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The Ibaté paleolake in SE Brazil: Record of an exceptional late Santonian palynoflora with multiple significance (chronostratigraphy, paleoecology and paleophytogeography)

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A B S T R A C T

The Cretaceous Bauru Group of the Paraná Basin in Brazil is a widespread continental unit well known for its vertebrate and invertebrate fossiliferous content. The São Carlos Formation is an exception among its distinct and dominantly reddish siliciclastic units, which are otherwise devoid of palynomorphs. It includes an unique unit, the Ibaté Bed, which corresponds to the lower interval of the Fazenda Nossa Senhora de Fátima Member (FNSF Mbr) and is represented by a dark grey organic silty-argillaceous rhythmite with a rich palynoflora. These rocks are the main focus of this study. Samples were collected from the type section of the formation that is located in the central area of the São Paulo State. Identified palynomorph types are as follows: 32 pteridophyte spore taxa, 31 gymnosperm pollen taxa and 64 angiosperm pollen taxa. Acritarchs, prasinophytes and phytoclasts were also recognized. Seven new taxa are proposed: *Anacolosidites eosenonicus* sp. nov., *Leiosphaeridia ibateensis* sp. nov., *Stellatia* gen. nov., *Trichomites brevifurcatus* gen. et sp. nov., *Trichomites duplihelicoidus* gen. et sp. nov., *Trichomites simplex* gen. et sp. nov. and *Tricolpites joelcastroi* sp. nov. In quantitative terms, the ephedroid pollen grains — e.g., *Equisetosporites*, *Gnetaceaepollenites* and *Steevesipollenites* — are predominant. Their occurrence associated with *Classopollis* grains suggest a warm climate tending towards dryness. Some levels are relatively rich in pteridophyte spores, suggestive of contribution from lakeside vegetation. The permanent presence of freshwater is attested by conspicuous microalgal remains (*Botryococcus*, *Pediastrum*, *Staurastrum* and prasinophycean phycomata), recognizable via fluorescence microscopy. Significant amounts of microalgal remains in some samples suggest episodic blooms in the lake, probably induced by eutrophication. The Ibaté Bed corresponds to a depositional scenario involving a distal lacustrine environment with low-oxygen conditions in its bottom waters. As observed in offshore Brazilian basins, the presence of *Anacolosidites eosenonicus* sp. nov., combined with the absence of *Steevesipollenites nativensis*, indicates a late Santonian age for the bed (ca. 84 Ma). Other associated index-palynomorphs are compatible with this time assignment, which is reinforced by the presence of carbonized sclereids that are associated with the "Great Santonian Wildfire" recorded in coeval marine offshore strata of the Campos and Santos basins. The FNSF Mbr is stratigraphically related to the uppermost part of the Adamantina and Uberaba formations of the Bauru Group. Among all known Brazilian Late Cretaceous palynological continental records, this is the richest one ever detected. Although Late Cretaceous in age, the composition of the Ibaté Bed palynoflora reflects better the mid Cretaceous ASA Paleophytogeographic Province.

1. Introduction

The São Carlos Formation is a thin Upper Cretaceous unit included in the widespread Cretaceous Bauru Group of the Paraná Basin, Brazil (Castro et al., 2002). This continental group is mostly formed by reddish sedimentary rocks, including sandstones, siltstones and shales. In some units (e.g. Adamantina Formation) it contains an important fossil content comprising vertebrates, invertebrates, ostracods and charophyta girogonites (Dias-Brito et al., 2001). The absence of organic-walled microfossils in these rocks is noteworthy since they are highly susceptible to oxidation. The São Carlos Formation, which contains several levels of dark and fine sediments, occurs in a small part of the central area of the São Paulo

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State, Southeastern Brazil. It crops out in only a few known sites in the vicinity of São Carlos and Ibaté towns, where the type section is localized. It is exposed along a creek situated in the Nossa Senhora de Fátima Farm on the border of the São Carlos and Ibaté municipalities (Fig. 1).

According to Castro et al. (2002), the siliciclastic succession of the São Carlos Formation – around 40 m thick – includes, from the base to the top, three distinct facies: **a**. a marginal lacustrine sandy interval, the "lower sandstone", lying directly on basalts of Serra Geral Formation (Early Cretaceous, ~130 Ma); **b.** a lacustrine argillaceous unit, corresponding to the Fazenda Nossa Senhora de Fátima Member (FNSF Mbr); and **c.** a fluvial sandy interval, the "upper sandstone", abruptly overlying the lacustrine sediments (Fig. 2).

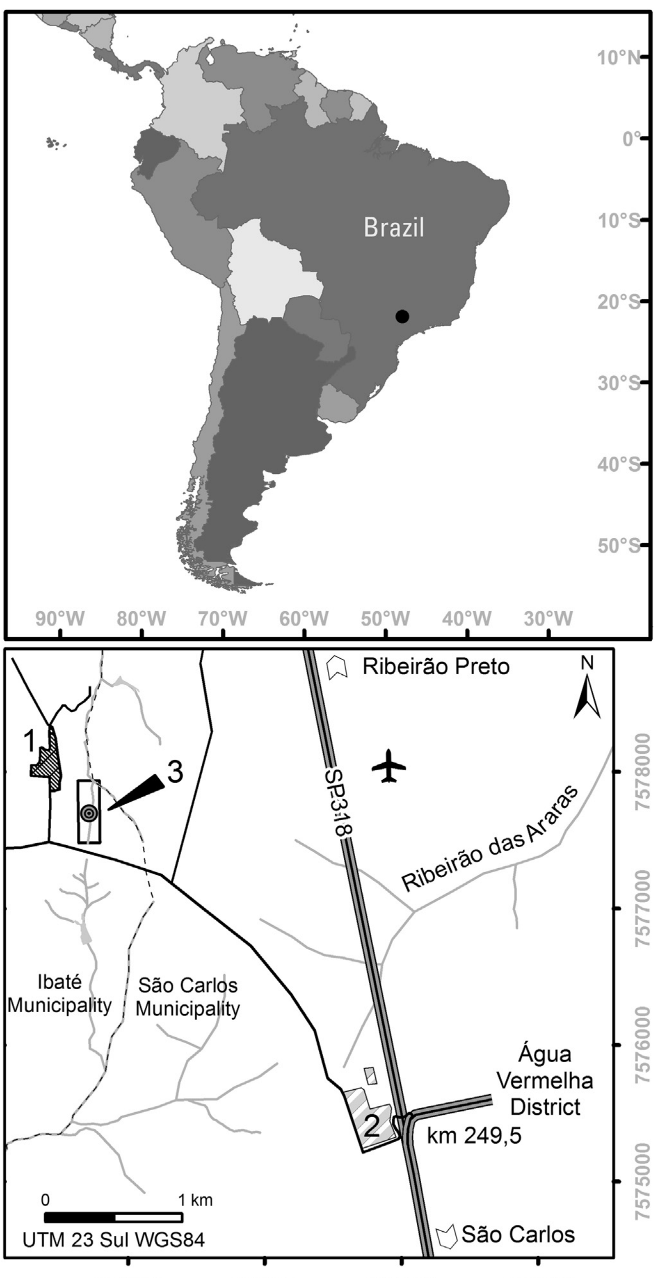

Fig. 1. Outcrop location of the São Carlos Formation type-section. A: geographic position in South America. B: detail of the studied area. 1. Fazenda Nossa Senhora de Fátima Farm headquarters; 2. Factory; 3. Location of the São Carlos Formation type-section.

The lacustrine argillaceous rocks are the focus of this study due to the presence of a rich content of palynomorphs in some levels of the FNSF Mbr, as was previously indicated in Castro et al. (2002). Here we provide an exhaustive documentation of its palynological content, including a list of the recognized palynomorphs, description of new taxa and photomicrographs of the more representative elements of the assemblage. In addition, we discuss its significance in terms of stratigraphic age, paleoenvironment, climate and paleophytogeography.

2. Geological setting

2.1. The FNSF Mbr

Rocks of the FNSF Mbr were initially studied by Mezzalira (1974) and considered as Cretaceous or Cenozoic deposits; they were referred to as including dark brown to dark grey shaly argillaceous siltstones and reddish argillaceous siltstones. The dark shaly siltstones were first investigated from a palynological point of view by Lima et al. (1986) and dated as Coniacian. However, no photomicrographic documentation was provided. These latter authors assigned these rocks to the Cretaceous Bauru Group.

As originally described by Castro et al. (2002), the FNSF Mbr (8.2 m thick), is composed of three argillaceous intervals (Fig. 2). The lower one, FNSF 1 (0.9 m thick), as well as the upper one, FNSF 3 (3.8 m thick), mostly consist of reddish sandy-argillaceous rhythmites, with some rare dark argillaceous laminae. They correspond to more proximal and shallow lake conditions. Between them, FNSF 2 (3.5 m thick) is composed of silty and argillaceous laminae couplets, and roughly corresponds to the interval studied by Lima et al. (1986); it represents deposition in a more central lacustrine area.

2.2. The Ibaté Bed

FNSF 2 contains a significant fossil content, including palynomorphs, ostracods, conchostracans, vertebrate fragments, bivalves, microgastropods, macroscopic plant debris, and fish scales (Mezzalira, 1974, 1989; Lima et al., 1986; Dias-Brito et al., 2001, 2002; Castro et al., 2002; Rohn et al., 2005). Its lower part (1.3 m thick), here named Ibaté Bed, is a dark grey silty-argillaceous rhythmite, richer in organic matter than the 2.2 m thick upper part of this interval, with TOC frequently above 1.0% up to 2.5% (Castro et al., 2002). The Ibaté Bed is the most fossiliferous interval of the FNSF Mbr. It yielded a diverse and rich palynological content, which as discussed below is exceptional in the context of the Bauru Group.

3. Material and methods

The studied material has been sampled from the type section of the São Carlos Formation (UTM 23 7577.6 km, 197.75 km). Among 30 collected samples, 17 of them contain a rich palynological assemblage that constitutes the object of this study (Supplementary Table A). All samples were prepared by standard processing methods of Petrobras' Laboratory (Uesugui, 1979) using hydrochloric and hydrofluoric acids to remove respectively carbonate and silicate mineral components. For each palynological slide, palynomorph content was identified taxonomically and counted for the whole slide using both transmitted light and fluorescence microscopy. Only one slide (SC-14) presented more than 300 specimens. Six slides (UNESP-6, SC-7B, SC-8, SC-10, UNESP-4.1, SC-14) containing more than 100 specimens were chosen to make some quantitative analyses. The optical photomicrographs were taken using a Leica DFC310FX camera coupled with a Leica DM 2500P microscope in laboratory of the UNESPetro (Center for Petroleum Geosciences). Around 30 different taxa derived from two samples presenting

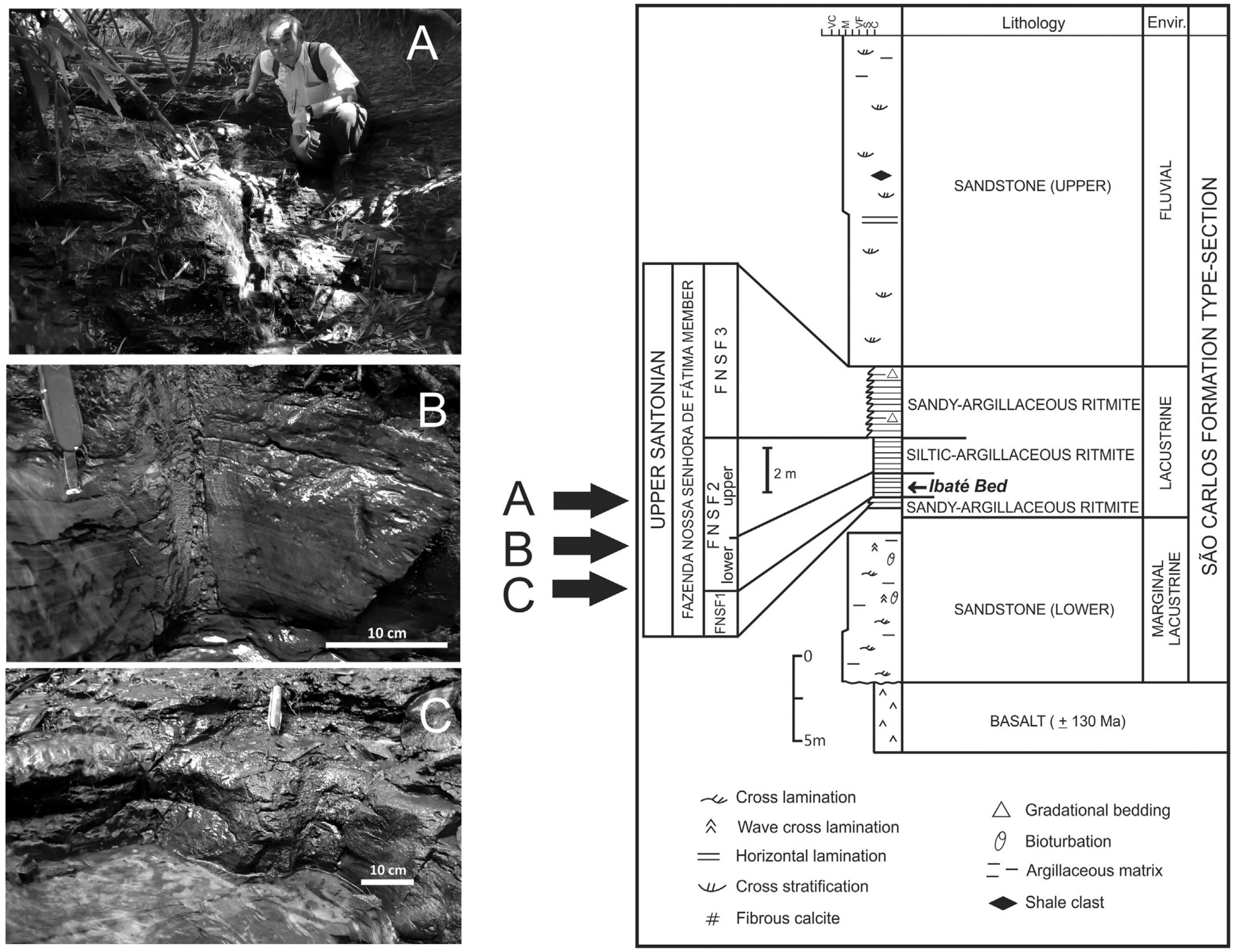

Fig. 2. Schematic lithological log of the São Carlos Formation type-section, with enlargement of the FNSF Mbr/Ibaté Bed. A–C: photos of key levels along the FNSF Mbr. A: sandy/silty-argillaceous rhythmite laying just above the top of the Ibaté Bed. B: organic-rich dark grey silty-argillaceous rhythmite (typical Ibaté Bed lithology). C: grey silty-argillaceous rhythmite at the base of the Ibaté Bed (modified from Castro et al., 2002).

especially well preserved palynomorphs – UNESP-5 and UNESP-6 – were documented by scanning electron microscopy (SEM) at Petrobras Research Center (Rio de Janeiro, Brazil), using the Zeiss EVO 40 apparatus. Additional SEM images for details of *Anacolosidites eosenonicus* and *Tricolpites joelcastroi*, two new pollen species, were obtained with a Zeiss EVO MA15, of the UNESPetro SEM Laboratory. All the palynological slides, including those with the new taxa, are deposited in the UNESP (São Paulo State University) collection, IGCE-UNESPetro, in Rio Claro, Brazil, and are referred to as UNESPλ-BP. For the comparison of the assemblage with those of the distinct phytogeographic provinces, we have chosen papers that bring at least three common species and respective photomicrographs from the worldwide literature.

