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# 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

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**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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## 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.

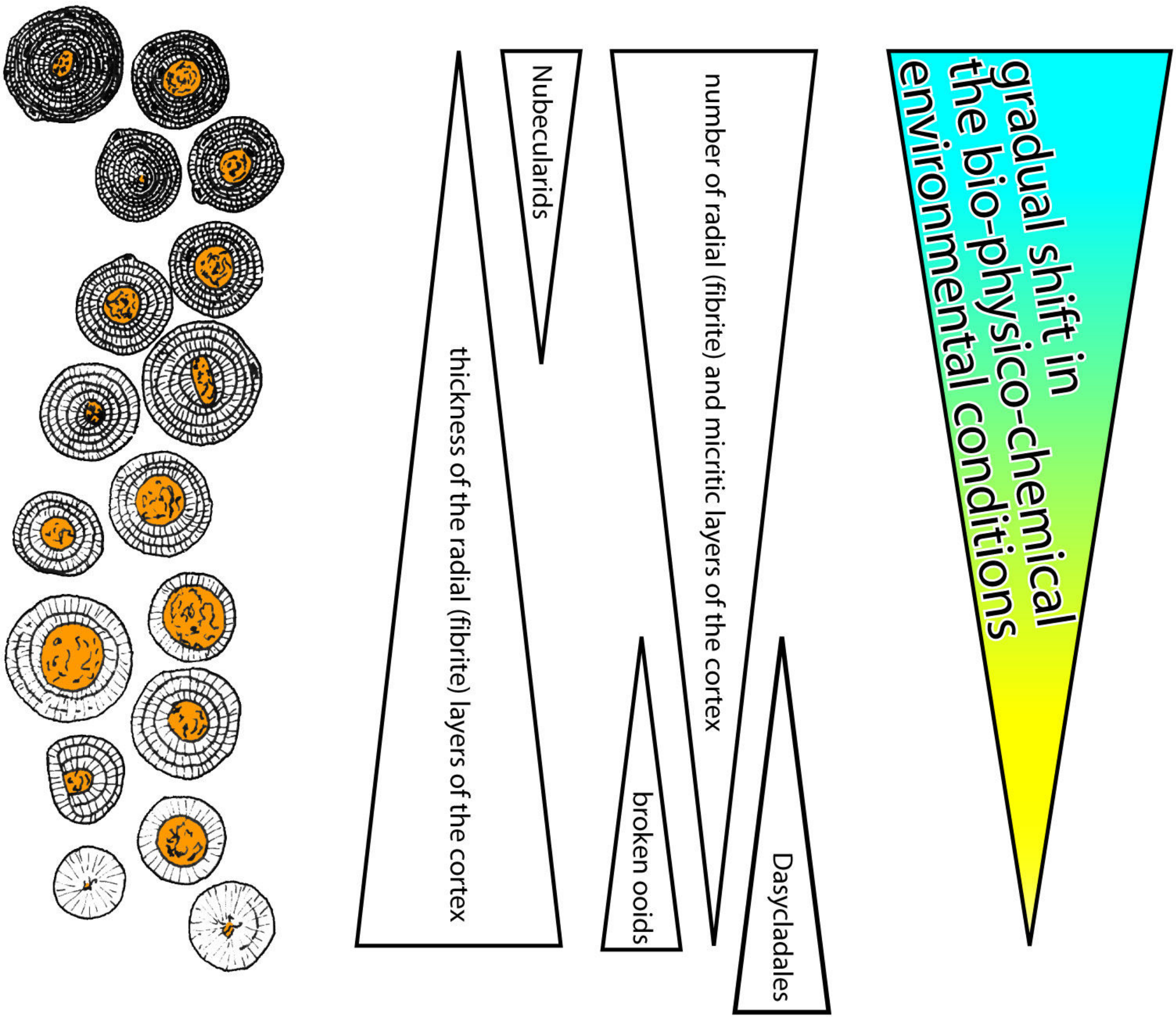
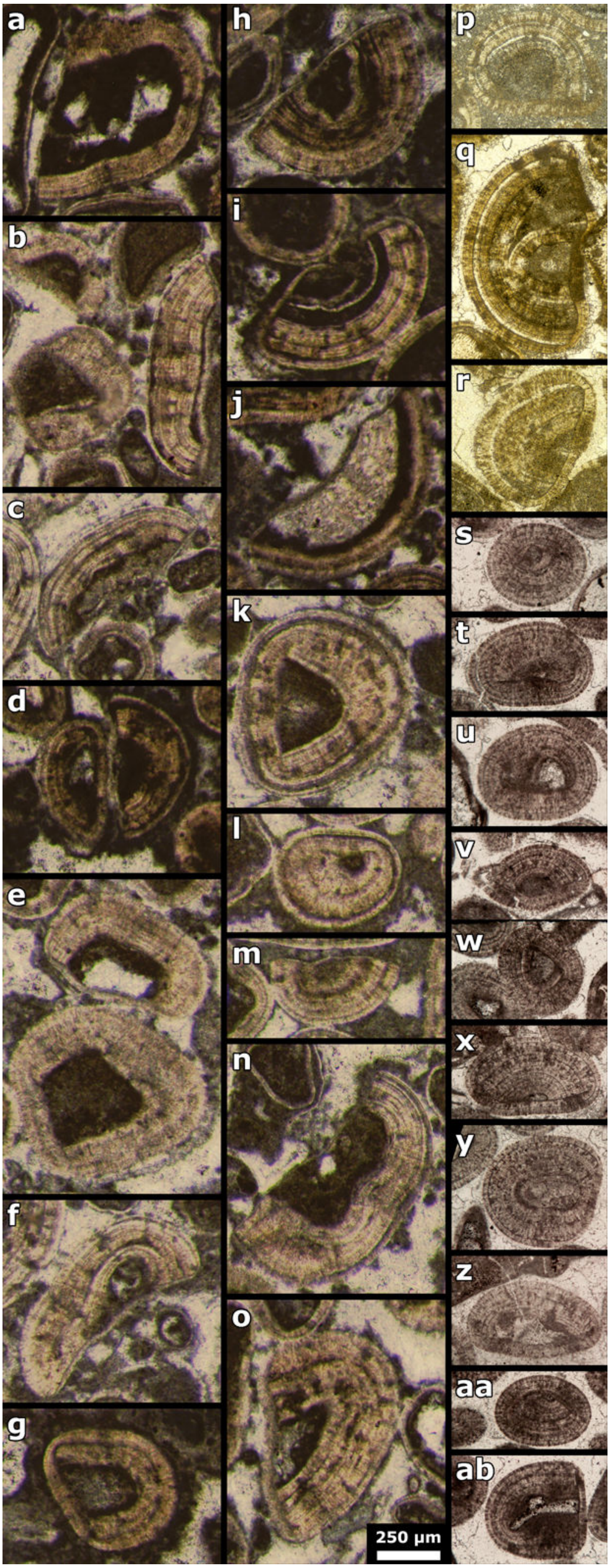



