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

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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 oo-molds (referred to as 'distorted' ooids).

Keywords:

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

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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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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.

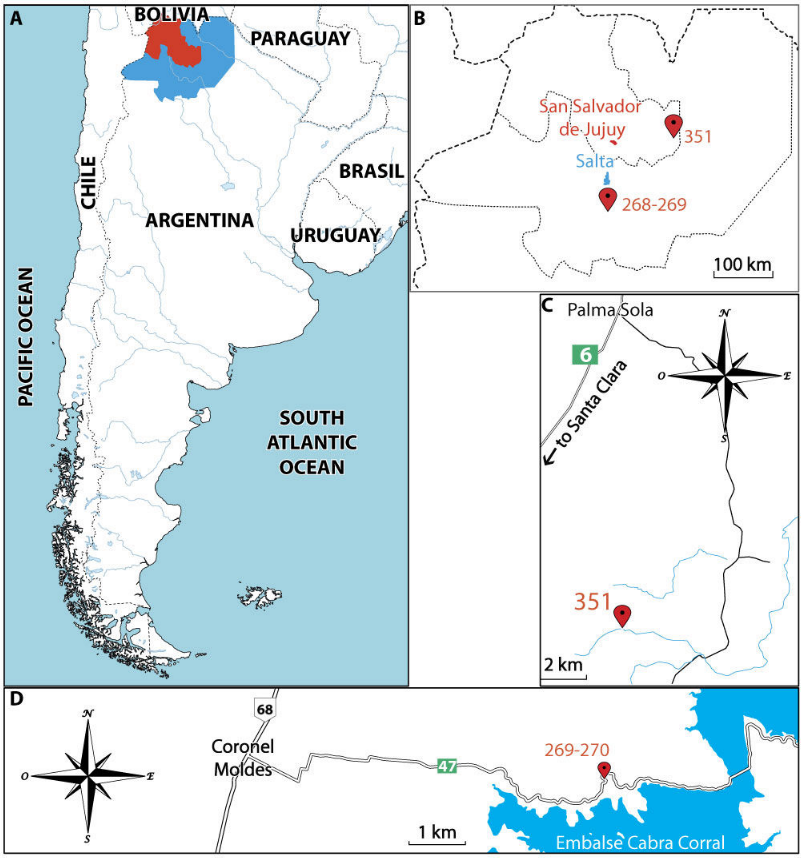


Figure 1: A) Location map of the provinces of Jujuy (red) and Salta (blue) in Argentina; **B)** location map of the sampling localities 268-269 in the Province of Salta and 351 in the Province of Jujuy; **C)** location of the sampling locality 351 in a canyon section 6.5 km south of Palma Sola, Province 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.

