



The Proterozoic Qinggouzi microfossil assemblage and its biostratigraphic constraints on the Great Unconformity in northeastern North China Craton

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ABSTRACT

The Great Unconformity at the Precambrian-Cambrian boundary has been recognized on several continents and may provide critical insights into the environmental context of the Cambrian explosion. However, the geodynamic drivers, geochronological duration, and paleogeographic extent of the Great Unconformity remain unconstrained in many cases. Recently, a major depositional gap of varying magnitudes has been reported around the Precambrian-Cambrian boundary in several regions of North China, leading to the interpretation that the Great Unconformity may have been widespread but diachronous across the North China Craton. However, the magnitude of the Great Unconformity remains unknown in northeastern North China, largely because of the poor age constraints on the thick Proterozoic–Cambrian successions in this region. Here we use biostratigraphic data to constrain the depositional age of Proterozoic strata below the Great Unconformity in northeastern North China. We report a diverse organic-walled microfossil assemblage from the Qinggouzi Formation in southern Jilin Province, northeastern margin of the North China Craton. Typical late Mesoproterozoic to early Neoproterozoic microfossils, including *Trachyhystrichosphaera aimika* and *Proterocladus antiquus*, are present in Qinggouzi assemblage, providing a solid biostratigraphic constraint on the Qinggouzi Formation. Given that the overlying Shuidong Formation contains typical early Cambrian small shelly fossils, our new data indicate that the Great Unconformity in northeastern North China represents a major depositional gap of >200 Myr. Thus, the new data, along with other available biostratigraphic and geochronological data from over the world, provide robust constraints on the paleogeographic extent, chronostratigraphic duration, and diachronous nature of the Great Unconformity.

1. Introduction

The Great Unconformity, as envisioned initially, refers to a long-term depositional gap between the Precambrian basement and overlying Phanerozoic sediments in the Great Basin of United States (Powell, 1875; Yochelson, 2006). This unconformity has been subsequently shown to be widespread in North America (Karlstrom and Timmons, 2012). Even more interesting is the possibility that the protracted continental

denudation during the Great Unconformity and subsequent global transgression in the Cambrian may have substantially affected seawater chemistry by adding a substantial amount of weathering flux into the Cambrian ocean. Thus, the Great Unconformity may have been an environmental trigger for the Cambrian explosion (Peters and Gaines, 2012). However, whether the Great Unconformity represents a globally synchronous event or comprises multiple diachronous events of regional scale has been a matter of debate (DeLucia et al., 2018; Keller et al.,

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2019; Flowers et al., 2020; Flowers et al., 2022; McDannell et al., 2022). To decipher the nature of the Great Unconformity, the distribution and duration of this unconformity at different locations need to be documented and characterized. Recent studies have uncovered a significant depositional gap at the Precambrian-Cambrian boundary in western, southern, and eastern margins of the North China Craton, but the duration of these gaps varies across the craton (Sun et al., 2022). For example, there is a gap of 200–300 Myr at the Precambrian-Cambrian boundary in several regions of eastern North China (Tang et al., 2015; Li et al., 2019; Wan et al., 2019; Li et al., 2020b). In contrast, the magnitude of this depositional gap may be less than 30 Myr in southern and western margins of the North China (Shen et al., 2010; Yang et al., 2019; Chen et al., 2020; Wang et al., 2021b). These findings suggest that the Great Unconformity is widespread but diachronous (Flowers et al., 2020). However, whether the Great Unconformity exists in northeastern North China remains unknown, mainly because the poor age constraints on the Qinggouzi Formation that disconformably underlies the early Cambrian Shuidong Formation in southern Jilin Province (Bureau of Geology and Mineral Resources of Jilin, 1988). For example, Yin (1987)

and Gao et al. (1995) suggested that the Qinggouzi Formation is Neoproterozoic in age based on micropaleontological data, whereas Duan et al. (2005) proposed that it is Cambrian in age on the basis of regional lithostratigraphic correlation. This knowledge gap hampers our ability to determine the occurrence and magnitude of the Great Unconformity in northeastern North China. In this study, we carried out a micropaleontological analysis of black shale samples from the Qinggouzi Formation in southern Jilin Province. Our study revealed a diverse assemblage of organic-walled microfossils, including *Trachyhystrichosphaera aimika* that is present in latest Mesoproterozoic and early Neoproterozoic strata globally, as well as several other pre-Cryogenian elements. The new biostratigraphic data indicate that the Qinggouzi Formation is latest Mesoproterozoic to early Neoproterozoic in age, suggesting a > 200 Myr depositional gap before the early Cambrian resumption of deposition in northeastern North China. Integrated with available biostratigraphic and geochronological data from elsewhere, our study demonstrates the diachronous nature of the Great Unconformity in the North China Craton.

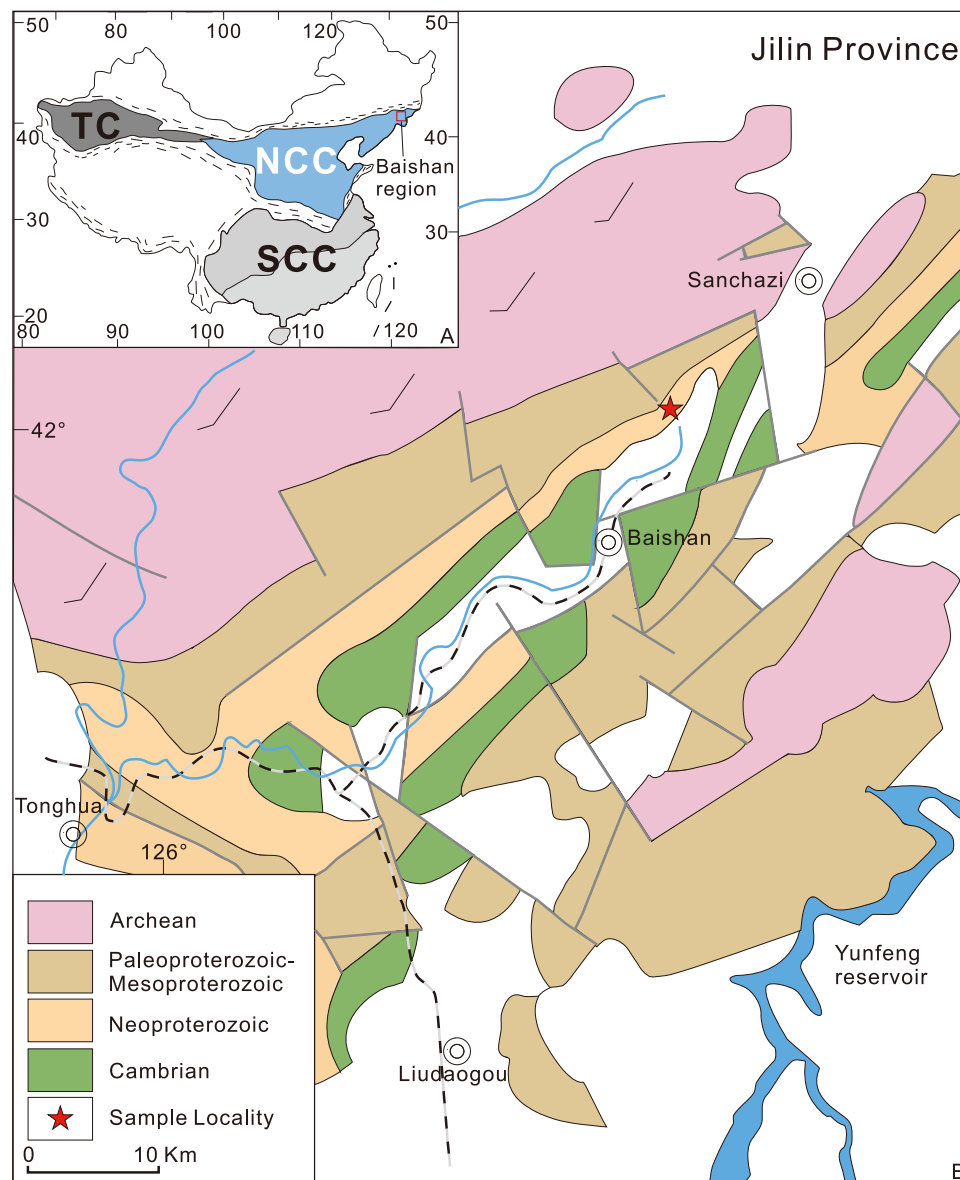


Fig. 1. Geological map of southern Jilin Province in the North China Craton (NCC), showing the location of Baishan region (red square in A) and the sampled Yingzuilazi section (red star in B) in Baishan region. Modified from 1:500,000 Geological Maps of Jilin Province (Jin, 1984). SCC, South China Craton; TC, Tarim Craton. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Geological setting

The southern Jilin Province is located in the northeastern margin of the North China Craton (Fig. 1). The Mesoproterozoic to Neoproterozoic sedimentary sequence in southern Jilin Province is well-preserved with a maximum thickness of 4146 m (Bureau of Geology and Mineral Resources of Jilin, 1988). The sequence unconformably sits on metamorphic basement of the Mesoproterozoic Laoling Group (Pang et al., 2021; Bureau of Geology and Mineral Resources of Jilin, 1988) and is unconformably overlain by the phosphatic conglomerate of the early Cambrian Shuidong Formation. The sequence consists of, in ascending order, the Baifangzi Formation and the Xihe and Hunjiang groups. The Baifangzi Formation, 883 m in thickness, has sporadic exposures and is dominated by sandstone and shale. The unconformably overlying Xihe Group, which consists of the Diaoyutai, Nanfen, and Qiaotou formations, is dominated by siliciclastic rocks. The Diaoyutai Formation measured 388–599 m in thickness is mainly composed of a basal conglomerate succeeded by gray quartz sandstone and sandstone. The conformably overlying Nanfen Formation, 245–1039 m in thickness, is dominated by dark grey and yellowish-green silty shale in the lower member, greyish argillaceous limestone in the middle member, and yellowish shale and siltstone in the upper member. The overlying Qiaotou Formation is 234–248 m in thickness and is dominated by gray quartz sandstone and yellowish-green shale (Bureau of Geology and Mineral Resources of Jilin, 1988).

The conformably overlying Hunjiang Group is divided into the Wanlong, Badaojiang, and Qinggouzi formations in ascending order. The Wanlong Formation is 233–711 m in thickness and consists of gray limestone and dolomitic limestone interbedded with siltstone and shale. Molar tooth structures are pervasive in the thick-bedded limestone of the Wanlong Formation. The succeeding Badaojiang Formation, 289–586 m in thickness, is characterized by clastic limestone and gray stromatolitic limestone with chert beds at the base. The uppermost unit of the Hunjiang Group, the Qinggouzi Formation, is 58–80 m in thickness. The lower Qinggouzi Formation consists of gray medium- to thick-bedded brecciated limestone with molar tooth structures. The middle Qinggouzi Formation is dominated by greyish yellow dolomitic limestone interbedded with black shale. The upper Qinggouzi Formation is mainly composed of laminated black shale with limestone lenses.

The depositional age of the Qinggouzi Formation remains unclear due to lack of reliable radiometric dates. Although abundant organic-walled microfossils have been previously reported from the Qinggouzi Formation (Xu and Tian, 1985; Yin, 1987; Gao et al., 1995), few of them are biostratigraphically diagnostic. The youngest population of detrital zircons from the underlying Qiaotou and Wanlong formations are dated at 1119 Ma and 1181 Ma, respectively (Zhang et al., 2021), providing a maximum age constraint for the Qinggouzi Formation. In addition, the Qinggouzi Formation is unconformably overlain by the early Cambrian Shuidong Formation which is dominated by gray phosphatic conglomerate and maroon sandstone. A host of small shelly fossils have been reported from the Shuidong Formation, indicating a depositional age of Cambrian Age 3–4, roughly 520–514 Ma (Yue et al., 1990). Thus, the Qinggouzi Formation can be roughly constrained between the latest Mesoproterozoic to early Cambrian.

3. Materials and methods

In this study, a total of nine shale samples, all of which are fossiliferous, have been collected from the Qinggouzi Formation at the Yingzuilazi section (41°58'45.95"N, 126°25'46.60"E) in Baishan city, southern Jilin Province (Fig. 2). The shale samples were digested using low-manipulation maceration techniques (Butterfield et al., 1994; Tang et al., 2013; Tang et al., 2015) in the palynological laboratory of Nanjing Institute of Geology and Palaeontology (NIGPAS). Most of the recovered specimens were manually transformed and individually mounted on glass slides for transmitted light microscopy (TLM). Exceptionally

preserved specimens were selected and prepared for scanning electron microscopy (SEM) analysis. Smear slides were prepared for TLM and measurements of additional specimens. All illustrated specimens are repositied in NIGPAS.

A bipartite network analysis was conducted to better understand the taxonomic similarity between the Qinggouzi microfossil assemblage and other late Mesoproterozoic to early Neoproterozoic fossil assemblages in North China. Several default community-detection algorithms in R package igraph were operated in order to evaluate the community structures and modularity scores (i.e., Q), which is used to measure the partition quality of a community. A high value of Q indicates that the vertices within the community have high similarity, while the similarity between vertices outside the community is low. The visualization and layout of networks were accomplished in RStudio using the igraph package and ForceAtlas2 algorithm (Jacomy et al., 2014).

4. Diversity of the Qinggouzi microfossil assemblage

Abundant organic-walled microfossils were revealed from the Qinggouzi Formation, including 41 species belonging to 29 genera and 3 unnamed forms. In general, the Qinggouzi microfossil assemblage is characterized by abundant sphaeromorphic acritarchs, filaments, and colonial aggregates, representing a mixture of eukaryotes, possible eukaryotes, and prokaryotes. See Supplementary Data for systematic paleontology.

4.1. Eukaryotes

Determining the eukaryotic affinity of Proterozoic microfossils is challenging due to lack of cytological features such as nuclei, organelles, cytoskeleton, and cell membrane with detectable sterols (Knoll, 2014). But a combination of morphological traits can be helpful to infer a eukaryotic affinity. These traits include large vesicle size, complex wall ornamentations and sculptures, presence of internal bodies, and excystment structures (Xiao, 2013). Accordingly, there are 14 morphotaxa from the Qinggouzi assemblage assigned to eukaryotes (Fig. 2). These eukaryotic taxa include (1) acanthomorphic acritarchs: *Trachyhystrichosphaera aimika* Hermann in Timofeev et al., 1976 emend. Butterfield et al., 1994 (Fig. 3A–F), *Caudosphaera expansa* Hermann & Timofeev in Jankauskas et al., 1989 (Fig. 4A–G), *Germinosphaera bispinosa* Mikhailova, 1986, emend. Butterfield et al., 1994 (Fig. 5A–C), *Eotylotopalla apophysa* (Vorob'eva et al., 2009) Ye et al., 2022 (Fig. 5D), and Unnamed Form A (Fig. 9D–G); (2) sculptured acritarchs: *Valeria lophostriata* (Jankauskas, 1979) Jankauskas, 1982 (Fig. 5E–H), *Culcitulisphaera revelata* Riedman and Porter, 2016 (Fig. 6A–D), *Dictyosphaera* sp. (Fig. 6E–F), *Lophosphaeridium* sp. (Fig. 7A–B), *Pololeptus rugosus* (Yin, 1985) Yin and Sun, 1994, emend. Tang et al., 2013 (Fig. 7C–E); (3) pteromorphs (spherical vesicles with an extended equatorial flange): *Simia annulare* (Timofeev, 1969) Mikhailova in Jankauskas et al., 1989 (Fig. 8A–D); (4) disphaeromorphs (vesicle enclosing another vesicle): *Pterospermopsisomorpha insolita* Timofeev, 1969 emend. Mikhailova in Jankauskas et al., 1989 (Fig. 8E), *Pterospermopsisomorpha pileiformis* Timofeev, 1966 emend. Mikhailova in Jankauskas et al., 1989 (Fig. 8F–H); and (5) multicellular green alga: *Proterocladus antiquus* Tang et al., 2020 (Fig. 9A–C).