**Figure 1:** Stratigraphical model for the Villeperdue oil field and other oil fields of the Paris Basin, France (modified from GRANIER, 1994, 1995, 1996).

## 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.

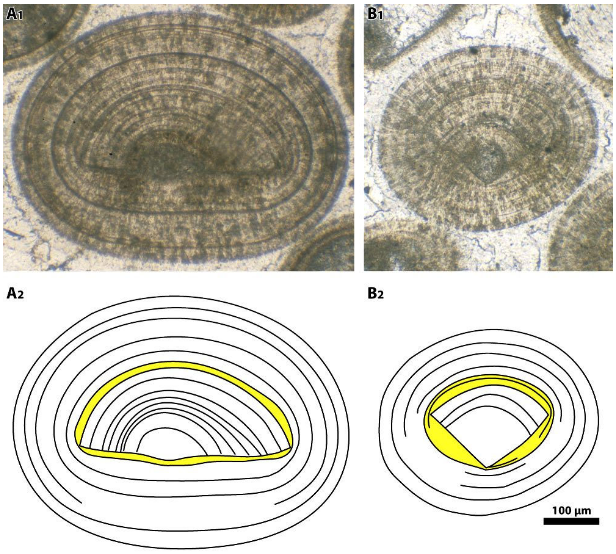



**Figure 3:** Broken and regenerated ooids. The healing phase, corresponding to the early stage of regeneration, is colored in yellow in drawings A2 and B2. A1-2) sample HL 723, Alicante, Spain; B1-2) sample HL72B, Alicante, Spain. Graphical scale bar for all photomicrographs and drawings = 100 µm.

