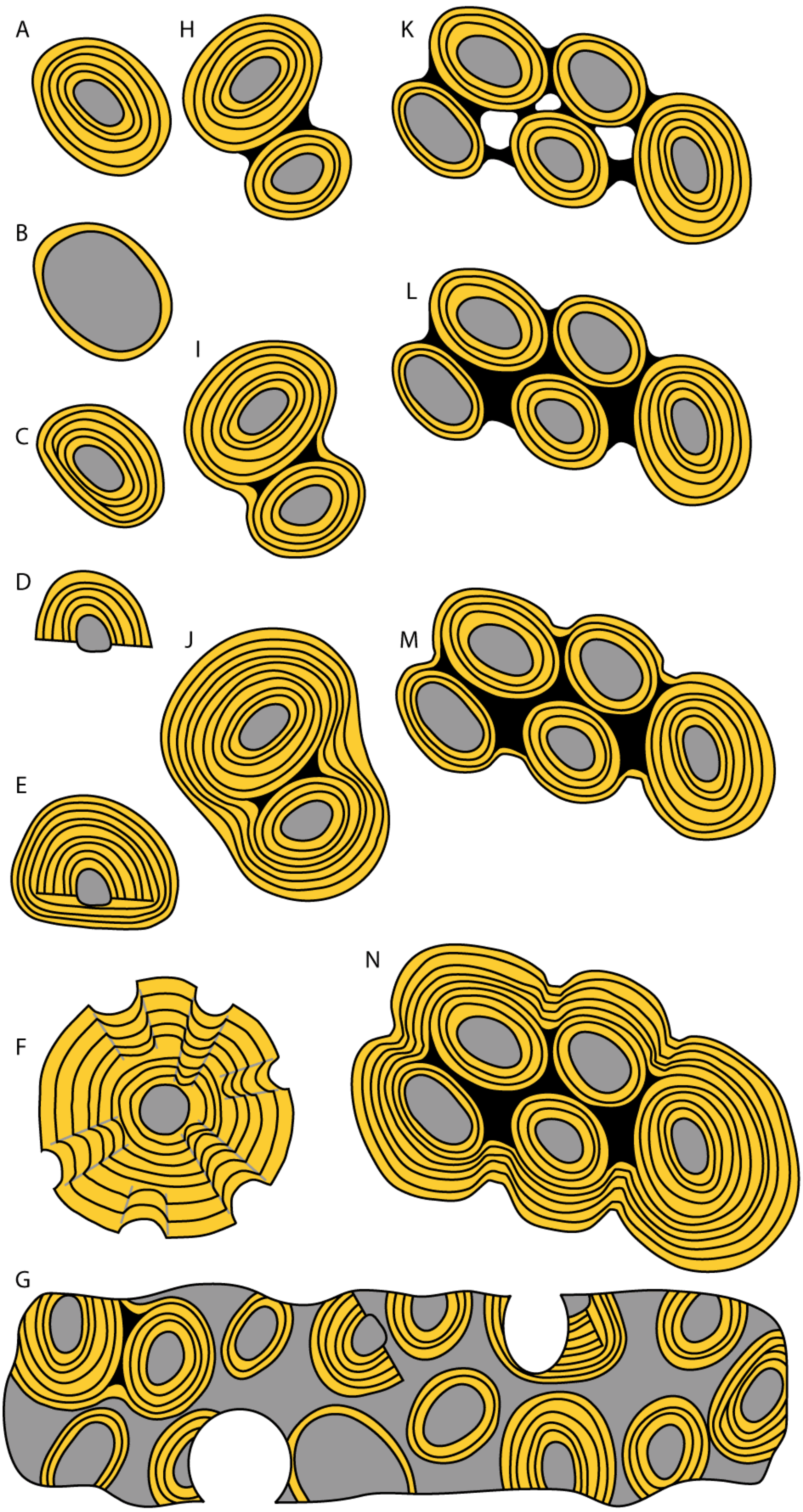

◀ **Figure 7:** Various morphologies of coated grains: **A)** regular ooid; **B)** superficial ooid; **C)** hiatus ooid, regenerated; **D)** hemiooid or broken ooid *sensu stricto*; **E)** broken ooid *sensu lato*, broken but regenerated; **F)** cerebroid or pitted ooid; **G)** oolitic lithoclast with borings; **H)** aggregate with two ooids; **I)** superficial biooid or superficial complex ooid; **J)** biooid or complex ooid; **K)** aggregate or grapestone (initial amalgamation stage); **L)** lump (advanced amalgamation stage); **M)** superficial bothryoid; **N)** bothryoid.

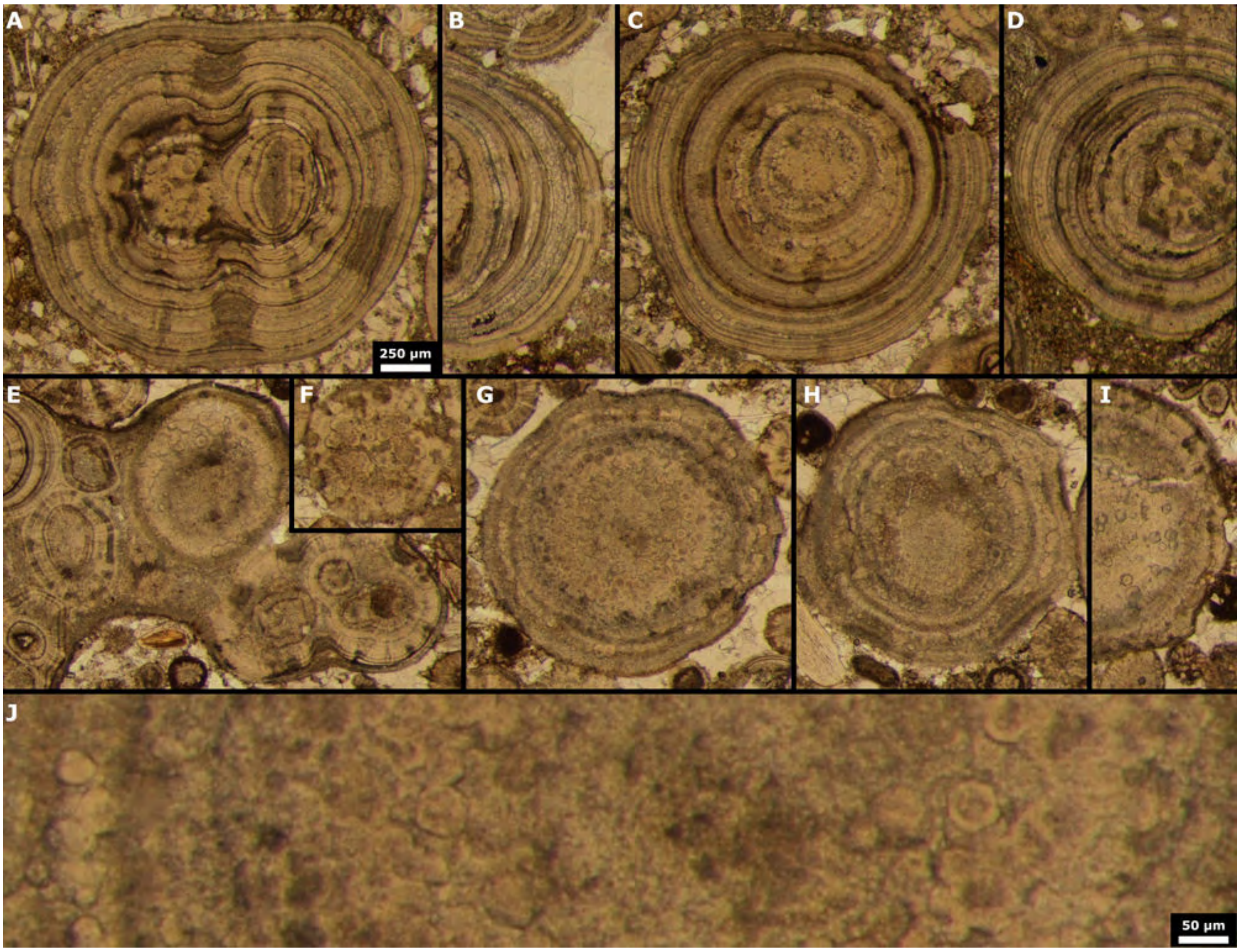

Figure 8: Thin sections AG 269 (A-E) and AG 270 (F-J): **A)** large complex ooid (with a biooid nucleus), quite similar to some bothryoids); **B)** large ooid with recrystallized cortical layers (localized cementation –following some leaching- cannot be fully excluded); **C-D)** large ooids with recrystallization mosaics in tangential sections of their inner cortical layers and scattered replacement crystals in their outer layers; **E)** bothryoid with a recrystallization mosaic in one ooid of the original lump; **F-I)** large ooids with recrystallization mosaics in tangential sections of their inner cortical layers; **J)** detail of the mosaic of the ooid G. Scale bars: A-I) 250 µm; J) 50 µm.

argued that "the statement that aragonitic ooids are commonly dissolved does not imply the converse, *i.e.*, that dissolved ooids were originally aragonitic". Subsequently, finds questioning the earlier views showed up in discrete case studies from the Middle Jurassic of France (GRANIER, 1995b, 2014), the Lower Cretaceous of Switzerland (GRANIER *et al.*, 2014, 2016), and the Middle Cretaceous of Angola (GRANIER, 2019). Likewise, partly recrystallized Salta ooids and bothryoids (ARA 269-270) represent one more case study to add to the reference list because they document the replacement of HMC (not aragonite) by LMC. The Jujuy ooids (ARA 339, Fig. 9), as the Hauterivian ooids from Switzerland (GRANIER *et al.*, 2014, 2016) before, represent a more tricky case: **1)** the inner cortex is made of brownish HMC fibers with a radial-concentric habit; **2)** the outer cortex is made of LMC crystals, either yellowish blocky (replacement) or hyaline drusy (cement). Based on existing literature (BUCZYNSKI & WILKINSON, 1982; TUCKER, 1984; CHOW & JAMES, 1987; HEYDARI & MOORE, 1994; ALGEO & WATSON, 1995), these Jujuy ooids could have been interpreted as "two-phase" or "bimineralic", *i.e.*, HMC for their inner cortices and aragonite for their outer cortices, but a more credible option is outlined below.

Long before the first author (GRANIER, 1995b, 2014; GRANIER *et al.*, 2014, 2016) several authors (*e.g.*, DANGEARD, 1936; NEWELL *et al.*, 1960; FREEMAN, 1962; TRICHET, 1968; SHEARMAN *et al.*, 1970; KAHLE, 1974; SANDBERG, 1975; HALLEY, 1977) agreed upon the dual nature, mineral and organic, of oolitic cortices. However, a few among them stressed a possible significant impact of the organic content (its presence or its removal through oxidation) during diagenetic processes (*e.g.*, SHEARMAN *et al.*, 1970; SANDBERG, 1975; GRANIER, 1995b, 2014; GRANIER *et al.*, 2014, 2016).

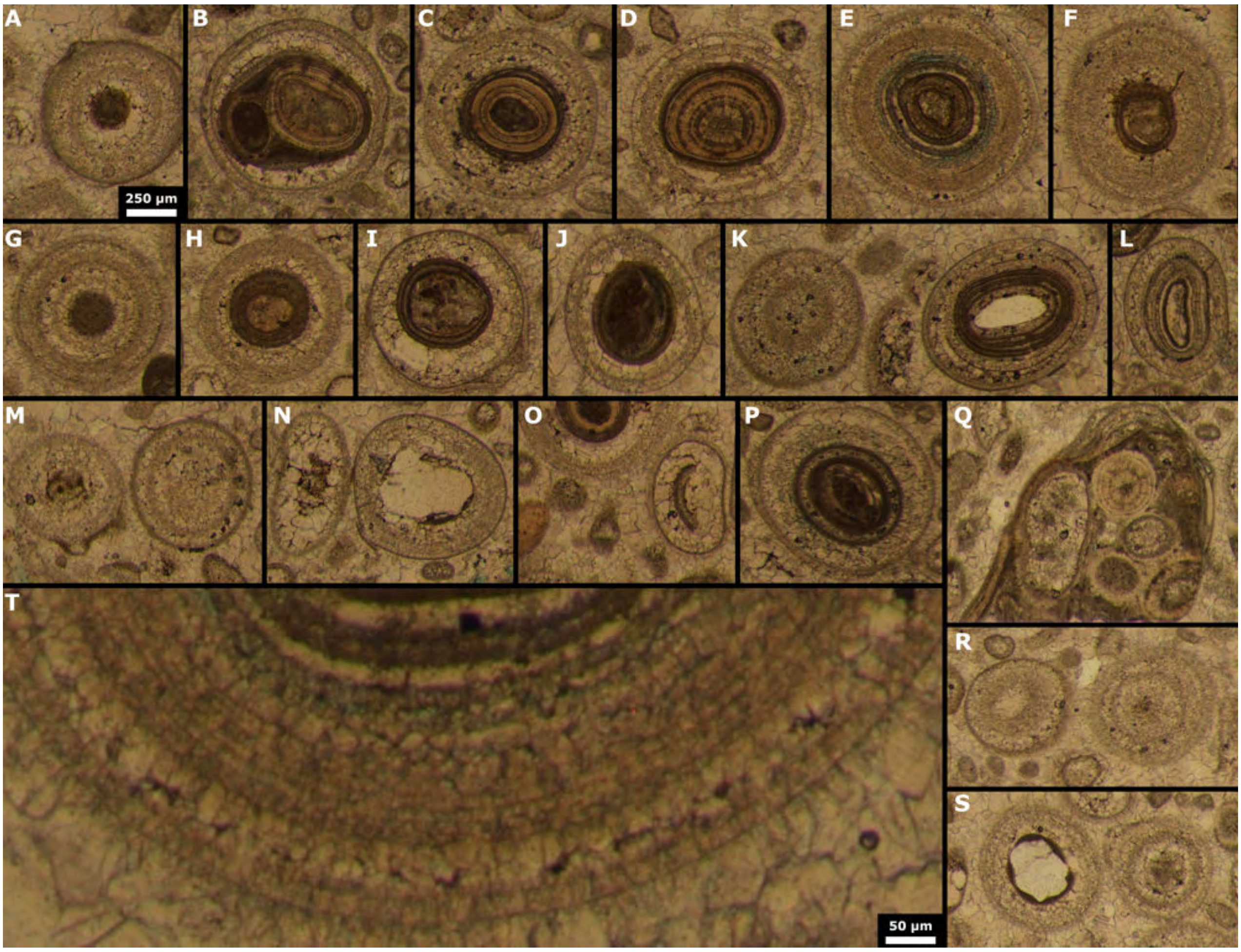

Figure 9: Thin section AG 339: **A-S)** partly leached and cemented oolitic cortices, including A?, B-F, ? G, H-L, ?O) oolitic sections displaying a radial inner cortex; B) biooid as a nucleus (= inner part); C) hiatus ooid as a nucleus (= inner part); K, N, S) ooids with quartz nuclei; Q) oolitic lithoclast with an oolitic cortex; **T)** detail of the "brick-like texture" of the ooid E. Scale bars: A-S) 250 µm; T) 50 µm.

In the case of Pleistocene ooids from Abu Dhabi, some cortical layers of the aragonite ooids could be missing (Fig. 1). It is suggested that, in these specific layers, the oxidation of the organic matter in the meteoric vadose zone facilitated the leaching of aragonite by acidic fresh-water. This model for Pleistocene aragonite ooids can easily be transposed to ancient HMC ooids. With this picture in mind, the "two-phase" or "bimineralic" model stumbles.

According to Tucker (1984), "Two phase ooids could either reflect" **1)** "the reworking of ooids from one area into another where a different mineral was being precipitated, or" **2)** "some change in the physico-chemical conditions at the site of ooid formation, causing a change in the carbonate mineral being precipitated". Both hypotheses, to be valid, need to be two-way processes. However, to our knowledge, that is never the case. When an ooid has both an inner cortex and an outer cortex the layers of the former remain unaltered whereas there is no record of ooids with unaltered outer cortical layers and recrystallized or leached and cemented inner cortical layers.The alternative hypothesis presented in the case of the Hauterivian ooids from Switzerland (Granier *et al.*, 2014, 2016) suggests that the key features explaining the centripetal diagenetic processes are related to the organic content in their oolitic cortices, *e.g.*, "the ratio of mineral to organic material" and variations of "the degree of oxidation of the organic matter" within discrete cortical layers, as well as the more or less advanced "centripetal oxidation process". The latter authors (Granier *et al.*, 2014, 2016) further concluded that the Swiss ooids were originally monomineral, *i.e.*, made almost exclusively of HMC. This last hypothesis is the only one tenable that explains the fabrics of the Jujuy ooids (ARA 339). *Ipso facto* it is also a valid hypothesis for explaining many earlier so-called "two-phase" or "bimineralic" ooids (actually probably mostly monomineralic ooids with HMC cortices).

7. Conclusions

On the basis of the present study and reinterpreted observations from our predecessors, it is proposed that:

1) ancient HMC ooids and aragonite ooids could never occur in the same sample, *i.e.*, they probably never occurred at the same time in a same location, and

2) the association of radial fabrics with partly or fully leached or recrystallized calcite ooids points to original cortices being composed mostly of HMC, and neither of aragonite nor with a "two-phase"/"bimineralic" nature.

The logic behind this proposed hypothesis is that it is unlikely geochemical settings favoring either HMC ooids and/or aragonite ooids occur adjacent to one another, and to date no two such settings have ever been seen.

Acknowledgements

This paper is dedicated to our former colleague, the late Edmond Ousset (1954-2021). Amongst other responsabilities during his full career with Total, he was Chief Geologist in "Filiale France" at Paris La Défense from 1988 to 1991 and Exploration Manager in Total Austral at Buenos Aires from 1995 to 1998. The Argentinian material studied here was collected by the second author (P.L.) during a joint mission of Total - Compagnie Française des Pétroles, and IFP - Institut Français du Pétrole from October 5 to November 3, 1988. He acknowledges the support of his IFP colleagues, Bernard Colletta, Jean Letouzey, and Roland Vialy, for fieldwork. The first author (B.R.C.G.) would like to thank Phil Salvador for his appreciated help with the original (English) text and to Christopher G. St. C. Kendall for a stimulating discussion on radial HMC ooids.

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Carnets Geol. 22 (8)

E-ISSN 1634-0744
DOI 10.2110/carnets.2022.2208

The KALKOWSKY Project - Chapter IV
Case study of the Happy Spraberry oil reservoirs in NW Texas (with a micropaleontologic and biostratigraphic supplement): Collapsed molds should not be treated as a category of distorted ooids

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Daniel VACHARD [3]

Abstract: The subsurface upper Spraberry Formation in NW Texas is dominantly composed of calcareous turbidites and debris-flows. The petrographic analysis of its porous grain-supported fabrics revealed the presence of controversial superimposed compaction fabrics, sometimes referred to as "distorted ooids". Based on the paragenetic sequence, it is demonstrated that these allochems were not distorted. In fact, the related zigzag and silcrow (§) patterns result from the collapse of molds, either oomolds or biomolds, in response to mechanical compaction of the fragile framework made up of isopachous Low-Mg Calcite cement surrounding these empty molds. As a side finding, this stratigraphic unit, which was said to be late Kungurian in age, is proved to be nearly 7 millions of year older.

Key-words:
- NW Texas;
- Permian;
- ooids;
- oomolds;
- compaction

Citation: GRANIER B.R.C., KENDALL Ch.G.St.C. & VACHARD D. (2022).- The KALKOWSKY Project - Chapter IV. Case study of the Happy Spraberry oil reservoirs in NW Texas (with a micropaleontologic and biostratigraphic supplement): Collapsed molds should not be treated as a category of distorted ooids.- *Carnets Geol.*, Madrid, vol. 22, no. 8, p. 311-332.

Résumé : *Le projet KALKOWSKY - Chapitre IV. Étude de cas des réservoirs pétroliers de Happy Spraberry dans le nord-ouest du Texas (avec un supplément micropaléontologique et biostratigraphique) : Les cavités de dissolution effondrées ne doivent pas être traitées comme une catégorie d'ooïdes déformés.-* La Formation Spraberry supérieur reconnue dans des gisements pétroliers du nord-ouest du Texas correspond pour l'essentiel à des turbidites calcaires et coulées de débris. L'analyse pétrographique de ses faciès poreux à grains autoportés a révélé la présence de structures superposées de compaction, structures controversées parfois appelées "ooïdes déformés". Sur la base de la séquence paragénétique, il est démontré que ces allochems n'ont pas été significativement déformés. En fait, les motifs associés en zigzag et ceux en § (deux S combinés, symbole typographique de paragraphe) résultent de l'effondrement de moules de dissolution, soit d'ooïdes, soit de bioclastes, en réponse à la compaction mécanique de la structure fragile constituée par le ciment isopaque en calcite peu magnésienne délimitant ces cavités. Par ailleurs, cette unité stratigraphique, à laquelle on attribuait un âge Kungurien supérieur, s'avère être près de 7 millions d'années plus ancienne.

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Published online in final form (pdf) on June 2, 2022
[Editor: Michel MOULLADE; technical editor: Bruno R.C. GRANIER]

Mots-clefs :

- nord-ouest du Texas ;
- Permien ;
- ooïdes ;
- moules de dissolution d'ooïdes ;
- compaction

1. Introduction

This is the fourth contribution to the Kalkowsky Project (for details see earlier contributions: Granier & Lapointe, 2021, 2022a, 2022b) and a reminder of the importance of careful petrography. During the preparatory work for a manuscript discussing a paper recently published in the journal *Sedimentology* [*], the first author (BRCG) received a temporary loan of a set of 40 thin sections from 7 wells of the Happy Spraberry oil field in the Garza County (NW Texas, USA). The cored intervals comprise both siliciclastic and calcareous turbidites, as well as debris-flows, from the Leonardian upper Spraberry Formation (*e.g.*, Handford, 1981), late Kungurian in age according to Ahr and Hammel (1999, and followers: Clayton & Kerans, 2013) but probably older, *i.e.*, latest Sakmarian to early Artinskian as established by one of us (D.V.): See § Appendix: Micropaleontologic and biostratigraphic supplement. Where the rock has retained a certain amount of both residual primary intergranular and secondary moldic porosity, the best flow units correspond to calcareous grainy turbidites with up to 33% porosity and variable permeability reaching 124 mD. The petrographic study of the thin sections revealed that many molds are not forming separate vug pores *sensu* Lucia (1983), but touching vug pores *sensu* Lucia (1983), contributing to improving their connectivity, hence their permeability. The corresponding fabric is quite unique: Should these pores have been filled with LMC (Low-Mg Calcite) cement they would have been identified either as "pseudooliths" or "verwitterte Kalksteinkörner" [corroded limestone allochems] (Bornemann,1886, Pl. VII, fig. 1), "zerbrochene und auseinander gezogene Oolithkörner" [broken and pulled apart ooids] (Frantzen, 1888, Pl. III, figs. 2-3), "oolithes déformées" [distorted ooids] (Cayeux, 1935, Pl. XV, fig. 55), "distorted oolites and pseudoolites" (Carozzi, 1961, Fig. 6), "deformed recrystallized pisoliths" in chains or in clusters (Kettenbrink & Manger, 1971, Fig. 3.B, 3.D-F), "distorted ooids" (Radwański & Birkenmajer, 1977, Fig. 16.d-e; Richter, 1983, Fig. 3.H; Cantrell & Walker, 1985, Fig. 9.C-D), "distorted pisomolds" (Conley, 1977, Fig. 5.A-D), "spastolithic (deformed) and elephantine (trunk-to-tail) connected ooids" (Wilkinson *et al.*, 1984, Fig. 6.F; Chatalov, 2003, Fig. 1.a-b), or "spastoliths" (Scholle & Ulmer-Scholle, 2003, p. 240 middle-upper, p. 354 middle). Contrary to our predecessors who were dealing with surface samples, hence fully cemented, tight limestones, we have subsurface material sampled from cores from a depth of about 1500 m TVD (true vertical depth). Because these rocks lack ultimate stages of cementation reported from most surface sampling, the interpretation of the paragenetic sequence and the related resulting fabrics is significantly easier.

