

The Palynology of the Barut Formation (Early Neoproterozoic, Tonian) from the Alborz Mountains, Northern Iran

Mohammad Ghavidel-Syooki*

*Institute of Petroleum Engineering, School of Chemical Engineering, College of Engineering,
University of Tehran, Tehran, Islamic Republic of Iran*

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Abstract

Precambrian organic-walled microfossils provide significant evidence for early biological evolution and stratigraphic correlation. This study presents the analysis of 30 surface samples collected from the Barut Formation at the Bashm locality, situated 7 km north of Shahmirzad in the Alborz Mountains of northern Iran. Based on the recovered microfossil assemblage, this study reassigns the age of the Barut Formation from the broadly designated late Proterozoic to the early Neoproterozoic (Tonian), providing new constraints on the Precambrian stratigraphy of northern Iran. The investigation documents 47 carbonaceous microfossil taxa belonging to 25 genera, all recorded for the first time from the Barut Formation. The assemblage comprises 29 taxa from 14 genera interpreted as probable cyanobacteria, including *Cephalonyx shahmirzadensis* sp. nov., *Eomycetopsis alborzensis* sp. nov., *Obruchevella parva*, *Proterocladus* spp., and *Siphonophycus* spp. Eleven eukaryotic acritarch taxa from eight genera were also identified, including *Dictyotidium iranense* sp. nov., *Germinosphaera* spp., *Jacutianema solubila*, and *Trachyhystrichosphaera aimika*. Seven additional taxa assigned to *Leiosphaeridia*, *Arctacellularia*, and *Navifusa* exhibit uncertain affinities. The assemblage includes one new genus and seven new species. Several taxa serve as reliable Tonian index fossils, and, together with the absence of large acanthomorphic acritarchs, support a Tonian age (~1000–720 Ma) for the Barut Formation. This age reassignment indicates a ~720–538.8 Ma depositional hiatus before the early Cambrian Zaigun Formation and places the Barut Formation within the earliest phase of Neoproterozoic evolution associated with the initial breakup of the Rodinia supercontinent.

Keywords: Carbonaceous microfossils; Bashm locality; Shahmirzad city; Alborz Mountains.

Introduction

Ancient horst-like uplifts across the Iranian Plateau widely expose Precambrian rocks. Although radiometric ages are lacking or rare, their Precambrian assignment rests on their stratigraphic position beneath the

Neoproterozoic group and well below paleontologically dated Lower Cambrian deposits (1). Stöcklin and Setudehnia classified these rocks into four major groups (2), as summarized in Table 1.

This study focuses on the Neoproterozoic, a distinctive geological unit of major rock- and time-

* Corresponding Author; Tel: 02161114726; Email: m_ghvidelsyooki@yahoo.com or m.ghavidel@ut.ac.ir

Table 1. Stratigraphic classification of the principal Neoproterozoic groups of Iran based on Stöcklin and Setudehnia (1971).

Eon	Era	Group	Description	Examples and Distribution	Remarks
Proterozoic	Neoproterozoic	1. Metamorphic rocks	Highly metamorphosed and partly granitised sequences derived mainly from sedimentary and volcanic materials.	Chapedony Formation (Central Iran); similar complexes in Azerbaijan and other regions.	Poorly studied but offer valuable research opportunities.
		2. Younger metamorphic complexes	Low-grade metamorphic rocks composed mainly of sericite–chlorite schists, phyllites, quartzites, and minor marbles.	Boneh Shurou Complex; Barir Formation; Gorgan Schists*	Provide an essential record of Iran's Precambrian evolution.
		3. Non- metamorphic sediments	Non-metamorphic or barely metamorphic sequences	Kahar, Bayendor, Soltanieh Dolomite, Barut, Morad Series, Kalmorz, Taknar and Tashk formations	Fossil bearing: <i>Chuaria circularis</i> , stromatolites (<i>Collenia</i> sp., <i>Biconulites</i> sp., <i>Conophyton</i> sp. and <i>Minjaria</i> sp.), archaeocyathids,
	Mesoproterozoic	4. Light-Colored alkali granites	Intrusive rocks that locally altered the younger metamorphic complexes. Some intrusions predate Infracambrian sedimentary rocks, whereas others cut into lower Infracambrian beds.	Doran, Muteh, and Bornavard (older intrusions); Chador Malu, Zarigan, and Narigan (younger intrusions)	The younger intrusions may represent plutonic equivalents of acidic extrusive rocks interbedded with Infracambrian sediments.

stratigraphic importance. It consists of cherty dolomites, red to variegated micaceous shales, siltstones, and sandstones, with thicknesses ranging from a few meters to more than 3,000 meters and a wide distribution across Iran (2). The Neoproterozoic transitions upward into dated Lower Cambrian strata (Figures 1, 2) and overlies the Precambrian basement, separated by either a pronounced nonconformity or a less distinct disconformity (2). Stratigraphic position, stromatolites (especially within the *Collenia* Limestone Horizon), and *Problematica* fossils and carbonaceous macrofossils from the Chapoghlu Shale Member of the Soltanieh Dolomite Formation indicate a Late Neoproterozoic age (3). These fossils closely resemble assemblages reported from other Neoproterozoic successions worldwide. In northern and northwestern Iran, the Neoproterozoic sequence includes, in ascending order, the Bayandor Formation (2), the Soltanieh Dolomite with the Chapoghlu Shale Member, and the Barut Formation (Figure 3). These units extend into central and eastern Iran with slight variation except for the Bayandor Formation. Local facies changes occur in places, such as the Gharadash Formation, which contains rhyolitic volcanics interbedded with cherty dolomites. In the northern Kerman area, the Neoproterozoic laterally grades into diapiric saline deposits, such as the Ravar Formation, which correlates with the Hormuz Salt in the

Zagros Mountains, the Eastern Arabian Peninsula, and the Punjab Saline Series in Pakistan. The Neoproterozoic group is most persistent in Central Iran and the southern Alborz Mountains, but thins and pinches out northward into the northern Alborz and Azerbaijan. It is absent in several Precambrian horst elements within the Central Iran sedimentary cover (2).

Geological setting and lithostratigraphy of the Barut Formation

The Barut Formation takes its name from the village of Barut-Aghaji in the northwestern Soltanieh Mountains of northwest Iran. At the Bashm locality, 7 kilometers north of Shahmirzad city in the Alborz Mountains (Figure 1). The formation consists of a distinctive succession of alternating stromatolitic dolomites, limestones, variegated shales, siltstone, and sandstone (Figures 2, 3). The formation transitions between the underlying massive Soltanieh Dolomites and the overlying red-purple shales of the Zaigun Formation, which lack carbonate interbeds (Figures 2A, B).

According to Stöcklin and Setudehnia (1971), the Barut Formation is widely distributed across northern and central Iran and exhibits relatively uniform lithological characteristics throughout its extent. However, its thickness varies considerably between different localities. In the present study, the Barut

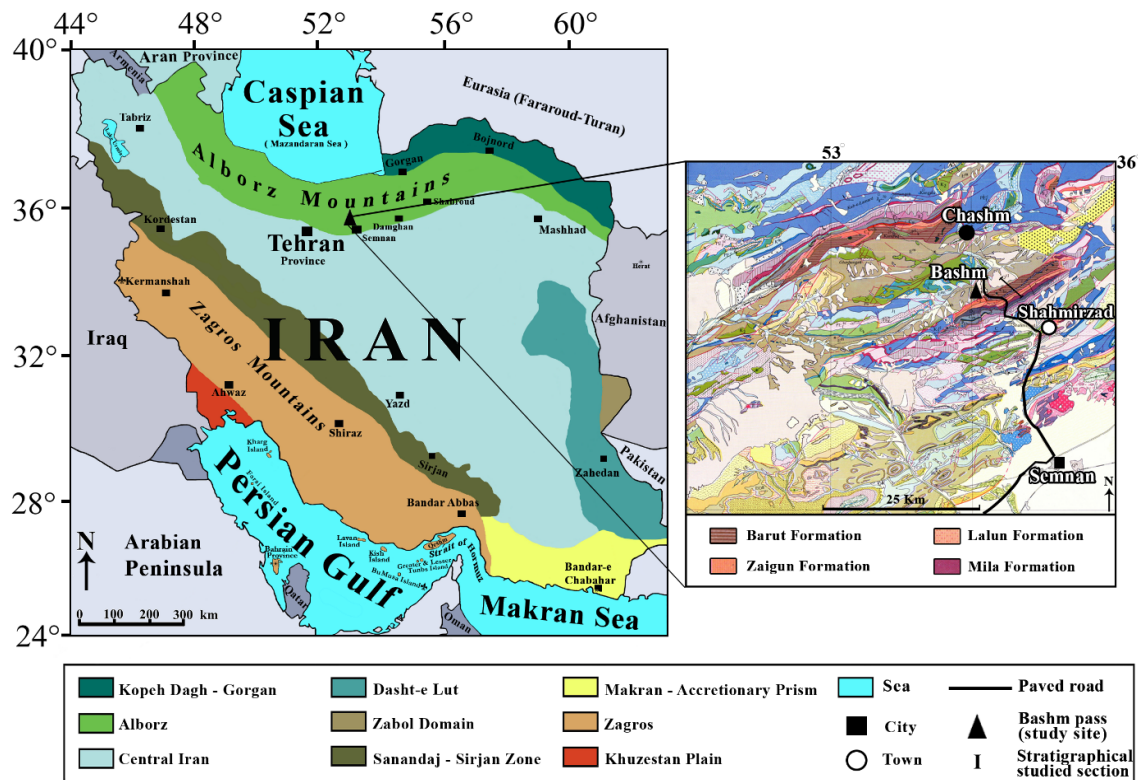


Figure 1. Geographic setting of the Bashm locality, located north of Shahmirzad at the entrance to Chashm Pass in the southern Caspian Sea region, Alborz Mountains, northern Iran, showing the distribution of Precambrian and Paleozoic outcrops (modified from Ghavidel-Syooki, 2025).

Formation is distinguished by a sharp lithological change at its lower boundary, which marks a conformable contact with the underlying Soltanieh Dolomite. The basal part of the Barut Formation consists of dark, platy stromatolitic limestone, dolomite, and shale, which grade upward into dark-colored chert-bearing stromatolitic units interbedded with shale. The upper boundary of the Barut Formation is conformable with the overlying Zaigun Formation and is characterized by a 50-cm-thick horizon of dark stromatolitic dolomite (3).

The Barut Formation primarily consists of stromatolitic limestone and dolomite, with intercalations of black, papery shale, purple shale, and fine-grained, sandy shales in the study area. These micaceous sandy shales vary in color from green-grey to violet and black. More than 50 stromatolitic dolomite and limestone horizons occur throughout the succession, ranging from a few decimeters to 30 meters thick, and commonly display thin laminations (Figure 2 D). Abundant chert nodules (Figure 2E) form layers only a few millimeters to centimeters thick. Calcareous shales dominate the upper part of the formation (Figure 2F). Some dolomite

horizons in this interval exhibit cellular and brecciated textures, indicating dissolution of anhydrite. Stöcklin and Setudehnia (1971) noted that extensive lateral interfingering occurs between the Soltanieh Dolomite and Barut formations and between the Barut and Zaigun formations. This relationship demonstrates the diachronous nature of the formation boundaries and accounts for much of the observed thickness variability. Therefore, the Barut Formation is more appropriately regarded as a facies-controlled depositional unit rather than a discrete chronostratigraphic interval.

Regional correlations place the Barut Formation alongside the parts of the Ravar Formation in northern Kerman, which partly correspond to the Hormuz Salt Series in southern Iran. Stromatolitic fossils, including *Collenia* sp. and *Biconulites* sp., occur frequently in its dolomites and limestones of its type locality. In this study, the author records, for the first time, stromatolitic fossils of *Minjaria* sp. (Figure 2D) and *Conophyton* sp. (Figure 2E) from the Barut Formation in Iran. Stratigraphically, the Barut Formation lies approximately 800 meters below the Lower Cambrian Zaigun and Lalun

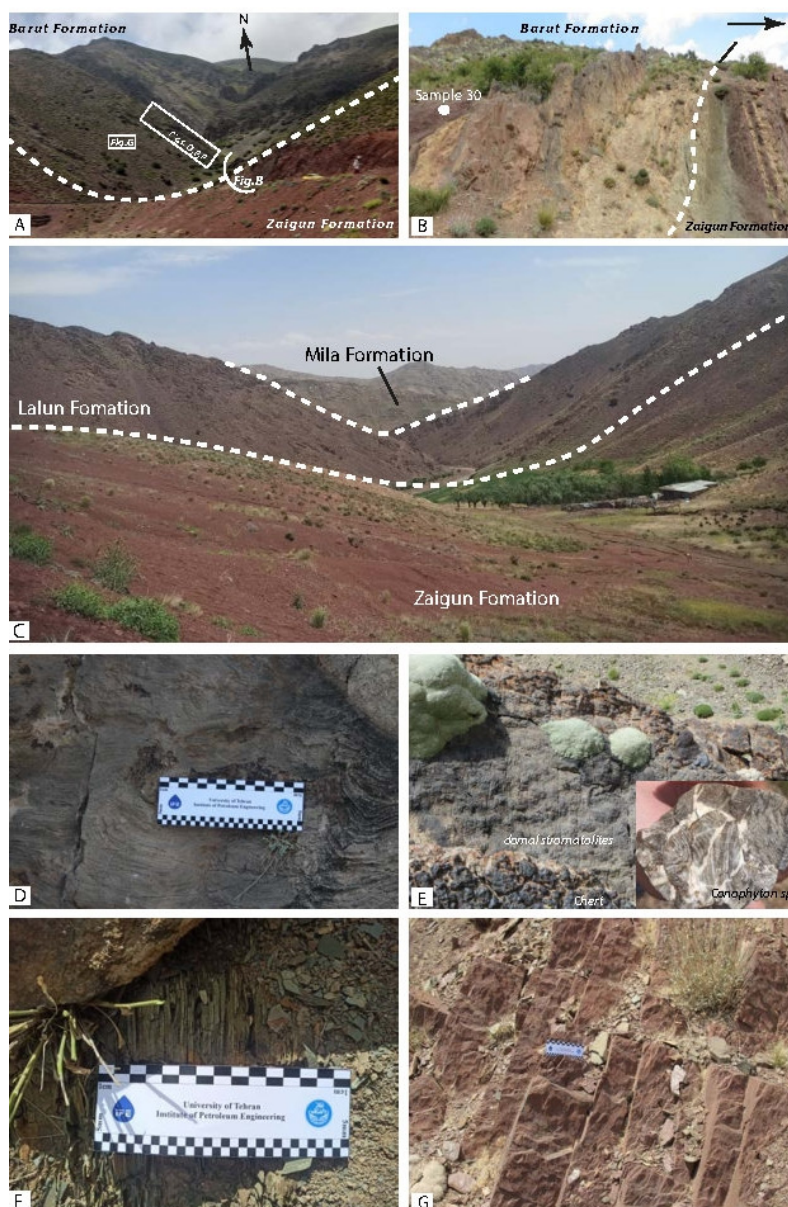


Figure 2. Field photographs of the Tonian Barut Formation and the overlying Cambrian Zaigun, Lalun, and Mila formations at the Bashm locality, north of Shahmirzad city, Alborz Mountains, northern Iran, together with close-up views of selected sedimentary features. (A, B) Contact between the Neoproterozoic Barut Formation and the Lower Cambrian Zaigun Formation, characterized by red-purple shale and siltstone, shown in sections perpendicular (A) and parallel (B) to bedding. (C) Cambrian stratigraphic succession comprising the Zaigun, Lalun, and Mila formations; white lines indicate contacts between lithostratigraphic units. (D) Minjaria stromatolites displaying wavy structures. (E) *Conophyton* sp. with stromatolitic lamination, domal stromatolites, and a varnish chert layer within carbonate intervals. (F) Olive-gray shale interbeds. (G) Red, medium- to thick-bedded sandstones.