- **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.

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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.

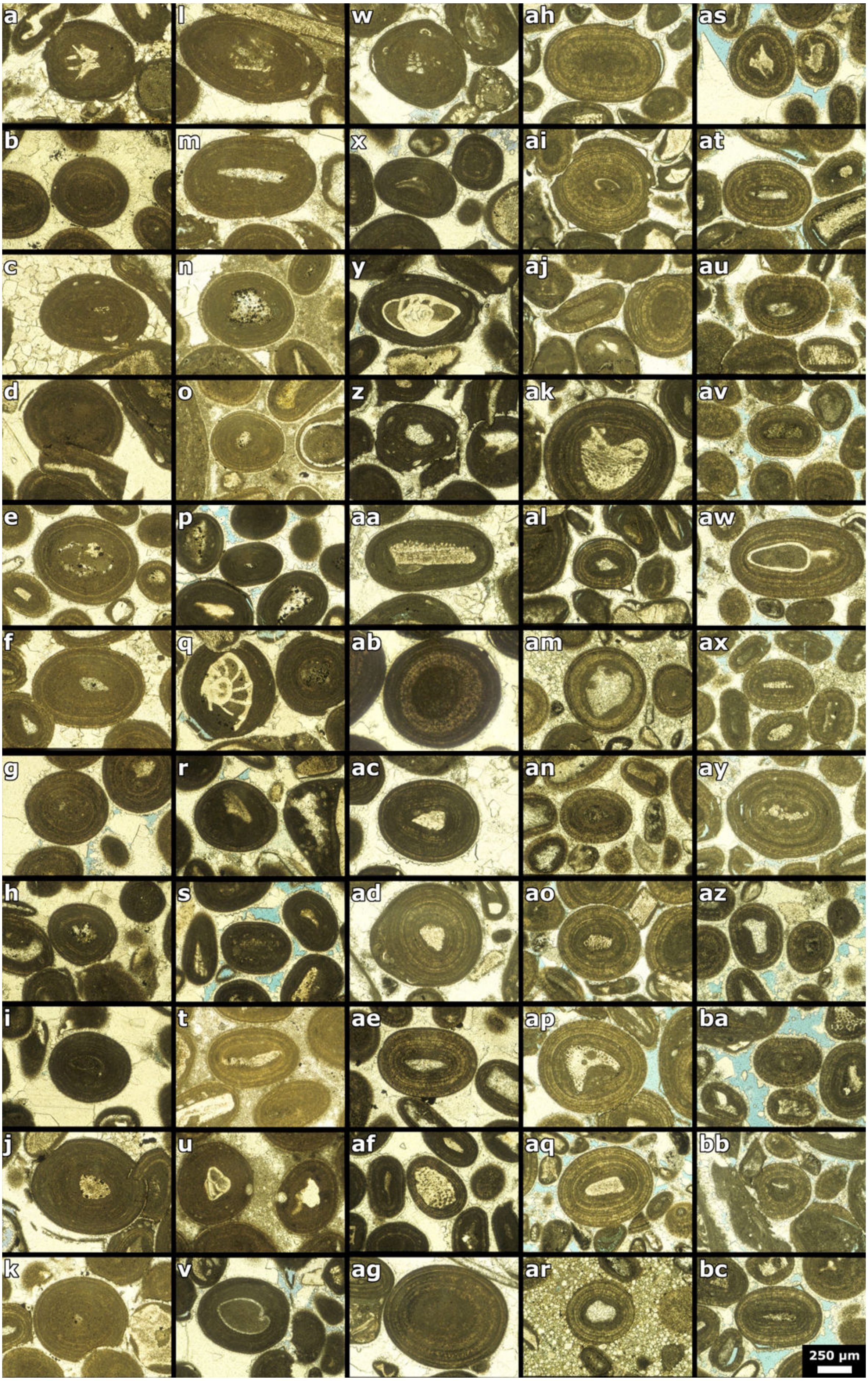
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**Plate 2:** Villeperdue VPI-01 (VPU44), **concentric ooids**: a) 1820.50 m; b) 1820.75 m; c) 1821.00 m (with a broken ooid); d) 1821.25 m; e) 1821.50 m; f) 1821.75 m; g) 1822.00 m (with a broken ooid); h) 1822.25 m; i) 1822.50 m; j) 1822.75 m; k) 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.

