

Petrography and Palynology of Carbonate Concretions From the Lower Cretaceous Romualdo Formation Lagerstätte, Brazil

Guilherme Andrade Xavier

guilhermeandraxavier@gmail.com

UNICAMP: Universidade Estadual de Campinas <https://orcid.org/0009-0000-0510-6961>

Ludmila C. do Prado

URCA: Universidade Regional do Cariri

Tito Aureliano

Universidade Federal do Rio Grande do Norte

Alcina Barreto

Universidade Federal de Pernambuco

Fresia S. Ricardi-Branco

UNICAMP: Universidade Estadual de Campinas

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Abstract

Carbonate concretions are among the most effective taphonomic capsules in the sedimentary record, isolating organic material from diagenetic alteration and enabling the preservation of three-dimensional skeletal structures, soft tissues, and associated microbial communities. The concretions of the Romualdo Formation (Aptian–Albian, Araripe Basin, Northeast Brazil) exemplify this preservational potential as part of one of the world's foremost *Konservat-Lagerstätten*, yielding vertebrate, invertebrate, and plant material. Despite the wealth of systematic research on these concretions, their diagenesis and internal palynological content remain poorly characterized relative to the broader palynological literature on the enclosing shales. Here we present integrated petrographic and palynological analyses of eight carbonate concretions nucleated around distinct organic substrates (fish remains, coprolites, and phytodetritus) collected from two shale horizons. Scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) and polarized-light petrographic microscopy, together with palynological slides analyzed under transmitted-light optical microscopy, revealed that concretion formation was syngenetic to early diagenetic, and proceeded through three stages: (i) fluorapatite nucleation on organic substrates at or near the sediment–water interface; (ii) carbonate precipitation during the first centimeters to meters of burial; and (iii) pyrite precipitation under progressively reducing conditions. Microfossils within the concretion matrix, including ostracodes (e.g., *Pattersonocypris*) and miliolid foraminifera, mirror those of the host shales, corroborating early cementation of ambient sediment. The palynological assemblage is dominated by *Classopollis* and *Uesuguipollenites*, with subordinate lycophyte spores, monilophyte spores, green algae (*Botryococcus*), and dinoflagellates (*Batiacasphaera*), collectively indicative of a warm, arid-to-semi-arid coastal–estuarine setting under strong marine influence during the late Early Cretaceous.

INTRODUCTION

Carbonate concretions are discrete, mineral-rich masses that nucleate around organic material within sedimentary sequences and precipitate from carbonate-saturated pore fluids during early diagenesis (Sellés-Martínez, 1996; Mozley, 1996). Their early cementation shields encapsulated organic remains from compaction, bioturbation, and geochemical alteration, enabling preservation of three-dimensional skeletal structures, soft tissues, and entire microbial assemblages that would otherwise be lost (Martill, 1988; Briggs, 2003; Muscente et al., 2017). This taphonomic role makes concretion-hosted assemblages indispensable archives for high-resolution reconstructions of ancient ecosystems, providing organismal, geochemical, and paleoenvironmental information at a level of detail rarely achievable through other preservational pathways (Martill, 1988; Kellner, 1996; Heimhofer et al., 2017; Aureliano et al., 2018; Araripe et al., 2022; Bom et al., 2023; Pêgas et al., 2025). Nowhere is this more evident than in the Romualdo Formation (Aptian–Albian) of the Araripe Basin, Northeast Brazil, whose shale-hosted carbonate concretions constitute one of the world's most celebrated *Konservat-Lagerstätten* (Maisey, 1991; Martill, 1993; Neumann & Cabrera, 1999; Fambrini et al., 2020; Cisneros et al., 2022; Macário et al., 2025). These concretions preserve an extraordinary diversity of organisms, including fishes, pterosaurs, crocodiliforms, turtles, crustaceans, echinoids and mollusks, in some cases with their soft tissues,

representing a coastal–estuarine ecosystem under strong marine influence during the early opening of the South Atlantic Ocean (Maisey, 1991; Martill, 1993; Custódio et al., 2017; Aureliano et al., 2014, 2018; Abreu et al., 2020; Duque et al., 2023; Prado et al., 2025; Macário et al., 2025). Despite this wealth of systematic and taphonomic data, palynological investigations have focused predominantly on the enclosing shales rather than on the concretions themselves, leaving the palynomorph content of these bodies, and the paleoenvironmental signal it encodes, largely uncharacterized (Arai & Assine, 2020; Lacerda et al., 2023; Nascimento et al., 2023). Here, we present integrated petrographic and palynological analyses of eight carbonate concretions from the Sobradinho Section of the Romualdo Formation to constrain concretion-forming processes and reconstruct the Lower Cretaceous ecosystem they preserve, filling a critical knowledge gap in the palynological record of this globally significant lagerstätte (Teixeira et al., 2017; Fürsich et al., 2019; Bom et al., 2023; Antonietto et al., 2026).

GEOLOGICAL SETTING

Araripe Basin

The Araripe Basin (Fig. 1) is one of four interior basins of north-eastern Brazil. It covers more than 9,000 km² and extends across the states of Ceará, Piauí, and Pernambuco (Fambrini et al., 2020). The basin lies within the Borborema Province, bounded to the north by the Patos Shear Zone and to the south by the Pernambuco Shear Zone. Its origin is linked to tectonic reactivation associated with the rifting of the Gondwana Supercontinent during the Mesozoic, which reactivated pre-existing shear zones, created subsiding depressions, and allowed the formation of the north-eastern interior basins (Fambrini et al., 2020). Beurlen (1962) reported a total stratigraphic thickness of 850 m, with the Cariri Formation at the base and the Exu Formation at the top.

The stratigraphy of the Araripe Basin is subdivided into five major depositional sequences (Assine, 1992, 2007; Fambrini et al., 2020). The Paleozoic sequence (Late Ordovician–Early Silurian age) was deposited directly over the Precambrian crystalline basement and consists solely of the Cariri Formation, medium- to coarse-grained sandstones deposited in a braided fluvial system (Cunha-Silvestri et al., 2017). The second sequence, the Initial Rift sequence, of Late Jurassic age, comprises the Brejo Santo Formation (red mudstones and shales deposited in a lacustrine setting) and the Missão Velha Formation, which includes sandstones deposited in a shallow, high-energy fluvial system (Assine, 2007; Fambrini et al., 2020).

The third sequence, the Rift Climax sequence of Neocomian age, consists of the pelites and sandstones of the Abaiara Formation (Fambrini et al., 2020). The fourth sequence, the Post-rift I of Aptian–Albian age, contains the Santana Group, comprising the Barbalha, Crato, Ipubi, and Romualdo formations (Neumann & Cabrera, 1999; Fambrini et al., 2015; Fambrini et al., 2020). The fifth sequence, the Post-rift II of Albian–Cenomanian age, includes the Araripina Formation characterized by its fine-grained sandstones and yellowish to reddish-purple mudstones, and the fluvial sandstones of the Exu Formation (Assine, 2007; Fambrini et al., 2020; Aureliano & Ghilardi, 2024).

The Santana Group

The study area falls within the Santana Group, formerly referred to as the Santana Formation (Neumann & Cabrera, 1999; Fambrini et al., 2020). The group comprises the Barbalha, Crato, Ipubi, and Romualdo formations. Both the Crato and Romualdo formations are recognized as *Konservat-Lagerstätten* owing to their exceptional fossil diversity and preservation (Maisey, 1991; Cisneros et al., 2022; Macário et al., 2025).

The Barbalha Formation consists of conglomeratic coarse-grained sandstones exhibiting tabular, planar, and trough cross-stratification, together with channel-fill structures and ferruginous crusts. The succession shows an overall upward-fining trend capped by pelitic intervals (Fambrini et al., 2015). The depositional environment is interpreted as shallow, laterally extensive, ephemeral channels that transition upward into a fluvial system (Fambrini et al., 2020).

The Crato Formation consists of calcareous shales interbedded with laminated, fossiliferous, argillaceous micritic limestones. Bituminous shales with elevated total organic carbon contents occur locally (Fambrini et al., 2020). The depositional environment is interpreted as lacustrine systems associated with an early Albian marine transgression (Assine, 2007).

The Ipubi Formation is characterized by evaporitic facies dominated by gypsum, laterally equivalent to marly shales. This unit is interpreted as reflecting extensive sabkha-type environments that advanced inland during episodes of marine ingression under an arid to semi-arid climate (Fambrini et al., 2020).

The Romualdo Formation

The Romualdo Formation (Aptian/Albian; U–Pb age of 10.5 ± 7.4 Ma based on three teeth of *Cladocycclus gardneri* Agassiz; Barreto et al., 2022) represents the uppermost unit of the Santana Group. It consists predominantly of sandstones interbedded with dark organic-rich shale intervals up to 5 m thick and carbonates. The carbonate concretions studied here occur within greenish shale beds (Custódio et al., 2017; Fambrini et al., 2020; Aureliano & Ghilardi, 2024; Tomé et al., 2026). Toward the top of the formation, shell beds up to 1 m thick have been interpreted as tempestite deposits (Sales, 2005; Custódio et al., 2017; Prado et al. 2025). The Romualdo Formation records deposition in an estuarine to shallow-marine environment influenced by sea-level fluctuations and marine ingressions associated with the opening of the southern Atlantic Ocean (Custódio et al., 2017; Araripe et al., 2022, 2025; Gomes et al., 2024; Prado et al., 2025; Tomé et al., 2026). Although the full extent of the marine connection with other correlative northeastern Brazilian contexts (e.g., Parnaíba Province, Sergipe-Alagoas) has not yet been fully resolved (Prado et al., 2025; Tomé et al., 2026), the high proportion of marine species in the western part of the Araripe Basin and the affinities with the Tethys Sea suggests that the most probable ingression route was via the Parnaíba Province (Melo et al., 2020; Araripe et al., 2022; Pedrosa et al., 2023; Nascimento et al., 2023; Prado et al., 2025; Antonietto et al., 2026).

Sobradinho Section

The Sobradinho section is located in the eastern Araripe Basin, between the municipalities of Porteiras and Jardim, and is the source locality for the concretions studied here. This section is considered the most complete exposure of the Romualdo Formation (Custódio et al., 2017). Teixeira et al. (2017) documented a stratigraphic thickness of approximately 80 m and recognized five principal intervals (Fig. 1). The Sobradinho section represents a relatively distal offshore position compared with other outcrops (e.g., Serra da Mãozinha). However the source area for plant debris lies closer to the section in its upper part (Fürsich et al., 2019).

The basal interval comprises black shales and laminated limestones attributed to a proximal depositional system. The second interval consists of black shales bearing carbonate concretions. Samples CP2/207, CP6/283, CP6/323, CP6/324, CP6/325, CP6/326, and CP6/327 were collected from this interval. Abundant amorphous organic matter, planktonic and benthic foraminifera, and ostracodes (Teixeira et al., 2017; Fürsich et al., 2019; Melo et al., 2020; Bom et al., 2023; Araripe et al., 2025) indicate a marine setting with anoxic conditions at the sediment–water interface. The third interval consists of black shales, massive sandstones, and shell beds with amorphous organic matter contents indicative of a proximal setting (Teixeira et al., 2017; Fürsich et al., 2019). The upper-middle interval consists of black shales interbedded with shell beds and abundant phytoclasts. Sample CP1/921 was collected from this interval. Sedimentary organic matter analyses indicate a transitional proximal-to-distal, estuarine setting with reduced salinity (Teixeira et al., 2017; Custódio et al., 2017; Fürsich et al., 2019). The uppermost interval of the Sobradinho section is characterized by sandstones associated with sand bars, with analyses indicating a proximal setting and low preservation of amorphous organic matter (Teixeira et al., 2017; Custódio et al., 2017; Fürsich et al., 2019).