4. Results

4.1. Palynological content

The assemblages consist of spores (32 taxa), gymnosperm pollen grains (31 taxa), angiosperm pollen grains (64 taxa), microalgal remains (9 taxa), fungal remains (one taxon) and phytoclasts (one seed cuticle type, 11 astrosclereid morphotypes and 3 trichome morphotypes), as illustrated in Figs. 3–14 and listed in the Appendix (in Supplementary material). The quantitative data (absolute counts) of these palynomorphs are given in Supplementary Table A.

Regali et al. (1974a) stated that Brazilian palynofloras were dominated by gymnosperms until the Turonian, and the diversity of angiosperms increased significantly in the interval Coniacian–Santonian. The palynoflora studied here is compatible with that assumption, presenting angiosperm diversity higher than that of gymnosperm, although quantitatively gymnosperm pollen was still dominant.

4.2. Systematic paleontology

Most taxa noted here have already been described in previous publications (see Appendix – in Supplementary material). However, we present 7 new species (two pollen grains, one microphytoplankton element and four phytoclasts). Among the phytoclasts, two new genera are proposed: *Stellatia* (fossil astrosclereids) and *Trichomites* (fossil trichomes).

Pollen [Pollenites, R. Potonié 1931]
Genus *Anacolosidites* Cookson & Pike, 1954, emend. Potonié, 1960
Type species: *Anacolosidites luteoides* Cookson & Pike, 1954

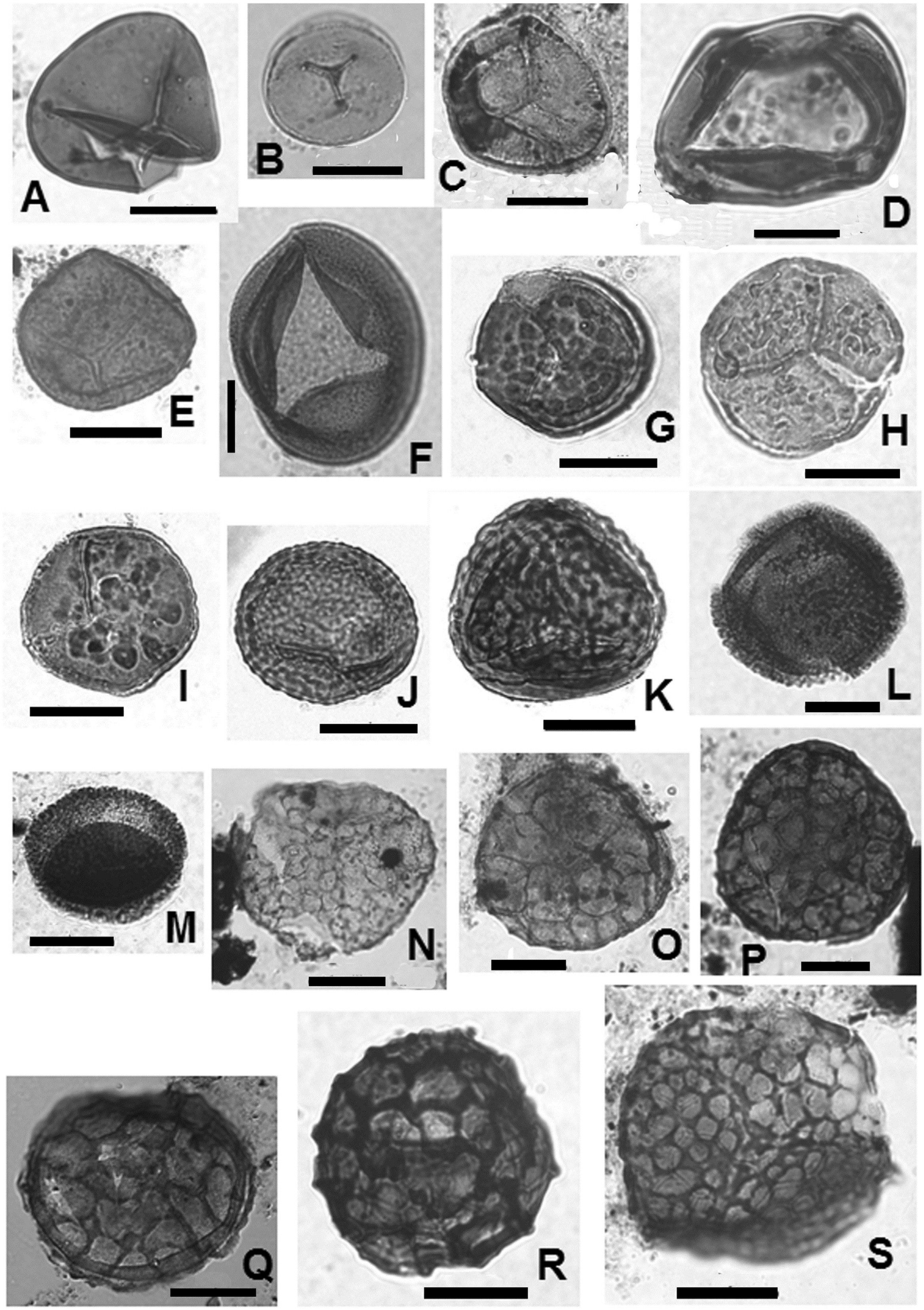

Fig. 3. Pteridophyte spores. A–D: psilate trilete spores. E–S: ornamented trilete spores. G–I: verrucate trilete spores. N–S: reticulate trilete spores. A, *Deltoidospora* sp. Sample UNESP-6; B, *Stereisporites* sp. Sample UNESP-5; C, *Biretisporites* sp. Sample UNESP-6; D, *Cyathidites* sp. Sample UNESP-4.1; E, *Osmundacidites* sp. Sample UNESP-6; F, *Osmundacidites wellmanii*. Sample UNESP-6; G, *Verrucosisporites* sp. 1. Sample SC-14; H, *Interulobites* sp. 1. Sample UNESP-4.1; I, *Interulobites* sp. 2. Sample SC-14; J, *Microreticulatisporites* sp. Sample SC-14; K, *Rugulatisporis caperatus*. Sample SC-8; L, *Gabonisporis vigourouxii*. Sample UNESP-6; M, *Gabonisporis* sp. Sample SC-14; N, *Retitriletes parvireticulatus*. Sample UNESP-4.0; O, *Retitriletes tenuis*. Sample UNESP-6; P, *Retitriletes eminulus*. Sample UNESP-4.1; Q, *Retitriletes* sp. Sample UNESP-6; R, *Retitriletes austroclavatidites*. Sample UNESP-4.1; S, *Klukisporites sphaerogoufus*. Sample UNESP-4.1. Scale bars = 20 μm.

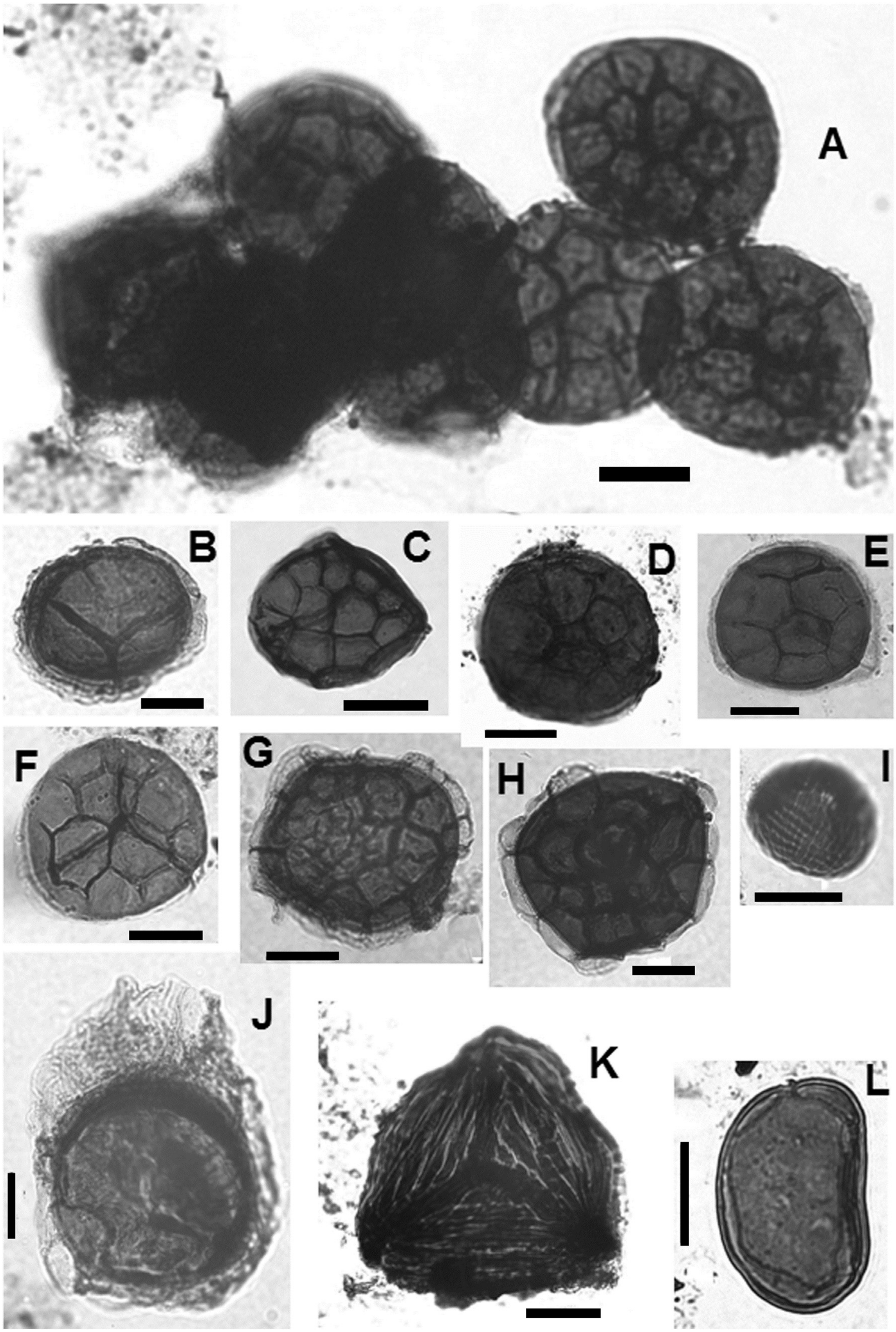

Fig. 4. Pteridophyte spores. A–K: trilete spores. L: monolete spore. A, cluster of *Zlivisporis* sp. Sample UNESP-6. B, *Zlivisporis simplex*. Sample UNESP-4.1; C, *Zlivisporis laevigatus*. Sample UNESP-4.1; D, *Zlivisporis cenomanianus*. Sample UNESP-6; E, *Zlivisporis reticulatus*. Sample UNESP-6; F, *Zlivisporis blanensis*. Sample UNESP-6; G, *Zlivisporis* sp. Sample UNESP-6; H, *Zlivisporis* sp. Sample UNESP-6; I, *Cicatricosisporites* sp. Sample UNESP-6; J, *Balmeisporites* sp. Sample UNESP-6; K, *Plicatella baconica*. Sample SC-8; L, *Laevigatosporites ovatus*. Sample SC-14. Scale bars = 20 μm.