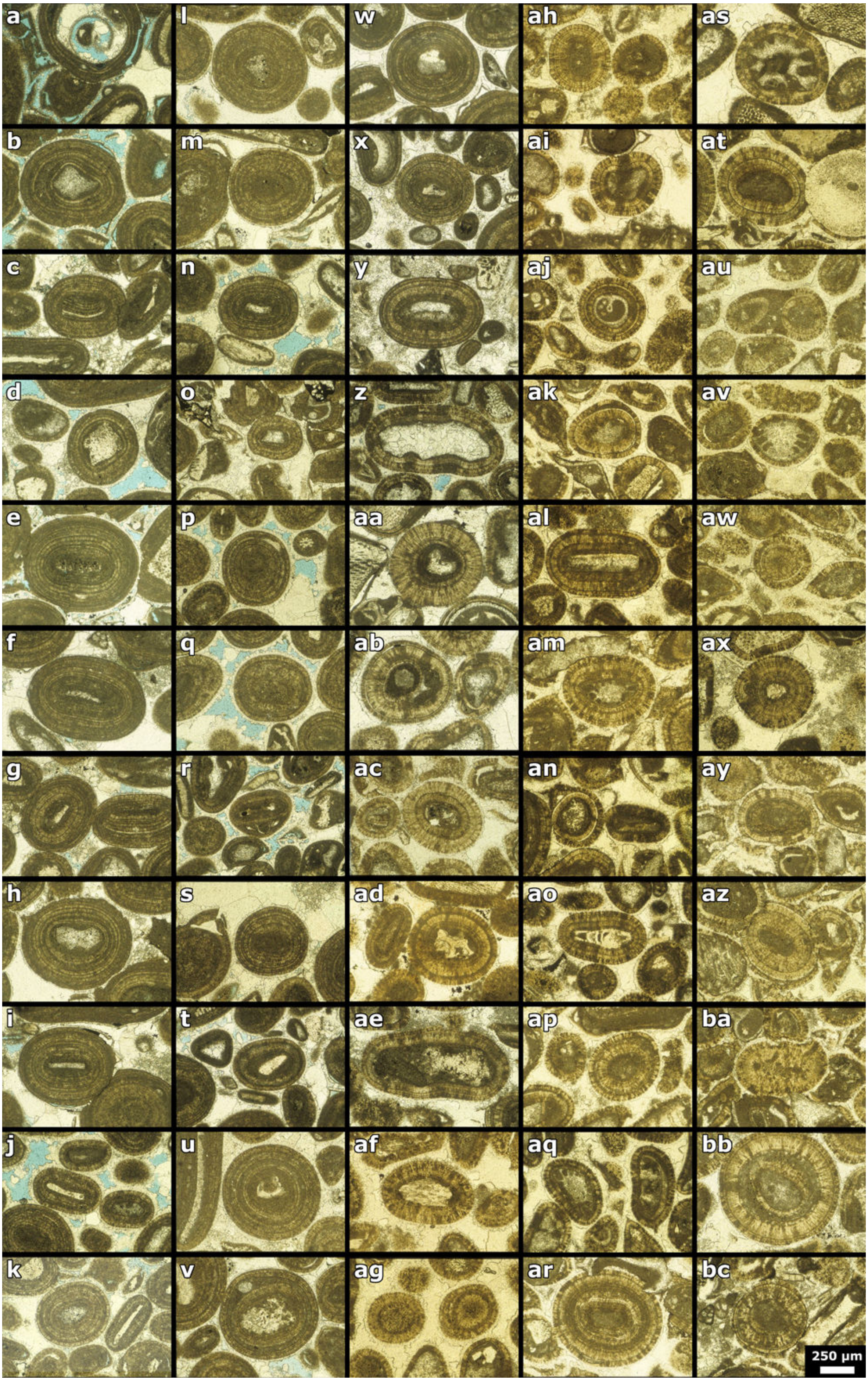
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**Plate 3:** Photomicrographs of broken ooids *sensu lato* and hiatus ooids from Greece, Argentina, and France. a-b, d-h, j-l) various broken ooids, partly regenerated or not; c) two broken ooids facing each other, possibly the two parts of the same 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.