2. Material and methods

The first author (BRCG) used a Wild Heerbrugg M5A binocular microscope to study the 40 thin sections. The latter were probably made from horizontal or vertical plugs taken from cores of 7 wells (Table 1) in the Happy Spraberry Field, located some 90 km SE of Lubbock, NW Texas. The core plug chips were impregnated with blue epoxy prior to the final cut, which helps visualizing the porous network. On each thin section a notch indicates the top. One third to half of each thin section surface is stained with Alizarin Red-S, which however proved to be useless considering the limited amount of dolomite in the rock samples. Photomicrographs of the material (*i.e.*, microfacies and microfossils) were taken in both transmitted and reflected lights with a Nikon D3100 camera mounted on the microscope.

Table 1 : List and location of the Happy Spraberry wells (Garza County, NW Texas, USA) operated by Citation Oil & Gas Corp. with studied samples:

Well	GSP	completion year
Lott 19#2	33°00'27.2"N 101°21'25.0"W	1989
Lott 19#3	33°00'12.1"N 101°21'25.5"W	2012
Lott 19#4	33°00'12.3"N 101°21'41.1"W	1990
Lott 19#5	32°59'59.2"N 101°21'41.3"W	2002
Lott 19#6	32°59'59.1"N 101°21'27.0"W	2016
Lott 19#10	32°59'52.4"N 101°21'54.5"W	1992
Lott 19#11	33°00'18.7"N 101°21'33.2"W	1992

3. Petrographic description of the material studied

Five out of forty thin sections studied, of which two (*i.e.*, Lott 19#3 4911' and Lott 19#4 4930') also include areas with the grainy turbidite facies, correspond to the debris-flow facies, *i.e.*, to lithoclastic floatstones with grainstone matrices. The extraclasts are mostly either silty mudstones or bryozoan-*Tubyphites* boundstones.

Thirty-seven thin sections display a grainstone facies. The allochems are mostly bioclasts and ooids. A significant number of the allochems were leached and remain as molds, whereas some others were cemented and a few recrystallized

[*] *Laya J.C., Albader A., Kaczmarek S., Pope M., Harris P.M. & Miller B. (2021).- Dissolution of ooids in seawater-derived fluids - an example from Lower Permian re-sedimented carbonates, West Texas, USA.-* Sedimentology*, vol. 68, no. 6, p. 2671-2706.*

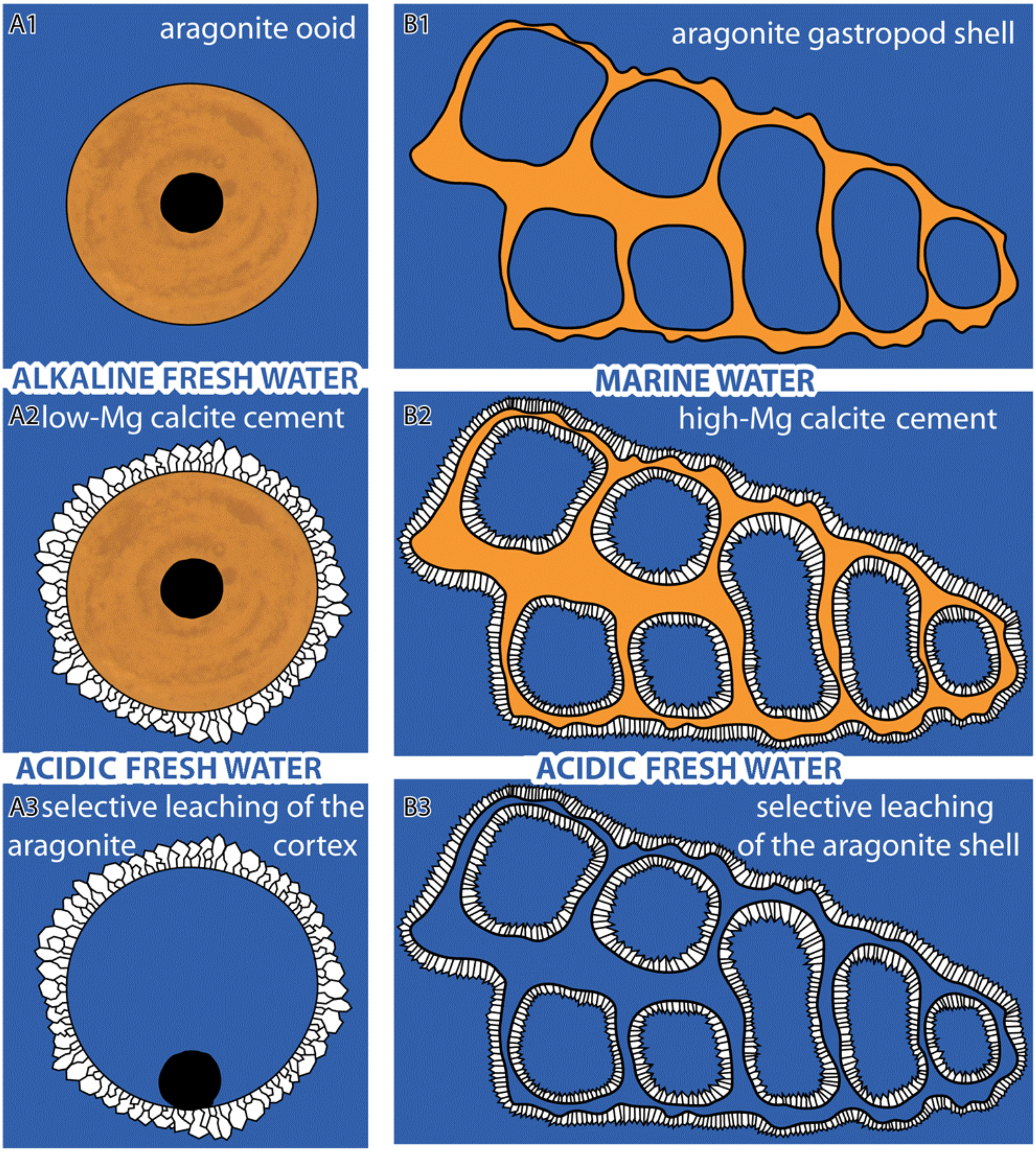


Figure 1: A1 to A3) Aragonite ooid cemented by Low-Mg calcite (LMC) in alkaline fresh water, followed by leaching of the cortical aragonite in acidic fresh water. B1 to B3) Aragonite gastropod shell cemented by High-Mg calcite (HMC) in marine water, followed by selective leaching of the gastropod shell aragonite in acidic fresh water, possibly due to the presence of acid from organic proteins.

sensu lato (recrystallized *sensu stricto* to form a mosaic of subequant LMC crystals or partly leached and cemented by drusy LMC cement). Common bioclasts are Bivalvia shells and crinoid ossicles, each category forming up to 10% of the grains. Bivalvia shells, which originally had an aragonite mineralogy, are commonly found as empty molds and micritic envelopes, and sometimes as partly or fully cemented molds and micritic envelopes; similar observations are made for the previously aragonite layers of those Bivalvia shells that once had a dual calcite and aragonite composition. It is noteworthy to mention that syntaxial overgrowths on HMC (High-Mg Calcite) crinoidal remains have surprisingly a rather limited extension. Two rare occurrences of ammonoid shells (? goniatites) are reported here from Lott 19#4 4958' and 4961.7'. Other bioclasts include echinoid spines, gastropod shells, brachiopod remains (including some spines), ostracods, and foraminifers. Among the foraminifers the tests of the primitive Miliolata that were made of

HMC are commonly leached (see § Appendix: Micropaleontologic and biostratigraphic supplement) whereas the larger pseudomonocrystalline echinodermal remains were not. Contrary to the primary nature of the angular molds (mostly the remains of former aragonite molluscan shells) there is always some ambiguity regarding the origins of the many rounded molds. The latter should not necessarily be described as oomolds because, although some retained a nucleus or few cortical layers, others were definitely both bioclasts and probable peloids. Some ooids were not leached but partly or fully recrystallized *sensu lato*. There is no evidence either that these ooids were ever micritized because micritization would have erased the concentric structures that remain visible in most recrystallized ooids. Besides the secondary moldic porosity after ooids or bioclasts the porous network comprises a significant volume of intergranular porosity, which is merely a residual primary porosity. Intergranular porosity is commonly found in the majority of the thin sections studied; it is lacking only when the centripetal drusy LMC cementation occluded these pores or when late dolomite or celestine cements occurred. Stylolites are rare, except where the debris-flow facies are tightly cemented or have contrasting lithologies. However, solution seams are common in the grainstone facies. They are often observed in collapsed moldic pores, next to residual intergranular pores.

4. Paragenetic sequence

Any study on cement stratigraphy implies that cementation and leaching cannot be coeval because both processes require fluids with different discrete pH. For example, two commonly observed sequences of events involving originally aragonite ooids (Fig. 1.A) and bioclasts (Fig. 1.B) are presented in Figure 1, redrawn after a sketch by the second author (Kendall, 2005).

With regard to the grainstone reservoir facies of the Plattsburg Limestone (uppermost Carboniferous) of Kansas, it is possible to reconstruct the paragenetic sequence on the basis of the above petrological observations.

First, peripheral micritization probably affected some bioclasts in their original shallow-water setting, hence predating their resedimentation in turbidites. Later, provided that the formerly aragonite or LMC bioclasts did not suffer any recrystallization *sensu stricto*, their leaching would form molds that correspond to a secondary, moldic porosity. Oolitic cortices are also eligible to recrystallization and/or leaching. Although it is commonly stated that leached ooids or recrystallized ooids were primarily aragonite ooids (*e.g.*, Buczynski & Wilkinson, 1982; Tucker, 1984), it cannot be excluded that they could have been primarily HMC ooids (*e.g.*, Granier & Lapointe, 2022b). The nature of the organic framework of these ooid cortices (as well as of some bioclasts), its amount, its degree of oxidation and the timing of the later are probably the keys to understand why some were selectively leached whereas others were recrystallized (*e.g.*, Skipwith & Shearman, 1965).

Second, the resedimentation of the various calcareous allochems in grainy turbidites led to a good grain sorting within the graded beds. There is no obvious evidence for mechanical compaction prior to cementation in the primary intergranular and intragranular pores of this calcareous sands.

Third, the intragranular (organic, *e.g.*, foraminifer chambers) pores, especially the smallest, were fully filled with a LMC cement while intergranular pores, as well as the larger intragranular pores, were incompletely filled with an isopachous cement made of small (*i.e.*, ~20 µm in width) more or less equidimensional (*i.e.*, "equant", or "granular" *sensu* Flügel, 2004) LMC crystals, and thus leaving some residual primary intergranular porosity (Pls. 1-3, figs. c, f, i, l, o, r, u). Considering the crystal habit, hence their LMC nature (Folk, 1974), such cementation could have taken place either in the meteoric phreatic zone or in the subsurface burial zone; the former setting should be excluded when considering both the depositional environment (turbidites) and the regional burial history. It is noteworthy that the common but volumetrically minor syntaxial overgrowths on crinoidal ossicles also contributed in reducing the intergranular porosity. Finally, this LMC cementation stopped quite early in the paragenetic sequence of most grainstone samples studied whereas the few tight grainstone samples (*e.g.*, Lott 19#3 4915'; Lott19#4 4919.3', 4926.9', 4937.5'; Lott 19#6 4948') were almost fully filled with a drusy LMC cement.

Fourth, the drusy LMC cement in the tight grainstone samples results from the competitive overgrowth of the originally equant LMC crystals in the former intergranular pores. Besides molds and micritic envelopes that are also affected by LMC drusy cementation, these samples are also characterized by the occurrence of recrystallized oolitic cortices (*e.g.*, Lott 19#3 4915'; Lott 19#4 4911.5'). It is assumed here that recrystallization probably occurred before leaching, preventing these oolitic cortices being leached. However a lack of oxidation of the organic framework of the oolitic cortices at the time of leaching would also have limited the dissolution efficiency. Therefore the hypothesis that the recrystallisation could have occurred after the leaching cannot be definitely ruled out.

Fifth, in the few tight grainstone samples studied, LMC cement occurs in some molds (*e.g.*, bioclastic molds). However, in most grainstone samples, dissolution molds (both bioclastic and oolitic) are empty indicating that cementation predated their leaching (*e.g.*, Shearman, unpublished; Conley, 1977; Scholle & Ulmer-Scholle, 2003; Flügel, 2004; Kendall, 2005).

Sixth, as seen above, there was no obvious evidence for mechanical compaction in the early stages. However, the leaching of aragonite and HMC of oolitic cortices and bioclasts to form a secondary moldic porosity, combined with the weak isopachous "granular" cementation, hence the presence of a residual primary intergranular porosity, all these features favoured the collapse of some of the largest pores. This late mechanical compaction implies a stratiform arrangement similar to that of the stratiform stylolites (Pls. 1-3, figs. a, d, g, j, m, p, s). However, as reported by Conley (1977), "linear series of elegant curves" that form "long zigzag chains" are not only arranged perpendicular to compaction stress (*i.e.*, stratiform), but also at an angle (Pls. 1-3, figs. b, e, h, k, n, q, t) delimitating breccia fragments. The brecciation was probably favored by differences in both size and shape existing between rounded moldic pores (mostly after ooids) and/or angular moldic pores (mostly after bioclasts).

Seventh, chemical compaction in the form of non-sutured pressure solution features (*e.g.*, Lott 19#2 4934'; Lott 19#4 4911.5', 4918') developed at a later stage when mechanical compaction could not accomodate the exceeding compaction stress.

Eighth, flushing of the brine out the reservoir rock with its replacement by oil brought an end to the paragenetic sequence.

This paragenetic sequence could be enhanced considering that 1) dissolution of the aragonite of the bioclasts [or the aragonite oolitic cortices] was not coeval to that of the HMC of the bioclasts [or the HMC oolitic cortices], 2) timings of recrystallisation of aragonite bioclasts and of aragonite or HMC oolitic cortices could be better constrained, 3) dissolution of the HMC of the porcellaneous foraminifer tests, 4) syntaxial overgrowths on echinodermal remains were not analysed, *etc.* However, on one hand, it is outside of the scope of this paper and, on the other hand, we were short in resource (no access to cathodoluminescence microscopy) and time to push forward our investigation.

5. Distorted ooids or collapsed molds

In the opinions of Bornemann (1886), Frantzen (1888), Carozzi (1961), or Kettenbrink and Manger (1971), the plastic deformation of their ooids was caused by compaction and preceded both lithification and cementation whereas according to 1) Radwański and Birkenmajer (1977), the distortion of the ooids is related to "boudinage"; 2) Wilkinson *et al.* (1984), it was caused by compaction following cementation and "during and/or following aragonite dissolution"; 3) Cantrell and Walker (1985), it is due to pressure-solution; and 4) Chatalov (2003), compaction initiated "early deformation" that "may have continued during the late diagenesis, *e.g.* through pressure-solution". However, in our case study, none of the above assumptions is valid because 'what were distorted' were indeed the molds, not the allochems (*i.e.*, neither bioclasts, nor ooids).

Although Conley (1977) quoted 48 times "distort-ed" grains for only 3 times "distorted pisomolds" (plus 2 times "undistorted pisomolds"), he was the first to correctly point out that he was not dealing with distorted ooids but distorted oomolds (Fig. 2). He pointed out that "Solution of some pisoliths followed precipitation of first generation cement and preceded compaction" (*op.cit.*, p. 561). Furthermore, he noted that the "cement framework" between the "pisomolds" could be "destroyed in varying degrees by compaction" and that it resulted in variety of unique fabrics. The first steps of his paragenetic sequence are rather similar to those of the paragenetic sequence we describe above for the upper Spraberry oolitic grainstone reservoir facies.

Figure 2, redrawn and adapted from Conley's (1977) Figure 8, illustrates the striking similarity between both paragenetic sequences. Our interpretation of the paragenetic sequence and that of the related structures are significantly easier because our subsurface samples lack the ultimate stages of cementation reported by Conley. Figure 3 is expanding Conley's model to include models for both the zig-zag pattern (Fig. 3, left column) *sensu* Carozzi (1961) and the typographic symbol of silcrow (§) (Fig. 3, right column) *sensu* Carozzi (1961).

The only minor flaw in Conley's interpretation is that he refers to "blocky" intergranular cement, which implies the absence of residual primary porosity, whereas we refer to isopachous LMC cement that did not fully filled the intergranular pores. According to Conley (1977, p. 561), the "cement framework failed at points of least strength and partially collapsed under compactional forces". However, he was reasoning in 2 dimensions only (Conley, 1977, Figs. 8-9), not in 3 dimensions. Besides the grain nature, their external morphology, their sizes and their arrangement are variable, compaction with "blocky" (*sensu* Conley) intergranular cement would have only produced stratiform seams and stylolites, never oblique chains of oomolds (Fig. 2), nor the silcrow fabric (Fig. 3, right column).

In the studied material, most collapsed molds are empty whereas others contain some material that is probably the remains of partly dissolved oolitic cortices (Pl. 1, figs. a, d, g-h, j-k, m-o; Pl. 2, figs. a-b, d-f, j-k, s-u) and oolitic nuclei, if any. In the latter case, similarity with the tight oolitic limestones documented by our predecessors (Bornemann, 1886, Pl. VII, fig. 1; Frantzen, 1888, Pl. III, figs. 2-3; Cayeux, 1935, Pl. XV, fig. 55; Carozzi, 1961, Fig. 6; Kettenbrink & Manger, 1971, Fig. 3.B, 3.D-F; Conley, 1977, Fig. 5.A-D; Radwański & Birkenmajer, 1977, Fig. 16.d-e; Richter, 1983, Fig. 3.H; Wilkinson *et al.*, 1984, Fig. 6.F; Cantrell & Walker, 1985, Fig. 9.C-D; Chatalov, 2003, Fig. 1.a-b; Scholle & Ulmer-Scholle, 2003, p. 240 middle-upper, p. 354 middle) are striking. The only difference is that our subsurface material (it is a producing oil reservoir) lacks final stages of LMC cements found in most specimens picked in outcrops.

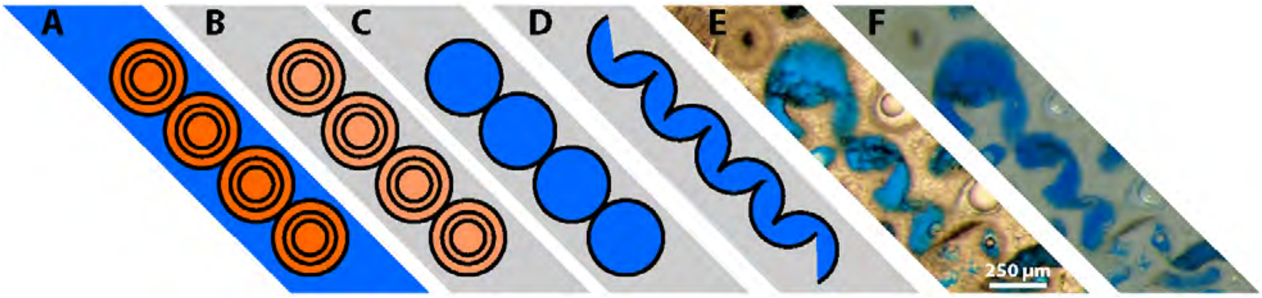
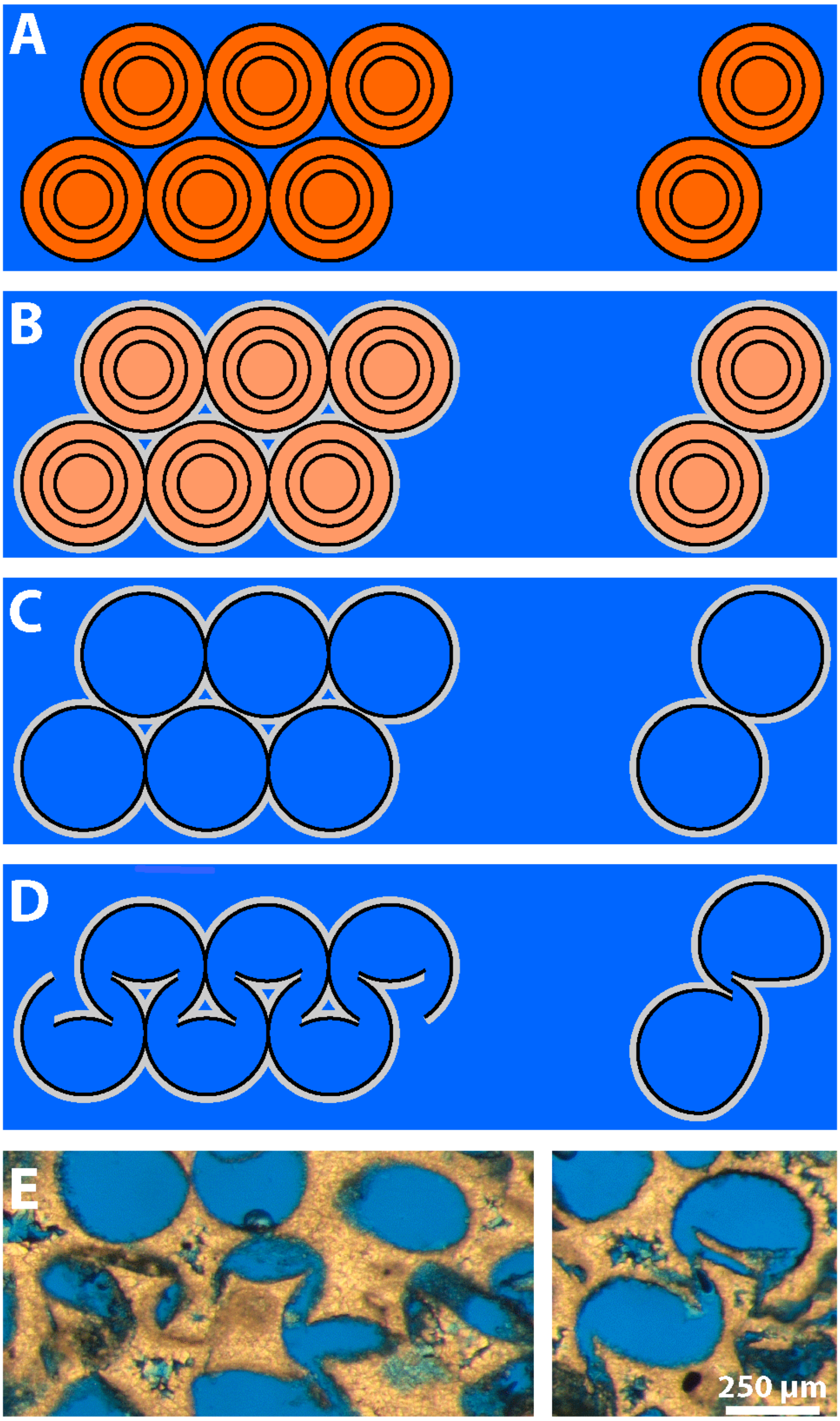


Figure 2: Schematic paragenetic sequence from aragonite or HMC ooids to a chain of distorted oomolds (redrawn and adapted from CONLEY, 1977, Fig. 8): A) undistorted ooids; B) cemented slightly oxided ooids; C) leached ooids, *i.e.*, oomolds; D) collapsed oomolds; E) transmitted light; F) reflected light. E-F: Lott 19#4 4918' (Scale bar = 250 µm). Orange: oolitic cortices; pale orange: oolitic cortices after oxidation; grey: "blocky" cement; blue: pores.



◀ **Figure 3:** Schematic paragenetic sequence from aragonite or HMC ooids to a chain of distorted oomolds: A) undistorted ooids; B) weakly cemented slightly oxided ooids; C) leached ooids, *i.e.*, oomolds; D) collapsed oomolds forming a zig-zag pattern to the left and the typographic symbol of silcrow to the right; E) to the left, photomicrograph of a zig-zag pattern *sensu* CAROZZI (1961), Lott 19#5 4958'; to the right, photomicrograph of the typographic symbol of silcrow (§) pattern *sensu* CAROZZI (1961), Lott 19#2 4934' (Scale bar = 250 µm). Orange: oolitic cortices; pale orange: oolitic cortices after oxidation; grey: isopachous cement; blue: pores.