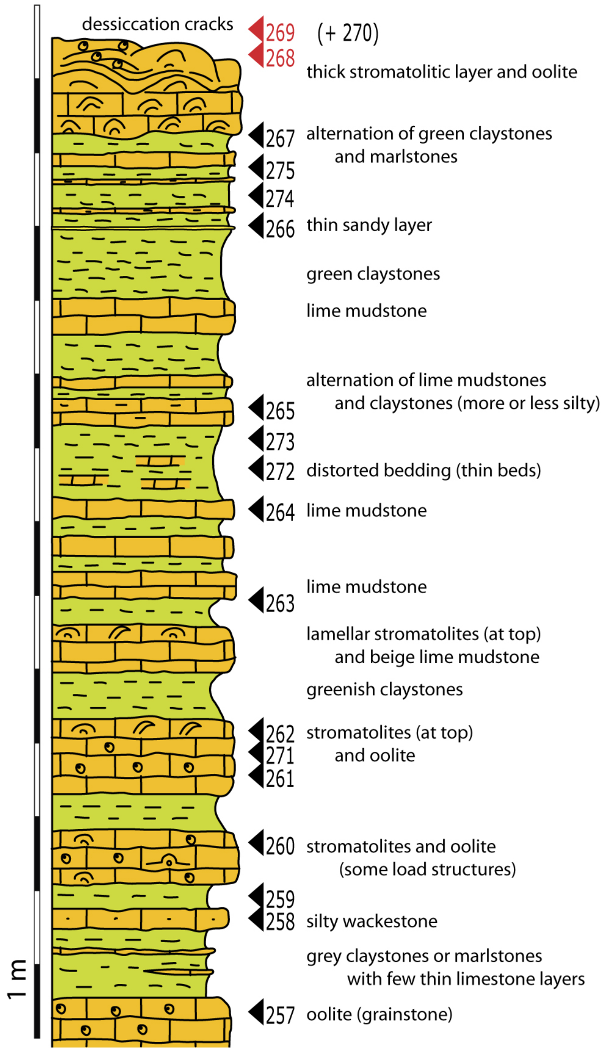


Figure 2: Shematic drawing of the Salta section (Cabra Corral) with location of samples 269 and 270 in bold red (excerpt from Granier & Lapointe, 2022b).

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.

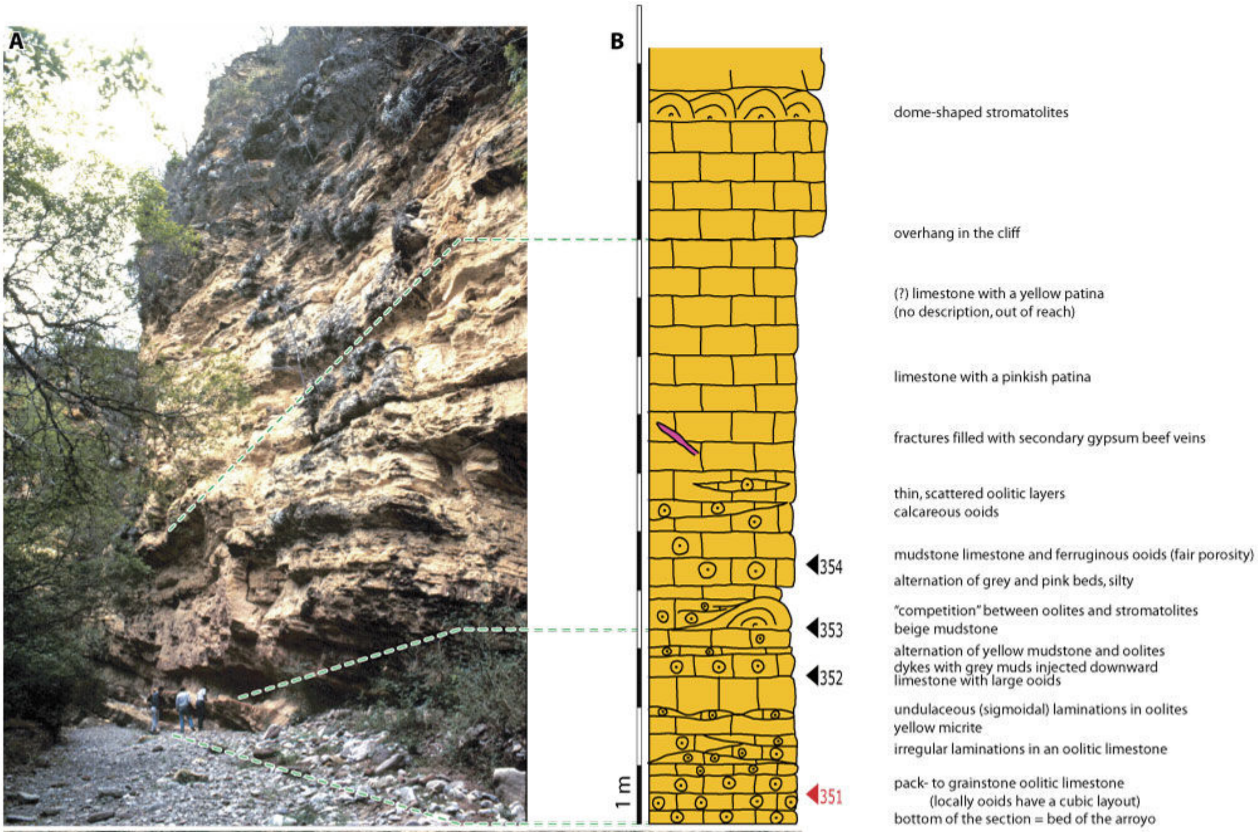
5. Discussion

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.