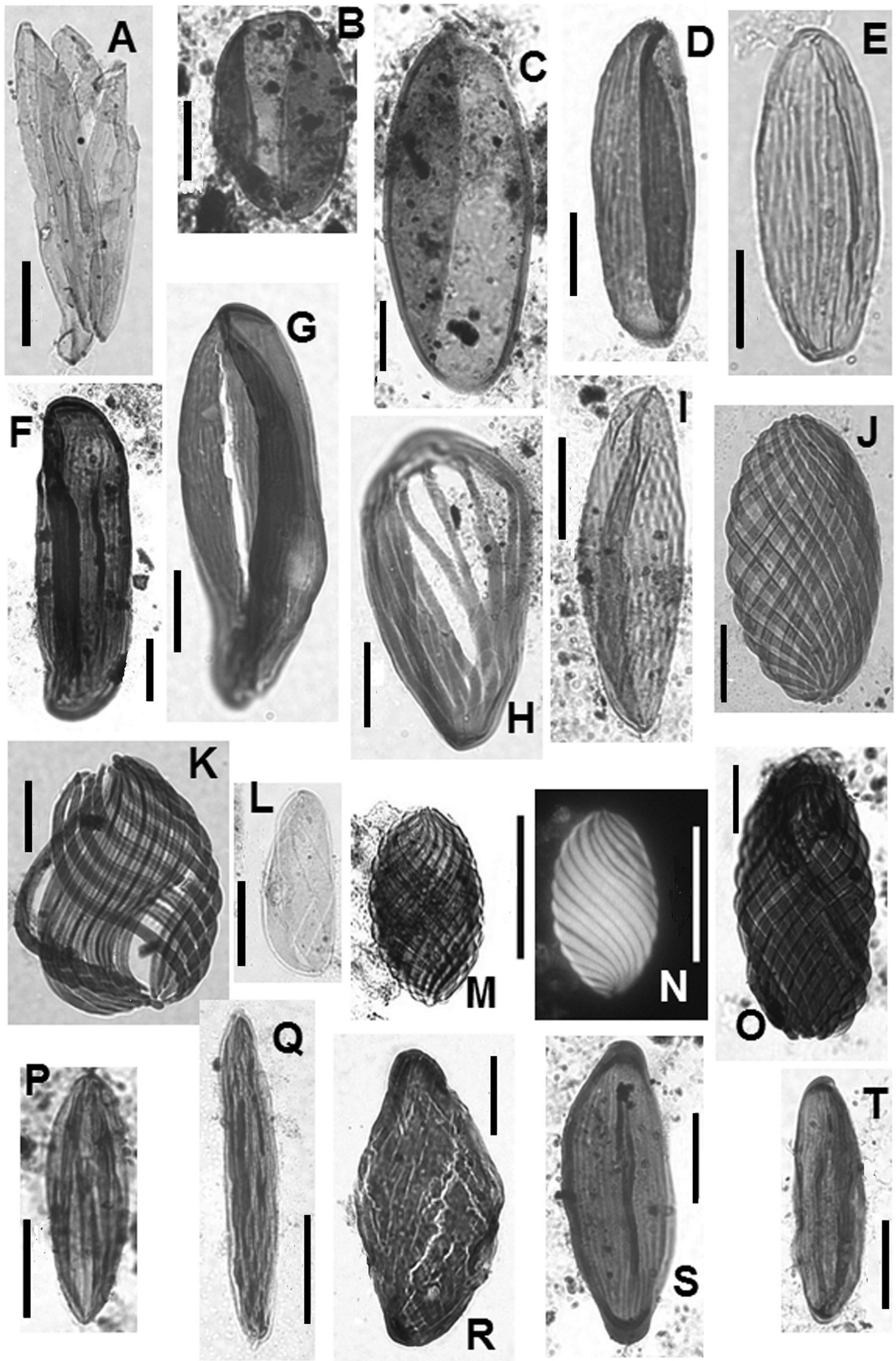

Fig. 5. Gymnosperm pollen grains. A–C: monosulcate pollen. D–T: ephedroid pollen. A – Tetragonal tetrad of *Monosulcites* sp. Sample UNESP-6; B, *Cycadopites fragilis*. Sample UNESP-4.1; C, *Cycadopites carpentieri*. Sample UNESP-4.1; D, *Equisetosporites multicostatus*. Sample UNESP-6; E, *Equisetosporites concinnus*. Sample UNESP-5; F, *Equisetosporites* sp. 1. Sample UNESP-6; G, *Equisetosporites* sp. 2. Sample UNESP-5; H, *Equisetosporites* sp. 3. Sample UNESP-6; I, *Equisetosporites* sp. 4. Sample UNESP-6; J, *Gnetaceaepollenites jansonii*. Sample UNESP-6; K, *Gnetaceaepollenites jansonii*. Sample UNESP-6; L, *Equisetosporites laticostatus*. Sample UNESP-6; M, *Gnetaceaepollenites barghoornii*. Sample SC-8; N, *Gnetaceaepollenites barghoornii*. Same specimen of M, under UV fluorescence; O, *Gnetaceaepollenites barghoornii*. Sample UNESP-6; P, *Singhia* sp. Sample UNESP-6; Q, *Singhia elongata*. Sample UNESP-6; R, *Steevesipollenites* sp. 1. Sample SC-8. S, *Steevesipollenites* sp. 2. Sample UNESP-6. T, *Steevesipollenites* sp. 3. Sample UNESP-4.1. Scale bars = 20 μm (except in M and N having 50 μm).

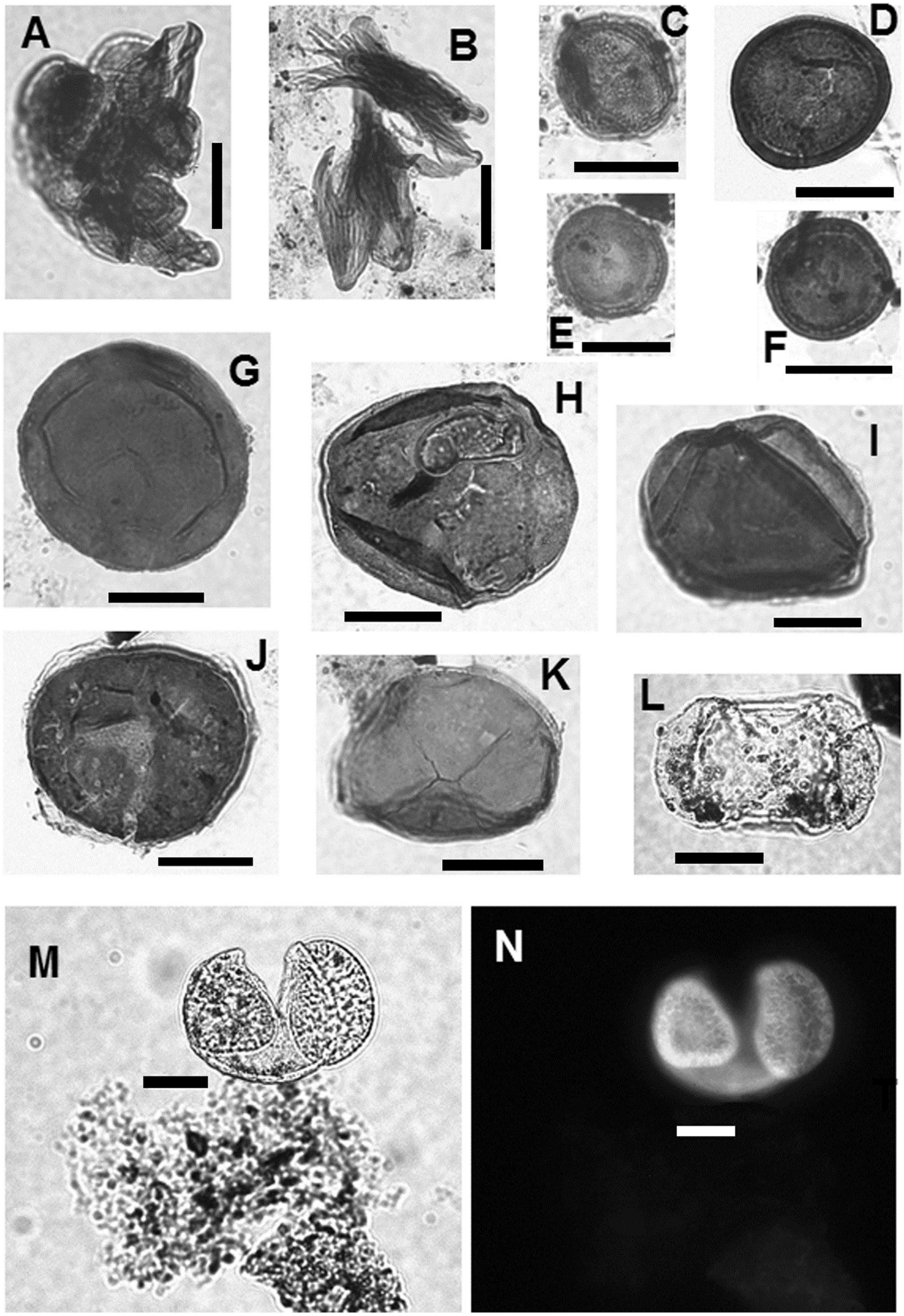

Fig. 6. Gymnosperm pollen. A–B: ephedroid pollen. C–F: *Classopollis*-type pollen. G–K: inaperturate pollen. L–N: bisaccite pollen. A, Cluster of *Equisetosporites* sp. Sample UNESP-4.1; B, Disaggregated tetrad of *Steevesipollenites* sp. Sample UNESP-4.1; C, *Classopollis* sp. Sample UNESP-4.1; D, *Classopollis* sp. Sample SC-14; E, *Classopollis classoides*. Sample UNESP-6; F, *Classopollis* sp. Sample UNESP-4.1; G, *Inaperturopollenites* sp. Sample UNESP-6; H, *Callialasporites* aff. *trilobatus*. Sample SC-14; I, *Callialasporites trilobatus*. Sample UNESP-4.1; J, *Inaperturopollenites simplex*. Sample SC-14; K, *Inaperturopollenites* cf. *simplex*. Sample UNESP-4.0; L, *Rugubivesiculites reductus*. Sample SC-13; M, *Podocarpidites* sp. and amorphous organic matter. Sample SC-8; N, *Podocarpidites* sp. Same microscopic field of M under UV fluorescence. Note that this amorphous organic matter is devoid of fluorescence. Scale bars = 20 μm.

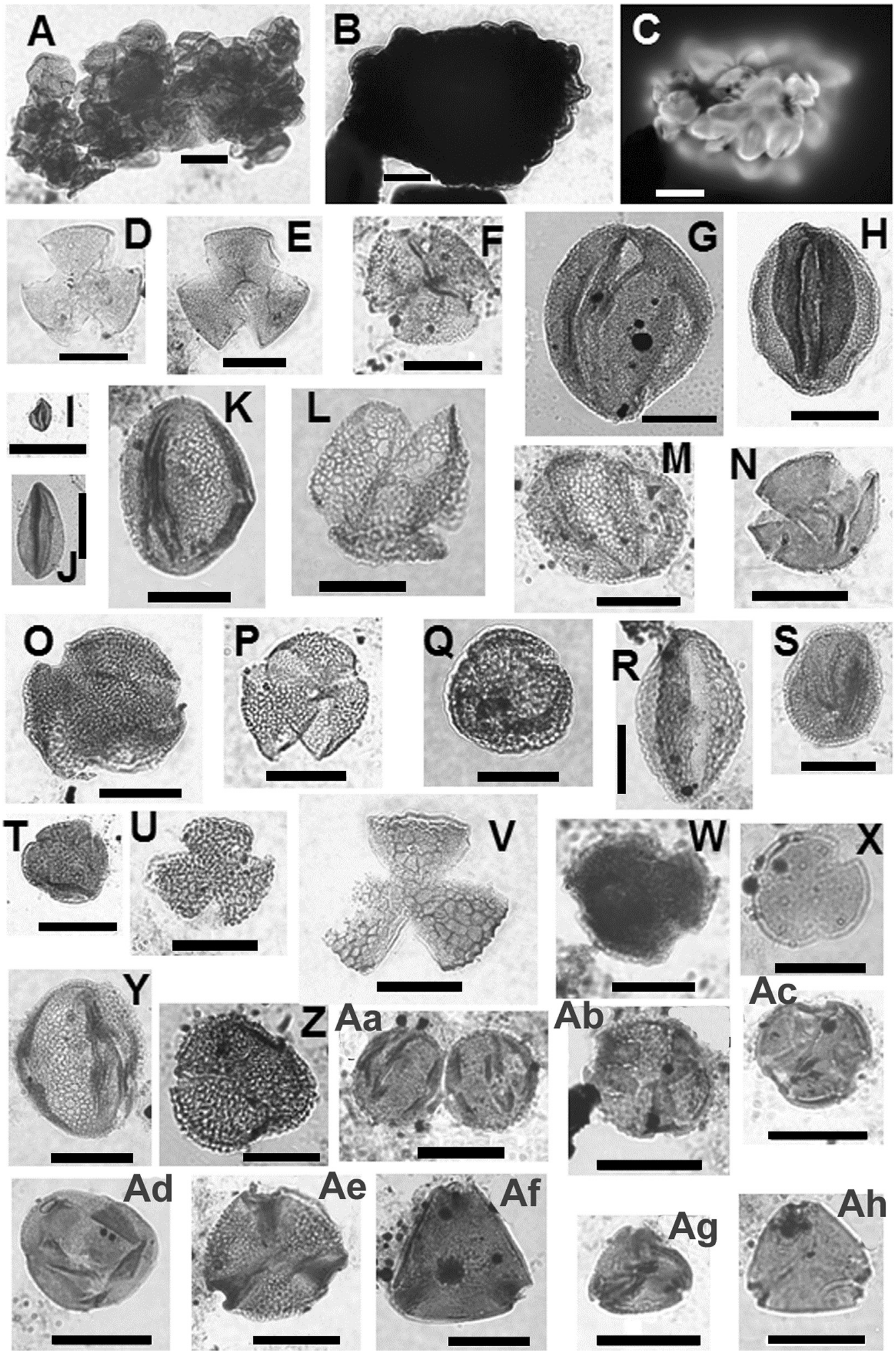

Fig. 7. Angiosperm pollen. A–W: tricolpate pollen grains. X – Z; 1–8: tricolporate pollen grains. A, Cluster of *Tricolpites minutus*. Sample UNESP-6; B, Cluster of *Cupuliferoidaepollenites parvulus*. Sample SC-8; C, Same microscopic field of B under UV fluorescence; D, *Tricolpites sagax*. Sample UNESP-4.1; E, *Tricolpites joelcastroi*. Sample SC-8; F, *Tricolpites vulgaris*. Sample UNESP-4.1; G, *Foveotricolpites gigantoreticulatus*. Sample UNESP-6; H, *Foveotricolpites tienabaensis*. Sample SC-14; I, *Tricolpites* sp. Sample SC-14; J, *Faxinoipollenites* sp. Sample UNESP-6; K, *Rhoipites* sp. Sample UNESP-5; L, *Satishia nigra*. Sample UNESP-6; M, *Retitricolpites virgeus*. Sample UNESP-4.1; N, *Baculatitricolpites manifestus*. Sample SC-14; O, *Foveotricolpites giganteus*. Sample SC-14; P, *Retitricolpites gageonnetti*. Sample SC-14; Q, *Hammenia triangula*. Sample SC-8; R, *Rousea patagonica*. Sample UNESP-6; S, *Retitrescolpites saturnum*. Sample UNESP-4.1; T, *Hammenia fredericksburgensis*. Sample SC-14; U, *Albertipollenites angululuminosus*. Sample SC-14; V, *Albertipollenites* sp. Sample SC-14; W, *Tricolpites foveolatus*. Sample UNESP-6; X, *Nyssapollenites squamosus*. Sample UNESP-6; Y, *Retitricolporites* sp. Sample UNESP-6; Z, *Retitricolporites salardii*. Sample UNESP-6; Aa, *Tricolporopollenites foveotectatus*. Sample UNESP-6; Ab, *Retitricolporites fekelensis*. Sample UNESP-5; Ac, *Tricolporopollenites micromurus*. Sample UNESP-6; Ad, *Tricolporopollenites subobscurus*. Sample UNESP-6; Ae, *Margocolporites mandjicus*. Sample UNESP-4.1; Af, *Tricolporopollenites* sp. Sample UNESP-4.1; Ag, *Tricolporopollenites aliquantulus*. Sample UNESP-4.1; Ah, *Sohlipollis* sp. Sample UNESP-4.1. Scale bars = 20 μm.