6. Conclusion

The uppermost Sakmarian to lowermost Artinskian calcareous turbidites and associated debris-flows of the upper Spraberry Formation in NW Texas comprise some oolitic grainstones that display peculiar compactional fabrics known in the past literature by many names including so-called "distorted ooids". A simplified paragenetic sequence drawn from the petrographic analysis starts with an isopachous LMC cementation filling in part intergranular pores. It is followed by oxidation of organic matter framework of many allochems, then the leaching of aragonite and HMC allochems (bioclasts, oolitic cortices), with the notable exception of the HMC echinodermal remains. It ends with compaction that led to the collapse of some moldic pores and the local limited development of solution seams. The ooids were not distorted but their molds did collapse. This interpretation better matches CONLEY's (1977), who presented a paragenetic model to explain the occurrence of distorted molds (*op.cit.*, Figs. 8-9). The only minor flaw in his model was to consider that the grain-supported fabric was fully cemented before leaching and collapsing. Our study of the Texan Permian material demonstrates that collapse would not have been possible without the presence of some residual intergranular porosity, hence the presence of a limited LMC cementation of these primary pores. The converse of this conclusion is also true: The occurrence of collapsed molds would imply the presence of a residual intergranular porosity at the time of collapse.

Acknowledgements

The first author (BRCG) would like to thank Citation Oil & Gas Corp., Houston - TX, for having granted him permission to use their material in this publication. He is very grateful to Jay PORTWOOD, Vice President - Reservoir, and Jorge L. ROMERO, Senior Reservoir Engineer, who acted as facilitator. He also wishes to thank the Association "*Carnets de Géologie*" and donators, namely D.M. BASSO, J. CHAROLLAIS, C. COLLOM, T. GRGASOVIĆ, R. MANNI, D.M. MARTILL, R. MARTINI, M.V. PARDO ALONSO, F. SCIUTO, M. SEPTFONTAINE, and R.W. SCOTT, for financial support. The authors acknowledge the help of Matt GENTRY, "Robert" HANDFORD, Felicitas KAISER, Charles KERANS, John LAYMAN II, "Bob" LOUCKS, Vincent MAZINGUE-DESAILLY, and Robert W. SCOTT when tracking material from the Spraberry Formation of the Happy Field (Garza County, Texas). By proxy of J.C. LAYA P.K. PUFAHL has arranged the loan of material that was previously studied by the late Professor Wayne M. AHR (1938-2011) and a group of MSc students (Matt GENTRY, John LAYMAN II, Vincent MAZINGUE-DESAILLY, ...), and that is currently stored at the Texas A&M University, College Station - TX. Finally, thanks are due to Jan GOLONKA, Brian PRATT, and Andreas "André" STRASSER for their careful review and useful suggestions (even if we did not follow up on all of these). The authors are solely responsible for the interpretations (and opinions) expressed here.

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Appendix: Micropaleontologic and biostratigraphic supplement

(Daniel VACHARD)

1. Bio- and chrono-stratigraphy

In the Lower Permian sedimentary series recently studied in New Mexico (LUCAS *et al.*, 2015), the investigated levels correspond to the latest Sakmarian and early Artinskian biozones 6 and 7 (Fig. 4), on the basis of the occurrence of *Pseudovermiporella*, *Praeneodiscus*, *Glomomidiella infrapermica*, *Grovesella*, and *Schubertella*, as well as the absence of *Pseudoreichelina*.

When compared with the Russian sequences, the studied samples seem to also correlate with the lower Artinskian beds of the Pre-Urals of Perm (BARYSHNIKOV *et al.*, 1982), on the basis of the occurrence of *Grovesella chomatifera* (ZOLOTOVA in BARYSHNIKOV *et al.*, 1982) and its nodosariates.

Classically, these units correspond to the *Tastubella pedissequa* Zone of larger fusulinids of Russia, *Praeskinnerella crassitectoria-P. guembeli* of the USA, and *Sweetognathus* "*whitei*" of the conodonts (RAUZER-CHERNOUSOVA, 1949; C.A. ROSS & J.R.P. ROSS, 1960; BENSH, 1987; HENDERSON *et al.*, 2012).

2. Assemblages

The observed assemblage comprises algae (Gymnocodiaceae, *Gyroporella*? sp.), foraminifers with microgranular tests (*Abadehellopsis* cf. *protea*, *Climacammina* sp., *Endothyra* sp., *Globivalvulina* spp., *Grovesella chomatifera*, *Grovesella* spp., *Neoendothyra* sp., *Palaeotextularia* sp., *Schubertella* sp., *Spireitlina* sp., *Tetrataxis* sp.), foraminifers with porcelaneous tests (*Ammovertella* sp., *Cornuspira* sp., *Glomomidiella infrapermica*, *Glomodiella* spp., *Hemigordiellina* sp., *Palaeonubecularia graiferi*, *Palaeonubecularia* sp., *Paraellesmerella* sp., *Planiinvoluta heathi*, *Praeneodiscus* spp., *Pseudovermiporella* sp., "*Tolypammina*" sp., *Tubiphytes obscurus*), and foraminifers with hyaline tests (*Nodosinelloides bella*, *N. shikhanica*, *Pachyphloia* sp., *Praerectoglandulina* cf. *turae*, *P. pusilla*).

3. Selected micropaleontology

***Gyroporella*? sp.**
Pl. 4, fig. 7

Description: A tangential section of a Dasycladale apparently aspondyl.

Occurrence: Lott 19#3 4915'.

***Spireitlina* sp.**
Pl. 5, fig. 42

Description: A transverse section of an immature (*i.e.*, only coiled) specimen.

Occurrence: Lott 19#3 4957'.

***Endothyra* sp.**
Pl. 4, fig. 6

Description: Subaxial section.

Occurrence: Lott 19#3 4960'.

***Neoendothyra* sp.**
Pl. 5, fig. 59

Description: An axial section of a small, compressed species with well carinated last whorl.

Occurrence: Lott 19#11 4891'.

***Palaeotextularia* sp.**
Pl. 4, fig. 7

Description: Several axial sections of a typical *Palaeotextularia* which exhibits 4-8 pairs of chambers.

Occurrence: Lott 19#3 4911'; Lott 19#4 4972.9'.

ZONATION	FORMATIONS		BIOSTRATIGRAPHIC MARKERS		REGIONAL STAGES	INTERNATIONAL STAGES
Zone 15	SAN ANDRES FORMATION		*Olgaorlovella davydovi* *Tubiphytes epimonellaeformis* *Geinitzina indepressa*	LEONARDIAN	CATHEDRALIAN	late Kungurian
Zone 14	SAN ANDRES FORMATION		*Hemigordiellina* spp.	LEONARDIAN	CATHEDRALIAN	middle Kungurian
Zone 13	GLORIETA SANDSTONE		barren of foraminifers	LEONARDIAN	CATHEDRALIAN	middle Kungurian
Zone 12	YESO GROUP		*Frondicularia* aff. *turae*	LEONARDIAN	CATHEDRALIAN	early Kungurian
Zone 11	YESO GROUP		*Ellesmerella rara* *Nestellorella* ? sp.	LEONARDIAN	CATHEDRALIAN	early Kungurian
Zone 10	YESO GROUP		*Globivalvulina novamexicana* *Orthovertellopsis protaeformis* *Glomomidiella infrapermica*	LEONARDIAN	CATHEDRALIAN	early Kungurian
Zone 9	HUECO GROUP	Apache Dam Formation		LEONARDIAN	CATHEDRALIAN	late Artinskian
Zone 8	HUECO GROUP	Robledo Mountains Formation	*Pseudoreichelina* sp. *Geinitzina* sp. 2 (*?multicamerata*)	LEONARDIAN	HESSIAN	middle Artinskian
Zone 7	HUECO GROUP	Community Pit Formation	*Praeneodiscus* sp. *Globivalvulina novamexicana* *Globivalvulina praegraeca* DAB 13 + DAB 14/DAC 1-DAC 5	LEONARDIAN	HESSIAN	early Artinskian
Zone 6	HUECO GROUP	Community Pit Formation	*Pseudovermiporella* sp. DAB 10 - DAB 12	WOLFCAMPIAN	LENOXIAN	latest Sakmarian
Zone 5	HUECO GROUP	Community Pit Formation	*Pachyphloia*? sp. *Geinitzina postcarbonica* *Nodosinelloides longissima* DAB 7 - DAB 9	WOLFCAMPIAN	LENOXIAN	late Sakmarian
Zone 4	HUECO GROUP	Community Pit Formation	*Nodosinelloides pinardae* *Globivalvulina parapiciformis* *Geinitzina postcarbonica* DAA 59 - DAA 69/DAB 2 - DAB 6	WOLFCAMPIAN	LENOXIAN	early Sakmarian
Zone 3	HUECO GROUP	Community Pit Formation	*Hedraites* sp. DAA 53 - DAA 58	WOLFCAMPIAN	NEALIAN	Late Asselian
Zone 2	HUECO GROUP	Community Pit Formation	*Geinitzina postcarbonica* *Nodosinelloides netschajewi* DAA 45 - DAA 52	WOLFCAMPIAN	NEALIAN	Middle Asselian
Zone 1	HUECO GROUP	Shalem Colony Formation	*Leptotricites* sp. (DAA 38), *Nodosinelloides longissima*, *Tubiphytes* sp., *Geinitzina* sp. (DAA 38), *Pseudovidalina* sp., *Pseudoschwagerina* sp. (DAA 42)	WOLFCAMPIAN	Newwellian	Early Asselian - latest Gzhelian

Figure 4: Comparison with regional and international stratigraphic scales in New Mexico (according to LUCAS *et al.*, 2015).

Climacammina sp.
Pl. 4, fig. 4

Description: Several subaxial sections seem to be more assignable to *Climacammina* than typical *Palaeotextularia*.

Occurrence: Lott 19#2 4930'.

Tetrataxis sp.
Pl. 5, fig. 60

Description: Several subaxial sections of a small *Tetrataxis*.

Occurrence: Lott 19#4 4923.8', 4937.5', 4960'; Lott 19#11 4891', 4905'.

Abadehellopsis cf. *protea* (CUSHMAN & WATERS, 1928)
Pl. 5, fig. 41

*1928 *Patellina protea* CUSHMAN & WATERS, p. 54-55, Pl. 7, figs. 8-10.

Description: *Abadehellopsis* was recently described in the Carnic Alps (Austria). However, one representative was known in Texas for a longer time period under the name of *Patellina protea*. It was recently refound in New Mexico (LUCAS *et al.*, 2015). One oblique section was found in our material.

Occurrence: Lott 19#4 4957.5'.

Globivalvulina spp.
Pl. 4, figs. 11, 15, 19

Description: Several subtransverse and subaxial sections of two or three small species.

Occurrence: Lott 19#2 4926'; Lott 19#3 4925', 4928'; Lott 19#4 4923.8', 4940.8', 4944.9', 4956', 4958', 4960'; Lott 19#5 4950'.

Grovesella chomatifera (ZOLOTOVA *in* BARYSHNIKOV *et al.*, 1982)
Pl. 4, fig. 9

*1982 *Schubertella sphaerica chomatifera* ZOLOTOVA in BARYSHNIKOV *et al.*, p. 21, Pl. 6, figs. 5, 8.

Description: A typical axial section of a small, nautiloid test with three whorls, the two first whorls are deviated at 90°. Proloculus spherical relatively large; chomata low and triangular with a tunnel poorly defined.

Occurrence: Lott 19#3 4915'5.

Grovesella spp.
Pl. 4, figs. 18, 20, 29; Pl. 5, fig. 43

Description: Several oblique sections.

Occurrence: Lott 19#4 4911.5', 4923.8', 4940.8', 4944.9', 4960'.

Schubertella sp.
Pl. 4, fig. 13; Pl. 5, fig. 52

Description: Several oblique sections.

Occurrence: Lott 19#3 4928'; Lott 19#5 4958'.

Planiinvoluta heathi (CUSHMAN & WATERS, 1928)
Pl. 4, figs. 2, 5, 26b

Description: Several subaxial sections of this abundant species with one series of an oscillating deuteroloculus, regularly increasing in height and width.

Occurrence: Lott 19#2 4930', 4940'; Lott 19#3 4911', 4928'; Lott 19#4 4933.1', 4944.9', 4960'; Lott 19#5 4942', 4945', 4950'; Lott 19#11 4891'.

Tolypammina sp.
Pl. 4, figs. 22, 25

Description: Several subaxial sections.

Occurrence: Lott 19#2 4926'; Lott 19#3 4915'; Lott 19#4 4926.9', 4933.1', 4950', 4957.5'.

Ammovertella sp.
Pl. 5, fig. 56

Description: Rare subaxial sections.

Occurrence: Lott 19#4 4926.9'; Lott 19#6 4958'.

Orthovertella sp.
Pl. 4, fig. 32

Description: Rare subaxial sections.

Occurrence: Lott 19#3 4909'; 19#4 4944.9'.

Palaeonubecularia graiferi (BARYSHNIKOV *in* BARYSHNIKOV *et al.*, 1982)
Pl. 4, fig. 23

*1982 *Tolypammina graiferi* BARYSHNIKOV *in* BARYSHNIKOV *et al.*, p. 11, Pl. 1, figs. 8, 12-13.
?2019 *Pseudovermiporella graiferi* (BARYSHNIKOV *in* BARYSHNIKOV *et al.*, 1982) - KRAINER *et al.*, p. 94, Pl. 36, figs. 4-8; Pl. 37, fig. 2 (center)

Description: This species is characterized by concentric rows of chambers and a thick wall. The wall is homogeneous and the perforated wall described by KRAINER *et al.* (2019) belongs probably to another species and perhaps genus.

Occurrence: Lott 19#4 4930'.

Palaeonubecularia sp.
Pl. 4, fig. 12

Description: An elongated test composed of two superposed series of chambers.

Occurrence: Lott 19#3 4925'.

Pseudovermiporella sp.
Pl. 5, fig. 39b

Description: A tangential section with numerous cylindrical pits. Wall neosparitized

Occurrence: Lott 19#4 4956'.

Paraellesmerella sp.
Pl. 4, fig. 26a

Description: Some sections of this recently discovered taxon in the Carnic Alps (VACHARD in KRAINER *et al.*, 2019)

Occurrence: Lott 19#4 4933.1', 4972.9'.

Tubiphytes obscurus
MASLOV, 1956
Pl. 5, fig. 47

Description: Rare typical bioconstructions.

Occurrence: Lott 19#4 4980.7'.

***Hemigordiellina* sp.**
Pl. 4, figs. 3, 14, 24, 39a

Description: Several small glomospirally coiled miliolates.

Occurrence: Lott 19#2 4930'; Lott 19#3 4928'; Lott 19#4 4926.9', 4933.1', 4944.9', 4961.7'.

***Cornuspira* sp.**
Pl. 4, figs. 4, 27, 28

Description : Rare, planispirally coiled, small foraminifers.

Occurrence: Lott 19#2 4930'; Lott 19#3 4915'; Lott 19#4 4937.5', 4940.8', 4944.9'.

***Hemigordius* sp.**
Pl. 4, fig. 1

Description: A discoid to subrectangular species with few planispirally coiled, evolute, last whorls.

Occurrence: Lott 19#2 4926'; Lott 19#3 4909', 4911'; Lott 19#4 4911.5'; Lott 19#5 4950'.

Glomomidiella infrapermica
VACHARD *et al.*, 2015
Pl. 4, fig. 39a

*2015 *Glomomidiella infrapermica* VACHARD *et al.*, p. 54, Figs. 22.1, 22.3, 23.1, 23.3, 23.7, 23.8, 35.9, 35.11, 35.14, 36.1-36.12, 36.16.

Description: Large species, streptospirally coiled, with small pseudo-septa and a neosparitized wall.

Occurrence: Lott 19#4 4956'.

***Glomomidiella* spp.**
Pl. 4, figs. 16, 21; Pl. 5, fig. 40

Description: Several subaxial sections.

Occurrence: Lott 19#3 4928'; Lott 19#4 4919.3', 4926.9', 4956', 4957.5', 4958', 4960'; Lott 19#5 4950'.

***Praeneodiscus* spp.**
Pl. 5, figs. 49, 58

Description: Several subaxial sections of this recently described genus of miliolates (KRAINER *et al.*, 2019).

Occurrence: Lott 19#2 4930'; Lott 19#3 4911', 4925', 4928'; Lott 19#4 4933.1', 4956', 4957.5', 4960'; Lott 19#5 4945', 4950'; Lott 19#11 4891'.

Nodosinelloides bella
(LIPINA, 1949)
Pl. 4, fig. 9; Pl. 5, fig. 53

*1949 *Nodosaria bella* LIPINA, p. 216, Pl. 4, fig. 9; Pl. 6, fig. 4.

Description: Small species with less than 10 globular chambers

Occurrence: Lott 19#3 4915'; Lott 19#4 4944.9'; Lott 19#5 4968'.

Nodosinelloides shikhanica
(LIPINA, 1949)
Pl. 5, fig. 54

*1949 *Nodosaria shikhanica* LIPINA, p. 217-218, Pl. 4, figs. 7-8; Pl. 6, figs. 3, 9.

Description: Small species, very compressed and with numerous chambers.

Occurrence: Lott 19#6 4946'.

***Nodosinelloides* sp.**
Pl. 5, fig. 55

Description: Small species with irregular chambers a curved axis of growth.

Occurrence: Lott 19#6 4946'.

Praerectoglandulina* cf. *turae
(BARYSHNIKOV *in* BARYSHNIKOV *et al.*, 1982)
Pl. 4, fig. 38; Pl. 5, fig. 57

*1982 *Frondicularia turae* BARYSHNIKOV *in* BARYSHNIKOV *et al.*, p. 33-34, Pl. 9, figs. 2-3.

Description: Rare subaxial sections.

Occurrence: Lott 19#4 4956'; Lott 19#11 4891'.

Praerectoglandulina pusilla
(MIKLUKHO-MAKLAY, 1954)
Pl. 4, fig. 36; Pl. 5, figs. 46, 48

*1954 *Geinitzina pusilla* GROZD. (in litt.) MIKLUKHO-MAKLAY, p. 34, Pl. 3, fig. 7.

Description: Several subaxial sections of this small species

Occurrence: Lott 19#2 4934'; Lott 19#4 4944.9', 4950'; Lott 19#5 4945'; Lott 19#11 4891'.

***Pachyphloia* sp.**
Pl. 4, figs. 10, 13-14, 16

Description: Several subaxial sections of a small, primitive species.

Occurrence: Lott 19#3 4911'; Lott 19#4 4944.9', 4956'.

Plates

Plate 1: Column 1 (A): a, d, g, j, m, p, s, "touching vugs" subparallel to bedding; column 2 (B): b, e, h, k, n, q, t, "touching vugs" oblique to bedding; column 3 (C): c, f, i, l, o, r, u, residual primary intergranular pores. Row 1: a-c, Lott 19#10 4939'; row 2: d-f, Lott 19#11 4891'; row 3: g-i, Lott 19#11 4905'; row 4: j-l, Lott 19#2 4926'; rows 5-6: m-r, Lott 19#2 4934'; row 7: s-u, Lott 19#2 4940'.

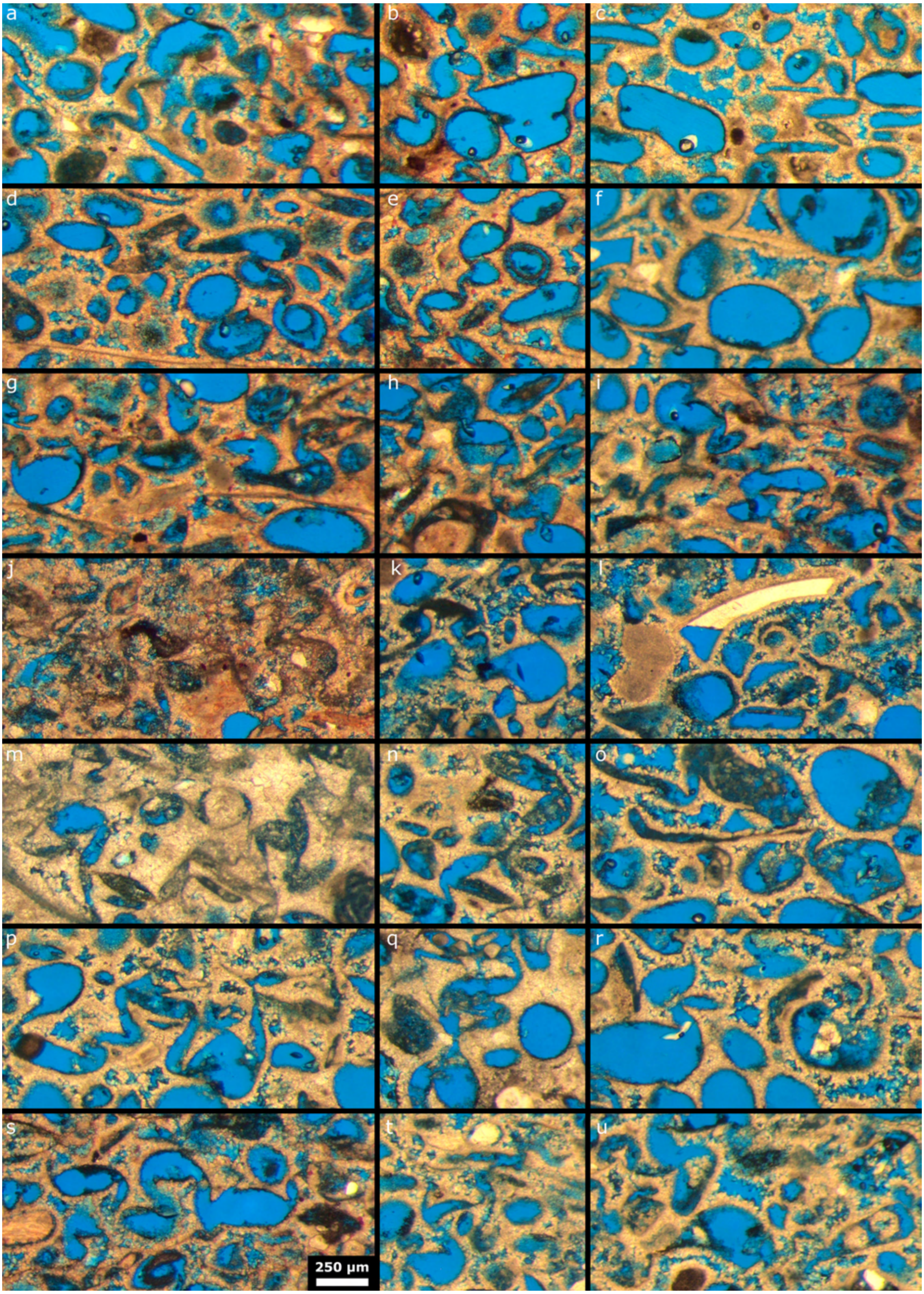
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Plate 2: Column 1 (A): a, d, g, j, m, p, s, "touching vugs" subparallel to bedding; column 2 (B): b, e, h, k, n, q, t, "touching vugs" oblique to bedding; column 3 (C): c, f, i, l, o, r, u, residual primary intergranular pores. Rows 1-2: a-f, Lott 19#4 4918'; row 3: g-i,, Lott 19#4 4926.9'; row 4: j-l, Lott 19#4 4937.5'; row 5: m-o, Lott 19#4 4940.8'; row 6: p-r, Lott 19#4 4957.5'; row 7: s-u, Lott 19#5 4958'.