Carbonate concretions of the Romualdo Formation

The concretions of the Romualdo Formation display variable morphologies, ranging from rounded to oval and irregular, that reflect the shape and orientation of the organic nuclei they enclose, as well as their position within the basin (Duque et al., 2023). In general, each concretion contains one or more prominent fossils at its center, surrounded by a microfossil assemblage disposed along laminations. Concretions lacking macrofossils and septarian concretions also occur (Saraiva et al., 2007; Fambrini et al., 2020). Previous studies describe these concretions as composed of argillaceous micritic limestone with laminations parallel to the bedding of the enclosing shales (Martill, 1988; Assine, 1992; Heimhofer et al., 2017; Duque et al., 2023; Pêgas et al., 2025).

The earliest documented records of carbonate concretions from what is now known as the Romualdo Formation date to the late Portuguese colonial period of Brazil. In 1800, the naturalist João da Silva Feijó, commissioned to survey the natural and mineral resources of the then captaincy of Ceará, described ‘petrified’ fish and amphibians with soft tissues still preserved (Silva & Cavalcanti, 2021). Part of this collection was taken to the Munich Museum by the German scientists Johann Baptist von Spix and Carl Friedrich Philipp von Martius, who published their findings in 1828. In 1841, Louis Agassiz established

the fish genus *Rhacolepis* after describing carbonate concretions collected near the municipality of Jardim in the state of Ceará (Maisey, 1991).

The concretions range in size from a few centimeters to several decimeters (Saraiva et al., 2007) and have yielded more than eleven fish genera (Fara et al., 2005; Saraiva et al., 2007), including *Araripelepidotes* Santos, 1990, *Tharrhias* Jordan & Branner, 1908, *Vinctifer* Jordan, 1919, *Cladocyclus* Agassiz, 1841, *Brannerion* Jordan, 1920, *Calamopleurus* Agassiz, 1841, *Notelops* Woodward, 1901, and *Rhacolepis*, among others. In addition to fish, the concretions preserve crocodilians, turtles, pterosaurs, dinosaurs, plant material, mollusks, decapod crustaceans, shrimps, ostracodes, foraminifera, coprolites, and amniotic eggs (e.g., Martill, 1993; Aureliano et al., 2014; Aureliano et al., 2018; Pereira et al., 2015; Prado et al., 2015, 2018; Abreu et al., 2020; Barbosa et al., 2025; Duque et al., 2023; Pêgas et al., 2025; Dino et al., 2026). In several cases, soft tissues including muscle, skin, dermis, and blood vessels are preserved (Kellner, 1996; Fambrini et al., 2020). This remarkable fossiliferous content, dispersed within shale-hosted concretions, has made the Romualdo Formation one of the most celebrated palaeontological units worldwide (Fambrini et al., 2020).

MATERIALS AND METHODS

Macroscopic descriptions of the concretions follow the classification scheme of Sellés-Martínez (1996). Coprolite descriptions follow the terminology of Häntzschel et al. (1968).

Material

Eight carbonate concretions collected from the Sobradinho site in the municipality of Jardim, Ceará (Fig. 2) were studied. The specimens are housed in the Scientific Palaeontological Collection of the Institute of Geosciences, University of Campinas, within the Paleobotany (CP1), Vertebrate (CP2), and Ichnofossil (CP6) collections. Samples CP1/921, CP2/207, CP6/323, CP6/324, CP6/325, and CP6/326 each consist of two halves (designated A and B). Sample CP6/327 consists of six fragments (designated A through F), and sample CP6/283 consists of a single half. Macrophotographs were obtained with a Canon EOS Rebel SL3 camera while image stacking was performed with the Helicon Focus® software. Additional images with greater magnification and detail were acquired using an AxioCam 105 color camera mounted on a Zeiss Stemi 2000-C stereomicroscope and the Zeiss Zen 2.5 Lite® software.

Petrography

Fourteen polished, coverslip-free petrographic thin sections were prepared from samples CP1/921A, CP2/207A, CP6/283, CP6/323A and B, CP6/324, CP6/325A and B, CP6/326A, and CP6/327A and B (Table 1). The thin sections were examined on a Zeiss AxioScope A1 polarized-light petrographic microscope equipped with an AxioCam MRc5 digital camera, operated through Zeiss Zen 2.5 Lite® software, at the Palaeohydrogeology Laboratory, Institute of Geosciences, University of Campinas.

Table 1 Analytical dataset for each sample

Sample	Petrography	SEM-EDS	Palynology
CP1/921	1 thin section		
CP2/207	2 thin sections		10 slides
CP6/283	3 thin sections	1 thin section	10 slides
CP6/323	2 thin sections		
CP6/324	1 thin section		
CP6/325	2 thin sections		
CP6/326	1 thin section		
CP6/327	2 thin sections		10 slides

Scanning Electron Microscopy with Energy-Dispersive X-Ray Spectroscopy (SEM-EDS)

SEM-EDS analyses were performed on a LEO 430i Zeiss scanning electron microscope coupled with an Oxford Instruments energy-dispersive X-ray spectrometer at the Electron Microscopy Laboratory, Institute of Geosciences, UNICAMP. The instrument operated at a landing voltage of 20.00 kV in high-vacuum mode. Thin section CP6/283A was carbon-coated before to imaging, and elemental data were acquired from selected points.

Palynology

For the palynological analysis, 10.06 g of sample CP2/207, 19.31 g of sample CP6/283, and 30.01 g of combined subsamples CP6/327C and D were processed. Each sample was dissolved in 37% HCl in 1 L beakers for 48 hours. At least three rinse cycles with distilled water were then performed, with each cycle left to settle for 24 hours until a neutral pH was attained, and the residue was retained. Ten palynological slides were prepared from each sample. For each slide, two to three drops of residue were mixed with two drops of Cellosize, then mounted under a coverslip with Entellan as the mounting medium. Slides were examined at 100× magnification on a Zeiss Axio Imager A1 optical microscope with image acquisition via an AxioCam MRc5 camera. A target count of 100 palynomorphs, including pollen grains, spores, microplankton, and dinoflagellates, was sought for each sample. Structured opaque phytoclasts were tallied separately throughout each count.

RESULTS

Macroscopic Description

All studied concretions are ellipsoidal to spheroidal in form. Their primary morphological differences reflect the nature of the fossil nucleus around each one developed (Fig. 2). Sample CP1/921 is characterized by its plant-fragment nucleus. Sample CP2/207 contains a *Rhacolepis* sp. specimen at its center, with bones and scales visible on the split surface. Samples CP6/283 and CP6/323 each contain a

discoidal coprolite nucleus. Samples CP6/324, CP6/325, and CP6/326 contain irregularly shaped coprolites. Sample CP6/327 contains an ellipsoidal coprolite.

Petrographic Characterization

All studied concretions share a matrix of micritic carbonate with dispersed amorphous organic matter and a cement of microcrystalline calcite.

Plant-nucleated concretion

Sample: CP1/921A (Figs 3a–d)

The bioclast assemblage consists of irregular fragments of structured, non-opaque plant tissue with subangular to angular and subrounded margins disposed in random orientations (Figs 3a–c). Structured phytoclasts with preserved tracheids and perforations are present, together with ostracodes with articulated (Fig. 3d) and/or disarticulated valves. No concentric laminations are present.

Osteichthyan-nucleated concretion

Sample: CP2/207A (Figs 3e–k)

Bioclasts include scales and bones of an osteichthyan (*Rhacolepis* sp.) at the concretion center (Figs 3e–f). Ostracodes with recrystallized articulated or isolated valves (Figs 3g–i), assigned tentatively to *Pattersonocypris* sp. and *Damonella* sp., are up to approximately 1 mm in length and range from rounded to elliptical in outline. Ostracode valves are locally aligned with the concretion lamination. Valve interiors are filled with pyrite or equant calcite crystals. Sparse miliolid foraminifera (*?Coryphostoma* sp.; see Fig. 3j) with micritized tests are present. Microbial mats encasing calcite crystals and bioclasts (Fig. 3k) are associated with concretion laminae. Amorphous organic matter associated with bacterial mucilage is abundant. The dominant porosity types are intragranular and moldic, the latter derived from the dissolution of ostracode valves in the outer zones of the concretion.

Coprolite-nucleated concretions

Sample: CP6/283 (Figs 3l–n)

The central coprolite is recrystallized and contains scattered osteichthyan bone fragments. Foraminifera and ostracodes display micritized tests (Figs 3l–m). Ostracodes are abundant, with articulated and disarticulated valves replaced by calcite crystals; articulated valves are aligned parallel to concretion lamination (Fig. 3n) and are generally less than 1 mm in length. Microbial mats, also parallel to lamination, are present in the medial zone of the concretion. Amorphous organic matter associated with bacterial mucilage is abundant. Dominant porosity is moldic, produced by dissolution of ostracode valves in the outer zones.

Sample: CP6/323A (Figs 4a–e)

The central coprolite contains scattered osteichthyan bone fragments (Fig. 4a). Ostracodes are aligned parallel to concretion lamination and to the coprolite surface (Fig. 4b), with lengths of approximately 1 mm. Some retain articulated, elliptical valves. Ostracode valves are partially to wholly filled by pyrite crystals (Figs 4c–d). Thin biofilm laminae and abundant amorphous organic matter associated with bacterial mucilage are present (Fig. 4e). Porosity is intragranular and moldic, produced by ostracode valve dissolution.

Sample: CP6/324B (Figs 4f–h)

The central coprolite contains scattered osteichthyan bone fragments enveloped by phosphate (Fig. 4f) and displays structures interpreted as coprophagous trace marks (Figs 4g–h). Ostracodes are generally aligned with concretion lamination and range in length from 1 to 2 mm. Some valves are filled by pyrite. Amorphous organic matter associated with bacterial mucilage is abundant. Dominant porosity is intragranular and moldic.

Sample: CP6/325B (Figs 4i–m, 5a)

Fluorapatite crystals replace the central coprolite (Fig. 4i). Small masses of pyrite occur between fluorapatite crystals and the carbonate matrix (Figs 4j–k). Ostracodes are abundant, with some retaining articulated valves aligned with concretion lamination, while others are disarticulated and more randomly distributed (Fig. 4j). Locally, valves are cemented by micrite and form ostracode clusters. Lengths range from 0.5 to 2 mm. Some valves are partially replaced by pyrite; one foraminifer test is wholly recrystallized (Fig. 4m). Sparse structured non-opaque phytoclasts are present (Fig. 5a). Amorphous organic matter associated with bacterial mucilage is abundant. Dominant porosity is intragranular and moldic.

Sample: CP6/326A (Figs 5b–d)

Bioclasts are dominated by bone fragments within the central coprolite (Fig. 5b) and by ostracodes replaced by pyrite. The coprolite margin displays structures interpreted as coprophagous trace marks (Figs 5c–d). Dominant porosity is intragranular and moldic.

Sample: CP6/327F (Figs 5e–i)

Bioclasts are dominated by ostracode valves, most of which are aligned parallel to the concretion lamination (Figs 5e–f). Most valves are disarticulated while articulated valves are rare (Fig. 5f). Some ostracodes are partially to wholly replaced by pyrite (Figs 5f–g). Amorphous organic matter and phytoclasts associated with bacterial mucilage are abundant (Fig. 5h). Sponge spicules are present in small numbers (Fig. 5i). Dominant porosity is intragranular and moldic.