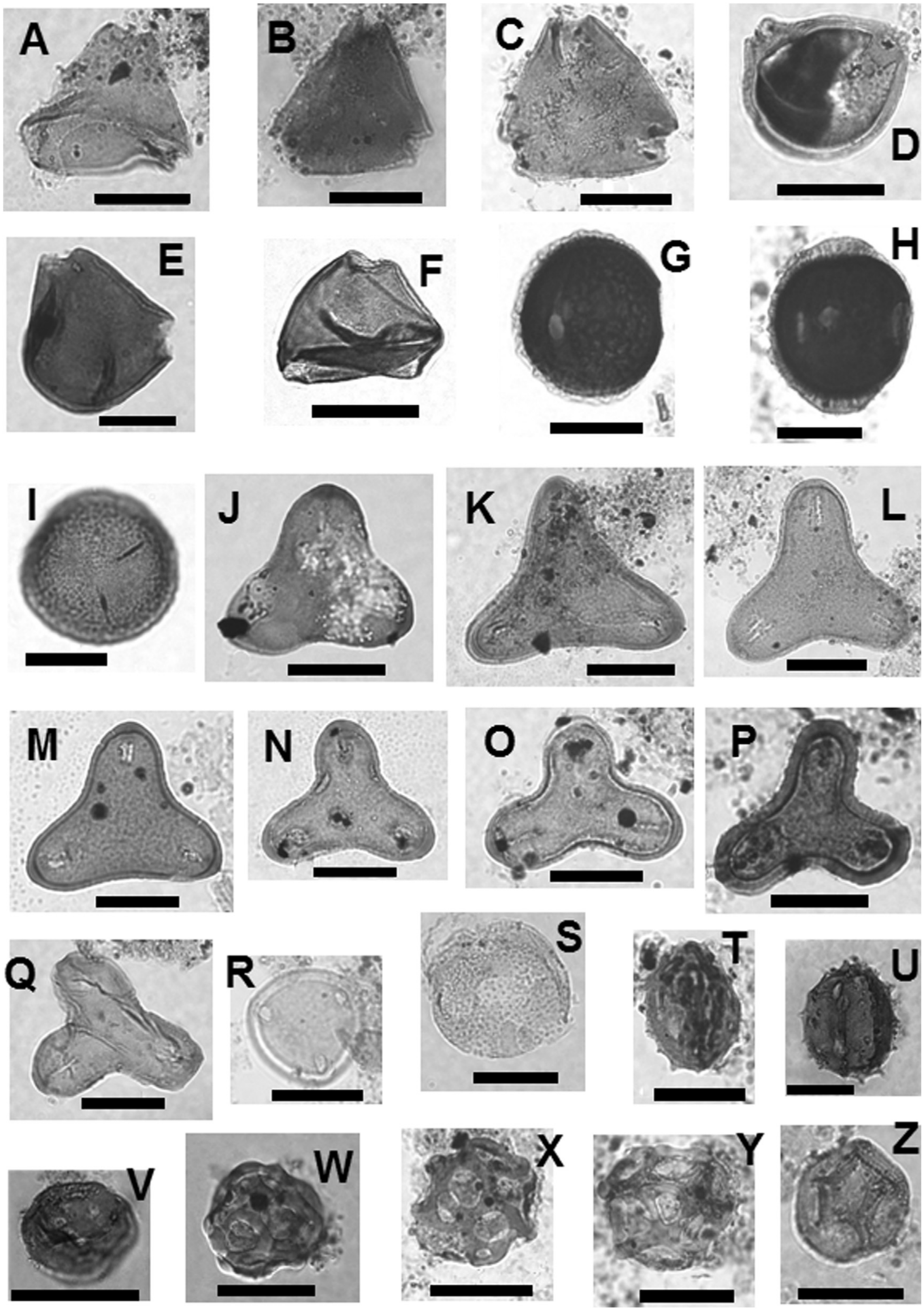

Fig. 8. Angiosperm pollen. A – C; G–H: tricolporate pollen grains. D – F; I–R: pollen grains belonging to group *Victorisporis*/*Anacolosidites*. S–Z: pollen grains with other aperture types. A, *Tricolporopollenites* sp. Sample UNESP-4.0; B, *Lewalanipollis* cf. *senectus*. Sample UNESP-6; C, *Holkopollenites chemardensis*. Sample UNESP-4.1; D, *Trudopollis* sp. Sample UNESP-4.0; E, *Victorisporis* sp. Sample UNESP-4.1; F, *Lewalanipollis senectus*. Sample SC-14; G, *Retitricolporites belmontensis*. Sample UNESP-6; H, *Retitricolporites belmontensis*. Sample UNESP-6; I, *Constantinisporis jacquei*. Sample UNESP-4.1; J, *Anacolosidites* sp. Sample UNESP-4.1; K, *Anacolosidites eosenonicus*. Sample UNESP-6; L, *Anacolosidites eosenonicus*. Paratype. Sample UNESP-5; M, *Anacolosidites eosenonicus*. Holotype. Sample UNESP-6; N, *Anacolosidites eosenonicus*. Sample UNESP-6; O, *Anacolosidites eosenonicus*. Sample UNESP-4.1; P, *Anacolosidites eosenonicus*. Sample UNESP-6; Q, *Anacolosidites eosenonicus*. Sample UNESP-4.0; R, *Victorisporis robertii*. Sample UNESP-4.0; S, *Cretacaeiporites scabratus*. Sample UNESP-5; T, *Hexaporotricolpites emelianovi*. Sample UNESP-4.1; U, *Hexaporotricolpites emelianovi*. Sample UNESP-4; V, *Psilaperiporites* sp. Sample UNESP-6; W, *Confossia vulgaris*. Sample UNESP-4.1; X, *Confossia vulgaris*. Sample UNESP-4.1; Y, *Confossia vulgaris*. Sample UNESP-6; Z, *Cretacaeiporites polygonalis*. Sample UNESP-6; Scale bars = 20 μm.

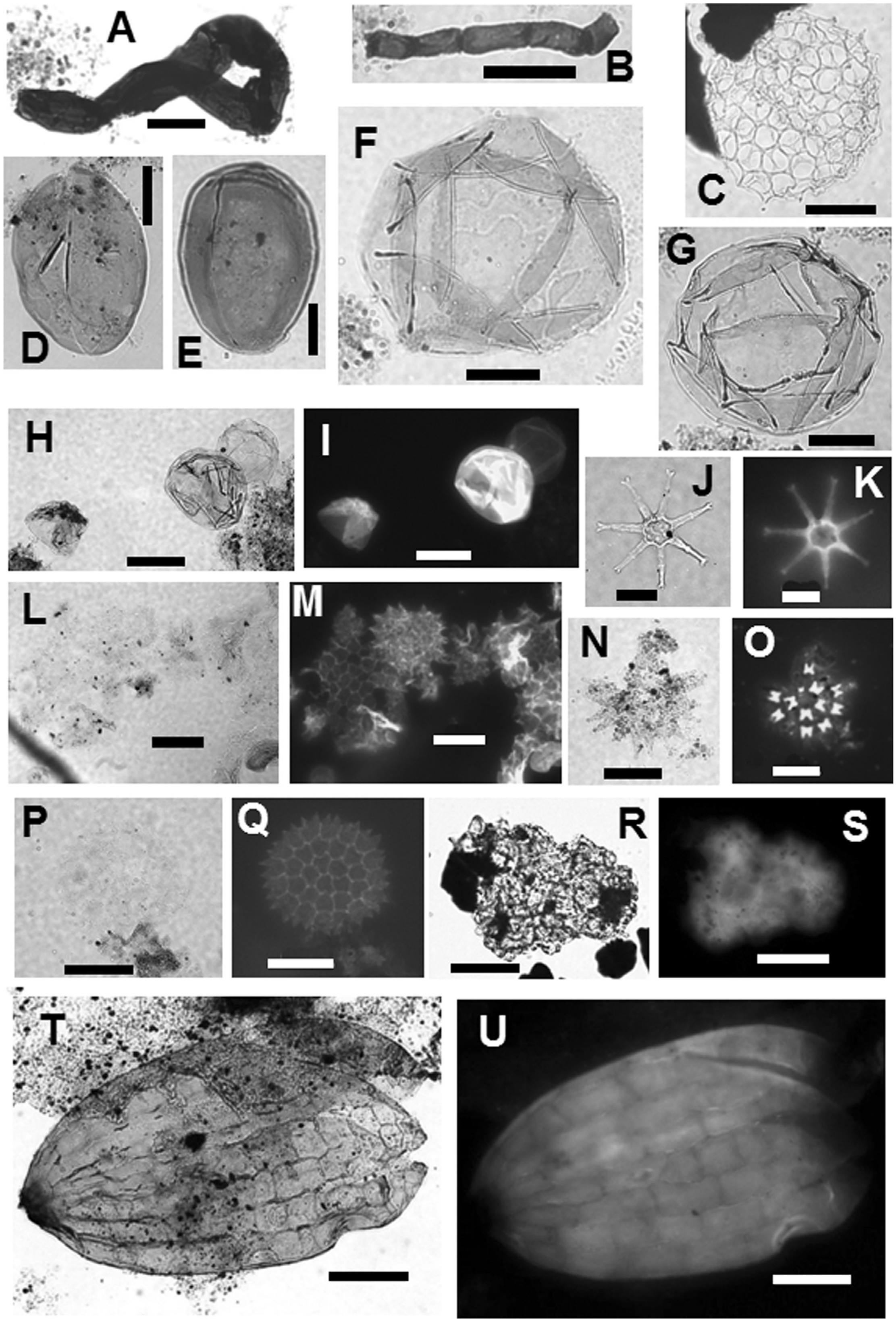

Fig. 9. Miscellaneous. A–B: fungal remains. C: *Incertae sedis*. D–S: algal remains. T–U: seed remain. A, Fungal remain (hyphae). Sample UNESP-4.1; B, Fungal remain (hyphae). Sample UNESP-6; C, *Schizosporis* aff. *reticulatus*. Sample UNESP-4.1; D, *Brazilea parva*. Sample UNESP-6; E, *Brazilea parva*. Sample UNESP-4.1; F, *Leiosphaeridia ibateensis*. Sample UNESP-5; G, *Leiosphaeridia ibateensis*. Sample UNESP-5; H, Microscopic field with 3 specimens of *L. ibateensis*. Sample SC-8; I, Same field of H under UV fluorescence; J, *Staurastrum* sp. Sample SC-11; K, Same field of J under UV fluorescence; L, Microscopic field with *Pediastrum* spp. Sample SC-14; M, Same field of L under UV fluorescence; N, *Pediastrum* aff. *mustersii*. Sample SC-13; O, same specimen of N under UV fluorescence; P, *Pediastrum boryanum*. Sample UNESP-4.0; Q, Same specimen of P under UV fluorescence; R, *Botryococcus* sp. Sample SC-15; S, Same specimen of R under UV fluorescence; T, *Spermatites* sp. Sample SC-7A; U, Same specimen of T under UV fluorescence. Scale bars = 20 μm (except in H, I, L, M, P, Q, R, S, T and U having 50 μm).

Generic description: besides the original diagnosis (Cookson & Pike, 1954) and the emended diagnosis (Potonié, 1960), we adopted the description for *Anacolosidites* proposed by Malécot & Lobreau-Callen (2005, p. 318) because of its more complete characterization.

Anacolosidites eosenonicus sp. nov.
Figs. 8K–Q and 14C–F

1977 Cf. *Accuratipollis* sp. *in* Ioannides & Colin, plate 4, figures 20–21 (p. 897).
2002 *Anacolosidites*? sp. A *in* Castro et al. (p. 356).
2006 Cf. *Anacolosidites* sp. *in* Arai et al., figure 2C (p. 128).
2016 *Anacolosidites* sp. A *in* Premaor, figure II.5S (v. 2, p. 14).

Holotype: Slide UNESP-6, C49 (Fig. 8M).
Paratype: Slide UNESP-5, C44/3 (Fig. 8L).
Type locality: Fazenda Nossa Senhora de Fátima (Ibaté municipality, São Paulo State, Brazil. UTM 23 7577.6 km, 197.75 km).
Type stratum: São Carlos Formation, FNSF Mbr, Ibaté Bed, upper Santonian.
Description: Isopolar pollen with radial symmetry; pollen outline triquete (strongly triangular concave) in polar view and peroblate in equatorial view; grain hexaporate (tri-diporate) with three pairs of elongate pores parallel to radius, located near the equator (about 1/6 of the equatorial diameter in from the perimeter of the grain); exine thickness normally uniform, but sometimes convex parts can present slightly thicker exine; ornamentation psilate to scabrate under the optical microscope, but observations under SEM reveal that it is characterized by tightly packed granules (see Fig. 14C–F).
Dimensions: holotype – total diameter = 47 μm; paratype – total diameter = 46 μm; diameter range = 32 (37) 47 μm (24 specimens); size of granules = 0.6–0.9 μm; exine thickness = 2–3 μm.
Derivation of name: from “Eosenonian” (early Senonian) that corresponds approximately to the interval Coniacian–Santonian that is the stratigraphic range of this species.
Remarks: *Anacolosidites eosenonicus* must be the oldest *Anacolosidites* species reported worldwide. Among the species mentioned in the inventory by Malécot & Lobreau-Callen (2005), *Anacolosidites striatus* Wiggins, reported from the Campanian of Alaska, was the oldest one. All other *Anacolosidites* species occur in the Maastrichtian–Neogene interval.
Comparison: *A. striatus* and *A. eosenonicus* are only two known *Anacolosidites* species having strongly triangular concave outline. *A. striatus* differs from *A. eosenonicus* in having a distinct striate ornamentation.
Botanical affinity: possibly Loranthaceae, because *Anacolosidites striatus* that is morphologically the closest species of *A. eosenonicus* was considered as possible Loranthaceae by Malécot & Lobreau-Callen (2005).