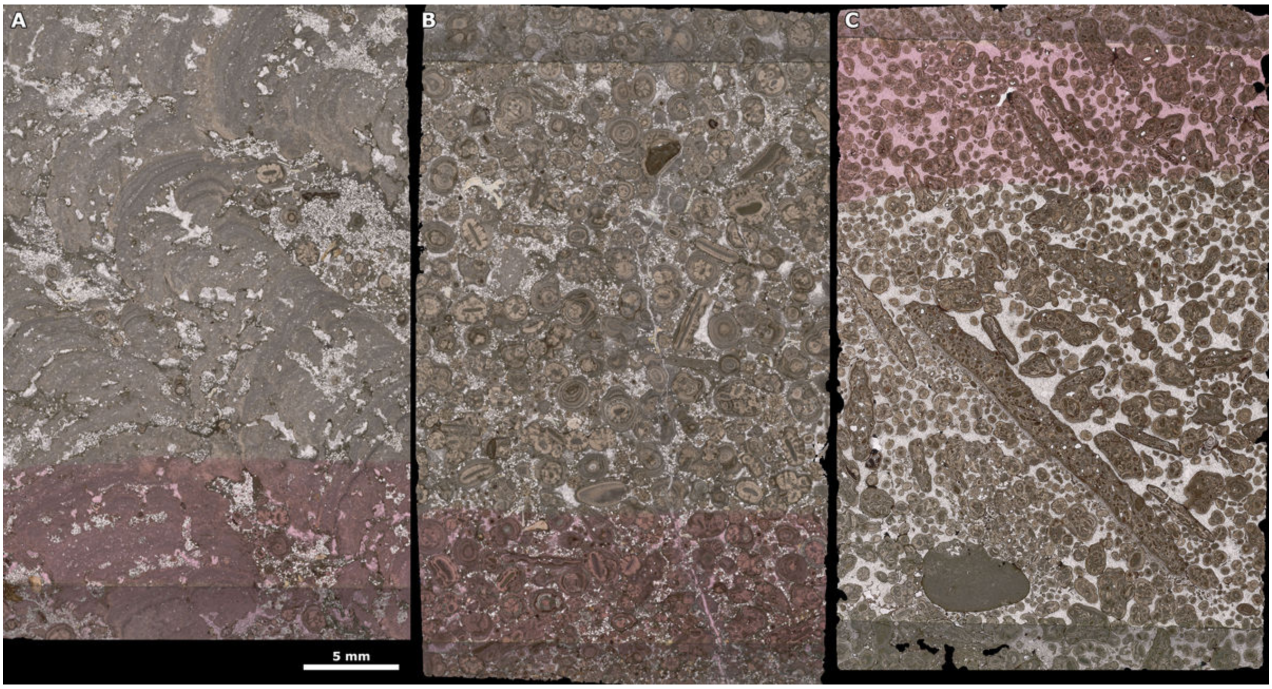


Figure 4: High resolution scans of the thin sections: **A)** three stromatolitic microcolumns, each approximately 1 cm wide, containing silt and coated grains in the stromatolitic inner vugs and in the intercolumnar space, ARA 268, **B)** floatstone of bothryoids and ooids with a silty matrix, ARA 269, **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.