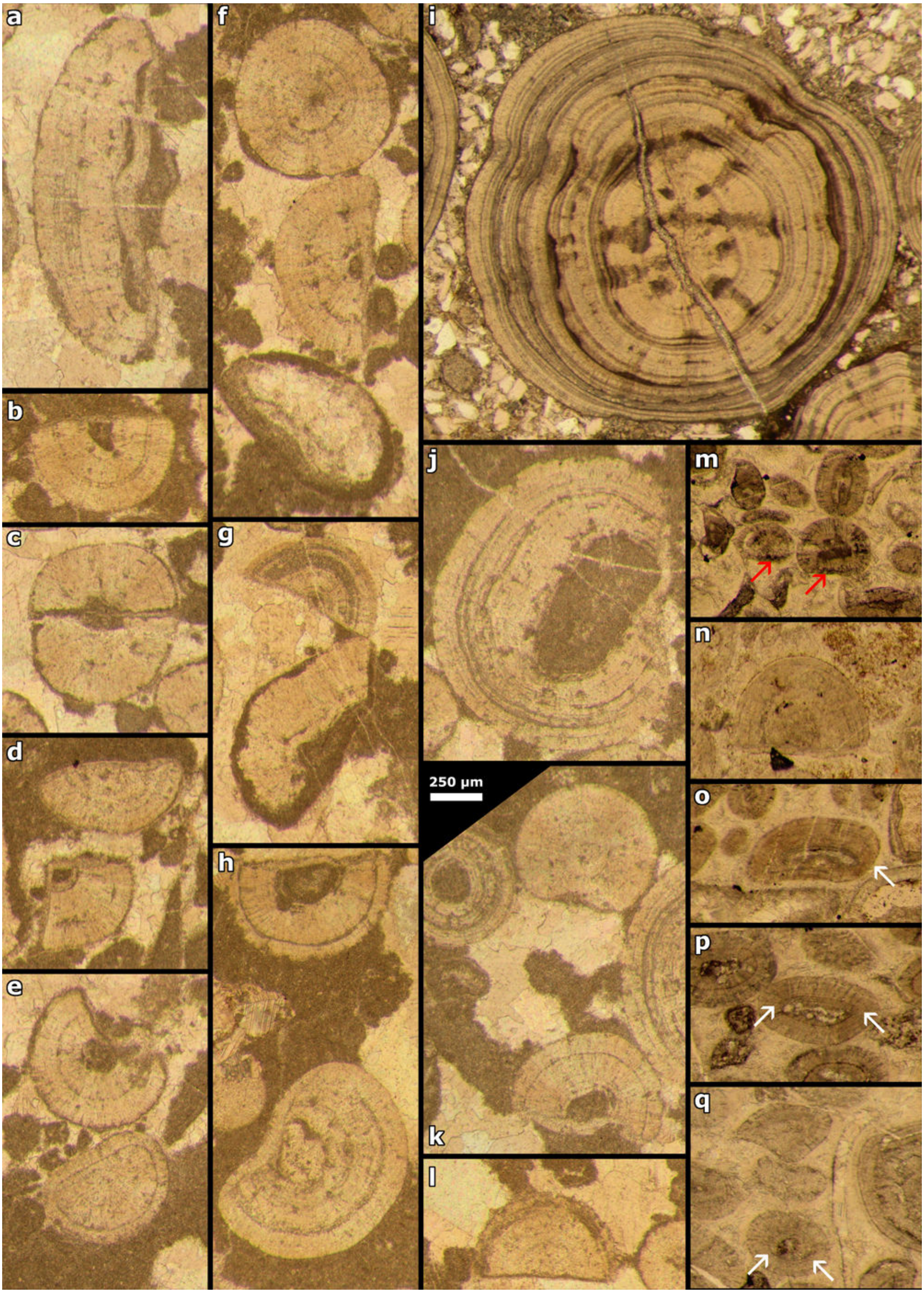
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**Plate 4:** Photomicrographs of broken ooids *sensu lato* from thin section (registered as ARA 288A = MHNG-GEPI-2024-10288 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland), Maiz Gordo Formation, Thanetian-Ypresian, junction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