Genus *Tricolpites* Cookson, 1947 ex Couper, 1953
Type species: *Tricolpites reticulatus* Cookson, 1947 ex Couper, 1953

Tricolpites joelcastroi sp. nov.
Figs. 7E, 13H–L

Holotype: Slide SC-8, Q57 (Fig. 7E).
Type locality: Fazenda Nossa Senhora de Fátima (Ibaté municipality, São Paulo State, Brazil. UTM 23 7577.6 km, 197.75 km).
Type stratum: São Carlos Formation, FNSF Mbr, Ibaté Bed, upper Santonian.
Description: Isopolar tricolpate pollen with radial symmetry; amb subtriangular in polar view and oblate to prolate spheroidal in e-
q-
uatorial view; three conspicuous colpi; exine thickness uniform; ornamentation scabrate seen under SEM to be granulate with granules distributed uniformly (Fig. 13I, K).
Dimensions: holotype – total diameter = 44 μm; granule diameter = 0.2–0.5 μm; total diameter range = 19 (26) 44 μm (10 specimens); exine thickness = 0.5–1.0 μm; density of granule = 4–6 granules per one square micrometer.
Derivation of name: in honour to Joel Carneiro de Castro, recognized Brazilian sedimentologist and stratigrapher and one of authors who established the São Carlos Formation.
Remarks: this species is the only tricolpate pollen having a conspicuous granulate ornamentation in the studied assemblage. *Tricolpites joelcastroi* resembles *Verrutricolpites* sp. illustrated by Vallati (2006, p. 89, fig. 6C), but differs in having finer verrucae (microverrucae).
Botanical affinity: indeterminate dicotyledon (Class Magnoliopsida).

Acritarchs [Acritarcha, Evitt 1963]
Genus *Leiosphaeridia* Eisenack, 1958
Type species: *Leiosphaeridia baltica* Eisenack, 1958

Leiosphaeridia ibateensis sp. nov.
Figs. 9F–G, 14I–J

Holotype: Slide UNESP-5, M63 (Fig. 9F).
Paratype: Slide SC-8, C57/1 (Fig. 9G).
Type locality: Fazenda Nossa Senhora de Fátima (Ibaté municipality, São Paulo State, Brazil. UTM 23 7577.6 km, 197.75 km).
Type stratum: São Carlos Formation, FNSF Mbr, Ibaté Bed, upper Santonian.
Description: organic-walled spherical vesicle; pylome absent; smooth thin wall which is conspicuously folded; high fluorescence under UV.
Dimensions: holotype – total diameter = 78 μm; paratype – total diameter = 72 μm; total diameter range = 60 (71) 80 μm (22 specimens); vesicle wall thickness = ca. 1 μm.
Derivation of name: from Ibaté municipality, where the São Carlos Formation type-section is located.
Botanical affinity: probably a prasinophyte. The prasinophycean affinity is compatible with its high fluorescence (Fig. 9I). This is also compatible with the point of view of Wall (1965) and Guy-Ohlson (1996).
Comparison: Among fresh-water *Leiosphaeridia*-type vesicles, *Leiosphaeridia ibateensis* is the biggest species according the following total diameter comparisons: *Leiosphaeridia* sp. B (in Volkheimer et al., 1977): 14–25 μm; *Leiosphaeridia menendezii* Volkheimer et al., 1977: 21–32 μm; *Leiosphaeridia dellapei* Volkheimer et al., 1977: 14–25 μm; *Leiosphaeridia* sp. (in Prámparo & Volkheimer, 2002): 25–35 μm; *Leiosphaeridia*-type 1 (in Narváez et al., 2014): 32–46 μm.

Phytoclasts
Stellatia gen. nov.

Diagnosis: fossil solid star-shaped organic particle having thick and opaque wall and which appears in palynological residues.
Type species: *Stellatia furcata* (Duarte & Arai) comb. nov.
Derivation of name: latin *Stella* – meaning star; star-shaped.
Remarks: The genus *Stellatia* is proposed herein to designate fossil remains derived from astrosclereids of vascular plants in substitution to ‘fossil sclereids’ proposed by Duarte & Arai (2010) as a new category of palynomorphs *sensu lato*.

Stellatia furcata (Duarte & Arai) comb. nov.

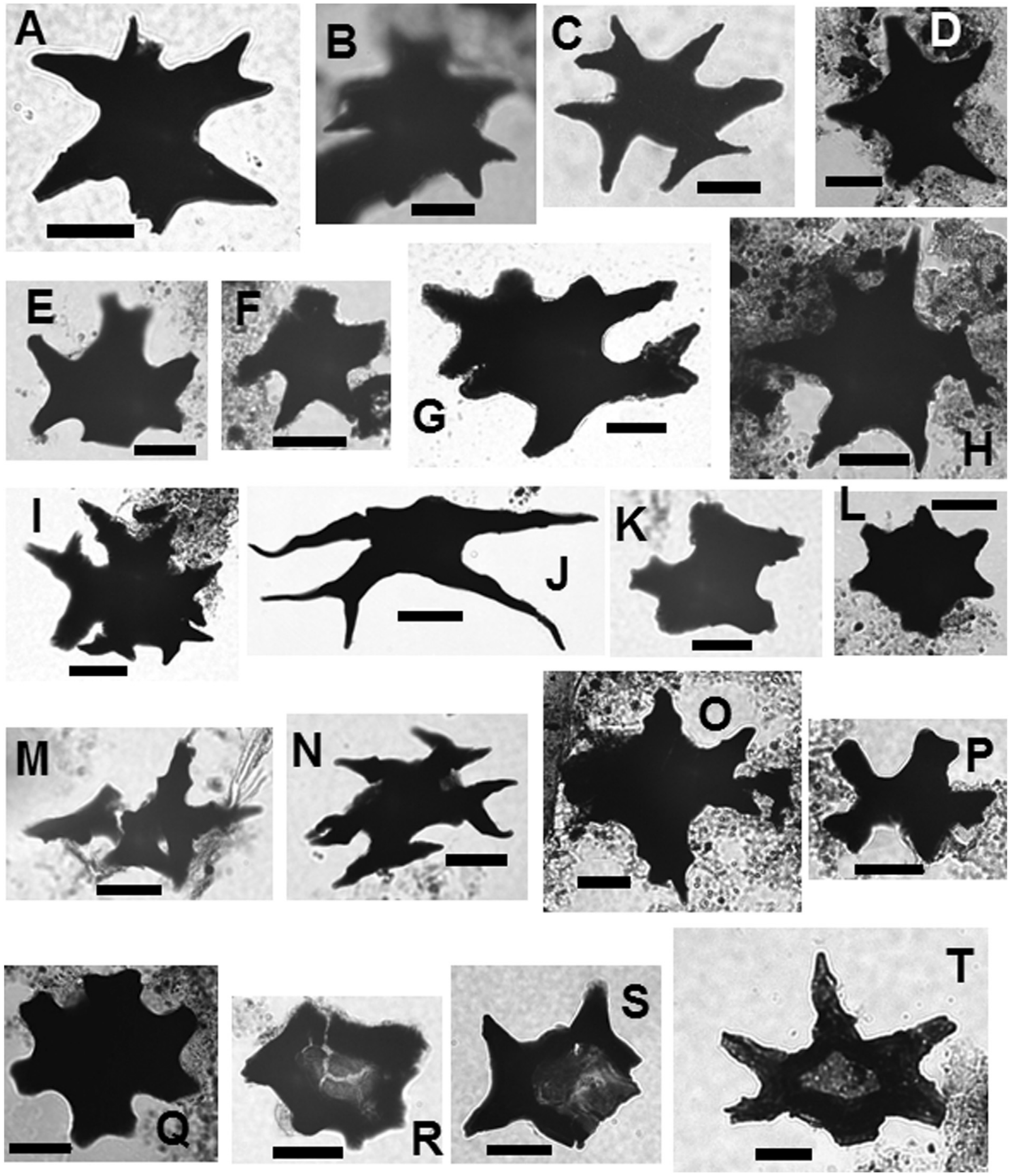

Fig. 10. *Stellatia* spp. (fossil astrosclereids). A, *Stellatia furcata*. Paratype. Sample SC-8; B, *Stellatia furcata*. Sample UNESP-6; C, *Stellatia furcata*. Holotype. Sample UNESP-4.1; D, *Stellatia simplex*. Holotype. Sample UNESP-6; E, *Stellatia furcata*. Sample UNESP-5; F, *Stellatia simplex*. Paratype. Sample UNESP-5; G, *Stellatia furcata*. Sample SC-8; H, *Stellatia spinosa*. Sample UNESP-4.1; I, *Stellatia aculeata*. Sample SC-8; J, *Stellatia elongata*. Sample UNESP-6; K, *Stellatia spinosa*. Sample UNESP-5; L, *Stellatia callosa*. Sample UNESP-6; M, *Stellatia spinosa*. Sample UNESP-6; N, *Stellatia furcata*. Sample UNESP-4.1; O, *Stellatia spinosa*. Sample SC-8; P, *Stellatia rotunda-truncata*. Sample SC-8; Q, *Stellatia rotunda*. Sample UNESP-6; R, *Stellatia brevis-tenuis*. Sample UNESP-6; S, *Stellatia tenuis*. Sample SC-8; T, *Stellatia tenuis-spinosa*. Sample SC-8. Scale bars = 20 μm.

Figs. 10A, B, C, E, G, N and 14L

2010 'Esclerócito tipo ramificado' (*forma furcata*) Duarte & Arai (Fig. 4F–I)

Holotype: Slide UNESP-4.1, O67 (Fig. 10C = fig. 4G *in* Arai & Duarte, 2010).
Paratype: Slide SC-8, S42/3 (Fig. 10A).

Type locality: Fazenda Nossa Senhora de Fátima (Ibaté municipality, São Paulo State, Brazil UTM 23 7577.6 km, 197.75 km).
Type stratum: São Carlos Formation, FNSF Mbr, Ibaté Bed, upper Santonian.
Description: outline stellate; 5 main arms; 2 to 4 of them can present bifurcation, resulting to 7 to 10 terminal arms; opaque and dark-colored.

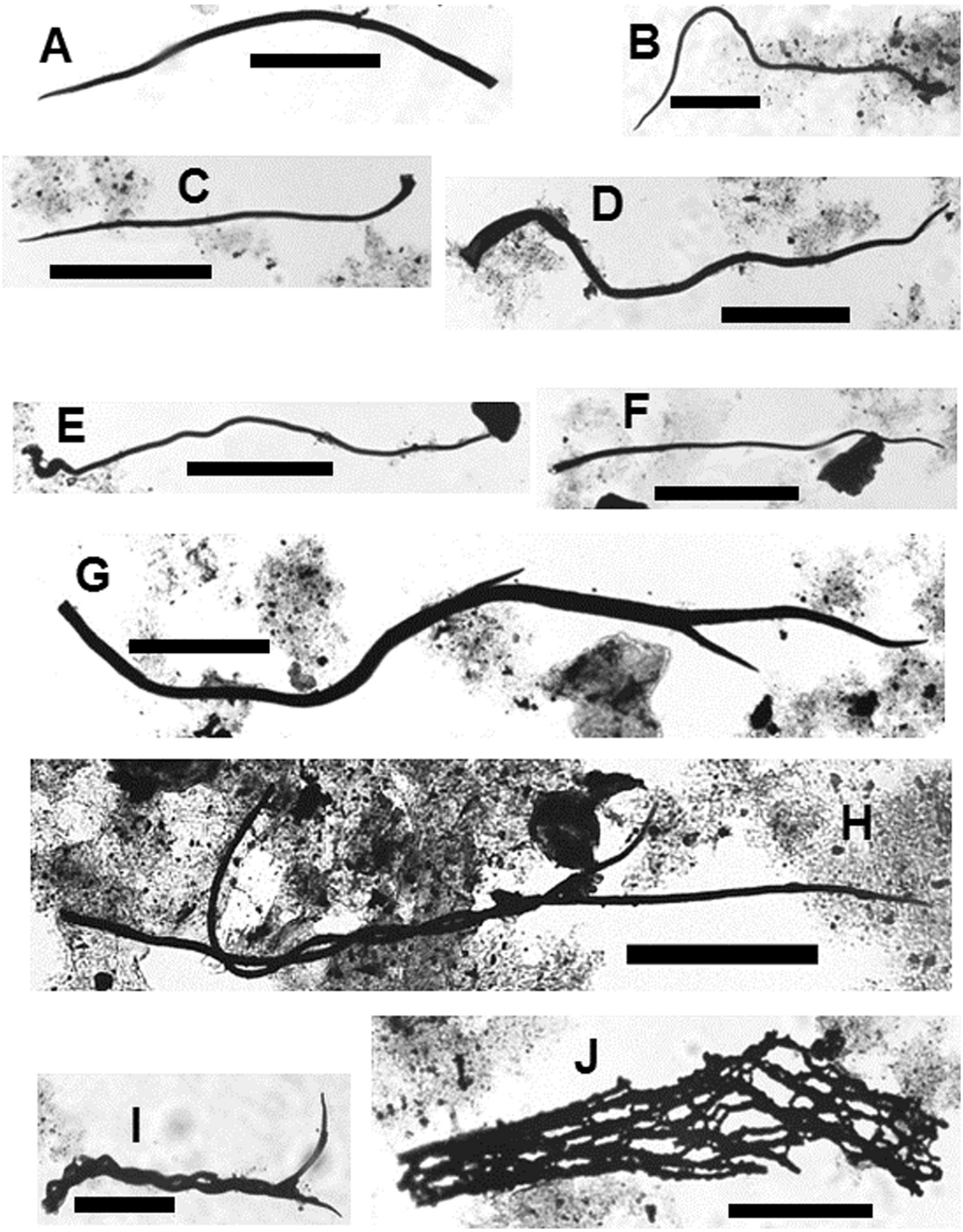

Fig. 11. *Trichomites* spp. (fossil trichomes) and woody organic matter. A, *Trichomites simplex*, thin recurved type. Sample UNESP-4.1; B, *Trichomites simplex*, thin sinuous type. Sample UNESP-4.0; C, *Trichomites simplex*, thin recurved type. Holotype. Sample UNESP-4.1; D, *Trichomites simplex*, thin sinuous type. Sample UNESP-4.1; E, *Trichomites simplex*, thin sinuous type. Sample UNESP-4.1; F, *Trichomites simplex*, thin sinuous type. Sample UNESP-6; G, *Trichomites brevifurcatus*. Holotype. Sample UNESP-4.1; H, *Trichomites duplihelicoidus*. Paratype. Sample SC-8; I, *Trichomites duplihelicoidus*. Holotype. Sample UNESP-6; J, Woody organic matter. Sample UNESP-6. Scale bars = 100 μm (except in B and I with 50 μm).