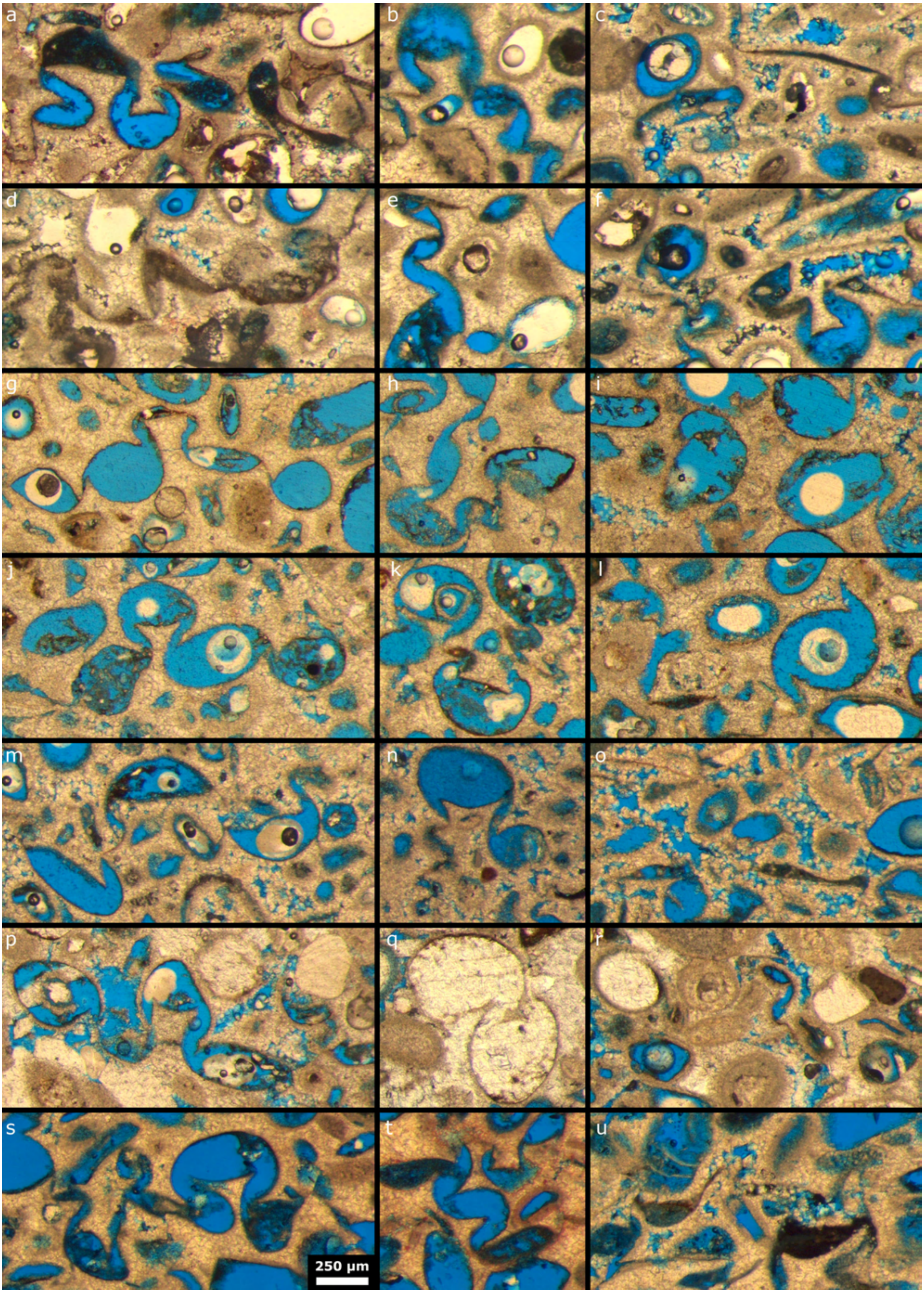
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Plate 3: Column 1 (A): a, d, g, j, m, p, s, "touching vugs" subparallel to bedding; column 2 (B): b, e, h, k, n, q, t, "touching vugs" oblique to bedding; column 3 (C): c, f, i, l, o, r, u, residual primary intergranular pores. Row 1: a-c, Lott 19#5 4968'; row 2: d-f, Lott 19#6 4946'; row 3: g-i, Lott 19#6 4948'; row 4: j-l, Lott 19#6 4952'; row 5: m-o, Lott 19#6 4955'; rows 6-7: p-u, Lott 19#6 4958'.

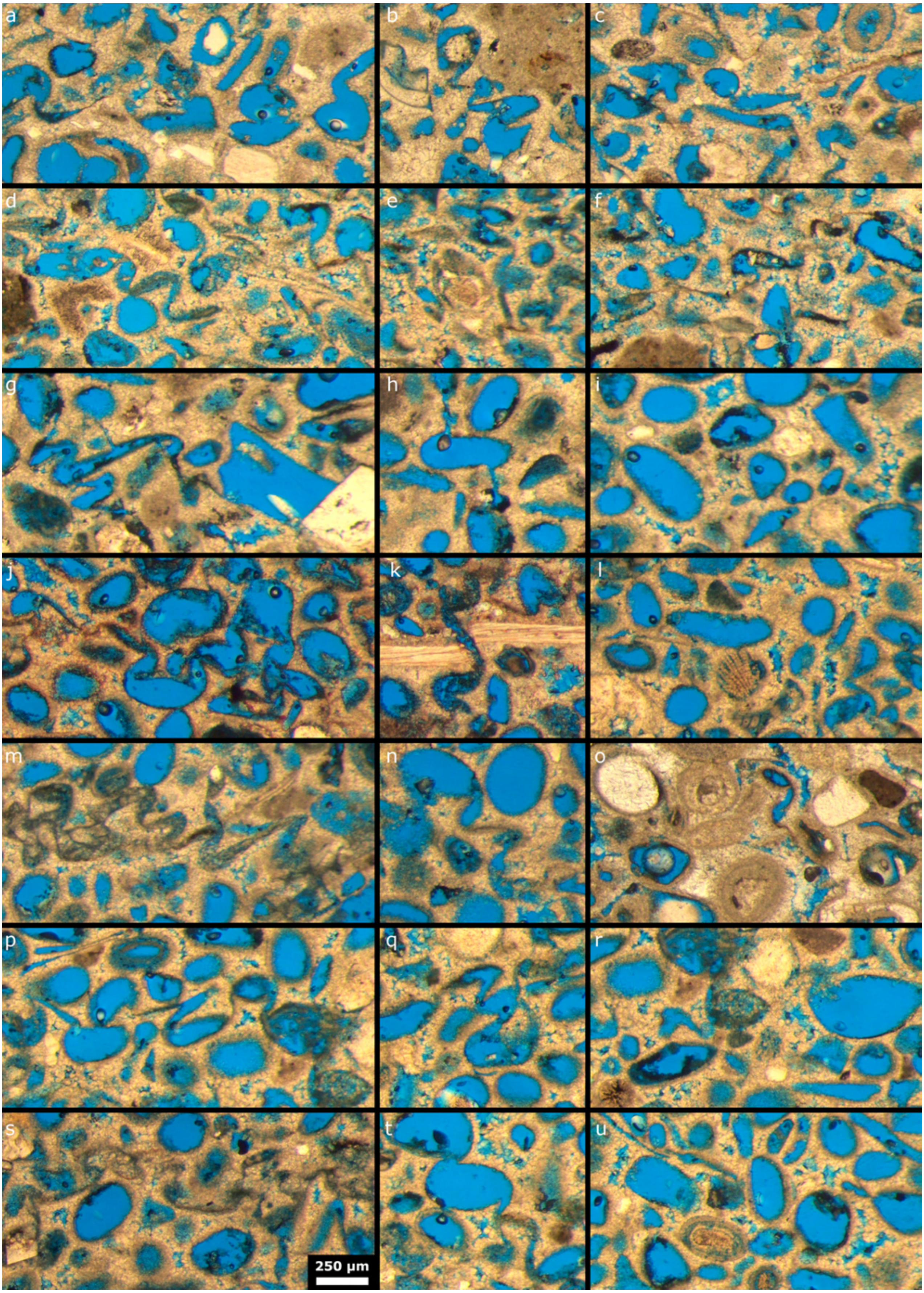
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Plate 4: 1. *Hemigordius* sp. Axial section. Lott 19#2 4926'; **2.** *Planiinvoluta heathi* (Cushman & Waters, 1928). Subaxial section. Lott 19#2 4930'; **3.** *Hemigordiellina* sp. Axial section. Lott 19#2 4930'; **4.** *Cornuspira* sp. (subaxial section, left) and *Climacammina* sp. (subaxial section, right). Lott 19#2 4930'; **5.** *Planiinvoluta heathi* (Cushman & Waters, 1928). Axial section. Lott 19#2 4940'; **6.** *Endothyra* sp. Subaxial section. Lott 19#2 4940'; **7.** *Palaeotextularia* sp. Axial sections. Lott 19#3 4911'; **8.** *Gyroporella*? sp. Tangential section. Lott 19#3 4915'; **9.** *Grovesella chomatifera* (Zolotova in Baryshnikov *et al.*, 1982). Axial section. Lott 19#3 4915'; **10.** *Praeneodiscus* sp. Oblique section. Lott 19#3 4925'; **11.** *Globivalvulina* sp. Axial section. Lott 19#3 4925'; **12.** *Praeneodiscus* sp. (oblique section, top left) and *Palaeonubecularia* sp. (with two superposed series of chambers, bottom). Lott 19#3 4925'; **13.** *Schubertella* sp. Oblique section. Lott 19#3 4928'; **14.** *Hemigordiellina* sp. Axial section. Lott 19#3 4928'; **15.** *Globivalvulina* sp. Transverse section. Lott 19#3 4928'; **16.** *Glomomidiella* sp. Axial section. Lott 19#3 4928'; **17.** *Hemigordius* sp. Axial section. Lott 19#4 4911.5'; **18.** *Grovesella* sp. Oblique section. Lott 19#4 4911.5'; **19.** *Globivalvulina* sp. Transverse section. Lott 19#4 4923.8'; **20.** *Grovesella* sp. Subtransverse section. Lott 19#4 4923.8'; **21.** *Glomomidiella* sp. Axial section. Lott 19#4 4926.9'; **22.** "*Tolypammina*" sp. Subaxial section. Lott 19#4 4926.9'; **23.** *Palaeonubecularia graiferi* (Baryshnikov *in* Baryshnikov *et al.*, 1982) with concentric rows of chambers and thick wall. Lott 19#4 4930'; **24.** *Hemigordiellina* sp. Subaxial section. Lott 19#4 4933.1'; **25.** "*Tolypammina*" sp. Axial section. Lott 19#4 4933.1'; **26a.** *Paraellesmerella* sp. attached on an ooid. Axial section. Lott 19#4 4933.1'; **26b.** *Planiinvoluta heathi* (Cushman & Waters, 1928). Subaxial section. Lott 19#4 4933.1'; **27.** *Hemigordiellina* sp. (subaxial section, left) and *Cornuspira* sp. (axial section, top right). Lott 19#4 4937.5'; **28.** *Cornuspira* sp. Axial section. Lott 19#4 4940.8'; **29.** *Grovesella* sp. Subaxial section. Lott 19#4 4940.8'; **30.** *Nodosinelloides bella* (Lipina, 1949). Axial section. Lott 19#4 4944.9'; **31.** *Pachyphloia* sp. Subaxial section. Lott 19#4 4944.9'; **32.** *Globivalvulina* sp. (subaxial section, left) and *Orthovertella* sp. (subaxial section, right). Lott 19#4 4944.9'; **33.** *Globivalvulina* sp. Transverse section. Lott 19#4 4944.9'; **34.** *Pachyphloia* sp. Transverse section. Lott 19#4 4944.9'; **35.** *Pachyphloia* sp. Subaxial section. Lott 19#4 4944.9'; **36.** *Praerectoglandulina pusilla* (Miklukho-Maklay, 1954). Axial section. Lott 19#4 4950'; **37.** *Pachyphloia* sp. Subaxial section. Lott 19#4 4956'; **38.** *Praerectoglandulina* cf. *turae* (Baryshnikov *in* Baryshnikov *et al.*, 1982). Axial section. Lott 19#4 4956'; **39a.** *Glomomidiella infrapermica* Vachard *et al.*, 2015. Transverse section. Lott 19#4 4956'.


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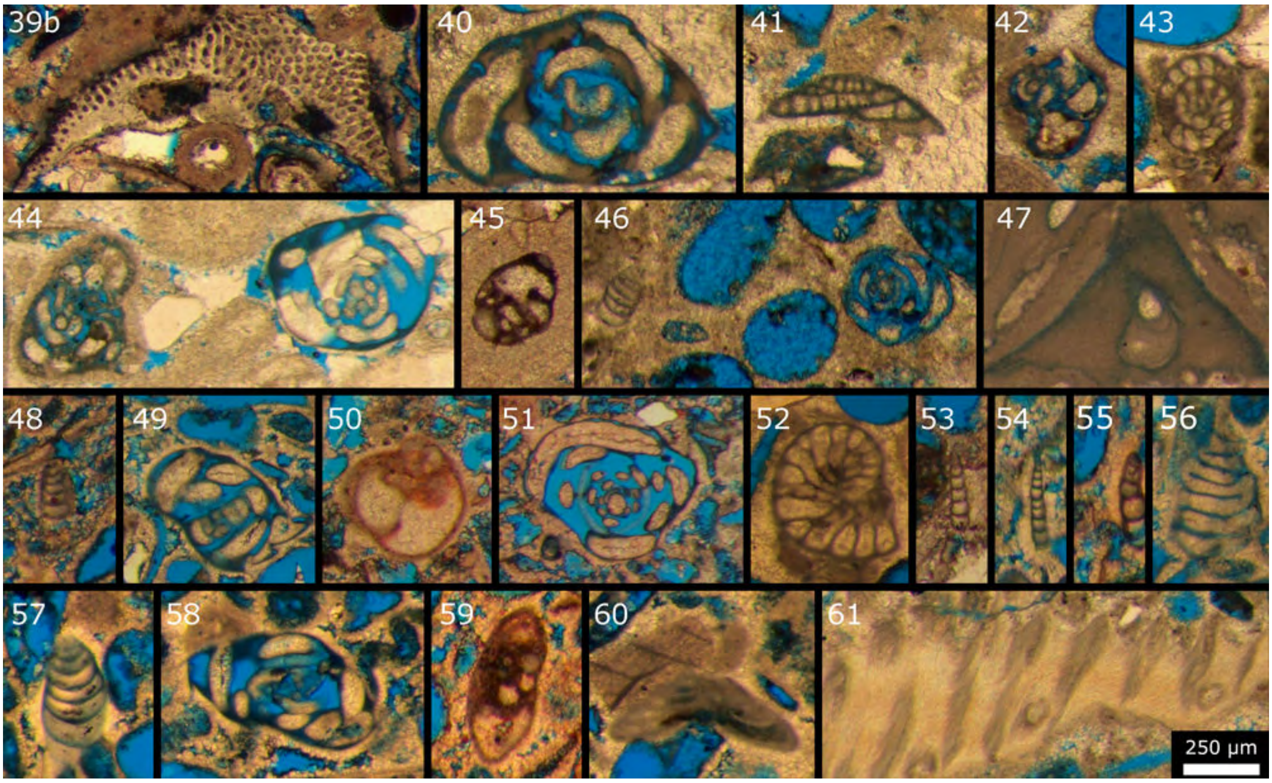

Plate 5: 39b. *Pseudovermiporella* sp. Tangential section. Lott 19#4 4956'; **40.** *Glomomidiella* sp. Subaxial section. Lott 19#4 4957.5'; **41.** *Abadehellopsis* cf. *protea* (CUSHMAN & WATERS, 1928). Oblique section. Lott 19#4 4957.5'; **42.** *Spireitlina* sp. Transverse section. Lott 19#3 4957'; **43.** *Grovesella* sp. Subtransverse section. Lott 19#4 4960'; **44.** *Spireitlina*? sp. (left) and *Glomomidiella* sp. (right). Lott 19#4 4960'; **45.** *Globivalvulina* sp. Oblique section. Lott 19#4 4960'; **46.** *Praerectoglandulina pusilla* (MIKLUKHO-MAKLAY, 1954) (subaxial section, left) and *Hemigordiellina* sp. (axial section, right). Lott 19#4 4961.7'; **47.** *Tubiphytes obscurus* MASLOV, 1956. Typical bioconstruction. Lott 19#4 4980.7'; **48.** *Praerectoglandulina pusilla* (MIKLUKHO-MAKLAY, 1954). Axial section. Lott 19#5 4945'; **49.** *Praeneodiscus* sp. Axial section. Lott 19#5 4950'; **50.** *Globivalvulina* sp. Subaxial section. Lott 19#5 4950'; **51.** *Glomomidiella* sp. Axial section. Lott 19#5 4950'; **52.** *Schubertella* sp. Subtransverse section. Lott 19#5 4958'; **53.** *Nodosinelloides bella* (LIPINA, 1949). Axial section. Lott 19#5 4968'; **54.** *Nodosinelloides sikhanica* (LIPINA, 1949). Subaxial section. Lott 19#6 4946'; **55.** *Nodosinelloides* sp. Axial section. Lott 19#6 4946'; **56.** *Ammovertella* sp. Subaxial section. Lott 19#6 4958'; **57.** *Praerectoglandulina* cf. *turae* (BARYSHNIKOV *in* BARYSHNIKOV *et al.*, 1982). Subaxial section. Lott 19#11 4891'; **58.** *Praeneodiscus* sp. Axial section. Lott 19#11 4891'; **59.** *Neoendothyra* sp. Axial section. Lott 19#11 4891'; **60.** *Tetrataxis* sp. Subaxial section. Lott 19#11 4891'; **61.** Brachiopod shell. Lott 19#3 4825'.

***Carnets Geol.* 24 (3)**

E-ISSN 1634-0744
DOI: 10.2110/carnets.2024.2403

The Kalkowsky Project - Chapter V
Asymmetric ooids from the Yacoraite Formation (Argentina)

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Philippe LAPOINTE [3]

Abstract: Asymmetric ooids are documented in a brackish Maastrichtian to Danian paleolake in NW Argentina. Their distinctive asymmetric growth pattern is likely related to an uneven distribution of the Extracellular Polymeric Substances (EPS) around the coated allochem, within which calcite fibers (*i.e.*, the 'fibrite') have grown. This pattern is unlikely to be mistaken for that of other 'eccentric' ooids, such as wobbly ooids, spiny ooids, hiatus ooids, half-moon ooids, 'broken' ooids *sensu lato*, or collapsed oomolds (referred to as 'distorted' ooids).

Keywords:

- ooid;
- microbial carbonates;
- Salta;
- Argentina;
- Maastrichtian-Danian

Citation: GRANIER B.R.C. & LAPOINTE Ph. (2024).- The KALKOWSKY Project - Chapter V. Asymmetric ooids from the Yacoraite Formation (Argentina).- *Carnets Geol.*, Madrid, vol. 24, no. 3, p. 75-82. DOI: 10.2110/carnets.2024.2403

Résumé : *Le Projet KALKOWSKY - Chapitre V. Ooïdes asymétriques de la Formation Yacoraïte (Argentine).-* Nous décrivons des ooïdes asymétriques provenant d'un paléolac saumâtre d'âge Maastrichtien à Danien du nord-ouest de l'Argentine. Leur mode de croissance particulier, *i.e.*, asymétrique, est probablement lié à une répartition inégale des substances polymériques extracellulaires (SPE) autour du grain cortiqué, au sein desquelles les fibres de calcite (*i.e.*, la "fibrite") se sont développées. Il est peu probable que ce mode de croissance puisse être confondu avec celui d'autres ooïdes "excentriques", tels que les ooïdes bancals, les ooïdes épineux, les ooïdes hiataux, les ooïdes en demi-lune, les ooïdes "cassés" *sensu lato* ou les moules effondrés d'ooïdes (parfois appelés ooïdes "déformés").

Mots-clefs :

- ooïdes ;
- carbonates microbiens ;
- Salta ;
- Argentine ;
- Maastrichtien-Danien

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Published online in final form (pdf) on January 20, 2024
[Editor: Michel MOULLADE; language editor: Phil SALVADOR; technical editor: Bruno R.C. GRANIER]

1. Introduction

The petrographic analysis of thin sections reveals that there is still much to be gleaned from microbial carbonates (Granier & Lapointe, 2021, 2022a, 2022b); this is the core idea behind the Kalkowsky Project. The material presented here documents a new occurrence of 'eccentric' ooids from the lacustrine (Maastrichtian to Danian) Yacoraite Formation (*e.g.*, Cónsole Gonella *et al.*, 2012; Freire, 2012) in NW Argentina.

2. Material and general setting

The material under study was collected by one of us (P.L.) with the assistance of three IFP colleagues (Bernard Colletta, Jean Letouzey, and Roland Vialy) from two distinct localities in the provinces of Salta and Jujuy in NW Argentina (Fig. 1):

1) on October 6, 1988: The first section (Fig. 2), already documented in Granier and Lapointe (2022b, Figs. 3.D, 4-5), was found approximately 60 km south of Salta. It is situated on a bend of Road 47 from Coronel Moldes to Puente Dique Cabra Corral (Fig. 1.D), precisely at 25°17'04.4"S 65°24'56.1"W (Province of Salta, Argentina). This outcrop, located in the Metán subbasin of the Salta Basin, is referred to as "Afloramento Viñuales" of the "Sequência Balbuena IV" of the Yacoraite Formation (Freire, 2012, Figs. 5.1, 5.10, 8.7) and is assigned a Danian age. Four petrographic thin sections were prepared from two rock pieces labelled ARA 268 and ARA 269, collected near the top of the logged section. Although the first two thin sections (ARA 268 and ARA 269) are likely lost, two new thin sections (AG 268 and AG 269, registered as MHNG-GEPI-2024-10268 and 10269 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland) were prepared from offcuts of the initial two;

2) on October 15, 1988: The second section, measured by the same group of field geologists (Fig. 3.B), is exposed in a canyon located 6.5 km south of Palma Sola, west of the truck road connecting this locality to El Sauzal, approximately 100 km east of San Salvador de Jujuy (Fig. 1.C), at around 24°05'24.0"S 64°17'46.4"W (Province of Jujuy, Argentina). This second Yacoraite section is situated in the Lomas de Olmedo subbasin of the Salta Basin and is presumed to be of Maastrichtian age. Two petrographic thin sections were prepared from one rock piece labelled ARA 351, collected near the bottom of the exposed section (Fig. 3.B-C). While the first thin section (ARA 351) is likely lost, a second thin section (AG 351, registered as MHNG-GEPI-2024-10351 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland) was prepared from an offcut of the original.

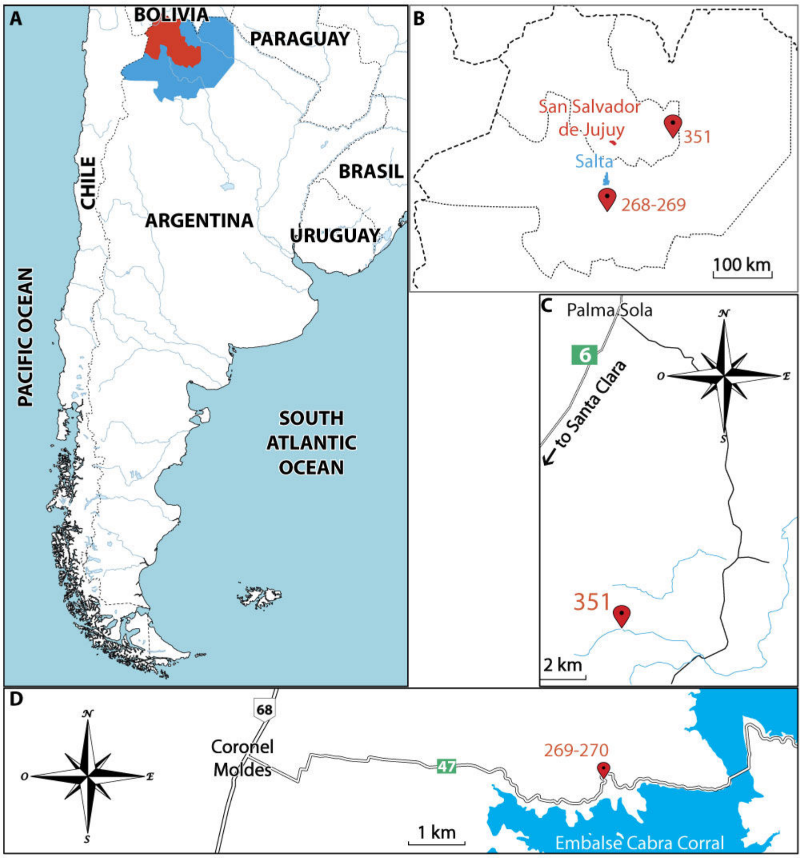


Figure 1: A) Location map of the provinces of Jujuy (red) and Salta (blue) in Argentina; **B)** location map of the sampling localities 268-269 in the Province of Salta and 351 in the Province of Jujuy; **C)** location of the sampling locality 351 in a canyon section 6.5 km south of Palma Sola, Province of Jujuy; **D)** location of the sampling localities 268-269 on a bend of Road 47 from Coronel Moldes to Puente Dique Cabra Corral, Province of Salta.