SEM-EDS Elemental Analysis

SEM-EDS analysis of sample CP6/283A revealed calcium as the dominant element in the matrix (Fig. 6), consistent with the microcrystalline calcite composition described petrographically. Point analyses of bone fragments and foraminifera detected fluorine and phosphorus (Fig. 6c), indicating the presence of fluorapatite. Analyses over high-backscatter regions detected iron and sulfur (Fig. 6c), consistent with pyrite. Magnesium was identified at several points (Fig. 6d). Manganese was recorded rarely (Fig. 6d).

Palynological Characterization

A total of 454 palynomorphs were counted across all three samples (Fig. 7). Pollen grains dominate in all samples, followed in abundance by spores, phytoplankton, and dinoflagellates, the later on sample CP6/327 only. Structured opaque phytoclasts were tallied separately (Fig. 7j). Seven taxa were identified in total: two spore genera (*Leptolepidites* and *Cicatricosisporites*), three pollen genera (*Equisetosporites*, *Uesuguipollenites*, and *Classopollis*), one microplankton genus (*Botryococcus*), and one dinoflagellate genus (*Batiacasphaera*). All samples contain abundant amorphous organic matter.

Sample CP2/207 yielded 162 palynomorphs: 62 phytoclasts, 63 pollen grains, and 37 spores, representing 39% pollen, 38% phytoclasts, and 23% spores. Taxa identified include *Cicatricosisporites*, *Equisetosporites*, and *Classopollis*.

Sample CP6/283 yielded 174 palynomorphs: 74 phytoclasts, 81 pollen grains, and 19 spores, representing 47% pollen, 42% phytoclasts, and 11% spores. Taxa identified include *Leptolepidites*, *Uesuguipollenites*, and *Classopollis*.

Sample CP6/327 yielded 121 palynomorphs: 18 phytoclasts, 94 pollen grains, 6 spores, 2 microplankton, and 1 dinoflagellate, representing 78% pollen, 15% phytoclasts, 5% spores, 1% microplankton, and 1% dinoflagellates. Taxa identified include *Leptolepidites*, *Classopollis*, and *Botryococcus*.

DISCUSSION

Petrographic and palynological studies of Romualdo Formation concretions have been conducted less frequently than systematic investigations of the fossils they contain. Foundational diagenetic studies (Martill, 1988, 1993; Maisey, 1991) examined concretion diagenesis and established initial formation models. Saraiva et al. (2007) proposed a morphological classification based on fossil content, stratigraphic position, shape, and associated sedimentary structures. More recent works have addressed the sedimentary environment associated with concretion formation and the influence of geographical position within the basin on concretion composition (Heimhofer et al., 2017; Fürsich et al., 2019; Duque et al., 2023; Tomé et al., 2026).

Remarks on the Romualdo Formation fossil diagenesis

Petrographic analysis shows a calcium carbonate matrix composed of microcrystalline calcite, with dispersed amorphous organic matter and localized micritic accumulations. SEM-EDS analysis identified magnesium-enriched regions, suggesting possible co-precipitation of dolomite. Most samples display

laminations parallel to those of the host shale (Assine, 1992; Heimhofer et al., 2017; Fambrini et al., 2020). Ostracodes and foraminifera show a tendency to settle along lamination planes, consistent with benthic behavior (Nascimento et al., 2023; Araripe et al., 2025).

Sample CP1/921, collected from the upper part (~90 m) of the Sobradinho section (Custódio et al., 2017; Melo et al., 2020; Prado et al., 2025), differs from the other samples in its randomly oriented phytoclasts, comparatively organic matter-poor matrix, and elevated abundance of structured non-opaque phytoclasts. The horizon from which it was collected yields concretions that are rarer and smaller than those from the 55–60 m interval of the section. These characteristics may record a palaeoenvironmental shift from a shallow marine, low bottom-water oxygen (dysoxic) setting to a more proximal setting with a stratified water column (Teixeira et al., 2017; Arai & Assine, 2020; Bom et al., 2023; Araripe et al., 2025; Prado et al., 2025; Ferreira et al., 2025).

The carbonate concretions of the Romualdo Formation are syngenetic to early diagenetic in origin (Sellés-Martínez, 1996). Petrographic, elemental, and geochemical data support the most widely accepted formation model (Martill, 1988; Heimhofer et al., 2017; Bom et al., 2023). Concretion nucleation began while the central organic substrate was still exposed at, or buried only a few millimeters below, the sediment–water interface, a syngenetic condition. As the sediment column thickened, carbonate precipitation occurred in response to changes in pore-water pH and/or salinity and the development of anoxic conditions (Bom et al., 2023; Araripe et al., 2025), continuing throughout the first centimeters to meters of burial in an early diagenetic setting (Sellés-Martínez, 1996).

SEM-EDS data for sample CP6/283A reveal elevated fluorine and phosphorus concentrations near bone fragments of Osteichthyes, indicating fluorapatite. This association reflects the release of phosphate during bacterial decomposition of muscle fibers. Phosphate did not remain in solution for extended periods, and it was rapidly precipitated as microspheres of francolite (Martill, 1988; Berna et al., 2004; Keenan, 2016; Keenan & Engel, 2017; Marchetti et al., 2019).

Pyrite crystals replace and infill ostracode valves in most samples, preserving grain morphology. In some samples, pyrite is concentrated in the concretion core; in most samples, however, pyrite abundance increases outward toward the concretion margins. Microbial mat evidence also occurs in association with concretion laminae. Together, these trends indicate that pyritization was continuous throughout the concretion's growth (Martill, 1988; Heimhofer et al., 2017). Pyrite precipitation resulted from a burial-driven transition to the sulfate-reducing zone, coupled with organic matter decomposition by sulfate-reducing microbial association (Sellés-Martínez, 1996; Briggs, 2003; Muscente et al., 2017; Osés et al., 2017; Oliveira et al., 2025).

SEM-EDS analysis also detected manganese. Pyrolusite can form in swamp, lacustrine, and marine environments as an alteration product of manganese-rich minerals, especially manganite (Peixoto et al., 2016). The manganese recorded here may represent residual pyrolusite crystals deposited at the sediment surface during the earliest stages of concretion growth.

Remarks on the Romualdo Formation palynology

The palynological assemblage of the concretions is dominated by *Classopollis*, followed by *Uesuguipollenites*, both derived from a coastal gymnosperm-dominated vegetation, with subordinate lycophytes (e.g., *Leptolepidites*) and monilophytes (e.g., *Cicatricosisporites*). This composition mirrors the microfloristic record reviewed by Antonietto et al. (2026), who documented a high concentration of *Classopollis* pollen grains, attributed to the cheirolepidiaceous conifer family, alongside ferns and lycophytes (e.g., *Cicatricosisporites*, *Leptolepidites*, *Cyathidites*, *Deltoidospora*, *Densoisporites*, *Echinatisporis*, and *Matonisporites*) in shale-hosted assemblages of the Romualdo Formation (Lacerda et al., 2023; Carvalho et al., 2022). It is worth noting that *Classopollis* and its macrofossil counterpart *Pseudofrenelopsis*, both referable to Cheirolepidiaceae, are characteristic of environments with low water availability, though they caution that the phenotypical responses of plants to xeric and mesohaline coastal habitats can be superficially similar (Alvin, 1982; Batista et al., 2017; Mendes et al., 2023; Antonietto et al., 2026). The lower taxonomic diversity of the concretion palynomorphs relative to the host shales is consistent with this interpretation: the concretion matrix records a filtered, locally derived signal from the sediment–water interface rather than the full regional floristic spectrum preserved in open shale horizons. The occurrence of green algae (*Botryococcus*) and dinoflagellates (*Batiacasphaera*) in the concretions indicates coastal depositional conditions with at least episodic marine influence (Teixeira et al., 2017; Arai & Assine, 2020; Lacerda et al., 2023). The presence of *Botryococcus*, in particular, is highlighted as reinforcing interpretations of freshwater-to-brackish lacustrine-transitional facies within the Romualdo Formation, consistent with a ‘paleo-mangrove forest’ estuarine setting rather than open-marine conditions (Antonietto et al., 2026). Ostracodes tentatively referred as *Pattersoncypris* (= *Harbinia micropapillosa sensu* Maia et al., 2025) are indicative of warm, arid to semi-arid brackish conditions, and, combined with the dinoflagellates and foraminifera, point to a shallow, restricted, marine-influenced palaeoenvironment (Arai & Assine, 2020; Lacerda et al., 2023; Nascimento et al., 2023; Antonietto et al., 2026). The shared microfossil content between concretions and host shales corroborates the interpretation that the sediment cemented around the concretions was the same material present at the sediment–water interface, and that diagenesis began at the earliest stage (Sellés-Martínez, 1996; Antonietto et al., 2026).

Remarks on the Romualdo Formation ecosystem

The palaeoenvironmental model for the Romualdo Formation characterizes it as a transgressive systems tract under marine influence (Assine, 2007; Custódio et al., 2017; Teixeira et al., 2017; Fambrini et al., 2020; Prado et al., 2025). Petrographic data corroborate this interpretation, particularly the presence of foraminifera in samples CP2/207 and CP6/283, which are diagnostic of marine or brackish-water conditions (Araripe et al., 2022, 2025). The abundance of plant fragments in sample CP1/921 signals a palaeoenvironmental change toward greater proximity to the continental margin, reinforcing the interpretation of a coastal marine to estuarine setting (Teixeira et al., 2017; Custódio et al., 2017; Prado et al., 2025).

CONCLUSIONS

Concretion formation in the Romualdo Formation proceeded through three principal stages. The first stage occurred when organic substrates were exposed at the sediment–water interface or buried beneath only a few millimeters of sediment, and is characterized by fluorapatite nucleation on organic remains, driven by the onset of microbial decomposition. The second stage comprises carbonate precipitation during the initial phase of burial. The third stage is characterized by pyrite precipitation under reducing conditions. Palynological assemblages dominated by *Classopollis* and *Uesuguipollenites*, together with dinoflagellates and marine microfossils, corroborate a coastal estuarine depositional environment with strong marine influence and a warm, arid-to-semi-arid palaeoclimate.

Declarations

All authors contributed to the study conception, design and writing. Material preparation, data collection and analysis were performed by Guilherme Andrade Xavier, Fresia S. Ricardi-Branco, Ludmila C. do Prado, Tito Aureliano and Alcina Barreto. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare there are no conflicts of interest for this manuscript.

DATA AVAILABILITY

All fossils and thin sections are deposited at Instituto de Geociências, Universidade Estadual de Campinas and are available upon request.