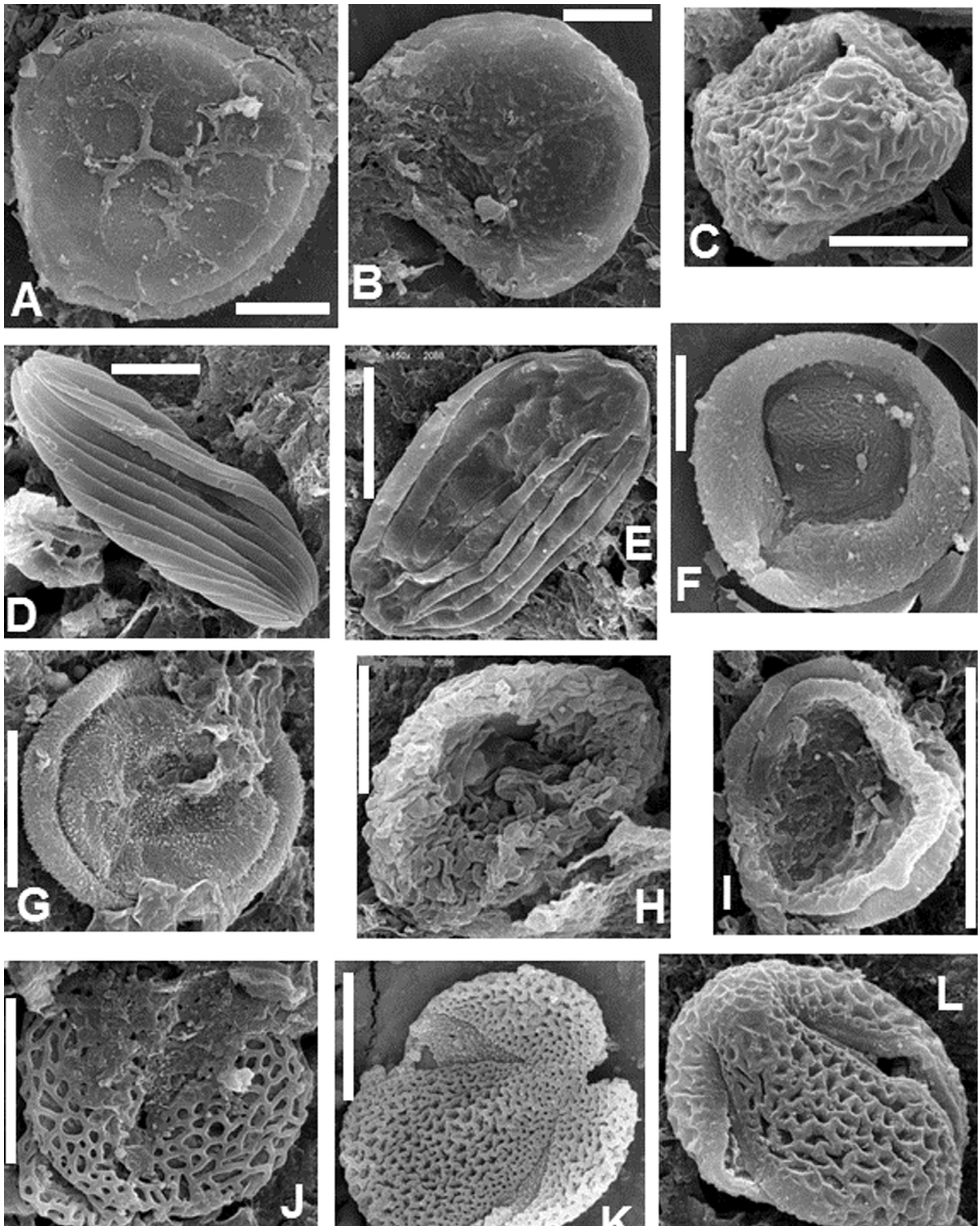

Fig. 12. SEM (Scanning Electron Microscope) photomicrographs. A, *Zlivisporis reticulatus*. Sample UNESP-6; B, *Foraminisporis simiscalaris*. Sample UNESP-6; C, *Klukisporites* sp. Sample UNESP-6; D, *Gnetaceaepollenites barghoornii*. Sample UNESP-6; E, *Equisetosporites strigatus*. Sample UNESP-5; F, *Classopollis* sp. Sample UNESP-6; G, *Classopollis* sp. Sample UNESP-6; H, *Callialasporites ugensis*. Sample UNESP-5; I, *Proxapertites*? sp. Sample UNESP-5; J, *Retitricolpites* sp. Sample UNESP-6; K, *Dryadopollis* sp. 1. Sample UNESP-6; L, *Dryadopollis* sp. 2. Sample UNESP-6. Scale bars = 20 μm.

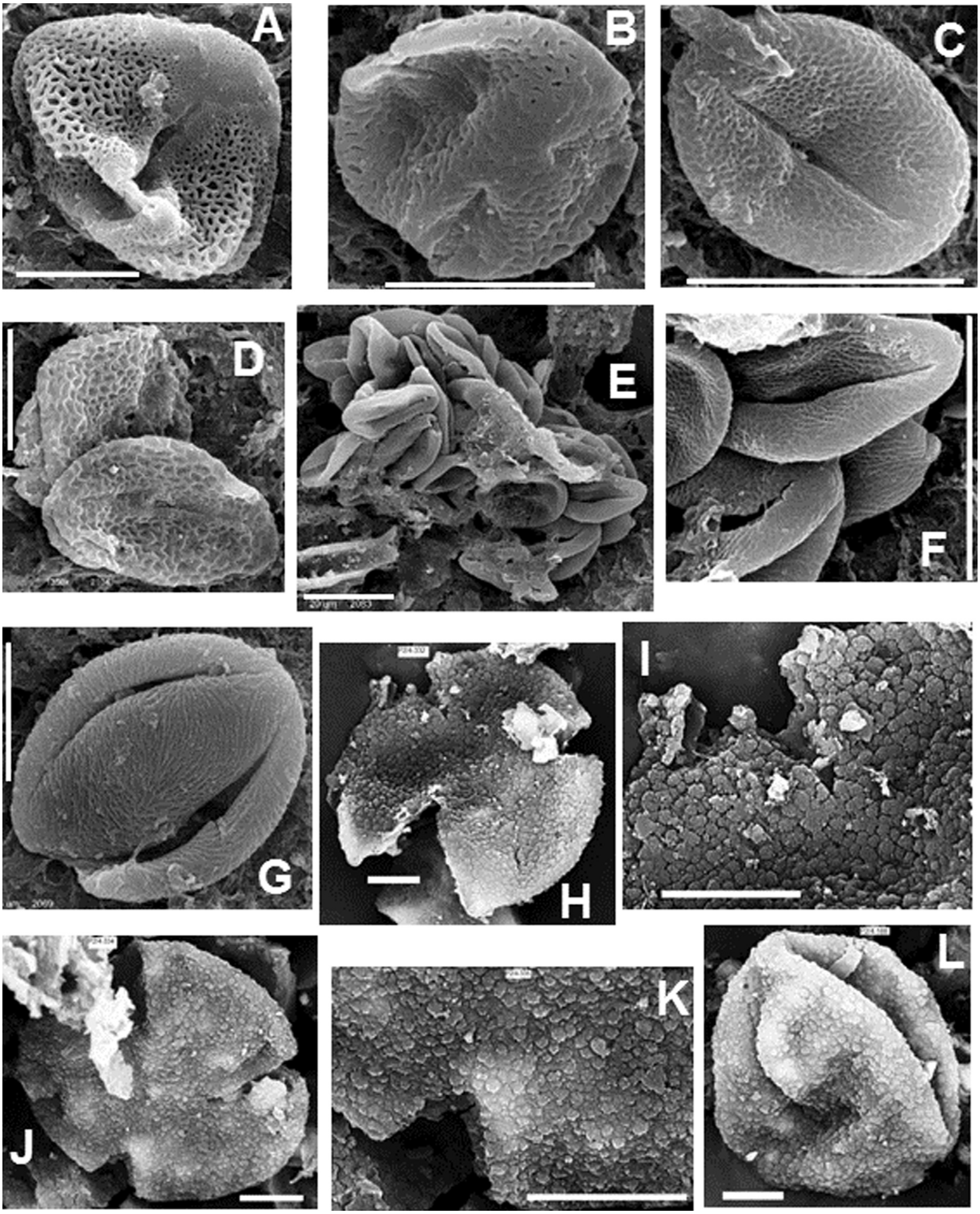

Fig. 13. SEM (Scanning Electron Microscope) photomicrographs. A, *Retitricolporites* sp. 1. Sample UNESP-6; B, *Retitricolporites* sp. 2. Sample UNESP-5; C, *Retitricolporites* sp. 3. Sample UNESP-5; D, *Retitricolporites* sp. 4. Sample UNESP-5; E, Cluster of *Retitricolporites* sp. 5. Sample UNESP-5; F, *Retitricolporites* sp. 5 (detail of lower right part of E); G, *Striatopollis trochuensis*. Sample UNESP-5; H, *Tricolpites joelcastroi* (polar view). Sample SC-8; I, *T. joelcastroi* (detail of upper part of H). Sample SC-8; J, *T. joelcastroi* (oblique polar view). Sample SC-8; K, *T. joelcastroi* (detail of lower part of J). Sample SC-8; L, *T. joelcastroi* (equatorial view). Sample SC-8. Scale bars = 20 μm (A–G); 5 μm (H–L).

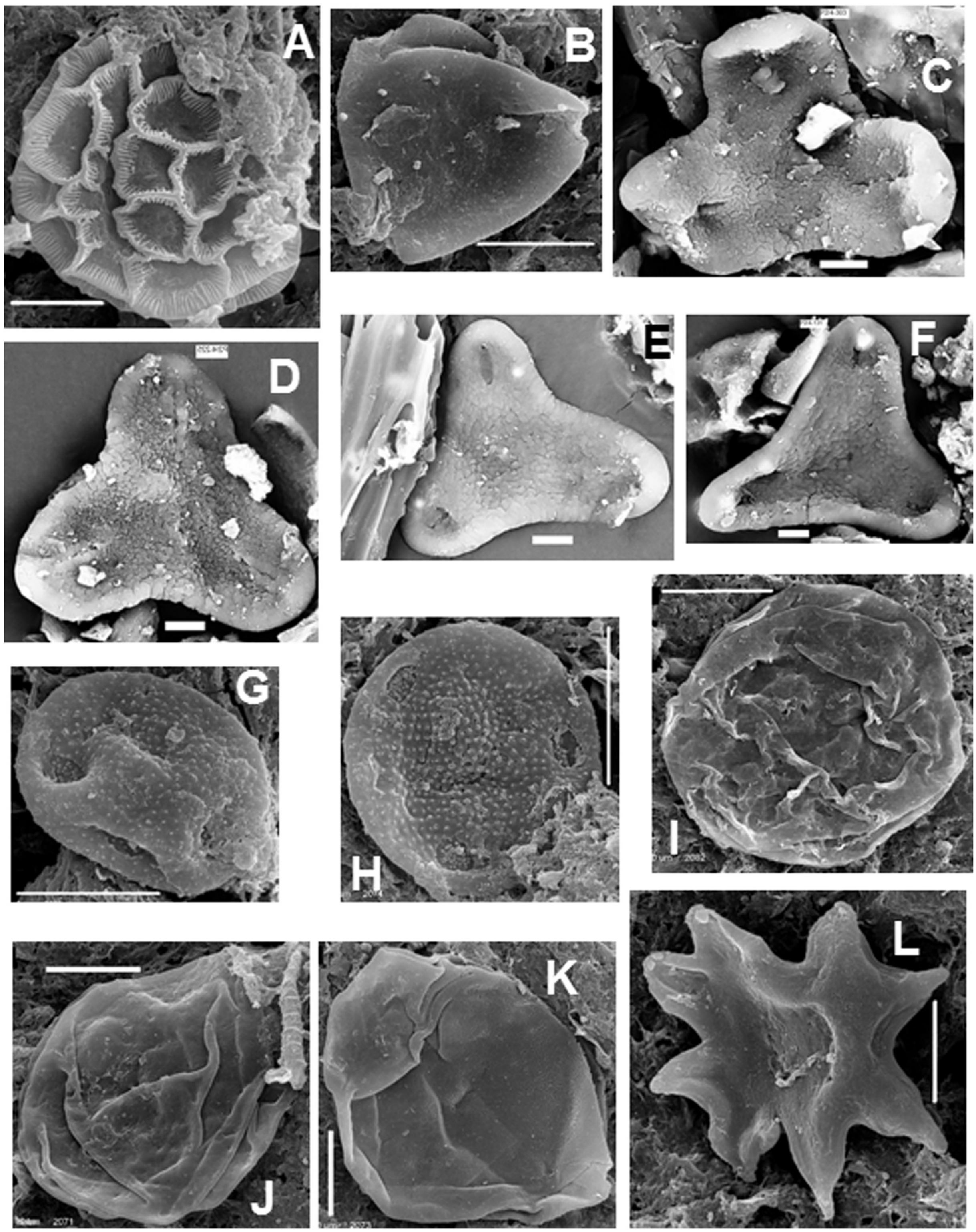

Fig. 14. SEM (Scanning Electron Microscope) photomicrographs. A, *Retimonocolpites* sp. Sample UNESP-6; B, *Subtriporopollenites minutipori*. Sample UNESP-6; C, *Anacolosidites eosenonicus*. Sample SC-14; D, *A. eosenonicus*. Sample SC-14; E, *A. eosenonicus* with charcoal (left). Sample SC-14; F, *A. eosenonicus*. Sample SC-14; G, *Cretacaeiporites scabratus*. Sample UNESP-5; H, *Psilastephanoporites brasiliensis*. Sample UNESP-5; I, *Leiosphaeridia ibateensis*. Sample UNESP-5; J, *Leiosphaeridia ibateensis*. Sample UNESP-5; K, *Leiosphaeridia* cf. *ibateensis*. Sample UNESP-5; L, *Stellatia furcata*. Sample UNESP-6. Scale bars = 20 μm (A, B, G–L); 5 μm (C–F).