Trachyhystrichosphaera aimika from the Qinggouzi Formation is characterized by heteromorphic processes unevenly distributed on vesicle surface (Fig. 3A–F), 54.1–259.5 µm in vesicle size, 0.7–7.4 µm in process basal width, and 3.1–30.0 µm in process length. *Caudosphaera expansa* is characterized by a spheroidal vesicle with a gradually tapering tail consisting of a bundle of fibers (Fig. 4A–G). A dark inner body is sometimes present (Fig. 4D–F). *Caudosphaera expansa* is 46.2–147.5 µm in vesicle diameter, 26.8–640.5 µm in tail length, 6.0–113.5 µm in tail basal width, and 53.5–132.0 µm in inner cell diameter. *Caudosphaera expansa* is distinct from morphologically similar forms, such as *Clavitrachoides rugosus*, *Germinosphaera bispinosa*, and

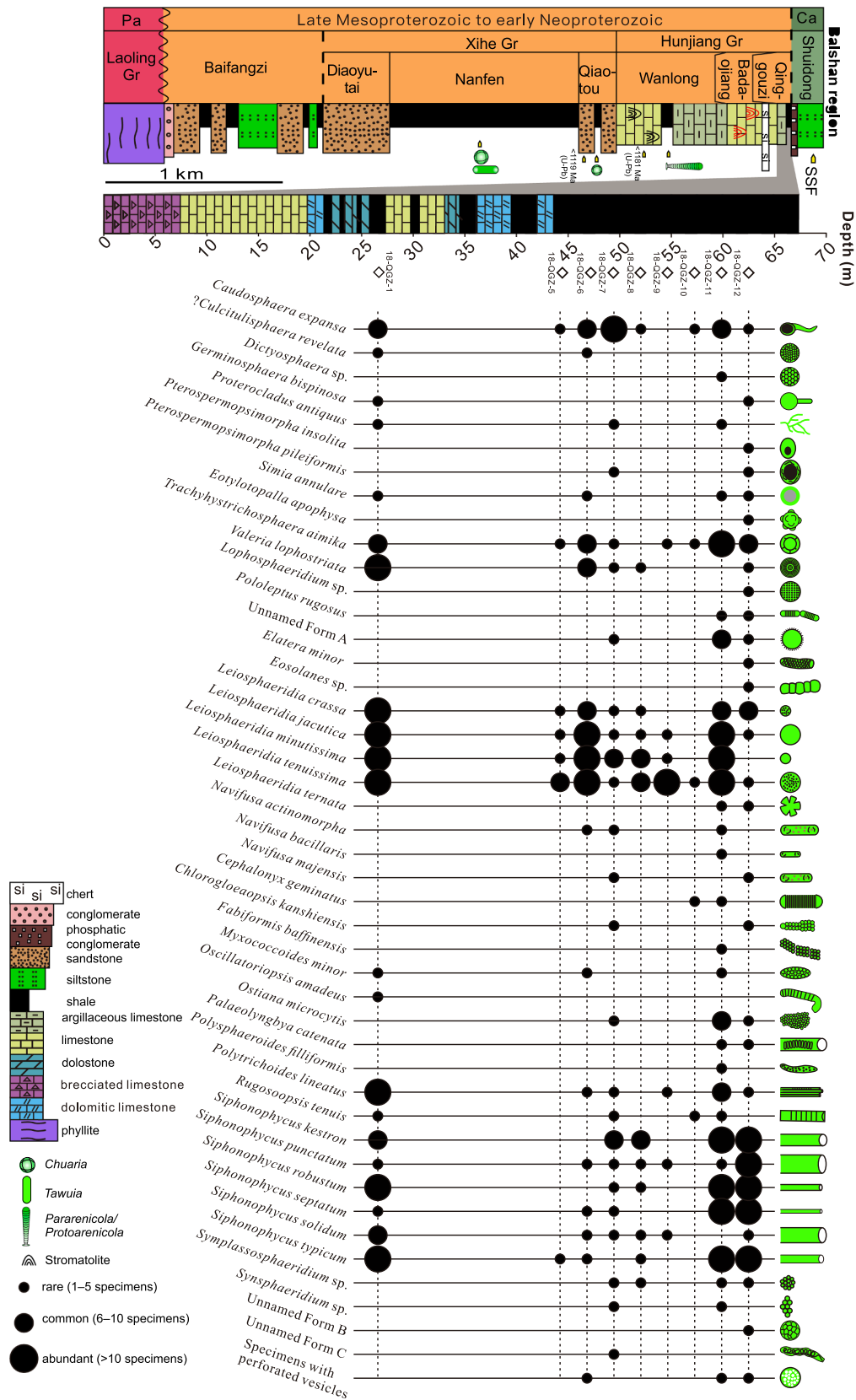


Fig. 2. Generalized stratigraphic column of Proterozoic-Cambrian strata in the Baishan region, showing fossil horizons and abundance by sample depth. Geochronological data are from Zhang et al. (2021). Carbonaceous macrofossil data are from Pang et al. (2021). Gr = Group. Ca = Cambrian. Pa = Paleoproterozoic.

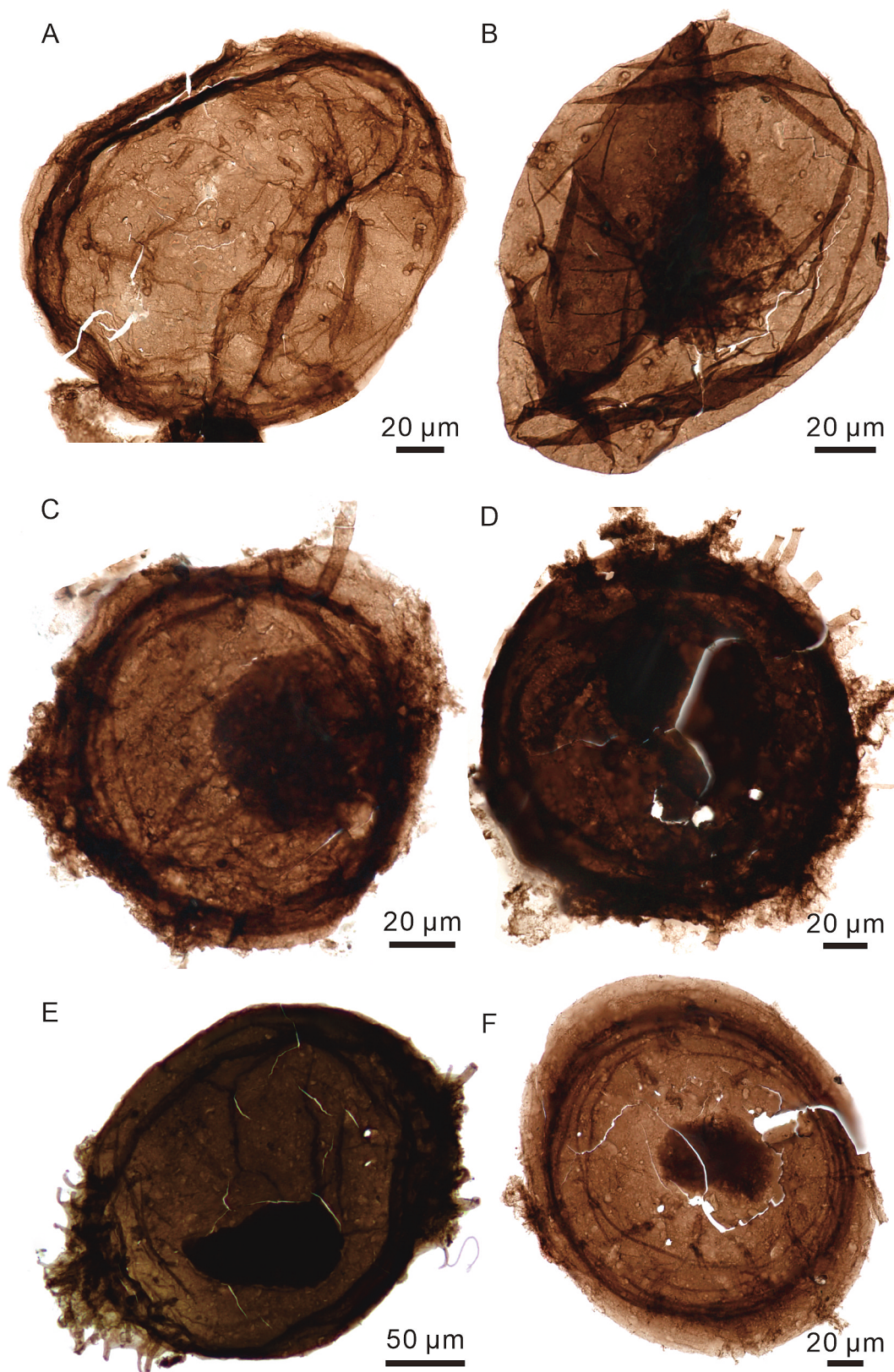


Fig. 3. *Trachyhystrichosphaera aimika* (A–F). (A) PB201523; 18-QGZ-12-13-1. (B) PB201524; 18-QGZ-1-39-3. (C) PB201525; 18-QGZ-11-26-15. (D) PB201526; 18-QGZ-11-4-7. (E) PB201527; 18-QGZ-12-4-1. (F) PB201528; 18-QGZ-5-1-6. All fossil images in this and other figures are transmitted light micrographs unless otherwise noted. For each illustrated specimen in this and other figures, a NIGPAS museum catalog number (prefix PB) and a slide or specimen number (prefix 18-QGZ-xx) are provided.

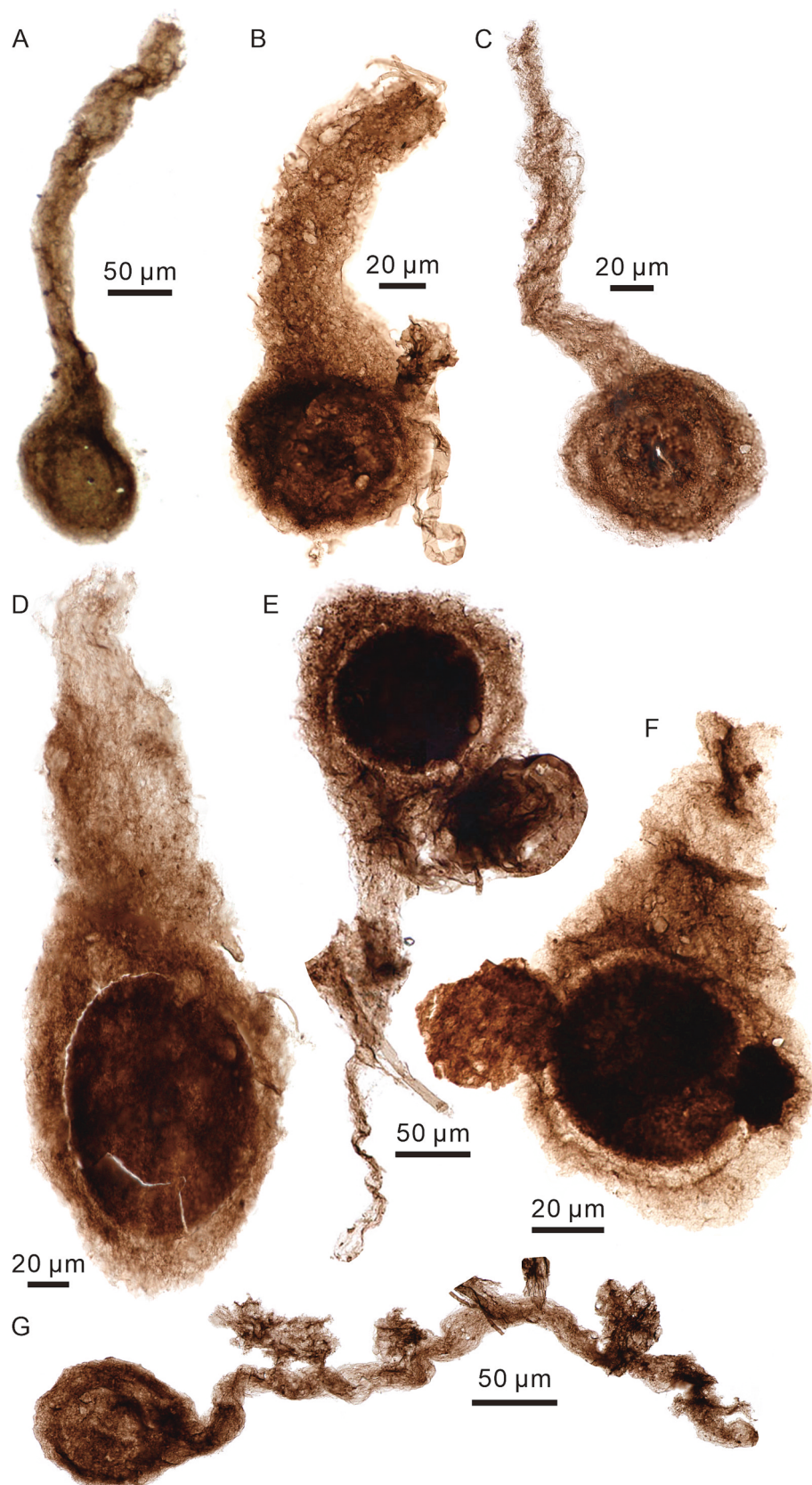


Fig. 4. *Caudosphaera expansa* (A–G). (A) PB201529; 18-QGZ-7-2-1. (B) PB201530; 18-QGZ-12-16-5. (C) PB201531; 18-QGZ-8-9-2. (D) PB201532; 18-QGZ-5-1-9. (E) PB201533; 18-QGZ-10-28-1. (F) PB201534; 18-QGZ-12-81-1. (G) PB201535; 18-QGZ-10-22-1.

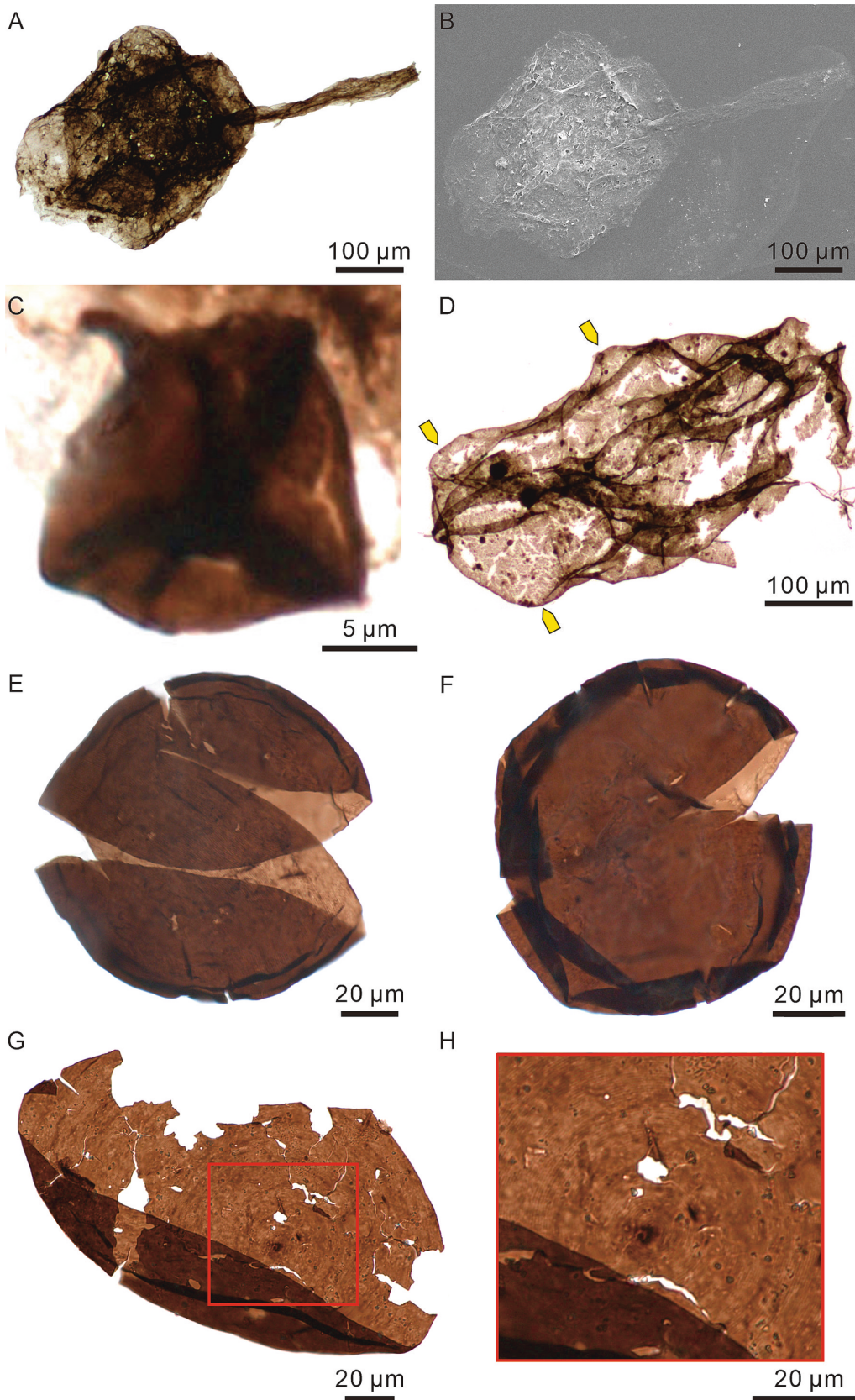


Fig. 5. *Germinosphaera bispinosa* (A–C), *Eotylotopalla apophysa* (D), and *Valeria lophostriata* (E–H). (B) is a scanning electron microscopy photograph of the same specimen in (A). Arrows in (D) mark the hemispherical process. (A–B) PB201536; 18-QGZ-12-1. (C) PB201537; 18-QGZ-1-50-6. (D) PB201538; 18-QGZ-12-4-2. (E) PB201539; 18-QGZ-1-8-5. (F) PB201540; 18-QGZ-1-23-2. (G) PB201541; 18-QGZ-7-12-3. (H) Magnification of box area in (G), showing concentric grooves on vesicle wall.