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Figures

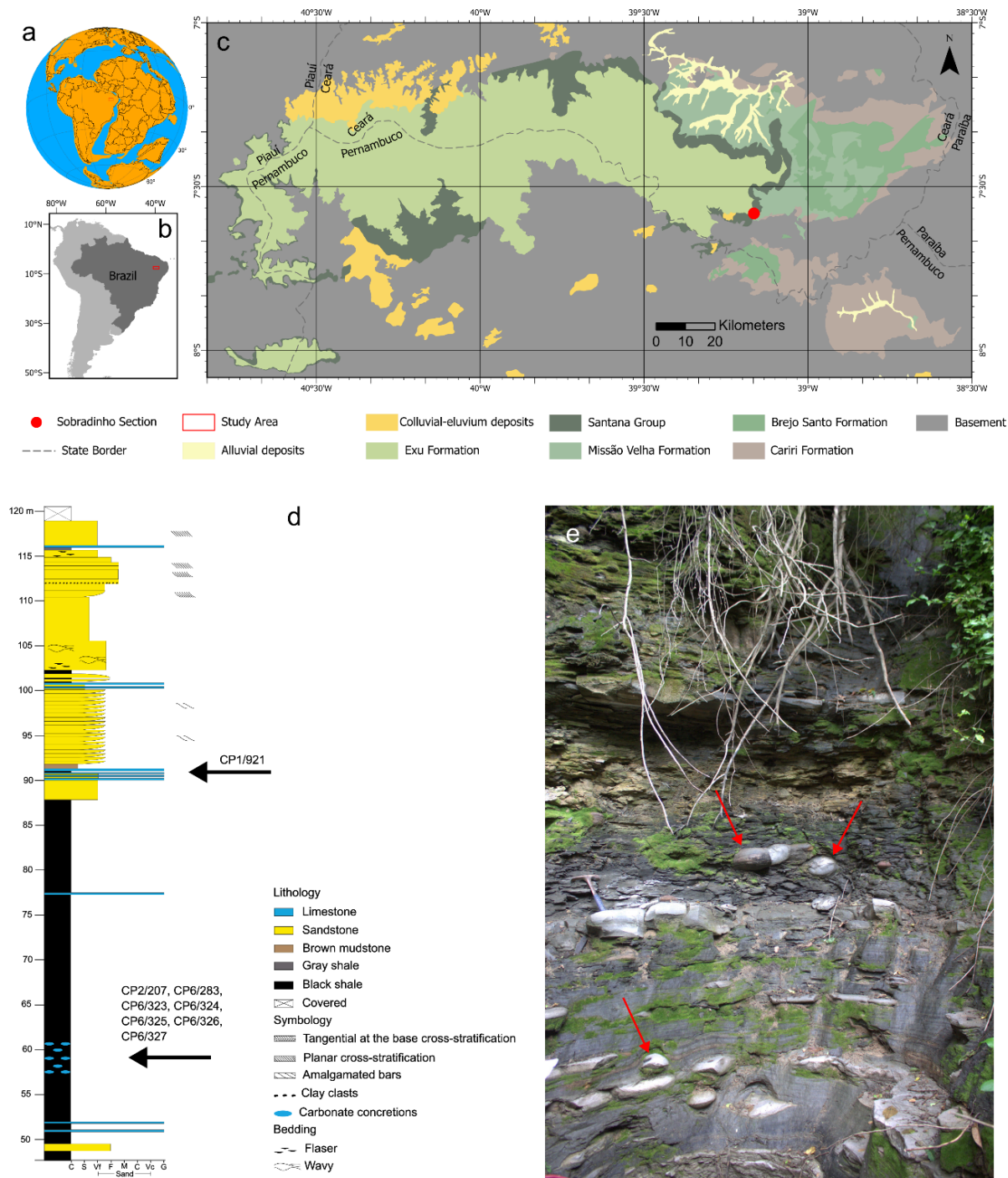


Figure 1

Location map of the Araripe Basin. a. Location of the Araripe Basin in the paleogeography of the Lower Cretaceous. b. Current location of the Araripe Basin in Brazil. c. Location map of the Araripe Basin showing the spatial distribution and lithostratigraphic framework of its stratigraphic units. d. Sobradinho section of the upper Lower Cretaceous Romualdo Formation (Araripe Basin), in the municipality of Jardim, Ceará state of Brazil, after Teixeira et al. (2017). Arrows indicate sample collection horizons (modified from Custódio et al., 2017; Araripe et al., 2022). e. Outcrop from which the samples were collected; the red arrows indicate in situ concretions

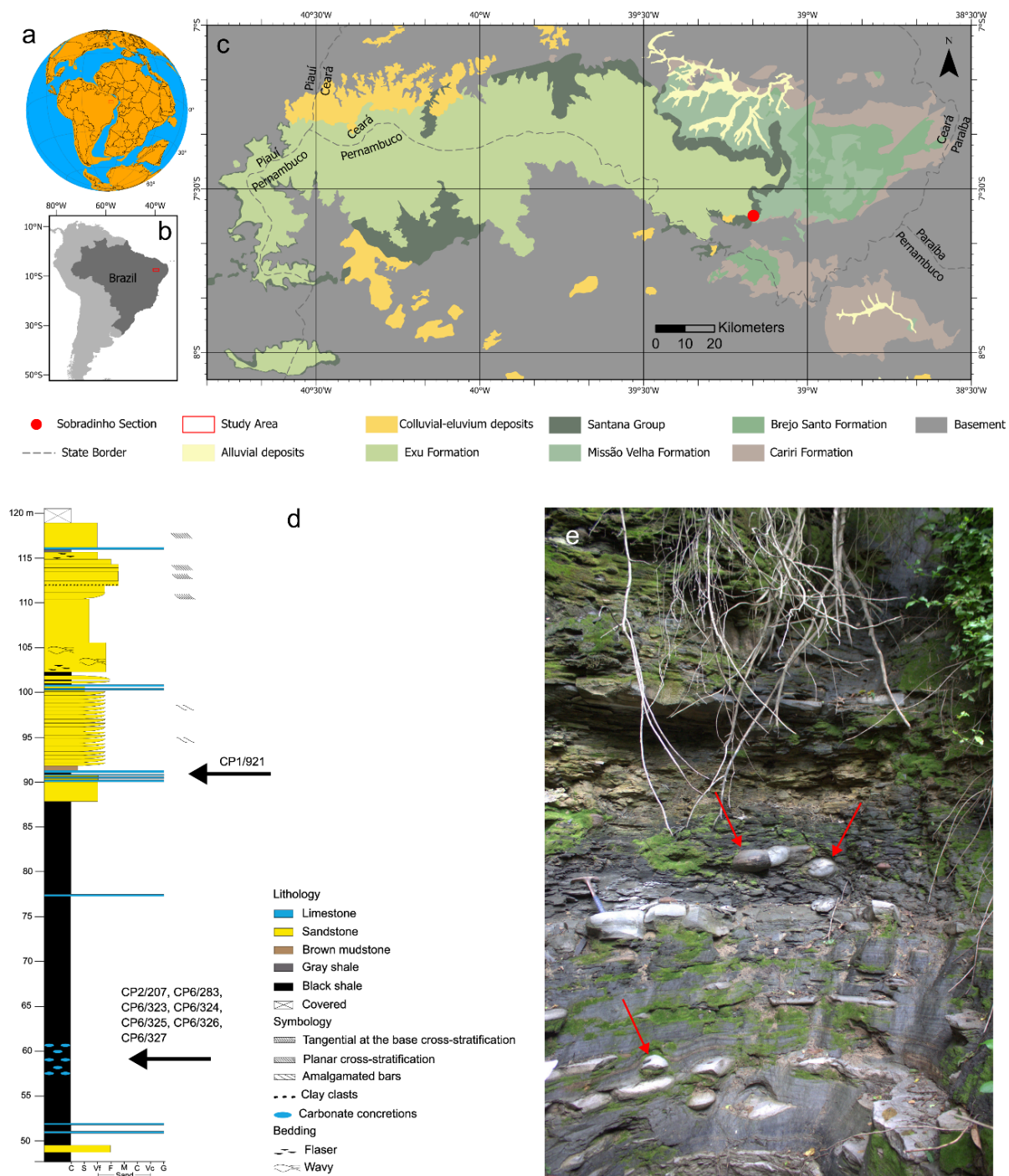


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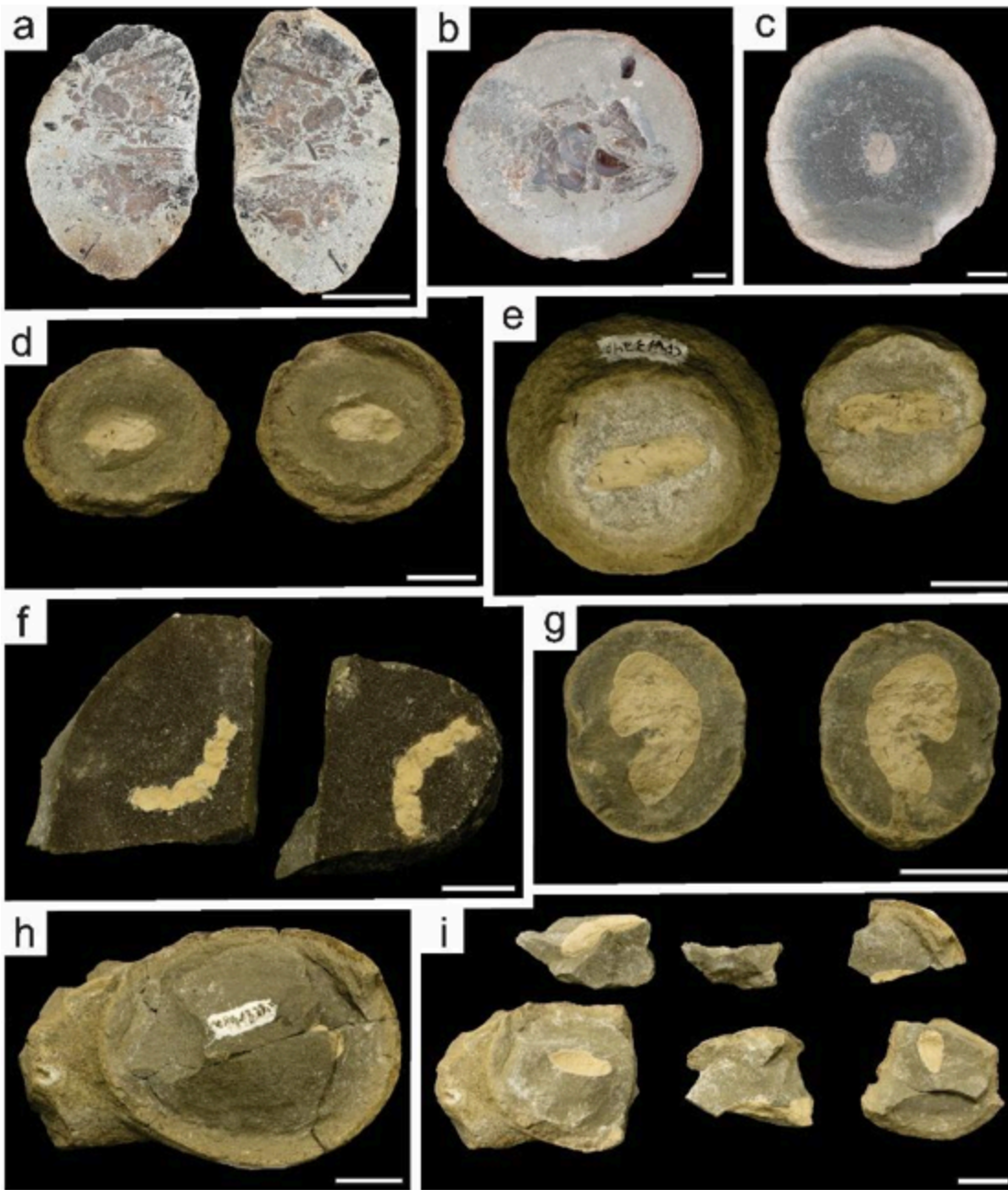


Figure 2

Studied carbonate concretions collected from the Sobradinho Section (Romualdo Formation). a. Sample CP1/921, split surface showing phytodetritus. b. Sample CP2/207, split surface with *Rhacolepis* sp. c-d. Samples CP6/283 and CP6/323, split surface with discoidal coprolite. e-f. Samples CP6/324 and CP6/325, split surface with irregular coprolite. g. Sample CP6/326, split surface with irregular coprolite. h-i. Sample CP6/327, closed and split, with ellipsoidal coprolite in six fragments. Scale bars = 2 cm