Dimensions: holotype – total diameter = 90 μm; paratype – total diameter = 68 μm; total diameter range 64 (76) 99 μm (7 specimens).
Derivation of name: latin *furcata* – meaning branched.
Botanical affinity: according to Duarte & Arai (2010), *Nuphar* spp. (Nymphaeaceae) produce very similar astrosclereids.

Trichomites gen. nov.

Diagnosis: all fossil plant-origin structures related to trichomes, as described by Arai & Duarte (2010).
Type species: *Trichomites brevifurcatus* sp. nov.
Derivation of name: Trichome + suffix '-ites'.
Remarks: The genus *Trichomites* is proposed herein to designate fossil remains derived from trichomes of vascular plants in substitution to "fossil trichomes" proposed by Arai & Duarte (2010) as a new category of palynomorphs *sensu lato*.

Trichomites brevifurcatus sp. nov.
Fig. 11G

Holotype: Slide UNESP-4.1, M54 (Fig. 11G).
Type locality: Fazenda Nossa Senhora de Fátima (Ibaté municipality, São Paulo State, Brazil UTM 23 7577.6 km, 197.75 km).
Type stratum: São Carlos Formation, FNSF Mbr, Ibaté Bed, upper Santonian.
Description: dark colored hair-like fossil trichome with short spines in alternating positions.
Dimensions (holotype): total length = 660 μm; length of spines = 30–40 μm; range of total length = 620 (650) 690 μm (5 specimens).
Derivation of name: latin *brevifurcatus* – meaning short branches.
Botanical affinity: probably Campanulaceae. According to Batterman & Lammers (2004), trichomes with alternating branches are found in Lobelioideae (Campanulaceae).

Trichomites duplihelicoidus sp. nov.
Fig. 11H, I

2010 'Tricoma duplo delgado trançado' *in* Arai & Duarte, fig. 3L (p. 181).

Holotype: Slide UNESP-6, Y8 (Fig. 11I).
Paratype: Slide SC-8, Q47 (Fig. 11H).
Type locality: Fazenda Nossa Senhora de Fátima (Ibaté municipality, São Paulo State, Brazil UTM 23 7577.6 km, 197.75 km).
Type stratum: São Carlos Formation, FNSF Mbr, Ibaté Bed, upper Santonian.
Description: dark colored, twin woven hair-like fossil trichome.
Dimensions: holotype – total length = 164 μm; paratype – total length = 458 μm; range of total length = 164 (253) 458 μm (4 specimens).
Derivation of name: latin *duplihelicoidus* – meaning double helicoid.
Botanical affinity: unknown.

Trichomites simplex sp. nov.
Fig. 11A–F

2010 'Tricoma simples delgado' *in* Arai & Duarte, fig. 3A–3E (p. 181).

Holotype: Slide UNESP-4.1, D55/4 (Fig. 11C).
Type locality: Fazenda Nossa Senhora de Fátima (Ibaté municipality, São Paulo State, Brazil. UTM 23 7577,6 km, 197,75 km).
Type stratum: São Carlos Formation, FNSF Mbr, Ibaté Bed, upper Santonian.
Description: dark colored simple hair-like fossil trichome without spines or branches.
Dimensions (holotype): total length = 267 μm; diameter near base = ca. 4.5 μm; range of total length = 219 (350) 450 μm (6 specimens).
Derivation of name: latin *simplex* – meaning simple.
Botanical affinity: several dicotyledon families possess simple hair-like trichomes – e.g., Brassicaceae, Fabaceae and Rutaceae (Metcalfe & Chalk, 1988).

5. Palynostratigraphy and age of the Ibaté Bed

Several pollen taxa indicate that the studied samples are confined to the Coniacian – Santonian chronostratigraphic interval (89.8–83.6 Ma, ICS, 2017). Some of the pollen taxa belong exclusively to this interval such as *Anacolosidites eosenonicus*, *Foveotricolpites gigantoreticulatus*, *F. tienabaensis* and *Victorisporis robertii* (Fig. 15). Lima et al. (1986) already gave a similar Coniacian chronostratigraphic assignment for samples from an "equivalent section" (from another close-by stream in the same area). The material studied by those authors contains similar palynological assemblage to that found in the Ibaté Bed. They mentioned the following common species: cf. *Accuratispollis* sp. (= *Anacolosidites eosenonicus*), *Classopollis classoides*, *Confossia vulgaris*, *Constantinisporis jacquei*, *Cretacaeiporites polygonalis*, *Gabonisporis vigourouxii*, *Gnetaceaepollenites jansonii*, *Hexaporotricolpites emelianovi*, *Tricolpites tienabaensis* (= *Foveotricolpites tienabaensis*), *Victorisporis roberti* and *Zlivisporis blanensis*. Nevertheless, their paper was limited to a short preliminary report, with no detailed qualitative and quantitative data, such as that given here.

Anacolosidites eosenonicus sp. nov. was firstly called "cf. *Accuratipollis* sp." by Ioannides and Colin (1977) who reported in the Coniacian–Santonian of the DSDP Site 356. Lima et al. (1986) and Azevedo et al., 1987 kept this provisional name, but considered this taxon as a guide-pollen for the Coniacian. It was renamed as *Anacolosidites* sp. in Viviers and Azevedo (1988), and frequently cited as "*Anacolosidites* sp. A" afterward. Its name was used to nominate the "*Anacolosidites* sp. interval zone" by the latter authors, and referred as Coniacian in age; its boundaries were defined based on the last occurrences (LOs) of *Steevesipollenites nativensis* (base) and *Anacolosidites* sp. (top).

Several marine sections drilled in offshore areas of the Campos and Santos basins, and calibrated with respect to foraminifera and nannofossil zones, indicate that the *Anacolosidites* sp. Zone, herein renamed as *Anacolosidites eosenonicus* Palynozone, is restricted to the upper Santonian (Arai et al., 2010). The top of the *Anacolosidites eosenonicus* Palynozone coincides with the first occurrence (FO) of *Globotruncanita* spp. (foraminifera) indicating the Santonian–Campanian boundary (Viviers et al., 2005) and occurs between the LOs of the nannofossil species *Eprolithus moratus* and *Lithastrinus grilli* that occur respectively in upper Santonian and in lower Campanian. Furthermore, the top of the *Anacolosidites eosenonicus* Palynozone is situated between the LOs of the dinoflagellate species *Oligosphaeridium pulcherrimum* and *Nelsoniella aceras* that occur respectively in the middle Santonian and in middle Campanian (Arai et al., 2010). The absence of *Steevesipollenites nativensis* in the Ibaté Bed indicates that the interval in question is directly located within the *Anacolosidites eosenonicus* Palynozone. Therefore, we assign all studied samples to the upper Santonian (ca. 84.5–83.6 Ma). Considering data published by Dias-Brito et al. (2001), the Ibaté Bed is stratigraphically related to the uppermost part of the Adamantina and Uberaba formations (Bauru Group units). This Uberaba Formation was considered close to 83 Ma and Santonian in age (Dias-Brito et al., 2001, p. 284, 288).

6. Paleoenvironmental significance

Among terrestrial palynomorphs, ephedroid pollen (*Ephedra*-type pollen) such as *Equisetosporites*, *Gnetaceaepollenites* and *Steevesipollenites* have consistent abundance (Fig. 16; Supplementary

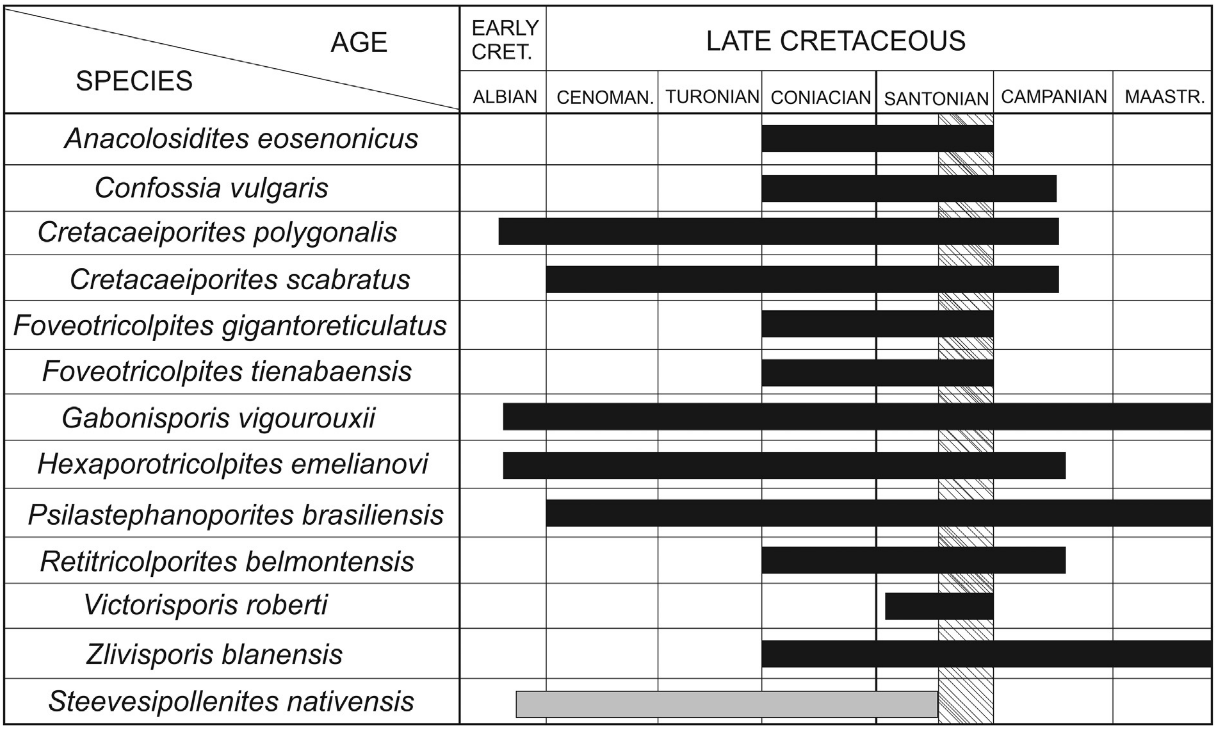

Fig. 15. Stratigraphic range of principal index-palynomorphs. The absence of the guide-pollen *Steevesipollenites nativensis* assures a late Santonian age for the studied section. The interval pointed out by hatched signature corresponds to the inferred age of the Ibaté Bed.

Table A). Their occurrence associated with *Classopollis* grains suggest a warm climate tending towards dryness, as pointed out by the assumption of several authors (e.g., Srivastava, 1968; Arai and Coelho, 2001; Naváez et al., 2014). This must be the paleoclimatic condition that prevailed at the studied area during the late Santonian. The trilete spores, also frequently present throughout the studied section, indicate that some more humid phases occurred during this time. As the proportions of the palynomorph groups mentioned are inversely correlated, it is possible to follow the trends of the climatic fluctuations. The increase of pteridophyte spores may reflect a lacustrine expansion phase, associated with more humid conditions that favored the development of lakeside vegetation. *Gabonisporis vigourouxii* is related to the aquatic fern family Marsileaceae, as suggested by studies of fossil and extant Marsileaceae spores (e.g., Lupia et al., 2000; Takahashi et al., 2001; Schneider & Pryer, 2002). Since *Gabonisporis vigourouxii* is one of most frequent spore species, this suggests a flourishing lakeside pteridophytic flora.

Some samples show abundant occurrence of algal elements. When only one type of microalgal remains prevails over other algal types, it is suggestive of phytoplankton blooms in the lake caused by eutrophication (Diersing, 2009). *Botryococcus*, *Pediastrum*, *Staurastrum* and prasinophyte remains were recognizable under fluorescence microscopy (Fig. 9I, K, M, O, Q, S). The quantitative distribution of microalgal remains indicates that, when *Staurastrum* dominates, the frequencies of *Botryococcus* and *Pediastrum* are low (Fig. 16). There is often an inverse relationship between *Botryococcus* and *Pediastrum* (e.g., Van der Zwan & Brugman, 1999; Shumilovskikh et al., 2014). According to Van der Zwan & Brugman (1999), the dominance of *Pediastrum* may represent a true freshwater phase in the lake, whereas the dominance of *Botryococcus* can reflect brackish conditions. This shift in microalgal dominance is probably due to climatic variations. Indeed, the abundance of *Pediastrum* is only reported in samples with a relatively high proportion of pteridophyte spores (e.g., sample SC-14), which is interpreted to reflect episodic lacustrine expansions. Prasinophytes (*Leiosphaeridia* spp.) seem also be incompatible with *Botryococcus*, but their presence is quite independent of *Pediastrum*, since we observe that prasinophyte peaks can coincide with those of *Pediastrum* (e.g., as in the sample SC-8) or not (e.g., as in the sample UN-5, where prasinophyte peak occurs in the absence of *Pediastrum*). The strata containing more *Botryococcus* than *Pediastrum* and Prasinophytes were likely deposited under low oxygen level in water body as suggested by Guy-Ohlson (1992) and Rodríguez-Amenábar & Ottone (2003).

From the combination of sedimentological, geochemistry and palynological data, we interpret the Ibaté Bed as a deposit formed in a distal lake with episodic low-oxygen/anoxic conditions in bottom waters.