formations, the oldest datable horizons that contain Archaeocyathan buildups of Toyonian age in the Lalun

Formation (1). This stratigraphic position supports assigning a Neoproterozoic age to the Barut Formation,

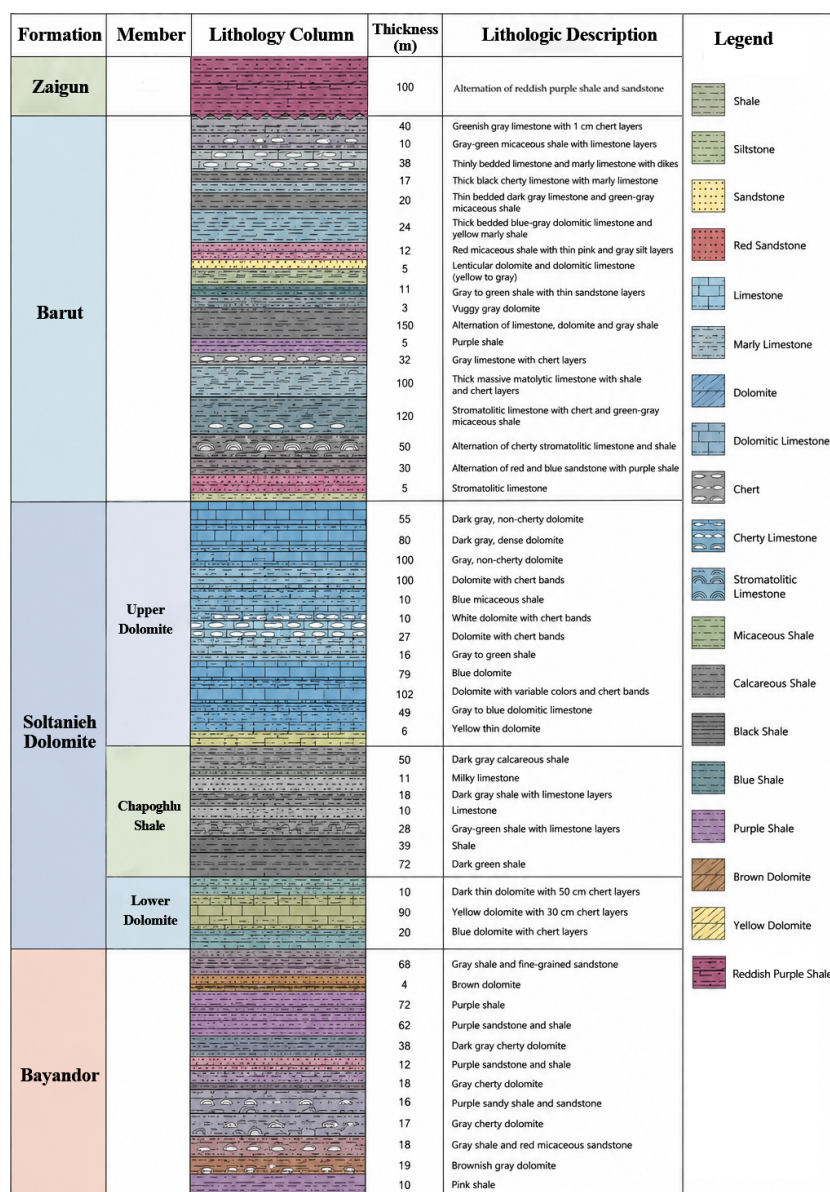


Figure 3. Generalized lithostratigraphic column of the Neoproterozoic succession in the Bashm section, illustrating formation thicknesses, lithological variations, and internal stratigraphic subdivisions.

although Lasemi and Amin-Rasouli assigned the Soltanieh Dolomite and Barut formations to the Cambrian Period (1).

Materials and Methods

The author analyzed material from the Neoproterozoic succession at the Bashm locality, 7 km north of Shahmirzad city, at the entrance to the Chashm

Pass in the Alborz Mountains, northern Iran. Thirty surface samples (MG-1 to MG-30), each labelled with the prefix MG (Mohammad Ghavidel-Syooki), were collected and processed at the Palynological Laboratory, Institute of Petroleum Engineering, School of Chemical Engineering, College of Engineering, University of Tehran. Palynomorphs were extracted from shale and chert using hydrochloric acid (HCl) and hydrofluoric acid (HF), and then neutralized with

distilled water after each treatment. The samples were not oxidised. Each residue was then treated with 30 mL of saturated zinc bromide (ZnBr₂; specific gravity 1.95) and sieved through 5-10 µm nylon meshes to remove fine debris and facilitate palynological analyses. The resulting preparations were mounted on glass slides and examined under optical and scanning electron microscopy (SEM). Selected specimens were studied in detail using both transmitted light microscopy and SEM.

Of the thirty samples, twelve proved productive, and eighteen were barren. The recovered cryptarch and acritarch taxa range from yellow to golden yellow, corresponding to a thermal alteration index (TAI) of 3–3.5. This value indicates the absence of metamorphism and suggests the potential for hydrocarbon generation in the Barut Formation (4). For reference and future research, the samples, slides, and SEM stubs are deposited in the Iranian Natural History Museum, Department of Organisational Environment (DOE), under accession numbers DOEMG-1 to DOEMG-30 for samples and DOESTubMG-19 to DOESTubMG-30 for stubs.

Systematic paleontology of carbonaceous microfossils of the Barut Formation

The classification of cryptarch and acritarch species from the late Neoproterozoic Barut Formation in the Bashm locality, 7 km north of Shahmirzad city in, the Alborz Mountains of northern Iran, as referenced in the text, and plates 1-11, have been meticulously documented and adheres to the guidelines set forth by the International Code of Botanical Nomenclature (ICBN: (5)). Below, the 47 species (25 genera) are presented in alphabetical order, accompanied by their respective author names. Almost all recovered carbonaceous microfossil taxa are assigned to well-known species. Therefore, their formal systematic treatment is not given here, and a detailed description is provided for the new species. Measurements are given in micrometers (µm), and their values are expressed as minimum, mean, and maximum.

Group CRYPTARCHA

Genus *Arctacellularia* German in (6)
Arctacellularia tetragonala (7, 8)
 (Plate 2, 1, 5, 9, 13; 2, 6, 10; 17, 21; 19 a, b; Plate 3, 17–19, 21–22)

Genus *Cephalonyx* Weiss in (9), emend. (10)

Type species. *Cephalonyx coriaceus*.

Cephalonyx shahmirzadensis sp. nov (Plate 11, 12–16)

Synonymy.

2016 *Cephalonyx* sp. — Sergeev et al. (11), Figures. 7.4,

7.8.

2000 *Oscillatorioropsis* spp. — Veis et al., pl. 2, Figure. 8.

Derivation of name. Named after Shahmirzad city, near the type locality.

Holotype. Specimen illustrated in Plate 11, 16.

Type stratum. Barut Formation (samples MG-19 to MG-30).

Type locality. Bashm locality, 7 km north of Shahmirzad city, the Alborz Mountains, northern Iran.

Diagnosis. A species of *Cephalonyx* is characterized by relatively small, unbranched pseudocellular filaments with well-defined sheaths, pseudocellular segments 74–148 µm long, sheath width 11–13 µm, and total filament length up to 180 µm.

Description. Filaments are unbranched and composed of cylindrical to weakly isodiametric pseudocells enclosed within a continuous sheath. Specimens measure 74–180 µm in total length (mean 127 µm). Sheath width ranges from 11 to 13 µm (mean 12 µm). Pseudocellular segments measure 74–148 µm in length (mean 111 µm). The sheath displays irregular margins that locally truncate pseudocellular boundaries. Internal cross-walls are absent, and preservation suggests a robust, organic-walled sheath.

Remarks. This study follows the emended diagnosis of *Cephalonyx* proposed by Butterfield et al. (10), who interpreted the taxon as a pseudocellular sheath rather than a true multicellular trichome. Previous authors suggested that some specimens represent compressed trichomes or sheaths lacking cross-walls (8, 12). Specimens from the Barut Formation consistently show well-defined pseudocellular sheaths with irregular margins that transect cell-like features, supporting assignment to *Cephalonyx*. Morphometrically, *C. shahmirzadensis* sp. nov. resembles *C. sibiricus* Weiss (in 9) but is distinctly smaller, justifying its recognition as a new species.

Occurrence. *Cephalonyx shahmirzadensis* sp. nov. occurs commonly in samples MG-19 to MG-30 of the Barut Formation at the Bashm locality, 7km north of Shahmirzad city, the Alborz Mountains, northern Iran (Figure 4). This taxon represents the first confirmed record of the genus from Iran.

Genus *Chlorogloeopsis* (7)
Chlorogloeopsis contexta (6, 8) (Plate 3, 1)
Chlorogloeopsis kanshiensis (7) (Plate 3, 5–10)
Chlorogloeopsis zairensis (7) (Plate 3, 2–4)

Genus *Cyanonema* (13)
Cyanonema attenuatum (13, 14) (Plate 2, 3, 7; 4, 8; 11–12; 15–16, 18; Plate 3, 11; 13–16; 20; 23–24)

Genus *Eoentophysalis* (15)
Eoentophysalis belcherensis (15) (Plate 1, 1–8; 16–22)
Eoentophysalis croxfordii nov. comb. (10) (Plate 1,

12,13)

Genus *Eomycetopsis* (13)

Eomycetopsis robusta (13) (Plate 5, 19–23)

Eomycetopsis filiformis (13) (Plate 5, 24)

Eomycetopsis alborzensis sp. nov. (Plate 5, 16–17)

Genus *Myxococcoides* (13)

Myxococcoides minor (13) (Plate 1, 10–11; 14–15)

Genus *Obruchevela* (16)

Obruchevela parva (Plate 5, 1)

Obruchevela valdaica (Plate 3, 12; Plate 5, 2–3)

Genus *Oscillatoriopsis* (13), emend. (10)

Oscillatoriopsis amadeus (10, 14) (Plate 10, 15; Plate 11, 18 a–c)

Oscillatoriopsis gigas (17) (Plate 10, 6)

Oscillatoriopsis longa (18), emend. (10) (Plate 8, 8, 11,

15–16; Plate 10, 7, 13; Plate 11, 10)

Oscillatoriopsis princeps (17) (Plate 8, 14, 18; Plate 9, 19b; Plate 10, 9–10, 18–19; Plate 11, 1, 5, 9; 2, 6; 11)

Genus *Palaeosiphonella*

Palaeosiphonella sp. (Plate 4, 13; Plate 5, 11–13)

Genus *Proterocladus* (10)

Proterocladus hermannae (10) (Plate 4, 15)

Proterocladus major (10) (Plate 4, 16–18, 20, 22)

Proterocladus minor (10) (Plate 4, 14, 19, 21, 23, 24)

Genus *Siphonophycus* (13), emend. (19)

Siphonophycus kestron (13) (Plate 5, 5–8, 14–15, 18;

Plate 10, 16; Plate 11, 19–20)

Siphonophycus punctatum (7), emend. (20) (Plate 11, 4, 8)

Siphonophycus solidum (10) (Plate 8, 5, 9, 13, 17; 6–7, 10, 12, 19–20; Plate 11, 3, 7; Plate 10, 8, 11, 14, 17, 20)

Siphonophycus typicum (10) (Plate 5, 4, 9, 10; Plate 11, 17)

Genus *Veteronostocale* (14)

Veteronostocale amoenum (14) (Plate 2, 14, 20, 22–24)

Group ACRITARCHA (21)

Genus *Dictyotidium*

Type species. *Dictyotidium dictyotum*

Dictyotidium iranense sp. nov. (Plate 6, 11–12)

Type locality. Bashm locality, 7 km north of Shahrizad city, at the first point of the Chashm Pass, the Alborz Mountains, northern Iran.

Holotype. Plate 6, 12.

Type stratum. Chert-bearing sediments of the Barut Formation (samples DOESTubMG-19 to DOESTubMG-30).

Derivation of name. Named after Iran, where the species was first described.

Diagnosis. Vesicles are hollow with a uniform reticulate surface. Low, distinct muri enclose polygonal lacunae whose floors bear scabrate to finely echinate projections. The combination of small vesicle size and coarse reticulate sculpture distinguishes *Dictyotidium*

iranense sp. nov. from all other species of *Dictyotidium*.

Description. *Dictyotidium iranense* sp. nov. occurs in samples MG-19 to MG-30 of the Barut Formation at the Bashm locality, Alborz Mountains, northern Iran (Figure 4; Plate 6, 11–12). Cysts are spherical to subspherical, locally polygonal, measuring 34.5–37 μm in diameter (mean 35.75 μm). The vesicle encloses polygonal internal lacunae 9.5–17.5 μm in diameter (mean 13.5 μm). Muri are low and distinct, 2–3 μm high. Excystment occurs through a simple cyclopylic opening.

Remarks. *Dictyotidium iranense* sp. nov. differs from *D. dictyotum* Eisenack, 1938, by its significantly smaller vesicle size ($\leq 37 \mu\text{m}$ versus $> 50 \mu\text{m}$) and by its coarse polygonal reticulation with low muri. It differs from *D. munificum*, and *D. dictyotum* var. *crissum*, in having finer, more compact reticulation and lacking thick, robust muri. Unlike *D. operculatum*, the new species lacks operculate excystment and instead displays a simple cyclopylic opening. These diagnostic features support its recognition as a new species.

Genus *Germinosphaera* (10)

Germinosphaera bispinosa (10) (Plate 6, 18)

Germinosphaera iranense sp. nov. (Plate 6, 19–20)

Holotype. Plate 6, 19.

Type locality. Bashm locality, 7 km north of Shahrizad city, southern Caspian Sea region, the Alborz Mountains, northern Iran.

Type stratum. Barut Formation (samples MG-19 to MG-30).

Derivation of name. The species name refers to Iran, where it was first described.

Diagnosis. Elliptical, organic-walled vesicles have thin walls and predominantly psilate surfaces. Cysts are smaller than those of other *Germinosphaera* species and are characterized by a distinct medium-split pylome; processes are absent or represented only by faint polar traces.