3. Descriptions of samples ARA 268, ARA 269, and ARA 351

Thin section ARA 268 (Fig. 4.A) reveals three stromatolitic microcolumns, each approximately 1 cm wide, containing silt and coated grains in the stromatolitic inner vugs and in the intercolumnar space. In contrast, the microfacies of thin sections AG 268, AG 269, and ARA 269 (Fig. 4.B) consist of 1) a floatstone of ooids and bothryoids (also spelled 'botryoids') with a silty matrix and 2) fibrous sparitic crusts growing on some bothryoids. The matrix also contains silt-sized quartz and some fish teeth.

The microfacies of both thin sections ARA 351 (Fig. 4.C) and AG 351 corresponds to a floatstone of bothryoids and oolitic lithoclasts with an oolitic grainstone matrix. Some lithoclasts exhibit a superficial oolitic coating. Ostracod shells are commonly observed as nuclei of ooids.

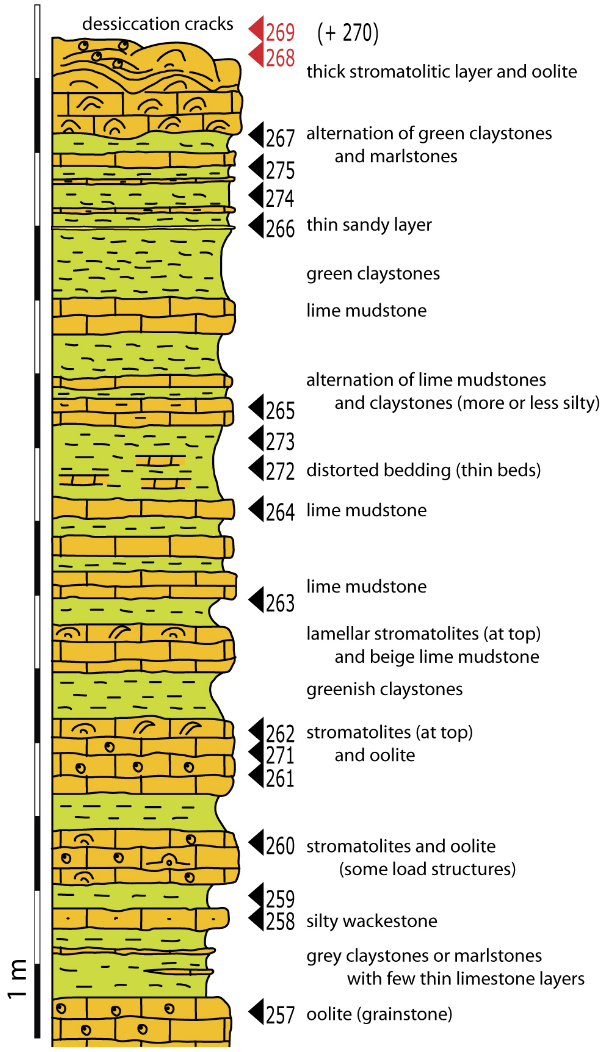


Figure 2: Shematic drawing of the Salta section (Cabra Corral) with location of samples 269 and 270 in bold red (excerpt from GRANIER & LAPOINTE, 2022b).

4. Descriptions of some ooids and bothryoids from thin sections AG 268, AG 269, AG 351, and ARA 351

The nucleus of one specimen from AG 268 (Figs. 5.B, 6.A) is a hemiooid *sensu* KALKOWSKY's (1908) classification. Similarly to most 'broken' ooids *sensu stricto*, the break lines align with the calcite fibers of the cortical layers. In this case, a half-piece of the ooid has undergone partial regeneration, a phenomenon also observed in the second half (Fig. 5.C), which was found approximately 5 mm away in the same thin section (Fig. 5.A). However, both pieces distinctly differ from typical 'broken and regenerated' ooids, *i.e.*, 'broken' ooids *sensu lato*, due to the non-continuous nature of their 'regenerated' cortices.

The siliciclastic nucleus of another asymmetric ooid from AG 268 (Figs. 5.E, 6.B) is protruding. Yellowish 'fibrite' (a neologism for 'fibrous calcite' as coined by GRANIER and LAPOINTE, 2022a, *i.e.*, "material with one large and two small dimensions" following FOLK, 1974) cortical layers are thicker right above the nucleus, and thin laterally and downward. It appears that the center of mass of the ooid did not change with the addition of a new fibrite layer. The amber-yellow tint of the fibrite crystals is unquestionably related to organic content (GRANIER, 2020), with calcite fibers incorporating a diffuse organic network, possibly the remnants of Extracellular Polymeric Substances (EPS).

A bothryoid from AG 269 (Fig. 5.D) is composed of a cluster of ooids, including one asymmetric ooid with an off-center siliciclastic nucleus, showing similarities with the previous example. Initially, the latter likely formed a first aggregate with another ooid, subsequently forming a biooid (*cf.* GRANIER & LAPOINTE, 2022b). New ooids joined to form a larger aggregate, then a bothryoid.

Ooids and bothyroids with anisopachous fibrite cortical layers are common among the coated grains of AG 351 (Fig. 5.F). The cortex of another asymmetric ooid from ARA 351 (Figs. 5.G, 6.C) exhibits significant variation in the thickness of its outermost layers.

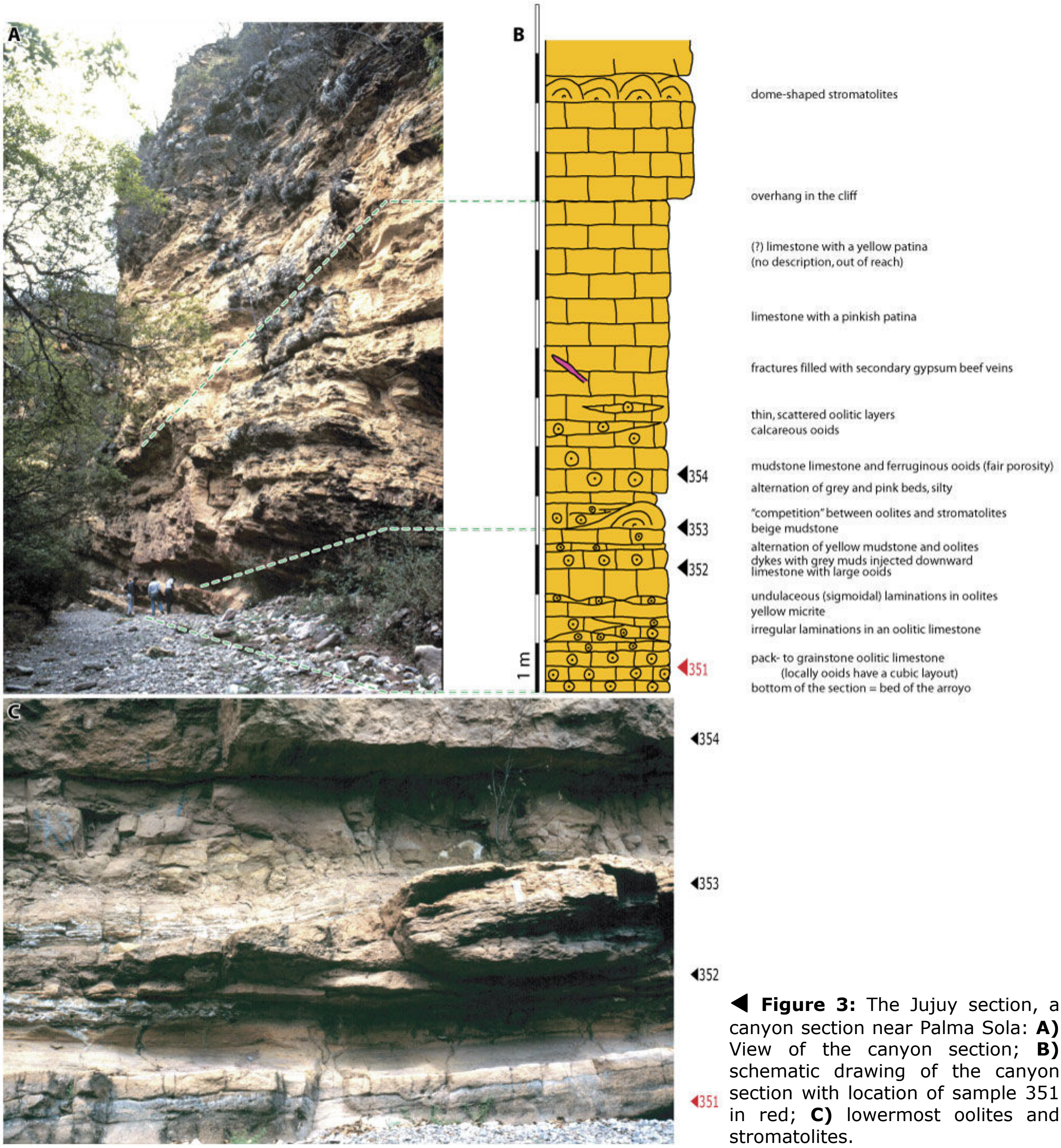
5. Discussion

In this chapter, Argentinian (Jujuy and Salta) asymmetric ooids are discussed in terms of differences and similarities with some other specific ooid types: 'broken' ooids *sensu lato*, 'distorted' ooids, half-moon ooids, hiatus ooids, and wobbly ooids.

Differences:

1) 'Broken and regenerated' ooids (CAROZZI, 1961): As stated previously, the nuclei of two specimens from AG 268 (Fig. 5.B-C), which are found approximately 5 mm away in the same thin section (Fig. 5.A), represent the two halves of the same original ooid. Both pieces have undergone partial regeneration. However, whereas the first layer of the 'regenerated' cortex is continuous in typical 'broken and regenerated' ooids, the Salta specimens (Fig. 5.B-C) are characterized by the non-continuous nature of their outer cortical layers. The latter commonly abut against the inner layers and include noticeable gaps.

2) 'Distorted' ooids (CAYEUX, 1935) and 3) half-moon ooids (WHERRY, 1915): Recently, GRANIER and coauthors (GRANIER *et al.*, 2022; GRANIER & KENDALL, 2022) demonstrated that some 'distorted ooids' are, in fact, collapsed oomolds, *i.e.*, a result of diagenetic processes involving leaching of the ooids followed by mechanical compaction. Similarly, half-moon ooids are formed through the leaching of oolitic cortices, causing the nuclei and some impurities to settle at the bottom of oomoldic cavities. Both types are associated to diagenetic processes. In contrast, the features observed in our Argentinian oolites are 'genetic', *i.e.*, indicating a relationship with synsedimentary growth processes.



◀ **Figure 3:** The Jujuy section, a canyon section near Palma Sola: **A)** View of the canyon section; **B)** schematic drawing of the canyon section with location of sample 351 in red; **C)** lowermost oolites and stromatolites.

4) Hiatus ooids: as defined by Berg (1944), such ooids exhibit some obliquely truncated cortical layers, suggesting that their asymmetry likely results from mechanical abrasion, indicative of erosional processes. Partly abraded layers of the inner cortex terminate beneath the boundary with the outer cortex. In contrast, in two ooids from AG 268 (Figs. 5.B-C, 6.A) some layers of the outer cortex terminate above the boundary with the inner cortex. More generally, the asymmetry observed in the Argentinian material is primarily associated with growth processes rather than abrasion.

5) Spiny ooids: According to Davaud and Strasser (1990), "the external cortices are deformed and detached from the underlying cortices near the points of contacts between the grains", which "strongly suggest a postdepositional origin for the spines". This type of ooid is associated with early diagenetic processes.

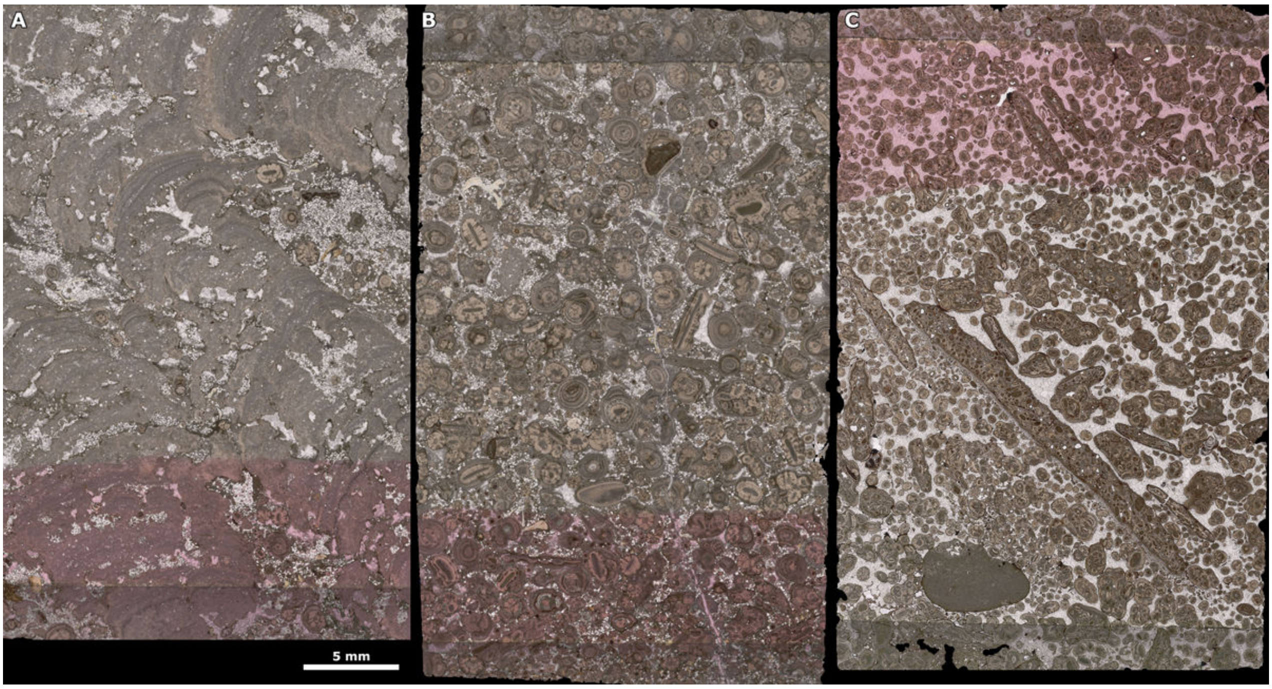


Figure 4: High resolution scans of the thin sections: **A)** three stromatolitic microcolumns, each approximately 1 cm wide, containing silt and coated grains in the stromatolitic inner vugs and in the intercolumnar space, ARA 268, **B)** floatstone of bothryoids and ooids with a silty matrix, ARA 269, **C)** floatstone of lumps and bothryoids with an oolitic grainstone matrix, ARA 351 (all likely lost). Scale bar for all scans = 5 mm.

6) Wobbly ooids: In the case of the Jujuy wobbly ooids (GRANIER & LAPOINTE, 2022a), the asymmetry is associated with the growth of micritic bumps, likely of microbial origin, and successive shifts of the center of gravity. In the material presented here, there are no micritic bumps; instead, incomplete yellowish 'fibrite' coatings are present. These coatings either thicken or thin and commonly abut against older layers. If these fibrite crusts were made of micrite, the Argentinian aymmetric ooids would unequivocally be classified as oncoids. In contrast to the previously described wobbly ooids (GRANIER & LAPOINTE, 2022a), the centers of mass in our Salta specimens of Figure 6.A-B, .D (samples AG 268 and AG 269) did not significantly move during the latest growth stages.

Similarities:

Salta asymmetric ooids (samples AG 268 and AG 269) exhibit some similarities with the modern "quiet water oölites from laguna Madre, Texas", as described by FREEMAN (1962). According to the latter, these asymmetric features "seem not to be the result of etching or abrasion but rather they appear to be primary features of these oölites" (*op. cit.*, p. 478). The specimen in figures 5.E and 6.B with its outlying siliciclastic nucleus (sample AG 268) shows even more striking similarities with certain ooids documented by FREEMAN (1962, Fig. 6, photomicrographs A and B). However, in contrast to FREEMAN's ooids, the cortices of which are composed of aragonite, the Argentinian coated grains were likely made of high-Mg calcite (GRANIER & LAPOINTE, 2022b).

It is worth mentioning that, whereas the nuclei of the ooids illustrated in figures 5.D-E and 6.B (samples AG 268 and AG 269) consist of siliciclastic grains, the ooid cortices never incorporated any silt-sized quartz grains, even when present in the matrix. This demonstrates that, unlike some stromatolites, ooids lack the capacity to agglutinate or bind such exogenous grains.

6. Conclusion

The distinctive ooids from the Maastrichtian-Danian Yacoraite Formation in NW Argentina, as described here, belong to a unique class of 'eccentric' ooids. Unlike the wobbly ooids, the examples studied here do not exhibit any micritic bumps, and their fibrite cortical layers are not isopachous. Instead, a discontinuous, anisopachous fibrite coating and, eventually, an eccentric position for their center of gravity are determining factors to explain their cortical asymmetry. Because they should not be confused with 'broken' ooids *sensu stricto*, 'broken and regenerated' ooids (CAROZZI, 1961), *i.e.*, 'broken' ooids *sensu lato*, 'distorted' ooids (CAYEUX, 1935), half-moon ooids (WHERRY, 1915), hiatus ooids (BERG, 1944), spiny ooids (DAVAUD & STRASSER, 1990), or wobbly ooids (GRANIER & LAPOINTE, 2022a), it is recommended to simply categorize them as asymmetric ooids.

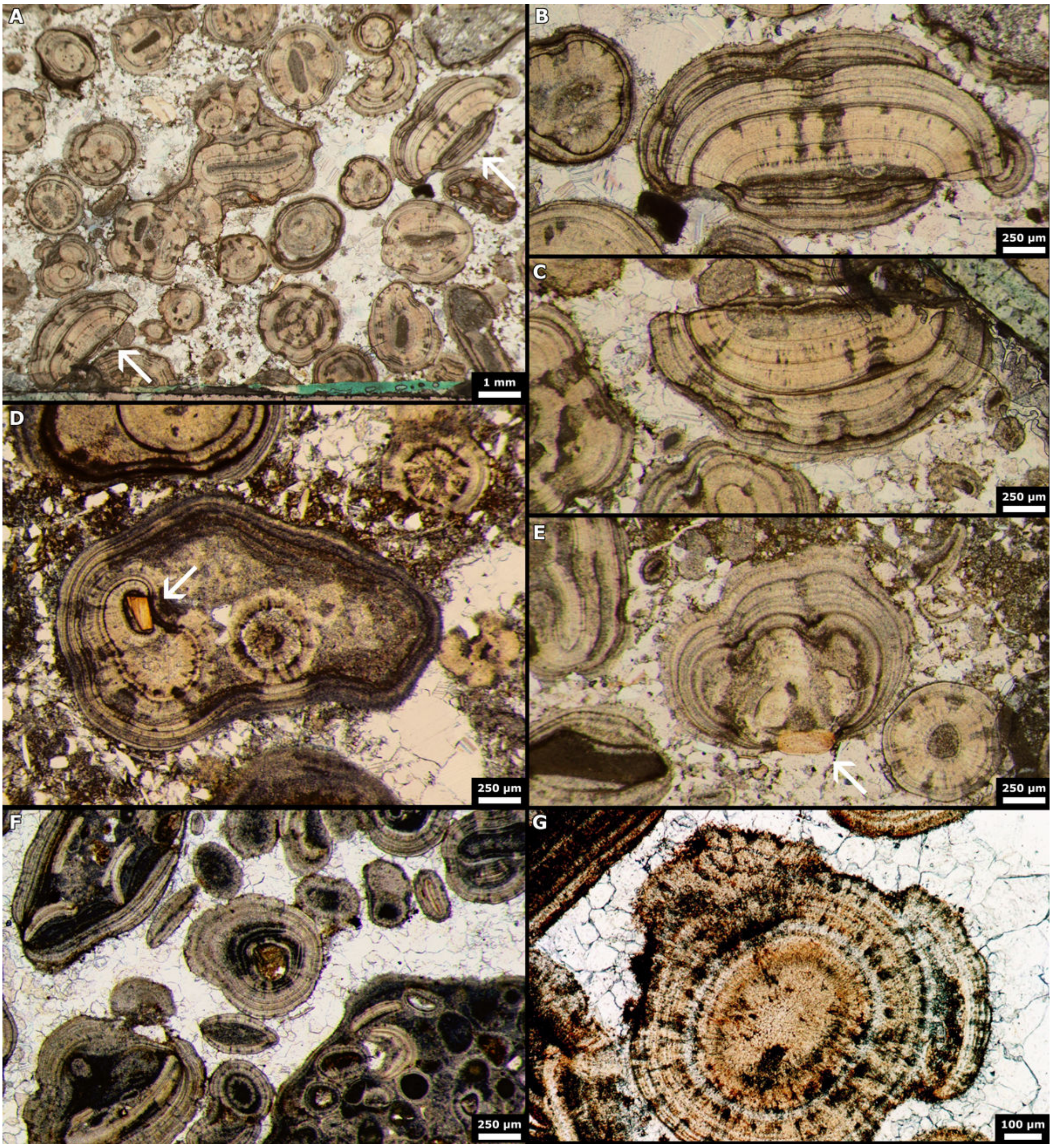


Figure 5: A-C, E) thin section AG 268: A) microfacies (the two half ooids are arrowed); B-C; broken and asymmetrically regenerated ooids; E) asymmetric ooid with a protruding siliciclastic nucleus (arrowed); **D)** thin section AG 269: bothryoid composed of a cluster of ooids, including one asymmetric ooid with its off-center siliciclastic nucleus (arrowed); **F)** thin section AG 351: ooid with an asymmetric cortex at the center of the photomicrograph; **G)** thin section ARA 351: ooid with an asymmetric, non-continuous cortex. A-E: Road 47 from Coronel Moldes to Puente Dique Cabra Corral, Province of Salta; F-G: south of Palma Sola, Province of Jujuy. A) scale bar = 1 mm; B-F) scale bar = 250 µm; G) scale bar = 100 µm.

Acknowledgements

The rock samples studied here were collected by the second author (P.L.) on the occasion of a joint mission of Total - Compagnie Française des Pétroles, and IFP - Institut Français du Pétrole from October 5 to November 3, 1988. He acknowledges the support of his IFP colleagues, Bernard COLLETTA, Jean LETOUZEY, and Roland VIALY, for fieldwork. The authors acknowledge the detailed reviews provided by Christopher G.St.C. KENDALL (University of South Carolina) and André STRASSER (Université de Fribourg/Univesität Freiburg) and their help in improving this short paper. The first author (B.G.) would like to thank Phil SALVADOR for his appreciated help with the final (English) text.