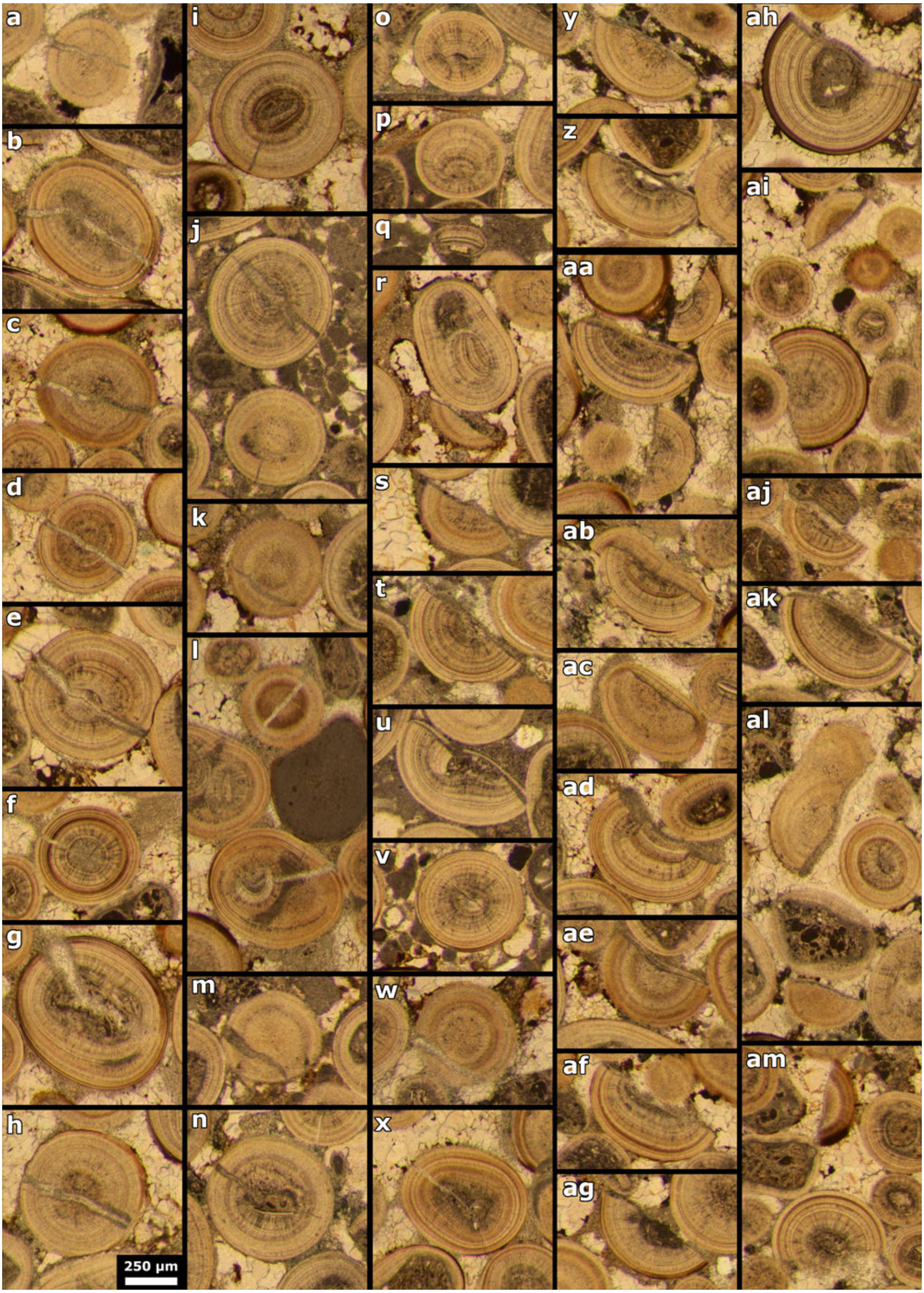
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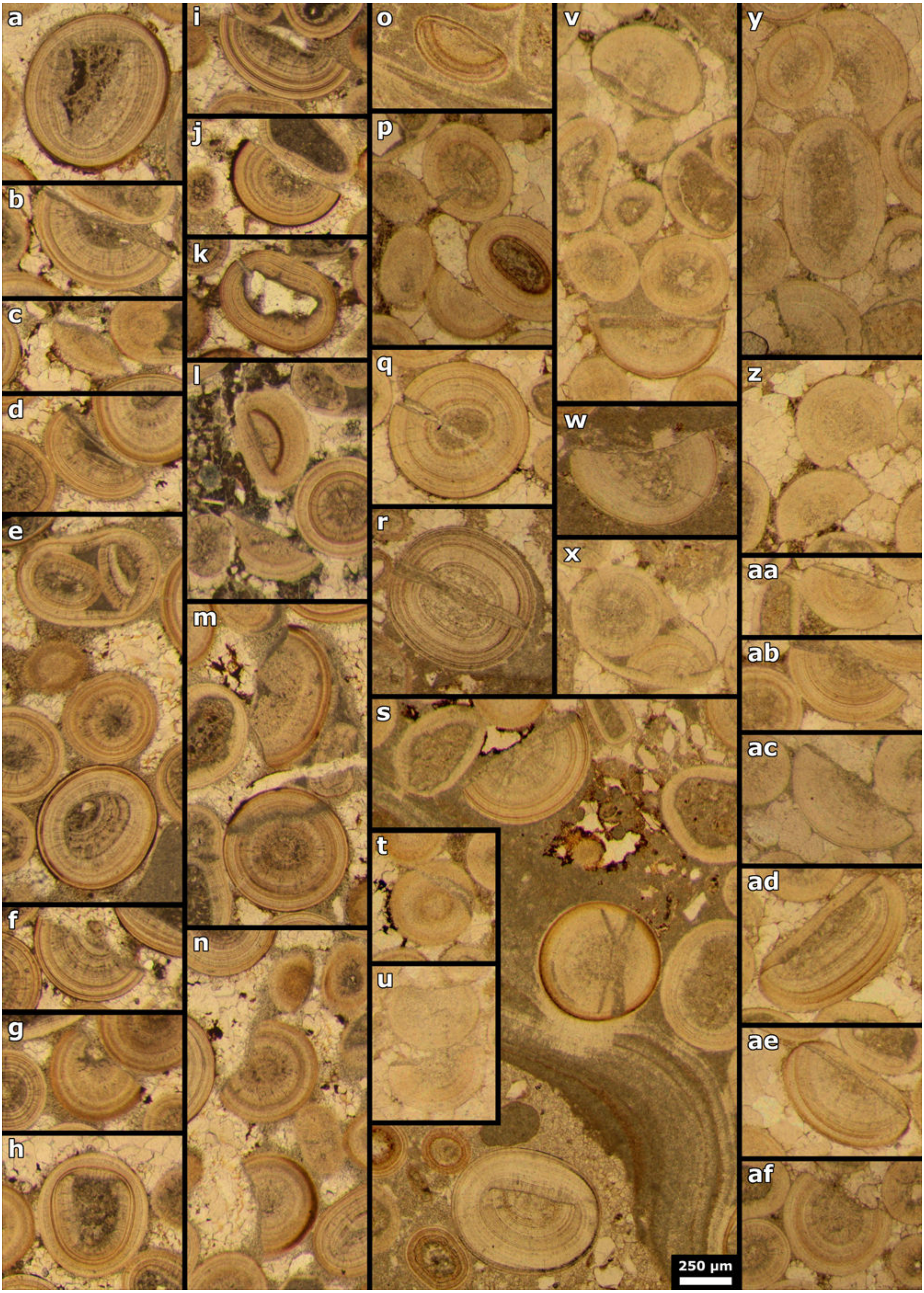
**Plate 5:** Photomicrographs of broken ooids *sensu lato* a-n) from thin section ARA 288A (registered as MHNG-GEPI-2024-10288 in the collections of the Musée