Description. *Germinosphaera iranense* sp. nov. occurs in samples MG-19 to MG-30 of the Barut Formation at the Bashm locality (Figure 4). Vesicles are elliptical, measuring 23–30 μm in maximum diameter (mean 26.5 μm) and 14–18 μm in minimum diameter (mean 16 μm). Vesicle walls are thin, 0.2–0.5 μm thick. Vesicle surface predominantly psilate, locally faintly granular. Traces of processes occur at both poles. Excystment occurs through a distinctive medium-split pylome.

Remarks. The Iranian material represents a morphologically distinct species within *Germinosphaera*. The combination of small vesicle size, elliptical outline, thin wall, and a medium-split pylome clearly distinguishes *G. iranense* sp. nov. from *G. bispinosa*, which exhibits larger vesicles and prominent

filamentous processes. The occurrence of *G. iranense* sp. nov. in the Tonian Barut Formation expands the morphological diversity of the genus and provides new evidence for early eukaryotic phytoplankton in northern Iran. Its recognition enhances palaeobiogeographical comparisons with Tonian assemblages from Norway, China, Africa, and now Iran.

Genus *Jacutianema* (18), emend. (22)
Jacutianema solubila (18), emend. (22) (Plate 6, 22–24; Plate 10, 12; Plate 8, 4)

Genus *Leiosphaeridia**
*Leiosphaeridia crassa** (Plate 9, 17)
*Leiosphaeridia jacutica** (23) (Plate 9, 14)
*Leiosphaeridia kulgunica** (Plate 6, 1–5)
*Leiosphaeridia minutissima** (Plate 6, 6–8; Plate 9, 1,2,4,5)

*Leiosphaeridia tenuissima** (Plate 6, 9; Plate 9, 3, 6–13, 15–16, 18–19a)

Genus *Lophosphaeridium*
Lophosphaeridium granulatum (7) (Plate 6, 10; Plate 10, 1–5)

Genus *Navifusa**
*Navifusa actinomorpha** (7), emend. (8) (Plate 6, 21)

Genus *Ostiana* (6)
Ostiana microcystis (6) (Plate 1, 9, 23,24)

Genus *Polysphaeroides* (6)
Polysphaeroides biseitus (Plate 4, 1, 5, 9)
Polysphaeroides filiformis (6) (Plate 4, 2–4, 6–8, 10–12)

Genus *Pseudocerebrospira* gen. nov.
Type species. *Pseudocerebrospira verminosa* sp. nov.

Derivation of name. From *pseudo* (Greek, false) and *Cerebrospira*, referring to its superficial resemblance to that genus.

Pseudocerebrospira verminosa sp. nov. (Plate 7, 22–23)

Derivation of name. From the Latin *verminosus*, meaning worm-like, referring to the cerebroid, wrinkled wall ornamentation.

Holotype. Specimen illustrated in Plate 7, 22.

Type stratum. Barut Formation (Tonian); samples MG-19 to MG-30.

Type locality. Bashm locality, 7 km north of Shahmirzad city, at the first point of the Chashm Pass, Alborz Mountains, northern Iran.

Diagnosis. Cysts are spherical, with organic walls measuring 29–36 μm in diameter, and robust walls bear prominent anastomosing, interfingering, or locally subparallel wrinkles that do not intersect. Both the cyst wall and ornamentation are composed of spongy tissue. Envelope rim absent.

Description. Vesicles are spherical to subspherical, measuring 29–36 μm in diameter (mean 32.5 μm ; $n = 10$).

Wall thickness ranges from 0.2 to 0.3 μm . The vesicle surface displays conspicuous cerebroid ornamentation formed by anastomosing, interfingering, or locally subparallel wrinkles that terminate freely and do not cross. The wrinkles are integral to the wall structure and represent primary morphology rather than post-depositional deformation. Both the cyst wall and the ornamentation consist of spongy organic material. An external envelope or marginal rim is absent.

Remarks. *Pseudocerebrospira* gen. nov. is erected for cerebroid, organic-walled acritarchs that resemble *Cerebrospira* in surface ornamentation but differ in their smaller vesicle size and lack of an envelope rim. The robust wall structure promotes preservation in fine-grained shale and siltstone deposited under low-energy, anoxic to dysoxic marine conditions. Iranian specimens closely resemble *Cerebrospira* reported from the Neoproterozoic of Spitsbergen (10) but are consistently smaller and lack an envelope, justifying generic separation. The taxon is interpreted as the cyst stage of a planktonic eukaryotic protist, possibly related to early algal or crown-group eukaryotes.

Occurrence. *Pseudocerebrospira verminosa* sp. nov. occurs commonly in samples MG-19 to MG-30 from the Barut Formation at the Bashm locality, 7 km north of Shahmirzad city, the Alborz Mountains, northern Iran (Figure 4).

Stratigraphic and geographic distribution. Tonian (ca. 1000–720 Ma). Currently known only from the Barut Formation of northern Iran.

Pseudocerebrospira persianense sp. nov. (Plate 7, 1–2, 5, 17–21)

Derivation of name. From *Persia*, the historical name for Iran.

Holotype. Specimen illustrated in Plate 7, 5.

Type stratum. Barut Formation (Tonian); samples MG-19 to MG-30.

Type locality. Bashm locality, 7 km north of Shahmirzad city, at the first point of the Chashm Pass, Alborz Mountains, northern Iran.

Diagnosis. Spherical organic-walled cysts with vesicle walls bear prominent anastomosing, interfingering, or rarely sub-parallel wrinkles that do not intersect. Both cyst walls and wrinkles are ornamented with echinate and granulate elements. Excystment structures are absent.

Description. Vesicles are spherical in outline (Plate 7, 1–2, 5, 17–21) and measure 28–35 μm in diameter (mean 31.5 μm ; $n = 15$). Wall thickness ranges from 0.1 to 0.2 μm . The vesicle surface displays well-developed cerebroid ornamentation composed of anastomosing, interfingering, and regularly wrinkled elements that terminate freely without intersection. Wrinkling precedes

wall fracturing, indicating that the ornamentation represents primary morphology rather than post-depositional deformation. Both the vesicle walls and the wrinkles are further ornamented by echinate and granulate elements, a feature unique within the genus. No excystment structures are observed.

Remarks. *Pseudocerebrospira persianense* sp. nov. differs from *P. verminosa* sp. nov. by the presence of echinate and granulate ornamentation on both the cyst surface and the wrinkles, as well as by its thinner vesicle wall. While both species share non-intersecting cerebroid wrinkles as a diagnostic generic feature, the additional surface ornamentation of *P. persianense* provides a clear basis for species-level distinction. The consistent development of ornamentation before wall breakage supports the interpretation of these features as biologically controlled structures. The species is interpreted as an organic-walled acritarch, most likely representing the cyst stage of a planktonic eukaryotic protist.

Occurrence. *Pseudocerebrospira persianense* sp. nov. occurs commonly in samples MG-19 to MG-30 from the Barut Formation at the Bashm locality, 7 km north of Shahmirzad city, the Alborz Mountains, northern Iran (Figure 4).

Stratigraphic and geographic distribution. Tonian (ca. 1000–720 Ma). Currently known only from the Barut Formation of northern Iran.

Pseudocerebrospira iranense sp. nov. (Plate 7, 3–4, 6–16)

Derivation of name. Named after Iran, where the species is described.

Holotype. Specimen illustrated in Plate 7, 3.

Type stratum. Barut Formation (Tonian); samples MG-19 to MG-30.

Type locality. Bashm locality, 7 km north of Shahmirzad city, at the first point of the Chashm Pass, the Alborz Mountains, northern Iran.

Diagnosis. Cysts are spherical, organic-walled, 31–38 µm in diameter, with vesicle walls bearing prominent anastomosing, interfingering, or rarely sub-parallel wrinkles that do not intersect. Both cyst walls and wrinkles are psilate. Excystment structures are absent.

Description. Vesicles are spherical in outline (Plate 7, 3–4, 6–16) and measure 31–38 µm in diameter (mean 34.5 µm; $n = 20$). Wall thickness ranges from 0.1 to 0.2 µm. The vesicle surface exhibits well-developed cerebroid ornamentation composed of anastomosing, interfingering, and regularly wrinkled elements that terminate freely without intersecting. Wrinkling develops before wall fracturing, indicating that the ornamentation represents primary morphology rather than post-depositional alteration. Both the cyst surface

and the wrinkles are psilate, lacking echinate or granulate ornamentation. No excystment structures are observed.

Remarks. *Pseudocerebrospira iranense* sp. nov. differs from *P. verminosa* sp. nov. by its larger vesicle size and psilate wall texture, and from *P. persianense* sp. nov. by the absence of echinate and granulate ornamentation. Although all three species share the diagnostic generic feature of non-intersecting cerebroid wrinkles, the consistently smooth (psilate) cyst surface and ornamentation of *P. iranense* provide a clear basis for species-level distinction. The species is interpreted as an organic-walled acritarch, most likely representing the cyst stage of a planktonic eukaryotic protist.

Occurrence. *Pseudocerebrospira iranense* sp. nov. occurs commonly in samples MG-19 to MG-30 from the Barut Formation at the Bashm locality, Alborz Mountains, northern Iran (Figure 4).

Stratigraphic and geographic distribution. Tonian (ca. 1000–720 Ma). Currently known only from the Barut Formation of northern Iran.

Genus *Trachyhystrichosphaera* (6), emend. (10)

Trachyhystrichosphaera aimika (6), emend. (10) (Plate 6, 13, 14, 17; Plate 9, 20; Plate 8, 1–3)

Genus *Vidalopalla* (24)

Vidalopalla verrucata (24, 25) (Plate 6, 15, 16)

Unnamed acritarch sp. A (Plate 7, 24)

Description. Two spheroidal, organic-walled acritarch vesicles are recorded from sample MG-19 of the Barut Formation at the Bashm locality, 7 km north of Shahmirzad city, the Alborz Mountains, northern Iran (Figure 4). Vesicles measure 30.6–47.9 µm in diameter and bear numerous, variably distributed processes up to 3.0 µm long and less than 0.5 µm wide. Scanning electron microscopy reveals a faveolate-to-reticulate wall ultrastructure. Internal structures and excystment features are not observed.

Remarks. The Iranian specimens closely resemble Unnamed acritarch sp. D reported from the mid-Neoproterozoic Alinya Formation of the Officer Basin, Australia (Riedman and Porter, 2016), particularly in vesicle shape, process morphology, and wall ultrastructure. However, the Barut Formation specimens are consistently smaller, precluding confident species-level assignment. Pending the recovery of additional material, the taxon is retained here in open nomenclature as Unnamed acritarch sp. A.

Occurrence. Unnamed acritarch sp. A is recorded from sample MG-19 of the Barut Formation at the Bashm locality in the Alborz Mountains, northern Iran (Figure 4).

Stratigraphic and geographic distribution. Tonian (ca. 1000–720 Ma). Currently known only from the Barut Formation of northern Iran.

* Indicates eukaryotic or prokaryotic microfossils.

Biostratigraphic and Paleogeographic Interpretation of the Microfossil Record of the Barut Formation

Over three decades ago, geologists described the Mesoproterozoic Era (1600–1000 Ma) as "the duller time in Earth's history", later termed the "boring billion" because the carbon cycle remained remarkably stable (26). The subsequent Tonian Period (~1000–720 Ma) marked a pivotal transition between this stable interval

and the Cryogenian "snowball Earth" glaciations (27), reflecting significant climatic and environmental change. Geochemical data indicate that the Tonian experienced substantial shifts in atmospheric oxygen and ocean redox conditions. Lyons et al.(2014) reported increasing oxygen concentrations in both the oceans and atmosphere (28), whereas Planavsky et al.(2014) argued that atmospheric pO₂ remained too low to support animal evolution until about 800 Ma (29). Guilbaud et al.(2015) demonstrated that mid-depth seawater shifted from

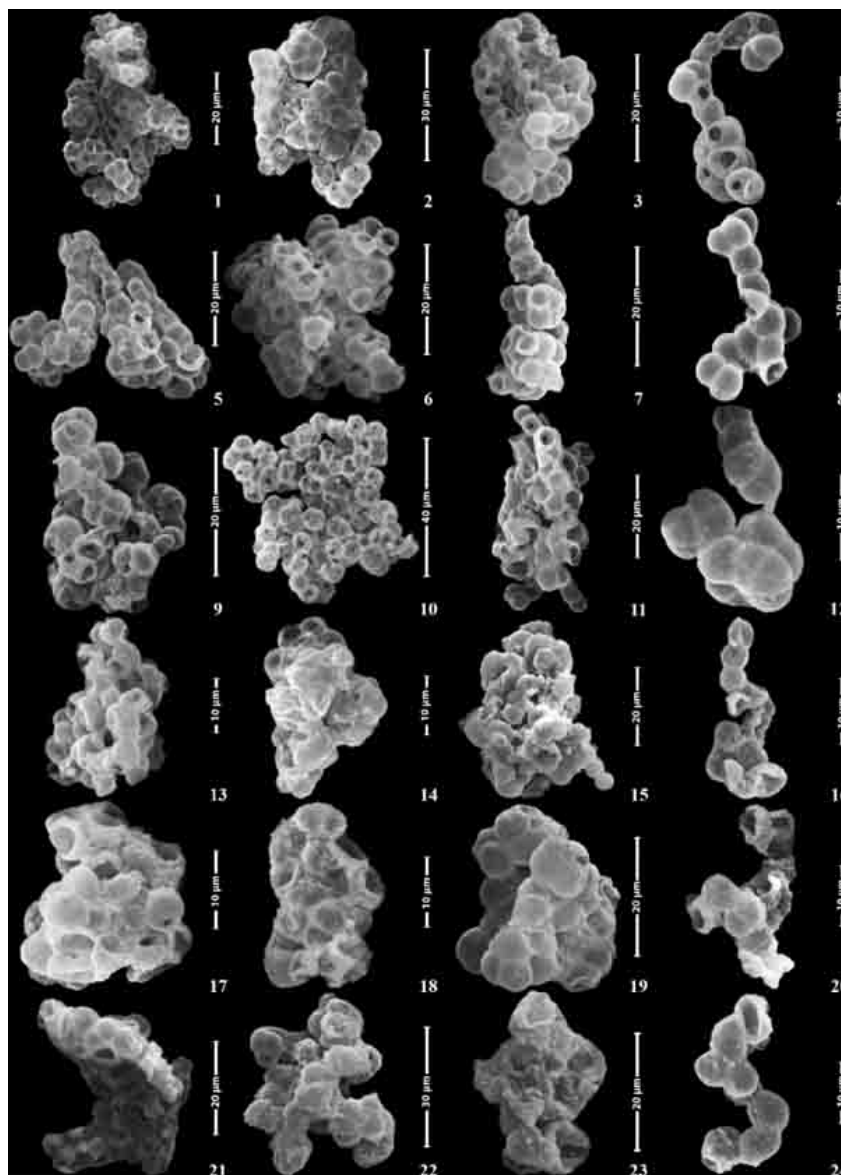


Plate 1. 1-8;16-22. *Eoentophysalis belcherensis* (15); 12, 13. *Eoentophysalis croxfordii* nov. comb. (10); 10-11; 14,15. *Myxococcoides minor* (13); 9, 23, 24. *Ostiana microcystis* (6).