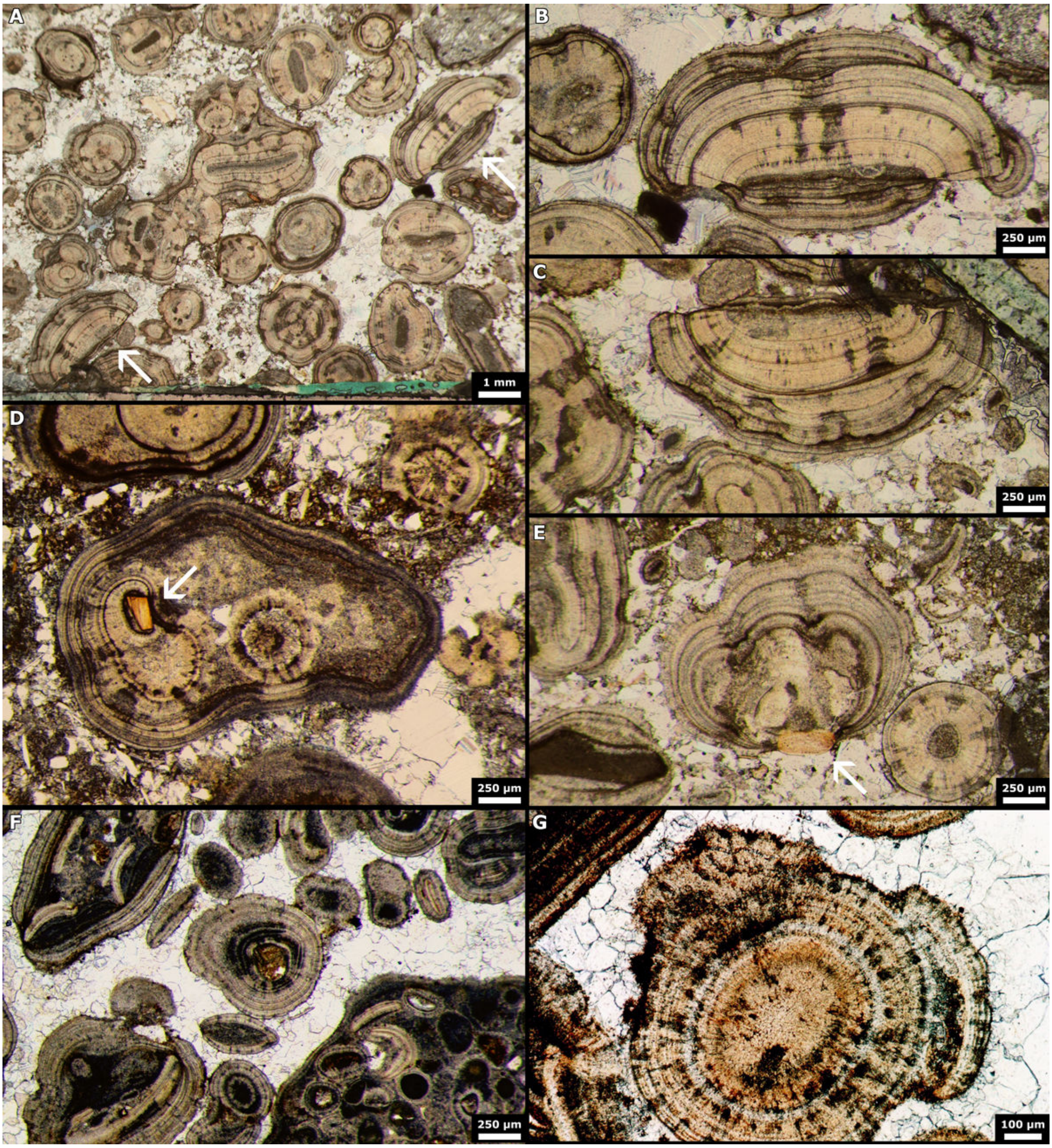


Figure 5: A-C, E) thin section AG 268: A) microfacies (the two half ooids are arrowed); B-C; broken and asymmetrically regenerated ooids; E) asymmetric ooid with a protruding siliciclastic nucleus (arrowed); **D)** thin section AG 269: bothryoid composed of a cluster of ooids, including one asymmetric 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.