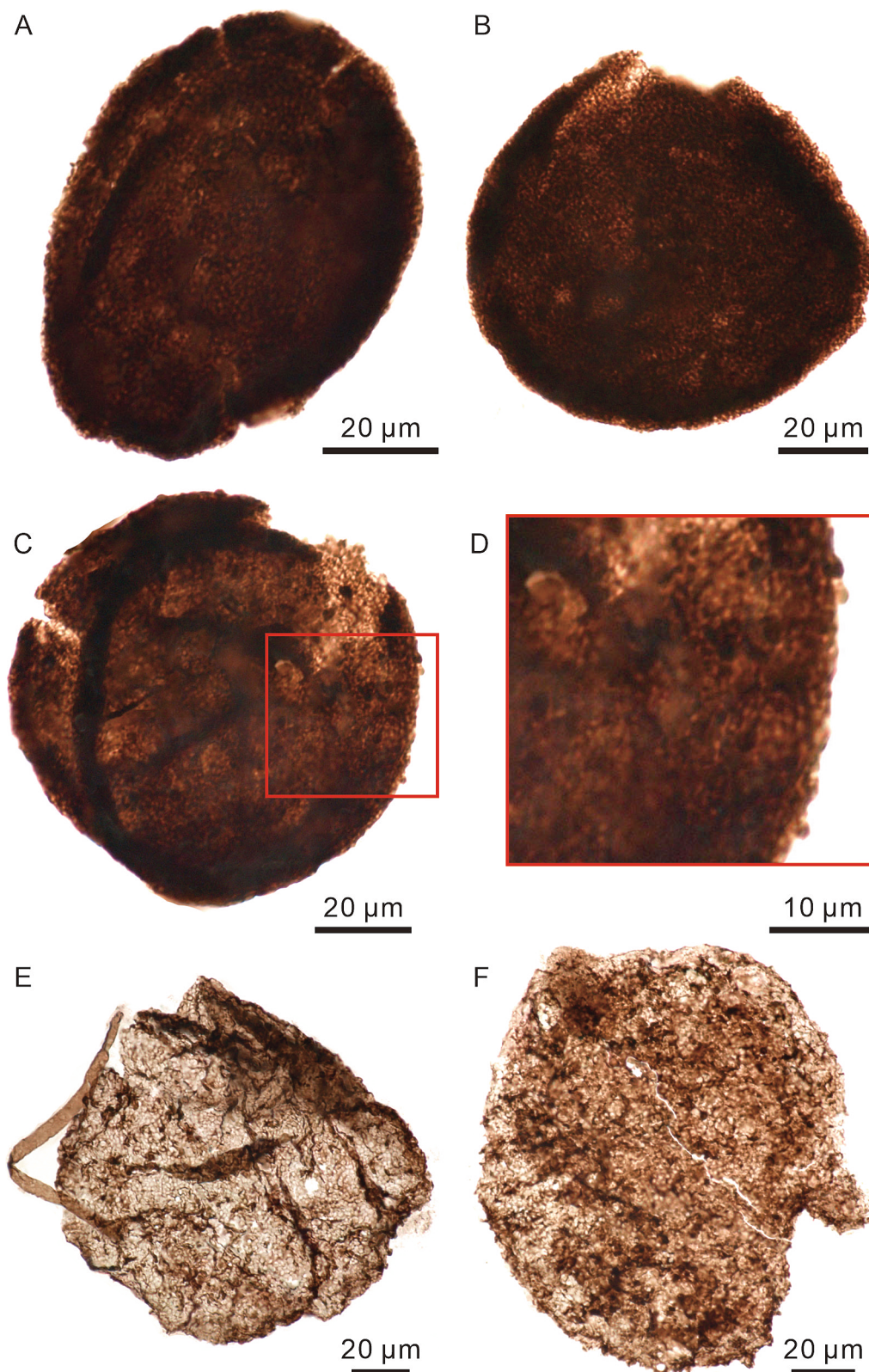


Fig. 6. *Culcitulisphaera revelata* (A–D) and *Dictyosphaera* sp. (E–F). (A) PB201542; 18-QGZ-6-57-3. (B) PB201543; 18-QGZ-1-28-10. (C) PB201544; 18-QGZ-6-21-4. (D) Magnification of box area in (C), showing tuberculate structures on vesicle outer surface. (E) PB201545; 18-QGZ-11-38-7. (F) PB201546; 18-QGZ-11-38-8.

Palaeovaucheria clavata, in its gradually tapering tail. *Germinosphaera bispinosa* (Fig. 5A–C) is characterized by a spheroidal vesicle (16.5–373.4 μm in diameter) with a thin cylindrical process that is 1.8–24.8 μm in basal width and 3.8–289.6 μm in length. A single

specimen of ovoidal vesicle (257.2 μm in width and 497.4 μm in length) bearing several prominent hemispherical processes is tentatively assigned to *Eotylotopalla apophysa* (Fig. 5D); the processes are 24.6–37.6 μm long and 79.3–80.1 μm wide. Additionally, spheroidal to ellipsoidal

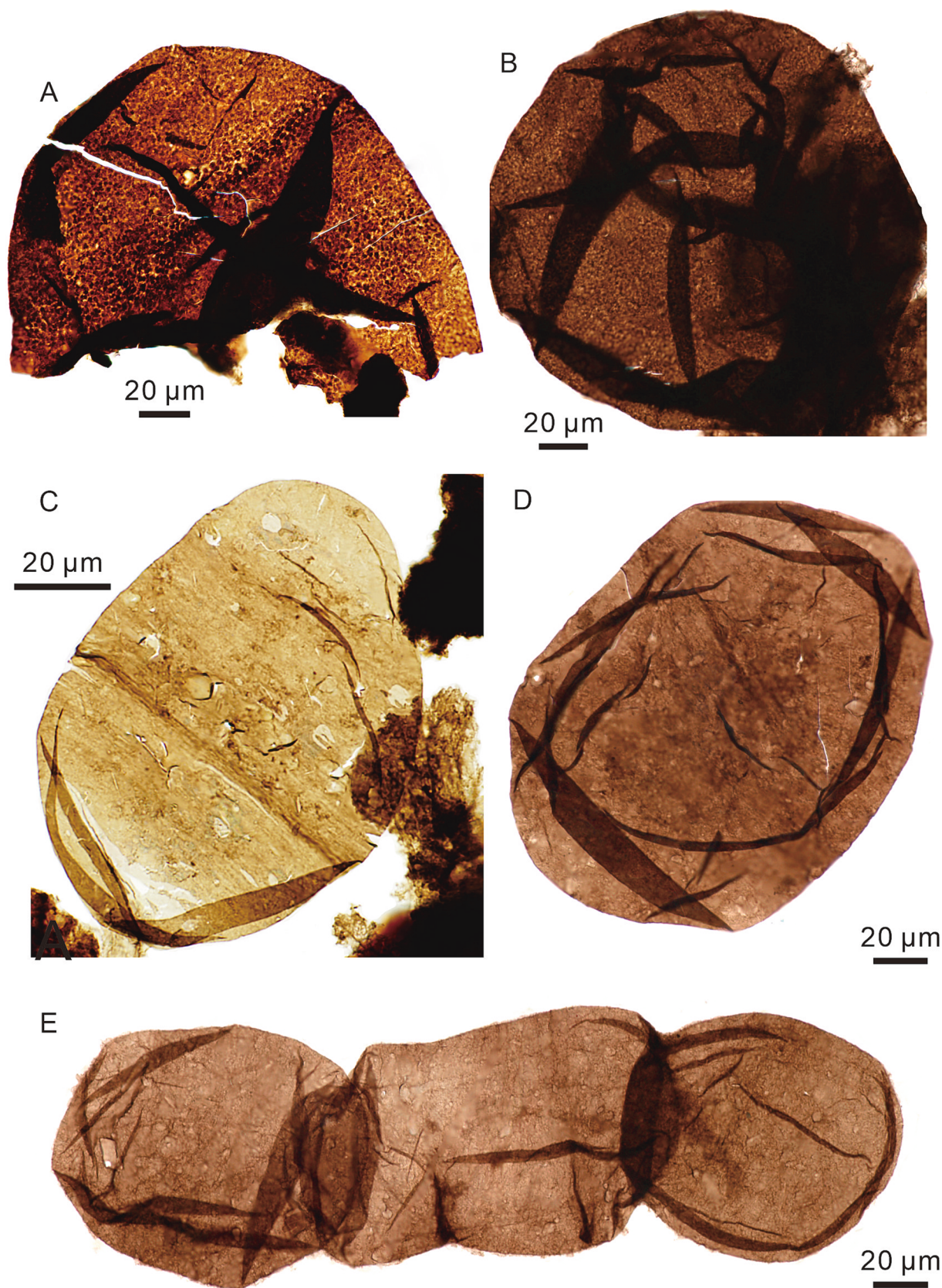


Fig. 7. *Lophosphaeridium* sp. (A–B) and *Pololeptus rugosus* (C–E). (A) PB201547; 18-QGZ-12-86-3. (B) PB201548; 18-QGZ-12-16-3. (C) PB201549; 18-QGZ-12-86-1. (D) PB201550; 18-QGZ-11-15-3. (E) PB201551; 18-QGZ-11-9-6.

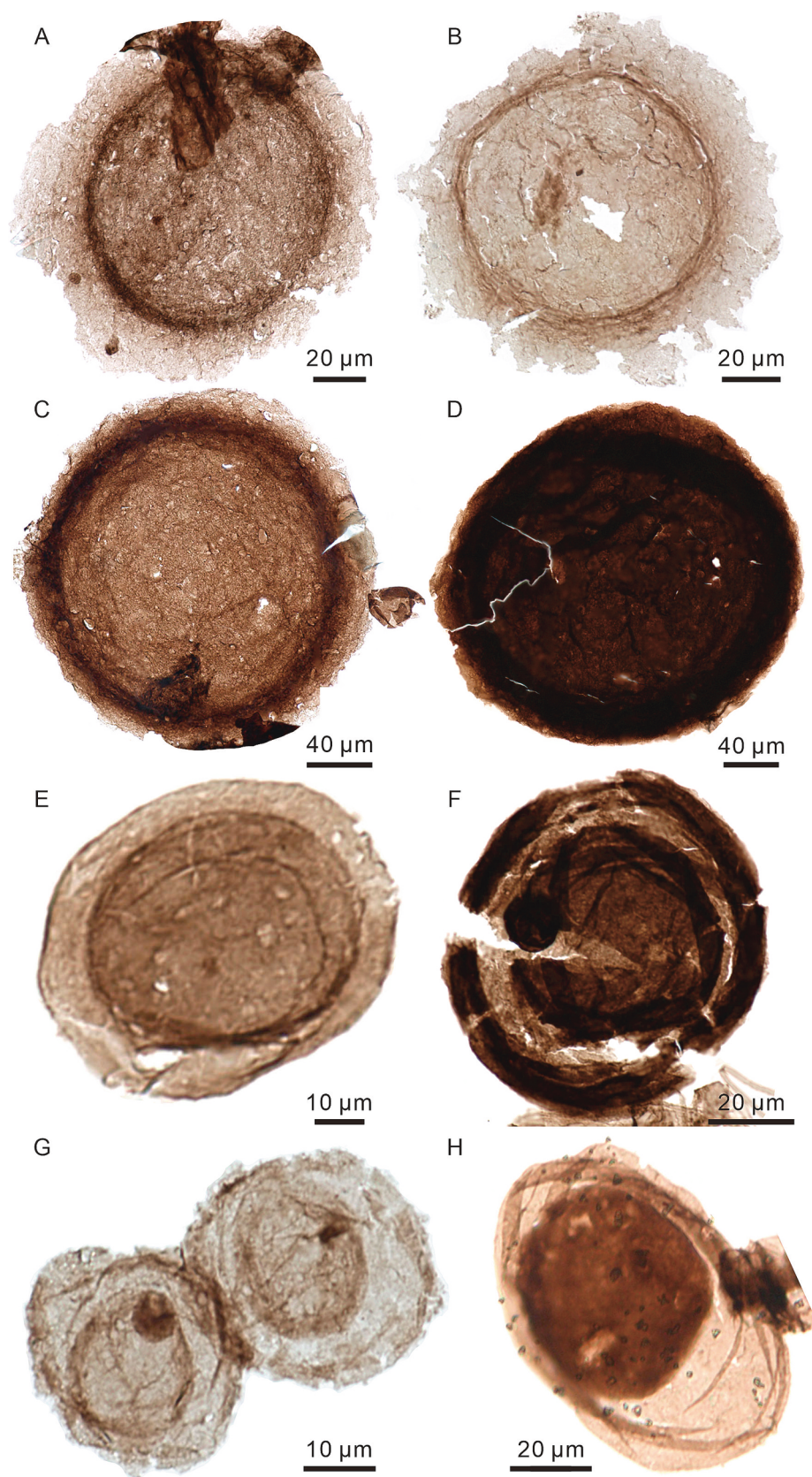


Fig. 8. *Simia annulare* (A–D), *Pterospermopsimorpha insolita* (E), *Pterospermopsimorpha pileiformis* (F–H). (A) PB201552; 18-QGZ-8-30-1. (B) PB201553; 18-QGZ-1-24-6. (C) PB201554; 18-QGZ-8-36-1. (D) PB201557; 18-QGZ-6-41-1. (E) PB201560; 18-QGZ-12-40-1. (F) PB201561; 18-QGZ-12-29-3. (G) PB201562; 18-QGZ-7-4-2. (H) PB201563; 18-QGZ-7-12-3.

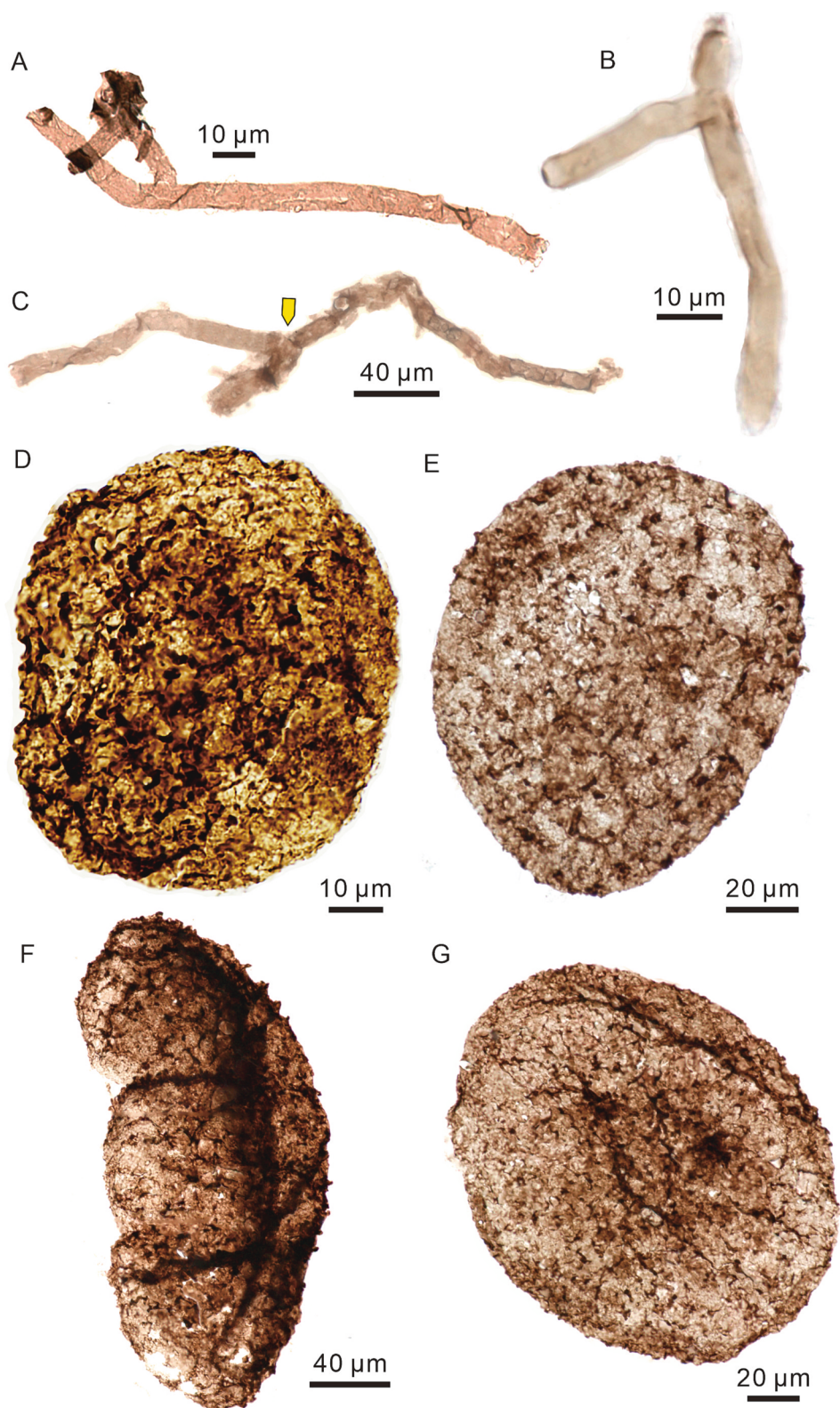


Fig. 9. *Proterocladus antiquus* (A–C) and Unnamed Form A, ornamented with numerous small conical processes (D–G). Arrow in (C) marks a septum. (A) PB201564; 18-QGZ-7-2-1. (B) PB201565; 18-QGZ-1-3-3. (C) PB201566; 18-QGZ-11-60-4. (D) PB201567; 18-QGZ-12-71-1. (E) PB201568; 18-QGZ-11-26-13. (F) PB201569; 18-QGZ-11-3-1. (G) PB201570; 18-QGZ-11-26-13.

vesicles ornamented with densely distributed conical processes (Fig. 9D–G), 38.9–243.2 µm in vesicle diameter, 1.5–3.2 µm in process basal width, and 1.2–5.2 µm in process length, were recovered from the Qinggouzi Formation. They are morphologically similar to *T. aimika*, but their processes are much smaller and shorter than those of *T. aimika*. Their processes also resemble those of *Lanulatisphaera lauffeldii* (Porter and Riedman, 2016). However, details of the processes are yet to be observed under scanning electron microscopy (SEM). Thus, we tentatively leave these specimens in an open nomenclature (Unnamed Form A).