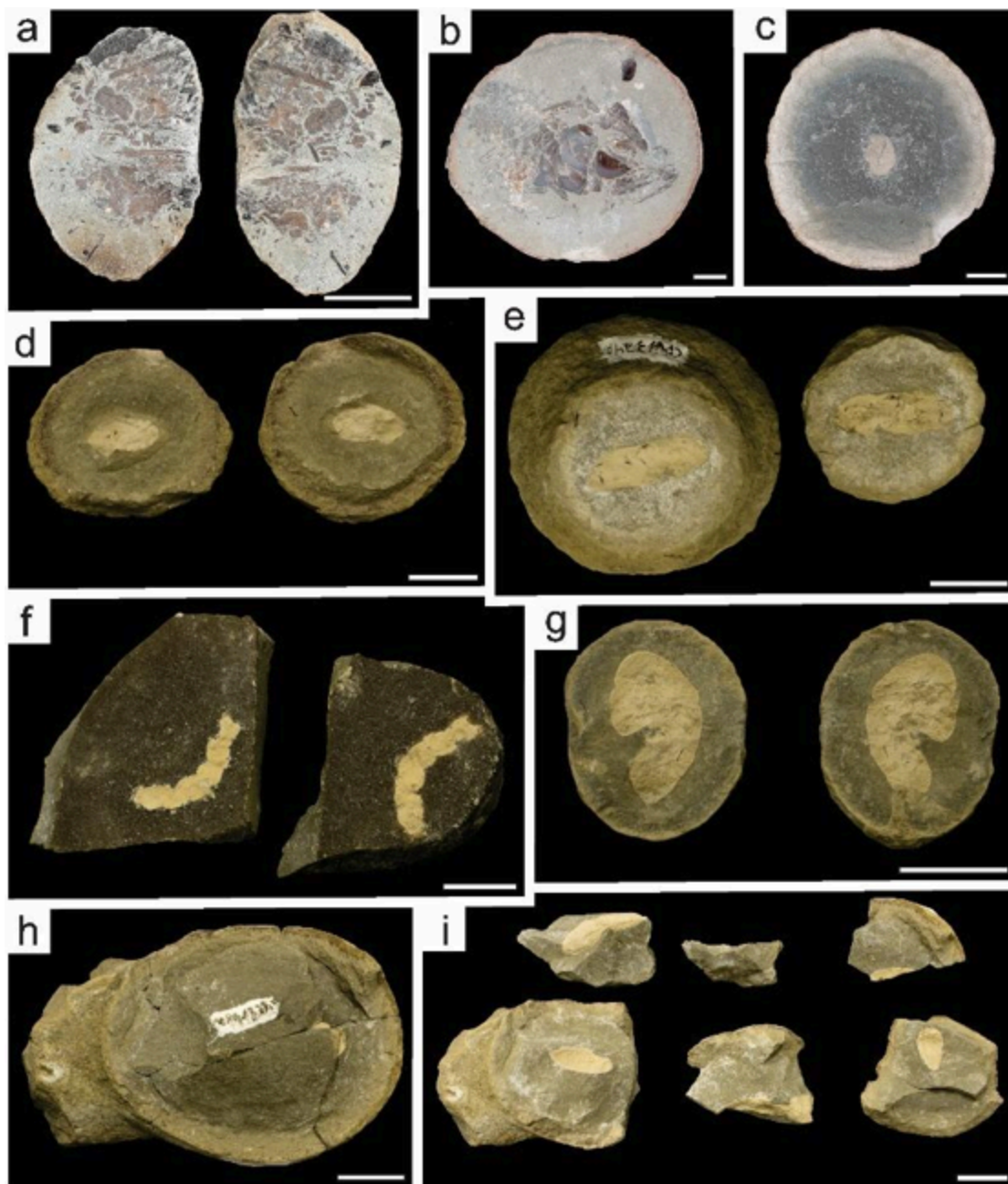


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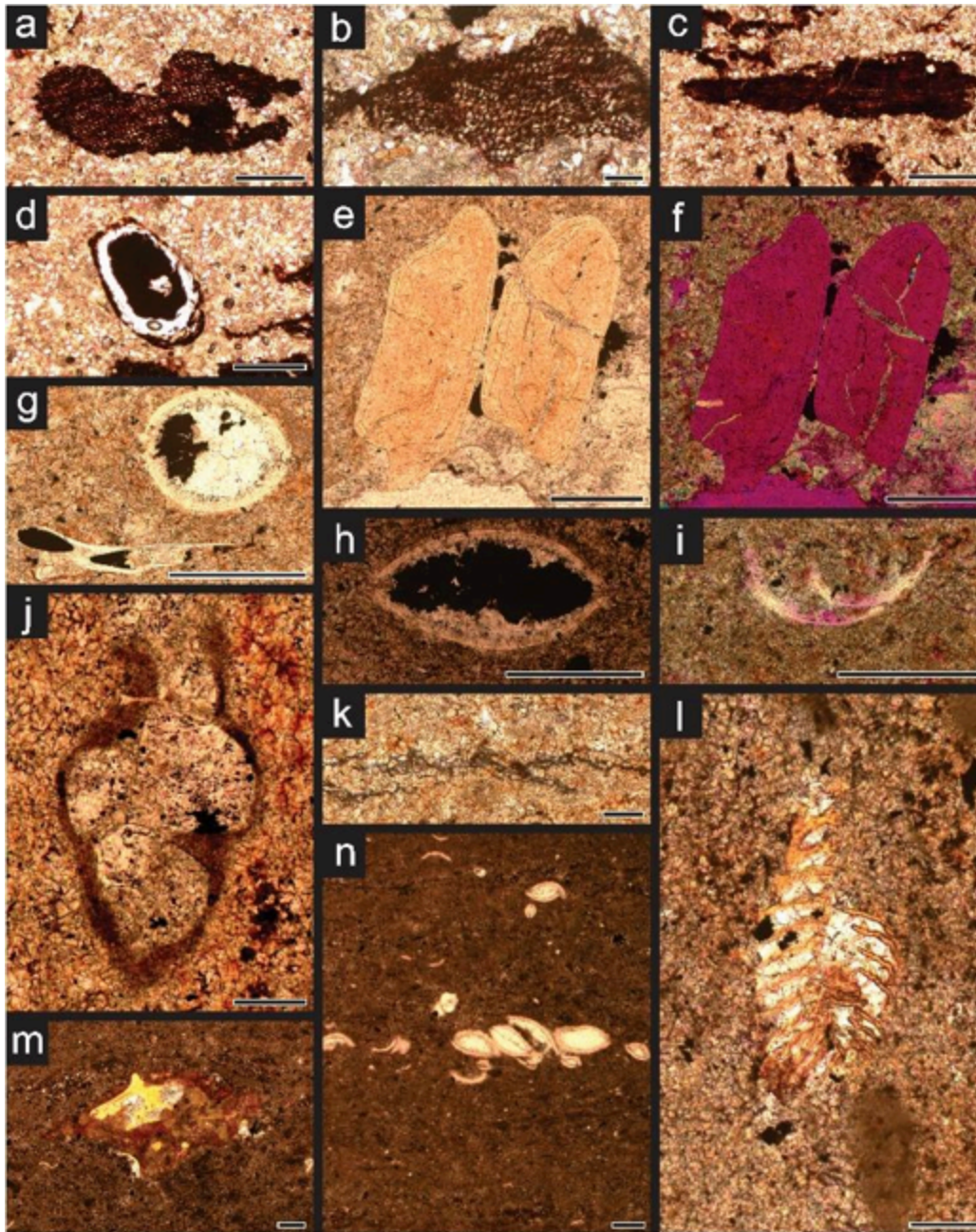


Figure 3

Polarized-light photomicrographs of bioclasts and textural features from samples CP1/921A, CP2/207, and CP6/283. a–c. Structured non-opaque phytoclasts (CP1/921A). d. Ostracode with articulated valves (CP1/921A). e–f. *Rhacolepis* sp. scales in plane-polarized light (e) and between crossed polars with gypsum plate (f) (CP2/207). g. Ostracode with micritized valves filled by calcite crystals and pyrite, with vertebrae (CP2/207). h. Ostracode with micritized valves filled by pyrite crystals (CP2/207). i. Disarticulated and recrystallized ostracode valves (CP2/207). j. Longitudinal section through a miliolid foraminifer with micritized test (CP2/207). k. Microbial mats encasing calcite crystals (CP2/207). l. Longitudinal section through a miliolid foraminifer with micritized test (CP6/283). m. Bone elements enveloped by the phosphatic coprolite mass (CP6/283). n. Articulated ostracodes aligned parallel to lamination (CP6/283). Scale bars: a, c, d, e, f, g, h, i, m, n = 500 µm; b, k = 10 µm; j, l = 100 µm