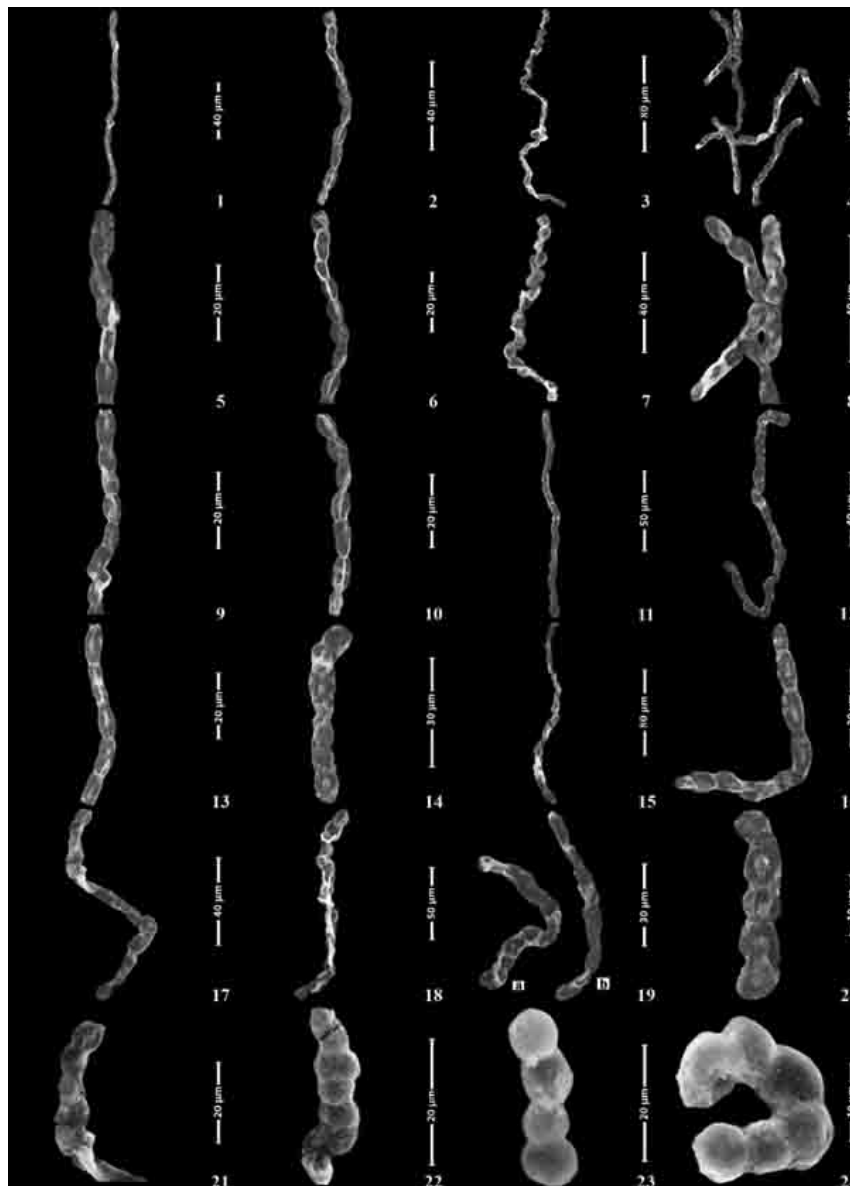


Plate 2. 1,5,9,13; 2,6,10; 17,21;19(a, b). *Arctacellularia tetragonalia* (7, 8); 3, 7; 4, 8; 11-12; 15-16, 18. *Cyanonema attenuatum* (13, 14); 14,20; 22-24. *Veteronostocale amoenum* (14).

sulfidic to ferruginous conditions, while deep waters remained anoxic (30). Reinhard et al.(2017) suggested that between 800 and 635 Ma, Earth experienced intermediate pO_2 levels and transitional redox states, marking a crucial step toward an oxygenated world that enabled complex life (31).

The Barut Formation microfossil assemblage is highly diverse (47 species belonging to 25 genera) and exceptionally well preserved. Nearly all taxa also occur in coeval Late Mesoproterozoic and Early

Neoproterozoic assemblages worldwide (Figure 5). Comparable taxa reported from the Tonian Chichkan Formation, Kazakhstan (32), Miroedikha Formation, Siberia (; 33; 34), and several Indian units, including the Sarda, Deoban Limestone, and Buxa Dolomite formations (35, 36). Similar assemblages also occur in the Gouhou, Liulaobei, Dongjia, and Tongjiazhuang formations, North China (37), as well as in the Svanbergfjellet and Draken Conglomerate formations, Spitsbergen of Norway (19; 10). Additional comparable

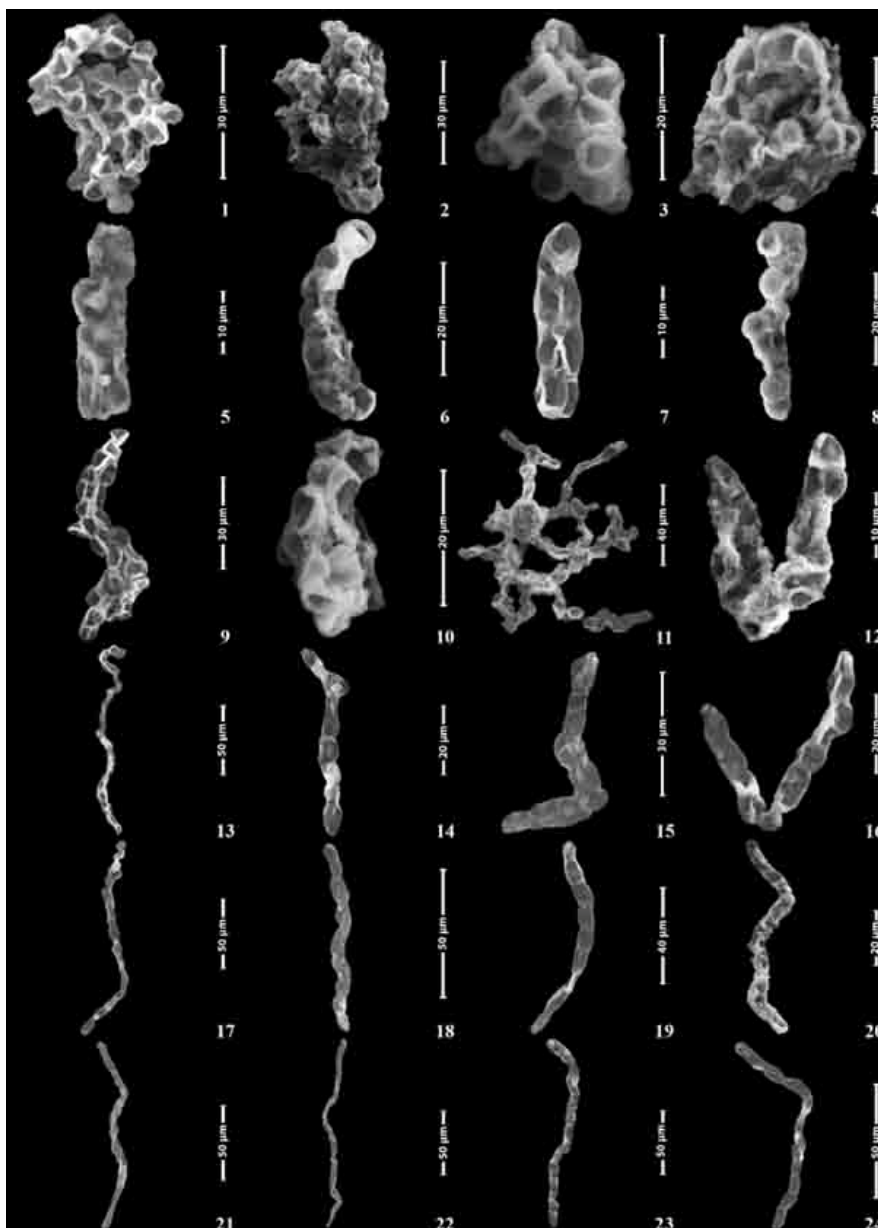


Plate 3. 1. *Chlorogloeopsis contexta* (6, 8); 2-4. *Chlorogloeopsis zairensis* (7); 5-10. *Chlorogloeopsis kanshiensis* (7); 11; 13-16; 20; 23-24. *Cyanonema attenuatum* (13, 14); 12. *Obruchevella valdaica*; 17-19; 21-22. *Arctacellularia tetragonala* (7, 8).

successions include the Wynniatt Formation, Lone Land, and Bylot Supergroup sequences of Canada (8, 38, 39); the Kanpa, Hussar, Alinya, and Bitter Springs formations of Australia (13, 14); the Thule Supergroup (Greenland; 40); the São Francisco Craton (Brazil); and the Atar/El Mreïti Group and Mbuji-Mayi Supergroup Africa (41; 42).

The Barut Formation assemblage includes a distinctive combination of Tonian-type taxa, such as

Arctacellularia tetragonala, *Eoentophysalis belcherensis*, *Chlorogloeopsis contexta*, *Cyanonema attenuatum*, *Eomycetopsis robusta*, *E. filiformis*, *Germinosphaera bispinosa*, *Jacutianema solubila*, *Leiosphaeridia jacutica*, *L. kulgunica*, *Lophosphaeridium granulatum*, *Myxococcoides minor*, *Ostiana microcystis*, *Obruchevella parva*, *O. valdaica*, *Proterocladus major*, *P. minor*, *P. hermannae*, *Siphonophycus solidum*, *Veteronostocale amoenum*, and

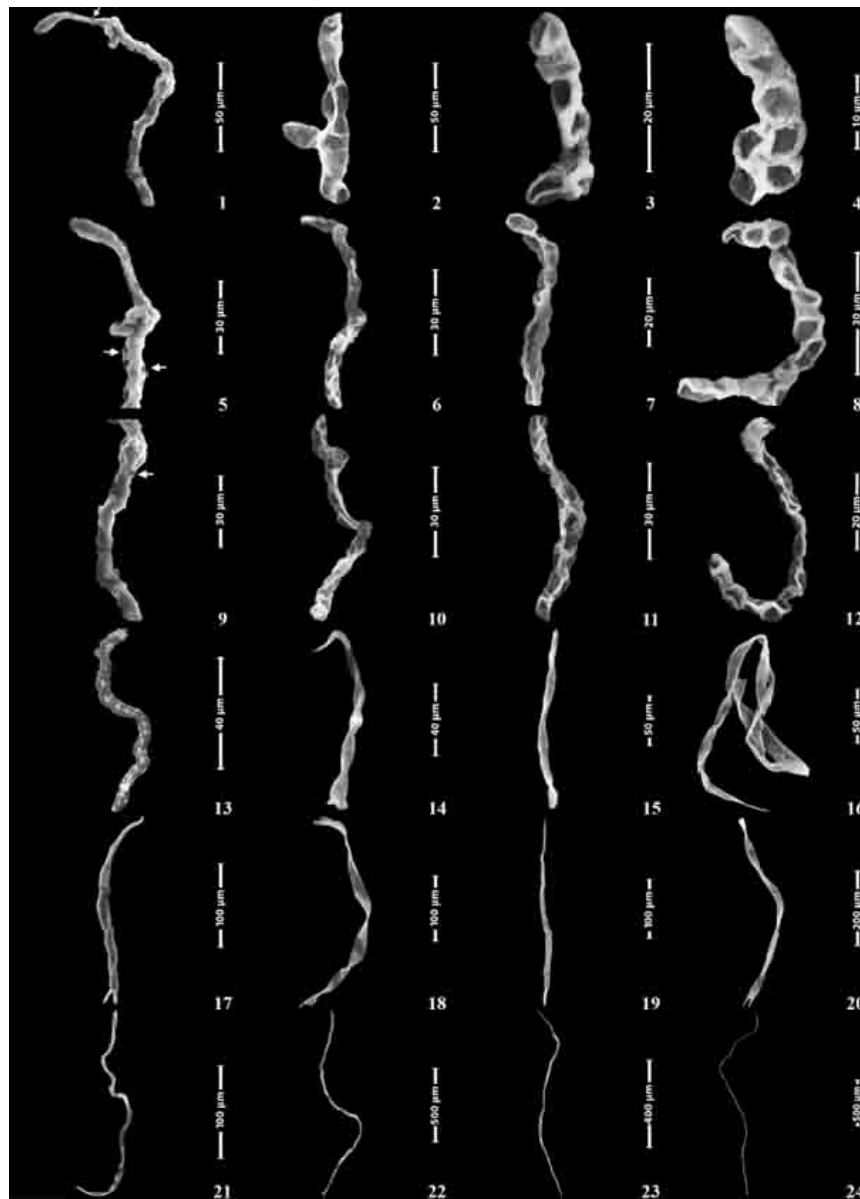


Plate 4. 1, 5, 9. *Polysphaeroides biseitus*; 2-4, 6-8, 10-12. *Polysphaeroides filliformis* (6); 13. *Palaeosiphonella* sp; 15. *Proterocladus hermannae* (10); 16-18; 20, 22. *Proterocladus major* (10); 14, 19, 21, 23, 24. *Proterocladus minor* (10).

Trachyhystrichosphaera aimika These morphotypes closely resemble those of the Tonian the Atar/El Mreïti Group and Mbuji-Mayi Supergroup Africa (41, 42), Chichkan Formation, Kazakhstan (32), Miroedikha Formation, Siberia (33, 34), Wynniatt Formation, Lone Land, and Bylot Supergroup sequences of Canada (8, 38, 39), the Kanpa, Hussar, Alinya, and Bitter Springs formations of Australia (13, 14), the Svanbergfjellet Formation, Spitsbergen of Norway (22) and the Tongjiashuang Formation, North China (37)).

Collectively, these correlations constrain the Barut Formation microfossil assemblage to the Late Mesoproterozoic–early Neoproterozoic (Tonian) interval, excluding any Cryogenian or Ediacaran affinity. Based on morphology, the carbonaceous microfossils fall into three groups: (A) eukaryotic organisms, (B) possible eukaryotic or prokaryotic organisms, and (C) prokaryotic (bacterial) organisms, discussed in the following sections.