7. Concurrence with the Great Santonian Wildfire

The so-called "Great Santonian Wildfire" was first recorded from areas of the Santos and Campos offshore basins in the western South Atlantic by Arai et al. (2006) and has been interpreted to be a series of recurrent events associated with volcanic activity. Strata coeval to this event present abundant charred and/or burnt organic particles. The most curious aspect in these strata is the coexistence of well-preserved palynomorphs with carbonized organic matter that suggests vegetation recoveries in the intervals between fire events (Fig. 17). Furthermore we have observed conspicuous presence of paleowildfire indicators such as charcoals (Fig. 14E), astrosclereids (*Stellatia* spp.: Fig. 10) and trichomes (*Trichomites* spp.: Fig. 11) within the Ibaté Bed which was deposited during late Santonian, when the fire climax apparently took place. The Ibaté Bed section, which is located about 300 km from the Santos Basin littoral, contains sclereids/trichomes that are systematically associated with a rich palynological assemblage. This differs from the situation observed in the offshore basins, where the strata bearing abundant sclereids and/or trichomes are virtually barren in palynomorphs. Taking into account the distance separating São Carlos

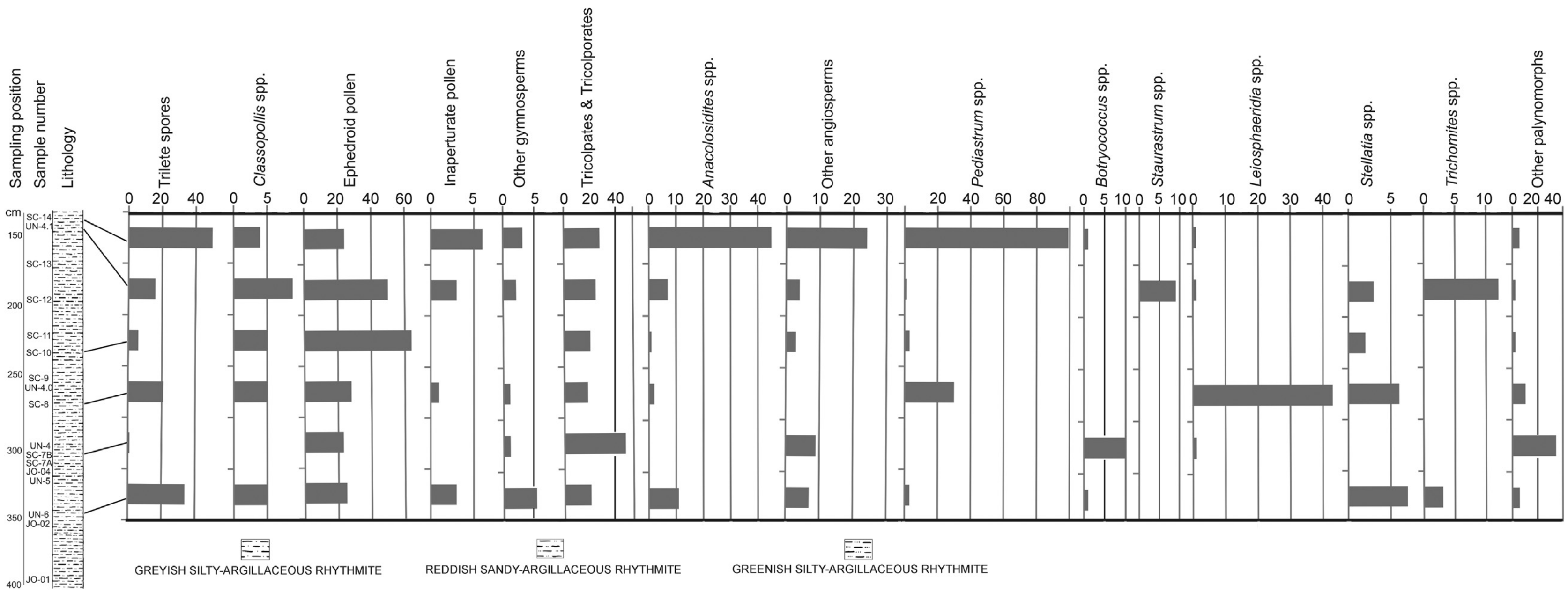

Fig. 16. Absolute frequency of principal palynomorph taxa. Left margin 1st column: sampling position in cm (datum = top of the FNSF Mbr). This graph is derived from 6 richest samples presented in Supplementary Table A (samples UNESP-6, SC-7B, SC-8, SC-10, UNESP-4.1 and SC-14).

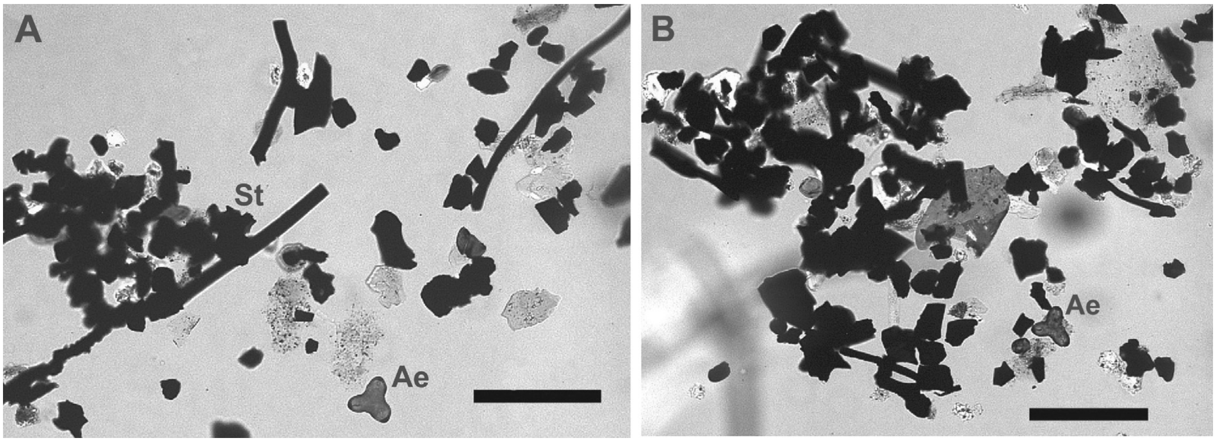

Fig. 17. Aspects of palynofacies typical of sedimentation occurred at the time of the Great Santonian Wildfire. Sample UNESP-4.1. There is dominance of charcoal (carbonized woody organic matter), but in both photomicrographs we can see well-preserved *Anacolosidites eosenonicus* pollen grains (Ae). In photo A, there is a *Stellatia* specimen (St). Scale bars = 100 μm.

and the coastal area, it is more plausible to consider that the wildfire signs recorded from the Ibaté Bed were associated with volcanic activity that occurred in the interior of the country, an area located around 100 km away from the São Carlos Formation type section (Coutinho et al., 1982; Dias-Brito et al., 2001).

8. Paleophytogeography

In terms of Late Cretaceous paleophytogeographic frameworks, the palynoflora studied here stems from a tropical paleomicrofloristic region that would correspond more or less to the Senonian Palmae Province (cf. Herngreen & Chlonova, 1981; Herngreen et al., 1996). Nevertheless, pollen grains typically derived from Palmae — e.g., *Longapertites*, *Mauritiidites* and *Spinizonocolpites* — are absent. On the other hand, the Ibaté Bed palynological content is closer to the pollen spectra from the middle Cretaceous ASA (African-South American) Province (Herngreen & Chlonova, 1981). This is due to the fact that several palynomorph species recovered are typical of the ASA Province, such as *Cretacaeiporites polygonalis*, *C. scabratus*, *Gnetaceaepollenites jansonii*, *Hexaporotricolpites emelianovi* and *Psilastephanoporites brasiliensis* which survived since middle Cretaceous. Palynofloras from west and northeast Africa share many common species (Supplementary Table B) with the studied section. Despite the geographic proximity, time-equivalent

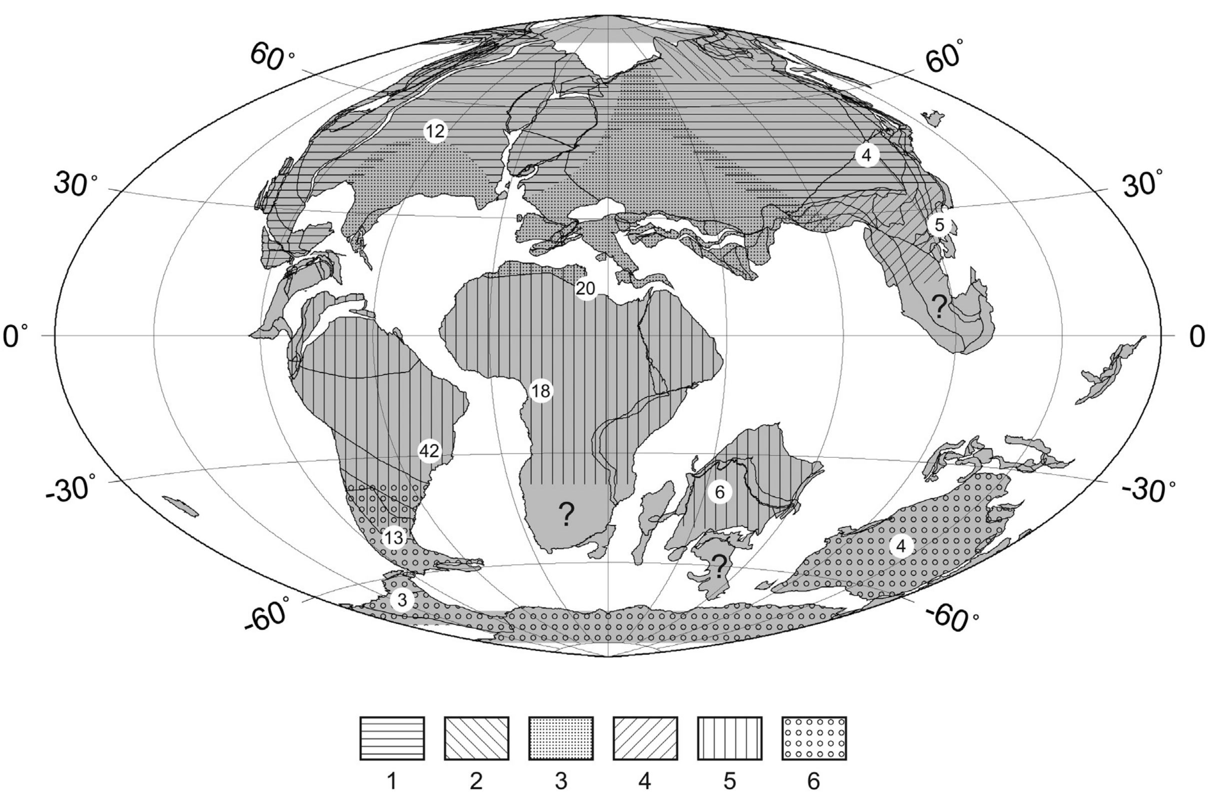

Fig. 18. The main Late Cretaceous palynofloral provinces (after Vajda and Bercovici, 2014, modified from Herngreen et al., 1996). The numerals, plotted on respective geographic sites, indicate the numbers of shared common species in relation to 42 selected species of the FNSF Mbr-Ibaté Bed, São Carlos Formation (see Supplementary Table B). 1–6: palynofloral provinces. 1: *Aquilapollenites* Province. 2: Khatanga-Lena Subprovince. 3: Normapolles Province. 4: *Schizaeoisporites* Province. 5: Palmae Province. 6: *Proteacidites*/*Nothofagidites* Province.

palynofloras from Argentina belong to another phytogeographic province and contain relatively few species in common with our material. This low number of common Cretaceous species between Argentina and São Carlos-Ibaté may be due to the incomplete nature of the upper Cenomanian–lower Campanian palynological record in Argentina, as indicated by Prámparo (2012). Herngreen et al. (1996) also assigned India to the Palmae Province, but in fact there are very few shared species when compared with the São Carlos-Ibaté record. The same is observed with respect to Antarctica, Asia, Australia and Europe. Besides the distance, these latter areas belong to other provinces, and were characterized by distinct paleoclimates. In order to show the similarity of the Ibaté Bed palynoflora with several Late Cretaceous palynofloras in the world, the Ibaté Bed assemblage was compared with those from 9 other palynofloristic provinces (Fig. 18).

9. Conclusions

The rich palynological content present in dark laminae of lacustrine silty-argillaceous rhythmites of the Ibaté Bed, FNSF Member, São Carlos Formation, previously dated as Coniacian–Santonian, is indicative of a late Santonian age. This new age assignment is based on palynostratigraphic relationships established from a reliable biostratigraphic framework based on integration of palynological, foraminiferal, calcareous nannofossil and dinocyst data.

Well-preserved palynomorphs are in the Ibaté Bed and represent the richest Upper Cretaceous palynological assemblage registered so far from a continental basin in Brazil. These deposits are stratigraphically related to the uppermost part of the Adamantina and Uberaba formations (stratigraphic units of the Bauru Group).

The predominance of ephedroid pollen associated with *Classopollis* grains is indicative of a warm climate tending towards dryness at the study area during the late Santonian. However, some more humid phases occurred during this time. The conspicuous occurrence of freshwater algal remains indicates that the Ibaté Bed rhythmites accumulated in a permanent aquatic environment. From the combination of sedimentological, geochemical and palynological data, we propose that the deposition occurred in a distal lake, frequently with episodic low-oxygen/anoxic conditions in lake bottom water. Therefore, at this time, the area would have been a very particular environment within the vast continental territory represented by the "Bauru Basin".

The presence of charcoals, astrosclereids (*Stellatia* spp.) and trichomes (*Trichomites* spp.) in the Ibaté Bed indicates that the late Santonian vegetation of this region was affected by wildfires. Some of the wildfire activity may have been associated with important volcanic activity occurring not far from there (around 100 km), which would have been coeval to the Great Santonian Wildfire recorded in coastal areas of some offshore basins in southeastern Brazil.

In general, among terrestrial palynomorphs, we observed a greater abundance of miospores derived from pteridophytes and gymnosperms, but, in terms of taxonomic diversity, angiosperm pollen represents the richest group. This could mean that the Santonian represented the beginning of the great expansion of the angiosperm group that occurred in the Late Cretaceous.

The exceptional late Santonian Ibaté Bed palynoflora is located at a transitional position between the middle Cretaceous ASA Province and the Senonian Palmae Province.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.cretres.2017.11.014.