Qinggouzi specimens of *Valeria lophostriata* are characterized by intensive and evenly spaced concentric striations (Fig. 5E–H), often with medial splits, 45.4–210.5 µm in vesicle diameter. Specimens identified as *Culcitulispheera revelata* (Fig. 6A–D) are 60.7–104.1 µm in vesicle diameter, and their somewhat opaque vesicles are ornamented with densely arranged circular or interlocking polygonal elements (0.9–1.2 µm in diameter; Fig. 6A–D). Blunt protrusions can be observed on the edge of the vesicles (Fig. 6D), indicating that the circular and polygonal elements were probably tuberculate protrusions compressed on the outer vesicle surface, a feature characteristic of *Culcitulispheera revelata* (Riedman and Porter, 2016). Specimens identified as *Dictyosphaera* sp. (Fig. 6E–F) are similar to *Culcitulispheera revelata* under TLM, with interlocking polygonal structures on the vesicles, which are 121.2–136.4 µm in diameter. However, these specimens have a much thinner vesicle wall and more importantly, no protrusions are observed on the edge of compressed vesicles. Thus, the polygonal structures are sculptures on the vesicle walls. Given that it is difficult to decide whether the polygonal structures are on inner or outer vesicle surface based on TLM, we tentatively place these specimens under an open nomenclature. Two specimens with possible verrucate surface sculptures on vesicle wall are tentatively assigned to *Lophosphaeridium* sp. (Fig. 7A–B). These specimens are 170.6–175.7 µm in vesicle diameter. Their verrucate vesicle sculpture needs to be confirmed using SEM in future studies. Spheroidal to barrel-like vesicles ornamented with dense transverse annulations are assigned to *Pololeptus rugosus* (Fig. 7C–E). The vesicles are 76.2–131.4 µm in diameter, and can be preserved solitarily or in chains (Fig. 7E).

The pteromorphic acritarch *Simia annulare* is also present in the Qinggouzi Formation (Fig. 8A–D). It has a translucent to semi-opaque, spheroidal central body surrounded by an extended equatorial flange with an irregular margin, 100.4–599.7 µm in overall diameter, 43.7–204.2 µm in central body diameter, and 5.5–22.5 µm in flange width. The central body sometimes has concentric folds.

The disphaeromorph acritarch *Pterospermopsimorpha* is superficially similar to *Simia* in having a central body surrounded by an apparent flange. However, the apparent flange in *Pterospermopsimorpha* is a taphonomic artifact from two-dimensional compression; it actually represents an outer vesicle, as can be ascertained by its smooth and regular margins. Most disphaeromorph specimens from the Qinggouzi Formation can be assigned to *Pterospermopsimorpha insolita* and *Pterospermopsimorpha pileiformis*. Specimens of *P. insolita* are characterized by a translucent and smooth-walled outer vesicle surrounding a darker inner body (Fig. 8E). The outer and inner vesicles are 61.2–75.1 µm and 46.6–57.3 µm in diameter, respectively, with the inner vesicle occupying 76% of the outer vesicle diameter. In contrast, *P. pileiformis* is characterized by a translucent and shagreen outer vesicle enclosing a semi-opaque inner vesicle (Fig. 8F–H). The outer vesicle is 27.6–88.7 µm in diameter, and the inner vesicle is 18.1–49.8 µm in diameter, occupying 62–74% of the overall diameter.

Finally, specimens of *Proterocladus antiquus* are characterized by branched, multicellular, and uniseriate filaments with intercellular septa and rounded apical termination (Fig. 9A–C). Three fragmented specimens of *P. antiquus* have been revealed in our study, 4.5–10.0 µm in filament width and 67.2–327.5 µm in length.

4.2. Possible eukaryotes

Large sphaeromorphic, tomaculate, and chain-shaped taxa in the Qinggouzi assemblage with smooth vesicle wall or simple ornamentations are interpreted as possible eukaryotes. These include (1) large sphaeromorphs: *Leiosphaeridia minutissima* (Naumova, 1949) Jankauskas in Jankauskas et al., 1989 (Fig. 10A–B), *Leiosphaeridia crassa* (Naumova, 1949) Jankauskas in Jankauskas et al., 1989 (Fig. 10C–D), *Leiosphaeridia jacutica* (Timofeev, 1966) Mikhailova and Jankauskas in Jankauskas et al., 1989 (Fig. 10E–F), *Leiosphaeridia tenuissima* Eisenack, 1958 (Fig. 11A), *Leiosphaeridia ternata* (Timofeev, 1966) Mikhailova and Jankauskas in Jankauskas et al., 1989 (Fig. 11B), and specimens with perforated vesicles (Fig. 11C–F); (2) nettomorphs: *Navifusa actinomorpha* (Maithy, 1973) Hofmann and Jackson, 1994 (Fig. 12A–B), *Navifusa majensis* Pyatiletov, 1980 (Fig. 12C–F), and *Navifusa bacillaris* (Hermann, 1981) Hofmann and Jackson, 1994 (Fig. 12G); (3) the tubular fossil *Elatera minor* Vorob'eva and Sergeev, 2015 (Fig. 13A–D); (4) the multicellular trichome fossil *Eosolena* sp. (Fig. 13E); and (5) one unnamed form that may represent dividing cells (Fig. 20A–C).

The smooth-walled sphaeromorph *Leiosphaeridia* is the most abundant genus in the Qinggouzi assemblage. Species identification of *Leiosphaeridia* is based on vesicle size and wall thickness (Jankauskas et al., 1989; Butterfield et al., 1994), and Javaux and Knoll (2017) argued that species identification should be based on population statistics, favoring modal rather than individual vesicle size as a classification criterion. Although dispute remains (Porter and Riedman, 2016; Zheng et al., 2022), for practical reasons we adopt the classification scheme of Butterfield et al. (1994). Thus, Qinggouzi specimens of *Leiosphaeridia* are here assigned to five morphospecies on the basis of wall thickness, vesicle dimension, and radial split structure (Butterfield et al., 1994; Liron and Moczydlowska, 2017): *L. minutissima*, thin-walled, < 70 µm in diameter (Fig. 10A–B); *L. crassa*, thick-walled, < 70 µm in diameter (Fig. 10C–D); *L. jacutica*, thick-walled, 70–800 µm in diameter (Fig. 10E–F); *L. tenuissima*, thin-walled, 70–200 µm in diameter, (Fig. 11A); and *L. ternata*, characterized by radially arranged peripheral splits (Fig. 11B). In addition, there are specimens of *Valeria lophostriata* (Fig. 11C) and smooth-walled sphaeromorphic vesicles (Fig. 11D–F) in our collection that are perforated with abundant densely arranged circular holes (1.4–2.8 µm in diameter), suggesting the perforations are not taxon specific. Given that the origin of these holes has been variously attributed to taphonomic artifacts, original biological structures, and predation via perforation (Grey and Willman, 2009; Porter, 2016; Liron et al., 2018; Li et al., 2019), we tentatively assign these specimens as “specimens with perforated vesicles”.

Three nettomorphs have been recovered from the Qinggouzi Formation, including *Navifusa actinomorpha*, *Navifusa majensis* and *Navifusa bacillaris*. Specimens of *N. actinomorpha* have a translucent tomaculate vesicle with rounded ends (Fig. 12A–B). The vesicles are 163.1–346.8 µm in length, 50.1–128.6 µm in width, and 2.1–4.6 in length/width ratio. It is noteworthy that some small discoidal structures (Fig. 12B), 2.9–5.0 µm in diameter, are found within the vesicle as no small discoids attached beyond the edge of the hosting vesicle, probably representing reproductive spores. Compare to *N. actinomorpha*, specimens of *N. majensis* are characterized by smaller vesicles but greater length/width ratios (Fig. 12C–F), with a vesicle length of 84.5–122.4 µm, vesicle width of 24.5–27.8 µm, and length/width ratio of 3.0–4.8. Small discoidal structures, 1.5–3.9 µm in diameter, are also found in the vesicles of *N. majensis*. In addition, specimens of *N. bacillaris* have an elongate rod-like vesicle with bluntly round ends (Fig. 12G). They are 4.1–6.0 µm in width, 23.3–23.5 µm in length, and 3.9–5.2 in length/width ratios, representing the smallest vesicle dimensions among the three species of *Navifusa* in the Qinggouzi Formation.

The spring-like fossil *Elatera minor* is characterized by a non-branching tube ornamented with numerous annular ribs on the surface (Fig. 13A–D). The tubes are 12.0–67.6 µm in diameter and 123.0–366.7 µm in length. Additionally, the multicellular trichome

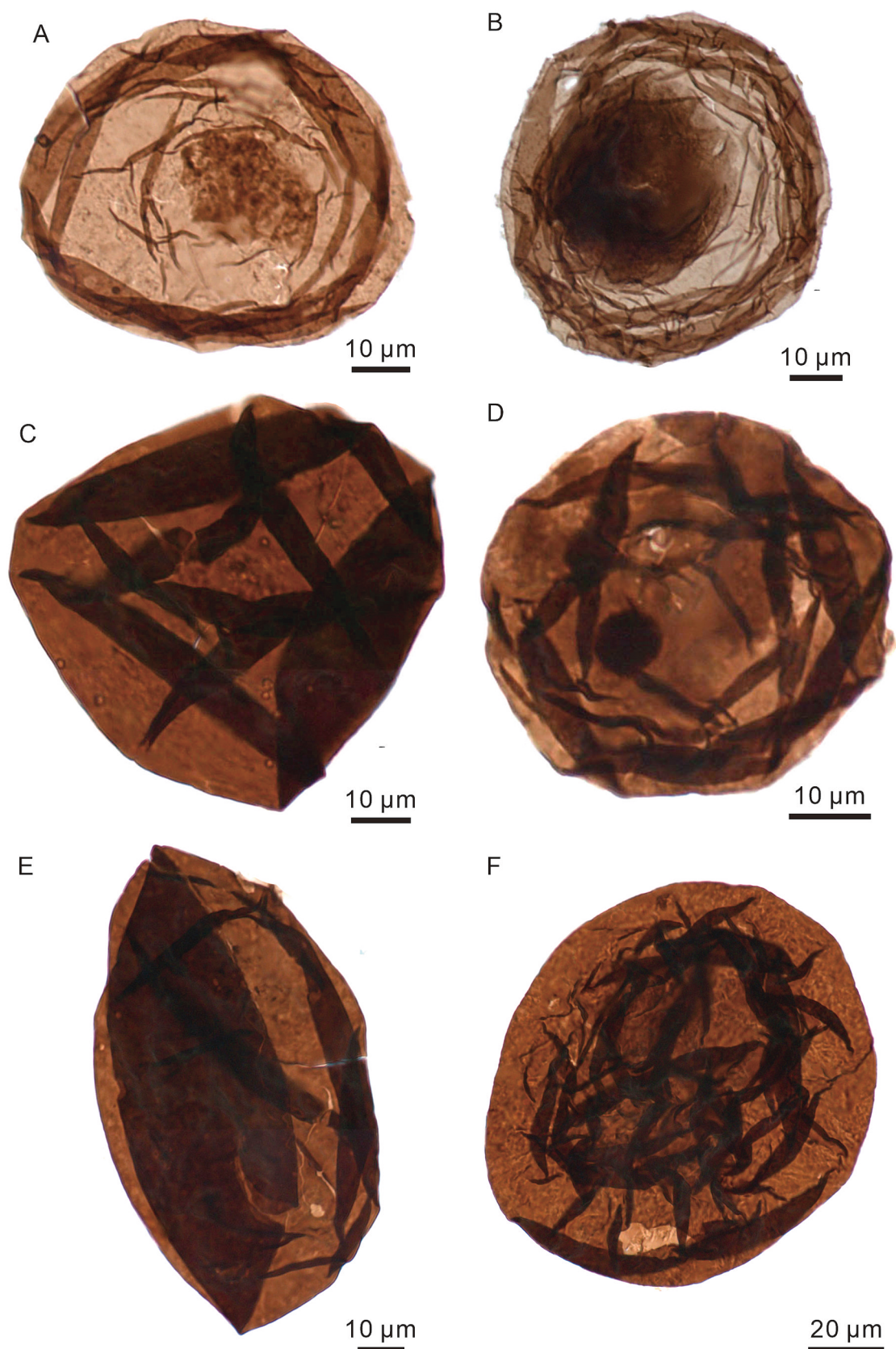


Fig. 10. *Leiosphaeridia minutissima* (A–B), *Leiosphaeridia crassa* (C–D), and *Leiosphaeridia jacutica* (E–F). (A) PB201571; 18-QGZ-1-3-5. (B) PB201572; 18-QGZ-1-23-3. (C) PB201573; 18-QGZ-1-27-8. (D) PB201574; 18-QGZ-1-26-8. (E) PB201575; 18-QGZ-1-33-2. (F) PB201576; 18-QGZ-11-3-11.