d'Histoire Naturelle de Genève, Switzerland) and o-af) from thin section ARA 288B (registered as MHNG-GEPI-2024-10289), Maiz Gordo Formation, Thanetian-Ypresian, junction of road 66 with road 34, Province of Jujuy (Argentina).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250 µm

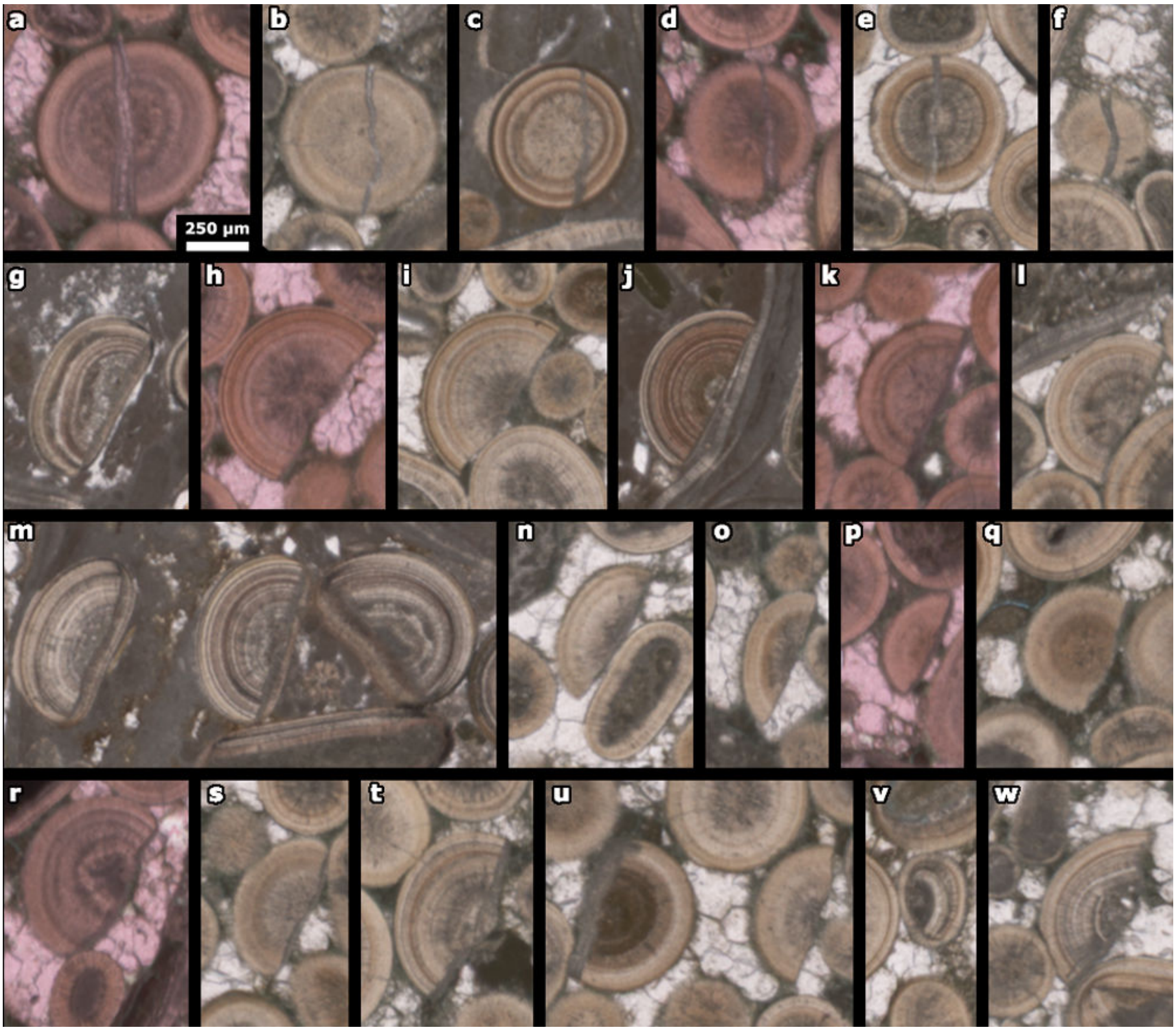


**Plate 6:** Photomicrographs of broken ooids *sensu lato* from thin section ARA 288, Maiz Gordo Formation, Thanetian-Ypresian, junction of road 66 with road 34, Province of Jujuy (Argentina): a-f) broken ooids *sensu stricto* with both fragments still facing each other; g-l, n-u, w) broken ooids *sensu 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.