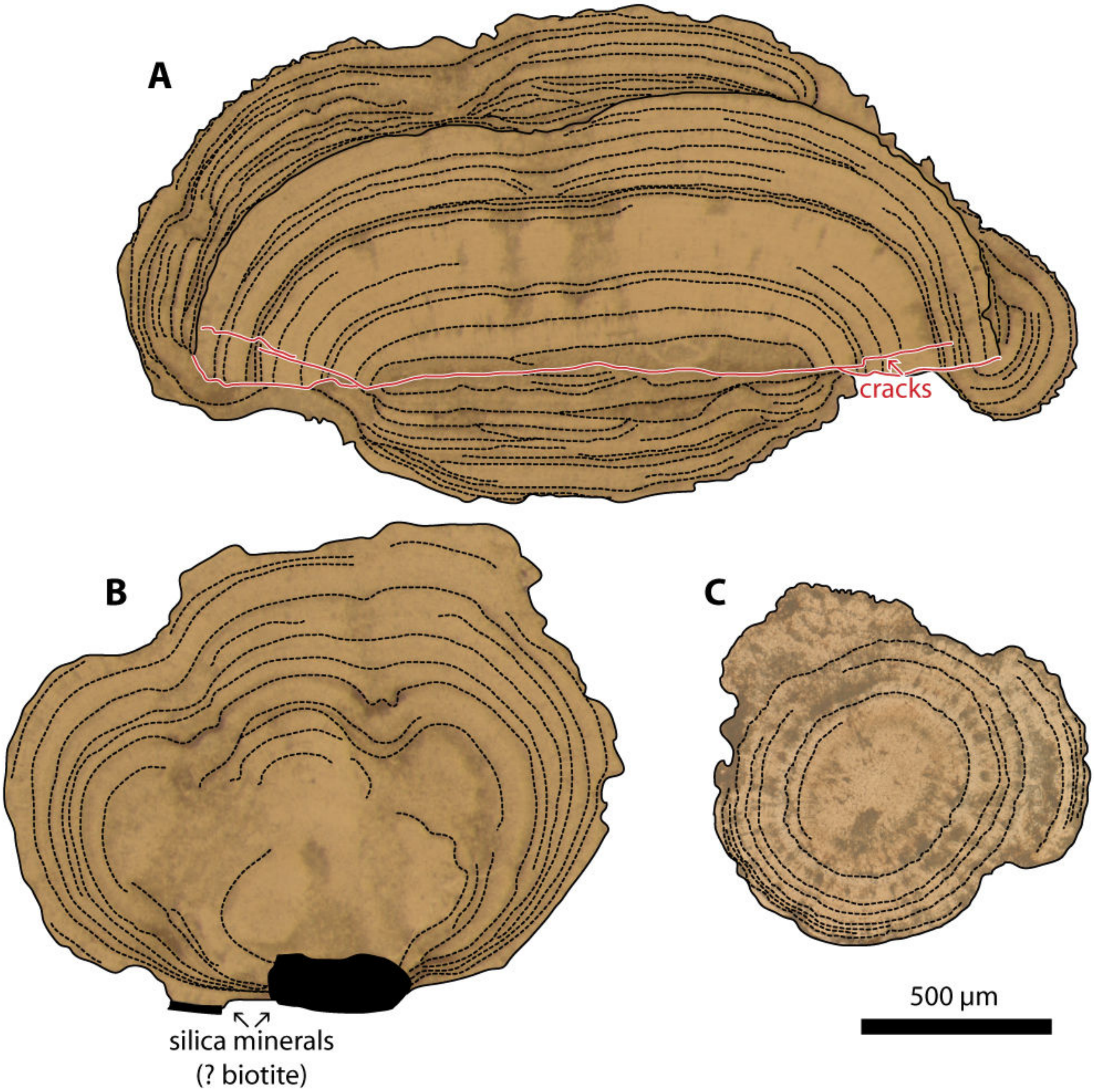


Figure 6: A-B) thin section AG 268, Road 47 from Coronel Moldes to Puente Dique Cabra Corral, Province of Salta: A) following the ooid breakage, growth of the regenerated cortex is restricted to a part of the fracture plane, one edge and the convex part, see Fig. 5.B; B) the center of mass of the ooid is likely the protruding siliciclastic nucleus controling the upward growth of the cortex, see Fig. 5.E; **C)** cauliflower-like developments on the outermost cortical layers, thin section ARA 351, south of Palma Sola, Province of Jujuy, see Fig. 5.G. Scale bar for all photomicrographs = 500 µm.

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Carnets Geol. 24 (5)
E-ISSN 1634-0744
DOI: 10.2110/carnets.2024.2405

The Kalkowsky Project - Chapter VI
A panorama of synsedimentary broken ooids

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Abstract: Broken ooids are known to occur in both aragonitic and calcitic ooids with radial fabrics. In the literature, it has been suggested that synsedimentary breakage could be related to attrition/mechanical impacts, hypersalinity, or desiccation. However, this paper demonstrates that none of the aforementioned phenomena provides a valid explanation. Although the exact process remains unknown (potentially involving some synsedimentary recrystallization), it is shown that: 1) the breakage is genetically linked to the radial fabrics; 2) the ratio of ooid breakages increases with the relative thickness of the radial cortical layers; 3) fracture growth in broken ooids proceeds centripetally.

Keywords:

- oolite;
- broken ooids;
- broken and regenerated ooids;
- radial fabrics;
- Argentina;
- France;
- Greece;
- Spain

Citation: Granier B.R.C. & Lapointe Ph. (2024).- The Kalkowsky Project - Chapter VI. A panorama of synsedimentary broken ooids.- *Carnets Geol.*, Madrid, vol. 24, no. 5, p. 91-112. DOI: 10.2110/carnets.2024.2405

Résumé : ***Le Projet Kalkowsky - Chapitre VI. Un panorama d'ooïdes brisés au cours de processus synsédimentaires.-*** Les ooïdes brisés sont observés dans les ooïdes aragonitiques et calcitiques présentant des textures radiaires. Dans la littérature, il a été suggéré que la cassure synsédimentaire pouvait être liée à des impacts mécaniques (attrition), à l'hypersalinité ou à la dessiccation. Toutefois, cet article démontre qu'aucun des phénomènes susmentionnés ne constitue une explication valable. Bien que le processus exact reste inconnu (impliquant potentiellement une recristallisation synsédimentaire), il est démontré que: 1) la cassure est génétiquement liée aux textures radiaires ; 2) le pourcentage de cassures d'ooïdes augmente avec l'épaisseur relative des couches corticales radiaires ; et 3) la croissance des fractures dans les ooïdes brisés est centripète.

Mots-clefs :

- oolithe ;
- ooïdes brisés ;
- ooïdes brisés et régénérés ;
- textures radiaires ;
- Argentine ;
- Espagne ;
- France ;
- Grèce

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Published online in final form (pdf) on February 29, 2024
[Editor: Michel Moullade; language editor: Phil Salvador; technical editor: Bruno R.C. Granier]

1. Introduction

After reading a paper on the Purbeck ooids described by STRASSER (1986), Robert BOICHARD, our former 'carbonate' colleague at Total - Compagnie Française des Pétroles, identified a continuum in the calcitic ooid texture from radial *auct.* to concentric *auct.*, and then to micritic *auct.* from the base to the top of the Callovian 'Dalle nacrée' Formation in the Paris Basin [Note: In 1992, following Robert BOICHARD's overseas departure, the first author (B.G.) was appointed to lead Paris Basin studies at the Scientific and Technical Center in Saint-Rémy-lès-Chevreuses]. As highlighted by GRANIER (1995, p. 149), "This gradual process is marked within the ooid cortex by a thickness decrease of the radial layers and an increase in the number of radial and micritic layers" (Pl. 1, figs. a-bc; Pl. 2, figs. a-bc) [Note: GRANIER (1994, 1995, 1996) also identified two tiny hiatuses in the continuum that he utilized for regional correlations (Fig. 1)], and "In addition, concerning ooid structures, hemiooids are common among the radial ooids" (Fig. 2.p-r)", rare among the concentric ooids" (Pl. 2, figs. c, g)", and absent among the micritic ooids." In conclusion, it appears that there is a correlation between the thickness of the radial layers and the ratio of ooid breakages.

The purpose of this publication is to further document this hypothesis. To achieve this, we first provide a concise review on broken and regenerated ooids in the literature. Secondly, we accompany this review with unpublished examples from diverse locations. Finally, we document unique Argentinian specimens.

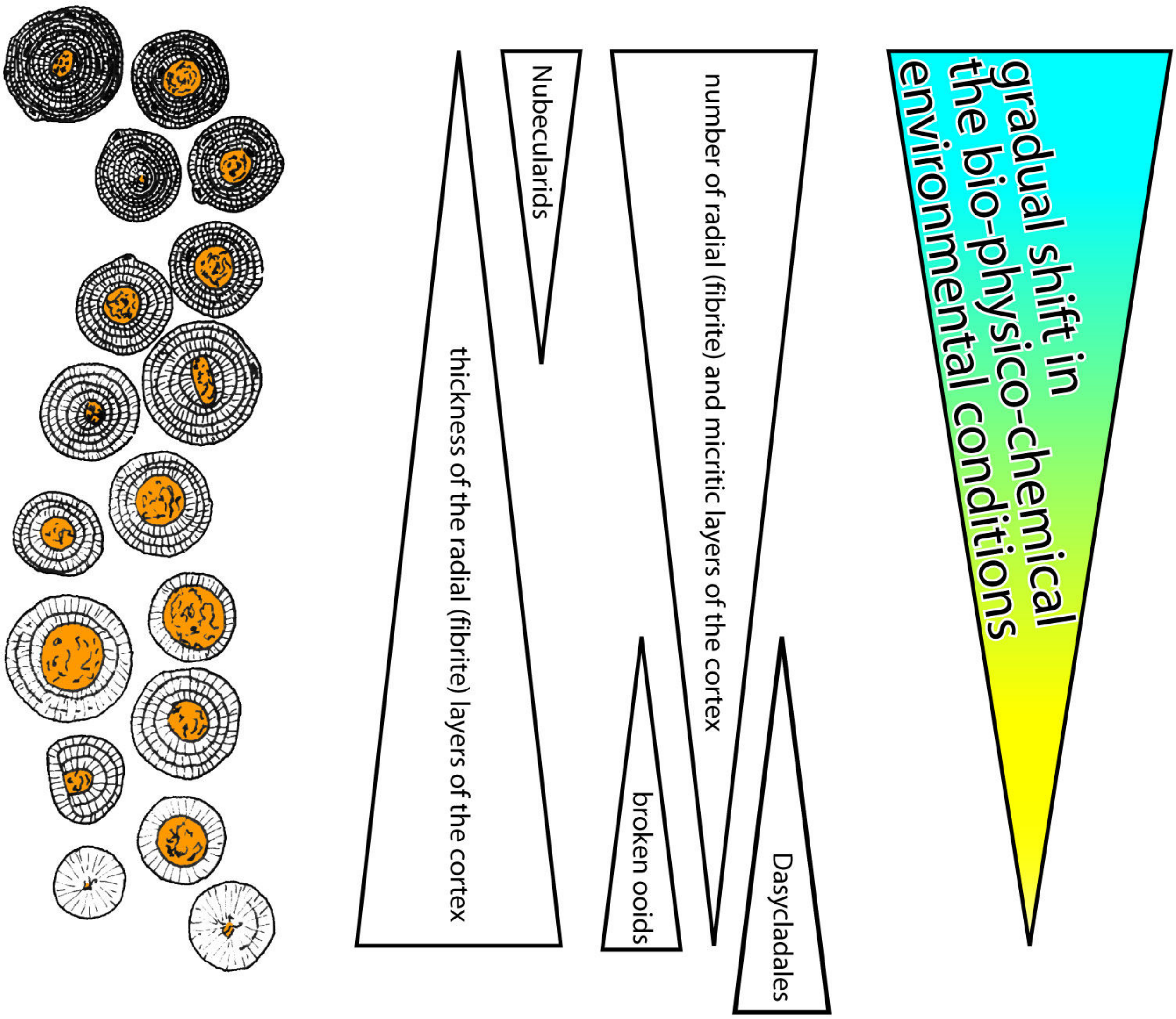
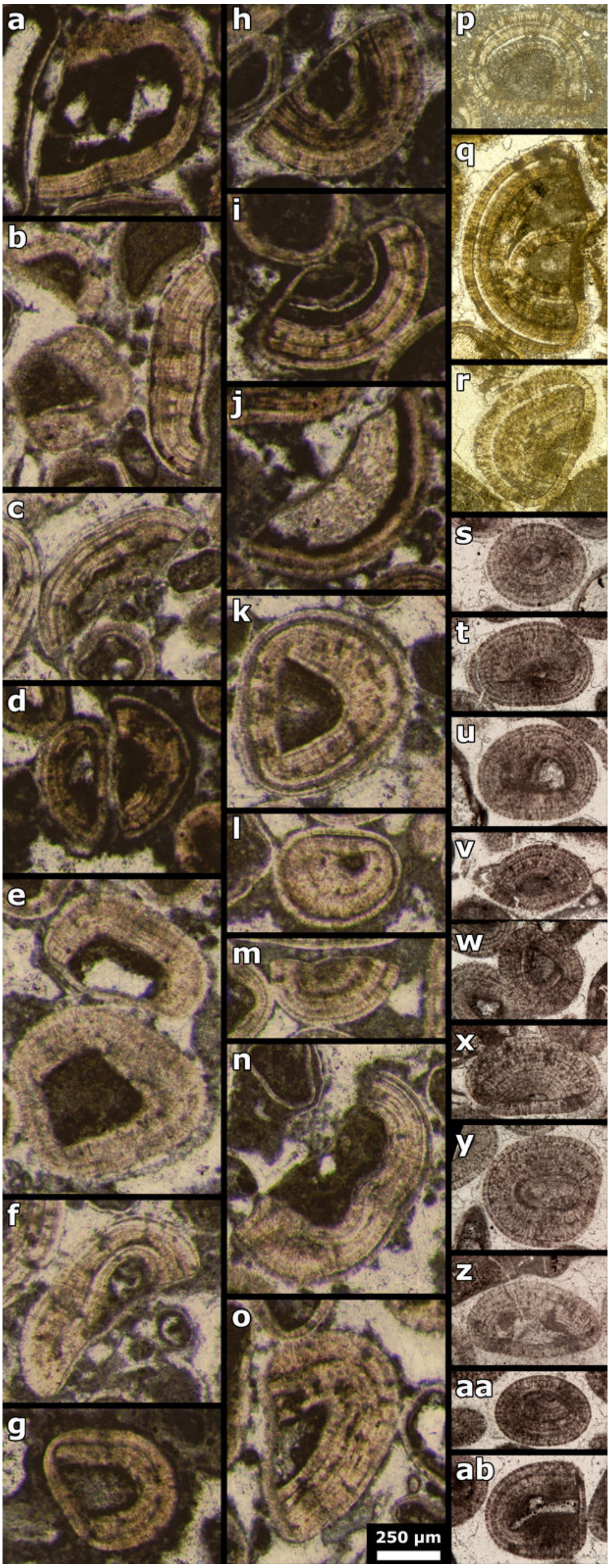


Figure 1: Stratigraphical model for the Villeperdue oil field and other oil fields of the Paris Basin, France (modified from GRANIER, 1994, 1995, 1996).

2. Material

The studied material comes from various stratigraphic intervals and geographic locations, offering a comprehensive view of the issue of broken ooids:

- **France**: The French material comprises:
    - photomicrographs of Lower Callovian ('Dalle nacrée') thin sections from cores of the Villeperdue VPI-01 (VPU44, national identifier BSS000 PRKQ) well, Le Gault-Soigny, 15 km SE of Montmirail (Marne), GPS coordinates 48°48'19.0"N 3°35'42.0"E (Fig. 2.p-r; Pl. 1, figs. a-bc; Pl. 2, figs. a-bc). Two cores, each with a core recovery of 100%, were taken from the interval 1,806.0-1,835.0 m CD (CD = core depth). The core-log depth matching for core 1 (1,806.0 - 1,824.0 m CD) corresponds to log depths in the range of 1,808.4 -1,826.4m LD (LD = log depth) with an offset of + 2.4 m. Similarly, for core 2 (1,824.0 - 1,835.0 m CD), the offset remains unchanged, and log depths span the interval 1,826.4 - 1,837,4 m LD. The base of the unit with radial ooids, marking the top of the 'Comblanchien' facies, was not reached. The top of this first unit (*i.e.*, the unit with radial ooids), also serving as the base of the unit with concentric ooids, is identified as a bored hardground at 1,827.1 m CD (1,829.5 m LD). The top of this second unit (*i.e.*, the unit with concentric ooids), which also serves as the base of the unit with micritic ooids, is characterized by an erosional surface at 1,813.3 m CD (1,815.7 m LD) overlaid by a layer of bored lithoclasts. The top of this last unit (*i.e.*, the unit with micritic ooids) is identified as a bored hardground at 1,806.2 m CD (1,808.6 m LD);
    - a few photomicrographs of Lower Devonian ('Formation de l'Armorique') thin sections (from PELHATE, 1980), currently stored in the collections of the former 'Laboratoire de Paléontologie et Stratigraphie du Paléozoïque' of the Université de Bretagne Occidentale in Brest, Plougastel-Daoulas (Finistère), GPS coordinates 48°19'35.0"N 4°27'14.2"W (Pl. 3, figs. m-q);



▶ **Figure 2:** Photomicrographs of broken ooids *sensu lato* and hiatus ooids from site 392A (DSSP Leg 44), France, and Spain. a-o) thin section from core 21-1; p-r) radial ooids, well VPI-01, Villeperdue, France: p) thin section 1,828.00 m; q) thin section 1,828.50 m; r) thin section 1,832.25 m; s) sample HL72B, Alicante, Spain (GRANIER, 1987, Pl. 21, fig. d); t, v-w, aa-ab) sample HL72A, Alicante, Spain; u, x-z) sample HL72B, Alicante, Spain. Graphical scale bar for all photomicrographs = 250 µm.

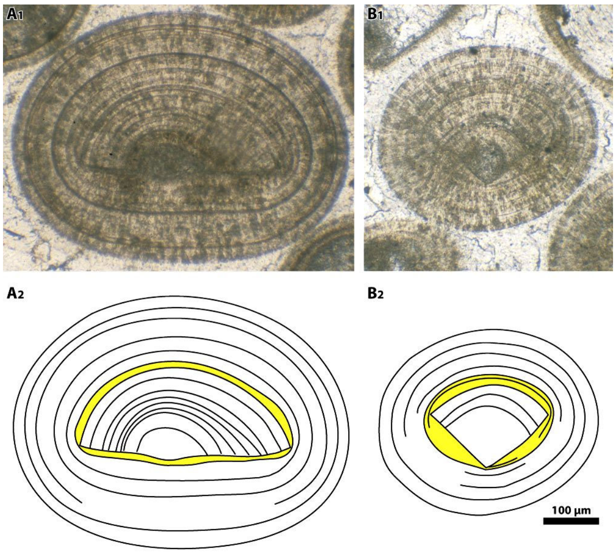


Figure 3: Broken and regenerated ooids. The healing phase, corresponding to the early stage of regeneration, is colored in yellow in drawings A2 and B2. A1-2) sample HL 723, Alicante, Spain; B1-2) sample HL72B, Alicante, Spain. Graphical scale bar for all photomicrographs and drawings = 100 µm.

- **Spain**: The two Lower Albian samples studied were collected by one of us (B.R.C.G.) at Serra Gelada (Alicante, Spain):
  - on April 14, 1984 (Granier, 1987): sample HL 72, A = MHNG-GEPI-2024-11152 et B = MHNG-GEPI-2024-11182, carabiniers no. 2, 'coupe des carabiniers' (Cami del Far), GPS coordinates 38°33'59.5"N 0°03'20.9"W (Figs. 2.s-ab, 3.B);
  - on May 1, 1985 (Granier, 1987): sample HL 723 = MHNG-GEPI-2024-11112, Relais no. 12, 'coupe du relais', below the Albir Radar Állomás, GPS coordinates 38°33'19.1"N 0°03'43.6"W (Fig. 3.A);
- **N Atlantic**, off Florida coast (USA): The DSSP Leg 44 material comes from Berriasian thin sections of core 21 of site 392A (Fourcade & Granier, 1989; Granier, 2019), GPS coordinates 29°54'37.8"N 76°10'40.8"W (Fig. 2.a-o);
- **Greece**: This Tithonian material was collected by J.-J. Fleury before 1978 (Bernier & Fleury, 1980; Fleury, 1980): sample GEA4 780 5525 = MHNG-GEPI-2024-10285 (Kanala, Gavrovo, Greece), GPS coordinates 39°01'04.0"N 21° 21'06.2"E (Pl. 3, figs. a-h, j-l);
- **Argentina**: The Maastrichtian-Danian material studied was collected by one of us (Ph.L.) accompanied by two IFP colleagues (namely Bernard Colletta and Jean Letouzey):
  - on October 6, 1988: sample ARA 269 from the Maastrichtian-Danian Yacoraite Formation (Cónsole Gonella *et al.*, 2012), Province of Salta (see Granier & Lapointe, 2022, Figs. 3.A-B, .D, 5), GPS coordinates 25°17'04.4"S 65°24'56.1"W (Pl. 3, fig. i). It corresponds to the thin section AG 269 = MHNG-GEPI-2024-10269;
  - on October 8, 1988: sample ARA 288 from the Paleocene-Eocene Maíz Gordo Formation (Del Papa, 1999), Province of Jujuy (see Granier & Lapointe, 2021, Fig. 1), GPS coordinates 24°22'23.82"S 64° 58'30.56"W (Pl. 4, figs. a-am; Pl. 5, figs. a-af; Pl. 6, figs. a-w). Only three petrographic thin sections were prepared from the piece of rock labeled ARA 288 that comprises both oolitic and stromatolitic facies: the first thin section (ARA 288) is probably lost, the second and third thin sections (AG 288A = MHNG-GEPI-2024-10288, AG 288B = MHNG-GEPI-2024-10289) were prepared from an offcut of the first.

3. Review of the calcareous broken ooids in the literature

Breakage and regeneration are commonly observed in aragonite ooids with radial fabrics whereas they are almost nonexistent in aragonite ooids with tangential fabrics. According to Halley (1977), "Broken ooid fragments comprise between one and three percent of the grains in Great Salt Lake ooid samples" whereas "In contrast, samples of normal marine ooids from the Bahamas" (...) "indicate that broken ooid fragments account for less than 0.01% of the grains in these ooid samples". There is a distinct separation in terms of breakage between the ooids with radial fabrics (Great Salt Lake type) and those with tangential fabrics (Bahamas or Persian Gulf type).

While reviewing the literature, we came across a singular example of broken aragonite ooids with tangential fabrics, as documented by Hesse (1973) in the Ita Mai Tai Guyot, a DSDP site located northwest of the Marshall Islands and north of Micronesia. In his report, the author asserted that the ooids were primarily aragonitic and secondarily calcitized. In fact, he simply endorsed the template model proposed by Shearman *et al.* (1970) to elucidate the "replacement of the cortex aragonite" (with tangentially arranged needles) "by low magnesian calcite" (with orthogonally arranged fibers). However, this assumption can be disproven, because the cortices of these calcitic ooids exhibit distinct, unaltered radial fabrics (see Hesse, 1973, Pl. 1, figs. 1-2; Pl. 2, figs. 3-4; Pl. 3, figs. 1-6; Pl. 4, figs. 1-6), similar to the numerous examples documented herein and elsewhere (*e.g.*, Granier, 1987, Pl. 20, figs. c-f; Pl. 21, figs. c-d). Additionally, we encountered a unique study of broken ooids with radial fabrics from the Holy Cross Mountains, purportedly composed of primary dolomite as indicated by Łabęcki and Radwański (1967). However, while it is plausible that the matrix is dolomicrite - more likely a secondary dolomicrite (formed after a primary microcrystalline calcite) - the fibrous habit of the crystals within the oolitic cortices suggests that these crystals have retained their primary mineralogy, implying they are still composed of primary calcite, not of dolomite.

If we exclude micritized or otherwise diagenetically altered ooids, calcite ooids exhibit only radial fabrics, with breakage and regeneration commonly observed. This is likely because breakage is genetically linked to the radial fabrics.

Table 1 provides a non-exhaustive list of broken and (mostly) regenerated ooids found in the literature, along with interpretations of their environmental settings, stratigraphic ascriptions, and geographic locations. All valid examples, whether aragonite or calcite ooids, exhibit radial fabrics.

Table 1: Review of the calcareous broken ooids in the literature.