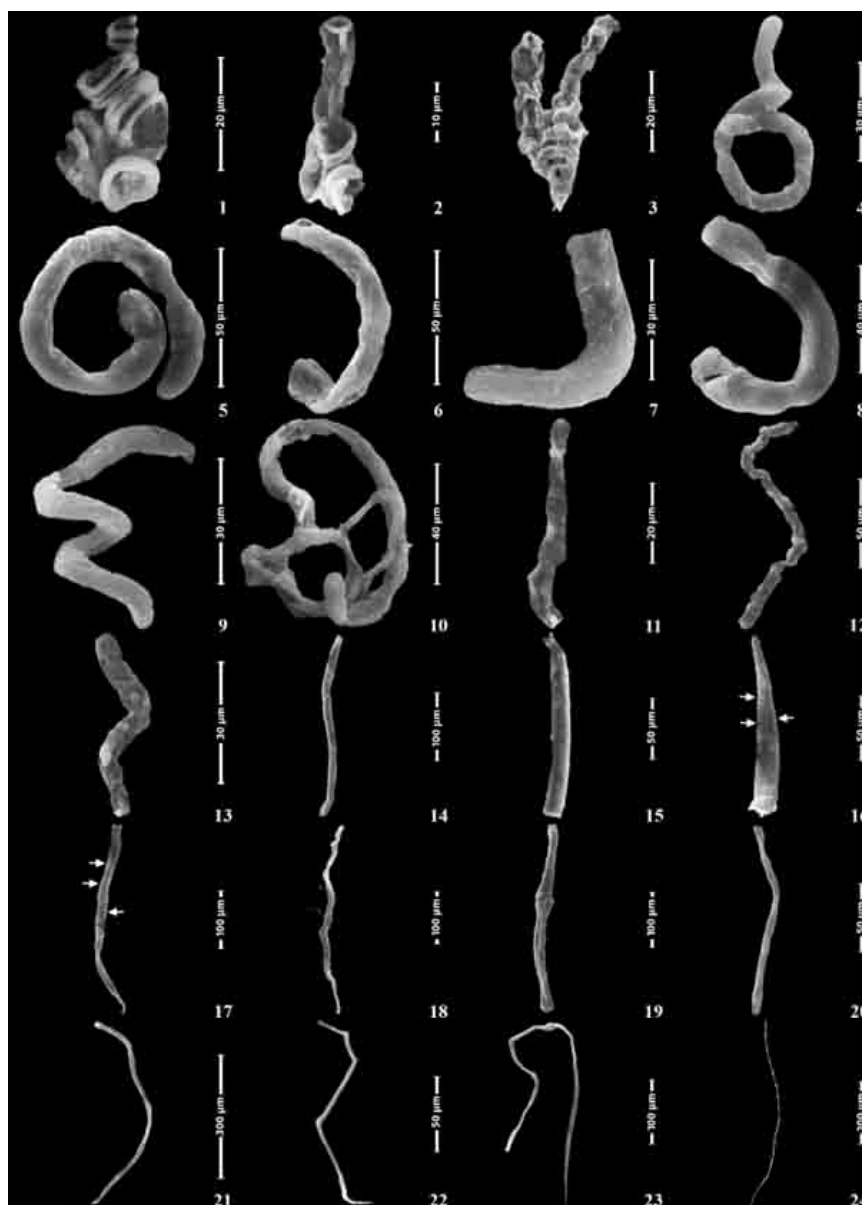


Plate 5. 1. *Obruchevela parva*; 2,3. *Obruchevela valdaica*; 4. Coiled *Siphonophycus typicum* (10); 5. Coiled *Siphonophycus kestron* (13); 6-8. Contorted *Siphonophycus kestron* (13); 9. Spiral *Siphonophycus typicum* (10); 10. *Siphonophycus typicum* (10); 11-13. *Palaeosiphonella* sp.; 14,15,18. *Siphonophycus kestron* (13); 16-17. *Eomycetopsis alborzensis* sp. nov. (a segment of *Eomycetopsis* sp. with perforation, denoted by white arrows); 19-23, *Eomycetopsis robusta* (13); 24. *Eomycetopsis filiformis* (13).

Results and Discussion

A) Eukaryotic organisms. All acritarch taxa in this group represent eukaryotic organisms and include eleven species assigned to eight genera: Each species is described in detail below.

Germinosphaera bispinosa (Plate 6, 18) occurs in the productive samples of the Barut Formation (MG-19

to MG-30) in the study area. Researchers have also reported this taxon from the Tonian Svanbergfjellet Formation (~811.5–788 Ma) in Spitsbergen, Norway (10, 22); the Tonian Tongjiazhuang Formation (~1000–720 Ma) of the Tumen Group, western Shandong, North China Craton (37); the late Mesoproterozoic–early Neoproterozoic (Tonian; ~1000–720 Ma) Mbuji-Mayi Supergroup in Congo (41); and the Mesoproterozoic

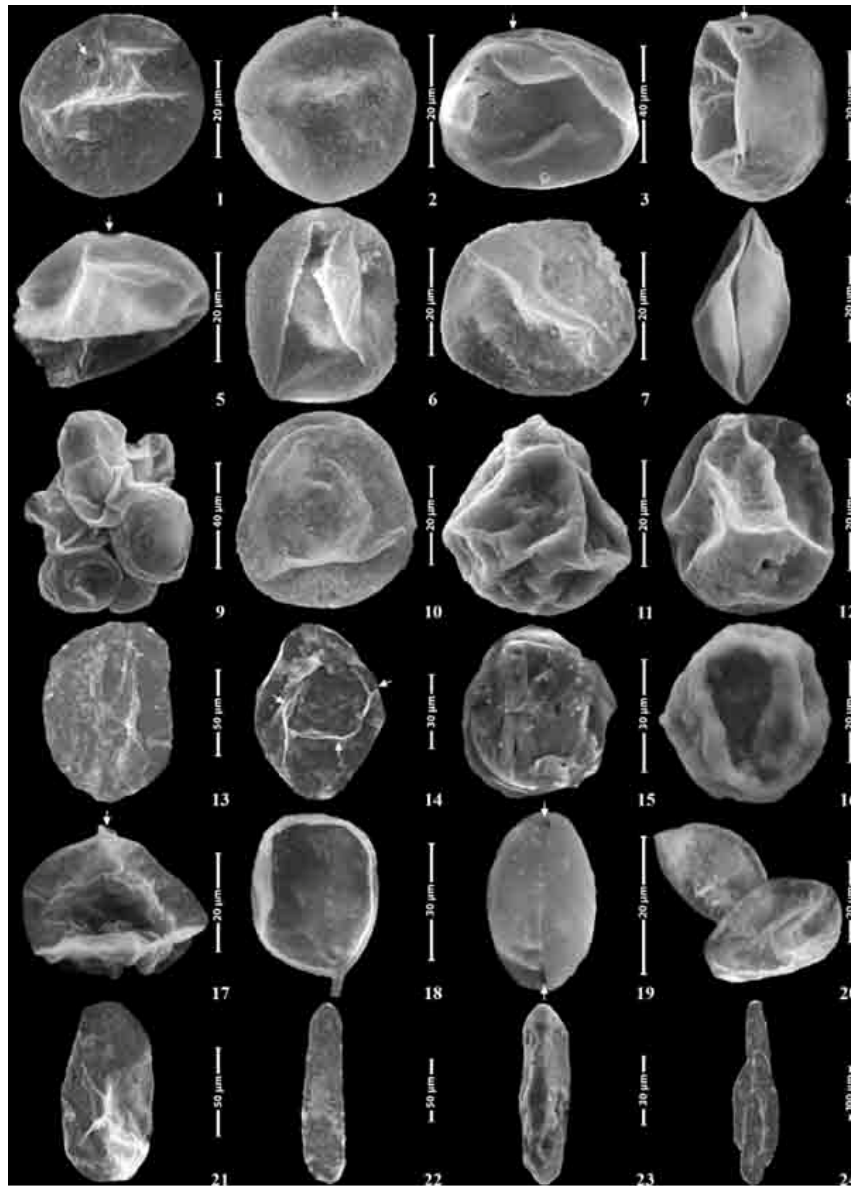


Plate 6. 1-5. *Leiosphaeridia kulgunica* (white arrow denotes sophisticated circular excystment structure (a pylome)); 6-8. *Leiosphaeridia minutissima*; 9. *Leiosphaeridia tenuissima*; 10. *Lophosphaeridium granulatum* (7); 11-12. *Dictyotidium iranense* sp. nov.; 13,14,17. *Trachyhystrichosphaera aimika* (6); 15-16. *Vidalopalla verrucata* (24); 18. *Germinosphaera bispinosa*; 19-20. *Germinosphaera iranense* sp. nov.; 21. *Navifusa actinomorpha* (7), emend. (8); 22-24. *Jacutianema solubila* (18).

shale-dominated Xiamaling Formation (~1.4–1.35 Ga) in North China., Its presence in the Barut Formation represents the first record of *G. bispinosa* in Iran, extending the species' paleogeographic distribution and enabling biostratigraphic and paleoenvironmental correlations between Iran, Norway, Africa, and China during the Tonian Period (Figure 5).

Jacutianema solubila (Plate 6, 22–24; Plate 10, 12; Plate 8, 4) co-occurs with *Germinosphaera bispinosa*

throughout the productive samples of the Barut Formation (MG-19 to MG-30) in the study area. Researchers have also documented this species in the Svanbergfjellet Formation (~811.5–788 Ma) in Spitsbergen, Norway (22); the Tonian Mbuji-Mayi Supergroup (~1000–720 Ma) in the Democratic Republic of Congo (41); the Tonian Atar/El Mreiti Group (~1000–720 Ma) of the Taoudeni Basin, Mauritania, northwestern Africa (42); the Tonian lower Shaler

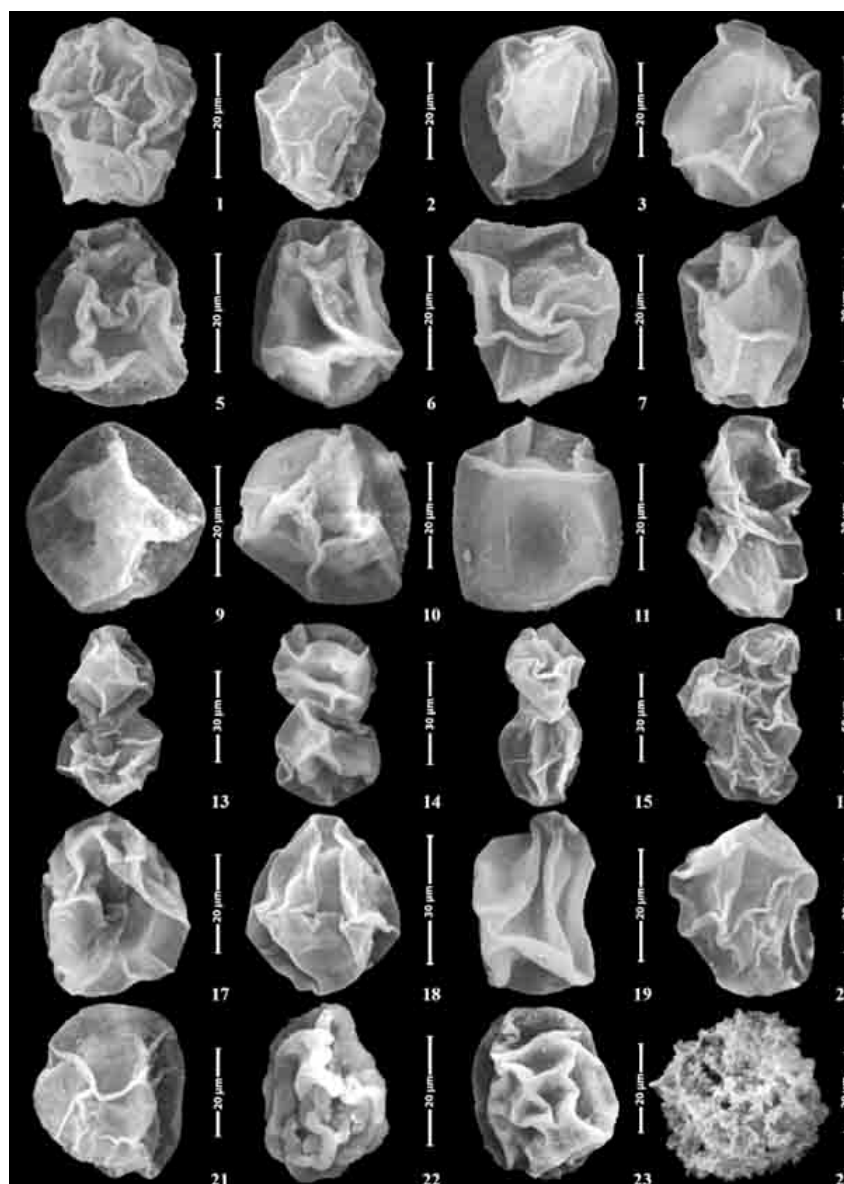


Plate 7. 1-2;5;17-21. *Pseudocerebrospira persianense* sp. nov.; 3-4,6-16. *Pseudocerebrospira iranense* sp. nov.; 22-23. *Pseudocerebrospira verminosa* sp. nov.; 24. *Unnamed acritarch* sp. A.

Supergroup (~1000–720 Ma), Arctic Canada (43); and the Tonian Tongjiashuang Formation (~1000–720 Ma) of the Tumen Group, western Shandong, North China Craton (37). Xiao and Tang further restricted *J. solubila* to the Tonian Period (~1000–720 Ma) and recognized it as a representative of crown-group eukaryotes (26). The presence of *J. solubila* in the Barut Formation represents the first record of this species in Iran, extending its paleogeographic distribution and enabling biostratigraphic and paleoenvironmental correlations

between Iran, Norway, Africa, Canada, and China during the Tonian Period (Figure 5).