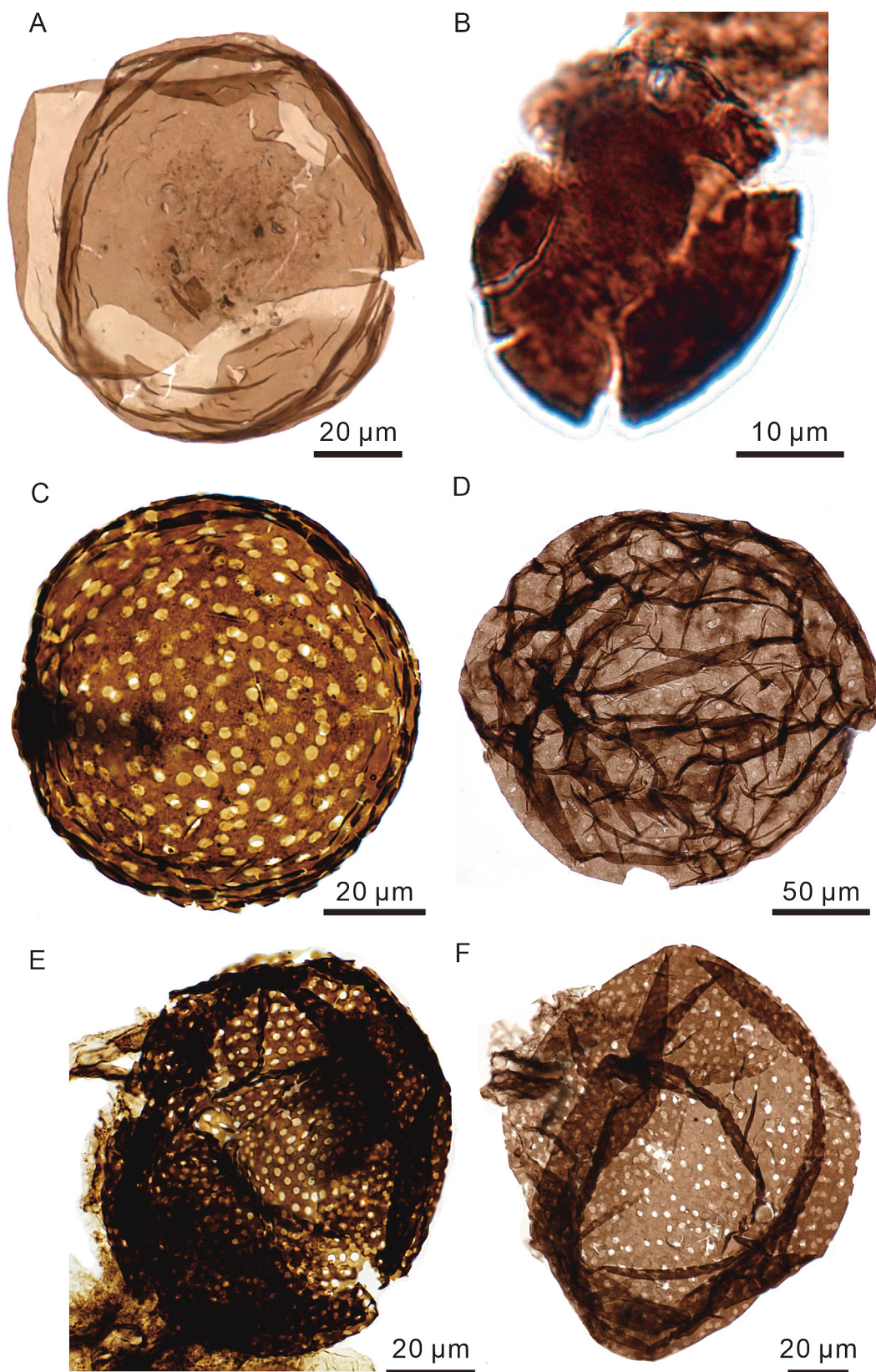


Fig. 11. *Leiosphaeridia tenuissima* (A), *Leiosphaeridia ternata* (B), and spheroidal fossils with well rounded perforations (C–F). (C) is a specimen of *Valeria lophostriata*, (D–F) are specimens of *Leiosphaeridia*. (A) PB201577; 18-QGZ-1-45-6. (B) PB201578; 18-QGZ-12-29-2. (C) PB201579; 18-QGZ-8-50-1. (D) PB201580; 18-QGZ-11-54-3. (E) PB201581; 18-QGZ-12-56-1. (F) PB201582; 18-QGZ-12-16-1.

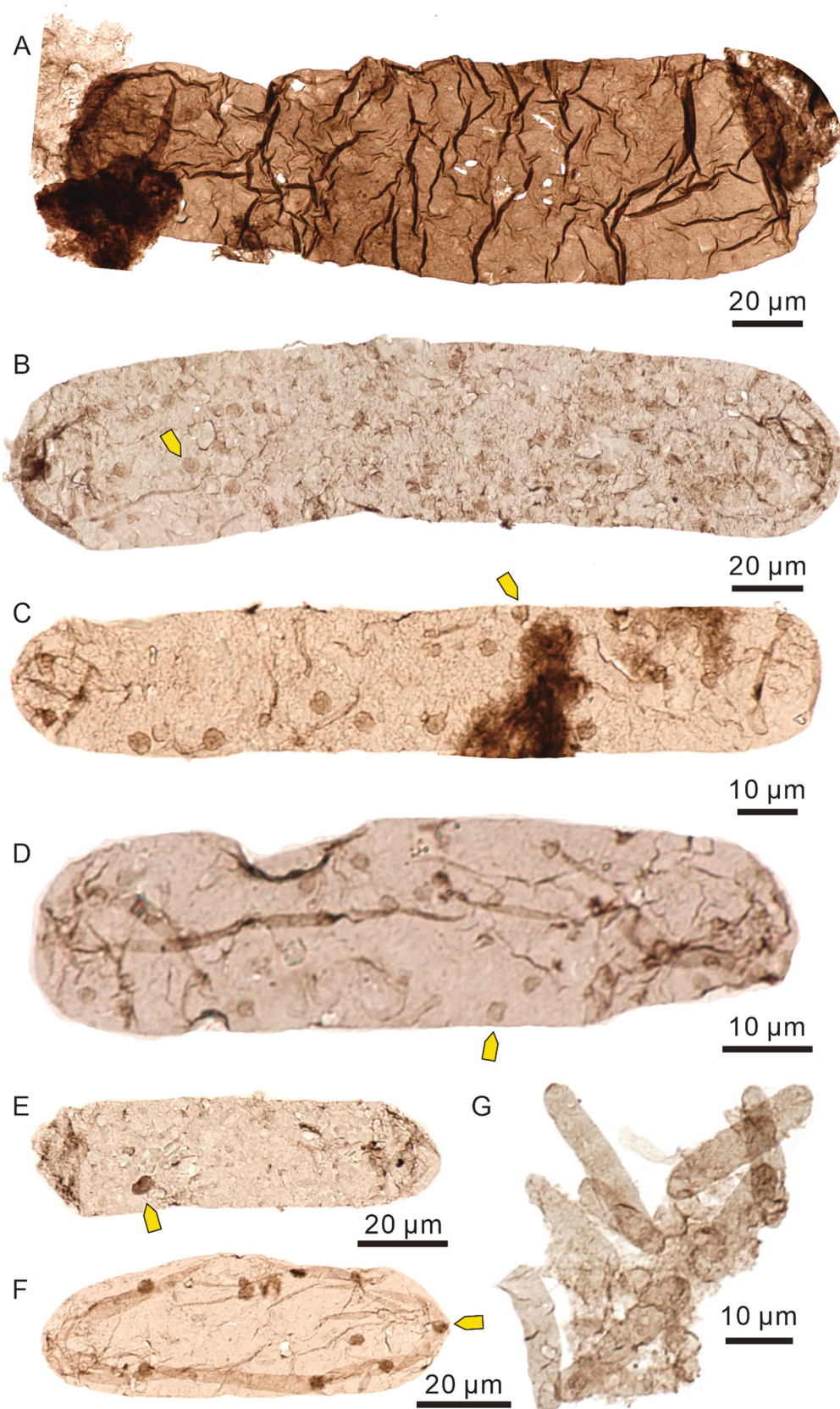


Fig. 12. *Navifusa actinomorpha* (A–B), *Navifusa majensis* (C–F), and *Navifusa bacillaris* (G). Arrows in (B–F) mark the discoidal structures. (A) PB201583; 18-QGZ-7-12-1. (B) PB201584; 18-QGZ-11-90-3. (C) PB201585; 18-QGZ-7-11-5. (D) PB201586; 18-QGZ-7-1-6. (E) PB201587; 18-QGZ-12-8-4. (F) PB201588; 18-QGZ-7-4-7. (G) PB201589; 18-QGZ-11-31-7.

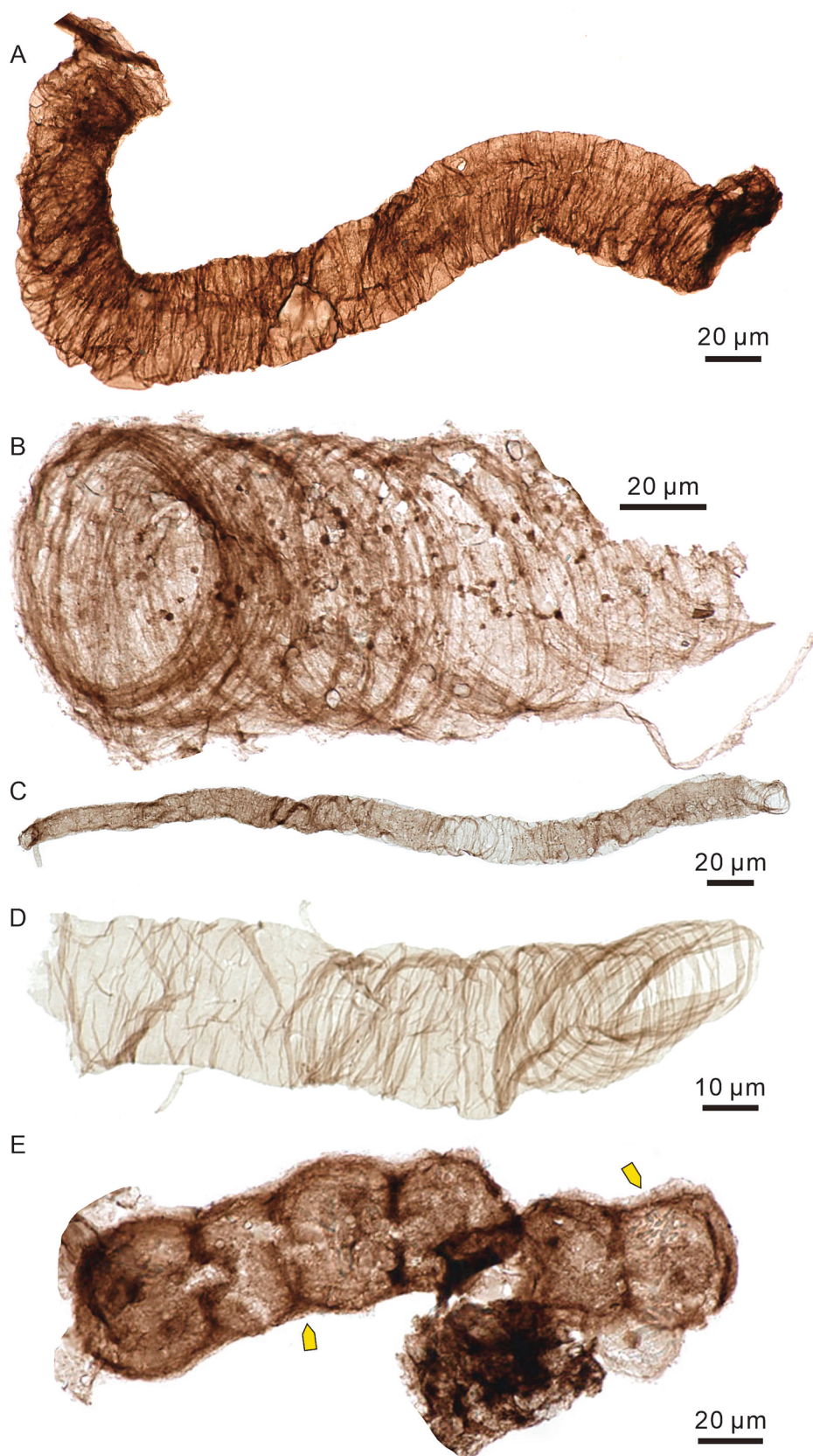


Fig. 13. *Elateria minor* (A–D) and *Eosolena* sp. (E). Arrows in (E) mark the mucilaginous matrix. (A) PB201590; 18-QGZ-10-11-4. (B) PB201591; 18-QGZ-10-30-1. (C) PB201592; 18-QGZ-10-26-1. (D) PB201593; 18-QGZ-7-1-24. (E) PB201594; 18-QGZ-7-1-23. (F) PB201595; 18-QGZ-10-28-1.

Eosolena sp. is composed of a chain of several oval vesicles with intercellular septa (Fig. 13E). Transverse constrictions occur at the septa. The trichome is 49.9–59.2 μm in width and up to 243.7 μm in total length. The Qinggouzi specimen of *Eosolena* is distinct from all known species of *Eosolena* for its much smaller vesicle diameter and may represent a new species (Li et al., 2020b). Given that only one specimen is available, we tentatively leave the specimen in an open nomenclature. Finally, several unicellular specimens from the Qinggouzi Formation show a prominent constriction in the middle of the vesicle, suggesting that they may have been at a dividing stage (Fig. 20A–C).

4.3. Prokaryotes

Spheroidal and filamentous aggregates are abundant in the Qinggouzi assemblage. The morphologies of these organisms are simple and similar to many extant bacteria. Thus, although many of these fossil forms are likely polyphyletic, we tentatively interpret them as prokaryotes. This category includes (1) filamentous trichomes: *Oscillatoriaopsis amadeus* (Schopf and Blacic, 1971) Butterfield, 1994 (Fig. 14H); (2) filamentous sheaths: *Rugosoopsis tenuis* Timofeev and Hermann, 1979, emend. Butterfield et al., 1994 (Fig. 14A–E), *Cephalonyx geminatus* (Jankauskas, 1980) Butterfield, 1994 (Fig. 14F–G), *Siphonophycus septatum* (Schopf, 1968) Knoll et al., 1991 (Fig. 15A–B), *Siphonophycus robustum* (Schopf, 1968) Knoll et al., 1991 (Fig. 15C–D), *Siphonophycus typicum* (Hermann, 1974) Butterfield in Butterfield et al., 1994 (Fig. 15E–F), *Siphonophycus kestron* Schopf, 1968 (Fig. 15G–I), *Siphonophycus solidum* (Golub, 1979) Butterfield in Butterfield et al., 1994 (Fig. 15J–K), *Siphonophycus punctatum* Maithy, 1973 (Fig. 15L), and *Polytrichoides lineatus* Hermann in Timofeev et al., 1976 (Fig. 16A–F); (3) filamentous sheaths containing cylindrical or spheroidal vesicles: *Palaeolyngbya catenata* Hermann, 1974 (Fig. 17A–B), *Polysphaeroides filliformis* Hermann in Timofeev et al., 1976 (Fig. 17C–D), *Fabiformis baffinensis* Hofmann in Hofmann and Jackson, 1994 (Fig. 17E–F), and *Chlorogloeopsis kanshiensis* (Maithy, 1973) Hofmann and Jackson, 1994 (Fig. 18A–B); (4) coccoidal forms: *Symplastosphaeridium* sp. (Fig. 18C–F), *Synsphaeridium* sp. (Fig. 19A–B), *Myxococcoides minor* Schopf, 1968 (Fig. 19C–D), *Ostiana microcystis* Hermann in Timofeev et al., 1976 (Fig. 19E–H); and (5) two unnamed forms (Fig. 20D–E).

One ribbon-like multicellular trichome is here identified as *Oscillatoriaopsis amadeus* based on its tabulate cells separated by true intercellular septa (Fig. 14H). No encompassing sheaths can be observed and slight constrictions are present at septa. This specimen is 11.6 μm in trichome diameter, 80.6 μm in trichome length, 11.0–12.7 μm in cell width, and 4.4–8.1 μm in cell length, with a cell length/width ratio of 0.55. *Oscillatoriaopsis amadeus* is distinct from other species of the genus in its trichome diameter of 8.0–14.0 μm (Butterfield et al., 1994).

Fragmentary specimens of *Rugosoopsis tenuis* are characterized by bilayered tubular sheaths bearing prominent annular wrinkles or ribs (Fig. 14A–E). The tubular sheaths are 56.1–373.9 μm in length, 15.0–54.2 μm in width. Filamentous specimens of *Cephalonyx geminatus* (Fig. 14F–G) are 32.5–34.2 μm in width, 77.2–157.2 μm in total length, ornamented with pseudocellular annulations (1.7–3.8 μm in length) that are separated by smooth and thin-walled intervals (0.5–2.0 μm in length), and have rounded terminal ends (Fig. 14G). These specimens are similar to the *Cephalonyx geminatus* specimen illustrated in Butterfield et al. (1994). The most common filamentous sheaths in the Qinggouzi Formation are morphospecies of *Siphonophycus* Schopf, 1968. Given their simple morphology and likely polyphyletic nature, we follow Butterfield et al. (1994) and Tang et al. (2015) to differentiate *Siphonophycus* specimens from the Qinggouzi Formation into 6 species based on filament diameter: *S. septatum*, 1–2 μm in filament diameter (Fig. 15A–B); *S. robustum*, 2–4 μm (Fig. 15C–E); *S. typicum*, 4–8 μm (Fig. 15F–G); *S. kestron*, 8–16 μm (Fig. 15H–J); *S. solidum*, 16–32 μm (Fig. 15K–L); and *S. punctatum*, 32–64 μm (Fig. 15M). Bundled and non-septate filaments with capitate ends from the Qinggouzi Formation are identified as *Polytrichoides lineatus* (Fig. 16A–F). These bundles are

100.5–811.9 μm in length, 8.8–56.0 μm in width, and 1.0–4.0 μm in single filament width.