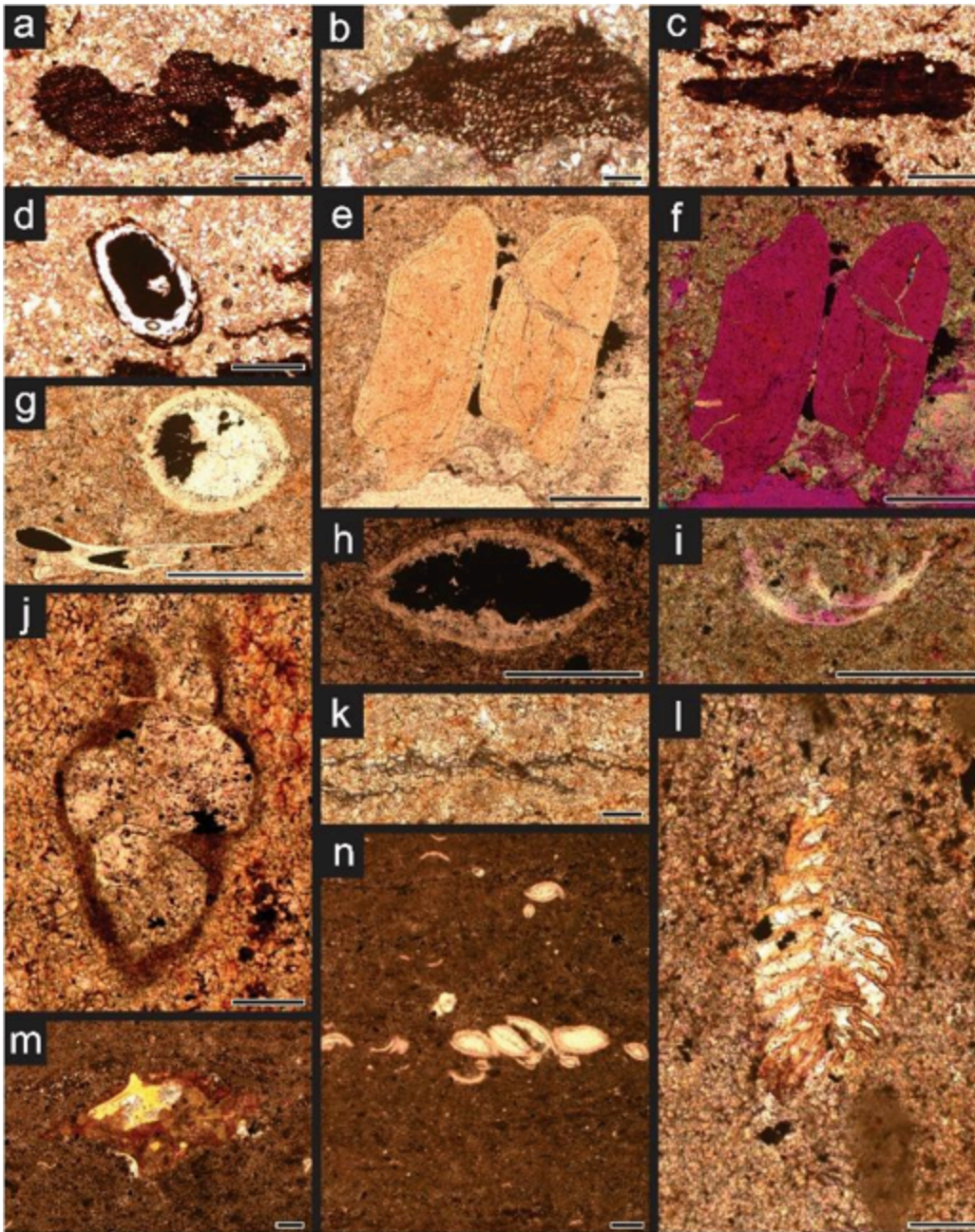


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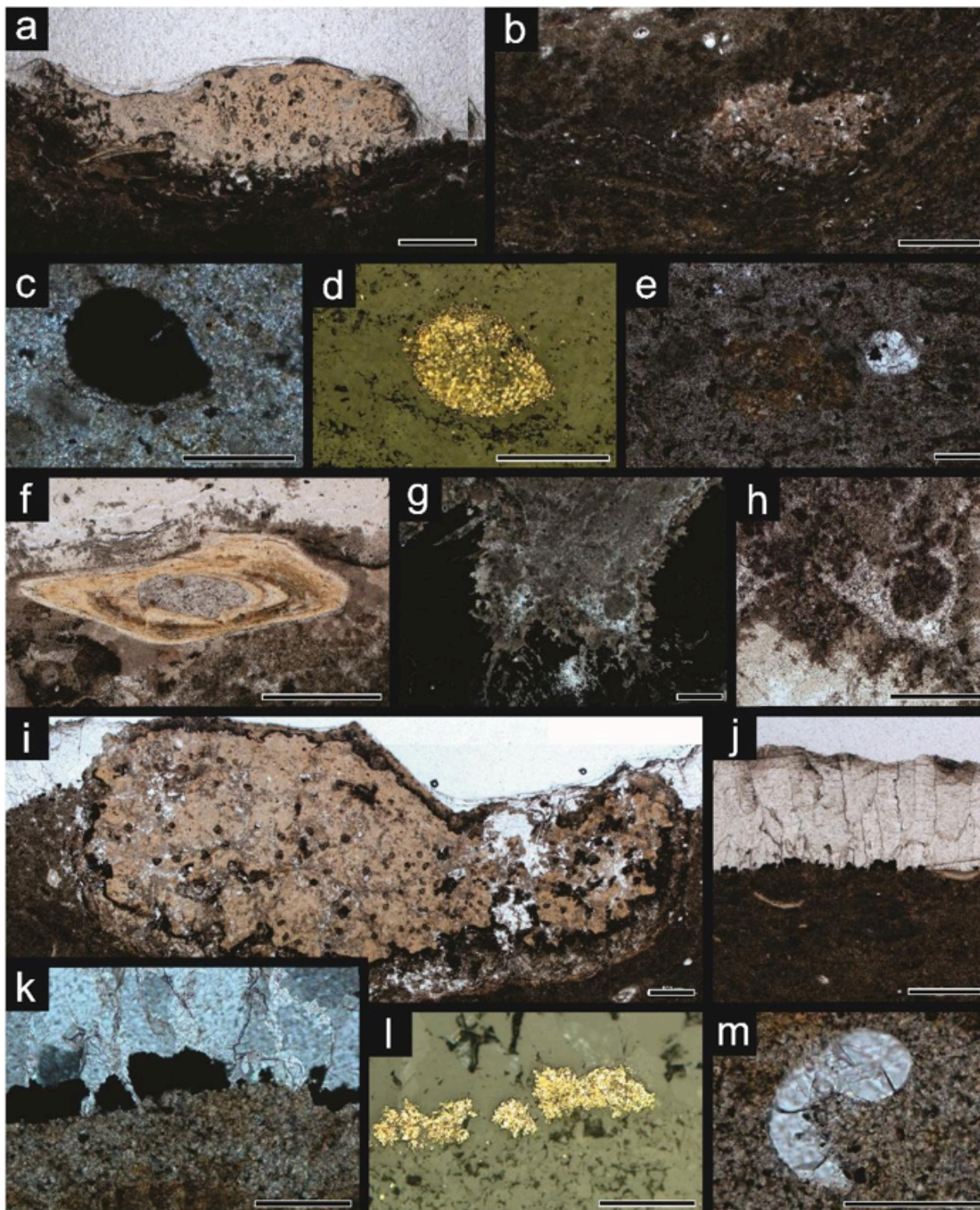


Figure 4

Polarized-light photomicrographs of bioclasts and textural features from samples CP6/323, CP6/324, and CP6/325. a. Transverse section through the central coprolite (CP6/323). b. Phosphatic mass with ostracodes in transverse section and peloids within lamination (CP6/323). c–d. Comparison of a pyrite-filled ostracode in plane-polarized and reflected light (CP6/323). e. Ostracode filled by recrystallized calcite and microbial mat (CP6/323). f. Bone element preserved within the central coprolite (CP6/324).

g–h. Outer margin of the central coprolite showing possible coprophagous traces, filled by peloids (CP6/324). i. Transverse section montage of the central coprolite (CP6/325). j. Calcite crystals near the concretion center (CP6/325). k–l. Pyrite associated with the concretion center in plane-polarized and reflected light (CP6/325). m. Foraminifer test recrystallized by calcite (CP6/325). Scale bars: a, b, f, g, h, i, j = 500 μ m; c, d, e, k, l = 100 μ m