Mineralogy	calcite	aragonite	aragonite	environment	age/location
Fabric	radial	radial	tangential		
Kalkowsky, 1908, Pl. V, fig. 2; Käsbohrer & Kuss, 2019, Fig. 13.F	'Hemiooids', broken and regenerated ooids				Lower Triassic, Germany
Carozzi, 1961, Figs. 6.A-O, 7.A-J	broken and regenerated ooids			normal marine	Lower Carboniferous, Alberta, U.S.A.
Carozzi, 1961, Fig. 8.A-G; D'Argenio *et al.*, 1975, Fig. 3; Halley, 1977, Fig. 3.a; Simone, 1981, Fig. 25; Käsbohrer & Kuss, 2019, Fig. 13.E		broken and regenerated ooids		hypersaline	Holocene, Great Salt Lake, Utah, U.S.A.
Łabęcki & Radwański, 1967, Pls. I-VI	broken and regenerated 'dolomite' ooids			hypersaline lagoon	Upper Triassic, Poland
Hesse, 1973, Pl. 2, figs. 1-2	broken ooid (replacement by low-Mg calcite)		broken ooid (original aragonite replaced)	normal marine	Lower Eocene or downward, Pacific Ocean
Hesse, 1973, Pl. 2, figs. 3-4	broken and regenerated ooid (replacement by low-Mg calcite)		broken and regenerated ooid (original aragonite replaced)	normal marine	Lower Eocene or downward, Pacific Ocean
Carbone & Civitelli, 1974, Figs. 2, 7, 12; D'Argenio *et al.*, 1975, Figs. 2.B1, 4.C; Simone, 1981, Fig. 15; Flügel, 2004, Pl. 13, fig. 4	broken and regenerated ooids			normal marine	'lowermost Cretaceous' or 'Late Jurassic-Early Cretaceous' *auct.*, Apennines, Italy
D'Argenio *et al.*, 1975, Fig. 2.A1; Simone, 1981, Fig. 24	broken and regenerated ooids			normal marine	'Late Jurassic-Early Cretaceous' or 'Neocomian' *auct*, off Gentry bank, N Atlantic Ocean
Bernier & Fleury, 1980, Pl. 1, fig. 3	broken ooids, broken and regenerated ooids				uppermost Jurassic, Greece
Tišljar, 1980, Pl. II, fig. 8; Pl. III, fig. 11; 1983, Fig. 4.C-F; 1985, Fig. 7.D-F; Tišljar & Velić, 1993, Fig. 6; Husinec & Read, 2006, Fig. 4.A-H; 2007, Fig. 5.D-F	broken and regenerated ooids (vadoids according to Tišljar, 1983)			hypersaline (according to Husinec & Read, 2006, 2007)	Tithonian (Upper Jurassic), Croatia
Tucker, 1984, Figs. 12-13, 20.A-B	broken and regenerated ooids			brackish to hypersaline	upper Middle Proterozoic, montana, U.S.A.
Granier, 1987, Pl. 20, figs. c-f; Pl. 21, figs. c-d	'hémi-ooïdes', broken and regenerated ooids			normal marine	Albian (Lower Cretaceous), Spain
Granier, 1996, Fig. 6.3, 6.7	broken and regenerated ooids			normal marine	Callovian (Middle Jurassic), France
Granier & Lapointe, 2021, Pl. 1, figs. j-l, n, p-q, u; Pl. 2, figs. a-d, h, p	broken ooids			brackish	Upper Paleocene - Lower Eocene, Argentina
Granier & Lapointe, 2021, Pl. 1, fig.a; Pl. 2, figs. e-g, n	broken and regenerated ooids			brackish	Upper Paleocene - Lower Eocene, Argentina

Plates 01 and 02 exhibit photomicrographs of ooids, randomly selected from thin sections taken with an average spacing of 25 cm from top to base of the Lower Callovian ('Dalle nacrée') oolite in the Villeperdue VPI-01 well. As observed in other wells from the Paris Basin and outcrops in Burgundy, they accurately document GRANIER's (1994, 1995, 1996) model of the stratigraphical succession of radial *auct.*, concentric *auct.*, and micritic *auct.* ooids (Fig. 1). Broken and regenerated ooids are commonly found in the unit with radial ooids (Fig. 2.p-r), and are also present, though less abundantly, in the unit with concentric ooids (Pl. 2, figs. c, g).

The ooids from the French Lower Devonian (Pl. 3, figs. n-q) and the Spanish Lower Cretaceous (Figs. 2.s-ab, 3.A-B) would also fall into the category of the 'concentric ooids' according to GRANIER (1994, 1995, 1996), which represents a category intermediate between ooids with dominating radial fabrics and those with dominating concentric fabrics. As observed previously for the French Middle Jurassic (Pl. 2, figs. c, g), broken ooids are not very common there as well.

The 'Upper Jurassic' *auct.*(including the Berriasian) broken ooids (Fig. 2.a-o) from the DSDP leg 44 site 392A (FOURCADE & GRANIER, 1989; GRANIER, 2019) and those from samples dredged off the Gentry Bank (D'ARGENIO *et al.*, 1975) likely originate from a contemporaneous oolitic formation. However, the latter were poorly dated, being assigned either to the 'Late Jurassic-Early Cretaceous' (D'ARGENIO *et al.*, 1975) or the 'Neocomian' (SIMONE, 1981; FLÜGEL, 2004), based on '*Cayeuxia* type algae', whereas samples from DSDP leg 44 site 392A were recently reassigned to the middle-upper Berriasian interval (GRANIER, 2019).

Based on the occurrence of the alga *Aloisalthella sulcata* (ALTH), the Greek oolitic formation is assigned a Tithonian age (BERNIER & FLEURY, 1980), although an early-middle Berriasian age cannot be excluded (GRANIER, 2019). It is likely that the Croatian 'Tithonian' oolitic formation studied by TIŠLJAR and his followers (TIŠLJAR, 1980, 1983, 1985; HUSINEC & READ, 2006, 2007) is contemporaneous. Broken ooids are very common in these facies (Pl. 3, figs. a-h, j-l), and TIŠLJAR (1983, 1985) originally interprets them as vadoids.

There are more broken ooids in the three thin sections (Pl. 4, figs. a-am; Pl. 5, figs. a-af; Pl. 6, figs. a-w) from the sample ARA 288, collected in the Province of Jujuy (Argentina), than in all other thin sections with broken ooids shown here. Notably, the ooid nuclei are commonly broken. However, the most significant feature is the presence of numerous broken ooids with both counterparts still facing each other (Pl. 4, figs. a-e, h, j-m, w; Pl. 5, figs. m, q-t; Pl. 6, figs. a-f), consistent with schematic drawings by CAROZZI (1961, Fig. 2.H-N) and a few of his photomicrographs (*ibid.*, Fig. 5.E, .G, .I). While CAROZZI's sketches hardly correspond to any of his photomicrographs, they exhibit striking similarities with our Argentinian material. For instance, **1)** our Pl. 4, figs. o-q and ab-ac, Pl. 5, figs. o, s (bottom part), and ad-ae, and Pl. 6, fig. g, correspond to CAROZZI's (1961) Figure 3.E; **2)** the fracture set in our Pl. 5, fig. s (middle part) shows some similarities with CAROZZI's (1961) Figure 2.I; **3)** the fractures in our Pl. 4, figs. k and m, and Pl. 5, figs. m (bottom part) and t, look very similar to CAROZZI's (1961) Figure 2.M.

We transcribe below some key excerpts of CAROZZI's (1961) contribution: "Before discussing the evolution of the various types of fragments generated by breakage phenomena, it is worth describing the general properties of the fracture networks that have affected the ooids. These breaks, numbering four to five in a given oolite, are essentially rectilinear or slightly undulating, often but not necessarily in a radial position. Some of these breaks may be parallel to each other, but more often, they intersect at variable angles" (translated from the French: "Avant de discuter l'évolution des divers types de fragments engendrés par les phénomènes de rupture, il convient de décrire les propriétés générales des réseaux de cassures qui ont affecté les oolithes. Ces cassures qui peuvent atteindre le nombre de quatre à cinq dans une oolithe donnée, sont essentiellement rectilignes ou légèrement ondulées, souvent mais pas nécessairement en position radiale. Quelques-unes de ces cassures peuvent être parallèles entre elles, mais le plus souvent elles se recoupent sous des angles variables").

"These fractures may have their maximum width in the middle of the ooid and become increasingly narrow radially, or they may have their maximum width at the periphery of the ooid and wedge inwards. Finally, they may be the same width along their entire length. The fractures are always filled with hyaline 'secondary' calcite; their hanging walls are well-defined, and sometimes, the filling calcite cement contains small angular fragments detached from the edges" (translated from the French: "Ces cassures peuvent présenter leur largeur maximale au milieu de l'oolithe et devenir de plus en plus étroites radialement, ou présenter leur largeur maximale à la périphérie de l'oolithe et se coincer vers l'intérieur" (...) ". Enfin, elles peuvent être de la même largeur sur toute leur longueur. Les cassures sont toujours remplies par de la calcite secondaire hyaline, leurs épontes sont bien définies et parfois la calcite de remplissage contient de petits fragments anguleux détachés des bordures").

"Statistically, the most frequent form of fracture appears to involve one or two main radial fractures with a few fine secondary fractures obliquely intersecting the previous ones. This system causes the ooids to break into half-spheres, with the possibility of subsequent fractures into smaller segments along the secondary fractures. Another aspect of ooid fracture is represented by a system of three main radial fractures with a few fine secondary fractures obliquely intersecting the first. This system leads to ooids breaking into more or less perfect thirds of spheres" (translated from the French: "Il apparaît statistiquement que la forme de rupture la plus fréquente correspond à une ou deux cassures principales radiales auxquelles sont associées quelques fines cassures secondaires recoupant obliquement les précédentes" (...) ". Ce système occasionne la rupture des oolithes en demi-sphères avec possibilité de ruptures ultérieures en segments plus petits le long des cassures secondaires. Un second aspect de la rupture des oolithes est représenté par un système de trois cassures principales radiales avec quelques fines cassures secondaires recoupant obliquement les premières" (...) ". Ce système conduit à la rupture des oolithes en tiers de sphères plus ou moins parfaits").

"Compared with fracture systems, ooids generally behave like rigid, homogeneous bodies, despite their concentric internal structure. However, in a few cases, fractures show local changes in orientation when they intersect a given group of concentric layers that have reacted differently to fracture forces. These changes in direction are repeated symmetrically on either side of the core and sometimes correspond to the outer concentric layers. Finally, in other cases, complicated networks of fine, highly curved fractures have developed, often following the boundaries between concentric layers for some distance, with some segments detached in this way" (translated from the French: "Par rapport aux systèmes de cassures, les oolithes se comportent en général comme des corps rigides et homogènes en dépit de leur structure interne concentrique. Cependant, dans quelques cas, les cassures montrent des changements locaux d'orientation lorsqu'elles recoupent un groupe donné de couches concentriques qui ont réagi de façon différente aux efforts de rupture. Ces changements de direction sont répétés symétrique ment de part et d'autre du noyau" (...) "et parfois correspondent aux couches concentriques extérieures, Enfin, dans d'autres cas, ont pris naissance des réseaux compliqués de fines cassures à forte courbure et qui souvent suivent sur une certaine distance les limites entre couches concentriques dont certains segments peuvent être détachés de cette manière").

4. Discussion

According to Halley (1977), "Hypersalinity and radial fabric in ooids would appear to be linked, although the nature of this relationship is not well understood". Nevertheless, when considering the numerous potential counter-examples provided above, associated with supposedly brackish or normal marine waters (Table 1), the radial fabric emerges as an unreliable indicator of hypersalinity. The stratigraphical succession of radial, concentric, and micritic ooids from the Upper Jurassic in the Paris Basin (Fig. 2.p-r; Pl. 1, figs. a-bc; Pl. 2, figs. a-bc) could be related to several factors, such as shorter periods of ooid growth, longer periods of ooid resting (with micritization of the outermost ooid cortex and possible mechanical (?) abrasion), the overall deepening upward of the set of parasequences, or a related increase in marine flows. In conclusion, this shift reflects a gradual shift in the bio-physico-chemical environmental conditions (Granier, 1994, 1995, 1996), rather than necessarily indicating a change in seawater salinity.

Still, according to the same author (Halley, 1977), "broken ooids are considered a significant indication of unusual salinities if they comprise more than 1% of the grains in an oolite". In the examples illustrated herein, the few broken ooids of the French Middle Jurassic (Fig. 2.p-r; Pl. 2, figs. c, g), the French Lower Devonian (Pl. 3, figs. n-q), and the Spanish Lower Cretaceous (Fig. 2.s-ab) are in agreement with normal marine water conditions.

The 'Upper Jurassic' *auct.* broken ooids (Fig. 2.a-o) of the North Atlantic from DSDP leg 44 site 392A (Fourcade & Granier, 1989; Granier, 2019) might be indicative of 'unusual salinity'; however, the microfossil assemblage, including the foraminifer *Protopeneroplis ultragranulata* (Gorbachik, 1971), suggests an open platform environment rather than a restricted platform environment.

Moreover, it might seem accurate to deduce that the broken ooids of Kanala, Greece (Pl. 3, figs. a-h, j-l), are indicative of 'unusual salinity'. According to Bernier and Fleury (1980), this oolite facies displays 'keystone vugs' and "ciments en ménisque" (more likely micritic bridges between grains), suggesting coastal shallow-water to locally subaerially exposed environments. It is likely that the paleoenvironmental conditions of the coeval Croatian 'Tithonian' oolite (Tišljar, 1980, 1983, 1985; Husinec & Read, 2006, 2007) are similar. However, Tišljar (1983, 1985) interprets it as vadolite, *i.e.*, a rock made of vadoids, whereas Husinec and Read (2006, 2007) disagree and propose that "they developed" (...) "in intertidal ponds" (...) "established on previously emergent hypersaline flats during transgressions".

In both North Atlantic and Adriatic examples, the contradicting interpretations suggest that it is neither feasible nor realistic to use broken ooids to discriminate between brackish and hypersaline settings.

The salinity in the Salta Basin (Salta and Jujuy provinces, Argentina) not only fluctuated over time but also varied across its various sub-basins. The faunal (fishes [*e.g.*, Cione *et al.*, 1985], gastropods [*e.g.*, Cónsole Gonella *et al.*, 2012], bivalvia), microfossil (ostracods [*e.g.*, Carignano, 2012], foraminifera [*e.g.*, Méndez & Viviers, 1973; Kielbowicz de Stach & Angelozzi, 1984]), and phycological (charophytes [*e.g.*, Musacchio, 1972, 2000]) assemblage lacks echinoderms and bryozoans, which are characteristic elements of marine environments. This suggests that, over time and across its various physiographic subdivisions, the Salta basin exhibits a range of lacustrine environments from brackish to hypersaline. Unfortunately, we lack geochemical and paleontological information specifically for the sampled intervals from the Jujuy and Salta provinces in Argentina. Furthermore, although the broken ooids of Jujuy (Pl. 3, fig. i) and Salta (Pl. 4, figs. a-am; Pl. 5, figs. a-af; Pl. 6, figs. a-w) likely occurred in a salt lake, it is not possible to determine whether they are indicative of brackish or hypersaline water environments.

In his seminal 1961 paper, CAROZZI describes broken and regenerated ooids (*i.e.*, "oolithes" (...) "brisées et régénérées"). He speculates that "mechanical impacts have either generated cracks inside the oolites without breaking them apart into distinct fragments, or have broken the oolites once in half-spheres mostly, or twice into smaller fragments of variable shapes". However, this is highly unlikely and contradicted by the common association of broken ooids with low-energy facies exhibiting a plurimodal distribution of the ooids (*e.g.*, FREEMAN, 1962; D'ARGENIO *et al.*, 1975; HALLEY, 1977; BERNIER & FLEURY, 1980; TIŠLJAR, 1980, 1983, 1985; SIMONE, 1981; STRASSER, 1986; HUSINEC & READ, 2006, 2007). In contrast, broken ooids are less common in high-energy facies with well-sorted allochems, such as those found in oolitic sandwaves (*e.g.*, GRANIER, 1987, 1994, 1995, 1996). For instance, broken ooids from the French Lower Devonian (Pl. 3, figs. n-q), the French Middle Jurassic (Fig. 2.p-r; Pl. 2, figs. c, g), and the Spanish Lower Cretaceous (Figs. 2.s-ab, 3.-AB) can be considered representative of such high-energy facies. However, in most cases (*e.g.*, Fig. 3.A-B), ooid fragments fossilized by the healing phase of the regenerated cortex retain sharp cutting edges, testifying to limited mechanical abrasion, if any.

According to TIŠLJAR (1980, 1983, 1985), "the breaking probably resulted from fast dehydration or transportation of vadoids, particularly by repeated reflooding of vadoid deposits". While his followers (HUSINEC & READ, 2006, 2007) consider that "Periodic exposure" (...) "in hypersaline ponds and restricted lagoons" (...) "caused grain breakage and regrowth of ooid cortices with submergence". However, one could argue that, in Great Salt Lake ooids, a breakage ratio higher than actually reported might have been expected.

The fracture patterns described by CAROZZI in the Lower Carboniferous of Alberta (1961, Figs. 2.H-N, 3.A-R) and illustrated here from the Paleocene-Eocene of Salta (Pl. 4, figs. a-am; Pl. 5, figs. a-af; Pl. 6, figs. a-w) do not conform to those of septaria. In septaria, fractures typically widen toward the center of the concretion, interpreted as centrifugal fractures. In contrast, as seen in CAROZZI's (1961) thin sections and our Argentinian specimens, fractures in ooids "may have their maximum width at the periphery of the cortex and wedge inwards" (Pl. 4, figs. f-g, i, l bottom, m-n, x; Pl. 5, figs. p-q) or "they may be the same width along their entire length" (Pl. 4, figs. a-e, h, j-m, w; Pl. 5, figs. m, q-t; Pl. 6, figs. a-f). This suggests that these fractures are wedge-shaped in three dimensions, and their growth was centripetal.

The cause of the breakage remains unknown; it could be related to the synsedimentary recrystallization of calcite fibers, which is likely more common with longer fibers. ŁABĘCKI and RADWAŃSKI (1967) reached a comparable conclusion, asserting that "the main cause of the fissuring of the ooides [*sic*] lies in their structure. Such a cause might be the mechanical heterogeneity of the oolitic envelope caused by the heterogeneity and non-uniformity of crystallization of the carbonate which forms the envelope." They further observed that hydrodynamic forces solely facilitated the separation of fragmented pieces from each other, dispersing them across various distances within the environment.

5. Conclusion

From the above examples and discussion, it is evident that there is no relationship, if any, between synsedimentary ooid breakage and a) 'mechanical impacts' (as defended by CAROZZI, 1961) or attrition, b) temporary subaerial exposure (supported by TIŠLJAR, 1980, 1983, 1985), or c) water salinity (suggested by HALLEY, 1977).

HALLEY (1977) believed that the "syndepositional breakage is the result of a syndepositionally developed radial fabric in ooids". Our review confirms that:

A. the ratio of ooid breakages increases from 1) the French Lower Devonian, the French Middle Jurassic, and the Spanish Lower Cretaceous to 2) the Argentinian Paleocene-Eocene, passing through 3) the North Atlantic Upper Jurassic *auct.* (*i.e.*, including the Berriasian) and the Croatian and Greek Upper Jurassic;
B. this increase correlates with the relative thickness of the radial cortical layers;
C. breakage is genetically linked to the radial fabrics;
D. the fracture growth in ooids (with radial fabrics) is centripetal, starting in the outermost cortex and eventually cutting through the nucleus.

Acknowledgements

The Argentinian rock samples presented here were collected by the second author (Ph.L.) on the occasion of a joint mission of Total - Compagnie Française des Pétroles, and IFP - Institut Français du Pétrole from October 5 to November 3, 1988. He acknowledges the support of his IFP colleagues, Bernard COLLETTA, Jean LETOUZEY, and Roland VIALY, for fieldwork. The authors acknowledge the kind reviews provided by Fabian KÄSBOHRER (Georg-August-Universität Göttingen) and Tadeusz PERYT (Polish Geological

Institute). The first author (B.R.C.G.) thanks Jean-Jacques Fleury for donating a set of his thin sections from Greece, and Phil Salvador for his appreciated help with the final (English) text.

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Plates

Plate 1: Villeperdue VPI-01 (VPU44), **micritic ooids**: a) 1806.25 m; b) 1806.50 m; c) 1806.75 m; d) 1807.00 m; e) 1807.25 m; f) 1807.50 m; g) 1807.75 m; h) 1808.00 m; i) 1808.25 m; j) 1808.60 m; k) 1808.75 m; l) 1809.00 m; m) 1809.25 m; n) 1809.42 m; o) 1809.50 m; p) 1809.52 m; q) 1809.75 m; r) 1810.00 m; s) 1810.25 m; t) 1810.50 m; u) 1810.50 m; v) 1811.10 m; w) 1811.25 m; x) 1811.50 m; y) 1811.75 m; z) 1812.00 m; aa) 1812.38 m; ab) 1812.75 m; ac) 1813.00 m; **concentric ooids**: ad) 1813.30 m; ae) 1813.50 m; af) 1813.80 m; ag) 1814.00 m; ah) 1814.25 m; ai) 1814.80 m; aj) 1815.00 m; ak) 1815.25 m; al) 1815.50 m; am) 1816.00 m; an) 1816.25 m; ao) 1816.50 m; ap) 1816.75 m; aq) 1817.00 m; ar) 1817.25 m; as) 1817.50 m; at) 1817.75 m; au) 1818.00 m; av) 1818.25 m; aw) 1818.75 m; ax) 1819.00 m; ay) 1819.25 m; az) 1819.50 m; ba) 1819.75 m; bb) 1820.00 m; bc) 1820.25 m. Graphical scale bar for all photomicrographs = 250 µm.

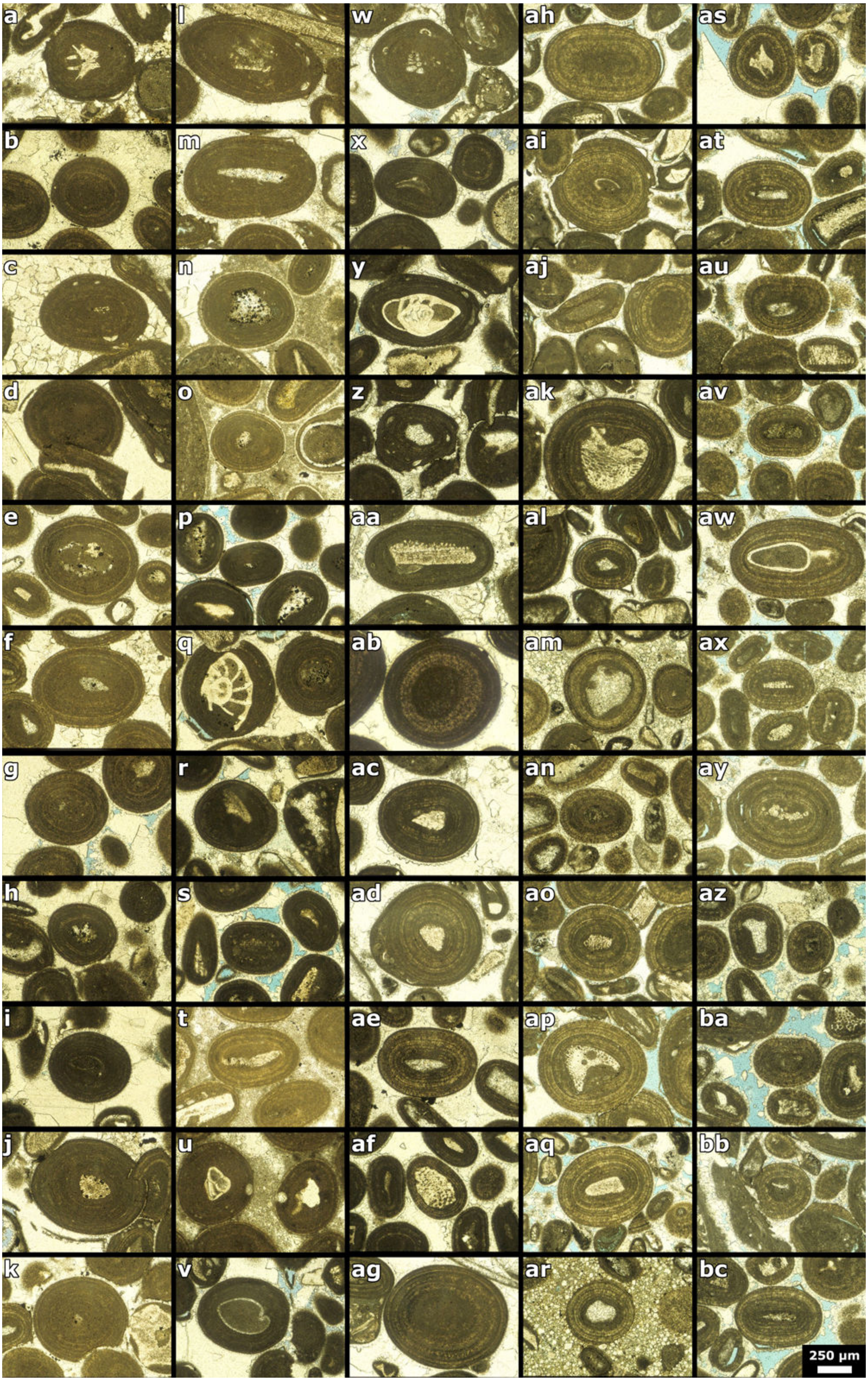
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Plate 2: Villeperdue VPI-01 (VPU44), **concentric ooids**: a) 1820.50 m; b) 1820.75 m; c) 1821.00 m (with a broken ooid); d) 1821.25 m; e) 1821.50 m; f) 1821.75 m; g) 1822.00 m (with a broken ooid); h) 1822.25 m; i) 1822.50 m; j) 1822.75 m; k) 1823.00 m; l) 1823.25 m; m) 1823.50 m; n) 1824.00 m; o) 1824.25 m; p) 1824.50 m; q) 1824.75 m; r) 1825.00 m; s) 1825.25 m; t) 1825.50 m; u) 1826.00 m; v) 1826.25 m; w) 1826.50 m; x) 1826.75 m; y) 1827.00 m; **radial ooids**: z) 1827.25 m; aa) 1827.50 m; ab) 1827.75 m; ac) 1828.00 m; ad) 1828.25 m; ae) 1828.50 m; af) 1828.75 m; ag) 1829.00 m; ah) 1829.25 m; ai) 1829.50 m; aj) 1829.75 m; ak) 1830.00 m; al) 1830.25 m; am) 1830.50 m; an) 1830.75 m; ao) 1831.00 m; ap) 1831.25 m; aq) 1831.50 m; ar) 1831.75 m; as) 1831.90 m; at) 1832.00 m; au) 1832.25 m; av) 1832.50 m; aw) 1832.75 m; ax) 1833.00 m; ay) 1833.25 m; az) 1833.50 m; ba) 1833.75 m; bb) 1834.10 m; bc) 1834.25 m. Graphical scale bar for all photomicrographs = 250 µm.