Two unbranched uniseriate and multicellular trichomes enveloped with a smooth-walled sheath are assigned to *Palaeolyngbya catenata* (Fig. 17A–B). The constituent cells are tabulate in shape, dislocated, reduced in size due to condensation, loosely and irregularly arranged, 6.2–9.4 μm in width, and 2.6–6.2 μm in length. The outer sheath is 20.9–22.8 μm in width and up to 280.9 μm in length. Qinggouzi specimens of *Polysphaeroides filliformis* are characterized by a translucent cylindrical outer sheath containing loosely arranged spheroidal vesicles (Fig. 17C–D). The outer sheath is 19.5–42.5 μm in width and 318.0–385.4 μm in length. The spheroidal vesicles inside the sheath are 5.5–8.7 μm in diameter. *Polysphaeroides filliformis* can be distinguished from the morphologically similar form *Chlorogloeopsis contexta* by its firm outer sheath, which is absent in *C. contexta*. Two cylindrical specimens composed of numerous tightly arranged vesicles surrounded by an incompletely preserved translucent membrane are assigned to *Fabiformis baffinensis* (Fig. 17E–F). These specimens are 197.0–228.3 μm in length, 23.4–40.7 μm in width, and the vesicles are 2.9–6.7 μm in diameter. The specimens of *F. baffinensis* are morphologically similar to *Polysphaeroides filliformis* but can be distinguished from the latter taxon by its more tightly arranged vesicles and its amorphous outer membrane. Cylindrical colonies consisting of two to three rows of tightly arranged spheroidal vesicles are assigned to *Chlorogloeopsis kanshiensis* (Fig. 18A–B). The cylindrical colonies are 36.3–40.0 μm across and up to 267.4 μm long. The constituent vesicles are 17.4–27.2 μm in diameter.

Specimens of *Symplastosphaeridium* sp. are characterized by spheroidal vesicles (3.0–39.8 μm in diameter) tightly packed into globular aggregates that are 30.6–150.9 μm across and are not surrounded by a common envelope (Fig. 18C–F). These specimens are distinct from *Synsphaeridium* sp. in their smaller vesicle size and globular colony shape. For comparison, Qinggouzi specimens of *Synsphaeridium* sp. are mostly irregular in shape, lacking an outer membrane (Fig. 19A–B), up to 200.0 μm in colony maximum dimension, and 9.4–44.0 μm in vesicle diameter. *Myxococcoides minor* from the Qinggouzi Formation consists of aggregates of vesicles covered by a translucent membrane, 22.9–107.8 μm in colony size, and 6.1–15.5 μm in vesicle diameter (Fig. 19C–D). Planar aggregates of *Ostiana microcystis* are composed of tightly packed spheroidal vesicles, 41.4–330.5 μm in colony size and 8.2–22.7 μm in vesicle diameter (Fig. 19E–H). No enclosing membrane is preserved.

Several specimens that cannot be identified to any existing taxa but may represent new forms are informally described as unnamed forms. Unnamed Form B is characterized by a spheroidal colony consisting of 12 tightly packed vesicles surrounded by a common membrane (Fig. 20D), 106.9–107.5 μm in colony diameter, 16.8–32.6 μm in vesicle diameter. Finally, Unnamed Form C is a helical filament (2.0–3.0 μm in width) enclosed in a smooth-walled outer sheath (86.7 μm long, 10.8 μm wide) (Fig. 20E). These unnamed forms may represent new taxa, but given the limited number of specimens available to us, they are treated as unnamed forms.

5. Results of the network analysis

To better understand the biostratigraphic correlation of the late Mesoproterozoic to early Neoproterozoic sequences in North China, we systematically compiled a dataset of fossil occurrences in these sequences. Both organic-walled microfossils and carbonaceous compression macrofossils are included in the database. We eliminated prokaryotes and *Leiosphaeridia* from our analysis owing to their extremely long stratigraphically range. We processed the data using bipartite network analysis in R package igraph to visualize the results (Fig. 21). The edge-betweenness algorithm returned a modularity (Q) score of 0.421 and identified six modules highlighted in different colors in Fig. 21, including three carbonaceous macrofossil modules and three organic-walled microfossil modules. The carbonaceous macrofossil modules are (1) the lavender module consisting of the Longshan

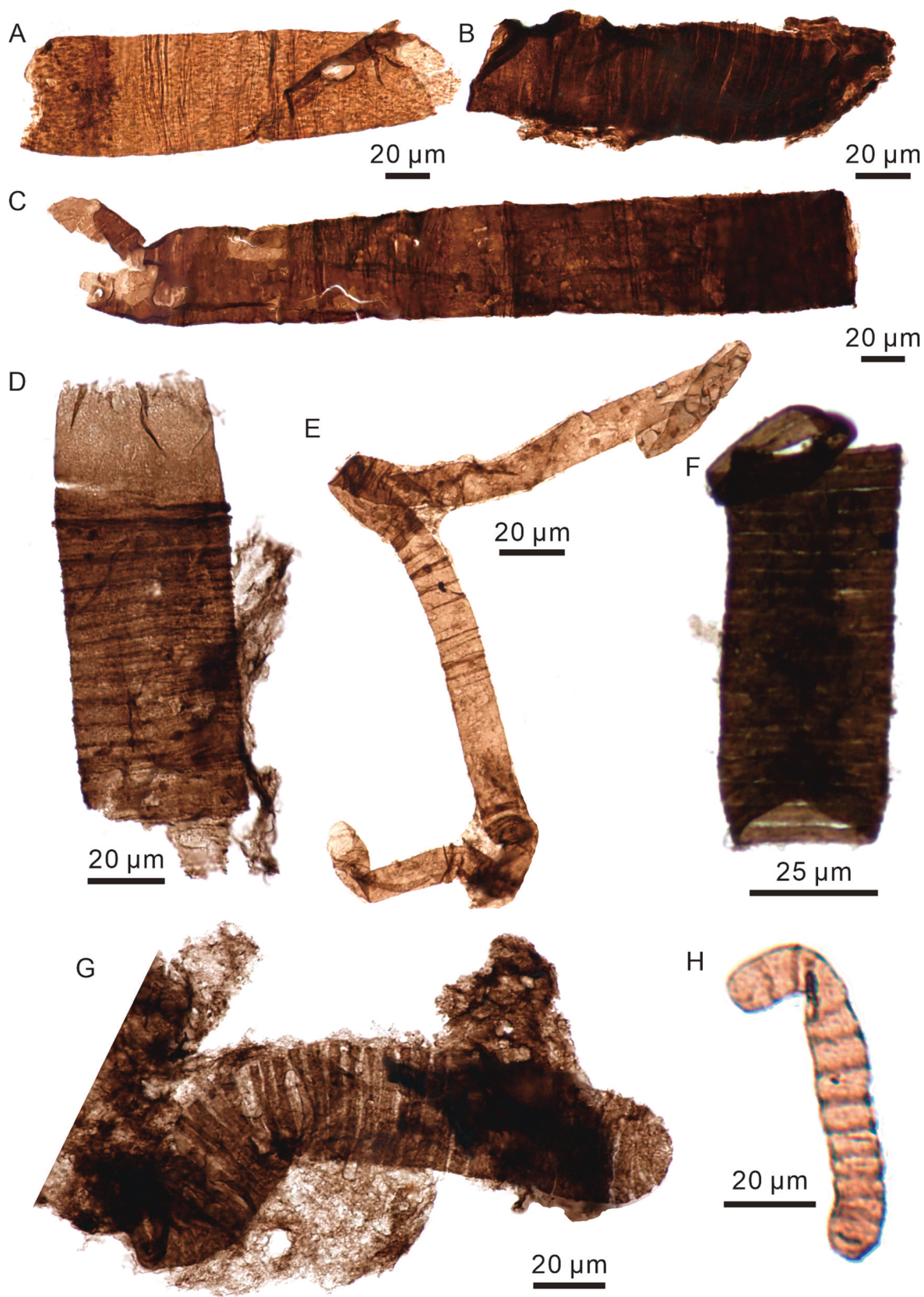


Fig. 14. *Rugosoopsis tenuis* (A–E), *Cephalonyx geminatus* (F–G), and *Oscillatorioopsis amadeus* (H). (A) PB201596; 18-QGZ-1-27-10. (B) PB201597; 18-QGZ-10-12-3. (C) PB201598; 18-QGZ-11-12-11. (D) PB201599; 18-QGZ-10-30-1. (E) PB201600; 18-QGZ-11-20-5. (F) PB201601; 18-QGZ-12-6-2. (G) PB201602; 18-QGZ-10-30-1. (H) PB201603; 18-QGZ-1-52-8.

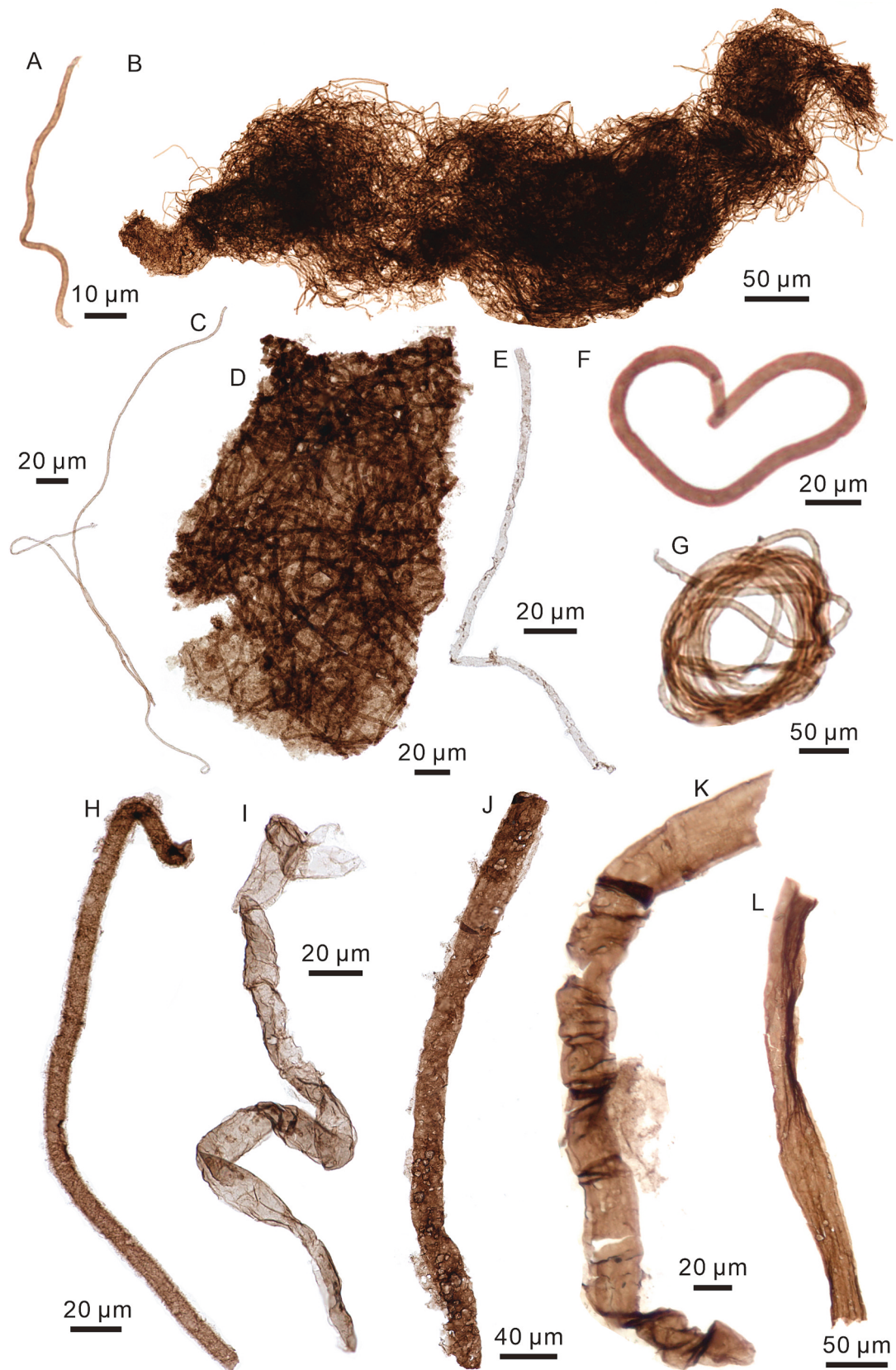


Fig. 15. *Siphonophycus septatum* (A–B), *Siphonophycus robustum* (C–D), *Siphonophycus typicum* (E–F), *Siphonophycus kestron* (G–I), *Siphonophycus solidum* (J–K), *Siphonophycus punctatum* (L). (A) PB201604; 18-QGZ-11-47-3. (B) PB201605; 18-QGZ-12-8-1. (C) PB201606; 18-QGZ-11-42-7. (D) PB201607; 18-QGZ-5-7-4. (E) PB201608; 18-QGZ-1-16-6. (F) PB201609; 18-QGZ-7-1-23. (G) PB201610; 18-QGZ-8-28-1. (H) PB201611; 18-QGZ-5-3-5. (I) PB201612; 18-QGZ-11-32-3. (J) PB201613; 18-QGZ-6-18-7. (K) PB201614; 18-QGZ-1-53-1. (L) PB201615; 18-QGZ-11-6-5.



Fig. 16. *Polytrichoides lineatus* (A–F). Arrows in (A–B) mark the pseudobranches and arrow in (C) marks the capitate end of the filaments. (A) PB201616; 18-QGZ-12-2-8. (B) PB201617; 18-QGZ-12-4-1. (C) PB201618; 18-QGZ-11-37-5. (D) PB201619; 18-QGZ-12-1-6. (E) PB201620; 18-QGZ-1-3-1. (F) PB201621; 18-QGZ-1-18-7.

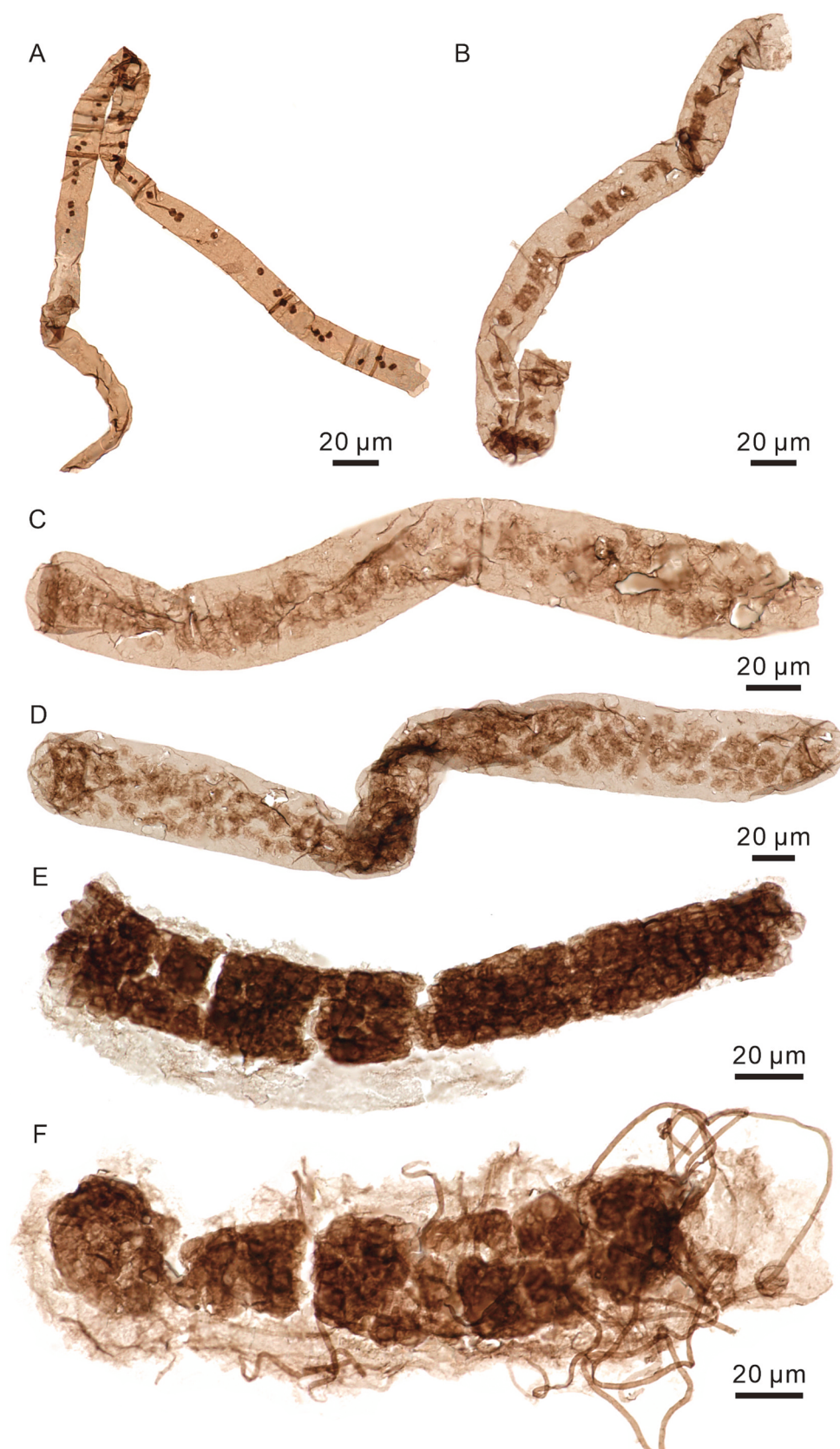


Fig. 17. *Palaeolyngbya catenata* (A–B), *Polysphaeroides filliformis* (C–D), and *Fabiformis baffinensis* (E–F). (A) PB201622; 18-QGZ-12-16-8. (B) PB201623; 18-QGZ-11-60-5. (C) PB201624; 18-QGZ-11-103-1. (D) PB201625; 18-QGZ-11-63-7. (E) PB201626; 18-QGZ-11-17-2. (F) PB201627; 18-QGZ-11-12-1.