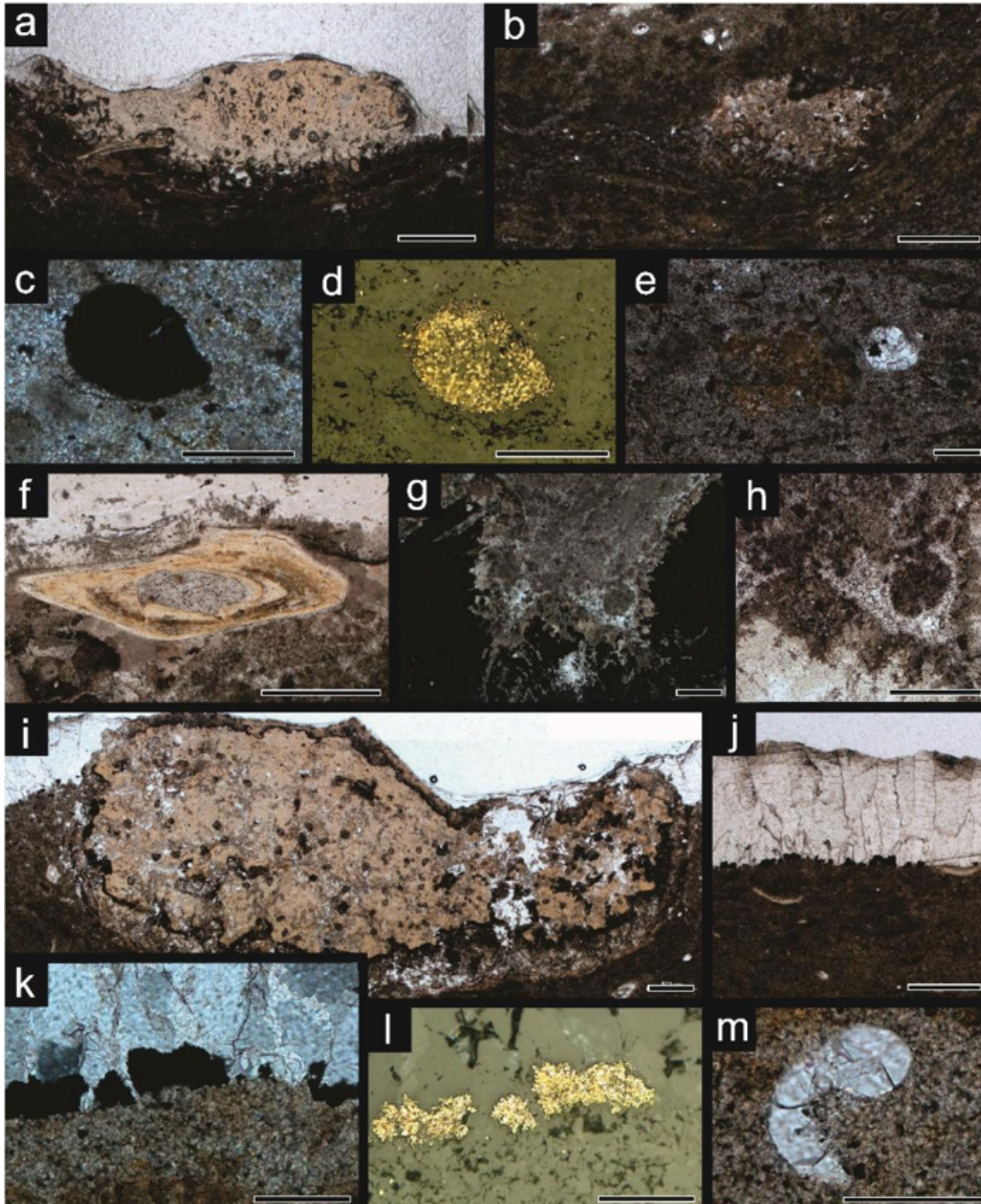


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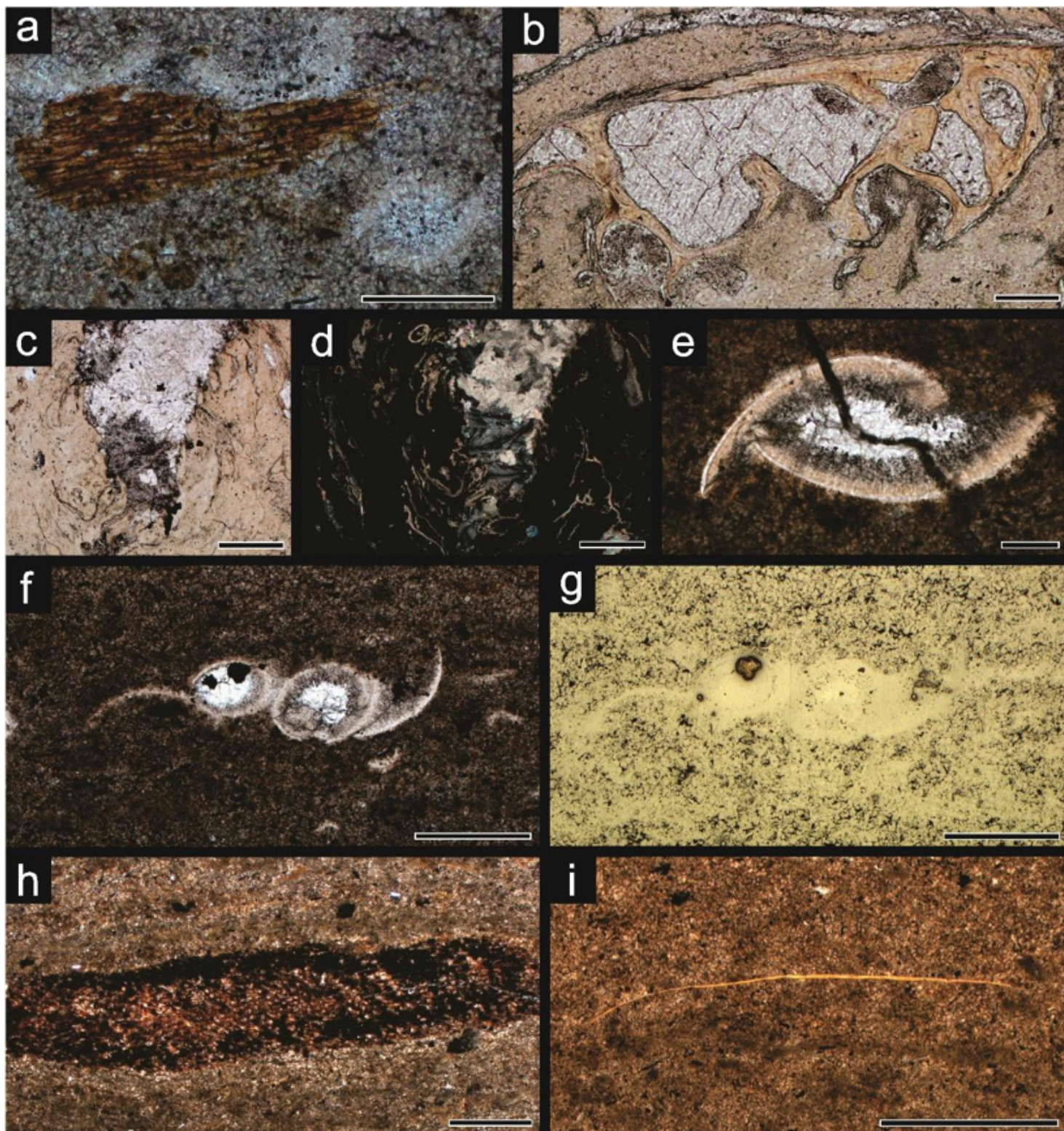


Figure 5

Polarized-light photomicrographs of bioclasts and textural features from samples CP6/325, CP6/326, and CP6/327. a. Structured non-opaque phytoclast and ostracode recrystallized by calcite (CP6/325). b. Bone element within coprolite filled by recrystallized calcite (CP6/326). c–d. Outer margin of the central coprolite showing possible coprophagous traces; d. between crossed polars (CP6/326). e. Ostracode with micritized articulated valves filled by recrystallized calcite, cut by fractures (CP6/327). f–g.

Ostracodes aligned with lamination, filled by calcite and pyrite crystals (CP6/327). h. Structured non-opaque phytoclast (CP6/327). i. Sponge spicule (CP6/327). Scale bars: a, b, d, e = 100 μ m; c, f, g, h, i = 500 μ m

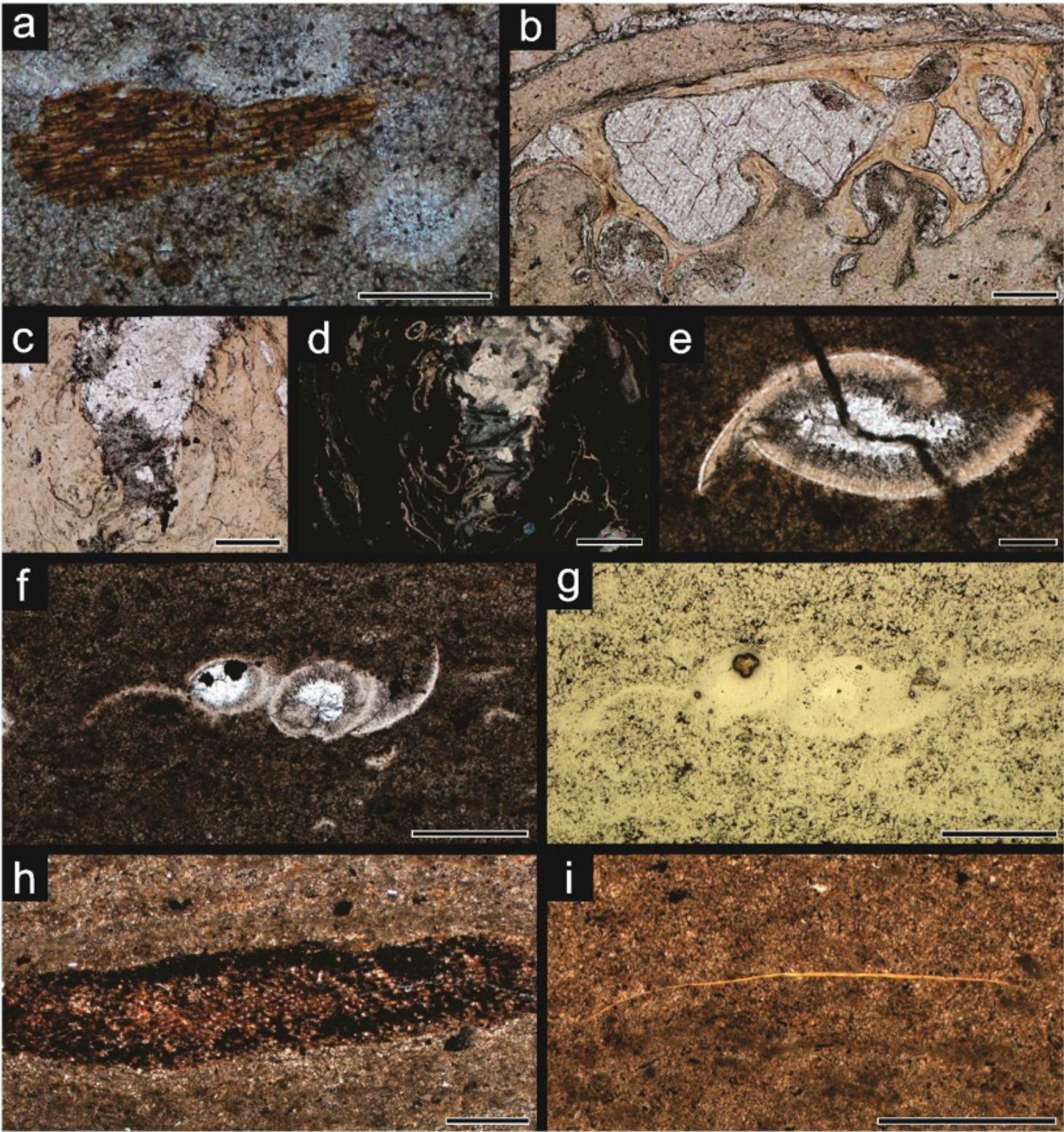


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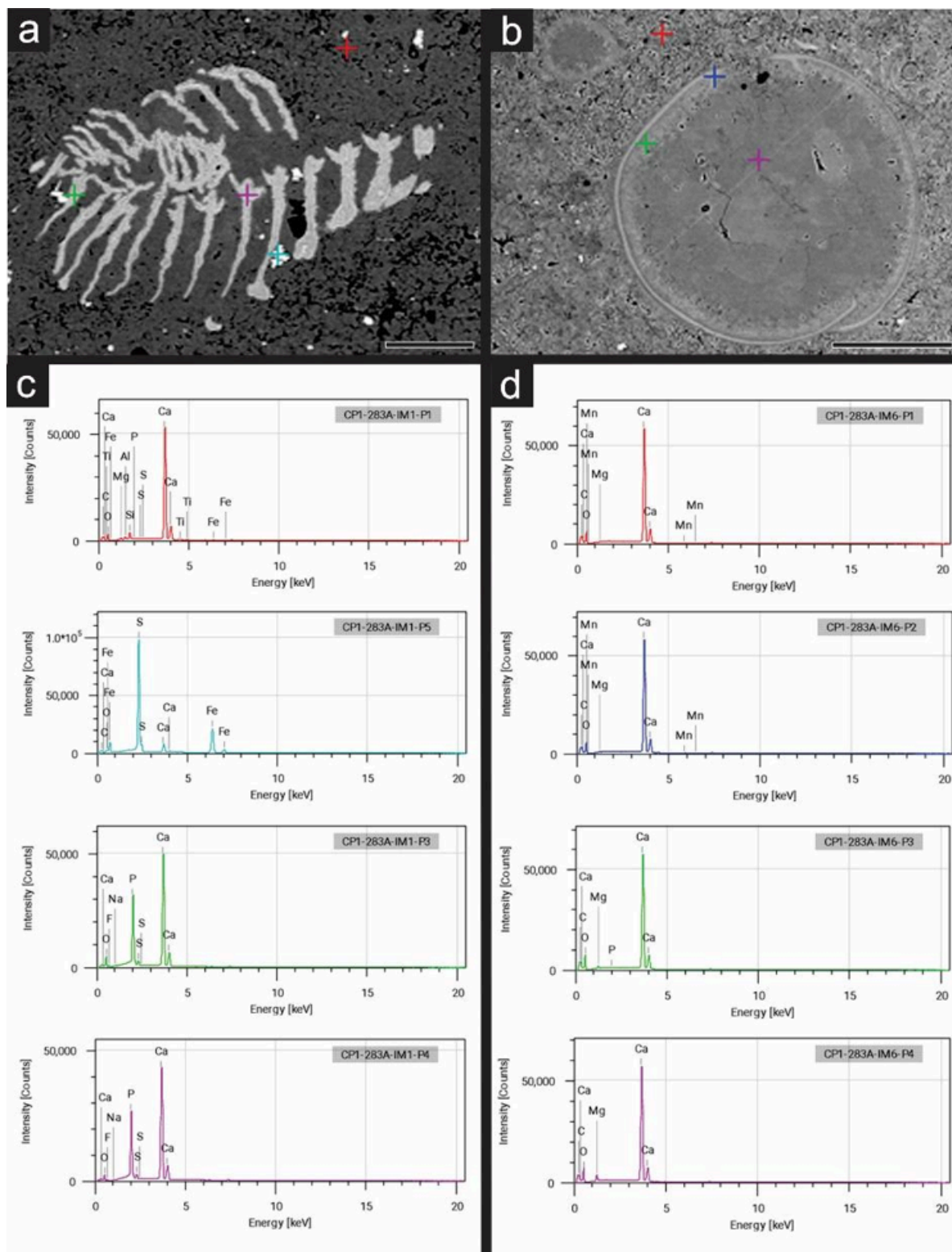


Figure 6

SEM-EDS compositional analysis of the sample CP6/283A. a. Miliolid foraminifer test and matrix. b. Ostracode with articulated valves, valve interior, and concretion matrix. c. EDS spectra for matrix (blue and red) and foraminifer test (green and purple). Crosses in (a) indicate analysis points. d. EDS spectra for matrix (red), valve (green and blue), and ostracode interior (purple). Scale bars: a, b = 100 μ m