Lophosphaeridium granulatum (Plate 6, 10; Plate 10, 1–5) occurs in the productive samples of the Barut Formation (MG-19 to MG-30) of the study area. This study documents the presence of this species in Iran for the first time. Researchers first described *L. granulatum* from the Neoproterozoic Vindhyan Basin, India (7), and subsequently recorded it from several Neoproterozoic successions, including the Bushimay Supergroup

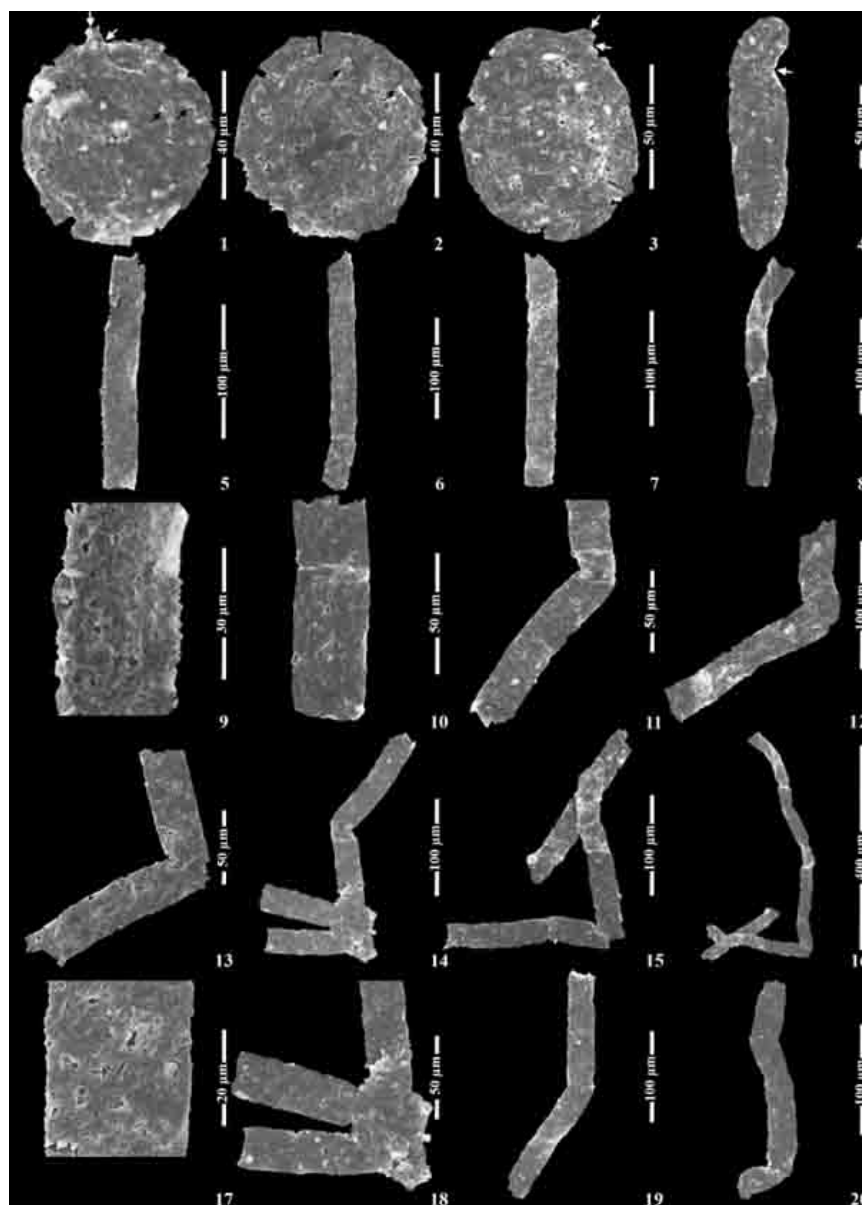


Plate 8. 1-3. *Trachyhystrichosphaera aimika* (6), emend. (10) (white arrows showing the broken processes); 4. *Jacutianema solubila* (22); 5,9;13,17;6,7,10,12,19-20. *Siphonophycus solidium* (10); 8, 11, 15, 16. *Oscillatoriopsis longa* (18), emend. (10); 14, 18. *Oscillatoriopsis princeps* (17).

(~1000–900 Ma), Kanshi, Zaire, Central Africa (7); the Bylot Supergroup (~1270–750 Ma), Baffin Island, Canada (8); and the Mbuj-Mayi Supergroup (~1000–750 Ma), Democratic Republic of Congo (41). Its occurrence in the Barut Formation extends the species' paleogeographic range to Iran and enables biostratigraphic and paleoenvironmental correlations between Africa, Canada, and Iran during the Tonian Period

Trachyhystrichosphaera aimika (Plate 6, 13, 14, 17; Plate 9, 20; Plate 8, 1–3) occurs in the productive samples of the Barut Formation (MG-19 to MG-30) at the Bashm locality, 7 km north of Shahmirzad city, in the Alborz Mountains of northern Iran. This species serves as a reliable index taxon because it exhibits distinctive morphology, a restricted stratigraphic range, and a broad paleogeographic distribution. Researchers have reported *T. aimika* from several Neoproterozoic successions

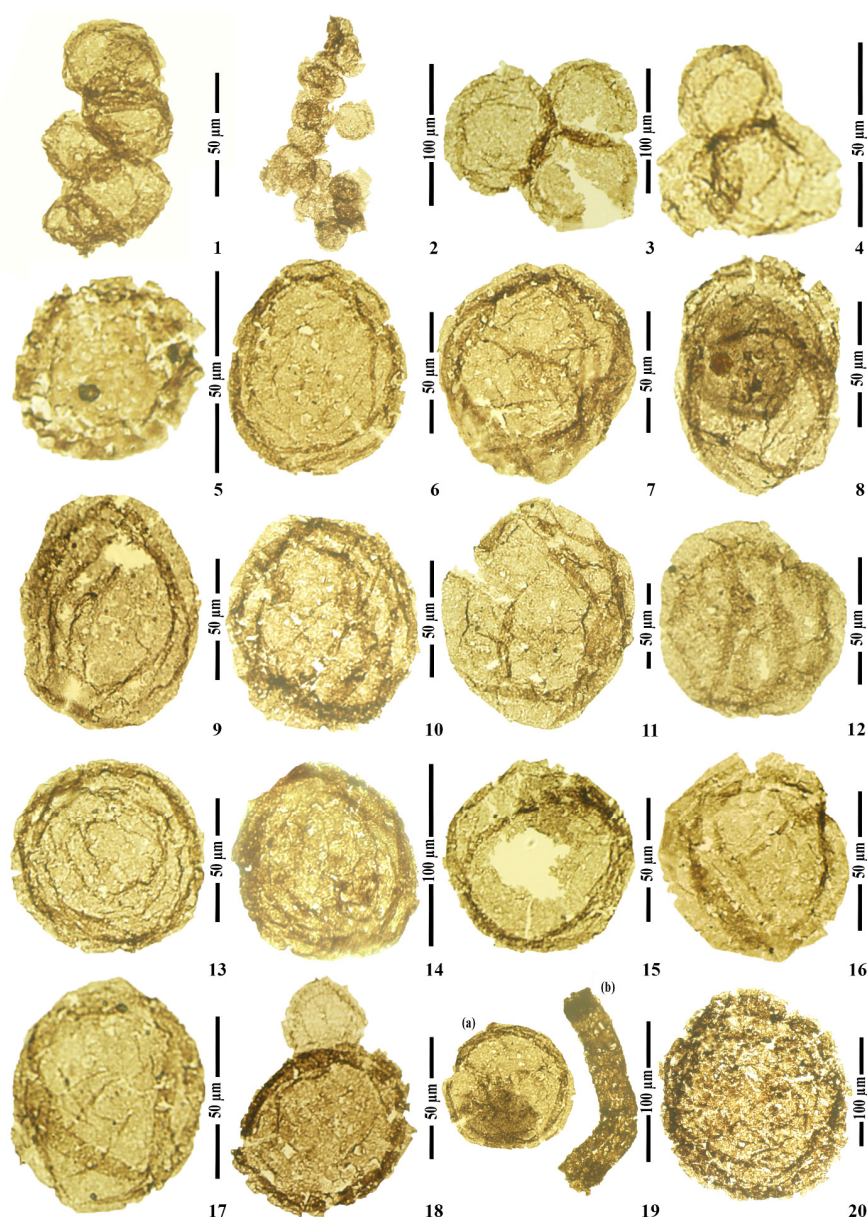


Plate 9. 1-2,4-5. *Leiosphaeridia minutissima*; 3, 6-13, 15-16, 18-19a. *Leiosphaeridia tenuissima*; 14. *Leiosphaeridia jacutica*; 17. *Leiosphaeridia crassa*; 19b. *Oscillatoropsis princeps* (black arrows indicate septated areas); 20. *Trachyhystriosphera aimika* (6), emend. (10).

worldwide, including the Lakhanda Formation (~1025 Ma; U–Pb zircon) in the Uchur-Maja region, southeastern Siberia, Russia (6); the Mirojedikha Formation (~1000–800 Ma) in Siberia and the Urals, Russia; the Wynniatt Formation (~850–750 Ma) in the Franklin Mountains, northwestern Canada (38); the Svanbergfjellet Formation, Akademikerbreen Group (~811.5–788 Ma) in northeastern Spitsbergen, Norway (10); the Mbuji-Mayi Supergroup (~1000–720 Ma) in the

Democratic Republic of Congo (41); and the Draken Conglomerate Formation (~800–700 Ma) in northeastern Spitsbergen (19). The occurrence of *T. aimika* in the Barut Formation extends its paleogeographic distribution to Iran. It reinforces its value for biostratigraphic and paleoenvironmental correlations among Russia, Canada, Norway, Africa, and now Iran (Figure 5).

Vidalopalla verrucata (Plate 6, 15–16) serves as another index microfossil for the Tonian interval of the

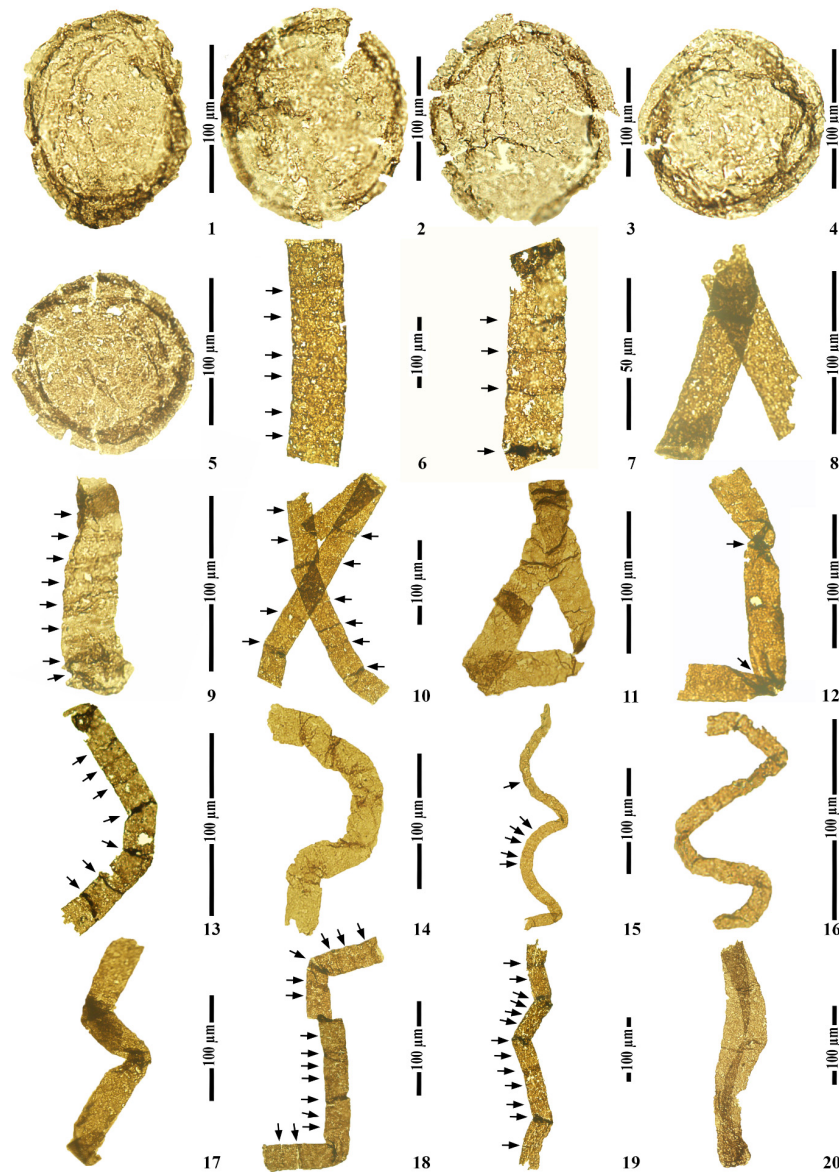


Plate 10. 1-5. *Lophosphaeridium granulatium* (7); 6. *Oscillatoripsis gigas* (17) (black arrows indicate septated areas); 7,13. *Oscillatoripsis longa* (18), emend. (10) (black arrows indicate septated areas); 8,11,14,17. *Siphonophycus solidium* (10); 9-10,18-19. *Oscillatoripsis princeps* (17) (black arrows indicate septated areas); 12. *Jacutianema solubila* (22) (black arrows indicate septated areas); 15. *Oscillatoripsis amadeus* (10, 14) (black arrows denote cell imprint); 16. *Siphonophycus kestron* (13); 20. *Siphonophycus* cf. *solidium* (10).

Barut Formation (MG-19 to MG-30). Researchers have reported this species from the mid-Neoproterozoic Alinya Formation (~811–716.5 Ma) in the Officer Basin, Australia (24), and from the Tonian Tongjiashuang Formation (~1000–720 Ma) of the Tumen Group, western Shandong, North China Craton (37, 43). The occurrence of *V. verrucata* in the Barut Formation extends its known paleogeographic range to Iran, reinforcing its value for biostratigraphic and

paleoenvironmental correlations among Australia, China, and now Iran (Figure 5).

B) Possible eukaryotes or prokaryotes (7 species from three genera)

This group comprises large, smooth-walled vesicles that lack diagnostic features, making their unambiguous assignment to either eukaryotes or prokaryotes difficult. It also includes sphaeromorphs with resistant organic walls and occasional excystment structures, such as

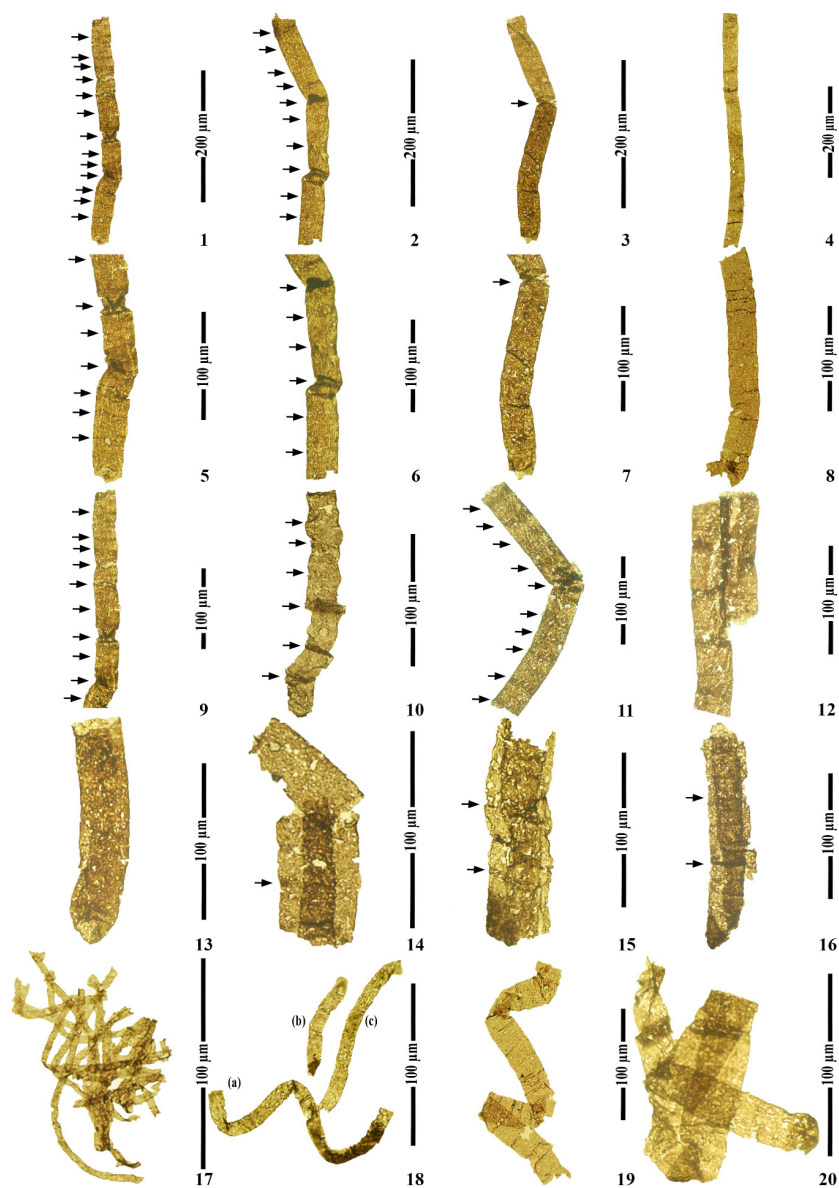


Plate 11. 1, 5, 9; 2, 6; 11. *Oscillatoropsis princeps* (17) (black arrows indicate septated areas); 3, 7. *Siphonophycus solidium* (10) (black arrows indicate septated areas); 4, 8. *Siphonophycus punctatum* (7), emend. (20); 10. *Oscillatoropsis longa* (18), emend. (10) (black arrows showing septate connection); 12-16. *Cephalonyx shahmirzadensis* sp. nov. (black arrows showing pseudo-septate connection and sheath); 17. *Siphonophycus typicum* (10); 18(a-c). *Oscillatoropsis amadeus* (10, 14) (black arrows denote cell septa); 19-20. *Siphonophycus kestron* (13).