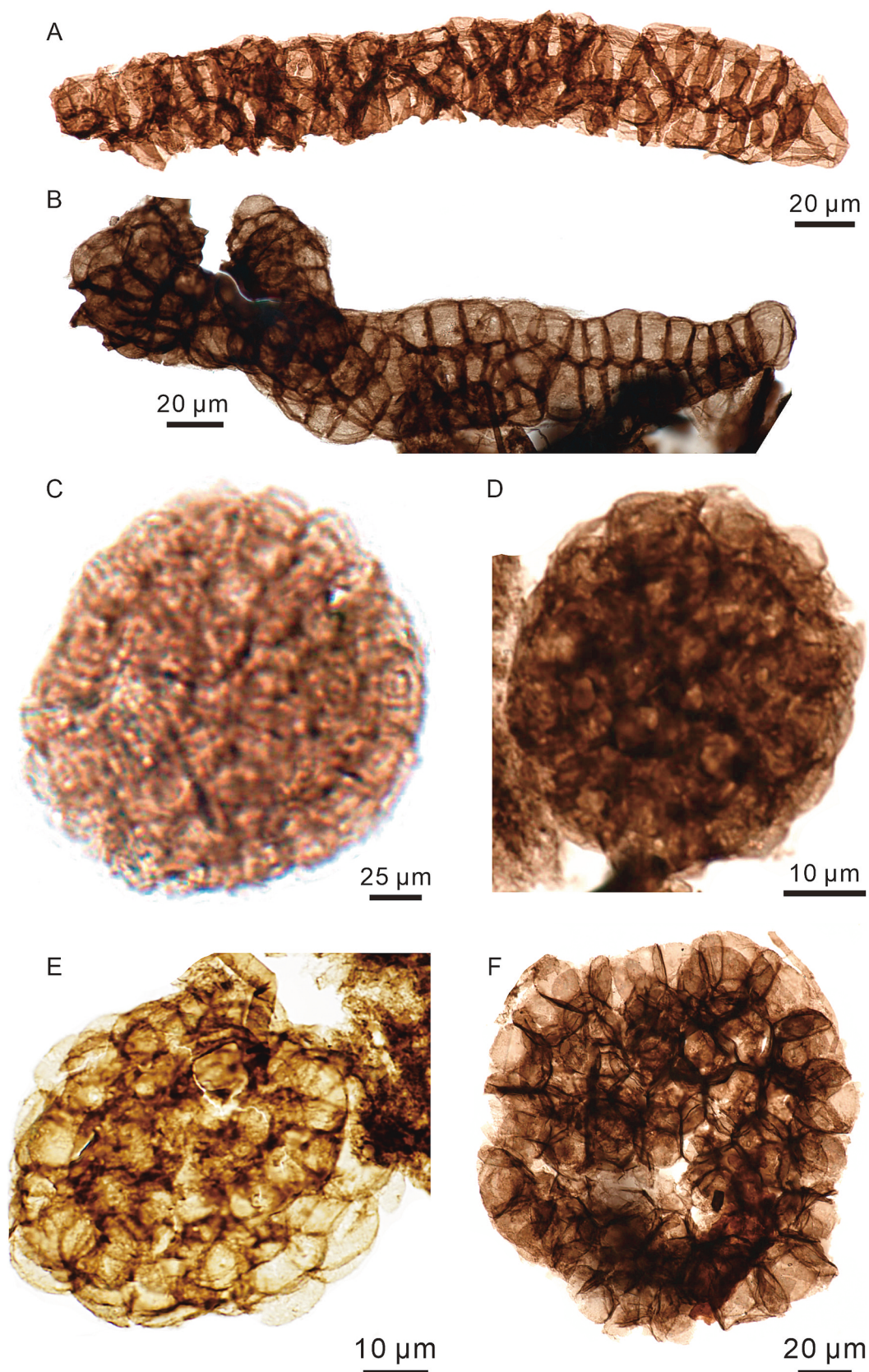


Fig. 18. *Chlorogloeopsis kanshiensis* (A–B) and *Symplassosphaeridium* sp. (C–F). (A) PB201628; 18-QGZ-12-29-1. (B) PB201629; 18-QGZ-7-1-14. (C) PB201630; 18-QGZ-7-1-16. (D) PB201631; 18-QGZ-8-8-10. (E) PB201632; 18-QGZ-12-28-5. (F) PB201633; 18-QGZ-8-48-1.

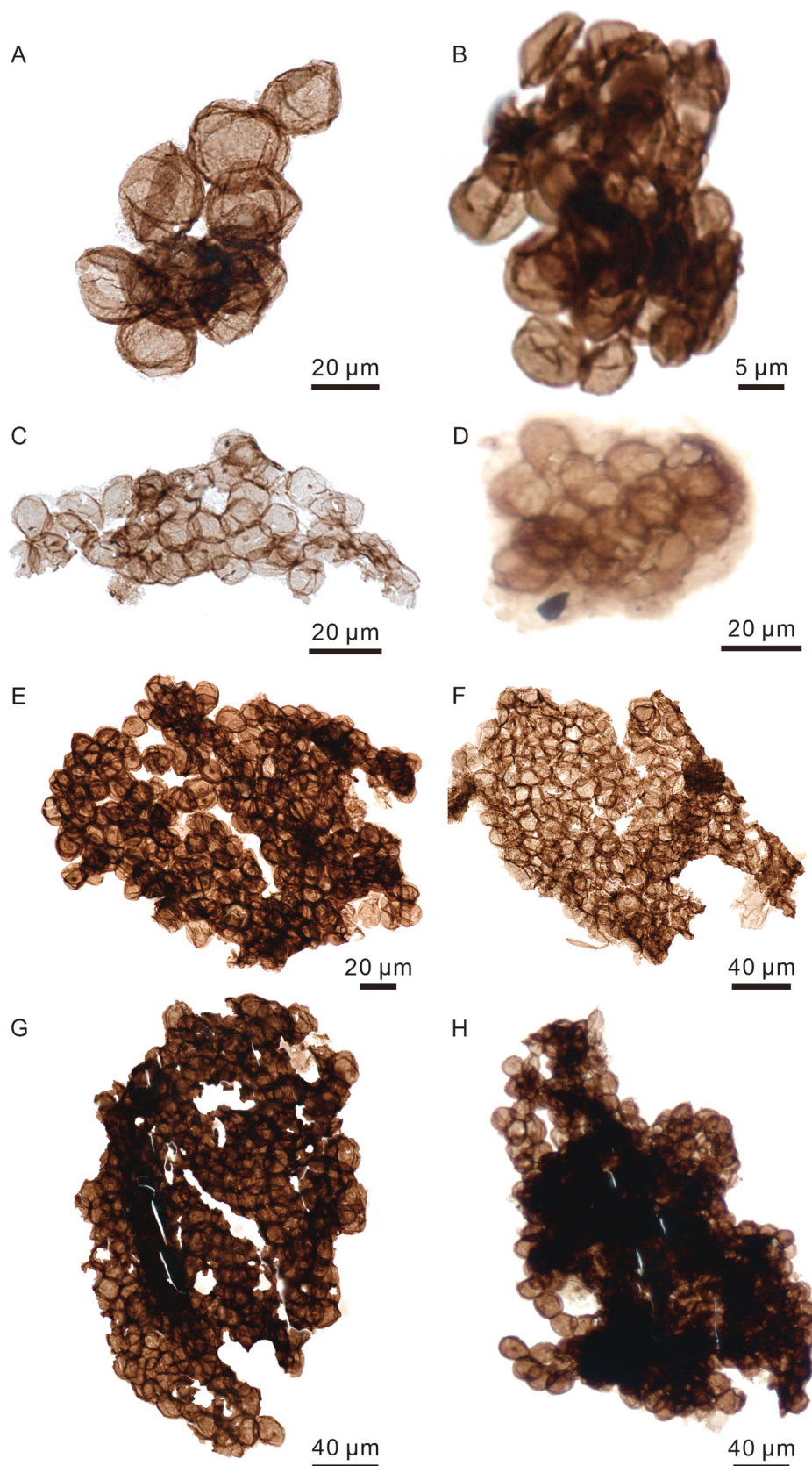


Fig. 19. *Synsphaeridium* sp. (A–B), *Myxococcoides minor* (C–D), *Ostiana microcystis* (E–H). (A) PB201634; 18-QGZ-11-26-5. (B) PB201635; 18-QGZ-6-5-2. (C) PB201636; 18-QGZ-11-96-5. (D) PB201637; 18-QGZ-11-48-4. (E) PB201638; 18-QGZ-11-32-15. (F) PB201639; 18-QGZ-12-26-1. (G) PB201640; 18-QGZ-6-20-6. (H) PB201641; 18-QGZ-11-19-5.

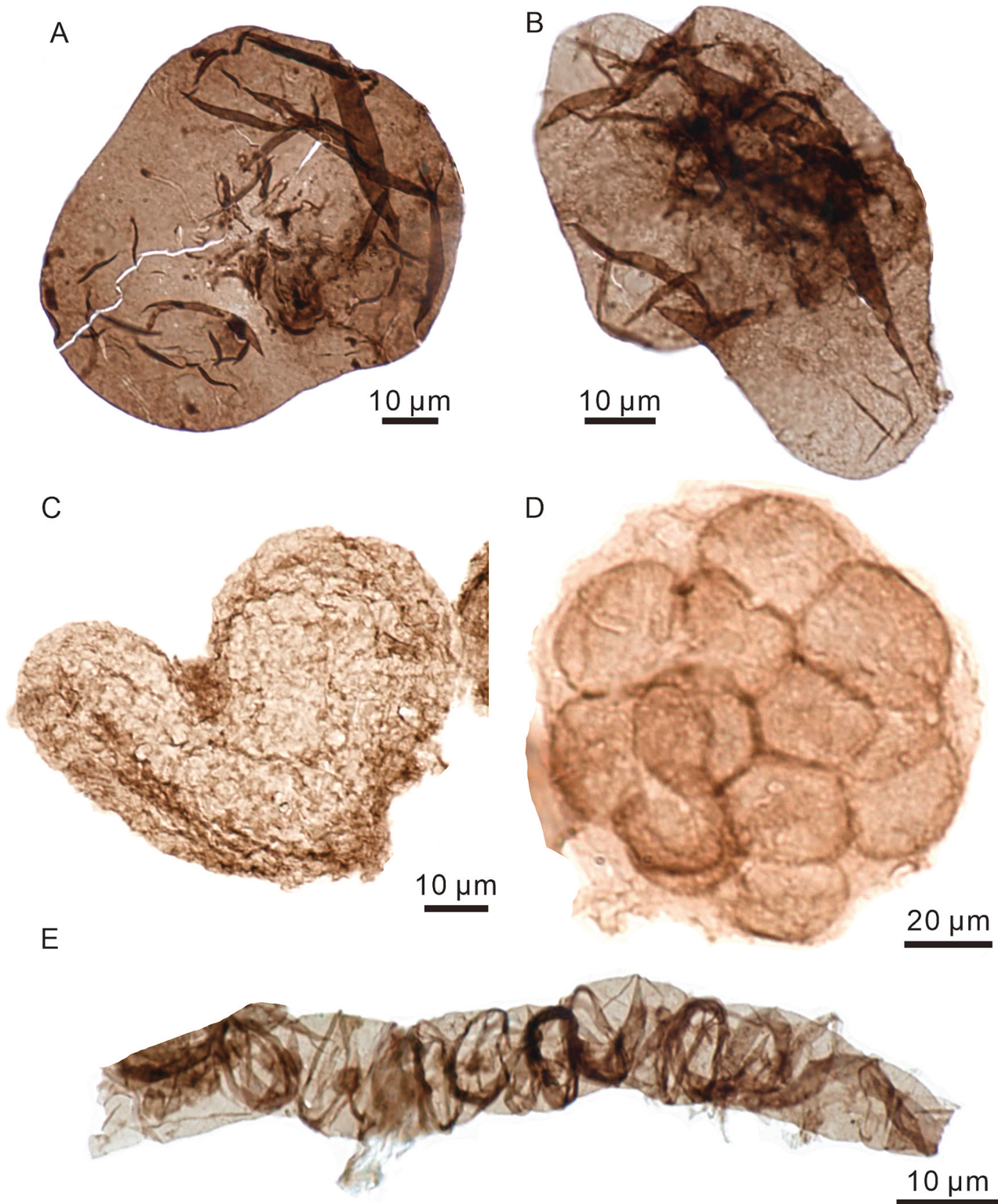


Fig. 20. Possible dividing cells (A–C), Unnamed Form B (D), and Unnamed Form C (E). (A) PB201642; 18-QGZ-1-11-7. (B) PB201643; 18-QGZ-11-111-1. (C) PB201644; 18-QGZ-12-81-1. (D) PB201645; 18-QGZ-12-23-2. (E) PB201646; 18-QGZ-7-2-3.

Formation mainly characterized by *Longfengshania-Paralongfengshania* assemblage (Wang et al., 2021a; Kuang et al., 2023); (2) the red module consisting of the Jiuliqiao, Changlingzi, Jinshanzhai, Nanguanling, Nanfen, Weiji, Qiaotou, Shijia, and Getun formations mainly characterized by *Churia-Tawuia-Sinosabellidites-Protoarenicola-Pararenicola* assemblage (Dong et al., 2008; Qian et al., 2009); (3) the pink module consisting of the Shiwangzhuang Formation with several genera, e.g.,

Horodyskia and *Anquitrachoides*, exclusively present in this stratigraphic unit (Li et al., 2020b; Li et al., 2023a). The three organic-walled microfossil modules are (4) the yellow-green module consisting of the Dongjia, Diaoyutai, Tongjiazhuang and Liulaobei formations, and is characterized by *Proterocladus-Germinosphaera-Trachyhystrichosphaera* assemblage along with several other isolated taxa (Li et al., 2019, 2023b; Tang et al., 2015; Yin and Guan, 1999; Yin, 1987); (5) the green module