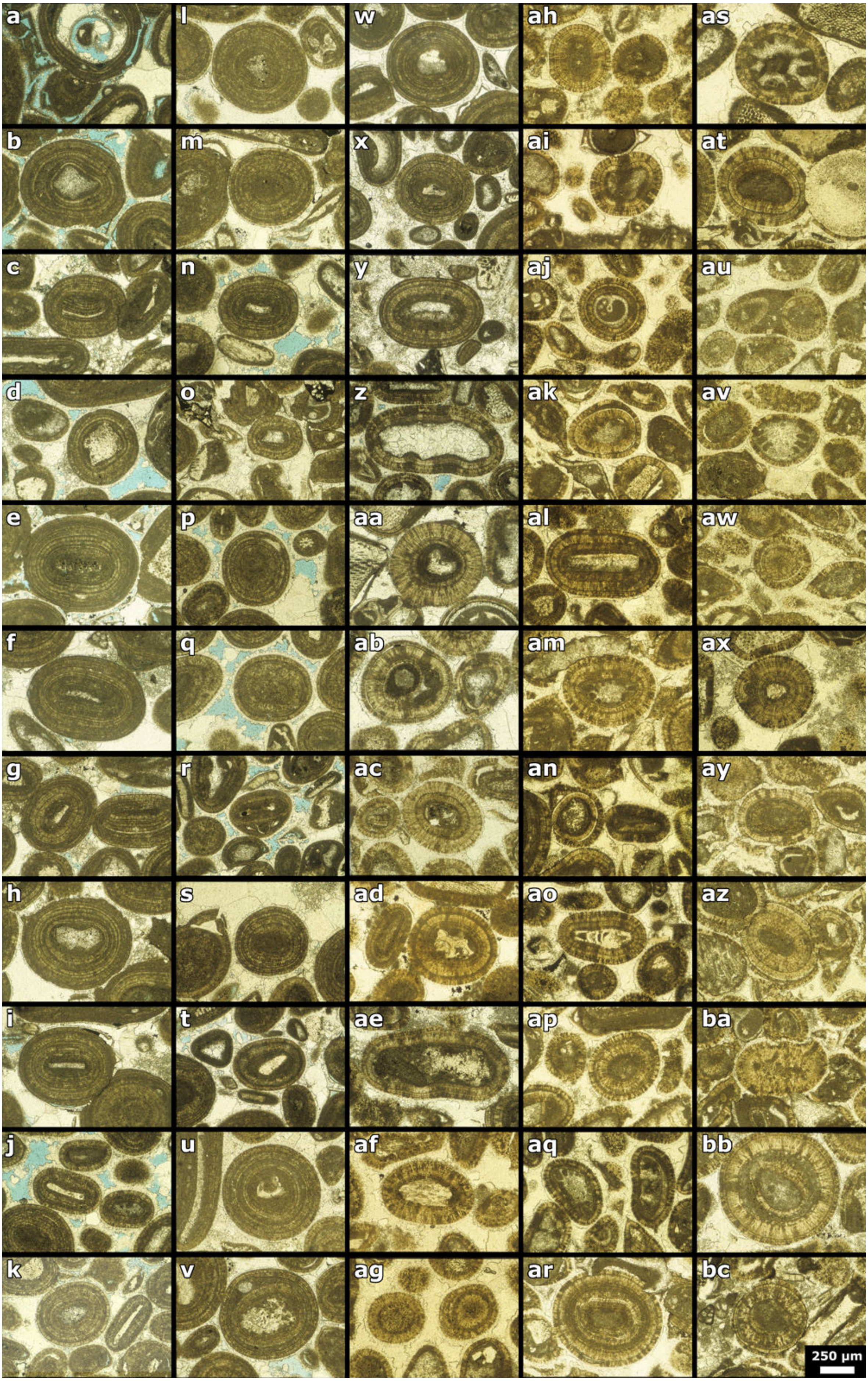
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Plate 3: Photomicrographs of broken ooids *sensu lato* and hiatus ooids from Greece, Argentina, and France. a-b, d-h, j-l) various broken ooids, partly regenerated or not; c) two broken ooids facing each other, possibly the two parts of the same original ooid; i) broken ooid with both parts still attached. Note that the breakage likely formed from the outside in; m) pressure solution (red arrows) gives the illusion of breaks in the oolitic cortices; n) hemiooid with a superficial regeneration of its cortex; o-q) hiatus ooids (white arrows). a-h, j-l) thin section GEA4 780 5525 (registered as MHNG-GEPI-2024-10285 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland), Kanala, Gavrovo, Greece; i) thin section AG 269 (registered as MHNG-GEPI-2024-10269 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland), Yacoraite Formation, Danian, Dique Cabra Corral, Province of Salta (Argentina); m-q) thin sections B.7363N (m, o), B.18591 (n), and B.7157 44 (p-q), Brittany, France. Graphical scale bar for all photomicrographs = 250 µm.

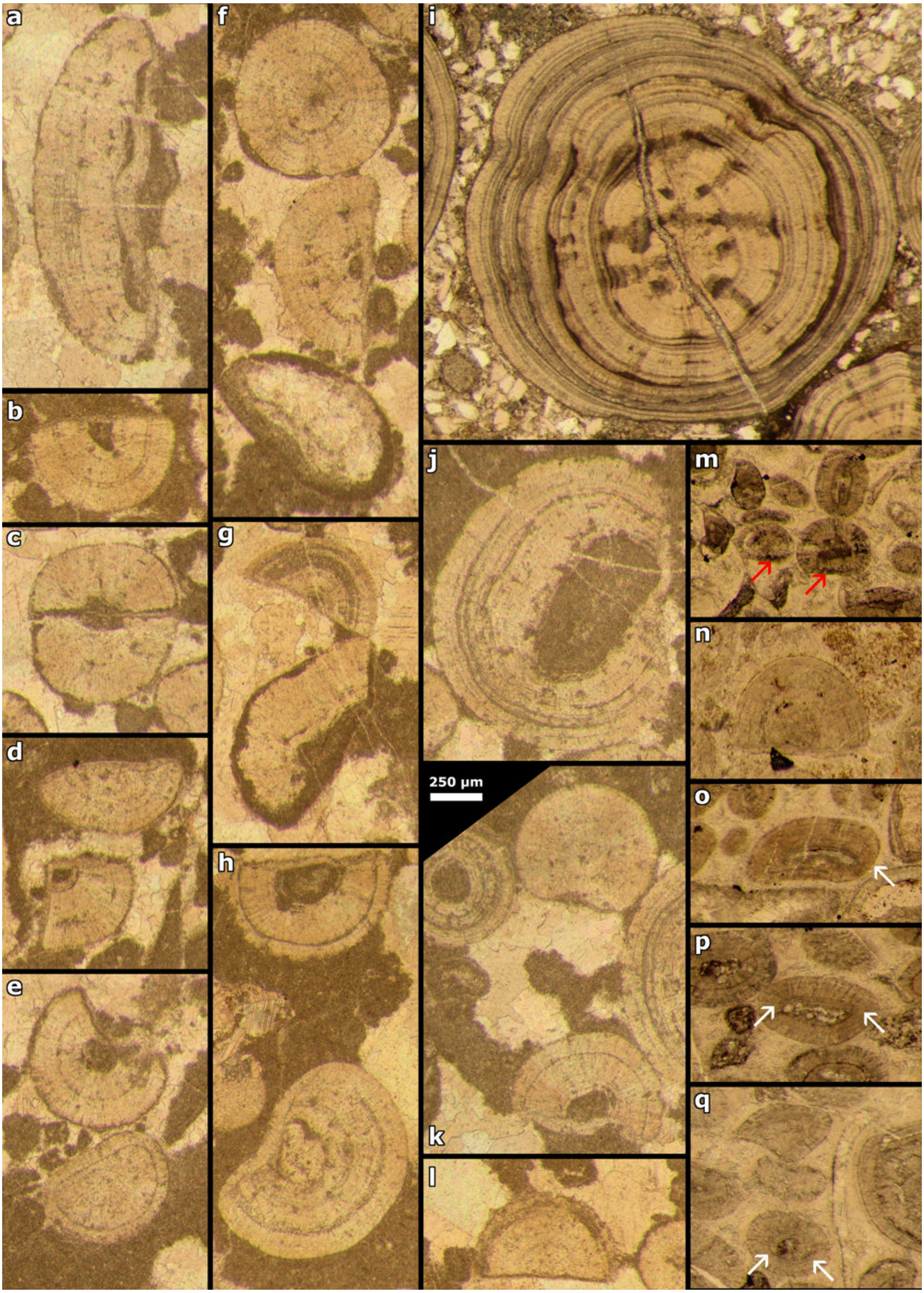
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Plate 4: Photomicrographs of broken ooids *sensu lato* from thin section (registered as ARA 288A = MHNG-GEPI-2024-10288 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland), Maiz Gordo Formation, Thanetian-Ypresian, junction of road 66 with road 34, Province of Jujuy (Argentina).

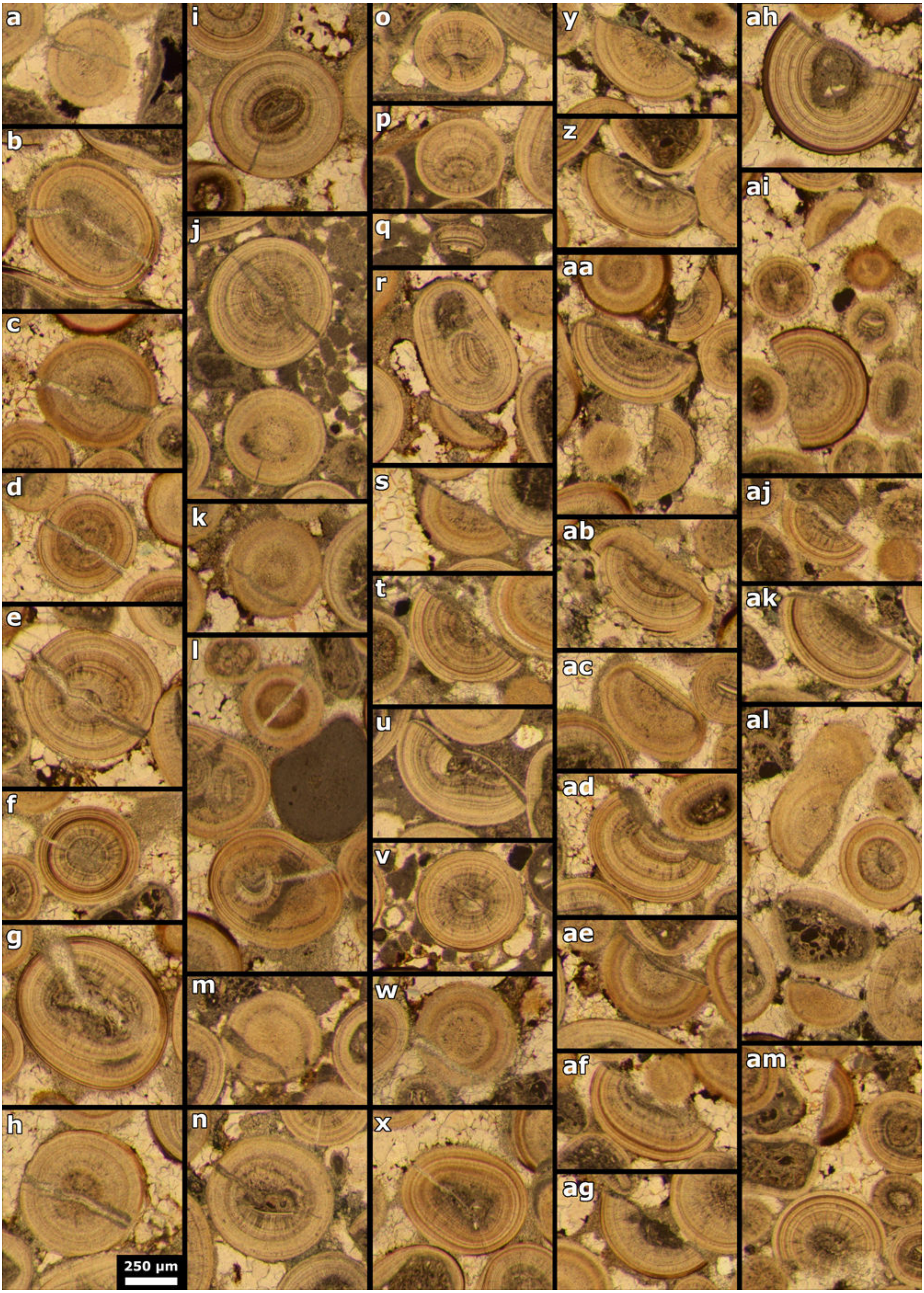
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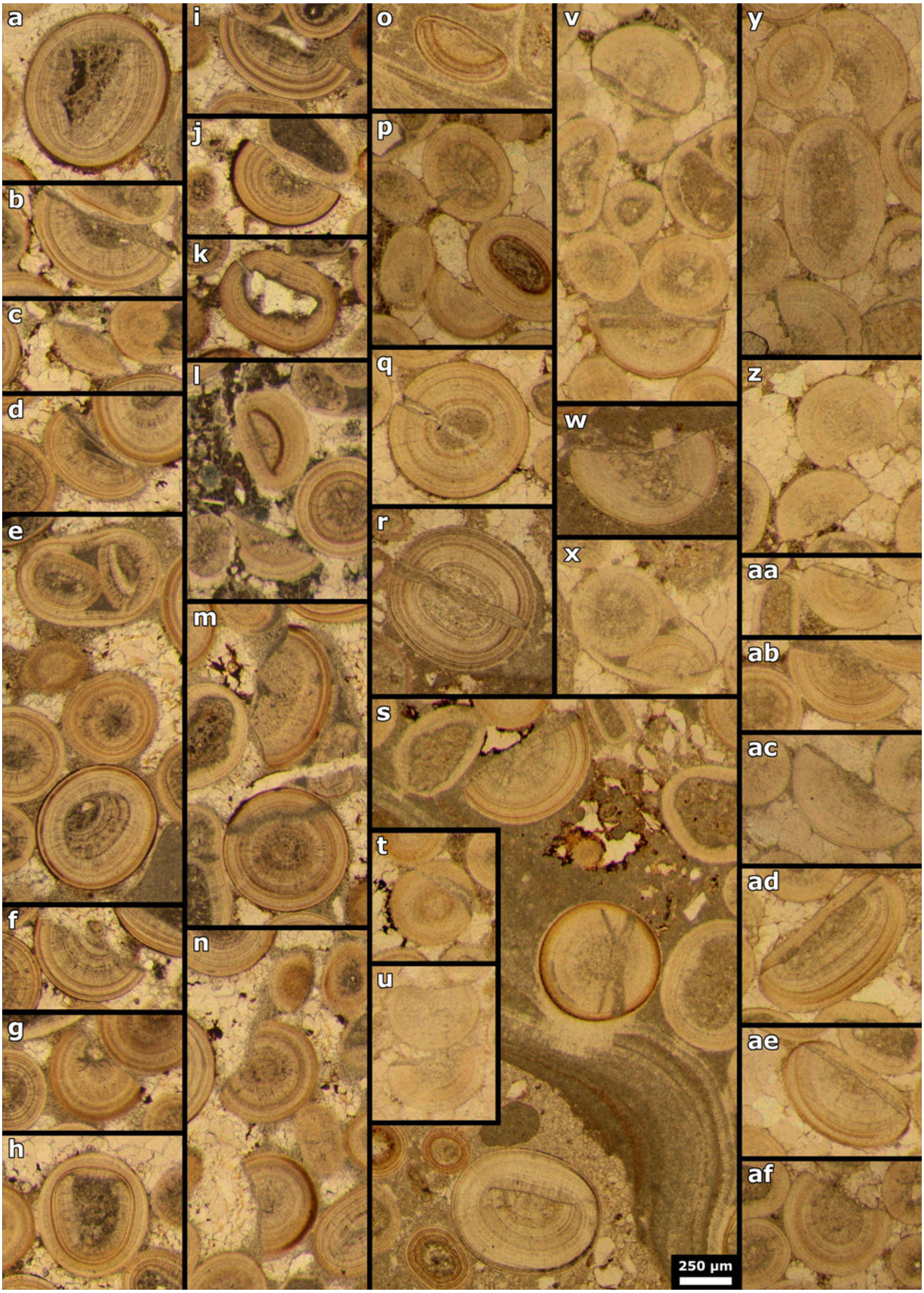
Plate 5: Photomicrographs of broken ooids *sensu lato* a-n) from thin section ARA 288A (registered as MHNG-GEPI-2024-10288 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland) and o-af) from thin section ARA 288B (registered as MHNG-GEPI-2024-10289), Maiz Gordo Formation, Thanetian-Ypresian, junction of road 66 with road 34, Province of Jujuy (Argentina).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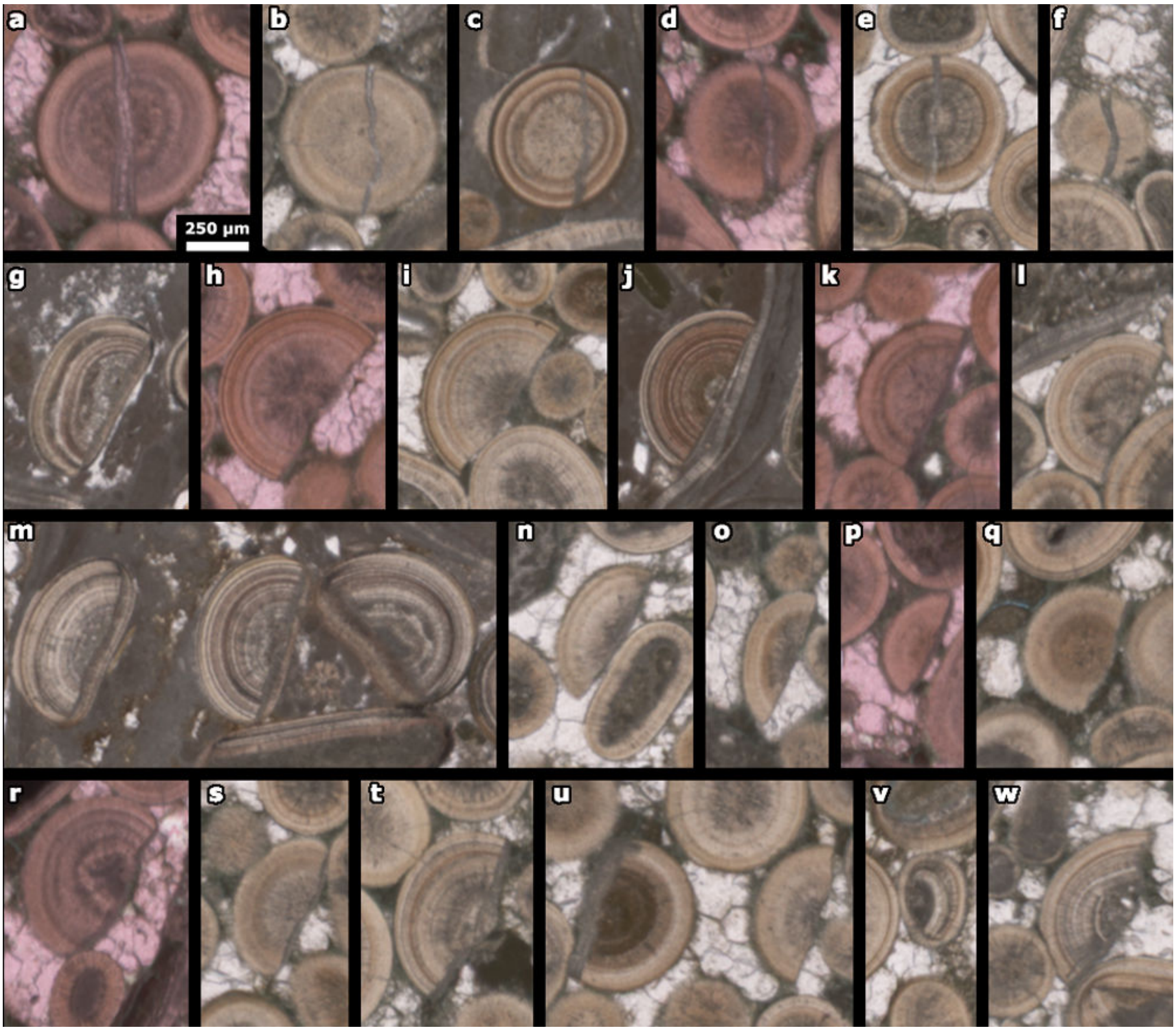

Plate 6: Photomicrographs of broken ooids *sensu lato* from thin section ARA 288, Maiz Gordo Formation, Thanetian-Ypresian, junction of road 66 with road 34, Province of Jujuy (Argentina): a-f) broken ooids *sensu stricto* with both fragments still facing each other; g-l, n-u, w) broken ooids *sensu stricto* with one fragment only; m, v) broken ooids *sensu lato*, *i.e.*, ooids broken, then regenerated. a) GRANIER & LAPOINTE, 2021: Pl. 1.l; b) GRANIER & LAPOINTE, 2021: Pl. 1.t; i) GRANIER & LAPOINTE, 2021: Pl. 1.j; j) GRANIER & LAPOINTE, 2021: Pl. 1.n; m) GRANIER & LAPOINTE, 2021: Pl. 1.a; s) GRANIER & LAPOINTE, 2021: Pl. 1.q; t) GRANIER & LAPOINTE, 2021: Pl. 1.k; u) GRANIER & LAPOINTE, 2021: Pl. 1.p; w) GRANIER & LAPOINTE, 2021: Pl. 1.u. Graphical scale bar for all photomicrographs = 250 µm.