several *Leiosphaeridia* species. Populations from the Mesoproterozoic Roper Group in Australia preserve multilayered walls. Their large size, excystment structures, and resistant composition provide diagnostic criteria for eukaryotes; nevertheless, *Leiosphaeridia* spp. likely represent a polyphyletic group. In the present dataset, the author identified five *Leiosphaeridia* species: *L. crassa* (Plate 9, 17); *L. jacutica*. (Plate 9, 14); *L.*

kulgunica (Plate 6, 1-5); *L. minutissima* (Plate 6, 6-8; Plate 9, 1-2, 4-5); and *L. tenuissima* (Plate 6, 9; Plate 9, 3, 6-13, 15-16, 18-19a). Other taxa with uncertain affinities include relatively large single oval vesicles such as *Navifusa actinomorpha* (Plate 6, 21) and vesicles forming multicellular chains, such as *Arctacellularia tetragonala* (Plate 2, 1, 5, 9, 13; 2, 6, 10; 17, 21; 19a-b; Plate 3, 17-19, 21-22).

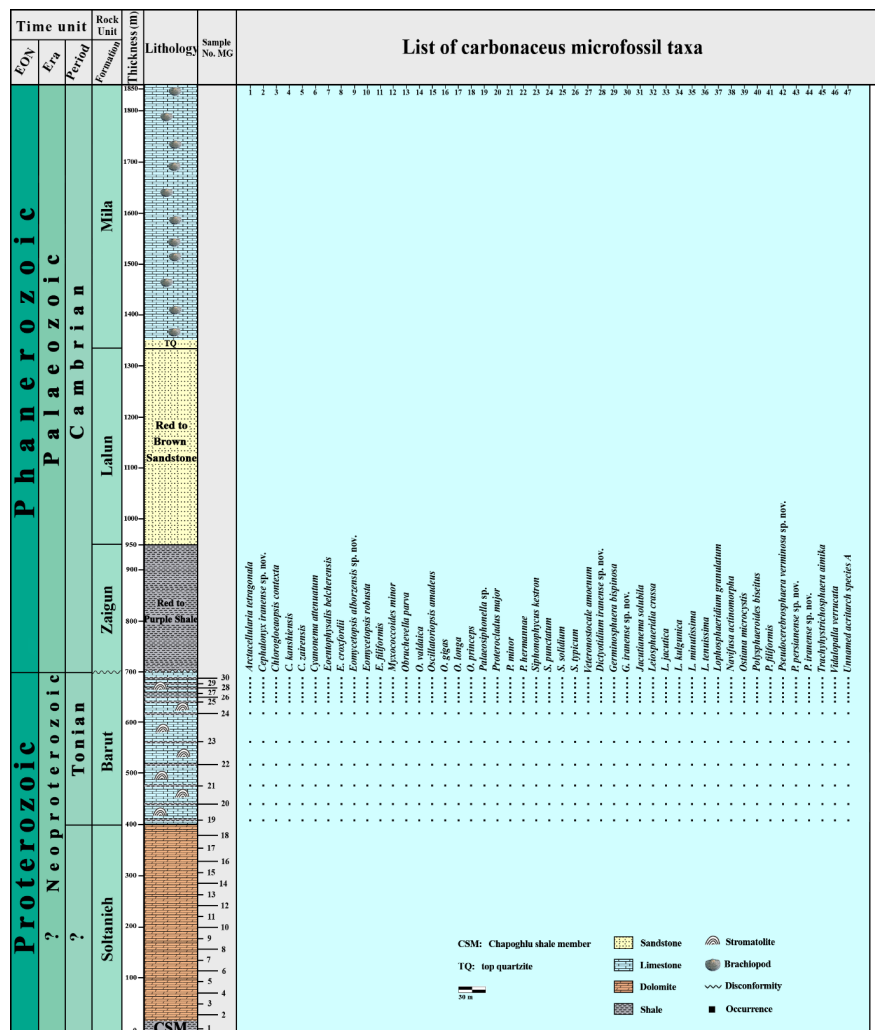


Figure 4. Lithology of Proterozoic and Paleozoic rock units and stratigraphical distribution of carbonaceous microfossil taxa throughout the Barut Formations at the Bashm locality in the Alborz Mountains of northern Iran (the samples of the upper part of Soltanieh Dolomite were Barren).

The polyphyletic genus *Leiosphaeridia* includes five species in the Barut Formation: *L. crassa*, *L. jacutica*, *L. minutissima*, *L. tenuissima*, and *L. kulgunica*. These taxa closely resemble assemblages from the Neoproterozoic (Tonian) Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10, 22); the late Mesoproterozoic to early Neoproterozoic (Tonian; ~1000–720 Ma) Atar/El Mreïti Group, Taoudeni Basin, Mauritania, northwestern Africa (42); Tonian–Cryogenian successions (~718–635 Ma) in Siberia, Russia (11); the late Mesoproterozoic to early Neoproterozoic lower Shaler Supergroup (~1000–720 Ma), Arctic Canada (43); Tonian subsurface shales (~1000–720 Ma) in Botswana (44); the Tonian Tongjiashuang Formation (~1000–720 Ma), Tumen Group, western Shandong, North China Craton (37); the

late Mesoproterozoic to early Neoproterozoic (Tonian) Mbuji-Mayi Supergroup (~1000–720 Ma), Democratic Republic of Congo (41); and the Ediacaran of Estonia (45). The occurrence of *Leiosphaeridia* and its species in the Barut Formation extends their known paleogeographic ranges to Iran, supporting biostratigraphic and paleoenvironmental correlations among Norway, Africa, Russia, Canada, China, Estonia, and Iran (Figure 5).

Arctacellularia tetragona (Plate 2, 1, 5, 9, 13; 2, 6, 10; 17, 21; 19a–b; Plate 3, 17–19, 21–22) occurs in the productive samples of the Barut Formation (MG-19 to MG-30) at the Bashm locality, which yielded specimens of *A. tetragona*, which, as a putative fungus at different life-cycle stages, was later synonymised by Baludikay et

al. (41) with its type species. *A. tetragonala* consists of barrel- to oval-shaped cells that occur singly or in chain-like arrangements. Its previous records include: The Bylot Supergroup, Baffin Island, Canada ($\sim 1092 \pm 59$ Ma; 8); the Atar/El Mreïti Group, Mauritania (~ 1000 –720 Ma; 42); the Mbuji-Mayi [Bushimay] Supergroup, Democratic Republic of Congo (~ 1000 –720 Ma; 41); and the Tonian Mirojedikha Formation, Russia (~ 1000 –800 Ma; 33). The Barut Formation provides the first Iranian record of *A. tetragonala*, extending its paleogeographic range and supporting biostratigraphic and paleoenvironmental correlations among Canada, Russia, Africa, and Iran (Figure 5).

***Navifusa actinomorpha* (Plate 6, 21)** occurs in the productive samples of the Barut Formation (MG-19 to MG-30) of the study area. Researchers have documented this taxon in the Xiamaling Formation (~ 1.4 –1.35 Ga), North China; the Tonian Mbuji-Mayi Supergroup (~ 1000 –720 Ma), Democratic Republic of Congo (41); and the Tonian Tongjiazhuang Formation (~ 1000 –720 Ma), Tumen Group, western Shandong, North China Craton (37). The Barut Formation provides the first Iranian record of *N. actinomorpha*, extending its paleogeographic distribution and supporting correlations among China, Africa, and now Iran (Figure 5).

C) Prokaryotes, probably bacteria (29 species from 14 genera)

This group includes all remaining microfossils with simple organisation, preserved in filamentous colonial aggregates or as filamentous and coccoidal forms. The Barut Formation microfossil assemblage contains the following taxa: *Chlorogloeaopsis contexta* (6, 8) (Plate 3, 1); *Chlorogloeaopsis kanshiensis* (Plate 3, 5–10); *Chlorogloeaopsis zairensis* (Plate 3, 2–4); *Cephalonyx shahmirzadensis* sp. nov. (Plate 11, 12–16); *Cyanonema attenuatum* (13, 14) (Plate 2, 3, 4; 7, 8; 11–13; 15–16, 18); *Eoentophysalis belcherensis* (Plate 1, 1–8; 16–22); *Eoentophysalis croxfordii* nov. comb. (10) (Plate 1, 12, 13); *Eomycetopsis robusta* (13) (Plate 5, 19–23); *Eomycetopsis filiformis* (13) (Plate 5, 24); *Eomycetopsis alborzensis* sp. nov. (Plate 5, 16–17); *Myxococcoides minor* (13) (Plate 1, 10–11; 14–15); *Obruchevella parva* (38) (Plate 5, 1); *Obruchevella valdaica* (8) (Plate 3, 12; Plate 5, 2–3); *Ostiana microcystis* (Plate 1, 9, 23–24); *Oscillatoriopsis longa* (10) (Plate 8, 8, 11, 15–16; Plate 9, Figures 7, 13; Plate 11, Figure 10); *Oscillatoriopsis princeps* (Plate 8, 14, 18; Plate 9, 19b; Plate 10, 9–10, 18–19; Plate 11, 1, 5, 9; 2, 6; 11); *Oscillatoriopsis gigas* (17) (Plate 10, 6); *Oscillatoriopsis* sp. (Plate 10, 15; Plate 11, 18a–c); *Palaeosiphonella* sp. (Plate 5, 12–13); *Polysphaeroides biseitus* (Plate 4, 1, 5, 9); *Polysphaeroides filiformis* (Plate 4, 2–4, 6–8, 10–12); *Proterocladus hermannae* (Plate 4, 15); *Proterocladus*

major (Plate 4, 16–18, 20, 22); *Proterocladus minor* (Plate 4, 14, 19, 21, 23, 24); *Siphonophycus kestron* (13) (Plate 5, 5–8, 14–15, 18; Plate 10, 16; Plate 11, Figures 19–20); *Siphonophycus punctatum* (20) (Plate 11, 4, 8); *Siphonophycus solidum* (Plate 8, 5, 9, 13, 17; 6–7, 10, 12, 19–20; Plate 11, 3, 7; Plate 10, 8, 11, 14, 17, 20); *Siphonophycus typicum* (10) (Plate 5, 4, 9–10; Plate 11, 17); *Veteronostocale amoenum* (14) (Plate 2, 14, 19–20, 22–24). The following sections describe each genus and its taxa within this group in detail.

Chlorogloeaopsis (*C. contexta*, *C. kanshiensis*, and *C. zairensis*) occurs throughout the productive samples of the Barut Formation in the study area. Previous studies have documented this genus and its species in the late Mesoproterozoic to early Neoproterozoic (Tonian; ~ 1000 –720 Ma) Mbuji-Mayi Supergroup, Democratic Republic of the Congo (41), and the Atar/El Mreïti Group, Taoudeni Basin, Mauritania (42). Among the three species, only *C. zairensis* also occurs in the Neoproterozoic (Tonian; ~ 811.5 –788 Ma) Svanbergfjellet Formation in Spitsbergen, Norway (10). The Barut Formation yields the first Iranian record of these taxa, extending their known paleogeographic distribution and supporting biostratigraphic and paleoenvironmental correlations among Africa, Norway, and northern Iran during the Tonian Period (Figure 5).

Cyanonema (*C. attenuatum*) occurs abundantly in productive samples of the Barut Formation (MG-19–MG-30) at the Bashm locality. Researchers have documented this taxon in several successions: the Tonian Svanbergfjellet Formation (~ 811.5 –788 Ma) in Spitsbergen, Norway (10); the Tonian Bitter Spring Formation (~ 1000 –900 Ma) in the north-central Amadeus Basin, Australia (13, 14); the Tonian Tongjiazhuang Formation (~ 1000 –720 Ma), Tumen Group, North China Craton (37); the Sinian (Vendian) Dengying and Meishucun formations (~ 610 Ma) at Jinning, Yunnan, southwest China; and Ediacaran deposits of Estonia (45). Schirrmeister et al. also investigated this species in broader studies of Precambrian cyanobacterial evolution (46). The Barut Formation yields the first Iranian record of *C. attenuatum*, extending its paleogeographic distribution and supporting biostratigraphic and paleoenvironmental correlations among Norway, Australia, China, Estonia, and now Iran (Figure 5).

Eoentophysalis (*E. belcherensis* and *E. croxfordii*) occurs commonly throughout the productive samples of the Barut Formation at the Bashm locality. Researchers have documented this genus and its taxa in several localities, including the Paleoproterozoic Belcher Supergroup (~ 1.9 Ga), Canada (15); the Mesoproterozoic Xiamaling Formation (~ 1.4 –1.35 Ga), North China; and

the Neoproterozoic (Tonian) Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10). The Barut Formation provides the first Iranian record of this genus and its taxa, extending their paleogeographic distribution and highlighting potential biostratigraphic, paleogeographic, and paleoenvironmental correlations among Canada, China, and Iran (Figure 5).

Eomycetopsis (*E. robusta*, *E. filiformis*, and *E. alborzensis* sp. nov.) occurs in the productive samples of the Barut Formation in the study area. Researchers have previously documented this genus and its taxa in several successions, including the Neoproterozoic (Tonian) Bitter Springs Formation (~1000–900 Ma), Central Australia (13, 14); the Dengying and Meishucun formations (~610 Ma), Sinian (Vendian) System, Jinning County, Yunnan Province, southwest China; the early Neoproterozoic (Tonian) Deoban Limestone Formation (~1000 Ma), Lesser Himalaya, India (35); and the Neoproterozoic (Tonian) Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10). More recently, Riedman and Porter (24) reported this genus among organic-walled microfossils in the early Neoproterozoic (Tonian) Alinya Formation (~811–716.5) of the Officer Basin, Australia. The Barut Formation provides the first Iranian record of this genus and its taxa, extending their paleogeographic distribution and supporting potential biostratigraphic and paleoenvironmental correlations among Australia, India, Norway, China, and now Iran (Figure 5).