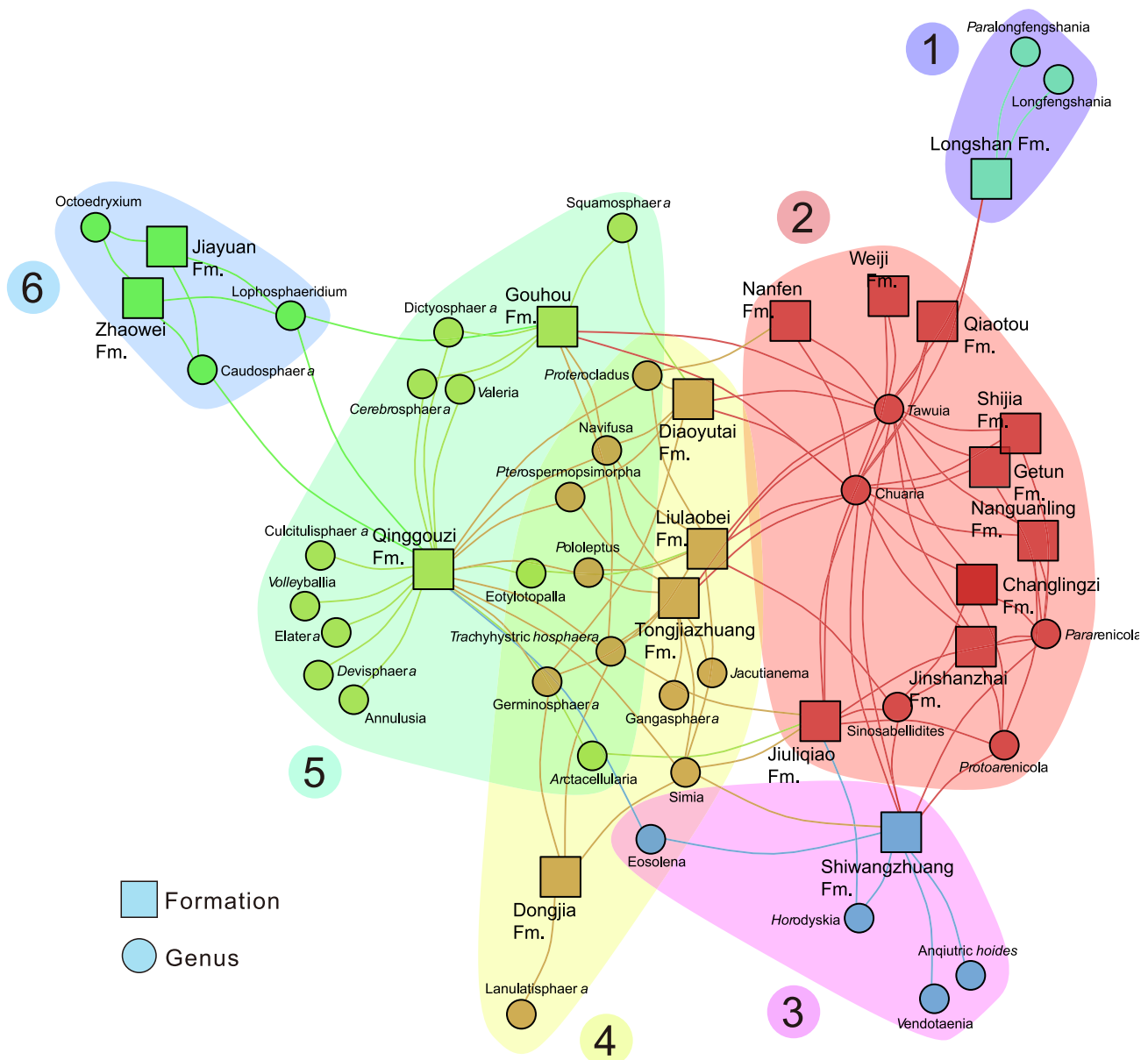


Fig. 21. Bipartite network of late Mesoproterozoic to early Neoproterozoic organic-walled fossils at the genus level (circles) and their occurrences in lithostratigraphic formations (squares) in North China. Network graph with modules identified using the edge-betweenness algorithm ($Q = 0.421$). See Supplementary Data for the raw data table and R codes.

consisting of the Qinggouzi and Gouhou formations, and is characterized by *Dictyosphaera*-*Cerebrosphaera*-*Valeria*-*Trachyhystrichosphaera* assemblage as well as several isolated taxa (Tang et al., 2015); (6) the teal module consisting of the Jiayuan and Zhaowei formations, and is distinguished by *Octoedryxium* (Zang and Walter, 1992). Modules 1, 2, and 6 are isolated from other modules, but modules 3, 4, and 5 overlap with each other due to various shared taxa.

6. Discussion

6.1. Biostratigraphic implications

The Qinggouzi assemblage, consisting of 41 species and 3 unnamed forms, is exceptionally diverse. It is dominated by abundant smooth-walled sphaeromorphs, filamentous microfossils, and aggregates of filamentous and coccoidal microfossils, with a relatively low diversity of acanthomorphs, ornamented sphaeromorphs, pteromorphs,

disphaeromorphs, and netromorphs. In general, the Qinggouzi assemblage is different from large acanthomorphic acritarchs in the Ediacaran Period (Xiao et al., 2014; Liu and Moczydlowska, 2019), but similar to late Mesoproterozoic to early Neoproterozoic assemblages from many continents (Butterfield et al., 1994; Tang et al., 2013; Baludikay et al., 2016; Loran et al., 2019).

Although many species in the Qinggouzi assemblage have long stratigraphic ranges, several biostratigraphically important taxa indicate that the Qinggouzi Formation is probably late Mesoproterozoic to early Neoproterozoic in age. Among these, *Trachyhystrichosphaera aimika* has been proposed as a potential index fossil of the latest Mesoproterozoic to early Neoproterozoic for its worldwide paleogeographic distribution in this time interval (Tang et al., 2013; Pang et al., 2020). In addition, the multicellular green alga *Proterocladus* may also be restricted to the latest Mesoproterozoic to early Neoproterozoic, with occurrences in the Nonesuch Formation in North America ($\sim 1078 \pm 24$ Ma) (Strother and Wellman, 2020), Nanfen, Diaoyutai, and Liulaobei

formations in North China (~1000 Ma) (Tang et al., 2020; Pang et al., 2021; Li et al., 2023a), Khastakh Formation in Siberia (~820–720 Ma) (Nagovitsin et al., 2015), and Svanbergfjellet Formation in Svalbard (~811.5–752.7 Ma) (Butterfield et al., 1994). Similarly, *Elatera minor* has so far been reported only from the Mesoproterozoic Kotuikan Formation in northern Siberia (Vorob'eva et al., 2015), as well as the Qinggouzi Formation (this study). Moreover, *Valeria lophotriata*, *Caudosphaera expansa*, and *Simia annulare* also have limited stratigraphic ranges and are mostly found in pre-Cryogenian strata (Baludikay et al., 2016; Agić et al., 2017; Tang et al., 2017).

Two organic-walled microfossil taxa that were not encountered in this study, but were previously reported from the Qinggouzi Formation (Yin, 1987; Gao et al., 1995) also indicate a Meso-Neoproterozoic age. One is *Annulusia annulata*, a C- or O-shaped tubular fossil that has also been reported from the lower Madhubani Group in Indian, Lakhanda Group in southern Siberia, and Alinya Formation in Australia (Hermann, 1990; Zang, 1995; Tang et al., 2017). Another is *Cerebrosphaera globosa* [originally identified as *Stictosphaeridium hunjiangensis* in Yin (1987) and *Nucellosphaeridium rugulosum* in Gao et al. (1995)], which is a spheroidal vesicle ornamented with prominent cerebral wrinkles and is a cosmopolitan taxon in ca. 800–740 Ma sediments (Porter and Riedman, 2016; Riedman and Sadler, 2018). Therefore, available organic-walled microfossil data indicate that the Qinggouzi Formation is latest Mesoproterozoic to early Neoproterozoic in age and no younger than the Tonian Period.

A late Mesoproterozoic to early Neoproterozoic age for the Qinggouzi Formation is also consistent with available chemostratigraphic data. Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) of carbonates from the underlying Badaojiang and Wanlong formations in southern Jinin Province are 0.705–0.707 (Liu et al., 2006b), values characteristic of latest Mesoproterozoic to early Neoproterozoic carbonates according to global compilations (Halverson et al., 2020; Zhou et al., 2020). Thus, both biostratigraphic and chemostratigraphic data converge to a late Mesoproterozoic to early Neoproterozoic age interpretation for the Qinggouzi Formation.

The depositional age of the Qinggouzi Formation can be further narrowed down on the basis of network analysis (Fig. 21), which shows that the Qinggouzi assemblage is taxonomically most similar to the Gouhou assemblage in the Huaibei region on the southeastern margin of the North China Craton. The Gouhou Formation contains organic-walled microfossils characteristic of latest Mesoproterozoic to early Neoproterozoic (Tang et al., 2015), and is constrained to be < 823 Ma based on detrital zircon ages (Yang et al., 2012; Wan et al., 2019). Considering the similarity between the Qinggouzi and Gouhou organic-walled microfossil assemblages, it is possible that both are late Tonian in age, an interpretation further supported by the presence of *Cerebrosphaera globosa* from the Qinggouzi Formation (Yin, 1987; Gao et al., 1995).

6.2. Implications for the Great Unconformity

The duration and global synchronicity of the Great Unconformity remain controversial. It has been proposed that the Great Unconformity may represent a globally synchronous exhumation event related to Cryogenian global glaciations (DeLucia et al., 2018; Keller et al., 2019; McDannell et al., 2022). However, it has also been argued that the Great Unconformity developed diachronously throughout the Neoproterozoic probably due to multiple regional tectonic activities (Flowers et al., 2020; Flowers et al., 2022; Sun et al., 2022).

The biostratigraphic data from the Qinggouzi Formation allows a better constraint on the Great Unconformity in North China. Given that the Qinggouzi Formation is Tonian in age and the overlying Shuidong Formation is early Cambrian in age (Zheng et al., 2023), a depositional gap of at least 200 Myr must exist between these two formations, confirming the Great Unconformity in southern Jilin Province. Indeed, the Great Unconformity is of similar magnitude in the Jiao-Liao-Xu-Huai region along the eastern margin of the NCC (Pang et al., 2021). For

example, a depositional gap of > 200 Myr is inferred between the Tonian Gouhou Formation and the early Cambrian Houjiashan Formation in the Huaibei region (Tang et al., 2015; Wan et al., 2019), between the Tonian Shiwangzhuang Formation and the early Cambrian Liguang Formation in western Shandong Province (Li et al., 2020a; Li et al., 2020b), between the Tonian Jing'eryu Formation and the early Cambrian Fujunshan Formation in the Tianjin area (Du and Tian, 1986), and between the Tonian Getun Formation and the early Cambrian Dalinzi Formation in southern Liaoning Province (He et al., 2017).

The “Great Unconformity” on the south and southwestern margins of the North China Craton, however, can be much shorter in duration. For example, the boundary between the late Ediacaran Tuerkeng Formation and the early Cambrian Suyukou Formation in Ningxia Autonomous Region (Wang et al., 2021c), between the late Ediacaran Fengtai Formation and the early Cambrian Houjiashan Formation in Huainan region (Cao et al., 2006), and between the late Ediacaran Dongpo Formation and the early Cambrian Xinji Formation in western Henan Province represents a < 30 Myr depositional gap (Zhang and Zheng, 2022). Thus, the Great Unconformity is widespread but diachronous and of variable magnitudes in the North China Craton (Fig. 22), although we note that the diachronous nature of the Great Unconformity in North China does not necessarily falsify Cryogenian exhumation as a major drive of this unconformity.

7. Conclusions

The Great Unconformity is known in the North China Craton, although its temporal duration may be variable in different regions. In southern Jilin Province of North China, the Great Unconformity is suspected to be between the Qinggouzi Formation and the overlying early Cambrian Shuidong Formation, but the exact depositional age of the former is poorly constrained. In this study, we document an exceptionally preserved assemblage of organic-walled microfossils from the Qinggouzi Formation in southern Jilin Province. A total of 41 species representing 29 genera, as well as 3 unnamed forms, have been recovered from the Qinggouzi Formation. The Qinggouzi assemblage is dominated by sphaeromorphic acritarchs and filamentous microfossils, and contains a moderate number of morphologically complex forms. The occurrence of *Trachyhystrichosphaera aimika*, *Proterocladus antiquus*, and *Elatera minor* indicates that Qinggouzi Formation is latest Mesoproterozoic to early Neoproterozoic in age, and it is probably Tonian in age considering available chemostratigraphic evidence and network analysis, implying a > 200 Myr unconformity between the Qinggouzi and overlying Shuidong formations in southern Jilin Province. Together with previously published data, the biostratigraphic data from the Qinggouzi Formation indicate that the Great Unconformity is widespread but diachronous in the North China Craton.

CRedit authorship contribution statement

Wentao Zheng: Data curation, Investigation, Writing – original draft. **Qing Tang:** Conceptualization, Data curation, Investigation, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Shuhai Xiao:** Funding acquisition, Supervision, Writing – review & editing. **Ke Pang:** Data curation, Funding acquisition, Writing – review & editing. **Junyao Kang:** Data curation, Writing – review & editing. **Guanjin Li:** Data curation, Writing – review & editing. **Chuanming Zhou:** Writing – review & editing. **Xunlai Yuan:** Writing – review & editing. **Bin Wan:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

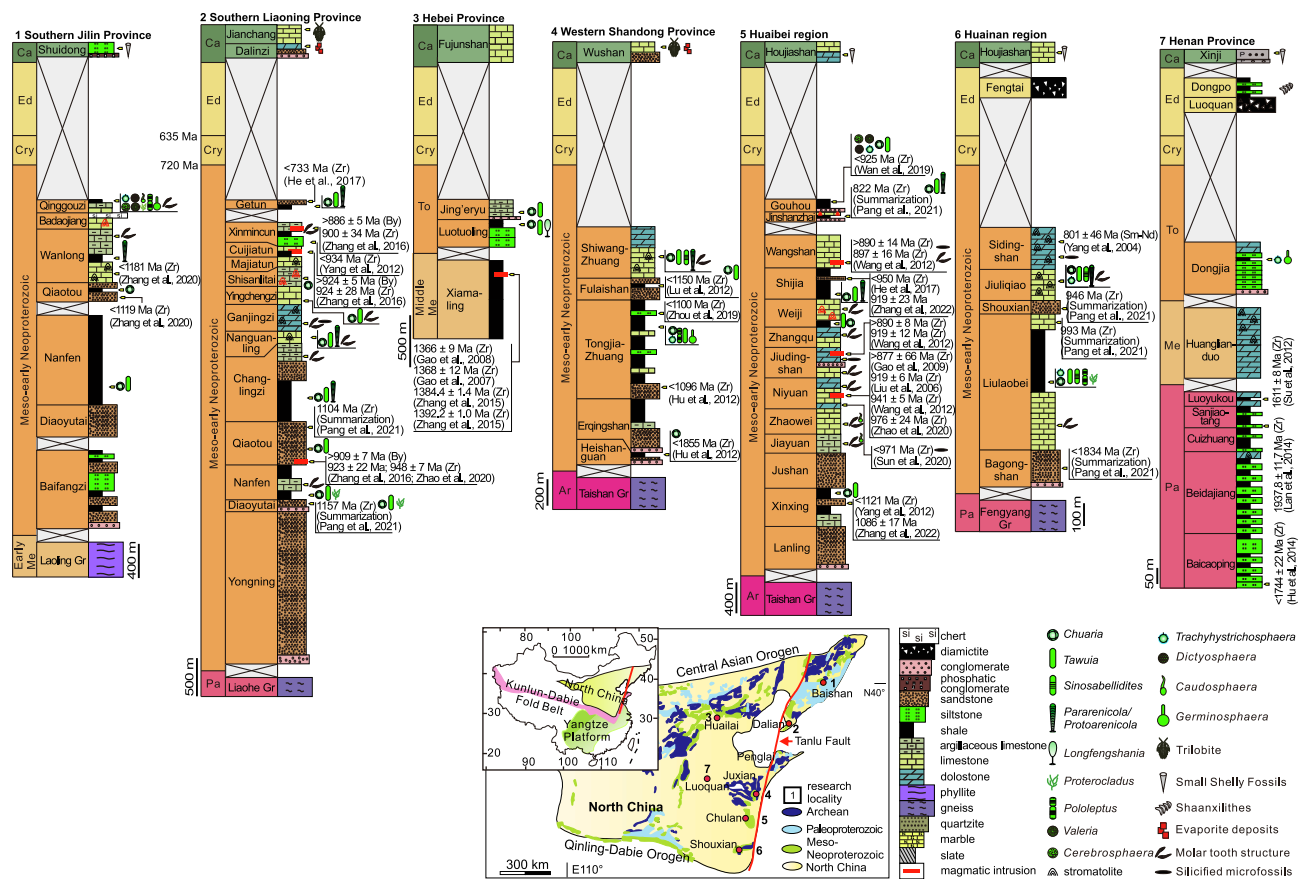


Fig. 22. Integrated stratigraphic columns of Meso-Neoproterozoic to early Cambrian successions in the Jiao-Liao-Xu-Huai realm showing the varying duration of the Great Unconformity. Symbol “<” denotes the youngest detrital zircon age populations; Symbol “>” denotes ages of intrusive igneous rocks. Gr = Group. Ca = Cambrian. Ed = Ediacaran. Cry = Cryogenian. To = Tonian. Me = Mesoproterozoic. Pa = Paleoproterozoic. Ar = Archean. Zr = Zircon. By = Baddeleyite. Paleontological data source see Pang et al., 2021. Geochronological data sources: Yang et al., 2004; Liu et al., 2006; Gao et al., 2007, 2008, 2009; Hu et al., 2012; Lu et al., 2012; Wang et al., 2012; Su et al., 2012; Yang et al., 2012; Hu et al., 2014; Lan et al., 2014; Zhang et al., 2015; 2016; He et al., 2017; Wan et al., 2019; Zhou et al., 2019; Sun et al., 2020; Zhang et al., 2020; Zhao et al., 2020; Zhang et al., 2022.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.precamres.2023.107130>.

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