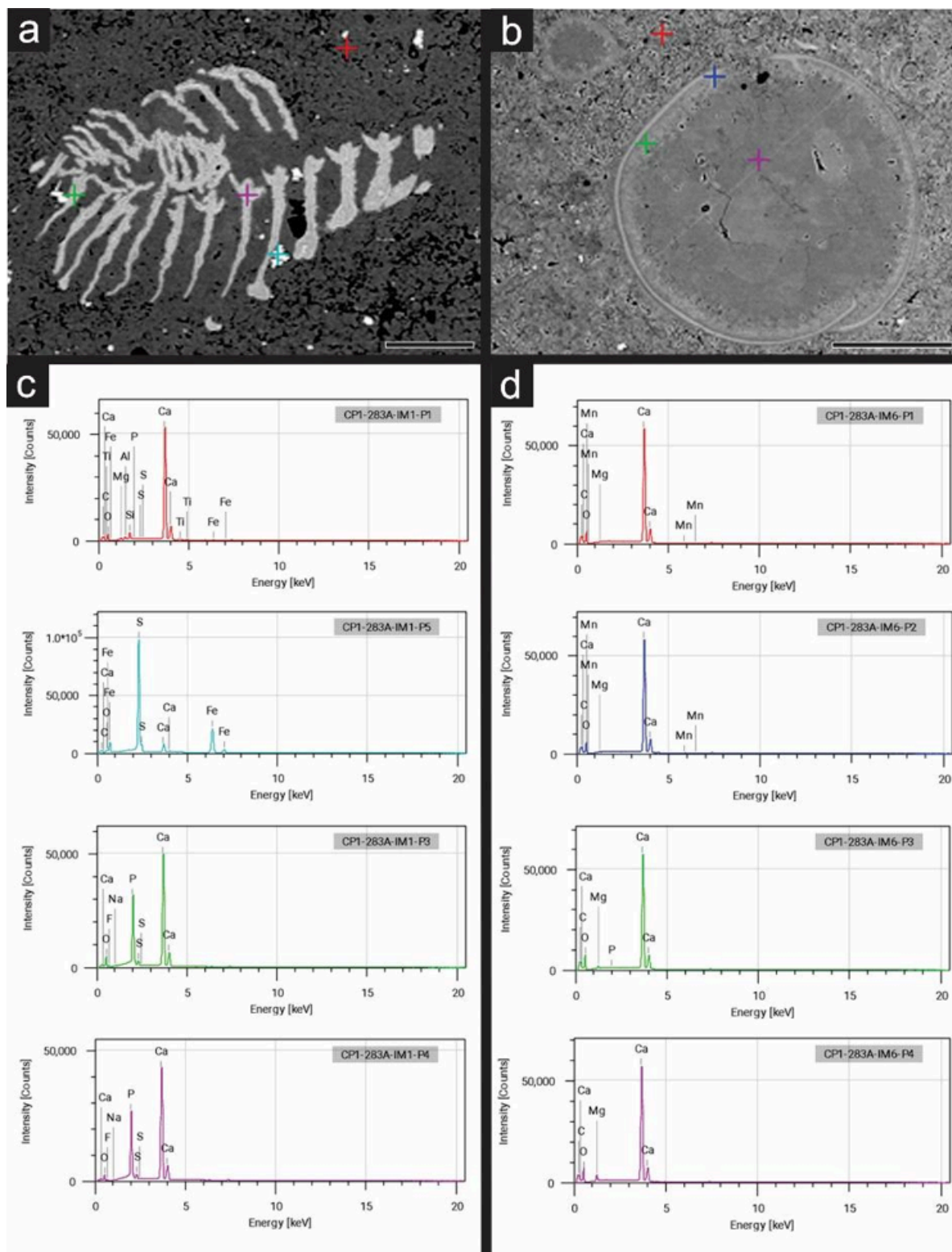


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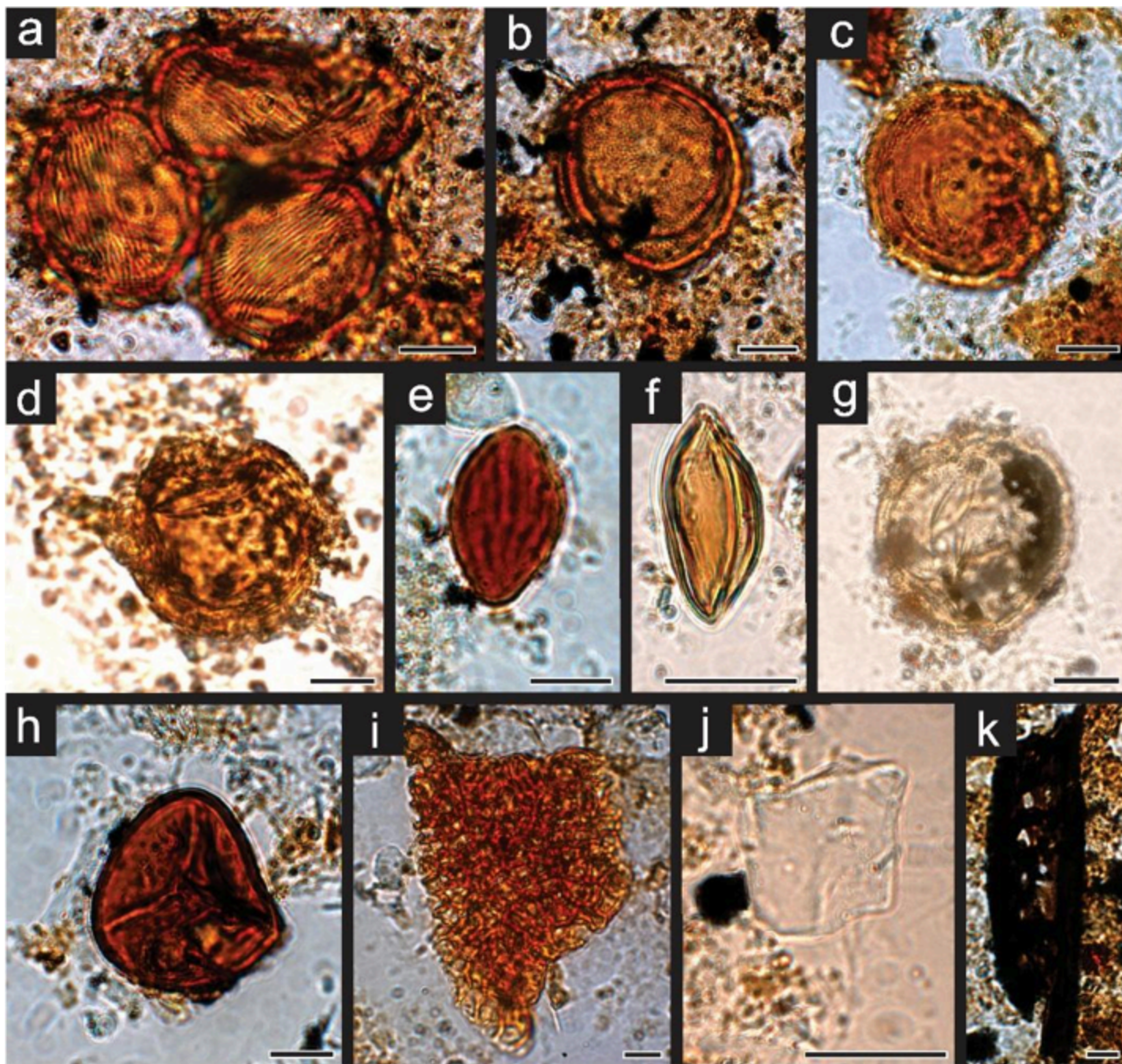


Figure 7

Palynomorphs recovered from concretions CP2/207, CP6/283, and CP6/327. a–c. *Classopollis* sp. (CP2/207 and CP6/327). d. *Leptolepidites* sp. (CP6/283). e–f. *Equisetosporites* sp. (CP2/207). g. *Uesuguipollenites* sp. (CP6/283). h. *Cicatricosisporites* sp. (CP2/207). i. *Botryococcus* sp. (CP6/327). j. Dinoflagellate (CP6/327). k. Structured non-opaque phytoclast (CP6/327). Scale bar = 20 μm

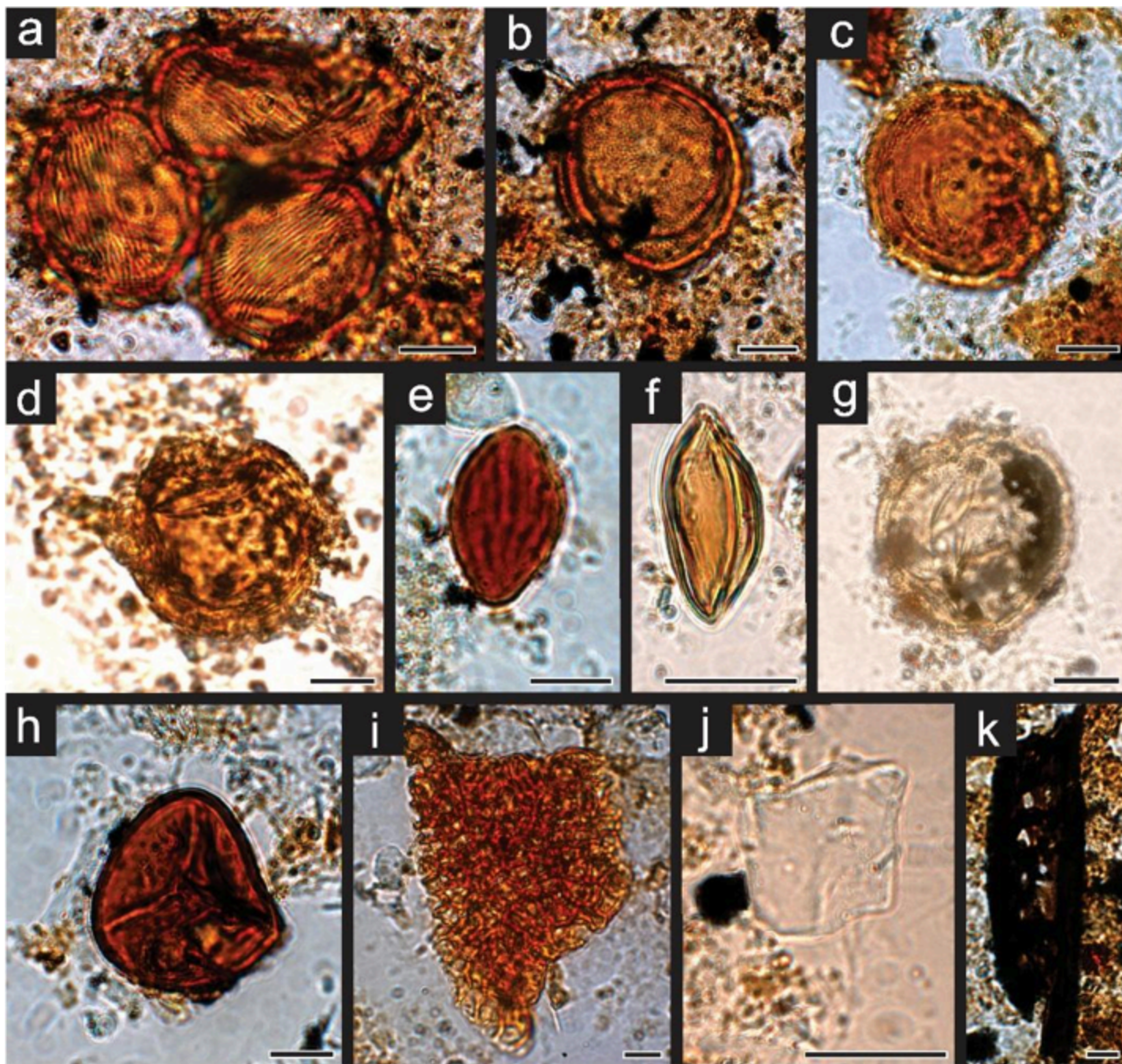


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