Myxococcoides (*M. minor*) and its species occur in the productive samples of the Barut Formation in the study area. This study documents the first record of this bacterial taxon in Iran. Researchers have previously reported it from several successions, including the late Proterozoic (Neoproterozoic) Bitter Springs Formation (~1000–900 Ma), central and north-central Australia (13, 14); the late Precambrian (Neoproterozoic) Deoban Limestone Formation (~1000 Ma), Lesser Himalaya, India (35); the Neoproterozoic (Tonian) Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10); the late Mesoproterozoic–early Neoproterozoic Mbuji-Mayi Supergroup (Tonian; ~1000–720 Ma), Democratic Republic of Congo (41); the late Mesoproterozoic–early Neoproterozoic lower Shaler Supergroup (~1000–720 Ma), Arctic Canada (43); and the late Neoproterozoic Chichkan Formation (~800–750 Ma), Southern Kazakhstan (32). The Barut Formation extends the known paleogeographic distribution of *M. minor*, highlighting potential biostratigraphic and paleoenvironmental correlations among Australia, India, Kazakhstan, Norway, Canada, and now Iran (Figure 5).

Ostiana (*O. microcystis*) and its species occur in productive samples of the Barut Formation in the study

area. This study records the first occurrence of this taxon in Iran. Researchers have previously documented it from several successions: the Neoproterozoic (Tonian) Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10); the late Mesoproterozoic–early Neoproterozoic Atar/El Mreiti Group (~1000–720 Ma), Taoudeni Basin, Mauritania (42); the Meso–Neoproterozoic Mbuji-Mayi Supergroup (~1000–720 Ma), Democratic Republic of Congo (41); the Tonian Tongjiazhuang Formation (~1000–720 Ma), Tumen Group, western Shandong, North China Craton (37); the late Mesoproterozoic–early Neoproterozoic lower Shaler Supergroup (~1000–720 Ma), Arctic Canada (43); the Neoproterozoic Wynniatt Formation (~850–750 Ma), Franklin Mountains, northwestern Canada (38); and in Siberia, where researchers question whether true Tonian–Cryogenian microfossils occur in Mesoproterozoic rocks (~1500 Ma; 47). The Barut Formation extends the known paleogeographical distribution of *O. microcystis*, highlighting potential biostratigraphic and paleoenvironmental correlations among Norway, Africa, China, Canada, Russia, and Iran (Figure 5).

Obruchevella (*O. parva* and *O. valdaica*) occurs in productive samples of the Barut Formation in the study area. This study documents the first occurrence of these taxa in Iran. Researchers have previously reported them from the Neoproterozoic (Vendian) sediments of the Russian Platform; the Mirojedikha Formation (~1000–800 Ma) and the Shorikha and Burovaya formations (~1000 Ma), Russia; the Bylot Supergroup (~1270–750 Ma), Baffin Island, Canada (8, 48); the Thule Supergroup (~1300–730 Ma), Greenland (40); the Avadh Formation (~1250–1150 Ma) and the Buxa Dolomite (~1000 Ma), India (36); the late Mesoproterozoic–early Neoproterozoic Mbuji-Mayi Supergroup (~1000–720 Ma), Congo, Africa (41); the Tonian Tongjiazhuang Formation (~1000–720 Ma), Tumen Group, North China Craton (37); the late Mesoproterozoic–early Neoproterozoic lower Shaler Supergroup (~1000–720 Ma), Arctic Canada (43); the early Neoproterozoic upper Alinya Formation (~811–716.5 Ma), eastern Officer Basin, Australia (24); and the Jubaylah Group (~600–540 Ma), the Arabian Peninsula (49). The Barut Formation extends the known paleogeographic distribution of *O. parva* and *O. valdaica*. It emphasises their value for biostratigraphic and paleoenvironmental correlations among Russia, Canada, Greenland, India, Africa, Australia, China, and now Iran (Figure 5).

Oscillatoropsis (*O. amadeus*, *O. gigas*, *O. longa*, and *O. princeps*) occurs in productive samples of the Barut Formation in the study area. This study records the first occurrence of this genus and its taxa in Iran. Researchers have previously documented this genus and its species

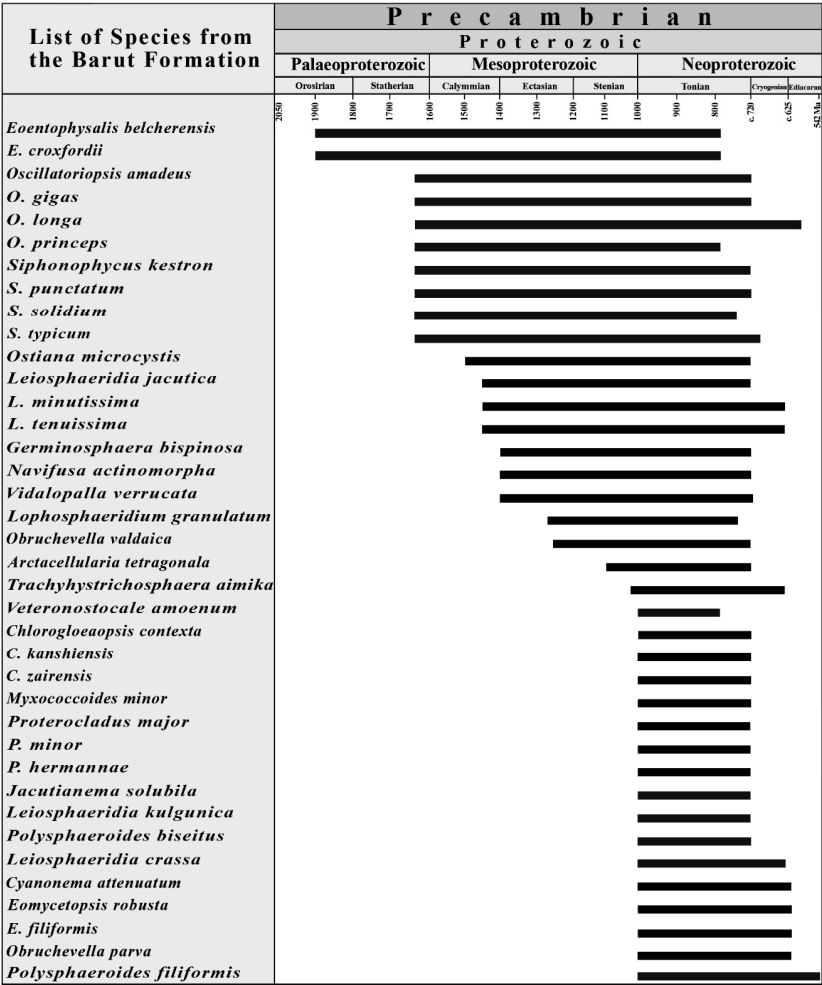


Figure 5. Stratigraphic ranges of carbonaceous microfossils in the Barut Formation, based on the radiometric references cited in the text and the new Precambrian chart (www.stratigraphy.org).

from several Precambrian successions: the Bitter Springs Formation (~1000–900 Ma), Central Australia (13); the Neoproterozoic (Tonian) Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10); the late Mesoproterozoic–early Neoproterozoic lower Shaler Supergroup (~1000–720 Ma), Arctic Canada (43); The Barut Formation extends the known paleogeographical range of *Oscillatorioopsis*, supporting biostratigraphic and paleoenvironmental correlations among Australia, Norway, Canada, China, and Iran (Figure 5).

Proterocladus (*P. major*, *P. minor*, and *P. hermannae*) occurs in productive samples of the Barut Formation in the study area. This study records the first occurrence of this genus and its taxa in Iran. Researchers have previously documented this genus and its species

from several Precambrian formations: the Neoproterozoic Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10); the Tonian Tongjiazhuang Formation (~1000–720 Ma), Tumen Group, western Shandong, North China Craton (37); and broader studies on evolutionary patterns and innovations during the Tonian Period (~1000–720 Ma; 26). This genus and its species occur only during the Tonian Period (~1000–720 Ma. The Barut Formation extends the known paleogeographic range of *Proterocladus* and confirms its Tonian age, supporting biostratigraphic and paleoenvironmental correlations among Norway, China, and Iran (Figure 5).

Siphonophycus (*S. kestron*, *S. punctatum*, *S. solidum*, and *S. typicum*) occurs in the Barut Formation in the

study area. This study documents the first occurrence of this genus and its taxa in Iran. Researchers have previously reported this genus from several Precambrian successions: the Bitter Springs Formation (~1000–900 Ma), central Australia (13); the Proterozoic Bylot Supergroup (~1092 ± 59 Ma), Baffin Island, Canada (50, 8); the lower Mesoproterozoic Kaltasy Formation (~1450 Ma), East European Platform (11); the late Mesoproterozoic–early Neoproterozoic Mbuji-Mayi Supergroup (Tonian; ~1000–720 Ma), Democratic Republic of Congo (41); the late Mesoproterozoic–early Neoproterozoic (Tonian; ~1000–720 Ma) Atar/El Mreïti Group, Mauritania (42); the lower Shaler Supergroup (~1000–720 Ma), Arctic Canada (43); the Svanbergfjellet Formation (~811.5–788 Ma), Spitsbergen, Norway (10); Tonian-age subsurface shales (~1000–720 Ma), Botswana, Africa (44); the Wynniatt Formation (~850–750 Ma), Franklin Mountains, northwestern Canada (38); the Ediacaran of Estonia (45); the Tonian Tongjiazhuang Formation (~1000–720 Ma), Tumen Group, western Shandong, North China Craton (37). The Barut Formation provides the first Iranian record of *Siphonophycus*, extending its known paleogeographic range to Australia, Canada, Norway, Estonia, China, and Iran, and confirms the Tonian age of the formation (Figure 5).

Veteronostocale (*V. amoenum*) occurs abundantly in productive samples of the Barut Formation in the study area. This study records the first occurrence of this genus and its species in Iran. Researchers have previously reported it from the Neoproterozoic Svanbergfjellet Formation (Tonian) (~811.5–788 Ma), Spitsbergen, Norway (10); the Dengying and Meishucun formations (~610 Ma), Sinian System, Jinning County, Yunnan Province, southwest China; the late Precambrian Bitter Springs Formation (~1000–900 Ma), north-central Amadeus Basin, Australia (14); the Neoproterozoic Buxa Dolomite (~1000 Ma), West Siang District, Arunachal Pradesh, India (36); and the Neoproterozoic Chichkan Formation (~800–750 Ma), southern Kazakhstan (32). The Barut Formation extends the known paleogeographical range of *V. amoenum* and underscores potential biostratigraphic and paleoenvironmental correlations among Australia, Norway, China, India, Kazakhstan, and Iran (Figure 5). This microfossil likely fixed nitrogen at night, when photosynthesis and oxygen production stopped. The occurrence of its representative taxa in the Barut Formation suggests that they engaged in similar activities approximately 1,000 million years ago.

Conclusions

Palynological analysis of the early Neoproterozoic (Tonian) Barut Formation provides significant geological

and paleontological insights. The study identified 47 carbonaceous microfossils assigned to 25 genera, including 29 species of probable cyanobacteria (14 genera), 11 eukaryotic acritarchs (8 genera), and 7 taxa of uncertain prokaryotic or eukaryotic affinity. This study records all these taxa for the first time from the Barut Formation. The microfossil assemblage includes one new genus and 7 new species, including *Cephalonyx shahmirzadensis* sp. nov., *Dictyotidium iranense* sp. nov., *Eomycetopsis alborzensis* sp. nov., *Germinosphaera iranense* sp. nov., *Pseudocerebrospira persianense* sp. nov., *Pseudocerebrospira iranense* sp. nov., and *Pseudocerebrospira verminosa* sp. nov., which enhance the biostratigraphic resolution of the Barut Formation and expand knowledge of Tonian microfossil diversity.

Radiometric and biostratigraphic evidence indicate that taxa such as *Eomycetopsis belecherensis* and *E. croxfordii* range throughout the entire Proterozoic Eon. In contrast, *Oscillatoriaopsis* spp., *Siphonophycus* spp., *O. microcystis*, *Leiosphaeridia* spp., *Germinosphaera bispinosa*, *Navifusa actinomorpha*, and *Vidalopalla verrucata* span the Mesoproterozoic and Neoproterozoic eras. The remaining taxa occur exclusively in the Neoproterozoic Era, confirming that the Barut Formation is Proterozoic rather than Lower Cambrian in age. Several taxa, including *Arctacellularia tetragonala*, *Chlorogloeopsis contexta*, *C. zairensis*, *C. kanshiensis*, *Germinosphaera bispinosa*, *Jacutianema solubila*, *Leiosphaeridia jacutica*, *L. kulgunica*, *Lophosphaeridium granulatatum*, *Navifusa actinomorpha*, *Proterocladus major*, *P. minor*, *P. hermannae*, *Siphonophycus solidium*, and *Trachyhystrichosphaera aimika*, serve as reliable index fossils. Their occurrence, combined with the absence of large acanthomorphic acritarchs, constrains the Barut Formation to a Tonian age (~1000–720 Ma). The Tonian Period marks the earliest phase of the Neoproterozoic Era, characterized by the breakup of the Rodinia supercontinent and early diversification of simple eukaryotic life. Comparisons with coeval assemblages worldwide support this interpretation and suggest a broadly similar microbial biosphere during the Tonian Period.

Cyanobacteria, among the earliest crown-group Eubacteria, played a crucial role in shaping Earth's biosphere for more than 2.5 billion years. They initiated oxygenic photosynthesis, transforming the atmosphere and hydrosphere, and gave rise to chloroplasts, ultimately leading to the evolution of plants. Modern cyanobacteria, such as those in the *Chroococcales*, *Nostocales*, and *Stigonematales* orders, continue to fix nitrogen and carbon, forming the foundation of primary productivity

in both ancient and modern ecosystems. The paleoenvironmental reconstruction indicates that some carbonaceous microfossils lived planktonically, whereas others inhabited benthic settings, suggesting that the Barut Formation accumulated in shallow-marine lagoonal to subtidal environments. Earlier geologists assigned the Barut Formation to either the Precambrian or the Lower Cambrian. However, the present palynological and stratigraphic evidence demonstrates that the Zaigun, Lalun, and Mila formations belong to the Cambrian, whereas the Barut Formation corresponds to the Neoproterozoic (Tonian) Era. These findings reveal a significant stratigraphic hiatus between the Barut and Zaigun formations, spanning the Cryogenian and Ediacaran periods ($\sim 720\text{--}538.8 \pm 0.2$ Ma).

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