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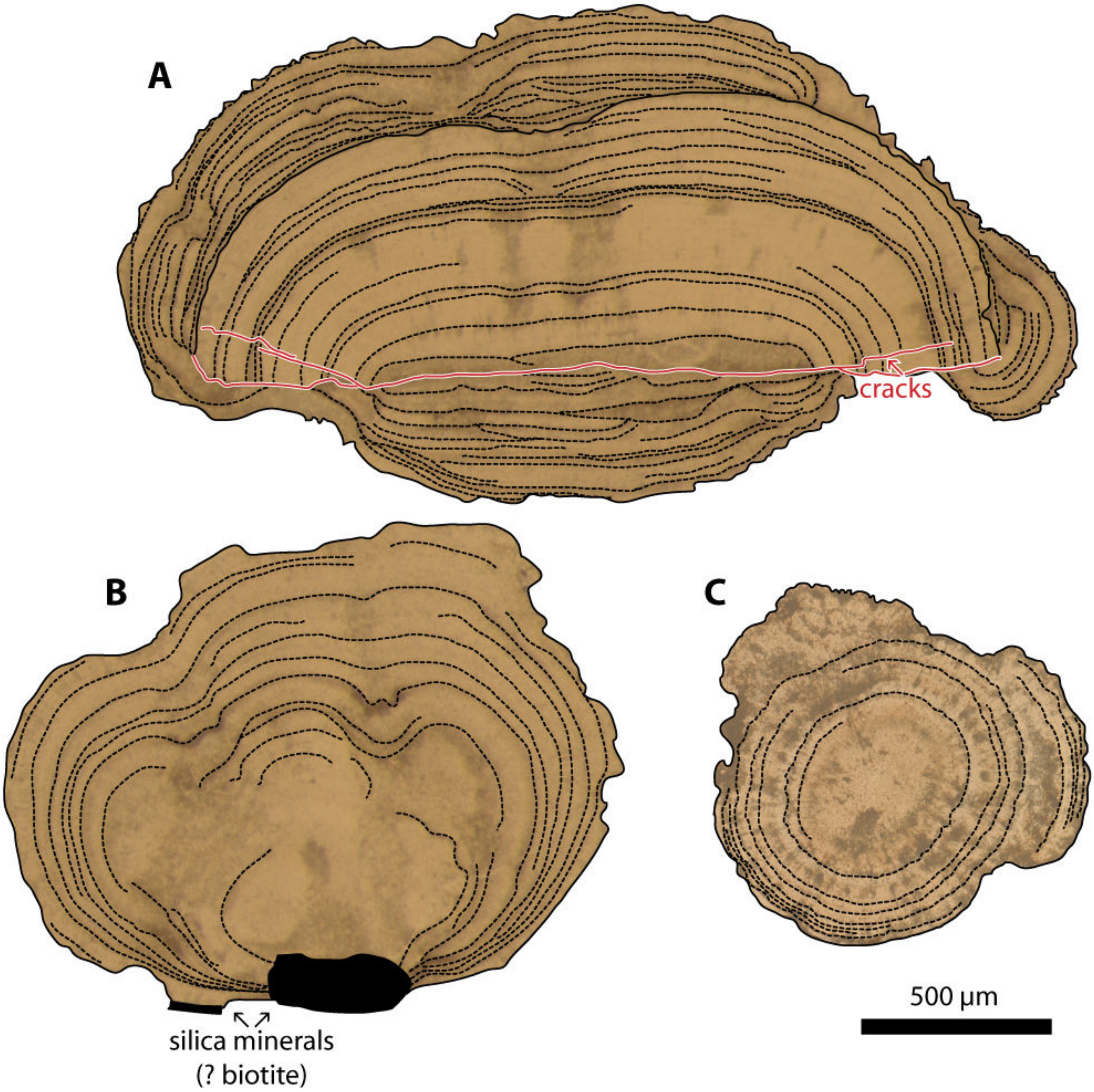

Figure 6: A-B) thin section AG 268, Road 47 from Coronel Moldes to Puente Dique Cabra Corral, Province of Salta: A) following the ooid breakage, growth of the regenerated cortex is restricted to a part of the fracture plane, one edge and the convex part, see Fig. 5.B; B) the center of mass of the ooid 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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